GUIDELINES FOR EVALUATION OF HOLES AND NOTCHES IN STRUCTURAL GLUED LAMINATED TIMBER BEAMS

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SCOPE

This technical note has been developed to assist engineers, architects, building officials, and others in evaluating the effects of holes and notches in structural glued laminated timber beams. These guidelines are applicable to holes that are to be used to provide access ("open") holes and are not applicable to holes drilled for mechanical fasteners or connectors. These guidelines only apply to round or rectangular holes as described herein and to the specific notch types described herein. Holes and notches in curved or tapered beams are not addressed.

INTRODUCTION

Structural glued laminated timber (glulam) is typically used in highly stressed engineering applications. Because glued laminated timbers are used in highly stressed applications, it is very important to avoid modification of these members in any manner that would adversely affect their intended structural performance. Holes and notches reduce the section available to resist stresses and also produce stress concentrations and tension stresses perpendicular to grain. As such, holes, notches, and other modifications to glulam should be avoided or limited. Where unavoidable, holes and notches should be placed in zones of lesser beam stresses.

Generally speaking, holes and notches must be approved by an engineer qualified in timber design. Small horizontal holes within the prescriptive limitations for horizontal holes included in this document are permitted without engineering analysis. Large horizontal holes, vertical holes, and notches always require engineering approval. It is recommended that the end grain surfaces exposed by the fabrication of holes and notches be coated with an end sealer to minimize potential checking.

HOLES

The procedures herein apply to holes fabricated through glued laminated timbers to accommodate the passage of electrical conduit, sprinkler lines, or other lines, but not to holes used to transfer load. Holes for mechanical fasteners and holes that transfer significant loads to the beam must be evaluated separately. AITC 104 *Typical Construction Details* [1] and the *Timber Construction Manual* [2] provide guidance on designing connections.

Permissible Horizontal Holes without Engineering Analysis

Drilled horizontal holes in uniformly loaded, simply supported beams are allowed in the zones NOT identified as critical (Figure 1) with the following limitations:

1. Holes must be a minimum of 4 hole diameters from the top or bottom surface of the beam and a minimum of 8 hole diameters from the end of the beam. The distance is measured from the edge of the hole to the nearest edge of the beam.

2. Maximum hole size is 1-1/2" diameter or a hole diameter equal to 1/10 the beam depth, whichever is smaller.

3. Maximum Number of Holes: The number of holes (not including holes related to connections) shall not exceed one hole per each 5 feet length of the member (i.e. 4 holes in a 20 foot member). (This rule does not apply to spacing of holes.)

4. Spacing between holes shall be a minimum of 8 hole diameters (based on the largest diameter of any adjacent hole in the member) from any other hole in the member. The distance is measured between the nearest edges of adjacent holes.
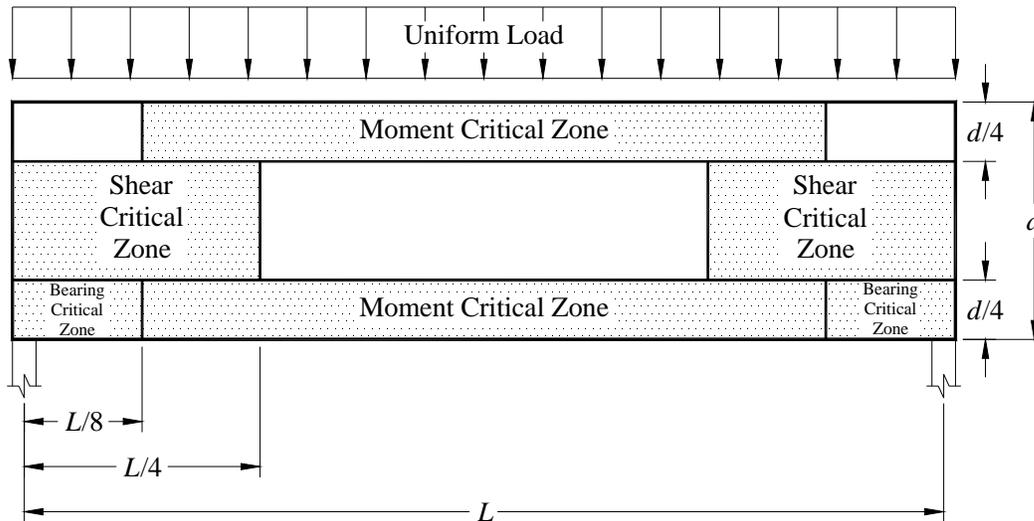

Figure 1. *Critical zones in a uniformly loaded, simply supported beam*

Engineering Evaluation of Horizontal Holes

Large horizontal holes **and** holes of any size in any of the critical zones must be approved by an engineer qualified in timber design. The presence of holes reduces the section capacity and creates stress concentrations which must be considered. The effect of the hole must be evaluated with regard to (1) bending capacity, (2) shear capacity, and (3) stress concentrations. The following sections describe analysis procedures for each of these cases, subject to the following limitations.

Limitations on Holes:

1. Concentrated loads at location of holes should be avoided.

2. Holes must be circular or rectangular with rounded corners (Figure 2).

3. The distance from the nearest edge of the hole to the face of the nearest support, l_a, must be greater than or equal to half the beam depth, d (Figure 2).

4. The distance from the nearest edge of the hole to the end of the beam, l_v, must be greater than or equal to the beam depth, d (Figure 2).

5. Rectangular holes must have a corner radius, r, of 1 in. or more (Figure 2). It is recommended that 2 in. diameter or larger holes be drilled at the corners of the hole prior to sawing the straight portions. **No overcutting is permitted**.

6. The hole dimension measured perpendicular to the longitudinal axis of the beam, v, must be less than or equal to half the beam depth, d (Figure 2). The dimension v must not exceed 14 inches.

