PREFABRICATED WOOD COMPOSITE I-BEAMS: A LITERATURE REVIEW

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ABSTRACT

This paper reviews the available literature on the state of the art of prefabricated wood composite I-beams. The results of analytical and experimental investigations illustrate the effects of materials, joint, geometry, and environment on the short- and long-term performance of I-beams.

Keywords: I-joist, I-beams, prefabricated I-beam, composite I-beam, structural component, composite wood assemblies, ply-web beam.

INTRODUCTION

Composite wood members are becoming more prevalent in structural system design, and they are expected to become even more important as demand for forest products continues to force improved utilization of available fiber resources.

Prefabricated wood I-beams represent an efficient use of materials for structural applications (Fig. 1). The I-beams are composite structural members that are manufactured using sawn or structural composite lumber flanges and structural panel webs; the flanges and webs are bonded together with exterior-type adhesives, forming the cross-sectional shape of an "I" (ASTM 1986; ICBO 1987). The state of the art of I-beams has a fragmented history, which has evolved from the efforts of many scientists. The object of this paper is to integrate the available literature to form a comprehensive review of the technology. We emphasize the performance of prefabricated wood composite I-beams and identify how the constituent materials, joints, geometry, and environment influence short- and long-term performance of the beams. Our discussion extends beyond empirical evidence to the relevant analytical methods that play important roles in the investigation of composite material and structure behavior. Consolidating the studies on I-beams will help focus future research needs.

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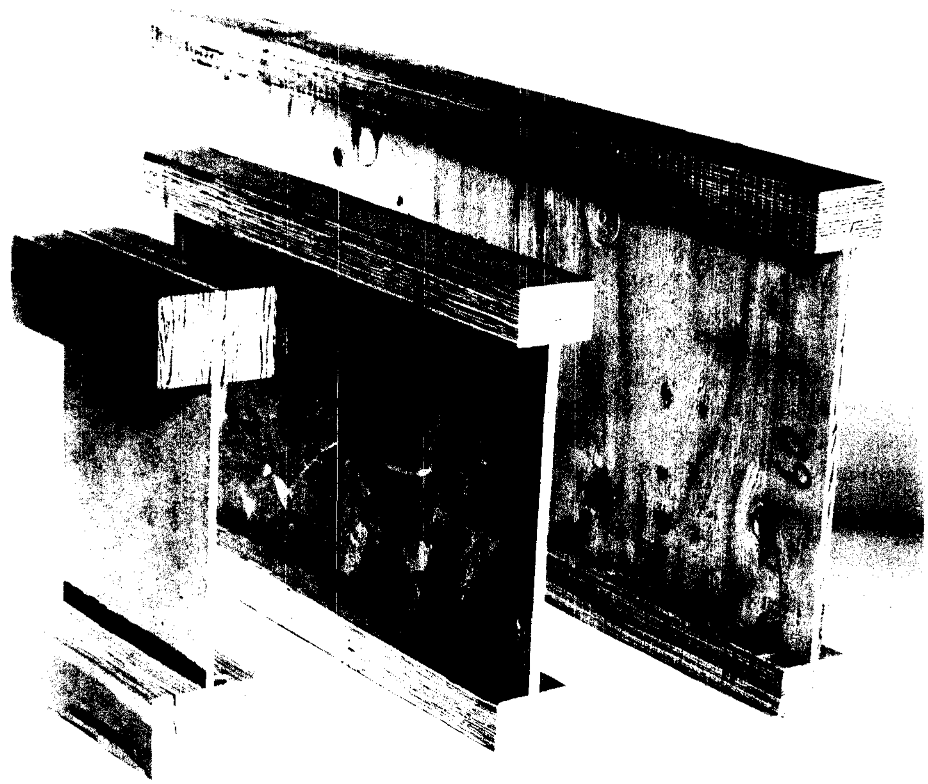

FIG. 1. Structural components of wood composite I-beams with laminated veneer lumber (LVL) flanges and hardboard, waferboard, or plywood webs (M84 0468).

EVOLUTION OF WOOD COMPOSITE I-BEAMS

The forest resource is changing. Average log size is diminishing, and as this occurs, wood quality is changing. The long and large lumber members needed for roof and floor framing in light frame and commercial construction systems are becoming less available and more expensive. However, researchers have estimated that 50 percent of wood fiber can be saved by using wood composite structural shapes (Nelson 1975; Tang and Leichti 1984). With increasing demand, lower value trees could be fully utilized if targeted for composite products.

Composite I-beams have been in use for many years. The pioneers of the aerospace industry realized the value of composite wood assemblies, and as early as 1920, I-sections were used for stringers, ribs, and longerons in wooden aircraft (Robins 1987). These early applications were designed to use the highest quality veneer, plywood, and solid wood for efficient performance. By the mid 1930s, composite I-beams with hardboard webs were found in European building structures (McNatt 1980). The efficiency of the I-shaped sections was recognized by researchers at the Forest Products Laboratory (FPL) while studying web buckling in composite assemblies (Lewis and Dawley 1943). Composite structural shapes have been used not only as roof support beams but also as floor joists, garage door headers, and framing components (McNatt 1980). The use of I-beams for these and other applications has been discussed by Koehl (1976), Keil (1977), and Germer (1986).

