Strengthening Wood Beams and Joists

ASCE Continuing Education Web Seminar

Presented by Alexander Newman, P.E.

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Agenda

- **Introduction: The basic approach**
- **Establishing allowable stress values of existing wood**
- **Strengthening beams and joists for flexure**
- **Strengthening for shear**
- **Questions and answers**

Acknowledgement

Many thanks to AF&PA's American Wood Council for a permission to reproduce parts of the Manual for Engineered Wood Construction and other publications. Much additional information is available at the AWC website http://www.awc.org

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- **Wood-Related ASCE Seminars** (**www.ASCE.org**)
  - **2-day seminar**: ***Design and Renovation of Wood Structures***
  - **Web seminars**

    Design of Wood Beams and Joists
    Design of Wood-Framed Sloped Roofs
    Designing with Engineered Lumber
    Specifying Lightweight Wood Trusses
    Design of Wood Columns and Wall Studs
    Design of Wood Connections
    Design of Wood Diaphragms and Shear Walls
    Minimizing the Effects of Shrinkage in Wood Structures
    Strengthening Wood Beams and Joists
    Investigation and Repair of Wood Structures
    Renovation of Wood Trusses
    Wind and Seismic Retrofit of Wood-Framed Buildings

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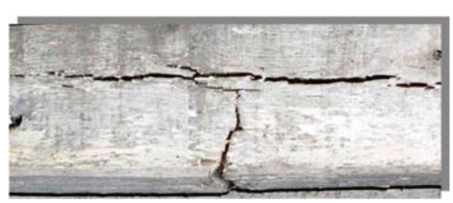
Introduction

- **Reasons for Strengthening Beams and Joists**
  - **Failure or observed deficiency**
  - **Higher load**
    - **Actual**
    - **Theoretical, from higher live-load code provisions**



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Introduction

❑ Typical Signs of Problems

- Excessive sag
- Evidence of attempted repairs (posts added, etc.)
- Distress found during inspection (e.g., decay, damage, fracture)
- Collapse

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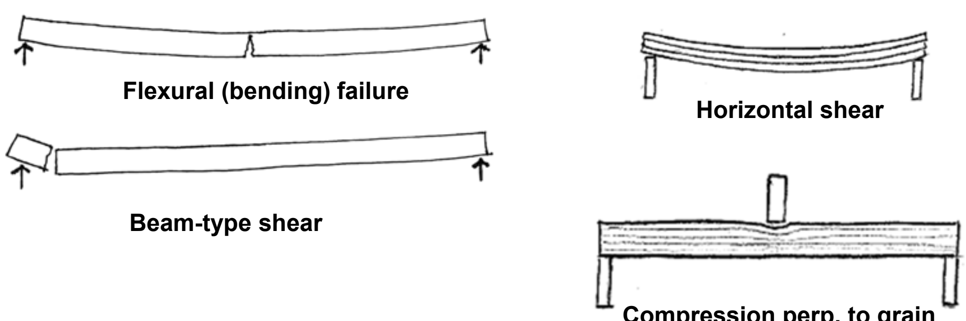
Introduction

❑ What Might Fail

- Some limit states



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Introduction

- **Do We Need to Strengthen for Theoretical Overstress?**
  - **Interpret code provisions carefully…**
  - **Model vs. renovation codes**

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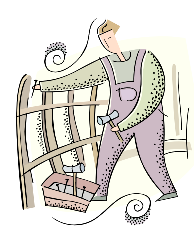
Introduction

- **IEBC Classification of Work**
  - **Repairs: Patching or restoration of materials for maintenance**
  - **Alteration – Level 1: Removal & replacement or covering existing materials with new that serve the same purpose**
  - **Alteration – Level 2: Reconfiguration of space, addition or elimination of openings, mod. of any system, or adding eq't**
  - **Alteration – Level 3: Work area exceeds 50% of total**
  - **Change of Occupancy**
  - **Additions**
  - **Also, Historic and Relocated Buildings**



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Introduction

- **Which Codes Do We Use for Assessment?**
- **Evolution of Wood Design Standards**
  - ***National Design Specification® for Wood Construction*** **(NDS®) by American Forest & Paper Association (AF&PA)**
  - **First ed. in 1944 (pub. by Nat'l Lumber Manufacturers Association):** ***NDS® for Stress-Grade Lumber and Its Fastenings***
  - **Later, NLMA changed its name to NFoPA (Nat'l Forest Product Association) and then to AF&PA**
  - **1971 ed. Added other wood products; title changed in 1977**
  - **1991: A major rewriting**

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Introduction

- **Today's NDS®**
  - **IBC 2012 Chapter 23, *Wood*, references NDS® 2012 ed.**
  - **IBC-09, -06 Chapter 23, *Wood*, references NDS® 2005 ed.**
  - **IBC-00 references 1997 NDS®**
  - **Local codes**
  - **Rational v. prescriptive provisions**

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AF&PA's American Wood Council

Introduction

- **Today's NDS® May Be More Lenient …**
- **E.g., Shear Provisions: NDS®-97 to NDS®-01**
  - **Increase in base shear values by ~ 1.95 times in response to change in ASTM D245-00, *Establishing Structural Grades and Related Allowable Properties for Visually Graded Lumber***
  - **So, for S-P-F F_v in 1997 = 70 psi, in 2005 = 135 psi**
  - **Removal of shear stress increase factor C_H**
- **Which Allowable Stresses to Use? (Next)**

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Establishing Allowable Stress Values

- **Development of Wood Design Values**
  - **"Conventional design" vs. rational design (from late 19th century)**
  - **Allowable stresses in city codes of late 1890s through early 20th century differed:**

    - For YP, F_b in Boston and Chicago was 1250 psi;

    - In Philadelphia, 1600 psi.
  - **Mid-1930s: Modern standards developed**

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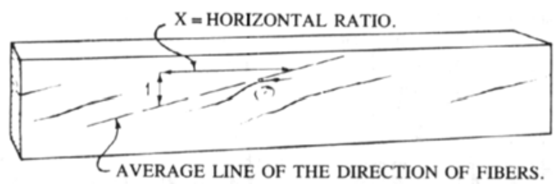
Establishing Allowable Stress Values

- **Design Wood Stresses Changed Over the Years**
  - **Old-growth lumber ("Dense" grade): Higher strength but gone**
  - **After 1960s, grading rules changed from testing small clear specimens to in-grade testing, defects and all – better consistency**
  - **But a more common problem: Sloped grain in otherwise properly graded lumber (was not considered as critical before?)**



