Advances in *in situ* evaluation of timber structures

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Summary

This paper discusses recent advances in nondestructive and semi-destructive techniques that are used to evaluate the condition and mechanical properties of wood members in structures with emphasis on historic buildings. Traditional methods for assessing the condition of timber are generally nondestructive, but may require probing or removal of small samples for species identification. Nondestructive techniques are useful for rapid screening of timber for potential problem areas or implying internal conditions, but typically are not particularly reliable for identifying material properties. Semi-destructive techniques require extraction of a small specimen for subsequent testing to determine elastic and strength parameters while preserving the integrity of the structural member. Both nondestructive and semi-destructive techniques are powerful aids to building conservation decisions.

Key words: wood structures; historic buildings; nondestructive evaluation; semi-destructive evaluation; resistance drilling; digital radioscopy; X-ray; core drilling; micro-specimens; mechanical properties

Prog. Struct. Engng Mater. 2004; **6**:94–103 (DOI: 10.1002/pse.170)

Introduction

Timber has been a traditional structural material for centuries, and numerous examples throughout the world demonstrate its durability and satisfactory performance. In historic structures, it is important to preserve the original fabric to the greatest extent possible. As timber is biodegradable, much of the damage observed in historic structures can be attributed to biodeterioration. The deterioration of structural members results in changes in geometry and load-bearing capacity. Replacement of deteriorated members may not be an acceptable option for structures of historic significance, and redesign may be necessary to sustain functionality of the structure.

Replacement of structural timber may be due to inappropriate assumptions about material strength or design values. The design values for timber in current standards are frequently based on 'in-grade' testing of full-size members (such as structural lumber) and estimates of the lower 5th percentile characteristic values. Current design values may not be appropriate for timber in historic structures, owing to assumptions of material quality or changes in design criteria. Although limited scientific evidence has been presented to document differences in quality between historic wood from 'old-growth' forests and new wood, it is known that old-growth material has higher mechanical properties compared to fast grown plantation-type wood[1]. It appears that the observed differences between mechanical properties of old and new timbers result from different growth rates, and thus differences in density, rather than age[2].

The design of any structural member is based on a stochastic approach where the probability of failure is kept reasonably low. For historic structures the accepted failure probability may be different from that generally accepted in design of new structures. Rejection of a timber member that has performed well for a century or longer simply because the member does not satisfy current design requirements is not sound practice. If a member 'works' we need to understand why it works. The mechanical properties of individual timbers in a new (not yet built) structure are not known, but often the mechanical properties of timbers in an existing structure can be measured *in situ* to reduce uncertainty about the resistance. Various methods can be used to estimate the load-bearing capacity of *in situ* timber structural members.

Nondestructive techniques are generally based on correlations between nondestructive and destructive parameters, and include stress wave, ultrasound and

Table 1 Average coefficients of variation for some mechanical properties of solid wood

Property	Variability (%)
Bending strength	7–20
Modulus of elasticity in bending	9–23
Impact bending	25
Compression parallel to grain	8–20
Compression perpendicular to grain	28
Shear parallel to grain, maximum shearing strength	14–22
Tension parallel to grain	25
Side hardness	20
Toughness	34
Specific gravity	5–13

other technologies[3,4]. For strength prediction, a major drawback of the nondestructive techniques is the relatively poor correlation between the measured nondestructive quantity and material strength. This correlation is often weak, owing to natural variability of wood properties, both between and within any sample. Table 1 lists the variabilities of typical mechanical properties of solid wood based on small-clear specimen tests[1]. The mechanical properties of wood vary significantly within a species. However, the variability of properties within a member is somewhat less than the variability between members, and is greater across the timber thickness when compared with the variability along the timber[5]. Density has a significant influence on wood mechanical properties[6] and the effect of a nondestructive parameter is frequently associated with the density. Density alone cannot explain the variability in mechanical properties and should not be relied upon as the sole predictor. Görlacher[7] has discussed the correlation between modulus of elasticity and strength of old timber and found that reasonable correlations can be developed for both new and old timber. Gloss[8] reports that the correlation coefficient between modulus of elasticity and either bending, tensile or compressive strength to range from 0.7 to 0.8. Moreover, no significant difference has been found between compressive, bending and shear strengths of old and new timber[2].

Destructive techniques for assessing mechanical properties of timbers in structures require removal of a sample of members from a structure and destructively testing them. Inferences are made about the strength properties of remaining members based on test values for sampled material. Clearly, such an approach is rarely acceptable in historic buildings, owing to the permanent loss of the pieces tested. As an alternative, various methods to evaluate timber *in situ* have been developed over the past several decades. List of various methods and their applicability can be found in the literature[9].

Nondestructive techniques

VISUAL INSPECTION AND SPECIES IDENTIFICATION

Visual examination of the wood allows for identifying components that are missing, broken or in an advanced state of deterioration. Missing components are those which have been removed or have fallen away, frequently due to extensive deterioration. If missing components were intended to provide structural support or protection from the elements (e.g. to prevent moisture intrusion), their replacement may be essential to prevent long-term damage to the structure. Visual inspection allows detection of past or current moisture problems, as evidenced by moisture stains on exposed surfaces. Further, visual inspection enables detection of external wood decay fungi or insect activity as determined by the presence of decay fruiting bodies, mycelial fans of fungal growth, insect bore-holes or wood substance removed by wood-destroying insects. Mycelial fans are the interconnected fibres of wood-destroying fungi (called hyphae). These fibres are the mechanism by which the fungus progresses through the wood. Visual inspection provides a rapid means of identifying areas that may need further investigation.