7. The distance from the nearest edge of the hole to the top, d_u, or bottom, d_ℓ, of the beam must be greater than or equal to 15% of the beam depth, d (Figure 2).

8. Where multiple holes are present, the nearest edges of adjacent holes must be separated by a distance equal to or greater than the largest of (1) 12 inches, (2) the beam depth, d, and (3) four times the hole diameter for round holes or four times the length of the diagonal for rectangular holes.
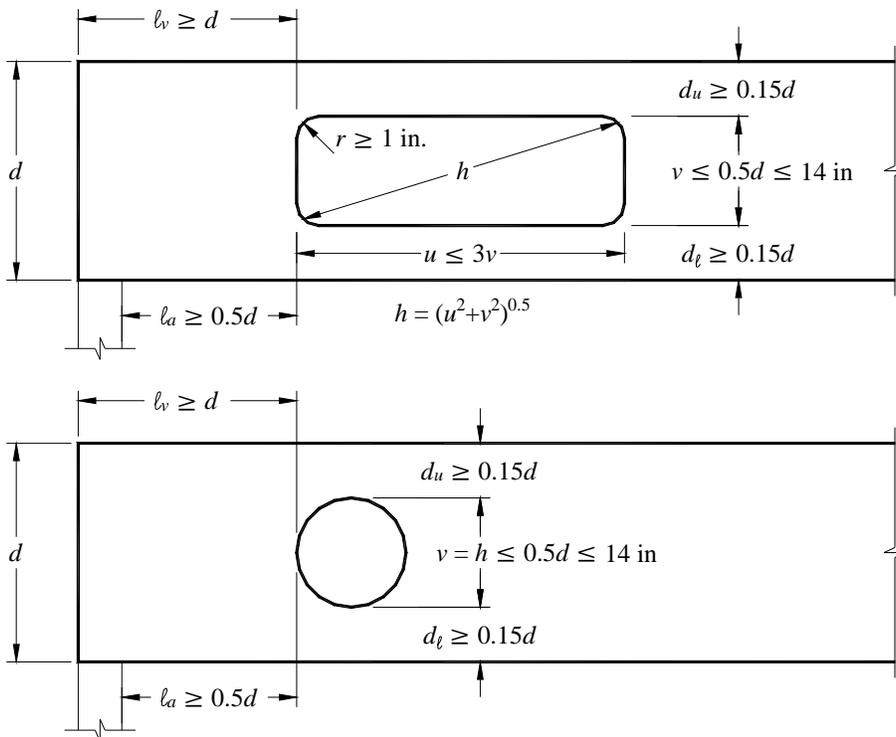
Figure 2. *Hole limitations for engineering analysis.*

Bending Capacity

The design bending capacity of the reduced (net) section must be evaluated and compared with the design bending moment at the location of the hole. The following steps are required:

1. The neutral axis at the section through the hole is located (Equation 1, Figure 3):

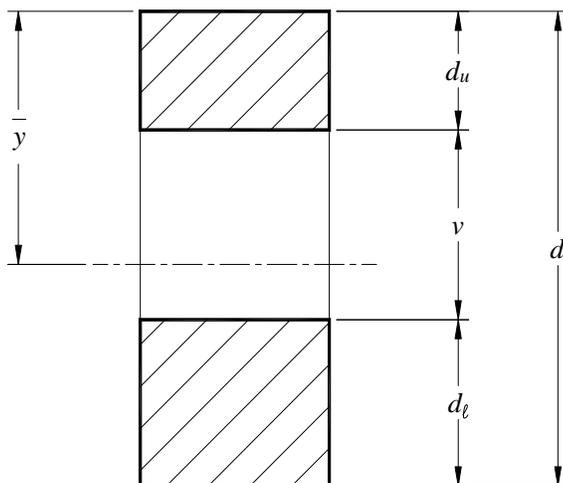$$\overline{y} = \frac{d^2 - 2vd_u - v^2}{2(d-v)} \tag{1}$$

Figure 3. *Location of neutral axis.*

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2. The moment of inertia of the net section is calculated (Equation 2):

$$I_{net} = b\left[\frac{d^3}{12} + d\left(\frac{d}{2} - \overline{y}\right)^2 - \frac{v^3}{12} - v\left(d_u + \frac{v}{2} - \overline{y}\right)^2\right]$$

(2)

3. The section modulus of the net section is calculated (Equation 3):

$$S_{net} = \min\left\{\frac{I_{net}}{\overline{y}}, \frac{I_{net}}{d - \overline{y}}\right\}$$

(3)

4. The bending capacity of the section is evaluated (Equation 4):

$$M \le F_b C_D C_M C_t \left(C_V \text{ or } C_L\right) S_{net}$$

(4)

Shear Capacity

The net section shear capacity at the hole must be evaluated and compared to the shear force at the hole (Equation 5):

$$V \le \frac{2b(d - v)F_v C_D C_M C_t C_{vr}}{3}$$

(5)

Stress Concentrations

A hole in a glulam beam disturbs the normal flow of stresses in the beam. Resulting stress concentrations can cause failure of the beam with cracks originating near the corners of the hole and propagating parallel to the grain. The following procedure is adapted (see commentary) for U.S. design from a method proposed Aicher and Hofflin [3]. The hole size, h, is defined as the diameter for round holes or the length of the diagonal ($\sqrt{u^2 + v^2}$) for rectangular holes.