The I-beams utilizing plywood webs have been used for more than 25 years (Booth 1974), and design standards and methods for these components are available (APA 1982). Although particle- and fiber-based panels have been approved for various applications, such as sheathing, underlayment, and shear walls, the industry has been slow to assign design values, which precludes these materials from being more fully utilized in primary structural applications. The hesitation in assigning design values is attributed to a lack of information on material properties, especially creep-rupture behavior. Furthermore, the environmental durability of these materials is often questioned—a problem with real and imaginary aspects. Because the safety of structural materials and components is related to their performance, a comprehensive understanding of the properties of composite panels and their complex interactions with environmental and random loading conditions is essential.

DESIGN METHODS

The design of wood composite I-beams allows the positioning of materials to take best advantage of their material properties. Combining lumber (or laminated veneer lumber) and plywood (or oriented strandboard or waferboard) into beams with an I-section provides a high degree of structural efficiency. In general, the flanges are designed to provide all moment capacity where cross-sectional sizes are determined using simple bending theory. The webs are assumed to carry all shear forces. Shear capacity is most often empirically based. Other necessary design criteria include bending and shear deflection, bearing capacity, and lateral stability. Typically, most users of commercially produced I-beams utilize manufacturer product catalogs to specify stock beams for particular applications.

Span-to-depth ratios of about 15:1 have been found suitable for most floor designs, though ratios of about 25:1 are used in roof applications. Obviously, a very high quality flange material is required for these high span-to-depth ratios.

Over 40 years ago, Withey et al. (1943) discussed the design of plywood webs in box beams, the result of research on aircraft structures at the FPL. The design of composite sections by the currently practiced allowable stress method is treated thoroughly by the APA design guide (1982), Hoyle (1973a, 1986), and the *Wood Handbook* (USDA 1987). Hoyle (1986) explained design methods for nonrectangular sections, such as I- and T-shapes, constructed of materials with different properties that are connected with either rigid or flexible fasteners or adhesives. Typically, commercially produced I-beams use rigid adhesives at the flange-web joint, eliminating shear slip at this joint, and simplifying the design process.

Emphasizing application for the design engineer, Maley (1987) described the use of wood I-beams. Design methods for ply-web beams following British standards were presented by Burgess (1970). The design of these components was extended to portal frames with nailed plywood gusset joints by Batchelar and Cavanagh (1984). In a general analysis of layered materials, Bodig and Jayne (1982) addressed the applied linear elasticity of orthotropic layered systems.

Stability considerations and general rules for bracing necessary for safe I-beam design were presented by Hoyle (1973a). Using a more theoretical approach, Zahn

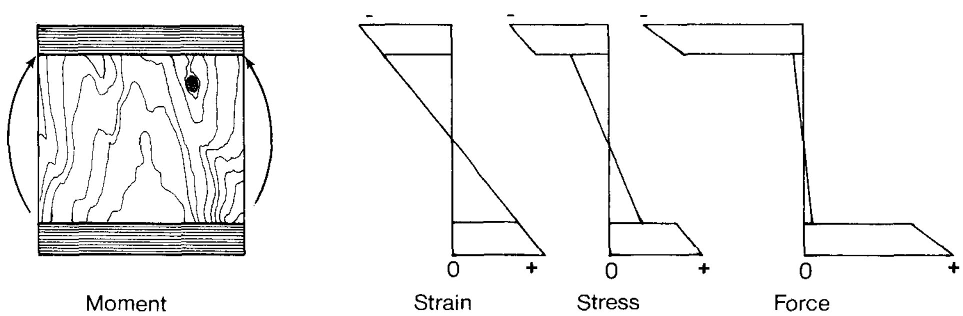

FIG. 2. Simplified representation of I-section mechanics. Pure moment load applied, the resulting axial strain distribution, stress distribution, and force distribution to produce section moment capacity.

(1983) described the forces in midspan bracing for rectangular members. Zahn's analysis can be extended to singly symmetric I-beams.

SHORT-TERM STATIC PERFORMANCE

Short-term strength and deflection performance are governed by many factors: loading conditions, material characteristics, and geometry of the member. As elementary bending theory indicates, the flanges of a wood I-beam carry most of the bending stresses (Fig. 2) and the web carries the bulk of the shear stresses (Fig. 3). The flange-web glueline transmits the stresses between adjacent components in the cross section. If materials with different characteristics are used in the composite member, beams with significantly different performance attributes can be designed.

