BOLTED TIMBER CONNECTIONS. PART I. A WAFER TECHNIQUE TO MODEL WOOD DEFORMATION AROUND BOLTS[1]

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ABSTRACT

An experimental technique to model wood material behavior in the plane perpendicular to the axes of bolts in joint members is described. In this technique, 0.8-mm-thick wood wafers sandwiched between glass plates, with a steel pin representing a bolt passing through them, are loaded in tension. Wood deformation and failure around the pin, visible through the glass plates as loading proceeds, are photographed, and load-slip curves are also recorded. Reported tests were limited to steel pins of 12.5-mm diameter; preliminary findings suggest that information can be gained that sheds light on the effects of growth-ring orientation, wood defects, bolt end-distance, and multiple-bolt positions. The technique may be used directly, to indicate the sensitivity of joints to design factors such as those above, or indirectly, when results are combined with bolt bending data obtained with X-ray scanning.

Keywords: Bolted joints, wafer technique, material behavior, design optimization, tensile loading.

INTRODUCTION

Attempts to develop efficient designs for bolted timber connections have, until quite recently, largely depended on empirical methods in which many joints of differing design have been manufactured and subsequently tested. Such was Trayer's (1932) approach, and he is widely credited with laying the foundations upon which current U.S. design practices are based. The work has served the design community well for over half a century. However, the increasing demand for modern structural systems, sensitive to changes in the nature of the raw material coming from today's forests (Bendtsen 1978; Galligan et al. 1980), has heightened the need for new design practices.

The behavior of even the simplest joint configuration is affected by a daunting array of interactive factors. The relatively small size of the round bolts that transfer load from one timber member to another is alone sufficient to create complex stress and strain distributions within the wood surrounding them, and this complexity is compounded by the tendency of the bolts to bend.

A more appropriate approach might be one through which we gain an understanding of how wood properties interact before forming models capable of predicting the behavior of whole joints. Noteworthy among such approaches are the European Yield Theory of Johansen (1949) for single bolts, and the work of Isyumov (1967), Cramer (1968), Lantos (1969), Wong and Matthews (1981),

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Rowlands et al. (1982), and Wilkinson (1986), who variously considered single- and multiple-bolted joints using a range of finite element and fracture mechanics analyses. Such approaches, which have been most competently reviewed by Soltis and Wilkinson (1987), have already provided some insight, and may ultimately furnish engineers with highly satisfactory design tools. Indeed, a number of models predict, quite accurately, the properties of idealized joints that have been fabricated within fine tolerances from uniform and defect-free material. Models developed by Lantos (1969), for example, satisfactorily predict the performance of joints with linearly oriented multiple bolts, and Lantos' theories have been employed in design methods (National Forest Products Association 1986). The effects of variability in wood properties due to growth fluctuations and defects, wood moisture content, joint fabrication tolerances, and load duration do, however, add extra dimensions to the design problem, and the complexity of wood structure and properties has required simplifying assumptions to be made in many of the analyses; this has limited their applicability somewhat. Most models depend entirely on theories of either elastic or plastic behavior without regard for their interaction. Moreover, these nonlinear material characteristics are themselves affected by the ever-changing combinations of multidirectional stress and strain that develop in the material surrounding connectors as loading progresses.

An experimental technique is described herein for modeling wood deformation in the plane perpendicular to the bolt axis. Thin wood wafers sandwiched between two plates of optical quality glass with a steel pin interposed are observed during loading. Information about the sequence of wood crushing and crack growth is captured photographically as the wafer is drawn past the stationary pin. The use of birefringent (Stieda 1965), moiré (Budynas 1977), or brittle films (Fritz 1967) or overlays to measure surface strains is inappropriate because the glass plates used to support the wood wafer would restrain free movement of the film. Furthermore, the present method has the advantage of enabling the mechanisms of wood deformation to be observed directly. Load-slip curves are also recorded. The technique may be used directly to gauge the sensitivity of the wafer-pin arrangement to factors such as wood quality and pin position, or indirectly when results are combined with bolt bending data collected by testing complete joints of corresponding design. The X-ray scanning method used to quantify bolt bending, and combination of the data from both X-ray scanning and the wafer technique, is dealt with in a related study (Humphrey and Ostman 1989). Further details of some of these experimental techniques are reported by Ostman (1985).

MATERIALS AND METHODS

Preparation of test specimens

Wood wafers with both tangential and radial surfaces were cut from a 150- × 150-mm × 4.8-m piece of clear, vertical grain, Pacific Coast Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] with a moisture content (MC) of approximately 60% (oven-dry basis). The parallel, or end-slicing, technique was used because it avoids the creation of lathe checks and enables thin wafers of high surface quality to be produced.