Analysis of Stress Concentrations:

1. The moment and shear on the section through the center of the hole are calculated.

2. The following condition must be satisfied (Equation 6) :

$$\frac{3V}{2bd}\left(1.23 + 0.82\frac{h}{d}\right) + \frac{0.6M}{bd^2}\frac{h}{d} \le 1.6 F_v C_{vr} C_D C_M C_t C_{vol}$$

(6)

$$\text{where: } C_{vol} = \left(\frac{1 \text{ in}^3}{v^2 b}\right)^{\frac{1}{5}}$$

(7)

These procedures do not account for concentrated loads occurring above or below the hole. Where concentrated loads occur at a section with a hole, additional analysis may be necessary to evaluate the localized effects of bending, shear, and tension perpendicular-to-grain. Analysis of localized bending stresses should include consideration of lumber grade placement through the depth of the glulam beam.

These procedures also do not account for potential buckling in the compression flange at the location of a hole. Additional analysis may be necessary where localized buckling is a possibility.

Engineering Evaluation of Vertical Holes

A vertical hole reduces the net width of the beam at the location of the hole and may significantly reduce the beam's bending and shear strength. Prior to drilling any vertical holes, a qualified engineer must be consulted.

It is recommended that drilling vertical holes in glued laminated horizontal beams be avoided whenever possible. Not only is there a reduction in section properties at the vertical hole, there are also stress concentrations due to the discontinuity of the wood fibers at the hole.   The minimum edge distance from either side of the member to the center of a vertical hole must be 3 times the diameter of the hole. The evaluation of vertical holes must also satisfy the following criteria:

1. The section modulus at the vertical hole must be based on the width of the member minus 1.5 times the hole diameter (Equation 8):

$$S_{net,v} = \frac{(b-1.5h_v)d^2}{6} \tag{8}$$

2. The maximum bending moment must not exceed the allowable fiber stress in bending multiplied by the reduced section modulus (Equation 9):

$$M \le F_b C_D C_m C_t \left(C_V \text{ or } C_L\right) S_{net,v} \tag{9}$$

3. The shear parallel to grain (horizontal shear) capacity at the section with the vertical hole must be based on the net section at the hole (Equation 10):

$$V \le \frac{2(b-h_v)dF_v C_D C_M C_t C_{vr}}{3} \tag{10}$$

NOTCHES

These guidelines apply to simply supported, single span, beams and to the ends of multiple span beams. Notches at center bearings of multiple span beams are not addressed.

Tension Face Notches

A decrease in strength is caused by stress concentrations induced at the corner of the notch as well as a reduction of the section available to resist the design stresses. Notches also induce tension perpendicular to grain stresses that interact with the shear parallel to grain forces causing a tendency for the member to split along a line extended from the corner of the notch. This type of notch should be avoided whenever possible. Under no circumstances should a simple span glued laminated timber beam be notched on the tension face other than at an end bearing.

Where a notch on the tension face cannot be avoided (Figure 4), the depth of a tension side notch is limited to a maximum of 1/10 the depth of the member, not to exceed 3 inches. The design shear reaction at the notch must be limited by Equation 11:

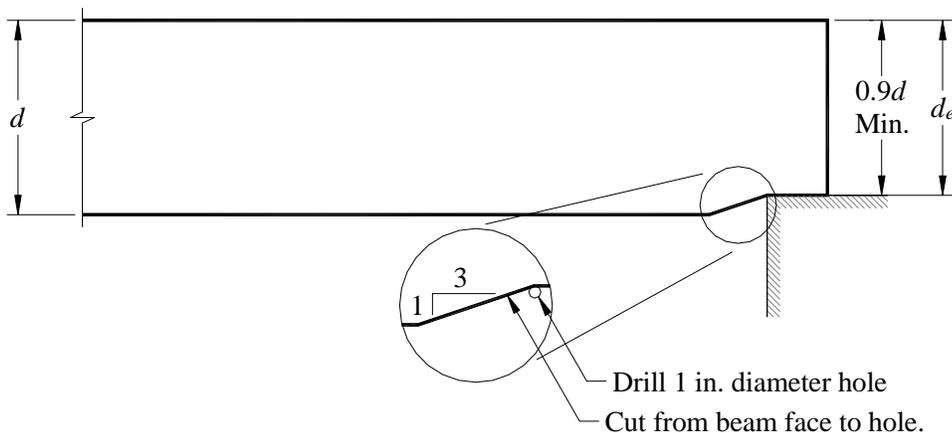$$R_v \le \frac{2bd_e F_v C_D C_M C_t C_{vr}}{3}\left(\frac{d_e}{d}\right)^2 \tag{11}$$

Figure 4. *End bearing notch detail*

A gradual tapered notch configuration in lieu of a square cornered notch or mechanical reinforcing at square cornered notches may be used to reduce the effects of stress concentrations at the reentrant corner of notches. The notch should be cut from the face of the beam to a drilled hole as shown in Figure 4.

The bearing capacity of the wood at the notch should also be evaluated. Tabular design values for bearing (compression perpendicular to grain) for glued laminated timbers are based on the relatively higher grade bottom lamination(s). Notching the beam at the support may result in bearing on lower grade material, which must be considered.

Compression Face Notches at Ends

In some instances, it may be necessary to notch a beam on its compression face at the end of the member. Limitations on such notches are shown in Figure 5. For the conditions shown, the design shear reaction must be limited according to Equation 12 or 13, as appropriate:

$$R_V \leq \frac{2}{3} b \left(d - \left(\frac{d - d_e}{d_e} \right) e \right) F_v C_D C_M C_t C_{vr} \qquad \text{where:} \quad e \leq d_e \qquad (12)$$

