EFFECTS OF BENDING MOMENTS ON THE TENSILE PERFORMANCE OF MULTIPLE-BOLTED TIMBER CONNECTORS: PART I. A TECHNIQUE TO MODEL SUCH JOINTS[1]

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ABSTRACT

The susceptibility of multiple-bolted timber joints to bending moments is considered in the light of several recent building failures. This study describes an experimental technique to model wood behavior in the plane perpendicular to the axes of multiple bolts in joint members that are subjected to simultaneous bending and tensile loads. Modeled joints consist of 0.8-mm-thick wood wafers sandwiched between clear plastic plates, with steel dowels representing bolts passing through them. Combined loads are applied by mounting the arrangement on a servohydraulic testing machine. Load and displacement data (both axial slip and bending) were recorded during testing to failure, and failure mechanisms were recorded photographically. Results of tests with two dowel configurations (conventional "three-in-a-row" and modified "triangular") suggest that relatively small bending moment levels can reduce the tensile performance of joints, and that bolt configuration is an important factor affecting this susceptibility. The modeling method may be a useful tool for developing joint designs with reduced susceptibility to bending moments and for investigating the effects of variables such as wood quality, growth ring orientation, and moisture content. The behavior of corresponding whole double-shear joints tested under a similar range of loading regimes and with wood of two grades will be reported in a companion paper.

Keywords: Bolted timber connectors, multiple bolts, combined loading, bending moments, tensile loading, wafer modeling technique, design optimization.

INTRODUCTION

Most timber joints are designed to transfer loads among members that function as struts or ties in building structures. It is therefore generally assumed that such joints carry only axial (tensile or compressive) loads, and most studies to date have been limited to these modes. Although this assumption is valid for joints with single bolts (behaving as pin-type connectors), it may not be so when multiple bolts, truss plates, and the like are used—such joints may experience a combination of axial and eccentric (bending) forces in service.

While bending forces on joints normally remain small, situations may arise in which they become large enough to affect overall performance. These situations may be the result of deficient structural design practices, structural

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settling, the weight of heavy members that are inclined, or catastrophic occurrences such as fire, earthquake, or hurricane. Indeed, a number of recent building collapses in North America (Larson 1988) are attributable to the failure of timber joints held together with multiple bolts of large diameter; postmortems on some of these failed systems suggested that bending moments transferred to the joints may have contributed to their demise.

G. W. Trayer (1932) was among the first to conduct laboratory tests on bolted timber connections. He tested hundreds of double-shear timber joints with both metal and wooden side plates, while varying the diameter, length, and spacing of the bolts. Many contemporary design specifications still reflect the results of this pioneering work. More recent research does, however, suggest that some generally accepted specifications are in need of revision. The need for improved design methods applies not only to the simplest double-shear joints with single bolts loaded uniaxially (Soltis and Wilkinson 1987; Humphrey and Ostman 1989a, b), but also to multiple-bolted systems subjected to diverse loading regimes.

Wilkinson (1980) and Thangjitham (1980) indicated that when metal side plates are used, the allowable load may be greater than that proposed by Trayer. McLain (1983) subsequently tested many joints, and the results suggested that when metal side plates are used with 12.5-mm-diameter bolts, an increase in allowable load (at a specified limiting slip) may be justified. The 1982 edition of the US National Design Specification (National Forest Products Association 1982) included an increase of 75% in allowable load when metal side plates were used instead of wood, for a range of bolt diameters; the previously accepted figure of 25% had been based on Trayer's work. While this rather dramatic increase appears to benefit the financier, it has also generated some controversy—particularly in light of the above-mentioned failures in structures incorporating joints with multiple large-diameter bolts. The 1986 edition of the National Design Specification (National Forest Products Association 1986) was modified to reflect some of these concerns; increases in allowable loads were made dependent on bolt diameter. However, this judgment apparently did not make allowance for the possible role that bending moments played in the failures.

No literature was found on the effects of bending moments on the axial performance of bolted joints. Several researchers have, however, considered the effects of combined loading on structural timber and laminated members (for example: Newlin and Trayer 1956; Hudson 1961; Norris 1962; Peterson 1965; Zahn 1982). Such studies have usually assumed that the stress at any point in a cross section of a structural member is equal to the sum of the imposed stresses; when the sum of these stresses exceeds the allowable stress, failure is deemed likely to occur.

Hirai (1984) reported on the effect of loading direction on the bearing properties of wood around bolts in a joint, while Hirai and Horie (1984) considered the effects of loading direction on the lateral resistance of single bolt joints made with steel side plates. This work is, however, only tenuously related to the issue of combined loading since it only concerns uniaxial forces.

To increase understanding of the mechanisms of deformation and failure operative within timber joints during loading, Humphrey and Ostman (1989a) developed an experimental modeling technique to represent longitudinal cross sections (perpendicular to the bolt axis) through joints. Thin wafers of wood equal in width and length to whole joint members were sandwiched between glass plates that were supported in a rigid frame, and a steel dowel (representing a portion of a bolt) was passed through them. Tensile loads were applied to the end of the wafer that protruded from the bottom of the frame, and wood behavior was viewed through the glass as the wafer was drawn past the stationary dowel.

To develop a technique for modeling the effects of bending moments on multiple-bolted joints, the present study used an extension of Humphrey and Ostman's basic approach. Steel dowels passing through wafers sandwiched between rigid transparent plastic plates represented bolts in any one of the three members of a double-shear timber joint. While the plastic restraining plates holding the dowels were supported, in-plane forces applied to the wafer mimicked combined loading on a joint member. Data on the effect of bending moment on tensile load versus deformation were collected as testing proceeded, and failure mechanisms were recorded photographically. Two different bolt configurations were tested. The principle of the technique is represented schematically as Fig. 1. Limitations of, and assumptions made in, the wafer modeling technique are addressed at some length in the preceding paper (Humphrey and Ostman 1989a). In the interest of brevity, the reader is referred to that paper.