Internal decay is often masked by the lack of evidence on the exposed surface of the wood. For advanced decay, where large internal voids are present near the surface, probing allows for detection of potentially serious deterioration. Probing the wood with a sharp pick is intrusive, but enables rapid detection of voids in the wood not visible on the surface. Even for the early stage of decay, termed incipient decay, probing is beneficial and can reveal areas of incipient decay. Wood without incipient decay tends to offer more resistance to probing, owing to the higher density and more intact internal wood structure.

Small samples of wood can be removed from the timber members for identifying wood species. Species identification is accomplished by examining the anatomical features of the wood under a light microscope. Samples need to be of sufficient size to remove ultra-thin sections from various faces of the wood sample to examine the microscopic features not visible to the naked eye. These features may include resin canals, common to many coniferous woods, such as pines, or tyloses, found in hardwoods, such as oaks. Identification of particular features under the microscope is the most common means of reliably determining species of wood once it is cut from a defoliated tree. The physical appearance of wood may change with time, owing to weathering factors (moisture, temperature and ultraviolet light), however, the microscopic features generally remain unchanged. Mechanisms such as decay, fire or chemical interaction may destroy the microstructure of wood (as would occur in complete combustion), but so long as the wood sample is not completely destroyed it is usually possible to identify features which determine wood species. Knowing the species is important for estimating structural capacity, as different species can have quite different strength properties. Wood species may also be important for determining the historical significance of a particular timber within a structure.

STRESS WAVE AND ULTRASOUND METHODS

Stress wave and ultrasound methods for investigating wood are based on propagation of sound waves through wood. Although the terms are often used interchangeably, stress wave methods are generally low frequency (in the audible range) while ultrasonic frequencies are above the audible range. A summary of some of the research on stress wave methods is provided by the US Department of Agriculture[10].

Although stress wave and ultrasonic methods are affected by numerous factors, including moisture content, wood species and growth ring orientation, they are useful means of screening the condition of wood in structures. The most common application of either method is to measure the time for sound to travel through a piece of wood. Longer propagation times are generally indicative of deteriorated wood, or wood with lower stiffness or density. Density is an important variable that must be measured if one wants to utilize stress wave analysis to estimate dynamic modulus of elasticity. Density measurements cannot be effectively taken nondestructively, so tabulated values for various species are used in combination with stress wave time to predict modulus of elasticity. An alternative approach during field inspections is to imply 'relative condition' (soundness) of material based on 'relative propagation time'.

Stress wave measurements used to predict modulus of elasticity are useful when stiffness or buckling is a concern. Estimates of material strength, based on predictions of modulus of elasticity, can be subject to considerable sources of variation, including the factors noted above for stress wave measurements, as well as errors in the correlation between modulus of elasticity and strength properties. This is one reason why other methods are being developed, including the core-drilling technique described later in this paper. Similarly, quantification of deterioration due to decay or insect damage is difficult with stress wave measurements. Techniques such as resistance drilling, provide a more reliable means of quantifying deterioration in timber *in situ*. Nonetheless, stress wave methods offer the ability to rapidly screen large volumes of timbers for deterioration. Employing stress wave measurements in conjunction with other more definitive measurements is often effective for investigating the condition and integrity of structural timbers.

PIN DRIVING AND SCREW WITHDRAWAL METHODS

The Pilodyn method uses a steel pin of a fixed diameter driven into the material by a dynamic force. The depth of penetration is correlated with material density. Görlacher[11] developed relationships between the depth of penetration of a standard pin and the density of the wood. The correlation coefficient varied from 0.74 to 0.92, and depended on number of measurements and species. The empirical relationships are affected by moisture content. Thus, one should adjust the Pilodyn measurements to a common wood moisture content, such as 12%. Nail withdrawal tests have been used to estimate the densities in standing trees[12] and the method is potentially suitable in historic structures. However, the method suffers from relatively low correlation between the wood density and applied force (0.3–0.85). This correlation seems to be affected by species, therefore, species-based calibrations are required.

Similarly, one can use a screw withdrawal test to make inferences of material properties[13]. The correlation between the force required and density or strength is relatively weak and is affected by a number of parameters, including direction with respect to annual rings and moisture content.

RESISTANCE DRILLING

Use of a small-diameter needle-like drill was introduced by Rinn[14]. The cutting resistance of a needle is recorded as a function of depth as the needle penetrates the timber. The resulting profile can be used to determine the location and extent of voids and variation in material density. This technique is highly effective for quantifying the extent of deterioration in timbers[15]. Some researchers[16] reported relatively high correlation between effective drilling resistance and wood density. The effective drilling resistance is expressed as the area enclosed by the drilling resistance path. A typical plot of drilling resistance versus position for a 300-year-old timber is shown in Fig. 1. The drop in the drilling resistance indicates internal defects. Locations of the internal defects are easily detected, but no quantification of mechanical properties is possible. Note that the vertical axis shows the relative drilling resistance. While resistance drilling data correlate well with the X-ray densitometry measurements[17], some recent research[18] indicates that the correlation between the overall value of the wood density and drilling resistance has not yet been adequately developed for use in *in situ* evaluation ($r^2 = 0.21$–0.69).