INFLUENCE OF FLANGES

Because the web possesses a somewhat lower modulus of elasticity (MOE), tension and compression stresses are amplified in the flanges (Samson 1981, 1983). As a result, the properties of flange material are especially important. Analytical and empirical methods have been used to evaluate the contributions of the flanges on the basis of material properties, grade, and connection methods (Superfesky and Ramaker 1976; Booth 1977; Fergus 1979; Samson 1981, 1983; Leichti 1986).

Because tension flange quality is a major factor in I-beam load capacity, producers utilize machine stress-rated (MSR) lumber, as well as laminated products for flange stock. Early research by Lewis et al. (1944c) indicated that excessive slope of grain (1:15 in lumber) reduced I-beam strength by 30% and that compression damage induced by reverse loading reduced strength 70%.

The influence of flange stiffness on the load capacity of double-webbed I-beams was investigated by Samson in 1983. Statistical analyses showed that more than 50% of the variation in load capacity of the I-beam was attributed to variation in the average MOE of the tension flange. Flanges were most efficient when the MOE of the tension flange was 1.25 times the MOE of the compression flange. Fergus (1979) also found that the performance of moment-critical beams was governed by flange stiffness and strength and that shear-critical I-beams were also sensitive to flange stiffness. The importance of flange stiffness was also noted by Hilson and Rodd (1979), whose study of the post-buckling behavior of hardboard-

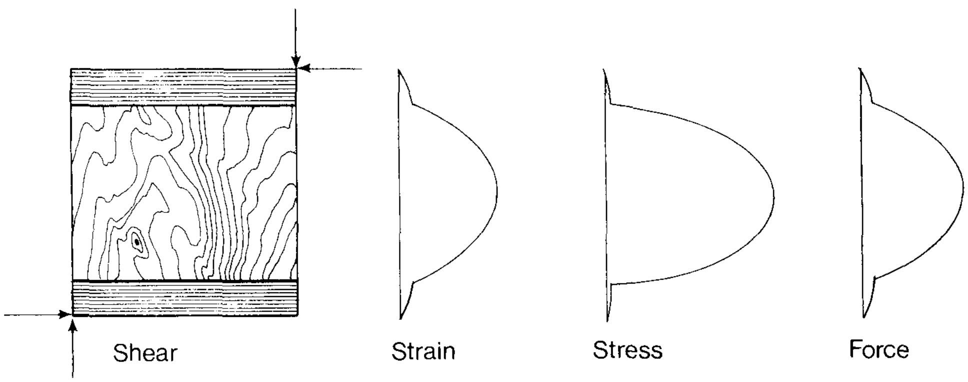

FIG. 3. Simplified representation of I-section mechanics. Shear force applied, the resulting shear strain distribution, stress distribution, and force distribution to produce shear capacity.

webbed I-beams indicated that stiffer flanges resist shape changes and carry greater shear loads after web buckling, leading to increased ultimate loads.

When the sections of flange material are properly jointed, I-beams longer than stock length lumber can be produced. Structural joints in lumber flanges can be developed with either finger or scarf joints (Jokerst 1981; APA 1982; Bullen and van der Straten 1986; Hoyle 1986). Although potentially stronger than the finger joint, the scarf joint is more difficult to produce in continuous manufacturing operations. The results of experimental tests on finger-jointed lumber in bending, tension, and compression have generally shown that the stiffness of the joined wood is not affected by the presence of the joint; however, strength is reduced below that of clear wood (Jokerst 1981). This reduction is more significant in higher strength flange material. Studies have shown that the strength of joined wood is reduced about 10% in compression; however, strength can be reduced as much as 50% in bending (Jokerst 1981; Leichti and Tang 1983; Leichti 1986). Nevertheless, in lower grades of lumber, the reduction in strength caused by the presence of a joint generally has less effect on flange material than a knot or knothole (Jokerst 1981).

The primary alternative material to sawn-lumber flange stock is laminated veneer lumber (LVL), a unidirectional laminate of graded veneers bonded with an exterior-grade adhesive. This type of lumber has been used extensively in commercial products (Trus Joist Corporation 1984; Gang-Nail Systems, Inc. 1985), though some producers utilize parallel-strand lumber. Because of their durability (Laufenberg 1982), reliable mechanical properties, and long lengths, LVL and parallel-strand lumber are well suited for production of structural components without end joints. Though not common commercially, these products are as easily and reliably end-jointed as solid lumber (Youngquist et al. 1984).

Less sophisticated materials have been investigated for use in I-beam flanges. Minimally machined half-stems of lodgepole pine (*Pinus contorta*) were tested for possible use as flange material by investigators who felt that the product could be competitive with joists using traditional flange types (Koch and Burke 1985). Ultimate bending tests indicated that failures, evenly divided between tension and compression, occurred largely in the flanges. Several problems need to be resolved before this product is acceptable; crucial problems include establishing methods for joining the stems to produce longer sections, assigning lumber grades, and accommodating the nonprismatic and geometrically variable cross sections in design. Because flange quality has a significant influence on I-beam performance, Solli and Lackner (1986) proposed evaluating strength properties and lumber quality of small cross-section lumber to establish alternative grading rules.