To complement the modeling technique, a related study tested whole joints of corresponding design under similar combined loading conditions. That work will be described and compared with results from the present study's model joint tests in a companion paper (Humphrey and Fantozzi 1995). Facial dimensions, dowel positions, and material for the whole-joint tests corresponded to those in the wafer tests reported here.

Data collected were not extensive; they should, however, be sufficient to demonstrate the applicability of the technique and to support the contention that the issue of combined loading on bolted joints must be better addressed by researchers, engineers, and regulating authorities. Most of this paper is therefore devoted to the experimental technique, its usefulness, and how best to interpret its results.

MATERIALS AND METHODS

Preparation of test wafers

The wafer approach allows the influence of material and geometrical factors on the behavior of joints to be assessed. To take full advantage of the approach, care must be taken in the preparation of the wafers, as well as in the application of forces during testing; otherwise, artificial stress concentrations and crack initiation sites may be introduced.

Wood wafers with radial surfaces were cut in the green condition from a piece of clear and straight-grained Pacific Coast Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco]. This material closely resembled the higher of the two grades of material used in the whole-joint study (Humphrey and Fantozzi 1995); it had a mean density of 540 kg m^{-3} when at 11% MC and a mean annual growth ring width of 3.7 mm. Radially surfaced wafers were used for consistency with the growth ring orientation typical in the whole-joint study. Parallel-, or end-, slicing was used to cut the material; this technique allows wafers of high surface quality to be produced.

A wafer thickness of 0.83 mm (when conditioned to 11% MC) was chosen in light of the variability and fine structure of the wood. As wafer thickness is reduced, 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 attributed to the interaction of visible characteristics (Humphrey and Ostman 1989a). However, as wafer thickness approaches the cellular level, continuity of material is lost, and the failure mechanisms could be significantly influenced by interfacial or boundary effects.

Following conditioning, the wafers were accurately machined to final dimensions of 819 × 90.0 mm, with the fibers carefully aligned in the long dimension. Holes were positioned with the aid of plastic templates and drilled with a specially ground edge-cutting drill bit that consistently produced smooth holes of 13.1-mm diameter; this hole size resulted in a diametric dowel clearance of 0.4 mm. In the future, the important effect of bolt hole clearance and fabrication tolerance on joint behavior could be investigated.

Wafer/dowel arrangements tested

Most tests involved a single row of three 12.5-mm-diameter dowels spaced according

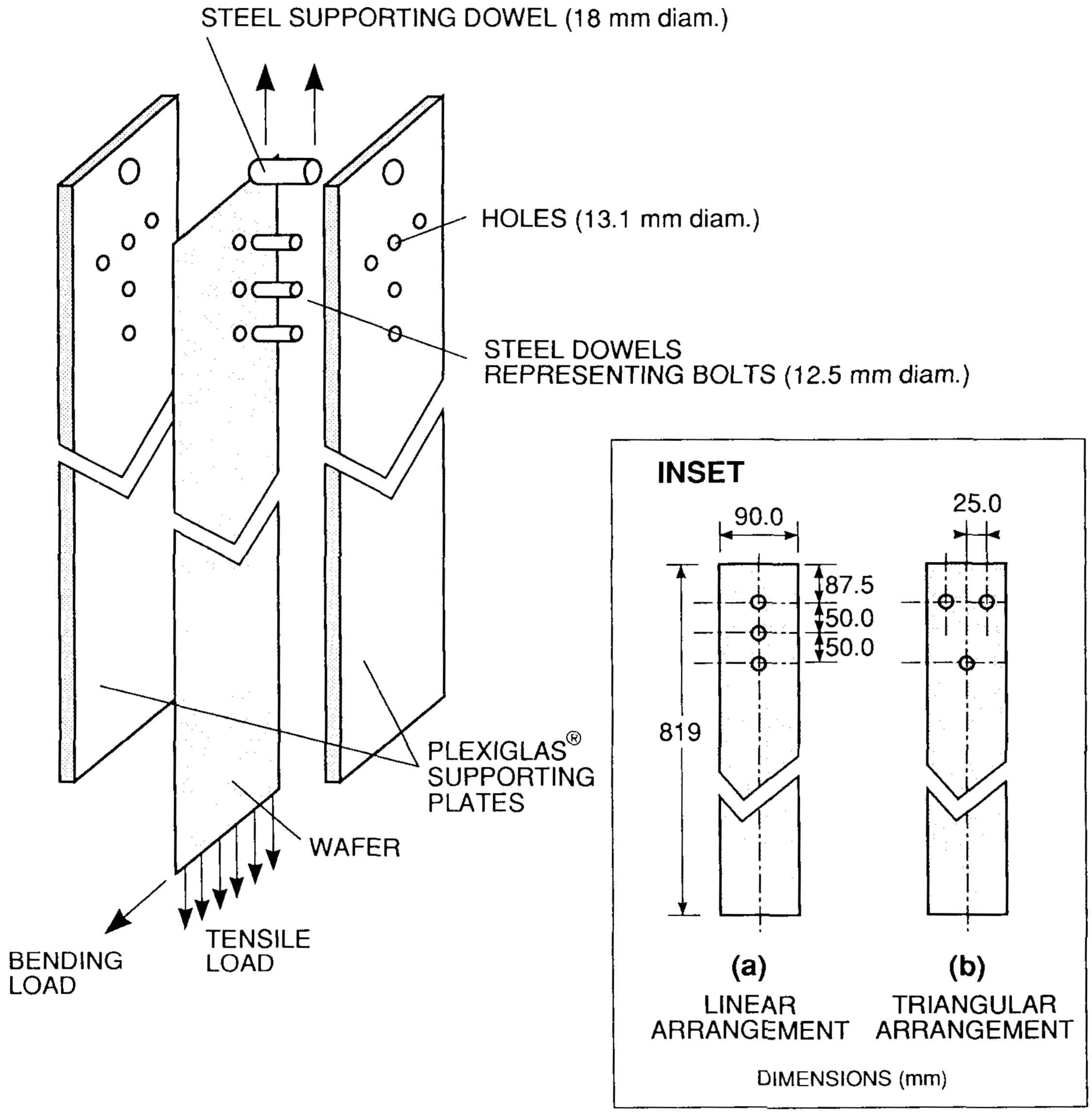

FIG. 1. The essential features of the joint modeling technique and (inset) two dowel arrangements: (a) the standard linear arrangement, and (b) alternative (triangular) arrangement selected for reduced susceptibility to bending moments.