DIGITAL RADIOSCOPY

Traditional X-ray technology, using film and high-energy X-ray sources, has been used to examine structures for over 40 years. However, owing to safety

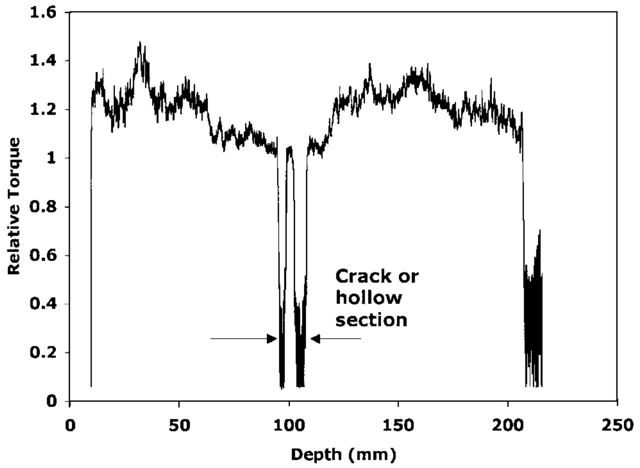

Fig. 1 Typical record obtained from drilling resistance measurement of 300-year-old timber with internal crack at 100 mm from the timber face

concerns and the high costs involved, use has been quite limited in structural timber evaluation. Use of digital real-time X-ray technology is quite recent and shows considerable promise for timber structures. Digital radioscopy offers significant advantages for assessment of structures over traditional X-ray techniques.

X-rays emitted from traditional high-energy electromagnetic radiation sources are capable of penetrating most materials used for building construction. Depending on the properties of the object being inspected, a photographic image is produced which reflects the density, thickness, energy absorption and chemical properties of the material.

Real-time radiography, or radioscopy, originated in the late 1800s. Termed fluoroscopy, it provided a two-dimensional image of an object of interest immediately on a screen. Because of its portable nature and ability to produce 'real-time' images, radioscopy, unlike film X-ray techniques, allows for easy manipulation of the test material during inspection, thereby allowing for better examination. Fluoroscopy had two primary disadvantages, which has limited its use: although somewhat portable there were safety concerns with the X-ray source and there was no means to store the image for later processing. Digital radioscopy does not have these disadvantages as technological advances make it safer to operate and images can be stored. Perhaps, though, the most useful feature is the ability to post-process the X-ray image by zooming in on particular details and changing contrast, brightness or position.

Hart[19] used X-ray analysis to examine the historic Narbonne house in Salem, Massachusetts. The goals of the examination were to determine the presence and configuration of wall bracing, possibly identify original window framing, and determine whether some of the framing had once been an exterior wall. Hart used a portable X-ray generator and Polaroid camera in the field to conduct the examination. The examination successfully identified the configuration of hidden structural braces. Further, the technique showed the type of fasteners used, and that the wood had no signs of decay. By examining exterior walls Hart was able to determine that no original window framing was present. The question of whether some of the framing had once been part of an exterior wall was inconclusive, owing to limited access with the X-ray equipment and modifications to the structure.

An X-ray examination of the House of Seven Gables was described by Wrenn[20]. Based on work conducted by Hart, Wrenn discussed the merits of using X-rays to assess the structural condition of wood in historic buildings. The ability to determine material conditions and construction without disturbing the fabric of the structure was seen as the primary benefit. However, Wrenn noted that the technique was limited by the inability to take an X-ray straight through an object and get a clear image.

Interest in the construction of the Delorme dome at Thomas Jefferson's Monticello led to an X-ray examination described by Harnsberger[21]. A Polaroid camera was used to record images taken through the domed roof. A portable X-ray emitter was mounted on a tripod near the dome ceiling while a receiver was placed above the exterior. The X-ray inspection revealed the type and pattern of fasteners used in the timber ribs supporting the dome. The examination allowed for an interpretation of Jefferson's use of Delorme's innovative timber framing system.

Concerns about load-carrying capacity led to an examination of connections in trusses in large military warehouses built prior to 1950[22]. The original structural framing in the buildings consists of timber frames with built-up timber trusses as roof supports. Cracks present in some of the truss chords, diagonals and verticals initiated the investigation to verify whether any metal fasteners exist in the connections between wood members that make up the trusses. A key question regarding structural integrity of the warehouses was whether metal fasteners were present in the connections in the built-up timber trusses. Although drawings of repairs to one warehouse were found that indicated that split ring connectors were present, it was not known whether this joint detail had been used in other warehouses. Therefore, digital radioscopy was used to examine the connections in selected warehouses to determine the presence of split rings; their size, number and condition; and the condition of the surrounding wood. A test configuration for the bottom chord with a single-bolted connection is shown in Fig. 2. This configuration was used for similar connections between horizontal truss chords and vertical and diagonal web members.