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NAVFAC MO-111.1

Establishing Allowable Stress Values

- **Lumber of WWII Vintage:**

Overly high stresses (1200-psi => 1800; 15 psf snow)

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Establishing Allowable Stress Values

❑ Watch out for Early Allowable Tension Stresses

- **Prior to 1965, F_t assumed = F_b, F_t was found by bending tests of clear straight-grain specimens and adjusting results**
- **Later, in-grade testing (ASTM D1990) yielded much smaller F_t**
  2x6 KD No. 1 SYP: F_t = 1750 psi in 1962, 1100 psi in 1971, and 900 psi in 1991 through 2005
- **Today, for 2x6 No. 1 SP F_t = 900 psi, F_b = 1650 psi**
  $F_t : F_b = 0.54$

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Establishing Allowable Stress Values

❑ How to Determine Properties of Existing Wood

- **By testing, visual evaluation, reasonable assumptions**
- **By allowable code value**
  (E.g., IEBC Table A1-D, allows for existing Douglas Fir wood the allowable stresses same as for current values of D.F. No. 1)
- **Engage a wood lab to test**
- **In no budget, assume reasonable properties for first check**
- **Check for approximate grade (e.g., structural grade req's knots to be tight, < defined size, no knot clusters)**
- **Become familiar with grading rules… remained fairly constant**

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Establishing Allowable Stress Values

❑ Properties of Existing Wood, Cont'd

- **Try Center for Wood Anatomy Research for questions regarding wood identification**

  http://www2.fpl.fs.fed.us/TechSheets/techmenu.html

  - This web site also mentions sources of wood ID kits and provides properties for various species

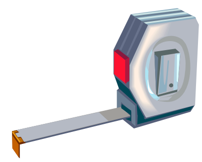
  - Specimens 1 X 3 X 6 inches are recommended for ID

- **A source on East Coast:**

  Wood Advisory Services, Inc.

  PO Box 1322, Millbrook, NY 12545

  http://www.woodadvisory.com



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Establishing Allowable Stress Values

❑ Properties of Existing Wood, Cont'd

- **A lab can perform on-site visual grading considering existing defects**
- **Once graded, use today's reference stress values?**

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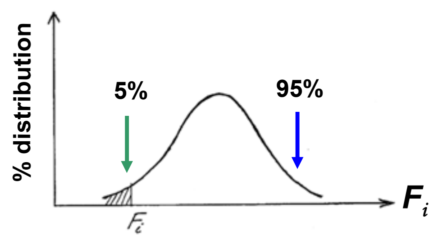
Establishing Allowable Stress Values

❑ Variability of Properties

- Reference design values in NDS® represent the 5th percentile in distribution of strength properties, i.e. 95% (but not all!) of all pieces within the grade are stronger
- Strength variation between 5th and 95th percentile ~ 70% of the reference design values
- No explicit factor of safety in wood…



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Establishing Allowable Stress Values

❑ Establishing Properties by Testing Specimens

- Cutting sections to fabricate 1x1" small clear test specimens for flexure (16" long) and compression for test per ASTM D143

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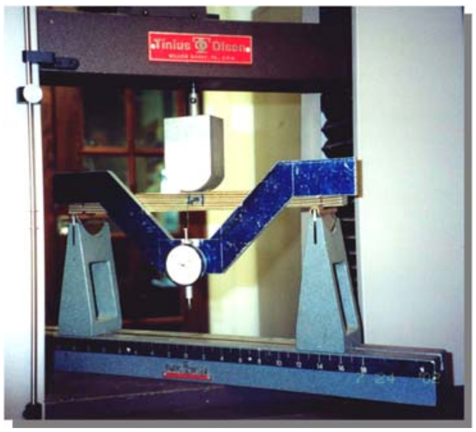
Establishing Allowable Stress Values

❑ Testing Specimens, Cont'd

- **Example, Cont'd: ASTM D143 bending and compression tests**



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Establishing Allowable Stress Values

❑ Or, Perform In-Situ Full-Scale Load Test

❑ In-Situ Load Test per IBC-03, -06

- **IBC-03, -06, for gravity-load elements: (IBC-06 Para. 1713.3.2)**
  - ➢ **Gradually apply twice the "unfactored design load"**
  - ➢ **Keep in place 24 hrs**
  - ➢ **Test OK if design load deflection is within limit*, and within 24 hrs after load removal 75% of max deflection is recovered, and no evidence of failure during or after test**

*IBC Table 1604.3

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Establishing Allowable Stress Values

- **In-Situ Load Test per IBC-12, -09**
  - **IBC-12 Sec. 1710.3.1, IBC-09 Sec. 1715.3.1, Test Procedure, per procedure above (uses 2 x "superimposed design load")**
  - **Then adds another loading cycle to 2.5 x "superimposed design load," or to destruction, or beyond deflection limits***
  - **Allowable superimposed design load is the lesser of:**
    1. **Load that produces deflection limit***
    2. **Failure load divided by 2.5**
    3. **Max. load divided by 2.5**

*IBC Table 1604.3

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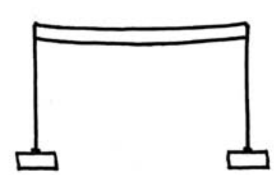
Strengthening for Flexure

- **General Methods of Strengthening**
  - **Passive vs. active methods**
  - **Shortening span**
  - **Adding members**
  - **Replacement**
  - **Post-tensioning (external prestressing)**
  - **Enlarging section**



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Strengthening for Flexure

- **Solution Depends on Extent of Strengthening…**
  - **Strengthen a few members (e.g., for added HVAC unit)**
  - **Or many (e.g., upgrade floor capacity for higher LL)**
- **…and on Other Factors**
  - **Historical interest**
  - **Accessibility (sides, top, bottom)**
  - **Deterioration**