$$R_V \leq \frac{2}{3} b d_e F_v C_D C_M C_t C_{vr} \qquad \text{where:} \quad e > d_e \qquad (13)$$
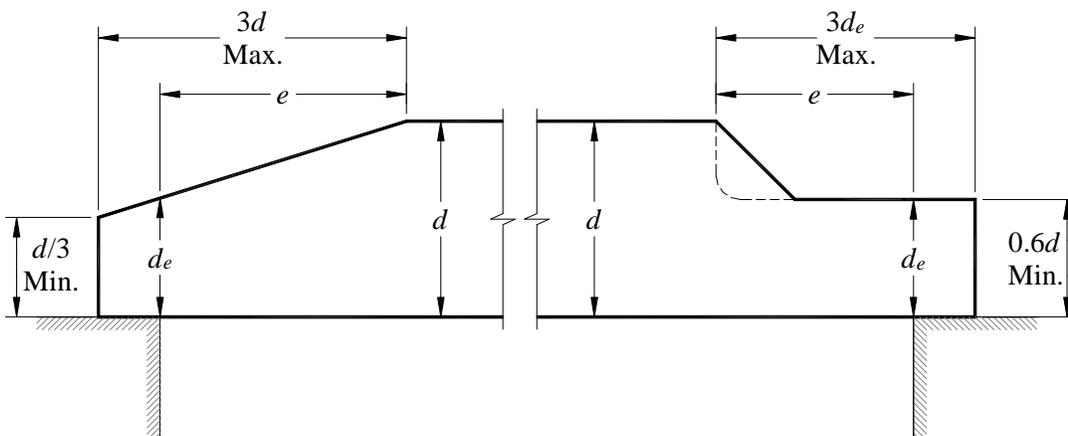

Figure 5. *Notch restrictions on compression face at ends*

Compression Face Notches Away from Ends

Occasionally, it is necessary to cut a notch across the width of the top of a glued laminated timber member to provide for passage of a small diameter plumbing or conduit run. Such notches are only permitted on the compression side of cross sections that are stressed to less than 50% of the allowable flexural stress. Member stresses must be evaluated based on the reduced (net) cross section resulting from the notch. Due to removal of high grade lumber at the surface, notching will also cause a reduction in allowable bending stresses. A preferred method for providing required passage for pipes, conduit, etc. is to mechanically attach additional (non-structural) laminations of depth equal to or greater than the desired notch. In this way the additional material is "notched" leaving the original structural member unaffected.

Notches for Hangers

Cantilevered hinge connections. The necessity to provide for the flush fit of a cantilever hinge connector is a commonly encountered field situation that requires the cutting of a notch or dap. For cantilever hinge connectors, the notch should be limited to the thickness of the steel plate.

Top mount saddle type hangers. AITC recommends that glued laminated members not be dapped at top mounted hangers when the thickness of the metal is such that is does not interfere with the installation of the floor

or roof sheathing or decking. If dapping is necessary, the dap should only be cut in zones of compression stress and should be limited to the thickness of the metal.

In all cases of dapping a glued laminated beam to accommodate a metal hanger, the designer must check the member stresses based on the reduced (net) section modulus resulting from the dap.

ADDITIONAL CONSIDERATIONS

Pressure-Treated Members

If it is necessary to notch or drill a glued laminated timber that has been pressure impregnated with a preservative treatment, all cut surfaces must receive a field treatment of preservative. One commonly used field preservative treatment is copper naphthenate. AWPA M4 [4] contains information and requirements for field treating.

Other Structural Applications

This technical note addresses the drilling and notching of glued laminated timber beams. However, similar considerations and limitations should be applied with respect to drilled holes and notches in any glued laminated timber member such as columns, arches, and truss members.

Other Loading and Support Conditions

Non-uniform loads. For non-uniform loading conditions, a qualified engineer must be consulted for evaluation and approval of holes and notches.

Continuous and cantilevered spans. All holes and notches in glued laminated timber for continuous or cantilevered spans, subject to any loading conditions, must be evaluated and approved by a qualified engineer. Generally, continuous span or cantilever span beams should not be notched in the top of the member over the support where negative moments exist. The engineer may choose to designate critical zones (dimensioned as appropriate) where field drilling is not allowed with a drawing similar to Figure 6 or Figure 7.
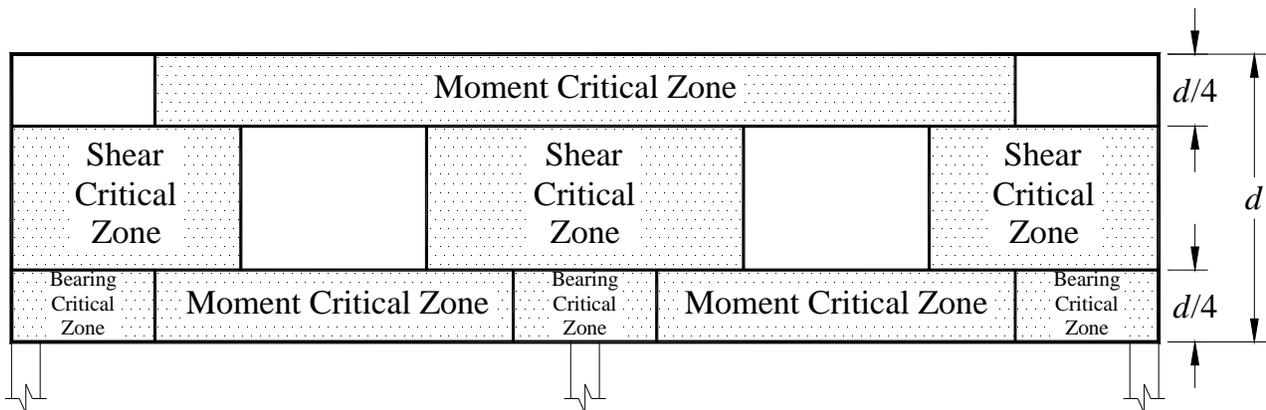