The radiograph resulting from the single-bolt connection is shown in Fig. 3. Four split ring connectors are visible in the radiograph. Although a scale is shown in Fig. 3, direct measurement of a

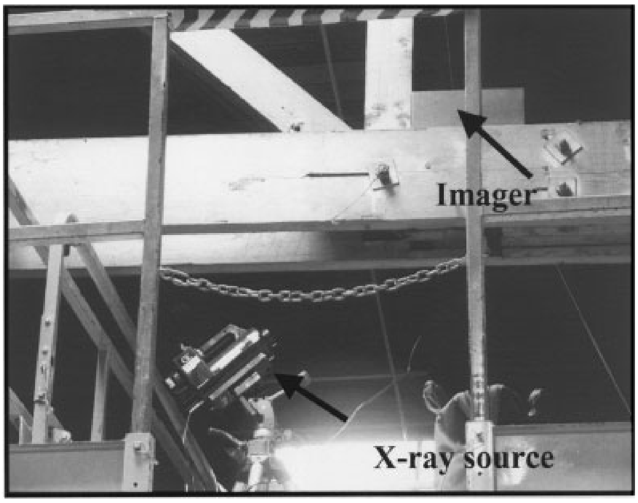

Fig. 2 Test configuration for digital radioscopy of bottom chord with a single-bolted connection

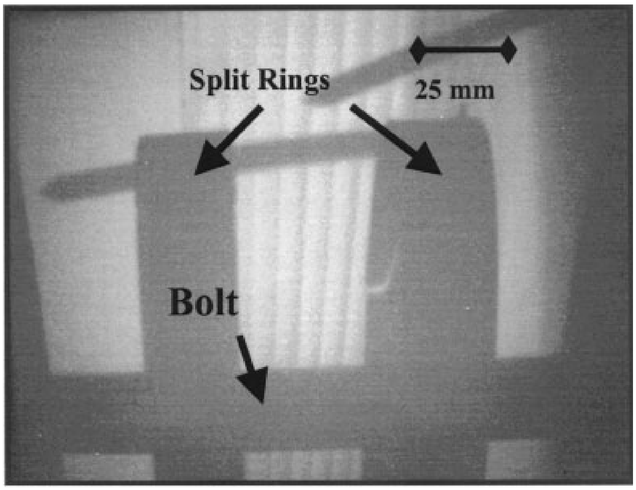

Fig. 3 Radiograph of bottom truss chord, view from below

component on the radiograph is not yet precise. Radioscopy essentially projects a three-dimensional object onto a two-dimensional image, resulting in somewhat distorted sizes. Precise dimensions can be obtained by stereoradioscopy and by measuring the distances between the X-ray source, the imager and the object of interest. The bolt, visible in Fig. 3, showed no evidence of corrosion as determined by observing the smooth, parallel edges of the bolt. The connections in the roof trusses used 4-in (10-cm) split ring connectors. Joints with diagonal web members used four split rings while splices in bottom chords used only two. As was observed on the bolts, the radiographs showed that the split rings are in good condition and do not exhibit signs of corrosion or failure. Further, on the basis of the radiographs, the wood adjacent to the fasteners is in good condition, and has not deteriorated.

In 1997 the balcony on Pavilion I at Thomas Jefferson's Academical Village at the University of Virginia collapsed. Four rods supported the balcony from above. The ends of the rods were embedded in timber beams and not accessible for visual inspection. The cause of the failure was determined to be a corroded iron rod. Post failure, digital radioscopy was used to determine whether corrosion of the iron rods could have been detected[22]. Fig. 4 shows an iron rod embedded in a timber beam in the same configuration used on Pavilion I. The rod was shown to have minimal surface corrosion as evidenced by the reduced cross-section of the rod within the beam. The remaining cross-section of the rod could be measured during post-processing of the radiograph data stored on a computer. Note the lack of a void in the wood surrounding the rod (no significant decay); a condition that might be expected if the corrosion was due to the presence of moisture.

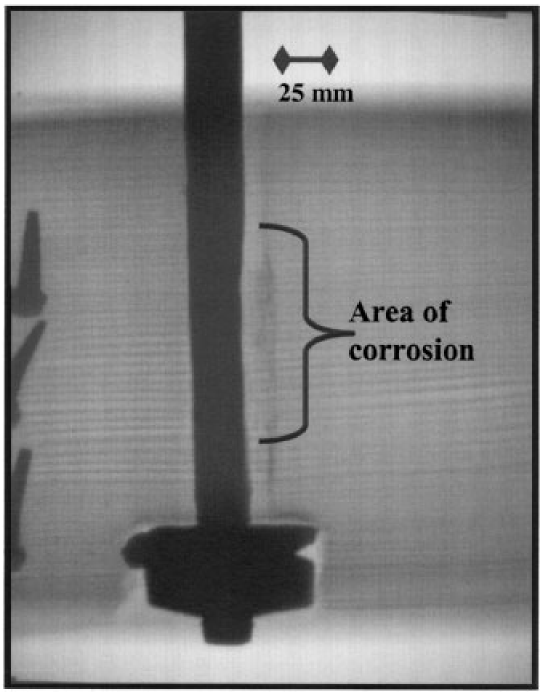

Fig. 4 Radiograph of a corroded rod embedded in a timber beam

Semi-destructive techniques

Reliability of the nondestructive techniques for determining material strength and stiffness can be enhanced by supplementing them with semi-destructive methods. In semi-destructive techniques, a small specimen is removed from a member and tested destructively. The size of the specimen relative to the size of the member must be sufficiently small that reduction in the cross-section is negligible. Member strength will always be lower than that of small specimens because of natural defects such as slope of grain, knots and wane that are always present in structural size pieces. Hence, the small specimen tests will represent an upper bound of the member strength and the strength of the full-size member must be estimated. No single method can give a full description of wood mechanical properties and a combination of methods is required for reliable strength prediction.