to National Design Specifications (National Forest Products Association 1986) (Fig. 1, inset a). Two factors influenced this choice of design. First, other workers have accumulated considerable experimental data on similarly sized double-shear joints (Stluka 1960; Wilkinson 1978; Humphrey and Ostman 1989a, b), and some comparison of results may therefore be possible. Second, the arrangement was manageable on the available testing equipment, while lying within the range of member sizes used in commercial building systems.

In addition to the standard linear dowel arrangement, a few wafers with a triangular pattern were tested (Fig. 1, inset b). This pattern was a first attempt to develop a joint design with reduced susceptibility to bending moments. The rationale underlying the design is considered later in the paper.

A number of wafers were photographed after they had failed. These photographs were analyzed to compare the failures resulting from each dowel configuration and bending moment.

Testing system

The testing apparatus (Fig. 2) was designed to provide support for the dowels (representing bolts), to keep the wafers flat while in-plane forces were applied, and to allow forces and displacements to be accurately applied and measured. The testing arrangement was mounted on a servohydraulic testing machine.

Changes occur in the geometry of joints as combined forces are applied to them. Horizontal forces (see Fig. 1) cause the joint to bend, while tensile forces tend to both straighten and elongate the joint. Without adjustment of the horizontal (bending) force applied during each test cycle, the increasing tensile forces would progressively reduce the bending moment experienced by the joint zone. Results would thereby become specific to the geometry of the testing setup employed. Furthermore, as a joint is loaded in tension, the wood in the immediate vicinity of the bolts is damaged, and its resistance to bending thereby decreases. Thus, horizontal deflection (bending) is likely to increase with increases in tensile load. This effect reflects the weakened nature of the system and shows why it is also inadequate to simply apply and maintain a fixed angular deflection to joints throughout their testing cycle. These factors apply equally to the testing of model (wafer) assemblies and whole joints.

For this reason, care was taken throughout each testing cycle to maintain a constant bending moment on the modeled joint zone itself[3] (in the immediate vicinity of the dowels). Continuous modification of the lateral (bending) force was therefore necessary. Though these procedures increased the complexity of the testing method, the results thereby became generally applicable to similar joints within any structural configuration.

Wafer-restraining plates and supporting frame.—Rigid plastic plates (9.5-mm optical-quality Plexiglas®) were used because they allow wood behavior to be observed during load application and also provide smooth and rigid support (Fig. 2). These plates were pneumatically clamped on either side of the wafer by using regulated air (see below). Five holes, each 12.5-mm diameter, were strategically drilled through the plates to accommodate the two patterns of dowel placement investigated (linear and triangular, Fig. 1). A universal joint linked the plastic plates to the load cell above via a steel dowel and hanger.

Air grips.—Hypodermic syringes were used as pistons and cylinders to clamp the plate/wafer assembly. These pneumatic clamps allowed the small wafer-restraining pressure to be accurately regulated independently of slight variations in wafer thickness. Thus, it was possible to keep the restraint almost constant from test to test; this uniformity, in turn, reduced the variability in frictional drag between wafer and plastic.

To achieve uniform clamping along the entire length of the wafer, ten syringes (each 12.5-mm-diameter bore) were mounted along two thin L-shaped aluminum strips (Fig. 3a). These strips ran along each of the long (vertical) sides of the plates and were connected to a common regulated air supply that was adjusted to effect a pressure of 1.67 kPa across the entire surface of the wafer.

Dowels representing small axial portions of bolts.—Assemblies were designed to restrain the plastic plates in the immediate vicinity of the dowels (Fig. 3b). Round stepped Plexiglas® plugs were fitted onto the ends of the short steel dowels, and machine screws were passed axially through the dowel/plug arrangement. These screws were gently but uniformly tightened, thus holding the plastic plates at a con-

[3] When bending moment values were calculated, it was assumed that the wafer rotated about the centroid of the arrangement of dowels (the middle one, for three in a line).