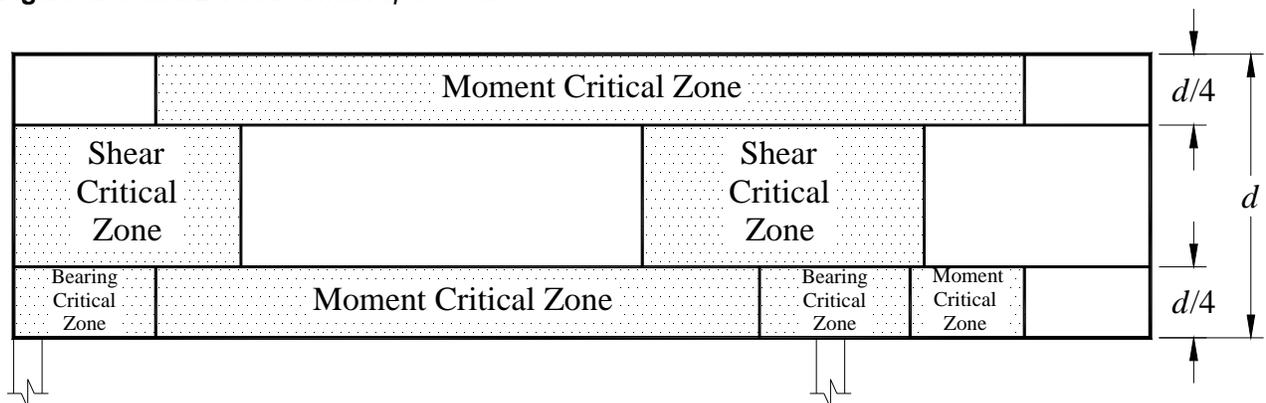**Figure 6.** *Critical zones in a multi-span beam*

Figure 7. *Critical zones in a cantilevered beam.*

Holes for Mechanical Fasteners and Connectors

For the installation of glued laminated timber, it is often necessary to drill holes in the member to attach connection hardware. AITC 104 *Typical Construction Details* [1] illustrates and describes various connections commonly used. AITC 104 [1] also indicates certain connection details that should be avoided, including connections which induce tension perpendicular to grain stresses and connections that restrain shrinkage. Connection design is governed by the National Design Specification® for Wood Construction [5].

Suspended Equipment Support

The necessity to provide support for building elements such as for suspended conduit, plumbing lines, mechanical units or ceiling fans is frequently encountered in the field. Such imposed loads should be suspended in such a manner that the load is applied to the top of the member (Figure 8) to avoid introducing tension perpendicular to grain stresses (load transferred through horizontal holes drilled in beam).
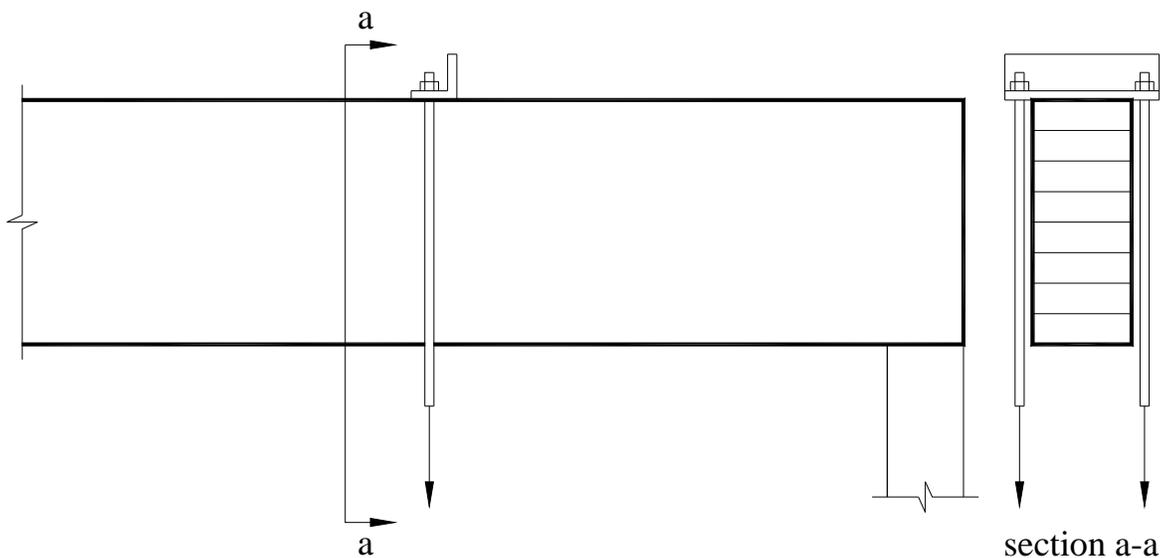
Figure 8. *Preferred connection detail for suspending heavy loads*

For horizontal holes carrying light loads such as small plumbing lines or electrical conduit, fasteners should be positioned at least 25% of the depth or 4 laminations, whichever is greater, away from the tension face of the member. If it is necessary to drill horizontal holes for the support of heavier loads, such as plumbing lines, mechanical units or other suspended loads, the holes should be located above the neutral axis of the member and at a section stressed to less than 50% of the design flexural stress. **In all cases, holes with loads must be evaluated by an engineer**. All effects of these added loads must be considered in the evaluation of the member.