CORE-DRILLING TECHNIQUE

Core-drilling has been used to establish physical properties of wood and other materials for some time[23–26]. The core-drilling technique consists of a core drill (either manually or electrically driven) and testing fixtures used to establish material properties, such as compressive strength and modulus of elasticity. Cores of approximately 12 mm diameter have been used to determine shear strength of glue lines in the laminated timbers[27]. Rug[23] described the use of 15-mm diameter cores to measure the compressive strength of old and new timber loaded in the direction parallel to fibres. He found almost perfect correlation between the core compressive strength and strength of standard 20 × 20 × 30 mm specimens. Schwab *et al.*[24] reported the correlation coefficient between the compressive strength of 10-mm cores and standard 20 × 20 × 60 mm specimens to be 0.77–0.96, depending on the species. The variabilites of standard and core specimen compressive strength were comparable. A similar procedure was discussed by Erler[28]. One of the problems of establishing the regression relationship between cores and standard specimens is that both methods are destructive and a spatial variation between specimens within a sample will affect the correlation relationship. Theoretically, the mapping between the core strength and standard prismatic compression specimen should yield a correlation coefficient close to unity[29]. Other uses of core drilling include determination of density and age of the tree from which a member was cut[30].

Fig. 5 shows the core drill and a tool used by the authors to extract cores of 4.8 mm diameter. Owing to the fibrous character of the wood material, extraction of a high-quality core needed for subsequent mechanical testing is difficult because of friction forces between the tool surface and the core that can lead to a shear failure during drilling. Therefore, the inner diameter of the hollow drill must increase towards the drill end. The lateral motion of the drill is prevented by fixing the drill to the structural member, and a steady cutting speed is achieved by the mechanical feed.

The diameter of the hole is 10 mm in this case. In isotropic or quasi-isotropic macroscopically homogeneous materials, one can test the core in compression along the longitudinal axis of the core. This, however, is impossible for anisotropic material such as wood where all properties are directionally dependent. The strength properties of wood along fibres are the most important since they directly control parameters such as bending, tensile and compressive strength along fibres. The strength across fibres is often of lower importance since compressive strength (mostly seen in bearing) rarely yields to a catastrophic failure. Differences in strengths along and across fibres are significant, with design values for tension across wood fibres approaching zero, and accurate orientation of the load with respect to fibres is critical in estimating the material strength. Therefore, a concave compression head is used to induce parallel-to-grain force (Fig. 6a). The core is loaded in the direction perpendicular to the longitudinal core axis, and this generates a relatively complex stress state. Two miniature LVDTs are used to measure the deformation of the core, (Fig. 6b). A typical load–deformation curve is shown in Fig. 7. Fig. 8 shows the correlation between the slope and modulus of elasticity of specimens ($r^2 = 0.76$) and (Fig. 9) shows the correlation between compressive strength of the ASTM specimen and apparent strength of the tested core[29]. Clearly, a perfect correlation cannot be achieved, owing to the destructive nature of both experiments and inherent variability between specimens. The detailed reasons for the differences are discussed elsewhere[29].

The slope of the load–deformation curve is used to derive modulus of elasticity. The yield point corresponds to the compressive strength of the material. One cannot calculate the modulus of

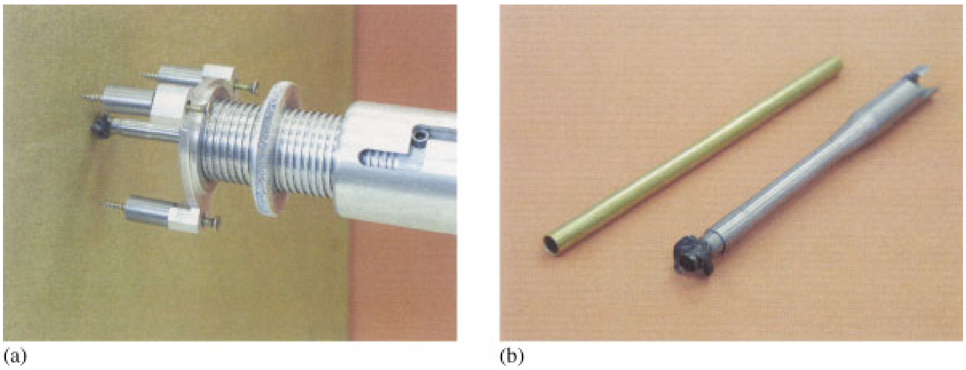
(a) (b)

Fig. 5 Core drilling device with the core drill for extraction of 4.8-mm diameter specimens

