NONDESTRUCTIVE EVALUATION TECHNIQUES FOR TIMBER BRIDGES

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An ongoing cooperative project is being conducted by Washington State University, the USDA Forest Service Forest Products Laboratory, and the US Federal Highway Administration to develop techniquies for the insppection, condition evaluation, and In-situ strength assessment of timber bridges. Overall structural integrity of a timber bridge is a function of both the integrity of the individual members and the structural system. Most current nondestructive evaluation (NDE) techniques for timber structures locus on detecting the presence of decay or naturally occurring defects in structural members. There is a need to combine inspection techniques for detecting localized flaws with a comprehensive assessment strategy that estimates their cumulative effects on overall structural integrity and strength.

INTRODUCTION

Timber bridges are often exposed to harsh environmental conditions. Over time, this exposure can lead to deterioration resulting from decay, insect attack, weathering, and mechanical damage. In turn, this deterioration may lead to a loss of structural integrity that is detrimental to the structure and its users. Nondestructive evaluation (N DE) is the science and art of determining the condition and properties of a material without impairing its future usefulness for its Intended purpose. Each NDE technique has both advantages and disadvantages that affect Its use, Proper application of NDE techniques allows for a more confident assessment of material properties and, in turn, structural integrity and residual capacity.

2. NDE OF TIMBER MEMBERS

Timber structural elements are susceptible to degradation due to environmental and loading conditions. This degradation weakens the member and can Inhibit the performance of the entire structure. A variety of inspection techniques can be employed to locate damage and decay in timber members in order to maintain structural performance.

2.1 Visual Inspection

Visual inspection is the simplest NDE technique, and should be the first step in assessing a timber bridge. Using visual inspection, technical personnel can quickly develop a qualitative assessment of the relative structural integrity of individual members. Obvious deficiencies can be easily identified, Including external damage, decay, crushed fibers in bearing, creep, or presence of severe checks and splits. Results of visual inspection can be employed to guide further NDE.

Visual inspection is very useful but has definite limitations. Variability stems from differences in visual acuity and training/experience of personnel. Access also poses problems. Components with limited access may be susceptible to increased error in interpretation of visual inspection, and unexposed components cannot be inspected at all. The results are qualitative, rather than quantitative, and knowledge is limited to the exterior surface of the wood.

2.2 Stress Wave

Stress waves are generated from an impact on the" surface of the material under investigation. The stress waves propagate at the speed of sound through the material and reflect from external surfaces, internal flaws, and boundaries between adjacent materials. The simplest method of utilizing stress waves is the time it takes for a stress wave to travel a specified distance. If the material dimensions are known, stress wave timing can be used to locate decay in timber members. Since stress waves travel slower through decayed wood than sound wood, the localized condition of a member can be determined by measuring stress wave time at incremental locations along the member. Locations that exhibit longer stress wave times are locations of potential decay.

Wave behavior in sound wood differs from that in decayed wood. In particular, a stress wave will typically attenuate more rapidly in decayed wood than in sound wood [1]. Bozhang and Pellerin were able to identify incipient decay by observing that sound wood transmitted higher frequency components while decayed wood transmitted only low frequency components [2].

A common use of stress waves is in determining the modulus of elasticity (MOE) for structural members. Using time-of-fright measurements over a predetermined length, the velocity of the stress wave can be calculated. Stress wave velocity can then be used to calculate the dynamic *MOE* of the material and estimate various strength properties using statistical correlations [1,3,4,5].

2.3 Ultrasonic

Ultrasonic inspection involves analysis of the characteristics of high fraquency ($f > 20$ kHz) stress waves propagating through a material. Ultrasonic inspection techniques have been explored for detecting strength-reducing defects such as knots, slope of grain, and decay in wood members. However, most applications of ultrasonic inspection for wood members have focused on estimating product quality in a manufacturing environment, rather than *in situ* condition assessment of members in wood structures.

Primary difficulties associated with ultrasounic inspection of wood memebers include effective ultrasonic coupling between the transducers and the wood surface, limitations on material dimensions for effective inspection due to the attenuative nature of wood, and requirements for access to opposing faces of wood members for transmitting and receiving ultrasonic energy. Since high frequency stress waves attenuate significantly over relatively short distances in wood (particularly for wave propagation across the wood grain), ultrasonic detection of decay and other defects is primarily effective in relatively small regions of wood members [6,7]. This limits the usefulness of ultrasonic field inspection for wood members with large cross sections in heavy timber structures. The requirement for access to opposing faces has been partially overcome in recent years with the development of a technique for introducing critically refracted longitudinal wave energy into wood products [8].