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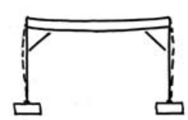
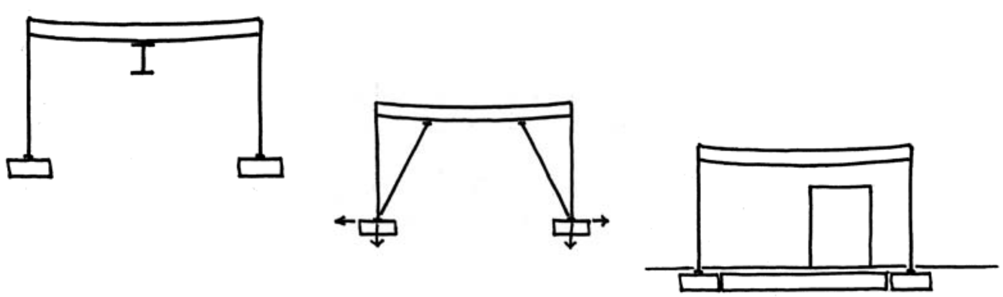
Strengthening for Flexure

- **Shortening the Span**
  - **Add columns, girders**
  - **Add diagonal braces (not knee-braces)**
    Check foundations or add new
  - **Add walls with openings**





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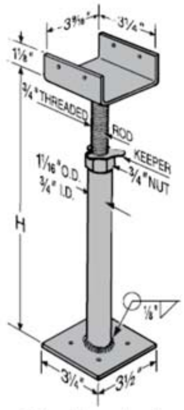
Strengthening for Flexure

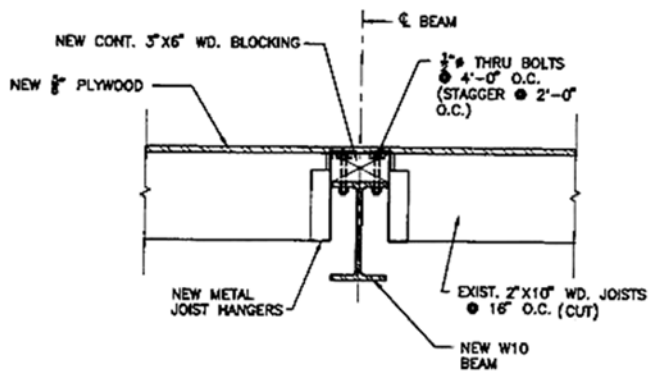
❑ Shortening the Span, Cont'd

- Active and passive approaches
- Active: Add jacks, raise floor, install supports, slowly lower



J Floor Beam Leveler

Simpson Strong-Tie, 4000# capacity



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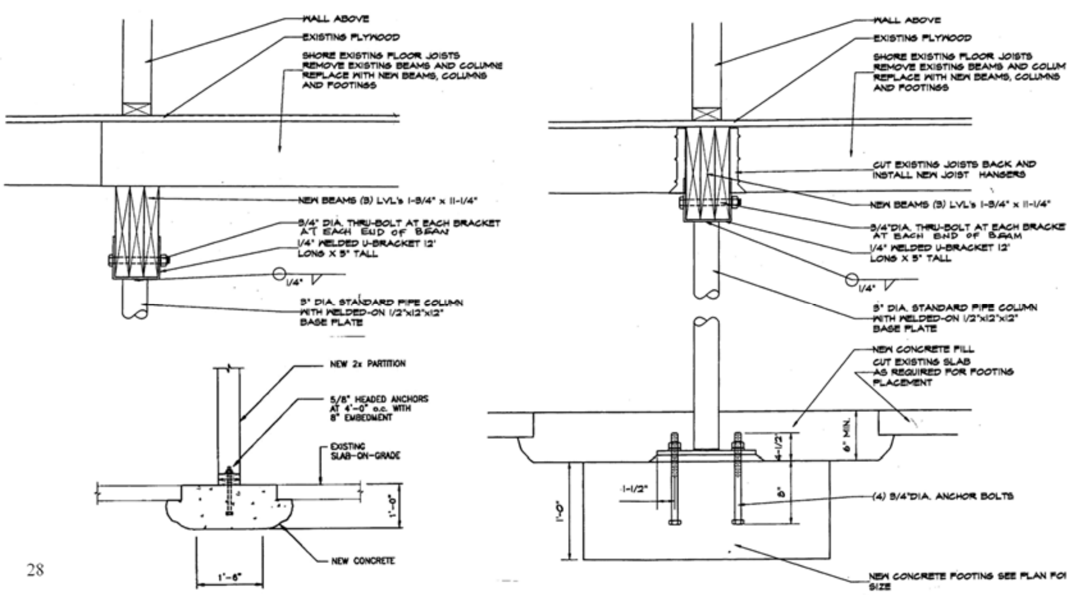
Strengthening for Flexure

❑ Shortening the Span of Joists



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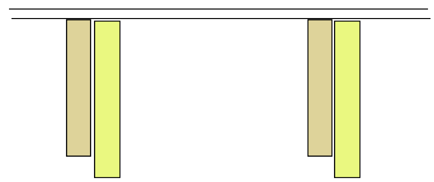
Strengthening for Flexure

- **Adding Members**
  - **Adding members: "Sistering" joists**



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Strengthening for Flexure

- **Adding Members, Cont'd**
  - **Using steel beams**

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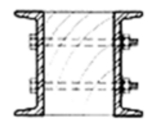
Strengthening for Flexure

❑ Design Example 1: Strengthening Wood Beam with Steel Channels

- **Problem**: Existing 8x12 (full dim.) beam is strengthened with two C12x20.7's. Assuming that both steel and wood carry load, find M_{max} for the composite section

$F_{b,\ steel}$ = 21,600 psi, E_{steel} = 29,000,000 psi

$F_{b,\ wood}$ = 1200 psi, E_{wood} = 1,400,000 psi



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Strengthening for Flexure

❑ Design Example 1, Cont'd

- **Solution**:

$n = E_{steel}/E_{wood}$ = 29,000,000/1,400,000 = 20.7

A_{steel} = 6.04 in^2, I_{steel} = 129 in^4 (for each piece), d_{steel} = 12"

A_{wood} = 8 x 12 = 96 in^2, I_{wood} = 8x12^3/12 = 1152 in^4, d_{wood} = 12"

Equivalent wood section $I_{tr} = n\ I_{steel} + I_{wood}$ =

20.7x129x2 + 1152 = 6492.6 (in^4)

$S_{tr} = I_{tr}{:}(d/2)$ = 6492.6/6 = 1082 (in^3)

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Strengthening for Flexure

- **Design Example 1, Cont'd**

The maximum allowable stresses in both steel and wood must not be exceeded, and one or another will control. Find stresses in steel if wood part is fully stressed:

$f_{b,\ steel} = nF_{b,\ wood} = 20.7 \times 1200 = 24{,}840 > F_{b,\ steel}$ **NG**

Or, if $F_{b,\ steel} = 21{,}600$ **psi,**

$f_{b,\ wood} = F_{b,\ steel} : n = 21{,}600/20.7 = 1043$ **(psi) OK**

$\Rightarrow$ **Use max. wood stress of 1043 psi, not to overstress the steel**

$M_{max} = f_{b,\ wood}\ S_{tr}/12{,}000 = (1043)(1082)/12{,}000 =$ **94.1 kip-ft**

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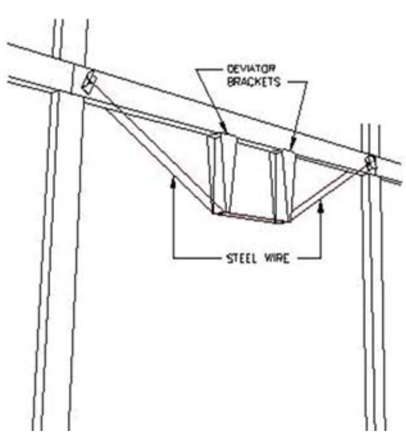
Strengthening for Flexure

- **Strengthening Flexural Members by External PT**
  - **The critical area…**



Wood truss c. 1910 with 2-2 ¼" tensioned rods supporting 2nd floor of car dealership.

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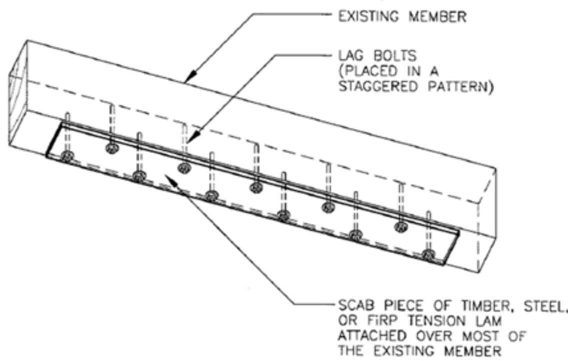
Photo courtesy Robert J. Bushmaker, MSE-TA, Inc.

Strengthening for Flexure

- **Strengthening by Scabbing**
  - **Wood, steel, laminated FRP pieces. Need not extend to supports for simple span.**
  - **Compute transformed properties by adjusting for *E*'s.**



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Strengthening for Flexure

- **Strengthening by Scabbing, Cont'd**
  - **Scabbed piece must be compatible with original**
  - **Steel is stronger & stiffer than wood; wood and FRP are more compatible**
  - **FRP is > $ but takes < space**
  - **FRP applied in 0.07" layers, pre-bonded to 2xs of sawn or LVL, attach w/ epoxy and lag screws.**

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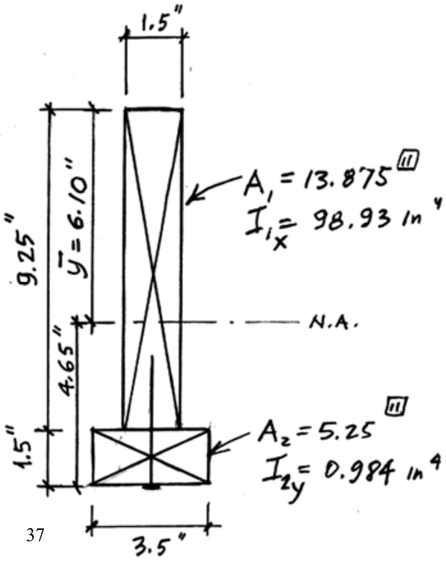
Strengthening for Flexure

❑ Design Example 2: Scabbing a Wood Piece



$$\bar{y} = \frac{13.875 \times 9.25/2 + 5.25\left(9.25 + \frac{1.5}{2}\right)}{(13.875 + 5.25)} = 6.10"$$

$$I_o = 98.93 + \left(6.10 - \frac{9.25}{2}\right)^2 \times 13.875 + 0.984 + \left(9.25 - 6.10 + \frac{1.5}{2}\right)^2 \times 5.25 = 209.95\ (in^4)$$

$$S_{TOP} = \frac{209.95}{6.10} = 34.42\ (in^3)$$

$$S_{BOT} = \frac{209.95}{4.65} = 45.15\ (in^3)$$

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PROBLEM:

- EXISTING 2×10's JOISTS SPACED 16" O.C. Spanning 15' were Designed for a HOUSE occupancy (40 PSF LL).
- THE HOUSE IS CONVERTED INTO AN OFFICE (50 PSF LL), WITH DL = 10 PSF (NEW & OLD)
- DESIGN REINFORCEMENT W/ SCABBED 2×4
- ASSUME S-P-F #1/#2 FOR JOIST & SCAB
- Use ACTIVE Approach (Jacked JOISTS)

SOLUTION:

USE $F_b = 875$ psi, $F_v = 135$ psi, $E = 1.4 \times 10^6$ psi

$F_b' = 875 \times 1.1 \times 1.15 = 1107$ (psi)

(1.1: SIZE FACTOR FOR 2×10; 1.15: REPET. FACTOR)

$M_{EXIST, MAX} = (10 + 40)\, 1.33 \times 15^2/8 = 1870\ \#'$

$M_{R, EXIST.} = 21.4 \times 1107/12 = 1974\ \#'$ FOR 2×10 ALONE

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$$M_{NEW\,(D+L)} = \underbrace{(10+50)\,1.33}_{w_0 = 79.8\ \#/LF} \times 15^2/8 = 2244\ ^{\#'} > 1974\ ^{\#'}$$

FOR scabbed SECTION $f_b = \dfrac{2244 \times 12}{34.42} = 782$ psi OK

$R = 79.8 \times 15'/2 = 598.5^{\#}$

$V_{MAX} = 79.8\left(\frac{15}{2} - \frac{9.25''}{12}\right) = 537^{\#}$

SHEAR ON ORIG. SECTION IF SCAB IS PARTIAL-LENGTH ...