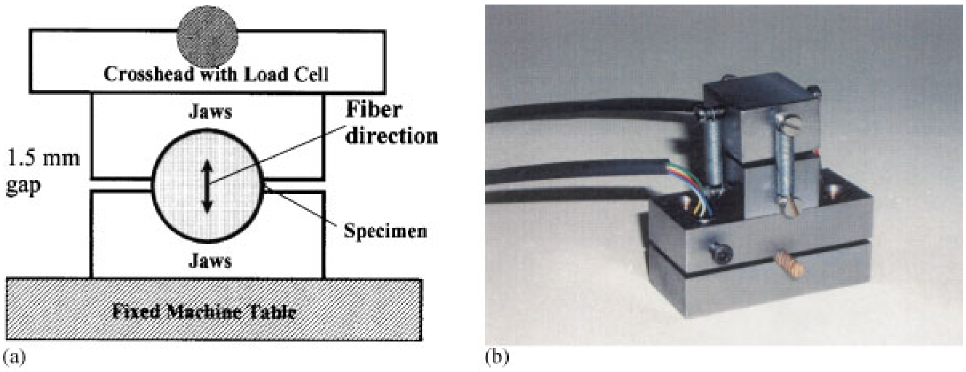

Fig. 6 Core and testing fixture for measurements of compressive strength and modulus of elasticity: (a) schematic; (b) actual device

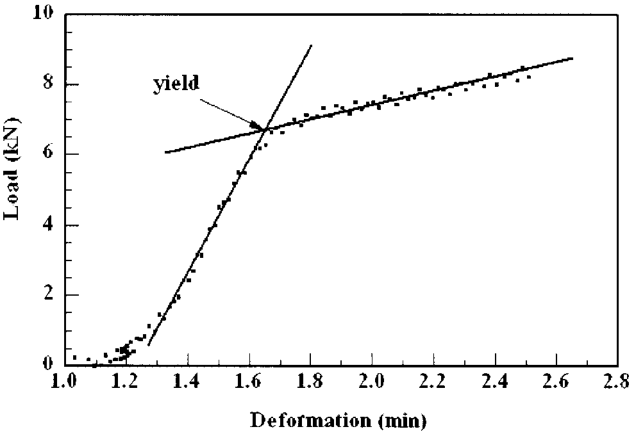

Fig. 7 Typical load-deformation curve for the 4.8-mm core tested in compression parallel to fibres[29]

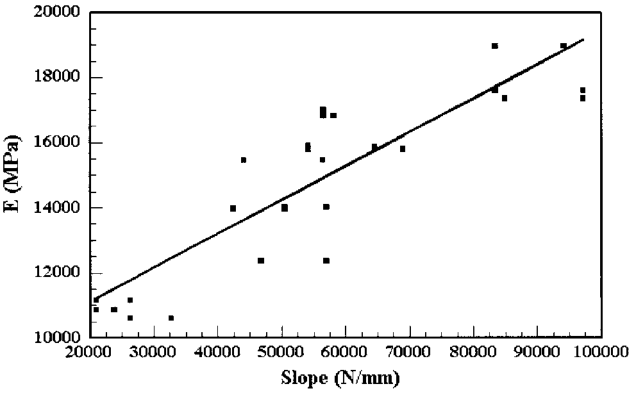

Fig. 8 Relationship between the slope of the load–deformation curve defined in Fig. 7 and modulus of elasticity of a small-clear specimen tested according to[1] ($r^2 = 0.76$)

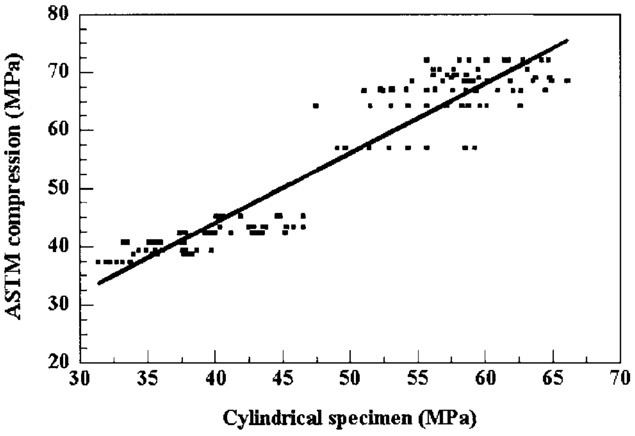

Fig. 9 Relationship between apparent compressive strength of the 4.8-mm core and the strength of small-clear specimens defined by[1]($r^2 = 0.89$)

elasticity from this test directly because of the nonuniform strain and stress distribution but the slope of force–deformation curves maps into the modulus of elasticity directly. From Fig. 6, it follows that maintaining the correct orientation of fibres with respect to the applied load (0°) is difficult and a slight error in orientation will result in reduced apparent strength and modulus of elasticity. The sensitivity of the strength measurements to error in angle of force with respect to fibres is shown in Fig. 10. The core-drilling technique suffers from sensitivity to an error in specimen orientation, but will always result in conservative estimates of material strength.