Selection of wafer thickness was influenced by: 1) opacity, which affects the transmission of light necessary for material observation; 2) issues related to wood

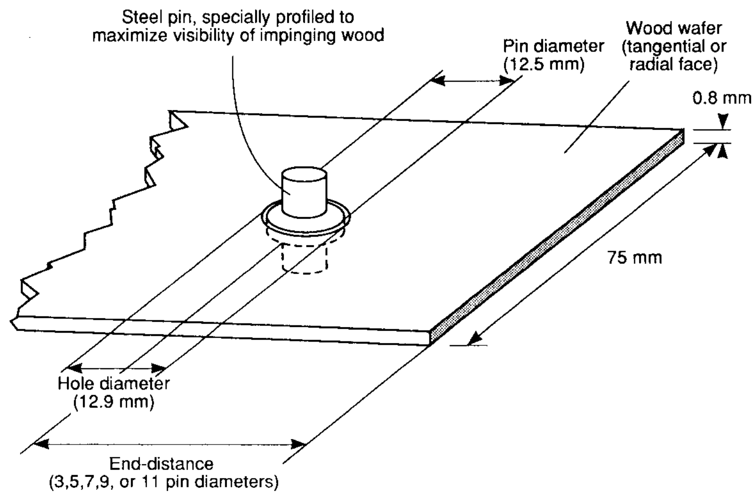

FIG. 1. Schematic representation of a drilled wood wafer with steel pin in position.

variability and fine structure; and 3) machining limitations. Regarding 2), as wafer thickness is reduced, so material characteristics visible on the surface become increasingly representative of those lying directly beneath. The effect of wood variability in this dimension is thereby reduced, and the behavior in the plane of the wafer can be directly attributed to the interaction of visible characteristics. However, as wafer thickness approaches the cellular level, continuity of material would be lost and the mechanisms of deformation and failure could be significantly influenced by interfacial or boundary effects. Following a range of trials, a wafer thickness of 0.8 mm was selected as a compromise among the three listed factors, enabling the effects of growth-ring structure (earlywood and latewood) to be resolved when tangentially surfaced wafers were tested, while maintaining a structural level an order of magnitude greater than the diameter of individual cells.

Testing procedure

A specially profiled steel pin (representing a circular cross section of a bolt) passes through a predrilled hole in the wafer (Fig. 1) and also through aligned holes in the optical quality glass plates. The testing assembly, held together in a rigid stainless-steel supporting frame, is mounted on a screw-driven universal testing machine (Fig. 2). The machine screws around the periphery of the supporting frame hold the components together during each test; controlling screw tightness with a miniature torque wrench allows almost uniform restraining pressure to be transferred across the wafer surfaces. The lower edge of each half of the frame is recessed to allow the wood wafer to pass through. This end of the wafer is attached to the cross-head of the testing machine with grips that transfer load uniformly across the width of the material. The upper part of the frame is connected to the load cell by a 12.5-mm diameter steel dowel that passes through the assembled frame and forms a self-aligning connection.

Intense rear illumination of the wood around the steel pin exposes changes in the wood as the wafer slides between the glass plates and is drawn past the stationary pin; these changes are recorded photographically (for each test, about

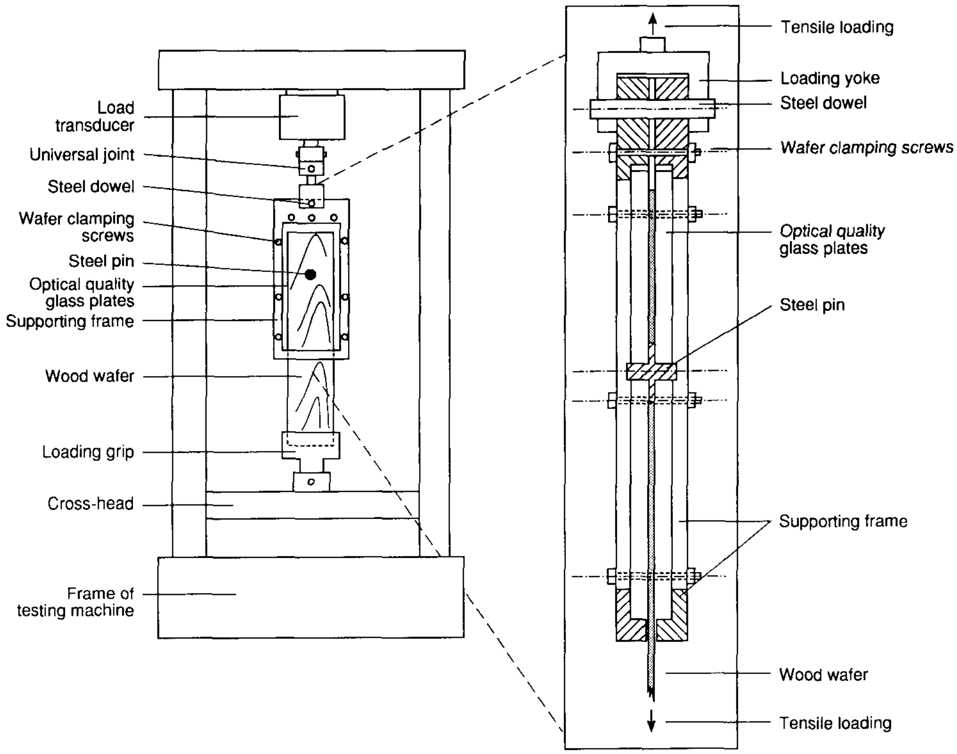

FIG. 2. Wafer-pin testing arrangement (frontal and enlarged cross-sectional views).