$f_v = \dfrac{537 \times 1.5}{13.875} = 58\ (psi) < 135$ OK

CHECK DEFLECTION (short-term only)

$w_L = 50 \times 1.33 = 66.5\ \#/'$

$\Delta_L = \dfrac{5 \times 66.5 \times 15^4 \times 1728}{384 \times 1{,}400{,}000 \times 210} = 0.258''$ $L/699 < L/360$ OK

$\therefore$ DEFLECTIONS OK

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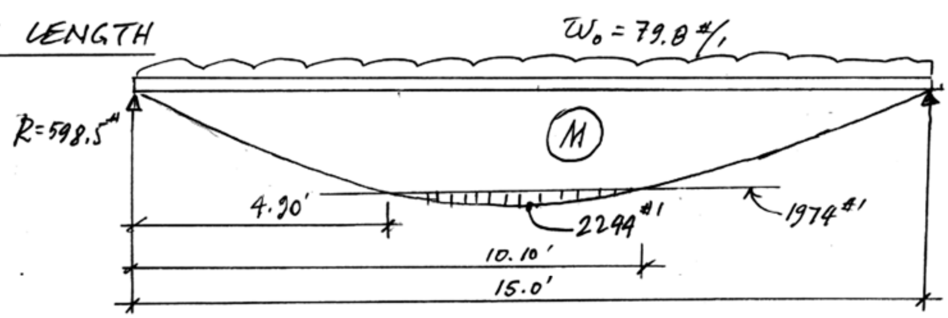
SCAB LENGTH



$M_{2\times10} = 1974 = 598.5L - \dfrac{79.8L^2}{2}$

$39.9L^2 - 598.5L + 1974 = 0$

$L_{1,2} = \dfrac{598.5 \pm \sqrt{598.5^2 - 4 \times 39.9 \times 1974}}{2 \times 39.9}$

$L_1 = 4.9'$ $L_2 = 10.10'$

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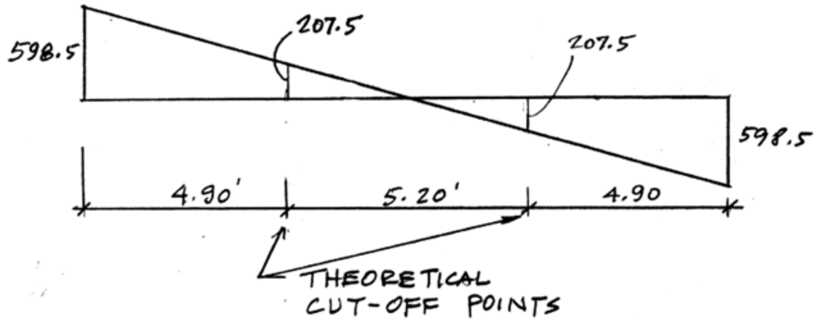

FASTENER DESIGN

FASTENERS AT ENDS: $F = \dfrac{MAy}{I_0}$

WHERE M = MOMENT AT THEORETICAL CUT-OFF POINT

A = AREA OF SCAB

y = DISTANCE FROM C.G. SCAB TO C.G. WHOLE SECT.

$= 4.65 - 1.5/2 = 3.9''$

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$$F = \frac{1974^{\#'} \times 12'' \times 5.25(in^2) \times 3.9''}{209.95\,(in^4)} = 2310^{\#}$$

IF USE NAILS, NDS Table 11N, 20d ($D = 0.192''$ 4" LG): $144^{\#}$

NEED $2310/144 = 16$ NAILS

IF LAG BOLTS, NDS TABLE 11J FOR $3/8''$ $Z_{\parallel} = 180^{\#}$

NEED $2310/180 = 12.8$, SAY 13 LAG BOLTS

SPACING (AT 4 DIA) $= 4 \times 3/8 = 1.5''$ o.c., END DIST. $7 \times 3/8 = 2\,5/8''$

LENGTH OF SCABS BEYOND THEORETICAL CUT-OFF POINT:

$= 2\,5/8'' + (13-1)\,1.5 = 20.625'' = 1.72'$

TOTAL SCAB LENGTH $= 5.2 + 1.72 \times 2 = 8.64'$ SAY $9'$

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FASTENERS ALONG THE LENGTH:

SHEAR FLOW $f = \frac{VA\bar{y}}{I_o}$ (#/in)

(V = SHEAR AT THEORETICAL CUTOFF POINTS)

$f = \frac{207.5^{\#} \times 5.25\,(in^2) \times 3.9''}{209.95\,(in^4)} = 20.2\,(\#/'')$

SPACING OF FASTENERS = $\frac{\text{FASTENER CAPACITY}}{\text{SHEAR FLOW}}$

FOR 3/8" LAG BOLTS SPACING = $\frac{180^{\#}}{20.2^{\#}/''} = 8.91''$ SAY $8\frac{3}{4}''$ O.C.

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AN ALTERNATE SOLUTION: FULL-LENGTH SCABS

NO END FASTENERS, BUT FOR INTERMEDIATE FASTENERS

$V = V_{MAX} = 79.8^{\#} \times 15'/2 = 598.5''$ (NEGLECT REDUCTION AT "d")

SPACING OF 3/8" LAG BOLTS AT ENDS

$8.91 \times \frac{207.5}{598.5} = 3.09''$ SAY 3" O.C.

THIS CAN BE INCREASED TOWARD THE MIDDLE OR KEPT CONSTANT

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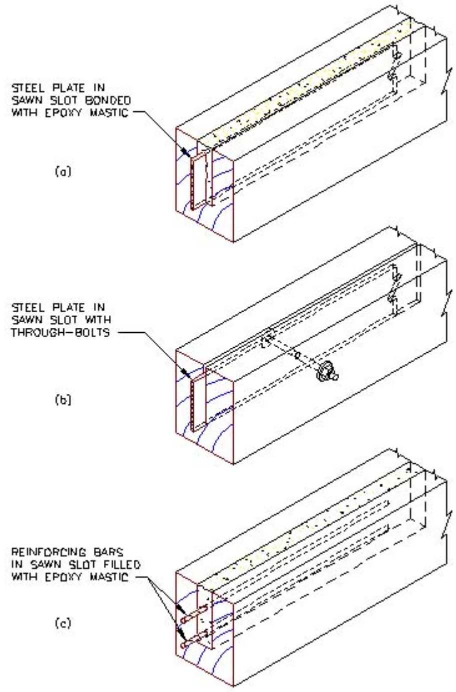
Strengthening for Flexure

- **Strengthening with Inside Reinforcement**
  - **When side members cannot be used (flush framing…)**
  - **Use SS or fiberglass bars**
  - **Good for termite damage repair**
  - **Problem: Rigidly joining dissimilar materials by epoxy, (*b*) is less rigid**