TENSION MICRO-SPECIMEN TECHNIQUE

One of the challenges in nondestructive evaluation of historic timber members is to estimate the strength in bending. Bending and compression along fibres are predominant types of loading. While compressive strength can be relatively accurately predicted from the core tests, the bending strength requires much larger specimens. If one knows the material strength in tension and compression, one can design a member under bending. The correlation between tensile and compressive strength of wood is weak because of different failure mechanism in tension and compression. A technique exists for extracting specimens of small cross-section from the timbers such that the cross-sectional area of specimens is significantly smaller than the area of the members. This is achieved by a small diameter thin kerf saw inclined at 45° relative to the surface of the beam (Fig. 11). Two cuts are required to obtain a prismatic

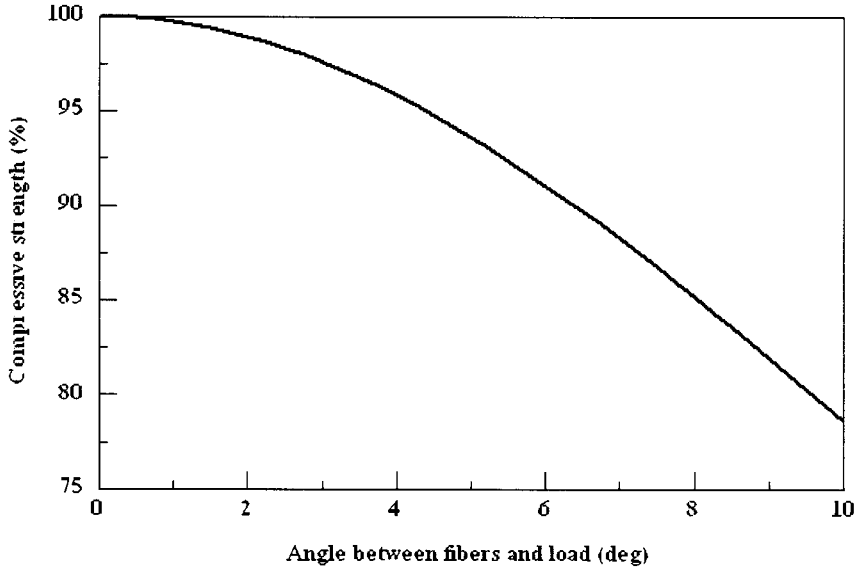

Fig. 10 Effect of misalignment between wood fibres and load on compressive strength. Compressive strength perpendicular to fibres is 10% of the one along fires

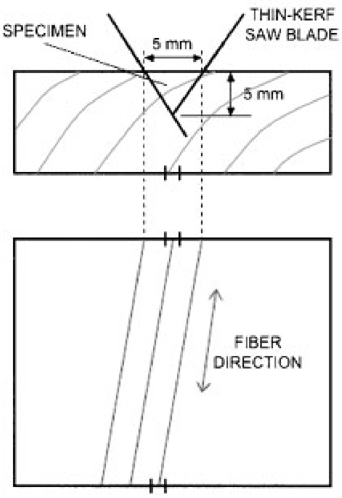

Fig. 11 Schematic of extracting the tension micro-specimen from timber surface

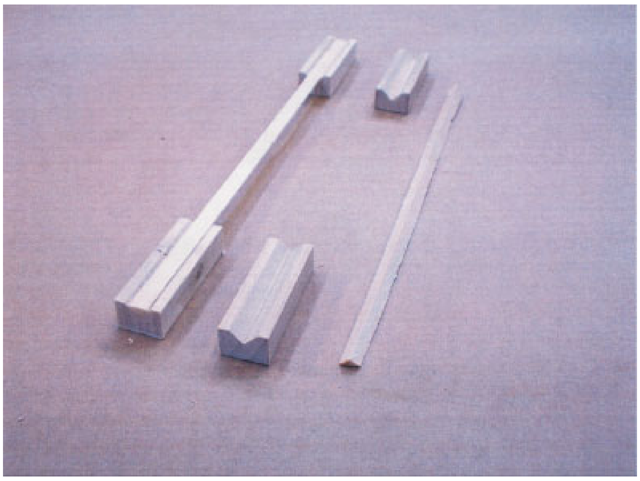

Fig. 12 Tension micro-specimen mounted on the test blocks

specimen of triangular cross-section. The side of the triangular specimen can be adjusted from 3 to 8 mm length, depending on the depth of the cut. The typical test specimen is shown in Fig. 12.

The ends of specimens are attached with epoxy adhesive to grooved wooden blocks so that potential end effects due to clamping are minimized. Tensile tests are performed with special grips (Fig. 13). A displacement transducer is used to measure deformation so that the modulus of elasticity in tension along fibers can be obtained. A typical stress–strain curve for a specimen is shown in Fig. 14. The cross-sectional area of the specimens is comparable to the cross-sectional area of the ASTM tension specimen (about 8 mm^2) that is required for small-clear specimens of wood[1]. Therefore, the values obtained from this test are directly comparable with the standard tests, and no correlation is needed. To induce failure in the central portion of the triangular specimen, it is recommended to reduce the cross-section of the mid-span. Such reduction can be done by sanding, but caution must be exercised to maintain a smooth plane to avoid variation in cross-sections.