2 frames/min during elongation at a rate of 1 mm/min). Additional photographs are taken following periods of rapid material activity. Care was taken to minimize heating and associated localized drying of the wafer by 1) shielding much of the equipment from the light with aluminum foil, 2) blowing air across the surface of the glass, and 3) using an infrared filter over the light source.

Load versus displacement data were collected for each wafer tested. Before these data were plotted, two corrections were made: 1) measured load values were corrected for frictional drag between the wood and glass, and 2) cross-head displacement values were corrected for elongation of the supporting frame and wood wafer. Regarding 1), sliding frictional drag forces were measured with tests conducted in the absence of the steel pin, and a mean value of 95 N was obtained (there appeared to be no significant difference between wafers with radial and tangential surfaces). Regarding 2), reliable values for slip of a typical wafer past the pin were obtained at selected stages during loading by projecting the photographs on a large screen where displacements could be inferred by scaling off the known diameter of the steel pin. The displacements were gauged within ± 0.05 mm from the undamaged portion of the hole in each wafer. Cross-head movement was compared with actual slip at a range of measured load values, and it was found that the frame and wafer extended by approximately 0.4 mm per kN of applied load; this correction was subsequently applied to all cross-head movement data.

Wafer-pin arrangements tested

A limited range of tests was conducted to evaluate the technique. For all tests, wafers were 75 mm wide and 430 mm long, and the amount that the diameter of each hole drilled exceeded that of the central annulus of the pin (12.5 mm) was held constant at 0.4 mm; small variations in bolt-hole clearance are known to significantly affect joint behavior (Wilkinson 1978). Two factors influenced this choice of wafer width and pin diameter. First, considerable experimental data have been accumulated on complete double-shear joints of similar configuration (Stluka 1960; Wilkinson 1978; McLain and Thangjitham 1983), and some comparison of results may, therefore, be possible. Second, the arrangement was manageable on the available testing apparatus while corresponding to joints lying within the range of sizes used in commercial building systems.

Most tests were with defect-free radially surfaced wafers incorporating a single pin at an end-distance of seven pin diameters (87.5 mm). This design has been termed the "standard configuration" for the purposes of the discussion to follow. To assess the potential versatility of the technique, selected aspects of the standard configuration were, however, varied in turn. These aspects included growth-ring orientation, wood defects (a knot) in the vicinity of the pin, different bolt end-distances, and three multiple-bolt configurations.

RESULTS AND DISCUSSION

Standard wafer-pin configuration

A representative load-slip curve for a defect-free radially surfaced wafer tested with a single pin at an end-distance of seven diameters is shown as curve "a" in Fig. 3. Because wood deformation is less clearly displayed for radially than tangentially surfaced wafers, only one photograph of the former (at an intermediate slip level) is included (Fig. 4). (A complete set of photographs is later presented for joints with tangentially surfaced wafers.) Some of the main zones and modes of stress apparent in the test results are represented schematically in Fig. 5 as an aid to discussion.

During the early stages of each test, applied loads were mainly absorbed elastically. Observation of wafer surfaces (Figs. 4, 6) suggests that, as loading progressed, two types of material damage occurred near the pin: compression parallel to and inclined to the grain (Fig. 5, modes "a" and "b"). The onset of these coincided with a leveling off of the load. It is reasonable to assume that the transverse compression of the fibers on either side of the pin led to the transfer of tension stresses perpendicular to the grain in material lying above and below the pin (Fig. 5, mode "c"). This is supported by the results of numerical analysis by a number of workers (e.g., Wong and Matthews 1981).

The relatively slow growth rate of the material tested meant that ring width was small (typically 3 mm) compared to pin curvature (6.25-mm radius). The position of the pin relative to impinging growth rings did not, therefore, appear to significantly affect mechanisms of longitudinal wood failure. For faster grown material or for smaller pins, where stress gradients within the material may be large in comparison with the number of growth rings per unit length, pin position relative to radial transitions within the impinging growth rings could, however, significantly influence behavior.