Flexural stiffness properties of I-beams with flanges molded from particle-based material were found to be comparable to that of a solid lumber beam of equivalent weight (Geimer and Lehmann 1975). However, bending strength was only half that of the lumber-flanged counterpart, and fractures were brittle in nature. The relatively poor performance was attributed to the lower tensile strength of the particle-based flanges.

The quality of flange material needed in wood I-beams is underscored by the fact that manufacturers are increasingly utilizing high quality composite structural lumber products, such as laminated veneer and parallel strand lumber.

INFLUENCE OF WEB

Web materials

Wood-based panel materials are used as webs in I-beams. Materials such as plywood, particleboard, waferboard, oriented strandboard (OSB), and hardboard are characterized by high shear modulus and shear strengths (through the thickness). Although these composite materials exhibit much lower bending strengths than solid or laminated wood used as flanges, they have higher shear properties.

The effect of shear modulus of the web material on total beam deflection was investigated by Leichti and Tang (1983) using a strain energy approach. As expected, the authors found that a lower shear modulus led to greater shear deflections. This reinforced the findings of Booth (1974) and Mohler and Ehlbeck (1973), who showed that shear deflection, a major component of total deflection, cannot be ignored in design.

Experimental tests performed by Percival et al. (1977) investigated the stiffness performance of experimental I-beams, constructed with various ½-in. web panels and nail-glued 2 by 4 flanges. Panel materials included plywood, underlayment particleboard, aspen waferboard, and mixed-hardwood particleboard. Results indicated that the waferboard-webbed I-beams were about 20% stiffer than the plywood webbed beams. The particleboard-webbed members were 10 percent stiffer. Though stiffness was the primary parameter investigated, Percival et al. (1977) speculated that the type of web material should affect load capacity.

Because of its relatively low variability and high shear modulus, particleboard has been studied as a web material (Hunt 1975, 1976; Tuk and Picado 1981; Johannesen 1983). Johnson et al. (1975) evaluated the performance of shear-critical, particleboard-webbed I-beams in flexure. Flexural rigidity and load capacity were estimated on the basis of elastic and strength properties, section geometry, and elementary beam theory. Load capacity was based on the weakest component, assumed to be the tensile strength of the particleboard web. Measured loads were greater than estimated, and failures began near the nails in the glued-nailed flanges. Measured flexural rigidity was less than estimated.

The FPL evaluated the use of hardboard as a web substrate through the testing of moment-critical beams constructed with ¼-in. webs and face-glued lumber flanges (Ramaker and Davister 1972; Superfesky and Ramaker 1976). Good agreement between predicted and measured deflections and stresses was reported.

In an extension of their prior study, Superfesky and Ramaker (1976) investigated the effect of web material and span length on mode of failure. Two different types of hardboard were used as web materials, and all beams had LVL flanges face-glued to the web panels. Results of tests on 6- and 12-ft-long beams showed that beam behavior was reasonably well predicted using elementary beam theory with transformed sections and material properties of the components. However, behavior of the shorter and more shear-critical beams as well as that of the longer members did not conform with the theory, even though shear deflections (Orosz 1970) were considered.

In an analysis of load-deflection curves, Superfesky and Ramaker (1976) showed that hardboard-webbed I-beams exhibit linear behavior to a load level equivalent to 60% of the rail shear strength of the hardboard web. As with the other experimental hardboard-webbed beams, the 12-ft beams failed in the tension flange, with essentially no inelastic deformation before failure. In their later study, Superfesky and Ramaker (1978) included two ¼-in. hardboards and ¼-in. plywood as web substrates. Under short-term destructive loading, the strength and stiffness of plywood-webbed beams were found to be about half that of equivalent hardboard-webbed elements.

Tests were conducted on I-beams with commercial insert-type flange-web joints and web panels oriented with the major panel axis perpendicular to the beam span (Leichti 1986). Findings indicated that web material has a statistically significant effect on I-beam stiffness and load capacity. The I-beams with OSB webs carried greater loads than those with waferboard or plywood webs, which had similar load capacities. Stiffness, as measured by load at a defined deflection, was similar for I-beams with OSB and waferboard webs but significantly lower for those with plywood webs. In subsequent studies of I-beams with webs of plywood, random waferboard, or OSB made of southern hardwoods (Chen et al. 1987), load capacities differed significantly as a result of web material; I-beams with OSB webs carried greater ultimate loads.

Web-ply orientation

The influence of web material orientation with respect to the beam flexural axis has not been clearly identified. Early experimental studies at the FPL with box- and I-beam constructions (Lewis et al. 1943, 1944; Lewis et al. 1944a, b) concluded that box-beam webs oriented at 45° were more efficient in carrying shear stresses than webs oriented at 0 or 90°. The studies further demonstrated that vertically and horizontally oriented panels had about the same shear strength.