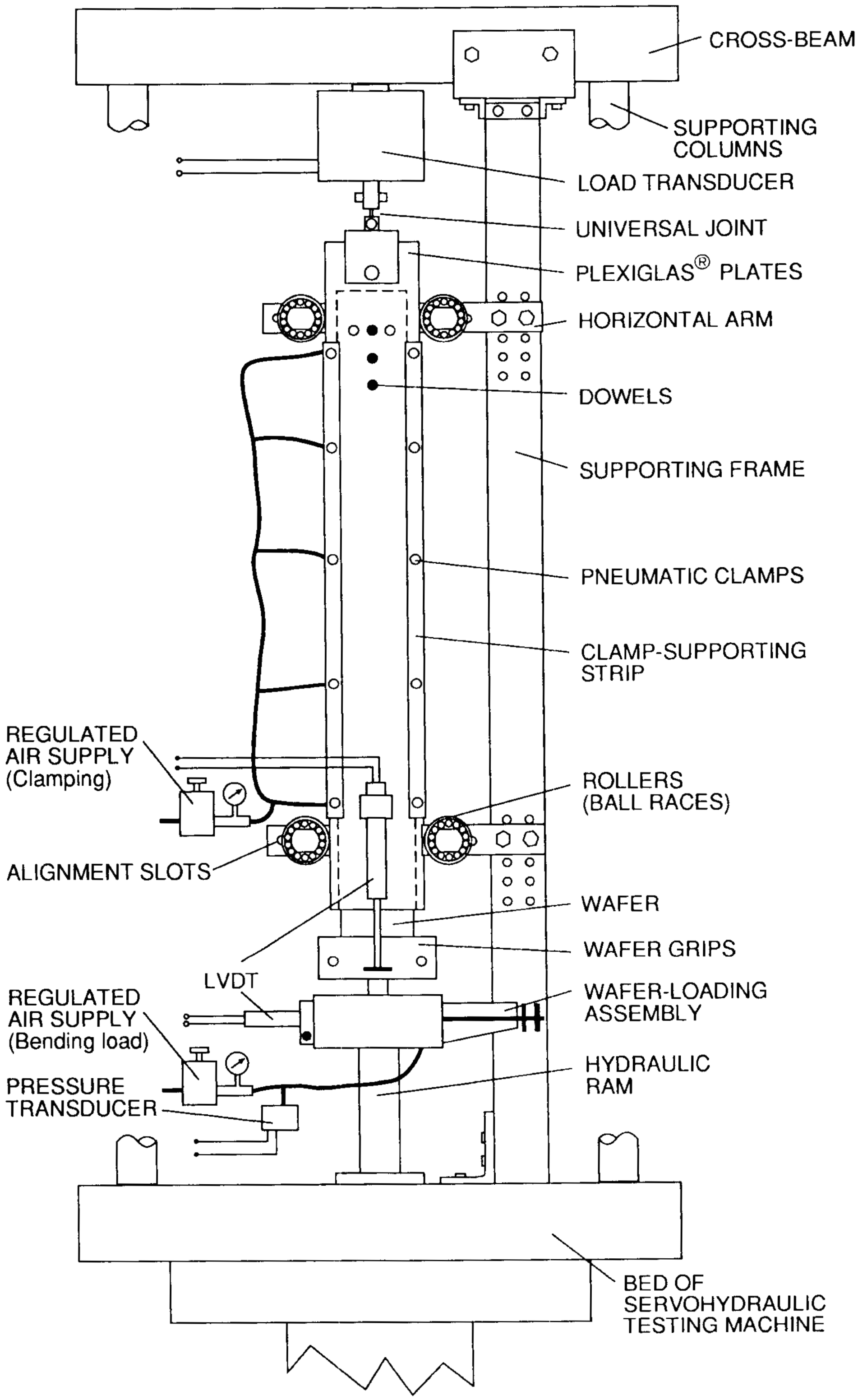

FIG. 2. Schematic view of the wafer testing apparatus mounted on the servohydraulic testing machine.

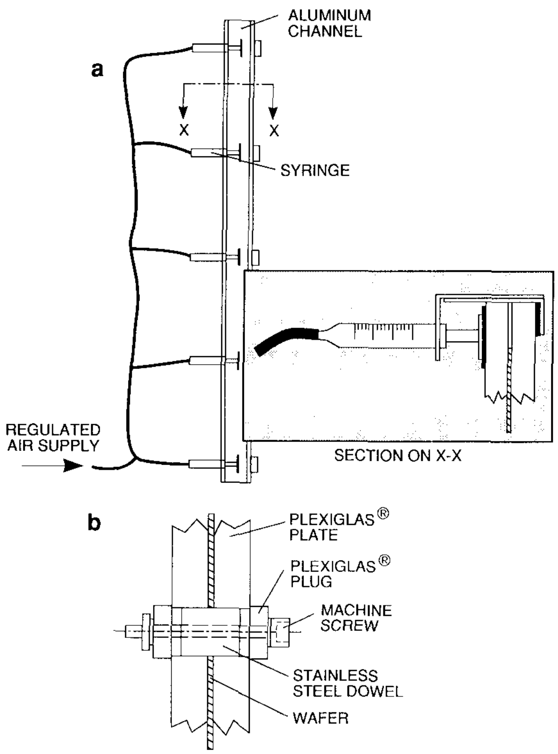

FIG. 3. Details of: (a) the air clamping system, and (b) dowel assemblies.

stant separation throughout the test. It is possible, however, that this arrangement led to some extra localized frictional drag that could not be easily quantified.

Wafer end-grip and load application assembly.—Both tensile (axial) and bending (horizontal) forces were transmitted to the wafer via a mechanism that was mounted on the hydraulic ram of the testing machine (Figs. 2 and 4). This comprised a pair of steel plates, between which the endmost 30 mm of the wafer was evenly gripped across its entire width; these plates were linked to a tracking box via a pair of precision ball races that acted as low-friction wheels. The races allowed the gripping plates to slide freely when horizontal (bending) forces were applied and also transmitted tensile loads to the wafer.

A small pneumatic cylinder and piston was used to apply bending forces to the wafer; the cylinder was mounted on the tracking box, with the piston rod connected to the gripping plates by two nylon threads that pulled the plates to apply horizontal force (Fig. 4a). The pneumatic pressure was adjusted with a regulator to control horizontal forces during each test.

Measurement devices.—A linear variable differential transformer (LVDT) with a 12.5-mm range was mounted vertically on the surface of one of the plastic restraining plates and linked to the wafer-gripping plates to measure vertical wafer slip. Horizontal displacement of the lower end of the wafer was sensed with another LVDT (25-mm range) that was mounted on the tracking box. In both cases, corrections to measured lengths were needed to compensate for changes in the geometry of the arrangement as loading progressed. These corrections were incorporated in the computer software used in the analog-to-digital data collection and conversion system (see below).

Axial (vertical) loads were measured with a 1.2 kN-capacity load transducer that linked the top of the plastic plates to the stationary cross-beam of the testing machine via the universal joint. Finally, the air pressure used to apply horizontal forces to the wafer was electronically sensed with a piezo-resistive transducer.