NOMENCLATURE

b = width of the beam

C_D = load duration factor

C_L = beam stability factor

C_M = wet-use factor

C_t = temperature factor

C_V = volume factor for flexure in glulam beams

C_{vol} = volume factor for stress concentrations at holes

C_{vr} = shear reduction factor

d = depth of the beam

d_e = depth of the beam minus the depth of the notch

d_ℓ = depth of the beam below the hole

d_u = depth of the beam above the hole

e = distance from the face of the support to the farthest edge of the notch

F_v = reference shear design value

F_b = reference bending design value

h = hole diameter for round hole

h = length of diagonal for rectangular hole, $\sqrt{u^2 + v^2}$

h_v = diameter of vertical hole

I_{net} = moment of inertia of net section through horizontal hole

L = beam span

ℓ_a = distance from the end of the beam to the nearest edge of the hole

ℓ_v = distance from the face of the support to the nearest edge of the hole

M = design bending moment at hole

r = radius of rounded corners on rectangular hole

R_v = vertical end reaction force

S_{net} = section modulus of net section through horizontal hole

$S_{net,v}$ = section modulus of net section through vertical hole

V = design shear force at hole

u = length of rectangular hole

v = dimension of hole measured perpendicular to member axis

COMMENTARY: STRESS CONCENTRATION ANALYSIS

For the analysis of stress concentrations due to round holes in glulam beams, Aicher and Hofflin [3] presented a model of the form:

$$f_{t\perp,u} \leq \frac{F_{t\perp,05,\text{Europe}} k_{\text{mod}}}{\gamma_M} k_{dis} k_{vol}$$

where: $f_{t\perp,u}$ = tension perpendicular-to-grain stress due to ultimate applied loads

$F_{t\perp,05,\text{Europe}}$ = European characteristic value for tension strength perpendicular-to-grain

(based on a reference volume of 10 liters)

γ_M = material safety factor for European design

k_{mod} = modification factor for duration of load, service conditions, etc.

k_{dis} = stress distribution factor

k_{vol} = volume factor for tension perpendicular-to-grain strength

The critical tension perpendicular-to-grain stress can be described as:

$$f_{t\perp,u} = \frac{3V_u}{2bd}\left(1.23+0.82\frac{h}{d}\right)+\frac{0.6M_u}{bd^2}\frac{h}{d}$$

where: V_u = shear force at location of hole at ultimate load level

M_u = bending moment at location of hole at ultimate load level

b = width of beam

d = depth of beam

h = diameter of hole

European Design Equation

The resulting design criterion (European basis) then becomes:

$$\frac{3V_u}{2bd}\left(1.23+0.82\frac{h}{d}\right)+\frac{0.6M_u}{bd^2}\frac{h}{d} \leq \frac{F_{t\perp,05,\text{Europe}} k_{\text{mod}}}{\gamma_M} k_{dis} k_{vol}$$

The volume factor for tension perpendicular-to-grain is:

$$k_{vol} = \left(\frac{10\left(10^6\right)\text{ mm}^3}{0.192h^2b}\right)^{\frac{1}{5}}$$

The stress distribution factor is:

$$k_{dis} = \begin{cases} 1.8 & \text{for } M/V < 5h \\ 1.9 & \text{for } M/V > 10h \\ 2.05 & \text{for pure moment} \end{cases}$$

Calibration Factor

Aicher and Hofflin [3] recommended the use of a calibration factor of 1.15 to increase the resisting stress. Comparison of the larger beam data presented by Daniellson [6] for round holes to the design equation presented herein did not support the use of the calibration factor, so it has been conservatively neglected in this technical note. Figure 9 illustrates the comparison of the data presented by Daniellson [6] to curves developed based on the procedures in this note.
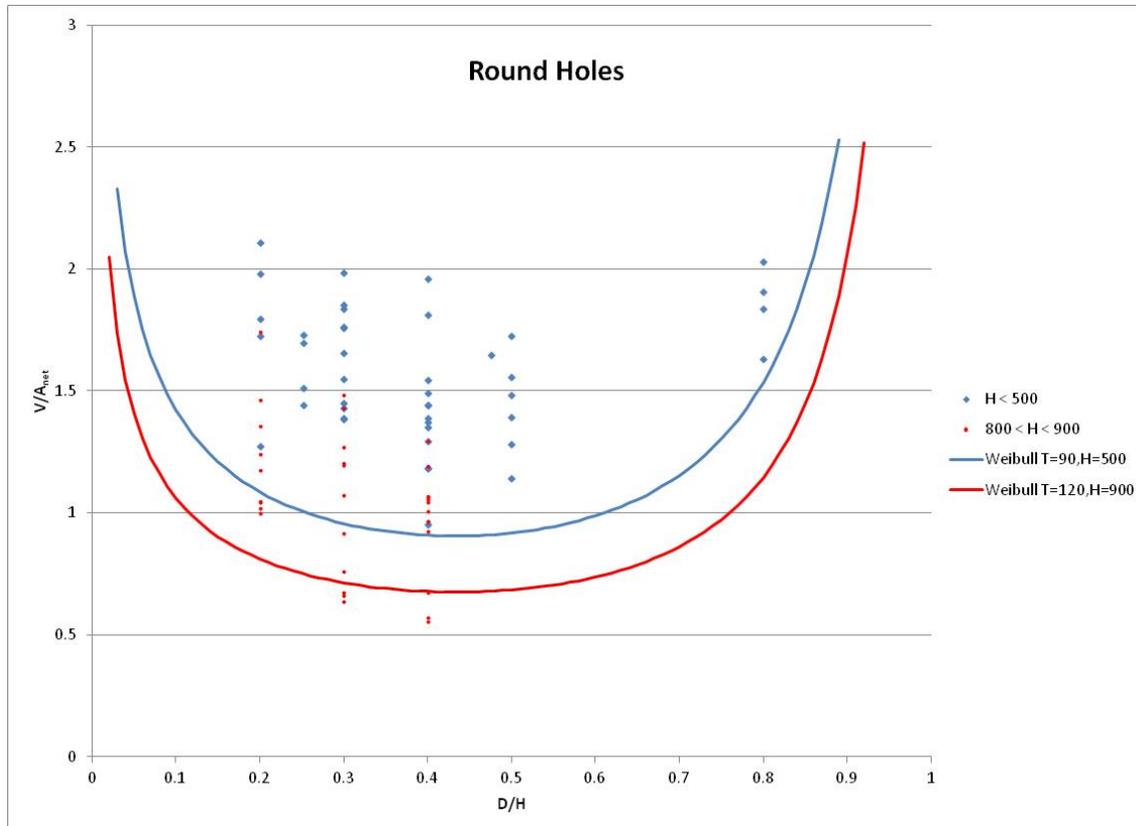

Figure 9. Comparison of test results from beams with round holes with predictive equations presented in this technical note. Procedures are conservative for all points that plot above the curves. H = beam depth, D = hole diameter, T = beam width, V = shear force at location of hole, A_{net} = net area of cross section. Curves represent a ratio of M/VH = 2. Points below the curves are captured for M/VH ratios matching test conditions.