More recently, the effects of web-ply orientation on the structural performance of wood composite I-beams were examined using finite element analysis (Fawcett and Sack 1977). The web was idealized as a stack of rectangular plate elements and the flanges as a series of truss elements. In general, the analyses indicated that web crippling performance was improved by increasing the number of web plies with grain perpendicular to the horizontal beam axis. Although this result is not supported by the earlier experimental studies (Lewis et al. 1943, 1944), most manufacturers produce I-beams with the major axis of the web ply oriented perpendicular to the beam axis.

Web reinforcement

Web reinforcement, an important element of the wood I-beam, serves to prevent flange distortion, web buckling under concentrated loads, knifing of the web through the flange, and lateral sway. Also, web reinforcement can significantly reduce the bearing length required. The requirements for reinforcement vary and are a function of beam geometry and the mechanical properties of the web substrate.

Web buckling was of major concern in early studies with lightweight sections intended for aircraft structures (Lewis and Dawley 1943; Lewis et al. 1943, 1944; Withey et al. 1943; Lewis et al. 1944a, b). One study showed that I-beams with plywood webs buckled inelastically under repeated stresses of approximately two-thirds the ultimate load (Lewis et al. 1943).

Web reinforcement is prescribed in the form of either bearing or intermediate stiffeners. Bearing reinforcement is located at reaction positions; such reinforcement increases the web-to-flange bearing area and improves the buckling performance of the web. Stiffeners are designed with consideration given to compression and rolling shear requirements (APA 1982). Maley (1987) found that bearing stiffeners can transfer 80 to 90% of the reaction capacity in deep I-beams but only 10 to 20% in shallower beams because the webs of shallow beams resist buckling.

The influence of web stiffeners in hardboard-webbed I-beams was recently investigated by Norlin (1988). Using analytical and experimental methods, he identified stiffener needs according to the ratio of free web height to web thickness and presented a method for estimating optimum stiffener spacing.

Specific web-reinforcement requirements are given by the APA (1982), the *Wood Handbook* (USDA 1987), and various I-beam product manuals; Hoyle (1986) overviews the use of web-reinforcement requirements in composite beam design.

In general, bearing reinforcement is required at reaction and concentrated load points. According to the APA (1982), intermediate stiffeners spaced 48 in. or less on center will develop all, or nearly all, the shear strength of a beam of normal proportions.

Web openings

The design of wood composite I-beams must allow for the passage of electrical conduit, plumbing lines, and heating and ventilation ducts to maximize headroom in a building.

Literature devoted to the analysis of openings in the webs of wood I-beams is limited; however, a substantial body of knowledge exists for round and rectangular openings in steel thin-webbed I-sections. Closed-form mathematical solutions for plates with openings and various boundary conditions are available in classical texts on the mechanics of materials.

The effects of circular web openings in moment- and shear-critical I-beams with plywood and OSB webs were studied by Fergus (1979). The study indicated that the bending strength of moment-critical I-beams was not affected by circular openings in the web, in spite of a removal of 70% of the web depth. Larger openings, however, can reduce shear capacity and decrease stiffness (Maley 1987). Although Fergus (1979) could not directly assess a performance change caused by web openings, the author noted that webs buckled around the openings in shear-critical I-beams with plywood webs but not in those with OSB webs.

Square openings cause stress concentrations at corners (Johannesson 1977), and large openings can lead to stress concentrations at the flange-web joint (Maley 1987).

In developing design information for round service openings in hardboard-webbed I-beams, Hilson and Rodd (1984) found that the ratio of beam height to distance between web stiffeners and the web slenderness interacted with the size of the web openings. For very slender beams, the authors suggested that openings relieved diagonal compression stresses, resulting in more uniform strain distributions and reduced buckling. In general, however, as opening size increased, strength decreased.

Thus, openings in wood I-beams can have a significant effect on shear strength and stiffness, depending on their size and location. Allowable sizes and locations of web openings for commercial products are clearly specified in the product catalogs of manufacturers. These recommendations are determined from experimental investigation, the results of which are typically proprietary.

Web joints

The effects of web butt joints on the strength and stiffness of I-beams were investigated by Leichti (1986) and Leichti and Tang (1989) through experimental testing and theoretical analysis of I-beams with discontinuous and continuous waferboard webs. The I-beams were 16 ft long and 10 in. deep, and those with discontinuous webs had butt joints that were spaced 48 in. apart. The web joints did not cause a significant difference in stiffness or load capacity of the beams. However, differences in failure characteristics were apparent. In analyzing these beams using the finite element method, sharp shear-stress gradients were found in the web at the tips of the web butt joints as well as in the flanges.

Mortensen and Hansen (1988) have recently reported test results for I-beams with open and gusset-plate-reinforced web butt joints. The open web butt joints closed in the compression zone during bending whereas strength and stiffness of the joint improved when gusset plates were utilized.