Many of the early efforts regarding ultrasonic inspection of wood members involved simple measurements of pulse travel time as indicators of knots, decay or slope of grain. However, researchers have recently begun to explore spectral analysis of ultrasonic signets for addtional sensitivity in detection of internal defects [9,10,11]. Future applications of ultrasonic inspection for *in situ* condition assessment of wood structures will depend primarily upon further progress in coupling technologies and development of advanced signal analysis techniques for assessment of material integrity and structural capacity.

2.4 Drill Resistance

Drill resistance is a quasi-nondestructive test that has been used to determine density end detect decay in trees and timber. It is classified as quasi-nondestructive because a small diameter (1.5mm - 3mm) hole remains in the specimen after testing. However, this hole is small enough to have only negligible structural effects on the remaining cross-section and may be sealed to prevent access for agents of decay.

Drill resistance devices operate under the premise that resistance to penetration is correlated with material density. Drill resistance is determined by measuring the power required to cut through the material. Plotting drill resistance versus drill tip depth results in a drill-resistance profile that can be used to evaluate the internal condition of a tree or timber member and identify locations of various stages of decay. The resistance profile can also be used to estimate member density and compares favorably with radiographic [12].

Due to the invasive nature of the drill resistance technique, and the fact that it provides a vary localized measure of density, this technique maybe best employed if used in conjunction with NDE methods that provide qualitative condition assessment (e.g., visual inspection) or regional condition assessment (e.g., stress wave or ultrasonic inspection). In such a scenario, visual or stress wave inspection could be used to locate expected regions of decay. Drill resistance measurements could then be taken at a limited number of key locations to determine the through-thickness condition of the wood. These measurements could be combined to predict *MOE* and possibly member strength.

2.5 Radiography

Radiography typically involves positioning a radiographic energy source on one side of an object and a recording medium such as film on the other side. Radiation travels through the object and exposes the film. Local material density controls how much radiation passes through the material resulting in a two-dimensional picture of density variation in the object under inspection. A more advanced technique called computed tomography (CT) can be used to produce a three-dimensional representation of the internal structure of an object. The object Is essentially radiographer at various orientations and then a computer is used to construct a three dimensional image.

The condition of structural timber members has been investigated using radiographic techniques both in the laboratory and under field conditions. Localized wood density has been accurately estimated by employing X-rays and gamma rays. Radiography has been used to investigate wood degradation due to fungal attack.

The investigation revealed that density determined radiographically corresponded well to gravimetrically-determined and decay [13].

Conventional radiographic techniques perform well In the laboratory and show promise for sawmill use, but the equipment poses some problems for *in situ* inspection of timber members. Portability and member access are two major problems for field implementation. The main drawback of using conventional radiographic techniques for inspecting structural members is that they utilize photoelectric absorption to produce an internal Image of the member. Photoelectric absorption inherently requires access to multiple sides of the member under inspection. Devices have been developed that require access to only one side of a member and develop density measurements by employing Compton scattering rather than photoelectric absorption. These devices include a portable device that measures reflected gamma rays and one that employs gamma back-scattering to predict localized density in wood members [14, 15].

2.6 Microwave / Ground Penetrating Radar

Microwave and millimeter wave inspection techniques involve the propagation of electromagnetic waves from probes (typically antennas) at frequencies ranging from 300 MHz to 300 GHz In dielectric (i,e., electrically insulating) materials. Separate transmitting and receiving probes may be employed for through-transmission techniques, or a single probe may be used for transmitting and receiving reflected wave energy. The term <<ground-penetrating radar>> is often used to describe reflected wave techniques that employ a single transmitting/receiving antenna.

Microwave inspection of wood has been investigated for assessment of material density, moisture content, and grain angle in automated lumber grading systems [16, 17]. Success has also been reported for detecting localized pockets of decay in standing trees [18]. Since electromagnetic waves are sensitive to the presence of moisture, it has been suggested that microwave techniques have significant potential for detecting decay in aging timber structures [19]. Furthermore, the detection of voids, decay, and delamination at the interface between timber bridge decks and asphalt wearing surfaces appears to be a natural extension of current commercial microwave inspection techniques for concrete bridge decks.

2.7 Vibration

Several areas of research have examined the use of vibration techniques to physically determine the condition of a material or structure. The theory is that all materials have a natural frequency at which they will vibrate. Any significant deviation from this theoretical frequency is an indication of possible damage in the member.

For timber nondestructive vibration techniques have primarily been used to determine *MOE* of the material. The technique of introducing vibratory motion into a single member and measuring its *MOE* is a basic physical phenomenon [20]. The resulting *MOE* supplies an indication of stiffness, but cannot directly measure the strength of the member. Correlatins between stiffness ans strength have been determined through emppirical studies so that the *MOE* can give an indication of strength based on these results.

