Architectural Structures: Form, Behavior, and Design

Arch 331
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Fall 2013

lecture
fifteen

wood construction: materials & beams

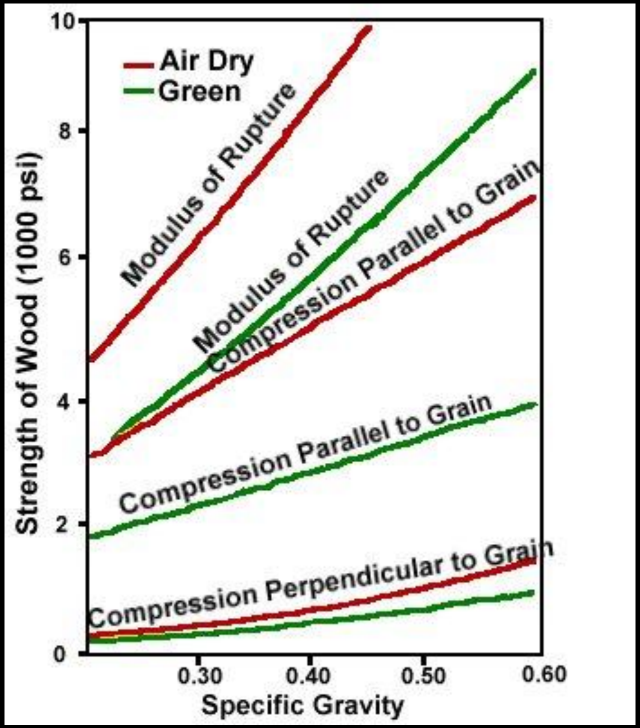
Wood Beam Design

- National Design Specification
  - National Forest Products Association
  - ASD & LRFD (combined in 2005)
  - adjustment factors x tabulated stress = allowable stress
  - adjustment factors terms, C with subscript
  - i.e, bending:

$$f_b \le F_b' = F_b \times \left(product\ of\ adjustment\ factors \right)$$

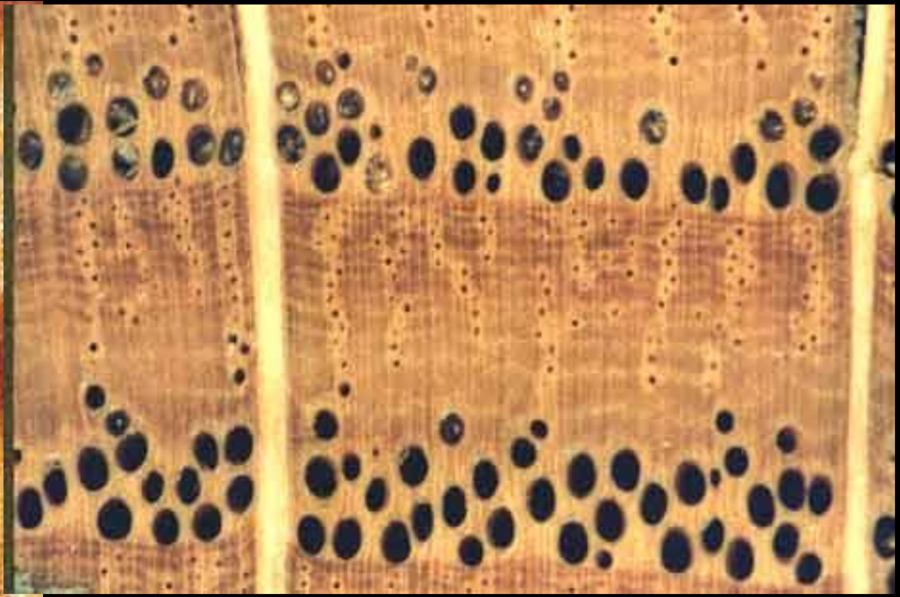
Timber

- lightweight : strength ~ like steel
- strengths vary
  - by wood type
  - by direction
  - by "flaws"
- size varies by tree growth
- renewable resource
- manufactured wood
  - assembles pieces
  - adhesives