The testing sequence

To ensure proper alignment of the system prior to each test, a very small pre-load was applied to the wafer. Care was taken to ensure that all load and displacement measuring devices were zeroed for each test; the necessary signal voltages were automatically initialized in the specially written data collection software.

Before tensile loading was initiated, the preselected moment was applied to the wafer. The main hydraulic piston was then lowered at a rate of 1.0 mm/min to apply the tensile load. This rate was selected so that good control of bending moment could be maintained throughout testing cycles for all the combinations of target bending moment and dowel arrangement investigated.

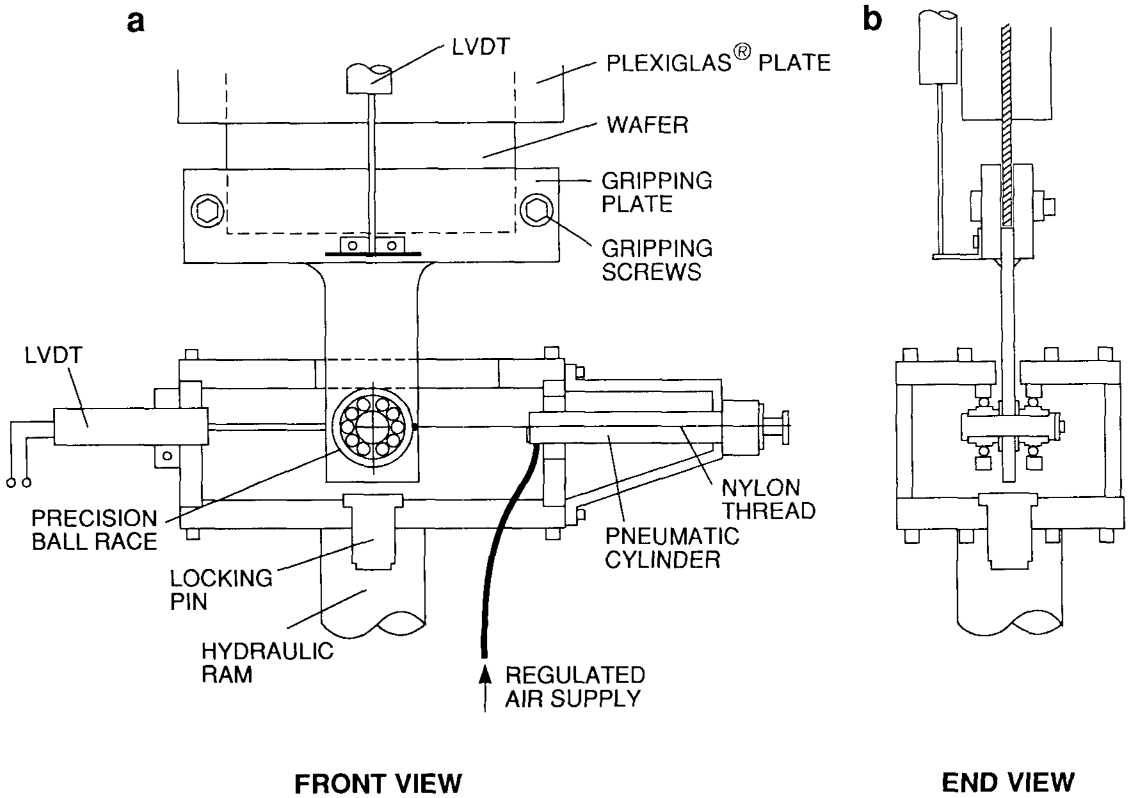

FIG. 4. Views of the wafer loading assembly: (a) the tracking box with front plate removed to expose the rolling loading arrangement, and (b) the assembled system.

Signals from the four transducers were each sampled every 0.64 seconds by the analog-to-digital data acquisition system. Following each data sampling cycle, the software program calculated the prevailing bending moment applied to the joint, compared this to the target value, and displayed the prevailing differential. The air regulator controlling the lateral wafer loading was manually adjusted throughout the testing cycle to minimize the displayed differential. Small variations in moment occurred because periodic bursts of material failure caused sudden changes in bending stiffness of the system. Such rapid changes could not be corrected instantaneously.

Bending moment levels applied to wafers

Preliminary tests established the range of moment levels appropriate for each dowel arrangement. In these tests bending loads alone were applied until failure occurred. Once the maximum bending strength was identified (15.2 Nm), moment levels of 0, 3.9 to 4.5, 9.3 to 9.9, and 14.6 to 15.2 Nm were employed.

Compensation for friction between the wafer and plastic plates

Following failure of each wafer, a further test was conducted to measure the force necessary to initiate slippage (to overcome static friction) in both the horizontal and vertical directions. For this purpose, each broken wafer was moved back to its original (untested) position and loads were reapplied; the enlarged holes meant that the dowels did not impede the onset of slippage. The derived load values were subtracted from all load data collected during the preceding wafer test.

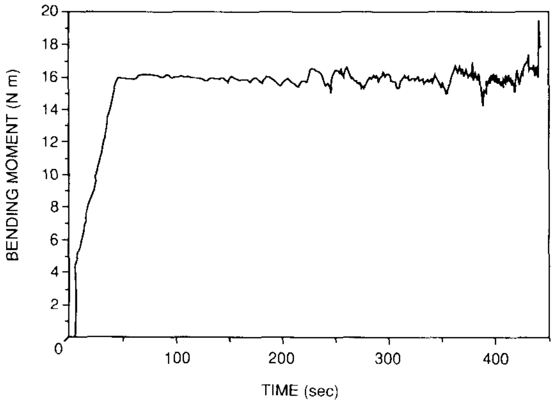

FIG. 5. A curve of moment versus time for a typical wafer tested to failure at target moment at 14.6 to 15.2 Nm.