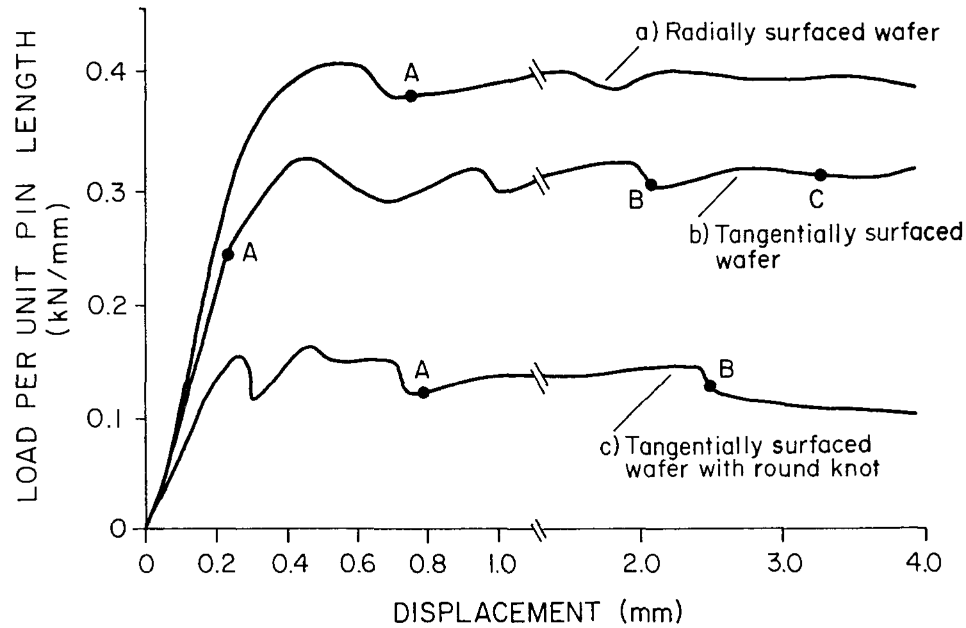

FIG. 3. Representative corrected load-slip curves for a) a radially surfaced wafer (code letter A corresponds to the stage at which the photograph in Fig. 4 was taken); b) a tangentially surfaced wafer (code letters A, B, and C correspond to the first three photographs in Fig. 6); and c) a tangentially surfaced wafer with a round knot (code letters A and B correspond to the first two photographs in Fig. 8). All pins were at an end-distance of seven pin diameters.

As cross-head movement continued, the length of the zone of compression parallel to the grain extending above the pin steadily increased, and loads supported by the system remained quite stable until catastrophic crack growth and failure. The boundary between the zone of fibers buckled parallel to the grain and surrounding intact material was clearly demarcated by shear dislocations (Fig. 5, mode "d"), which usually provided the initiation sites for longitudinal cracks.

Wafers failed when energy stored in the system was dissipated less rapidly than the energy necessary to maintain crack propagation. Clearly, therefore, the extent to which such cracks will propagate depends not only on the characteristics of the joints themselves, but also on the stiffness of the loading frame and length of the timbers linking the joints to the frame. This issue leads to difficulties when the fracture mechanisms reported by different researchers using widely differing testing arrangements for otherwise similar joints are compared. With the present approach, we could reduce distortion of the testing apparatus to very low values (as specified above) because absolute loads were orders of magnitude less than those necessary to test corresponding whole joints. The length of the material extending beyond the joints themselves was a compromise between maximizing axial stiffness and ensuring that wafer behavior remained unaffected by the proximity of the connection between the wafer and supporting frame. Clearly, joint testing methods must be standardized to overcome problems of comparability.

Lateral (parallel to the bolt's longitudinal axis) growth of cracks is not accounted for by the wafer technique. Stress gradients in the plane parallel to the bolt axis