Wood Properties

- cell structure and density



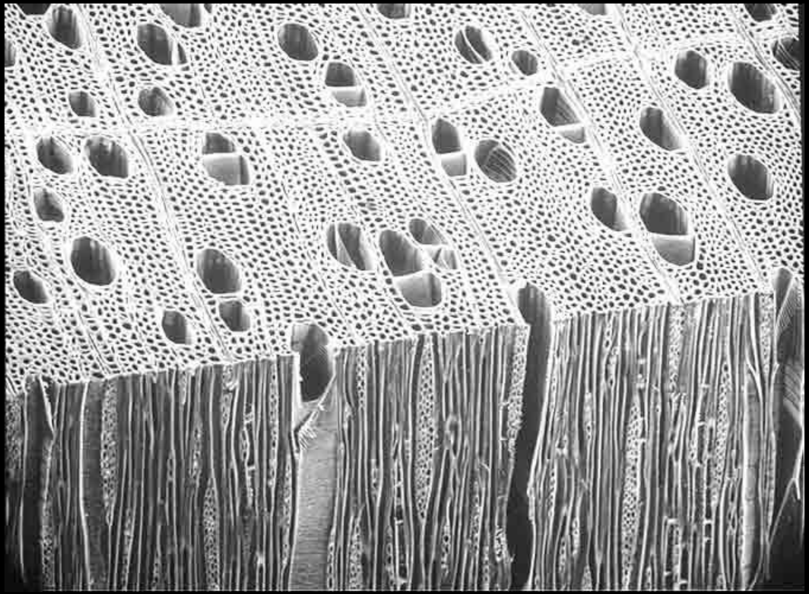
hardwood

http://www.swst.org/teach/set2/struct1.html

softwood

Wood Properties

- *moisture*
  - *exchanges with air easily*
  - *excessive drying causes warping and shrinkage*
  - *strength varies some*
- *temperature*
  - *steam*
  - *volatile products*
  - *combustion*



http://www.swst.org/teach/set2/struct1.html

Wood Properties

- load duration
  - short duration
    - higher loads
  - normal duration
    - > 10 years

- creep
  - additional deformation with no additional load

Structural Lumber

- *dimension – 2 x’s (nominal)*
- *beams, posts, timber, planks*
- *grading*
  - *select structural*
  - *no. 1, 2, & 3*
- *tabular values by species*
- *glu-lam*
- *plywood*

Species and commercial grade	Size classification	Extreme fiber in bending "F_b": Single-member uses	Extreme fiber in bending "F_b": Repetitive-member uses	Tension parallel to grain "F_t"	Horizontal shear "F_v"	Compression perpendicular to grain "$F_{c\perp}$"
		Design values in pounds per square inch				
SOUTHERN PINE (Surfaced dry. Used at 19% max. m.c.)						
Select Structural		2000	2300	1150	100	565
Dense Select Structural		2350	2700	1350	100	660
No. 1		1700	1950	1000	100	565
No. 1 Dense	2" to 4" thick	2000	2300	1150	100	660
No. 2	2" to 4"	1400	1650	825	90	565
No. 2 Dense	wide	1650	1900	975	90	660
No. 3		775	900	450	90	565
No. 3 Dense		925	1050	525	90	660
Stud		775	900	450	90	565
Construction	2" to 4"	1000	1150	600	100	565
Standard	thick	575	675	350	90	565
Utility	4" wide	275	300	150	90	565
Select Structural		1750	2000	1150	90	565

Adjustment Factors

- terms
  - C_D = load duration factor
  - C_M = wet service factor
    - 1.0 dry $\leq$ 16% MC
  - C_F = size factor
    - visually graded sawn lumber and round timber > 12" depth

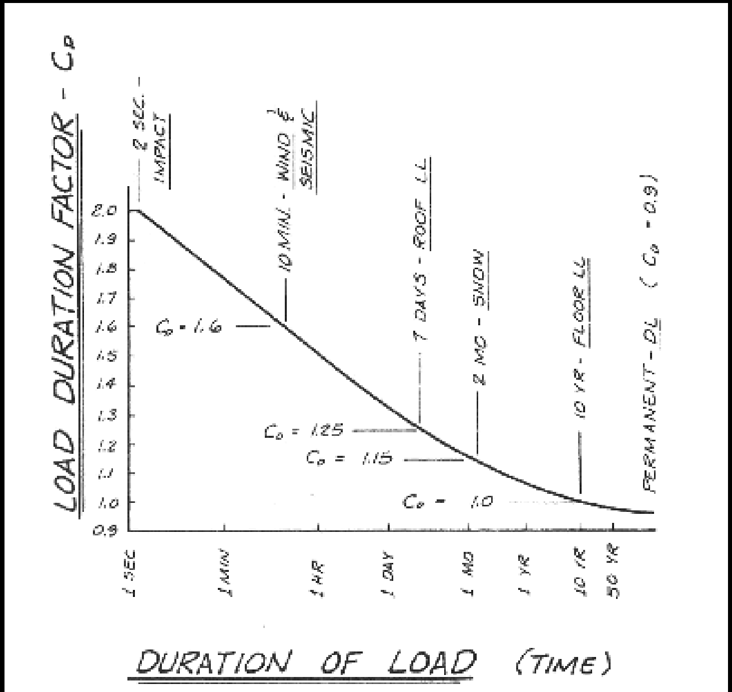


Figure 4.13 Madison curve.

$$C_F = (12/d)^{1/9} \leq 1.0$$

Table 10.3 (pg 376)