Rectangular Holes

Aicher and Hofflin [3] did not present procedures for the analysis of beams with rectangular holes, however, their procedure for round holes gives reasonable results when applied to rectangular holes with the hole size, h, defined as the length of the diagonal of the rectangular hole and the volume factor calculated based on the beam width and the dimension of the hole measured perpendicular to the beam's longitudinal axis, v. Beam test results reported by Daniellson [6] were compared with the predictive equations to verify reasonable fit with the data. Figure 10 illustrates the comparison of the data for beams with rectangular holes to a design curve developed according to the procedures presented herein.

$$h = \sqrt{u^2 + v^2}$$

$$k_{vol} = \left(\frac{10\left(10^6\right) \text{ mm}^3}{0.192 v^2 b} \right)^{\frac{1}{5}}$$

where: u = dimension of rectangular hole measured parallel to longitudinal direction
v = dimension of rectangular hole measured perpendicular to longitudinal direction
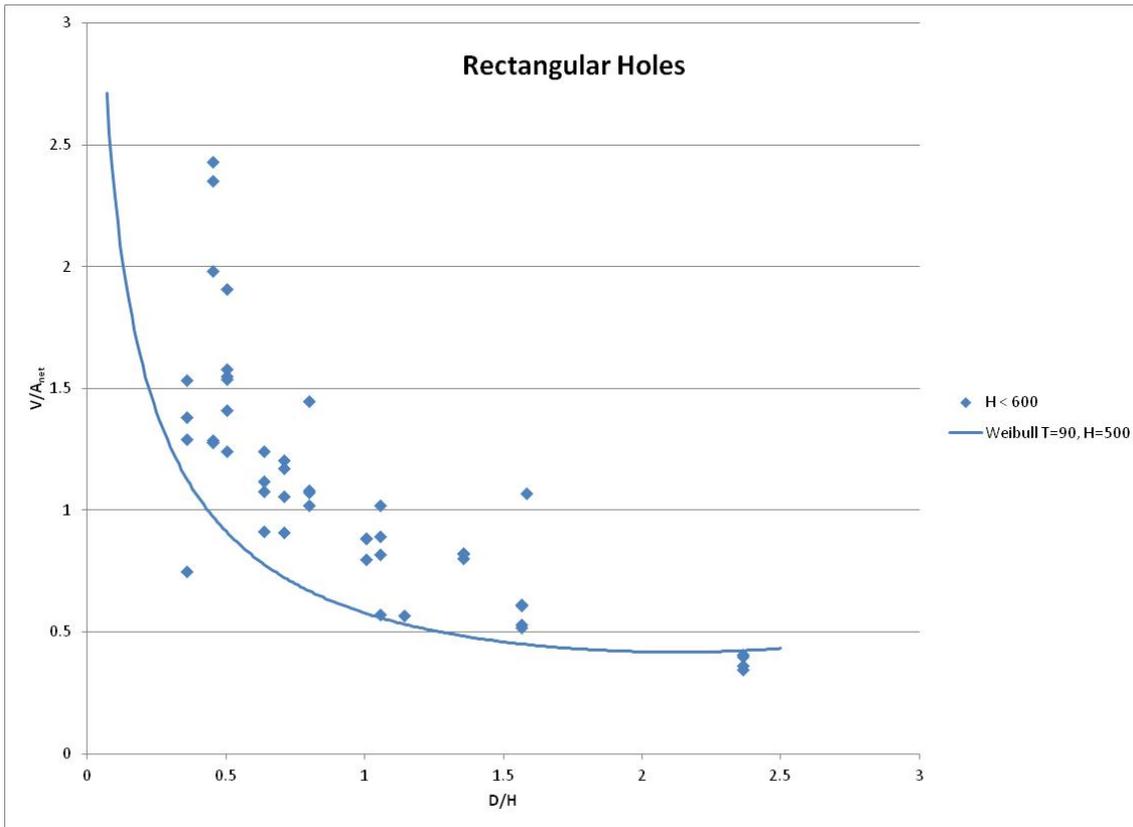
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Figure10. Comparison of test results from beams with rectangular holes with predictive equations presented in this technical note. Procedures are conservative for all points that plot above the curves. H = beam depth, D = hole diagonal length, T = beam width, V = shear force at location of hole, A_net = net area of cross section. Curve represents a ratio of M/VH = 2. Points below the curve are captured for M/VH ratios matching test conditions.

Derivation of U.S. Design Equations

There is no allowable design stress for tension perpendicular-to-grain in U.S. design, so the correlated property of shear stress is used in design. It is necessary, therefore, to relate the European tension perpendicular-to-grain characteristic value to the U.S. allowable shear value.