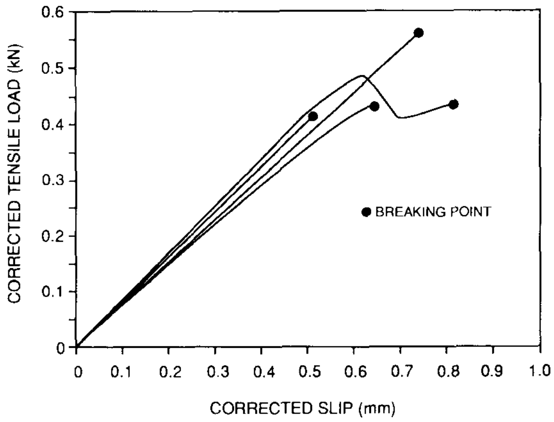

FIG. 6. Replicate axial load/slip curves (with geometrical and frictional corrections applied) for a single dowel arrangement (linear) and moment level (9.3 to 9.9 Nm).

In fact, variability in frictional drag among wafers was very small; in future tests averaged values (from preliminary tests without dowels) will be used.

Data reduction

Analog-to-digital conversion and calculations for controlling moment levels were necessarily performed by the computer in "real time." Secondary geometrical and frictional corrections and graph plotting of derived data were carried out after testing was complete; a second computer program was written to perform these functions automatically. Detailed information on the application of geometrical and frictional corrections will not be given here; though rather lengthy, these calculations were reasonably straightforward. Further details may be found in a thesis (Fantozzi 1989).

RESULTS AND DISCUSSION

Clearly, the goal was to maintain the target moment value as accurately as possible. Axial load and deformation (slip) during each loading cycle were the principal forms of data collected. Between 250 and 450 seconds lapsed between the onset of wafer loading and subsequent failure. Figure 5 shows a curve of moment versus time for a typical wafer tested to failure at a target moment value of 14.6 to 15.2 Nm (the most difficult one to control).

Figure 6 shows a set of replicate axial load/slip curves (with geometrical and frictional corrections applied) for a single combination of dowel arrangement (linear) and moment level (9.3 to 9.9 Nm). Averages of such curves will be used throughout the discussion below. A more detailed discussion of the statistical nature of the variability among such replicates is to be found in Fantozzi's thesis (1989). It should, in any case, be pointed out here that because replicate wafers did not all fail at the same level of slip, the averaged curves were only constructed up to the lowest slip sustained among the replicates. However, ultimate loads to failure for every wafer were used when averaged ultimate loads were calculated.

The effect of bending moment level on the axial load/slip behavior of the two dowel arrangements is shown in Fig. 7. Each line represents the mean of four replicate wafers, except in the case of the highest moment level applied to the linearly configured dowels (Fig. 7a)—here, all but one of the wafers failed during bending, before the application of tensile forces could begin.

Two-way analysis of variance (ANOVA) was conducted on the axial stiffness of the wafer arrangements in the early stages of their loading cycles (where they behaved almost lin-

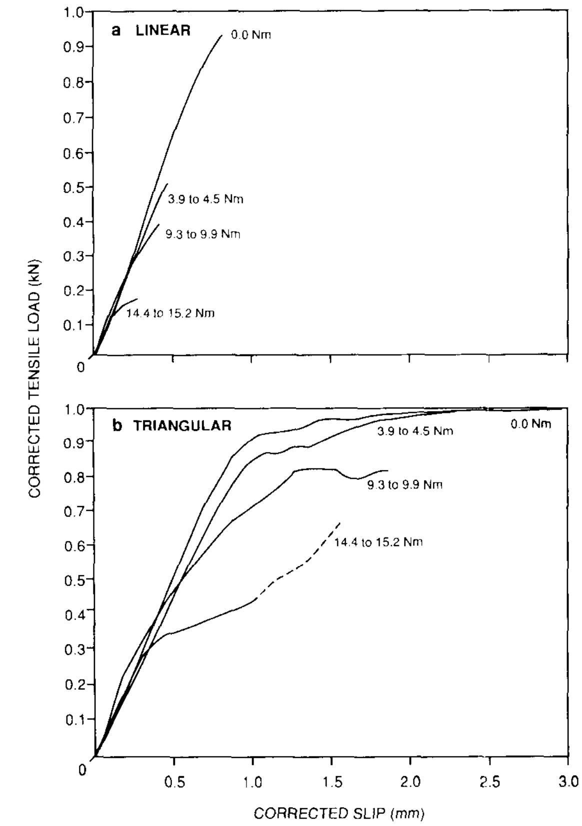

FIG. 7. Families of averaged axial load/slip curves at the four mean moment ranges: (a) linearly arranged dowels, and (b) triangular dowel configuration.

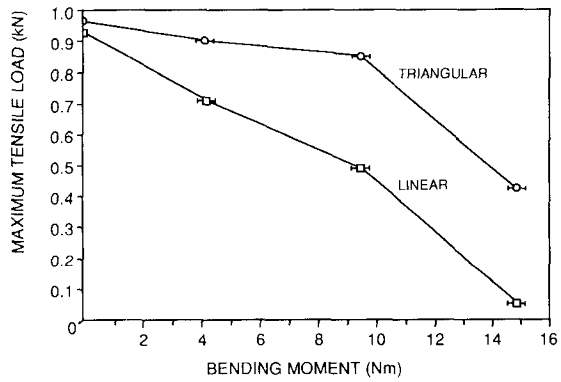

FIG. 8. Mean tensile load to failure versus applied moment for the two dowel arrangements.

early), and also on the ultimate loads to failure. The results of this analysis suggest that at the 0.05 exclusion level, the application of bending moments did not significantly change the axial stiffness of either dowel configuration. Furthermore, there was no significant difference in initial stiffness (before bending) between the two dowel arrangements.