Although wood composite I-beams with scarf, tongue and groove, V-groove, and finger-jointed web joints are commercially available, the performance information developed for these structural connections is proprietary. Also, in most applications manufacturers are moving away from controlling the location of web joints. The shear test being specified in standards that are evolving will incorporate the web joint regardless of type in the constant shear span so that the joint strength should always be reflected in the shear capacity.

FLANGE-WEB JOINT

The flange-web joint serves as the shear-resistant interface between adjacent components of the composite I-beam assembly and in most factory-type production I-beam members consists of a continuous glueline of rigid adhesive. Various joint geometries have been investigated, and they have been discussed in a review by McNatt (1980). Because of the many joint geometries possible

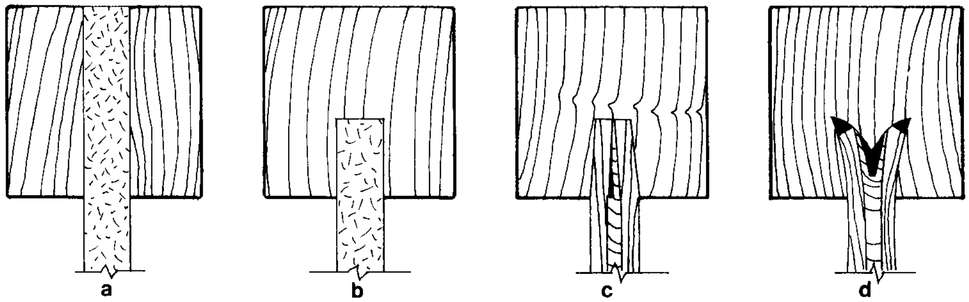

FIG. 4. Several flange-web joints. (a) Web nailed or bonded to double flanges, (b) routed groove with square-edged web, (c) tapered groove and web, and (d) Y-groove with split web.

(Fig. 4) and the various connection systems available, the flange-web joint is the source of considerable patent activity for commercializing I-beam products (for example, Troutner 1970).

The design of composite beams with flexible adhesive connections, rigid adhesive connections, and nailed joints is described by Hoyle (1986). However, I-beam members with mechanical fasteners and elastomeric adhesives are difficult to design properly, and adequate control of field fabrication is almost impossible.

Several analytical studies have focused on conditions similar to an insert-type flange-web joint. Keer and Chantaramungkorn (1975) derived the relationships between trench geometry, strain energy, and stress intensity. Haritos and Keer went on to derive stress distributions for a range of joint geometries (1980), and later (1985) they revealed how adhesive rigidity could amplify shear stresses at the interface.

Kuenzi and Wilkinson (1971) derived expressions that describe how fastener rigidity in the flange-web joint affects the performance of wood I-beams, and Heimeshoff (1987) derived differential equations for stresses and deformations in beams with nonrigid joints. Fageiri and Booth (1976) modeled the flange-web joint using nonlinear force-displacement characteristics; their theoretical predictions for stresses and deflections were in good agreement with experimental results. The model used was considered general enough to apply to any type of fastening system with a nonlinear force-displacement characteristic, including elastomeric joints.

The behavior of nailed flange-web joints in plywood-webbed I-beams has been studied in some detail (Gunadi 1969; Booth 1974; Fageiri 1974; Fageiri and Booth 1976; Mortensen and Hansen 1988). Booth (1974) showed that nailed flange-web joints suffer joint displacement, the result of incomplete interaction between the flange and web. He concluded that flange-web joint slip is great enough to be considered in design.

Nailed, stapled, or staple-glued flange-web joints were experimentally compared by Kumar et al. (1972) who found that the staple-glued member carried 50% more load and was stiffer than either the nailed or stapled members, which were nearly equal in load capacity. Voevodin and Kondratenko (1985) reached similar conclusions in comparing I-beam performance with mechanically connected flange-web joints or joints supplemented with bonding. The findings of van Wyk (1986), which showed that nails and screws in timber joints do not contribute to joint stiffness or strength when used in conjunction with a rigid adhesive, serve to support the contribution of adhesive to I-beam performance.

Voevodin et al. (1985) noted that I-beams did not perform well if the joints were not precisely machined and clamped during glue setting. To investigate possible improvements in glueline bonding pressure, Sliker and Suchsland (1982) constructed I-beams with locking flange-web joints. Beveled-edged plywood webs were pressed into LVL flanges that had grooves with amplitudes of $^1/_{16}$ and $^1/_{32}$ in. and a wave length of 12 in., which forced the webs out of plane into a sinusoidal shape. Tests on the beams indicated failure in horizontal or rolling shear, with some flange failure noted at web butt joints. Web amplitude was found to have no effect on failure stresses but did diminish stiffness. The I-beams with the $^1/_{32}$-in. amplitude webs were 92% as stiff as members with the planar webs, whereas those with $^1/_{16}$-in. amplitude grooves were only 86% as stiff. The actual use of I-beams with sinusoidal hardboard webs and glued joints is described by Stoy (1958).