Experiments were performed by the authors with several different species that included red oak, western cedar, hard maple, and southern yellow pine. The goal of the test was to observe failure modes and investigate the feasibility of the technique in strength evaluation of *in situ* timbers. Fig. 14 shows typical test results. The modulus of elasticity in tension and tensile strength can be easily obtained.

One of the drawbacks of these methods is the local character of measured quantities and the effect of position on the experimental data. A relatively large number of specimens must be extracted from the structure to ensure reliable data. Randomizing the distribution of samples is a critical procedure and

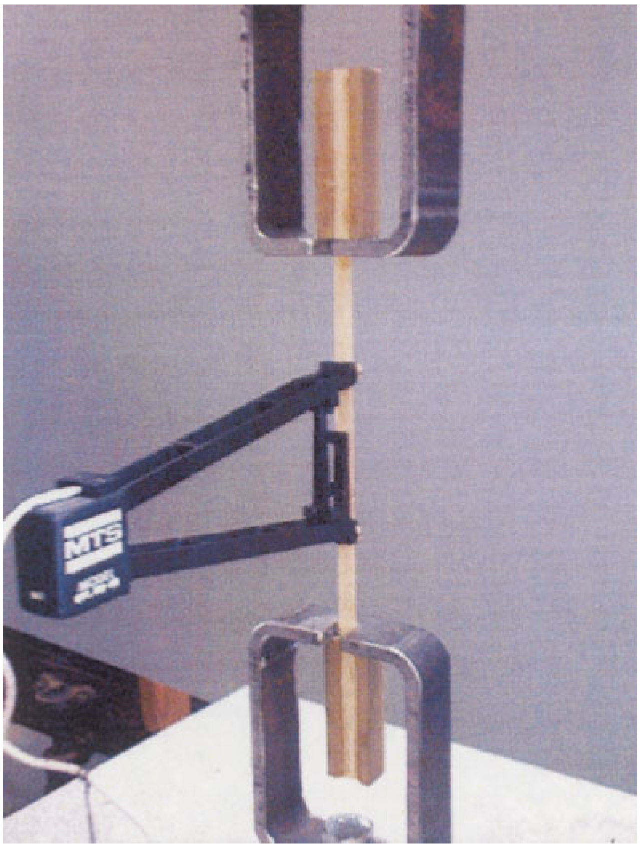

Fig. 13 Testing of the tensile micro-specimen. The central portion defining the gauge length is machined to a smaller cross-section

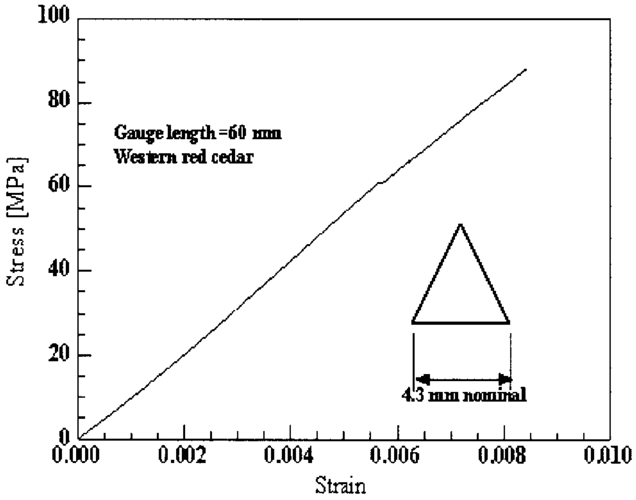

Fig. 14 Stress–strain relationship for a test of tensile micro specimen shown in Fig. 14

careful experimental planning must be involved. It should be pointed out that the semi-destructive methods give results comparable to small-clear specimens and the values must be converted to the properties of full structural members. This process requires known correlations between natural defects and mechanical properties. Although procedures for converting the small-clear specimens values to the design values exist[1], their application requires visual assessment of the defects, which is highly subjective.

Conclusions

Nondestructive techniques provide the means to rapidly screen timbers for potential problem areas, or they can be used to provide images of internal condition of construction. However, these methods suffer from relatively unreliable results when predicting material properties. The methods can give reasonable comparative measurements, but suffer from errors resulting from weak correlation between destructive and nondestructive parameters. Destructive methods are sometimes used to obtain direct strength measurements, but they require an extraction of the timber, which may be unacceptable in historic structures. Moreover, several members must be extracted to minimize the errors resulting from variability of material.

Digital radioscopy provides investigators with the means to assess connections and deterioration in timber structures without costly or damaging destructive testing. The type, location and condition of fasteners can readily be determined. Quantifying the remaining cross-section in timber damaged by termites, decay or other deterioration is feasible, but additional research is needed for the technique to be more useful to practitioners.

Semi-destructive methods can bridge the gap between indirect nondestructive and direct fully destructive methods of strength measurement. The weakness of the semi-destructive methods is the necessarily small size of specimens that leads to increased variability in test observations. This means that careful spatial distribution of samples and statistical experiment planning and evaluation is crucial to obtain representative data. The small specimens yield only material properties that must be further processed to calculate strength of full-size timbers. This is done via correlations with macroscopic parameters such as size and location of natural defects. The nondestructive methods such as ultrasound or stress wave analysis can play a role in minimizing the errors.

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