Adjustment Factors

- terms
  - C_{fu} = flat use factor
    - not decking
  - C_i = incising factor
    - increase depth for pressure treatment
  - C_t = temperature factor
    - lose strength at high temperatures

Adjustment Factors

- *terms*
  - C_r = *repetitive member factor*
  - C_H = *shear stress factor*
    - *splitting*
  - C_V = *volume factor*
    - *same as C_F for glue laminated timber*
  - C_L = *beam stability factor*
    - *beams without full lateral support*
  - C_C = *curvature factor for laminated arches*

Allowable Stresses

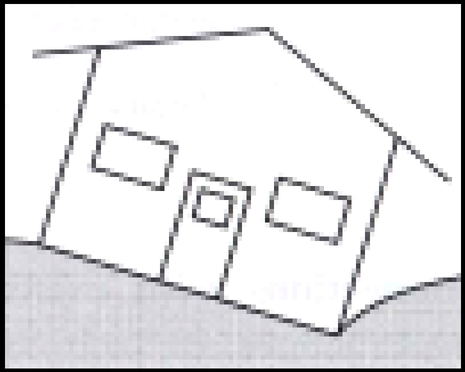
- design values
  - F_b: bending stress
  - F_t: tensile stress **strong**
  - F_v: horizontal shear stress **weak**
  - $F_{c\perp}$: compression stress (perpendicular to grain)
  - F_c: compression stress (parallel to grain) **strong**
  - E: modulus of elasticity
  - F_p: bearing stress (parallel to grain)

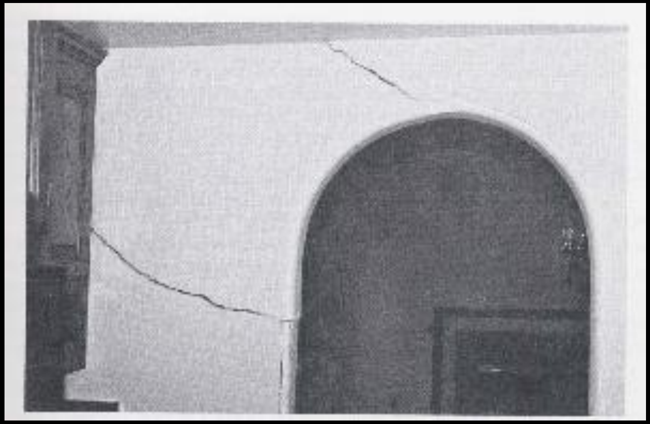
Load Combinations

- *design loads, take the bigger of*
  - *(dead loads)/0.9*
  - *(dead loads + any possible combination of live loads)/C_D*
- *deflection limits*
  - *no load factors*
  - *for stiffer members:*
    - Δ_T *max from LL + 0.5(DL)*

Beam Design Criteria

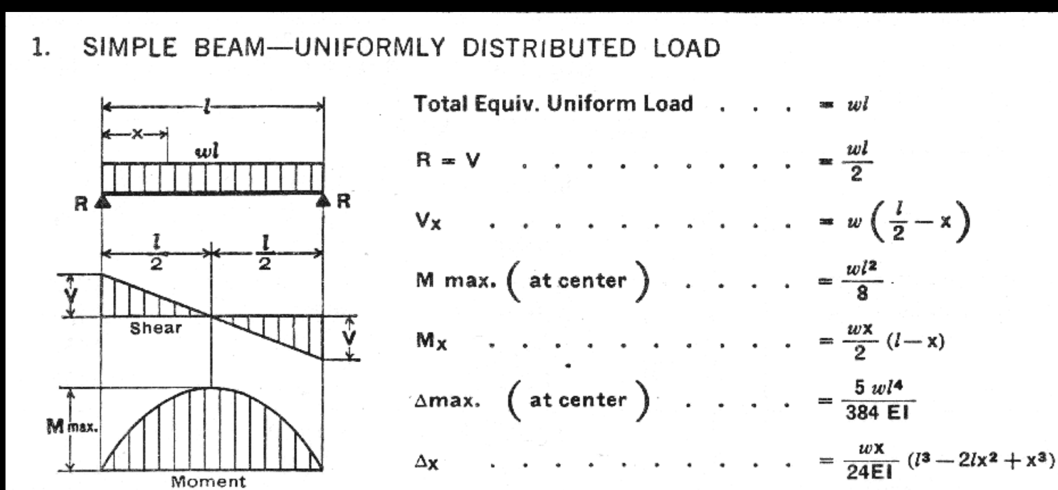
- *strength design*
  - *bending stresses predominate*
  - *shear stresses occur*
- *serviceability*
  - *limit deflection and cracking*
  - *control noise & vibration*
  - *no excessive settlement of foundations*
  - *durability*
  - *appearance*
  - *component damage*
  - *ponding*