Fastening-system efficiency depends on the rigidity of the joint formed, and rigid adhesives are considered most efficient (River and Gillespie 1981). Aside from the studies by Hoyle (1973b) and Kuenzi and Wilkinson (1971), adhesive rigidity has not been studied in wood composite I-beams with glued flange-web joints. However, the stress distributions as influenced by adhesive rigidity are described in the literature on applied mechanics (Haritos and Keer 1985).

EFFECT OF MOISTURE CONTENT ON I-BEAM STRENGTH AND STIFFNESS

Only limited work has been performed on the effects of moisture on the performance of wood I-beams. Chen et al. (1988b) evaluated the flexural performance of I-beams with nominal ⅜-in. webs of OSB, waferboard, and plywood under three environmental conditions: 70 F at 65% relative humidity (RH) (dry), 70 F at 95% RH (humid), and a 24-h water spray (wet). Ultimate load capacity was found to decrease for OSB and waferboard as moisture content increased from dry to humid. As moisture content changed from humid to wet, load capacity was further reduced for OSB-webbed beams, but not for waferboard-webbed beams. Load capacity of plywood-webbed beams was not affected significantly by changing moisture content.

Using a load-deflection ratio to express I-beam stiffness, the investigators also showed that increased moisture content reduced the load-deflection ratio for OSB- and plywood-webbed beams, but not for those webbed with waferboard. In the dry environment, the load-deflection function was linear; however, as moisture content increased, load-deflection responses became nonlinear. The load-deflection response of plywood-webbed I-beams was especially nonlinear under the wet condition; the beams often demonstrated extensive shear deformation and a nearly plastic response before ultimate failure.

LONG-TERM PERFORMANCE

Creep testing and modeling

The effects of load and environmental histories on the deflection of wood composite I-beams has been the subject of very few investigations. The high stresses carried by the web and flange materials and the adhesive bonding them are a cause of concern for the long-term creep (and ultimately creep-rupture) behavior of these members. A standard test to evaluate long-term creep and its effects on strength and stiffness is not available. Because of their high expense, performance tests of full-sized structural members that incorporate long-term gravity loads and environmental control have been limited.

In 1961, Cizek concluded that I-beams with particleboard and hardboard webs behaved similarly to I-beams with lumber webs under long-term loads. Kalina (1971) long-term-loaded I- and box-sections having various material combinations at a level equivalent to the short-term static proportional limit. During the load period, deflection increased in proportion to the logarithm of time, a relationship Cizek (1961) used to calculate creep deflections.

Leichti (1986) and Leichti and Tang (1986) reported the long-term behavior of I-beams with OSB, plywood, or waferboard webs loaded to a common normal stress in a constant hygrothermal environment. Time-deflection responses for I-beams and solid southern pine lumber under constant load were generated and compared. Creep displacement was modeled with a four-element spring and dashpot analog. Qualitative comparisons of the time-deflection response revealed no difference between I-beams and solid lumber.

Most recently, Wong et al. (1988) studied the creep behavior of OSB stressed-skin panels. The study demonstrated that the theories of linear viscoelasticity are applicable at low stress levels and constant relative humidity.

As computational methods and computer systems improve, traditional phenomenological creep models will likely be superseded by analytical methods verified by experimental data. This transition will greatly improve the knowledge base for the long-term performance of wood I-beams.

ENVIRONMENTAL EFFECTS ON CREEP

Research has demonstrated that deflection of hardboard-webbed I-beams is increased by repeatedly changing the relative humidity (Mohler 1961; Tyne 1978). Superfesky and Ramaker (1978) examined the relative performance of wood composite I-beams with webs of wet-formed hardboard, dry-formed hardboard, or plywood at two different span-to-depth ratios (l/d = 6 and 12) in three different hygrothermal environments (controlled cyclic humidity, uncontrolled interior, and uncontrolled protected exterior). They concluded that with a constant load (equivalent to 25% of maximum rail shear strength of the web material), cyclic humidity conditions accelerated the time to failure of the hardboard-webbed beams. When the hardboard-webbed beams were loaded at a level commensurate with that of the plywood-webbed beams, creep performance was satisfactory. The high shear modulus of the hardboard web material (relative to the plywood) appeared to be a mechanical attribute important to good long-term performance.

The influence of cyclic humidity on the shear modulus of wood composite panels was investigated by Tang and Yeh (1987); shear modulus typically declined with initial humidity increase. Decreased shear modulus can lead to increased deflection under constant loads (Leichti and Tang 1983). The I-beams with hardboard and plywood webs tested by Superfesky and Ramaker (1978) in the uncontrolled interior environment yielded similar creep characteristics when long-term deflections were expressed as a percentage of initial deflection. In the uncontrolled protected exterior environment, creep levels were higher for the plywood-webbed beams, but not the hardboard-webbed beams.