Part of the curve representing the highest moment level on the triangular configuration (Fig. 7b) is somewhat misleading, because the horizontal displacement necessary to maintain the target moment exceeded the limits of the apparatus. The portion of the curve where moment began to fall is therefore marked with a broken line. Had the target moment been maintained throughout these tests, the wafers probably would have failed sooner.

It is clear (despite the loss of control for some tests at high moment levels) that the onset of non-linearity and subsequent behavior to failure did differ markedly between the two arrangements. When tested in pure tension, the two configurations showed no significant difference in tensile loads to failure, but as moments increased, the linear arrangement was very much more affected than the triangular one (Fig. 7). Indeed, over the range of moments investigated, the effect on load to failure (Fig. 8) for the linear arrangement seemed almost directly proportional to moment (with an r^2 value of 0.88). Wafers with triangular dowel arrangements could, on the other hand, support loads about 70% greater than could their linear counterparts when subjected to moments in the order of 10 Nm.

Modes of wafer failure

A number of workers have undertaken analytical studies of the distributions of stress and strain in multiple-pin connectors during axial loading (e.g., Lantos 1969; Wilkinson 1980). Numerical analysis of stress distributions within different wafer/dowel arrangements was not, however, the objective of the present work. The following discussion is therefore qualitative in nature and is based on selected photographs of tested wafers.

Under purely tensile loading, conventional linear dowel arrangements lead to two planes of shear stress that are mainly concentrated in

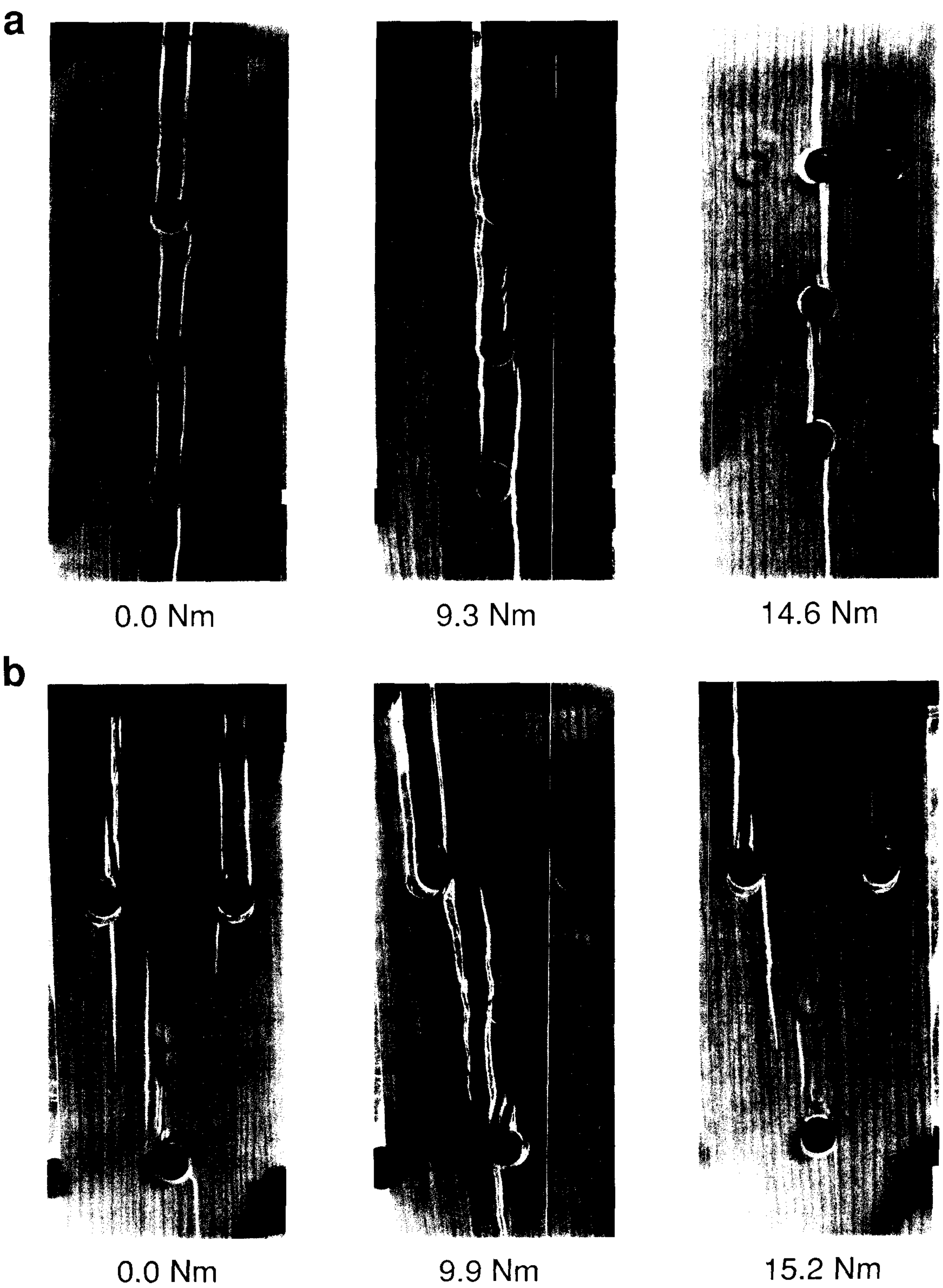

FIG. 9. Photographs of typical wafers tested under various moment levels: (a) wafers with linearly arranged dowels, and (b) wafers with dowels in the triangular arrangement.

narrow linear zones above the dowels (Fig. 9a). It is well known that in real joints, such arrangements of bolts normally fail in shear mode along these lines (hereafter referred to as "double-shear" failure), and little longitudinal wood crushing occurs. This pattern differs from the very significant longitudinal (and associated transverse) crushing that often occurs when singly bolted joints are tested to failure (Humphrey and Ostman 1989a).