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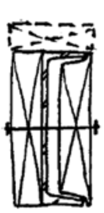
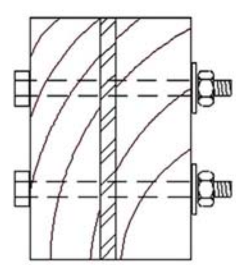
Strengthening for Flexure

- **Flitch Beam**
  - **Common but no clear standards, trial and error design.**
  - **Challenges recognized back in 1891.**
  - **Design as separate members, share load ~ rigidity?**
  - **For 2-2x side members, t_{pl} = (1400/29000)3 = 0.145”…**
  - **Bolt size: ½” for plates < ½” thick**
    5/8” for plates < ¾” thick
    ¾” for plates < 1” thick.
  - **Bolt spacing: 16”-2’ o.c. common.**
    For bracing plate, space 15-19” o.c.?
    In flush framing -- to transfer load





More info: Jim DeStefano, “Flitch Plate Beams,” *Structure*, June 2007.

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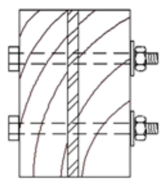
Strengthening for Flexure

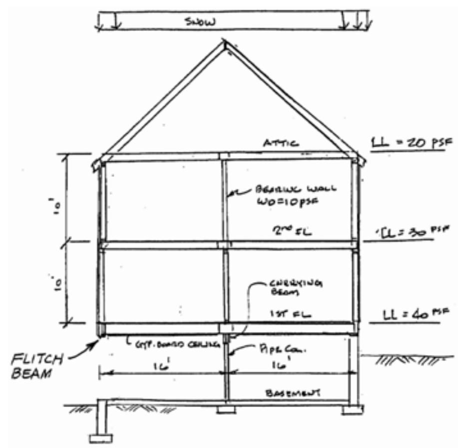
❑ Designing Flitch Beams

- As plates bent in strong direction
- New in AISC 2005 Spec. and now in 2010: Sec. F11, Rectangular Bars and Rounds

❑ Design Example 3:

Flitch Beam at House (ASD)





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Strengthening for Flexure

❑ Design Example 3, Cont'd

- **Given**: A36 steel, fit in 2-2x12s, house LL, 30-psf snow, L = 9'
- **Solution**: Assume floor, ceiling, roof, wall DL = 10 psf

Load on beam:

LL = (16'/2)(20 + 30 + 40) + 16'x30 = 1200 #/ft

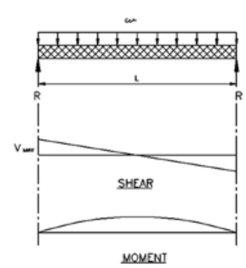
DL = 8'(10x3) + 16'(10) + 20'(10) + 20 = 620 #/ft

floors roof walls own

w_a **= 1820 #/ft = 1.82 k/ft**

M_a **= 1.82(9)^2/8 = 18.43 k-ft**

Assume lateral bracing L_b = 24" o.c.



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Strengthening for Flexure

❑ Design Example 3, Cont'd

- **Try 11 x ½" bar**

  $S_x = 0.5(11^2)/6 = 10.08$ in^3; $Z_x = 0.5(11^2)/4 = 15.125$ in^3

- **Nominal flexural strength, M_n**

  Flexural yielding: Check $(L_b d)/t^2$ vs. $(0.08E)/F_y$

  $(L_b d)/t^2 = (24 \text{x} 11)/0.5^2 = 1056 > (0.08 \text{ x } 29000)/36 = 64$

  => LTB controls

  Lateral-torsional buckling: Check $(L_b d)/t^2$ vs. $1.9E/F_y$

  $1056 < 1.9E/F_y = 1530$, so …

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Strengthening for Flexure

❑ Design Example 3, Cont'd

$M_n = C_b[1.52 - 0.274(L_b d)/t^2(F_y/E)]M_y$

where $M_y = F_y S_x = 36 \text{ x } 10.08 = 362.88$ k-in = 30.24 k-ft

$C_b = 1.0$ (conserv.)

$M_n = 1[1.52 - 0.274 \text{ x } 1056(36/29000)]30.24 = 35.10$ k-ft

ASD allowable strength = $M_n/\Omega_b = 35.1/1.67 = 21.02$ k-ft

21.02 > 18.43 (k-ft) OK

=> Use 11 x ½" bar

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Strengthening for Flexure

❑ Strengthening Beams Exposed to Moisture

- Is decay present? (If yes, need repair)
  - Wet climate?
  - Was it pressure-treated?
  - What is life expectancy?
- If thinking of strengthening with steel…
  - Aesthetically OK?
  - Need maintenance for steel?
  - Trapping moisture between steel and wood?
  - Is strengthening/repair economical vs. replacement?

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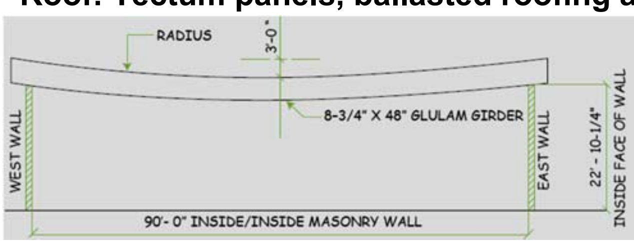
Source: Bruce Pooley, "Glulam Beam Repair," answer in Technical Questions and Answers, *Structure*, Fall 2000.