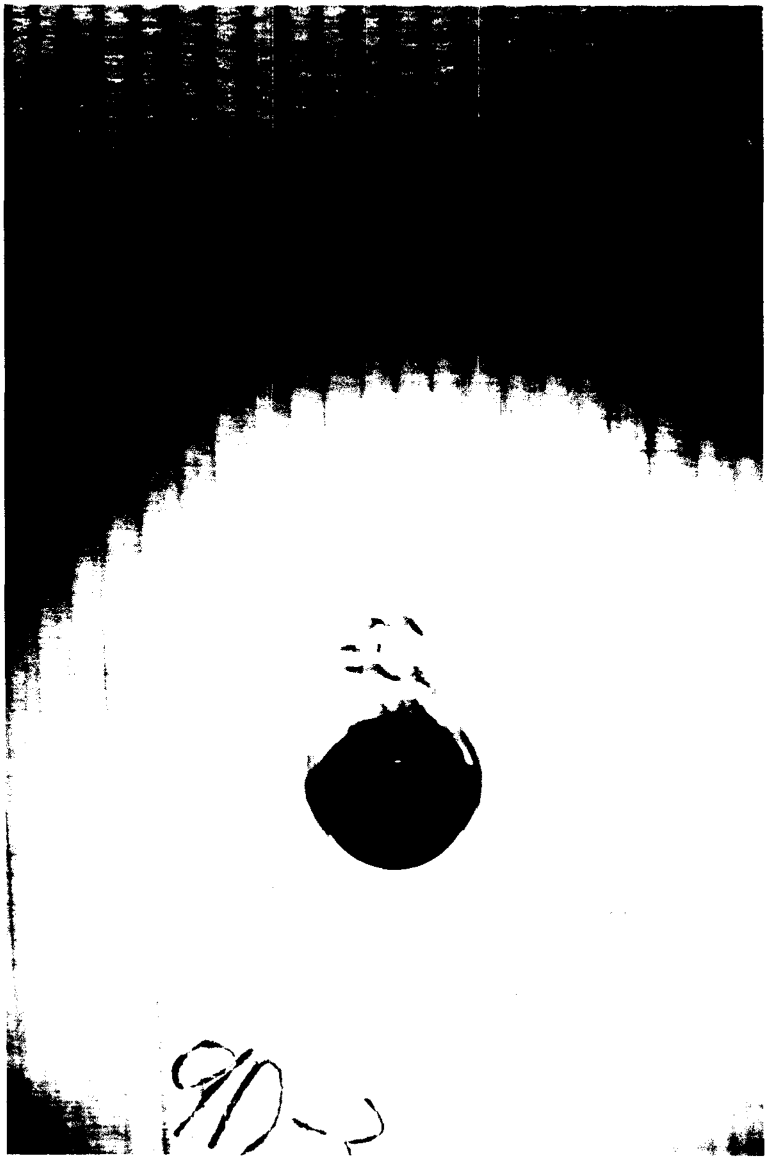

Fig. 4. Photograph corresponding to the stage marked with code letter A in Fig. 3a.

are not likely to become large, compared to those in the plane perpendicular to that axis. This assertion is supported by the results of models reported in the related study by Humphrey and Ostman (1989) and by models utilizing the European Yield Theory (Johansen 1949). In addition, propagation of lateral cracks is likely to play a major role only in catastrophic failure at the end of each test.

Comment may be appropriate here about the ranges of slip values included in the results from the tests. In current design codes (American Institute of Timber Construction 1985; National Forest Products Association 1986), design values for bolted connections are described in terms of allowable loads at specified joint-

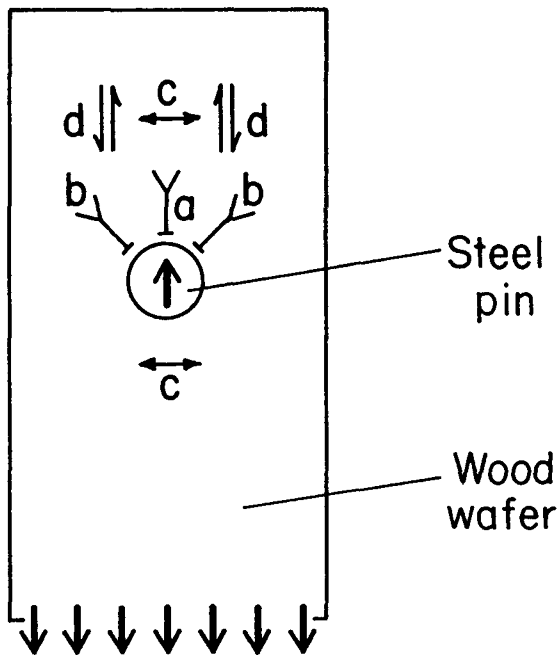

FIG. 5. Schematic representation of some of the main modes of stress and their approximate orientation in loaded wafers: a) compression parallel to the grain, b) compression inclined to the grain, c) tension perpendicular to the grain, and d) longitudinal shear. Bold arrows indicate external loads.

slip values. Slip values that occur before catastrophic failure of wafers with single bolts often far exceed what may be regarded as reasonable, and one could therefore question the relevance of such data. The following factors justify their inclusion: 1) some types of materials behavior operative at low slip values become pronounced at higher values; 2) localized movement of bolts within joints may exceed overall joint slip values as the bolts bend within the joint; and 3) it is often prudent when establishing design codes to acknowledge that demands far in excess of those anticipated in normal service do periodically occur—from poor structural design or construction practices, or during earthquake, hurricane, or fire; the behavior of connections when loaded to catastrophic failure then becomes important.

Some care is needed when directly applying the results of such tests on wafers to the behavior of corresponding joints. Whole joints sustain nonuniform strains due to bolt flexure. They are also affected by uncharted variability in the direction parallel to the bolt axis of the joint and frictional drag between side and main members—issues considered further in the related study by Humphrey and Ostman (1989) when bolt flexure is discussed.

Other wafer-pin arrangements

The behavior of tangentially surfaced wafers (Fig. 3, curve "b," and Fig. 6) resembled that of the radially surfaced wafers of the standard configuration (see Fig. 3, curve "a," and Fig. 4), although zones of localized densification were more evident in the former and the role of growth-ring structure differed.