Double-shear failure is evident in the first wafer shown in Fig. 9a, which was tested in pure tension (no bending). Somewhat similar behavior is evident for the corresponding triangular wafer (Fig. 9b), although the sequence of ruptures after primary failure is more complex; probably once the material above one of the two upper dowels fails in double-shear mode, axial symmetry of the system is lost and the wafer tends to twist.

When bending moments were applied, tension stresses perpendicular to the grain (in the plane of the bending force) were transferred to the material lying axially above and below the dowels (these stresses were in addition to the perpendicular-to-grain stresses that occur in all loaded joints because of the round shape of bolts). At higher moments, interaction of the above stresses with shear stresses tended to lead to a greater propensity for single-shear rather than double-shear failures. This tendency is clearly evident in the sequence of photographs in Fig. 9.

The triangular arrangement was selected in an attempt to reduce the axial concentration of shear stress on the wood. Also important was the reduction of tension perpendicular-to-grain stresses achieved near the end of the wafer. Lateral (bending) stresses were shared by all three dowels in the triangular arrangement, whereas the middle dowel of the linear arrangement supported little or no horizontal stress. In the triangular arrangement, the greatest horizontal stress was transferred to the dowel that lay farthest from the upper end of the wafer—this is a location where shear stresses were likely to be relatively small.

CONCLUSIONS

Working by trial and error toward optimal designs for structural connections is not an acceptable approach for such interactively complex systems. Models, be they purely theoretical or experimental as this one is, offer a necessary alternative to whole-joint testing.

The wafer modeling technique described here represents a two-dimensional approach to a three-dimensional problem. Eliminating the third dimension (parallel to the bolt axis) makes it easier to glean clues about material behavior within real joints, and to examine the interactive effects of specific wood characteristics and geometrical arrangements. Such interactions are difficult to control in whole joints. The technique could therefore prove useful as a tool for identifying the sensitivity of joint performance to a diverse range of design factors; not least of these is the issue of combined loading.

The results of these preliminary tests suggest that relatively small bending moments may have a significant effect on the tensile load to failure of joints, and that the conventional linear bolt pattern is more susceptible to such loading than some alternatives. Indeed, there is considerable potential for developing joint designs with reduced susceptibility to such moments, but with equal or even superior stiffness and strength. The applicability of the technique will be further addressed in the companion paper, where results will be compared with those from corresponding whole joints.

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REFERENCES

Fantozzi, J. 1989. Tensile failure characteristics of bolted wood joints subjected to bending moments. Master's thesis, Oregon State University, Corvallis, OR.

HIRAI, T. 1984. Effect of loading direction on the bearing characteristics of wood under a bolt. J. Japan Wood Res. Soc. 30(12):959–964.

———, AND K. HORIE. 1984. Lateral resistance of bolted wood-joints with steel side-members. J. Japan Wood Res. Soc. 30(12):965–972.

HUDSON, W. M. 1961. The effect of pre-compression on the static and impact bending strength of wood. Wood (London) 26(1):18–20.

HUMPHREY, P. E., AND J. FANTOZZI. 1995. The effects of bending moments on the tensile performance of multiple-bolted timber connections. Part II. Whole joint tests and comparisons with model results. Wood Fiber Sci. (in press).

———, AND L. OSTMAN. 1989a. Bolted timber connections. Part I. Wafer techniques to model wood deformation around bolts. Wood Fiber Sci. 21(3):239–251.

———, AND ———. 1989b. Bolted timber connections. Part II. Bolt bending and associated wood deformation. Wood Fiber Sci. 21(4):354–366.

LANTOS, G. 1969. Load distribution in a row of fasteners subjected to lateral load. Wood Sci. 1(3):129–136.

LARSON, E. 1988. A new science can diagnose sick buildings—Before they collapse. Smithsonian 19(2):116–131.

MCLAIN, T. E. 1983. Influence of metal side plates on the strength of bolted wood joints. Subcommittee on structural design and engineering properties. Madison, WI.

NATIONAL FOREST PRODUCTS ASSOCIATION. 1982. National design specification for wood construction. National Forest Products Association, Washington, DC.

———. 1986. National design specification for wood construction. National Forest Products Association, Washington, DC.

NEWLIN, J. A, AND G. W. TRAYER. 1956. Stresses in wood members subjected to combined column and beam action. Res. Rep. 1311. USDA Forest Prod. Lab., Madison, WI.

NORRIS, C. B. 1962. Strength of orthotropic materials subjected to combined stresses. Res. Rep. 1816. USDA Forest Prod. Lab., Madison, WI.

PETERSON, J. 1965. Wood beams prestressed with bonded tension elements. J. Struct. Div., ASCE 91(ST-1): 103–119.

SOLTIS, L. A., AND T. L. WILKINSON. 1987. Bolted-connection design. Gen. Tech. Rep. FPL-GTR-54. USDA Forest Prod. Lab., Madison, WI.

STLUKA, R. T. 1960. Theoretical design of a nailed or bolted joint under lateral load, M. S. thesis, Department of Civil Engineering, University of Wisconsin, Madison, WI.

THANGJITHAM, S. 1980. A method of evaluating the probabilistic resistance of bolted wood joints. Master's thesis, Virginia Polytechnic Institute, Blacksburg, VA.

TRAYER, G. W. 1932. The bearing strength of wood under bolts. Tech. Bull. 332. USDA. Washington, DC.

WILKINSON, T. L. 1978. Strength of bolted wood joints with various ratios of member thickness. Res. Pap. FPL 314. USDA Forest Prod. Lab., Madison, WI.

———. 1980. Assessment of modification factors for a row of bolts on timber connectors. Res. Pap. FPL 376. USDA Forest Prod. Lab., Madison, WI.

ZAHN, J. J. 1982. Strength of lumber under combined bending and compression. Res. Pap. FPL 391. USDA Forest Prod. Lab., Madison, WI.