PT Case Study

❑ Case Study: Strengthening Glulam by PT

- Problem: Failure of a roof glulam beam in the high-school gym in Defiance, Ohio on Jan. 2004
- Construction (c. ~1963):
  - 90' span D-F girders 8¾" x 48" spaced 12.5' with 2" lams, scarf joints, casein adhesive, curved down by 3'
  - Roof: Tectum panels, ballasted roofing added 20 yrs ago



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Case Study based on article by Gary W. Gray and Paul C. Gilham, "Glulam Beam Repair/Reinforcement," *Structure*, September 2006.
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PT Case Study, Cont'd

❑ **Investigation**

- **Bending failure:**
  - **Fracture of 3 bottom lams near midspan**
  - **Through-width crack propagated 12" up in a flat V shape, opened ¾", beam sagged 3"**
- **Data gathering:**
  - **Historic snow loading**
  - **DL**
  - **Internal moisture content**

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PT Case Study, Cont'd

❑ **Analysis**

- **Identified mfr (defunct but found a staff engineer)**
- **Orig. F_b = 2400 psi, but analysis used F_b = 1800 psi**
  - **Glulams made before 1970 did not use specific tension laminations. Tests by AITC and others predict a 25% reduction in F_b for those**
- **Ground snow 20 psf, orig. DL + coll. $\simeq$ 12 psf, but ballasted roofing increased DL**
- **Result: Overstress from DL by 24%, from DL + SL by 62%**
- **Plus, owner wanted to upgrade roof for 30-psf LL**
- **For failed beam, reduced effect. depth by 6" (3 broken lams)**

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PT Case Study, Cont'd

❑ Repair Method

- Shear dowels and PT for all beams

❑ Shear Dowels

- Steel rebars placed in oversized epoxy-filled holes at beam centerline (1 3/8" hole for 1" bar) to restore shear capacity and stitch beam. Dowels resisted all *V* within middle 50'
  - A cracked beam cannot be clamped and glued back
  - Dowel capacity developed by calcs and testing
  - Spacing: Shear flow divided by allow. dowel capacity (next)

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PT Case Study, Cont'd

❑ Shear Dowels: Some Numbers

The shear at 25 feet on each side of the beam centerline was calculated to be 18,076 pounds. The horizontal shear stress at this point is:

f_v = (3*18,076) / (2*346) = 78.36 psi.

The shear flow was:

v = 78.36 * 8.75 = 680.8 pli.

The total shear force in the damaged area was:

V = 680.8pli * 25.05′* 12 / 2 = 102,323 lbs.

The allowable load for one 1-inch ϕ grade 60 bar in 1⅜-inch ϕ epoxy filled hole (increased for duration of load) is:

P′ = 7,767 lbs. * 1.15 = 8,932 lbs.

The number of dowels required in 25 feet on each side of the center line is:

n = 102,323/8,932 = 11.46 *(say 12 minimum)*

The spacing used was determined by dividing the allowable load of the dowel by the maximum shear flow:

s=8,932/680.8 = 13.11 inches o.c.

(use 12-inch o.c.)

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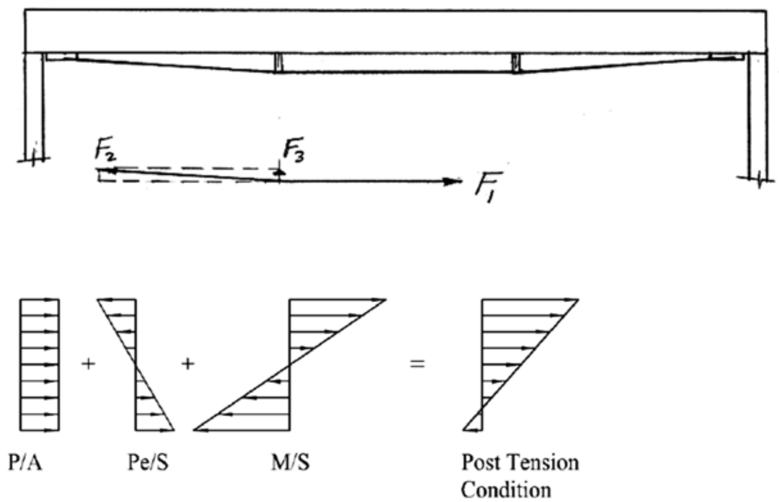
PT Case Study, Cont'd

❑ Post-Tensioning

- **PT stresses applied eccentrically; added depth = 8 ¼”**



Drawing by A. Newman

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PT **Applied load** **Combined**

PT Case Study, Cont'd

❑ Post-Tensioning Approach

- **Anchorage: Button-type wedge anchors, attached to wood by steel bars in drilled holes w/epoxy**
- **Cables: common ½” ASTM A416 Grade 270 seven-wire low relaxation strands**
- **Complexity increases if more than 1 cable used (it unloads stress in previously tensioned cable). Also, as beam deflects under roof load, cable is stretched, load in it increases**

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PT Case Study, Cont'd

- **PT: Some Numbers for Failed Beam**

  M_{avail} = 413,289 ft# (w/adj. for volume, C_d, neglect 6")

  M_{rq} = 745,450 ft#

  Total cable T_{rq} = 210,486#

  One ½" cable T_{rq} = 24,000# => Need 10 cables

  Use 5 anchor assemblies, each with 2 cables

Drilling injection & exhaust ports

Calibrated hydraulic jack

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PT Case Study, Cont'd

- **Construction Sequence**
  - **Jack up beam to approx. level. Place 2 HSS shores on timber cribbing w/jack at base (closed some cracks), locate 9' away from center to allow work at mid section.**
  - **Drill 1 3/8" holes to 6" above highest crack, 2 sets of small port holes (top and bottom of holes)**
  - **Seal sides w/epoxy paste**
  - **Place rebar; seal holes**
  - **Pump epoxy in lower ports until comes out of upper ports**
  - **Inspection of epoxy, lab test samples in glulam blocks**
  - **Place, tension cables**

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Strengthening for Shear

- Strengthening for Shear
  - Most common: Dealing with notches
  - Prior practice allowed notches at ends

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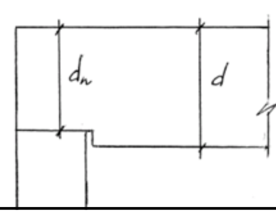
Strengthening for Shear

- **Before Reinforcement, Try Analysis**
  - **NDS®-12, -05 Sec. 3.1.2 & 3.4.3: Effect of notches on strength**
  - **Allowable notches in beams, joists per NDS® Sec. 4.4.3: At ends of sawn lumber over a support, max. notch depth = ¼ *d***
  - **Sec. 3.4.3: At tension-face notched ends cannot reduce shear within "*d*".**
  - **Para. 3.4.3.2(a): Adjusted shear // to grain in rectangular sections, where *d* is unnotched, d_n is notched depth is**

$$V'_r = \left[\frac{2}{3} F'_v \, bd_n\right]\left[\frac{d_n}{d}\right]^2 \geq V \qquad \text{or}$$

$$f_v = \frac{1.5V}{bd_n}\left(\frac{d}{d_n}\right)^2 \leq F'_v$$



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Strengthening for Shear

❑ Design Example 4: Stresses at Notch

- **Check shear resistance of existing full-section 2x10s joists spaced 16" o.c. spanning 16' at 1st floor of a house, with 3" notch. Use NDS®-12; lumber is Spruce-Pine-Fir No.1/No.2.**
- **Solution**