The thickness of the wafers was about one quarter that of the growth rings. The

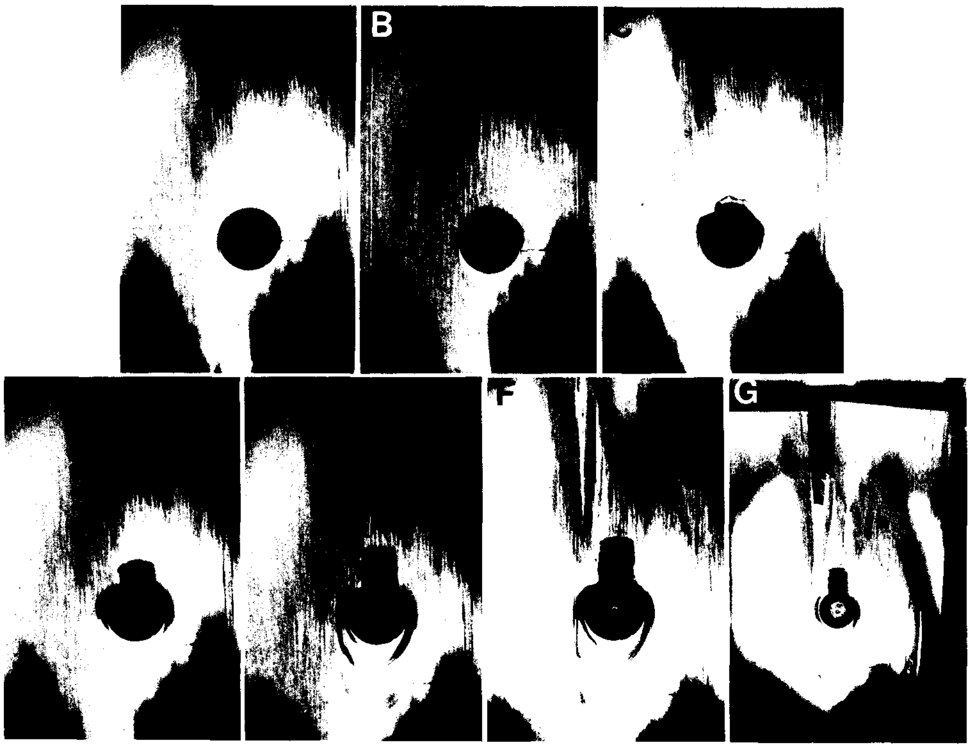

FIG. 6. Photographs for a tangentially surfaced wafer with pin at an end-distance of seven pin diameters, corresponding to the stages marked with code letters A, B, and C in Fig. 3b. Loads for D, E, and F did not vary appreciably from the load at C.

pin could therefore be located entirely in either latewood or earlywood or in a combination of the two. Clearly, curvature of the growth rings and their slight deviation from axial alignment meant that such control over growth-ring positioning could be maintained only in the immediate vicinity of the pin. The results do, however, shed some light on the effect of wood structure on localized material behavior.

Microscopic analysis of material compressed parallel to the grain above the pin in tangentially surfaced wafers (Fig. 5, mode "a") suggested that the darkening of the wood resulted from buckling and subsequent folding of fibers. The alternating folds were separated axially by about 1.1 mm. Repetition of tests with wafers 0.6 and 1.2 mm thick did not appear to influence the nature of this effect; therefore, the behavior probably was not an artifact of the testing method. Indeed, careful inspection of corresponding cross sections cut through complete joints after tensile loading revealed a similar pattern of material distortion (see Fig. 7).

Present U.S. design specifications for bolted joints (American Institute of Timber Construction 1985; National Forest Products Association 1986) include few conditions for wood quality in the immediate vicinity of connections, largely because so little is known about how specific defects affect localized material behavior and how localized behavior, in turn, affects overall joint performance. In a limited number of tests in which steel pins were positioned in wafers near a