European softwoods considered in the Eurocode have similar density to lower strength softwoods in the U.S. represented by the glulam general softwoods (SW) species group. A value of 0.5 MPa (72.5 psi) is used as a characteristic tension perpendicular-to-grain value for design with European softwoods. The allowable stress design (ASD) reference shear value for the SW species group is 195 psi. If it is assumed that the SW species group is similar to the European softwoods a factor can be derived to convert from a European design basis to a U.S. design basis.

$$F_{t\perp,05,\text{Europe}} = KF_v C_{vr} K_F$$

$$0.5\,\text{MPa} = K(195\,\text{psi})(0.72)(2.88)\left(\frac{1\,\text{MPa}}{145\,\text{psi}}\right)$$

$$K = 0.18 \quad \Rightarrow \quad F_{t\perp,05,\text{Europe}} = 0.18 F_v C_{vr} K_F$$

where: $F_{t\perp,05,\text{Europe}}$ = characteristic value in tension perpendicular-to-grain from European test

F_v = allowable stress shear reference value used in U.S. design

C_{vr} = shear reduction factor specified in U.S. design for non-prismatic members

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$$K_F \qquad = \text{format conversion factor for U.S. LRFD design}$$

The volume factor for tension perpendicular-to-grain also requires unit conversion for U.S. design:

$$k_{vol} = \left(\frac{10\left(10^6\right) \text{ mm}^3}{0.192v^2b} \right)^{\frac{1}{5}} = \left(\frac{610.2 \text{ in}^3}{0.192v^2b} \right)^{\frac{1}{5}} = 5.0\left(\frac{1 \text{ in}^3}{v^2b} \right)^{\frac{1}{5}} = 5.0C_{vol}$$

The partial safety factor for European design, $1/\gamma_M$, serves the same purpose and has approximately the same magnitude as the material safety factor, ϕ_v, used in U.S. LRFD design, therefore:

$$\gamma_M = \frac{1}{\phi_v}$$

where: ϕ_v = material safety factor for U.S. LRFD design

The European modification factor, k_{mod}, is essentially equivalent to the product of the U.S. factors for time effect, λ, wet-use, C_M, and temperature, C_t, therefore:

$$k_{\text{mod}} = \lambda C_M C_t$$

where: λ = time effect factor for U.S. LRFD design

         C_M = wet-use factor for U.S. design

         C_t = temperature factor for U.S. design

In addition, the minor differences in k_{dis} based on load distribution are neglected, and it is assumed that $k_{dis} = 1.8$ for all load cases. Substituting the relationships established above into the European design equation yields the following design criterion for U.S. LRFD design:

$$\frac{3V_u}{2bd}\left(1.23 + 0.82\frac{h}{d} \right) + \frac{0.6M_u}{bd^2}\frac{h}{d} \leq \frac{F_{t\perp,05,\text{Europe}}k_{\text{mod}}}{\gamma_M}k_{dis}k_{vol}$$

$$\frac{3V_u}{2bd}\left(1.23 + 0.82\frac{h}{d} \right) + \frac{0.6M_u}{bd^2}\frac{h}{d} \leq 0.18F_vC_{vr}K_F\phi_v\lambda C_M C_t \left(1.8\right)\left(5.0C_{vol}\right)$$

$$\frac{3V_u}{2bd}\left(1.23 + 0.82\frac{h}{d} \right) + \frac{0.6M_u}{bd^2}\frac{h}{d} \leq F_vC_{vr}K_F\phi_v\lambda C_M C_t C_{vol} \left(1.6\right)$$

Based on the chosen calibration point between U.S. allowable stress design (ASD) and U.S. load and resistance factor design (LRFD), ultimate loads are 1.5 times the service (allowable) loads.

$$M_u = 1.5M$$

$$V_u = 1.5V$$

where: M = bending moment at the location of the hole due to service loads

        V = shear force at the location of the hole due to service loads

The format conversion factor for U.S. LRFD design can be expressed as:

$$K_F = \frac{1.5C_D}{\phi_v \lambda} \quad \Rightarrow \quad \phi_v \lambda = \frac{1.5C_D}{K_F}$$

where: ϕ_v is the resistance factor for shear

K_F is the format conversion factor used to adjust the ASD reference shear design value for use in LRFD methodology

Therefore, the resulting U.S. ASD design criterion becomes:

$$\frac{3V_u}{2bd}\left(1.23 + 0.82\frac{h}{d}\right) + \frac{0.6M_u}{bd^2}\frac{h}{d} \le F_v C_{vr} K_F \left(\phi_v \lambda\right) C_M C_t C_{vol} (1.6)$$

$$\frac{3(1.5V)}{2bd}\left(1.23 + 0.82\frac{h}{d}\right) + \frac{0.6(1.5M)}{bd^2}\frac{h}{d} \le F_v C_{vr} K_F \left(\frac{1.5C_D}{K_F}\right) C_M C_t C_{vol} (1.6)$$

$$\frac{3V}{2bd}\left(1.23 + 0.82\frac{h}{d}\right) + \frac{0.6M}{bd^2}\frac{h}{d} \le F_v C_{vr} C_D C_M C_t C_{vol} (1.6)$$

U.S. Design Equations

The resulting design equations for both round and rectangular holes are as follows for U.S. ASD and LRFD design methodologies:

For ASD design:

$$\frac{3V}{2bd}\left(1.23 + 0.82\frac{h}{d}\right) + \frac{0.6M}{bd^2}\frac{h}{d} \le 1.6 F_v C_{vr} C_D C_M C_t C_{vol}$$

For LRFD design:

$$\frac{3V_u}{2bd}\left(1.23 + 0.82\frac{h}{d}\right) + \frac{0.6M_u}{bd^2}\frac{h}{d} \le 1.6 F_v C_{vr} \phi_v \lambda C_M C_t C_{vol} K_F$$

where: $C_{vol} = \left(\dfrac{1 \text{ in}^3}{v^2 b}\right)^{\frac{1}{5}}$

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