Extending this work with additional performance tests using the same I-beam types and environmental conditions, McNatt and Superfesky (1983) drew conclusions similar to those found earlier—that is, hardboard-webbed beams creep less than plywood-webbed beams because the shear stiffness of hardboard is so much greater than that of plywood. In a recent study, Norlin (1988) subjected I-beams with post-buckled hardboard webs to long-term loads in a humid environment. No unusual creep behavior was noted after 22 months despite buckled web conditions.

Chen (1988) and Chen et al. (1988a, b) studied the flexural behavior of several configurations of I-beams and southern pine lumber at 70 F under cyclic humidity conditions (65% RH elevated to 95% RH). The I-beams were webbed with waferboard, OSB, or plywood. At 65% RH, no significant differences in creep performance were noted; however at 95% RH, creep deflection increased rapidly, and significant differences in creep behavior were witnessed. Relative creep was least for the lumber, greatest for the OSB-webbed beams, and intermediate for the waferboard- and plywood-webbed beams. The rate of deflection leveled after conditions were returned to 65% RH in the second environmental cycle. Chen et al. (1988a) concluded that web material has a major influence on creep performance; specifically, web materials with high shear strength exhibit less creep in long-term loading under changing humidity.

The conclusions of McNatt and Superfesky (1983) and Chen et al. (1988a) indicate the importance of web material properties—shear modulus and shear strength, respectively—to creep performance.

LOAD DURATION

The effect of load duration on the flexural strength of I-beams was investigated by Superfesky and Ramaker (1978) and McNatt and Superfesky (1983). Strength values averaged slightly lower for long-term-loaded I-beams with plywood webs than for similar unloaded beams. Slightly higher values were found for long-term-loaded I-beams with hardboard webs.

Leichti (1986) and Leichti and Tang (1989) also studied the influence of load history on the load attributes of wood composite I-beams. Three variables—I-beam type, load history (no history or long-term-loaded), and interaction of I-beam type and load history—were statistically analyzed for members loaded to a common normal stress in a constant hygrothermal environment. Load history was found to be significant.

Finite element analyses coupled with strength theory (Leichti and Tang, 1989) indicated that long-term load may have produced some localized failures at the web butt joints. However, when the failures and load-deflection characteristics of initial and residual strength tests were compared, the influence of load history could not be defined. Although duration of load adjustments for wood composite I-beams has received some attention, the same values are used as for solid lumber.

DYNAMIC PERFORMANCE

The study of dynamic performance, including vibration and damping characteristics, of wood composite I-beams as individual members or system components is not reported in the literature. Composites and solid lumber differ in mass, nail-holding characteristics, and stiffness. Therefore, the dynamic performance of

I-beams is likely to be significantly different from that of sawn lumber. I-beams are usually bonded into a system of engineered components that produce a stiff, low-mass, low-damping concert of elements. Manufacturers have indicated some vibration problems for lighter I-beam sizes, and most manufacturers suggest possible remedies (such as shortening the span) in their product specifications. The problem of vibration needs to be addressed to determine product and system behavior and resultant consumer response.

RELIABILITY

The structural reliability of wood composite I-beams as it relates to creep was studied by Leichti (1986) and Leichti and Tang (1989). On the assumption that creep and its effect on serviceability would likely be the limiting failure mode in structural applications, the time-displacement response was modeled with a four-element mechanical analog. This function was used as the failure surface in a second-moment reliability analysis. Wood composite I-beams were shown to be more reliable and have longer reliable lifetimes than lumber. Sensitivity studies with the model revealed that the statistical means of the model variables controlled the length of reliable lifetime, whereas the variability of the means increased or decreased reliability.

Sharp and Gromala (1988) used reliability analysis as a tool to develop application consistency for wood composite I-beams. The I-beam components were assumed to interact as a system leading to multiple failure modes, each of which was assumed to have a separate probability distribution. The authors conducted a first-order, second-moment reliability analysis presented in a load and resistance design format that considered dead plus live loads.

Methods for time-dependent analysis and reliability-based design of wood composites are still developing. However, when reliability is considered in its traditional sense of adequate performance under the conditions encountered for a given period of time, field performance of wood composite I-beams has been satisfactory.

CONCLUDING REMARKS

For more than 40 years, the wood composite I-beam has been utilized in building construction. Since the early 1970s, technology and facilities have developed such that prefabricated wood composite I-beams could be mass produced.

The wood composite I-beam is a complex assemblage of orthotropic and anisotropic materials. Static performance of I-beams is influenced by the elastic and strength properties of the composition materials, adhesive rigidity, joint efficiency, web openings, and web stiffness. Furthermore, as with all wood and wood-based products, environment can significantly influence I-beam strength and stiffness. Although we know a great deal about static performance, we know much less about predicting the long-term performance, dynamic behavior, and reliability of these components.

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