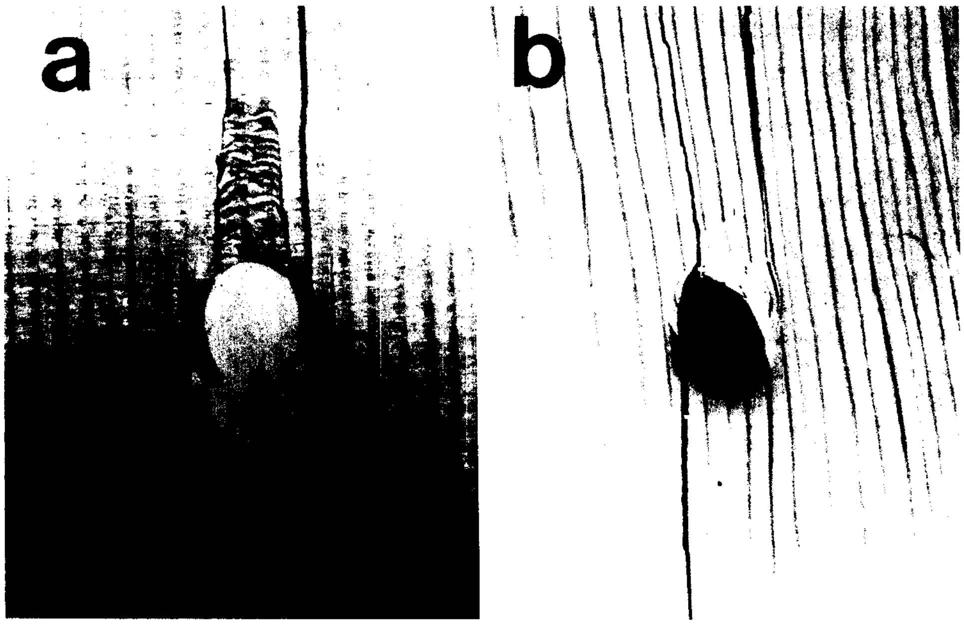

FIG. 7. Comparison of failure mechanisms in a) test wafer and b) corresponding longitudinal cross section through the main member of a complete joint.

range of defects, including a round knot (Fig. 8), the mechanisms of crack initiation and growth may be observed. A representative load-slip curve for such a test is shown as curve "c" in Fig. 3. Mathematical modeling of such arrangements is very difficult, and observing the behavior of wafers provides a useful alternative for investigating the specific effect of such defects on joint behavior.

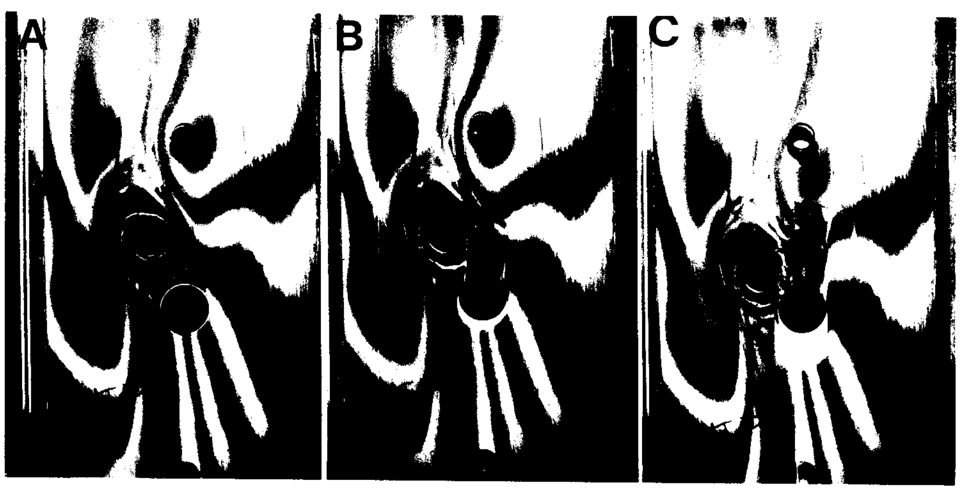

FIG. 8. Three stages in the loading of a tangentially surfaced wafer containing a round knot near the steel pin (two of the photographs correspond to the stages marked with code letters A and B in Fig. 3c).

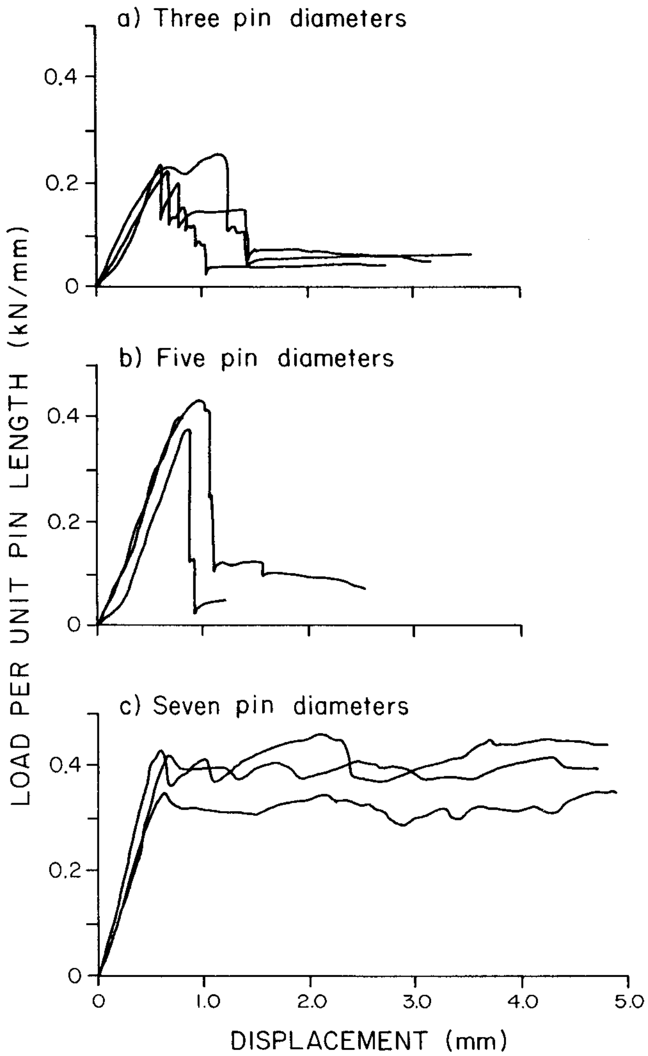

FIG. 9. Representative corrected load-slip curves for radially surfaced wafers with steel pins at three different end-distances: a) three pin diameters (37.5 mm), b) five pin diameters (62.5 mm), and c) seven pin diameters (87.5 mm). Note: The initial maximum load and displacement at that load for wafers tested with end-distances of nine and eleven pin diameters could not be distinguished from those at an end-distance of seven diameters.