Vibrational analysis has also been used to detect and locate damage in beams. Mazurek et al. applied Tishomenko beam theory and developed an analytical approach for evaluating how damage affects the dynamic behavior of an aluminum beam. The experimental vibrational response was recorded and compared with the analytical analysis. The first three mode shapes were employed to locate and determine the extent of damage in the beam. The mode with the greatest curvature at the damage location displayed the greatest initial change in mode shape [21]. Vibrational analysis may also be applicable to simple timber beams.

3. NDE OF OVERALL BRIDGE SYSTEMS

Nondestructive inspection of individual members provides valuable information about the localized condition of bridge elements. However, more information is required to assess the condition of a bridge as an entity. Two common methods employed for assessing the global condition of a bridge are dynamic system identification and diagnostic load testing. Bridge response to dynamic system loading can be compared to either a record of previous response or an analytical model of the bridge.

3.1 Dynamic System Identification

Vibration analysis techniques for full-scale structures have recently been investigated based on extension of the vibration methods used for simple-span members. However, the problem becomes much more complex since the structure has many more modes of vibration. Each vibration mode must be investigated in order to determine the characteristics of the structure. Modal analysis examines each mode shape of the vibrating structure and compares it either to previous experimental vibrational data on the structure or to predicted data obtained through finite element modeling. Differences in dynamic characteristics can be used to diagnose damage in the structure. The shape and natural frequencies of each mode are determined by placing sensors at various points on a bridge and exciting the structure. A variety of excitation sources have been employed including mechanical shakers, single known vehicles, and ambient vehicular traffic.

A study has been conducted on the dynamic response of a timber bridge in British Columbia, Canada. The researchers determined the natural frequencies of the bridge at five modes using a forcing hammer, ambient vibration, and a finite element model. The three methods were comparable for most modes. However, testing indicated that there was a significant effect on the frequency due to vehicle-structure interaction, particularly with a light vehicle (ambient vibration) [22].

Additional work on timber bridge dynamic response has been compteted in a cooperative study between Iowa State University, the Forest Products Laboratory, and the Federal Highway Administration. In preliminary results, the researchers established dynamic amplification factors for several bridges by comparing dynamic deflection data to static deflections [23,24]. The static deflection data was obtained by positioning a truck on the bridge span and measuring deflections. The dynamic deflection data was obtained by driving the same truck over the bridge at various speeds and approach conditions. The results indicated that the dynamic amplification factor is similar for two bridge types provided that approach conditions are similar. Future results will determine the effectiveness of this technique.

3.2 Diagnostic Static Load Tests

Diagnostic load tests typically involve relatively small static loads applied to a bridge. They provide valuable insight into the true elastic load-response behavior of a bridge, but they can only be used to aid in me prediction of the maximum load-carrying capacity of the structure. In contrast, larger proof loads must be applied to a bridge to directly determine a structure's safe load-carrying capacity.

4. CURRENT STATUS /PROJECT PLANS

A variety of NDE techniques can be employed by an inspector in order to determine the condition of an aging timber bridge. However, advances are needed to Improve the effectiveness of predicting timber strength end overall structural capacity from various NDE methods. The goal of this ongoing research is to develop a combination of techniques that will provide a more effective prediction of timber bridge condition and capacity. The components of this NDE system include advanced ultrasonic and stress wave inspection techniques for timber members and vibrational analysis of timber bridges. These techniques will be combined to pinpoint focalized damage in individual members and estimate the effects of this damage on the overall capacity of the structural bridge system.

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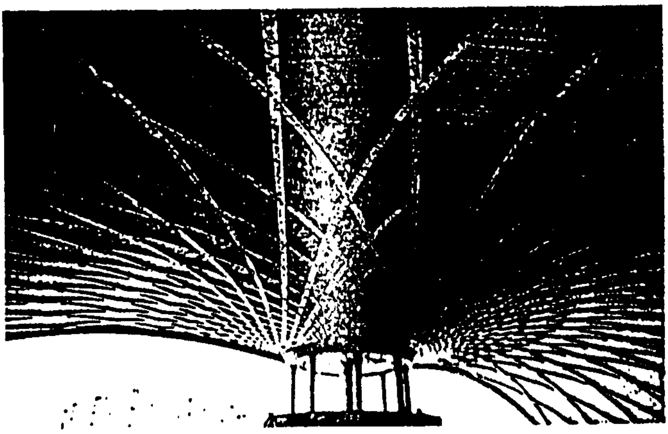

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