Using DL = 10 psf, LL = 40 psf, w_o = 50 x 16/12 = 67 #/ft

R = V = 67 #/ft x 8 ft = 536 #

For Spruce-Pine-Fir No.1/No.2 F_v = 135 psi

C_D = 1.0 and F'_v = 135 psi

For full 2x10, b = 2" d = 10" and d_n = 10" – 3" = 7"

$$f_v = \frac{1.5(536)}{2x7}\left(\frac{10}{7}\right)^2 = 117.2 \le 135\,(\text{psi}) \quad OK$$

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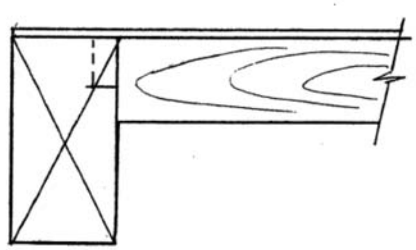
Strengthening for Shear

❑ Solutions for Shear Strengthening of Notches

- **If analysis fails and reinforcement is needed…**



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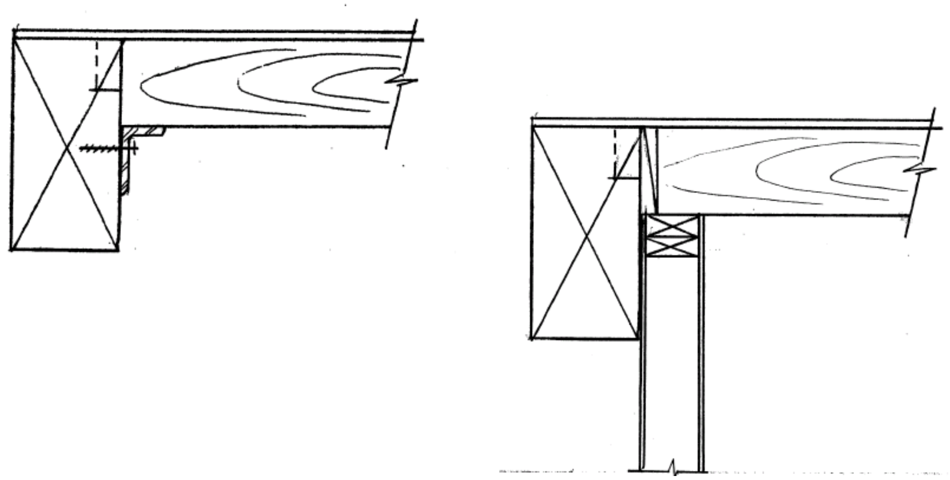
Shear Strengthening

- Best: Extend Support to Unnotched area



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- Further Reading
  - AP&PA Manual for Engineered Wood Construction, w/ Supplements, 2001
  - American Wood Council site and pubs at http://www.awc.org/index.html
  - D. Breyer et al, Design of Wood Structures – ASD, 5th ed., McGraw-Hill, 2003
  - K. Faherty and T. Williamson, Wood Engineering and Construction Handbook, McGraw-Hill, 3rd ed, 1999
  - Robert J. Ross, et al, *Wood and Timber Condition Assessment Manual*, Forest Products Society, www.forestprod.org
  - A. Newman, Structural Renovation of Buildings, McGraw-Hill, 2001
  - TM 5-620/NAVFAC MO-111/AFP 91-23, *Facilities Engineering Maintenance and Repair of Architectural and Structural Elements of Buildings and Structures*, May '90 http://www.usace.army.mil/publications/armytm/TM5-620/
  - NAVFAC MO-111.1, *Inspection of Wood Beams & Trusses*, 1985, free download at http://www.ccb.org/docs/OPER/MO111_1.pdf

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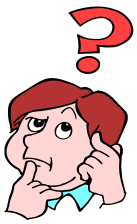

Q & A

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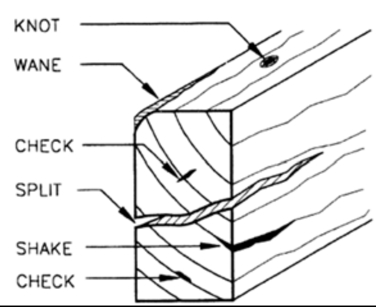
Bonus Material: Wood Defects That May Call For Strengthening

- **Common Wood Defects**
  - **Split: Wide separation of fibers II to grain (at ends, notches); *extends from one surface to another*.**
  - **Check: Surface opening along the grain, *does not extend through thickness*.**
  - **Shake: Thin separation between annual rings, along the grain.**
  - **Also: Knot, pitch pocket, wane, juvenile lumber**



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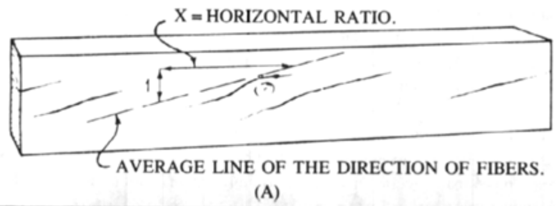
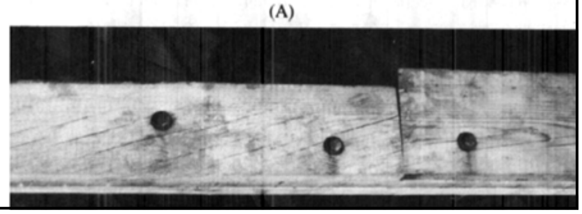
Wood Defects

❑ **Fibers Not Parallel to Axis**

- **Sloped grain (diagonal grain) can be found by examining pattern of checks… a problem if angle exceeds 15°**
- **Crossgrain**
- **Compression (reaction) wood (forms at sides of leaning or crooked trees)**





69 NAVFAC MO-111.1

Wood Defects

❑ **Which Wood Defects Are Most Dangerous?**

- **Compression wood, crossgrain, sloped grain.**
- **Minor knots, small wanes, pitch pockets rarely affect strength (limit by grading). Knots distort grain, are more important in bending regions.**
- **Splits, checks, shakes may be repaired**
- **Splits in sloped grain may form failure planes**

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