Test results corroborate the findings of numerous workers investigating the important effect of end-distance on joint performance (e.g., Trayer 1932; McLain and Thangjitham 1983; Harding and Fowkes 1984). Load versus slip curves measured for radially surfaced wafers, tested at end-distances of seven, nine, and eleven pin diameters, are not visually distinguishable (Fig. 9). Those tested with an end-distance of five diameters displayed ultimate strength values similar to those above but did, however, shear out at smaller slip values. An end-distance of three pin diameters caused premature shear failure at a reduced load, preceded by little localized wood damage.

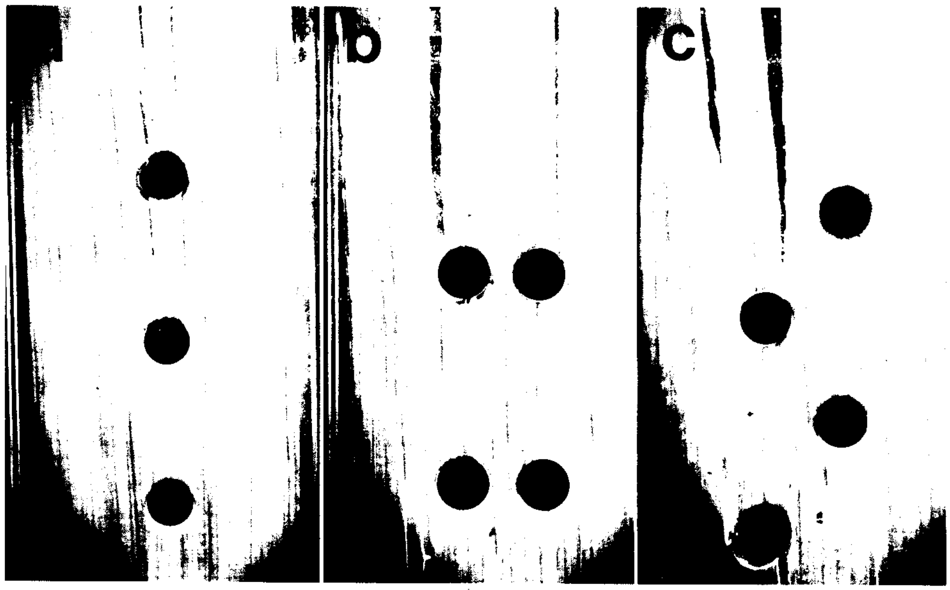

FIG. 10. Multiple-bolt configurations of radially surfaced wafers. The maximum loads that they supported before failure were: a = 500 N, b = 601 N, and c = 650 N.

Visible material damage before breakage was all but absent in radially surfaced wafers in which multiple bolts were positioned in three different configurations (Fig. 10). Two of the configurations (Figs. 10b and c) were chosen with a view toward reducing joint length while retaining the strength of the more conventional linear configuration (Fig. 10a); this was rationalized in terms of reducing the concentration of axial shear stresses.

Clearly, when whole joints are used in service situations, hole alignment may vary considerably, and load sharing among bolts is unlikely to be as effective as in wafers or complete joints manufactured to fine tolerances in the laboratory. Therefore, the wafer technique might also be applied to investigate the influence of fabrication tolerances on joint behavior. This could complement theoretical approaches (though there are few) and reduce the need for many costly tests on whole joints.

IMPLICATIONS

The technique described herein enables interactions among unique combinations of material and geometrical variables to be studied visually. It could be applied to configurations more elaborate than those presented here and made from wood of differing growth characteristics and quality.

The information gained may be used in three ways. Alone, it provides a means of directly indicating the sensitivity of joints to design variables. However, when applied to this end, the technique has certain limitations, including lack of provision for the effects of bolt flexure, material variability in the direction parallel to the bolt axis, and frictional drag between side and main members. It will likely be most useful for qualitatively tackling the issues of wood quality and fabrication accuracy, which have been difficult to analyze theoretically; after further development, it could be employed to investigate other modes of unidirectional and combined loading. The information gained also may be used as a tool for evaluating the reliability of predictions derived from theoretical models, particularly finite element simulation, and may be combined with bolt bending data to enable inferences to be made about the distribution of material behavior along the length of bolts in complete joints (Humphrey and Ostman 1989).

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