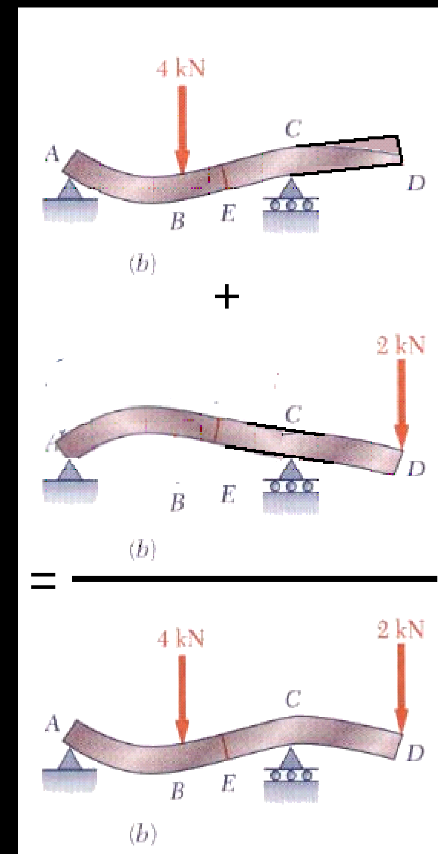
Beam Design Criteria

- superpositioning
  - use of beam charts
  - elastic range only!
  - "add" moment diagrams
  - "add" deflection CURVES (not maximums)



1\. SIMPLE BEAM—UNIFORMLY DISTRIBUTED LOAD

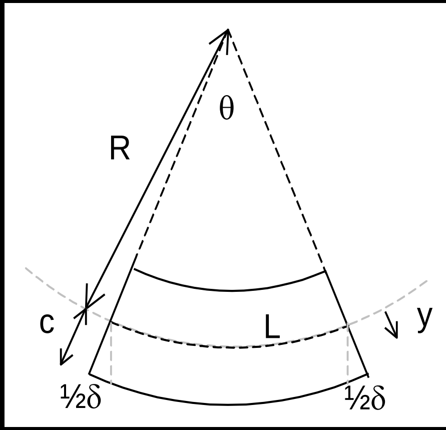
Total Equiv. Uniform Load	. . .	$= wl$
$R = V$	. . . .	$= \frac{wl}{2}$
V_x	. . . .	$= w\left(\frac{l}{2} - x\right)$
M max. (at center)	. . . .	$= \frac{wl^2}{8}$
M_x	. . . .	$= \frac{wx}{2}(l - x)$
Δmax. (at center)	. . . .	$= \frac{5wl^4}{384EI}$
Δx	. . . .	$= \frac{wx}{24EI}(l^3 - 2lx^2 + x^3)$

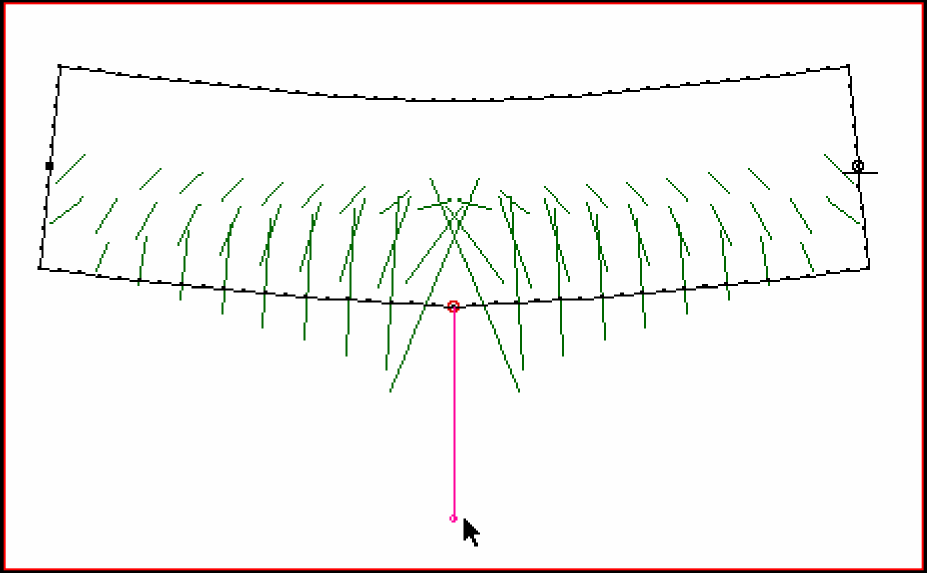


Beam Deformations

- curvature relates to
  - bending moment
  - modulus of elasticity
  - moment of inertia

$$\frac{1}{R} = \frac{M}{EI}$$





$$curvature = \frac{M(x)}{EI}$$

$$\theta = slope = \int \frac{M(x)}{EI} dx$$

$$\Delta = deflection = \int\int \frac{M(x)}{EI} dx$$

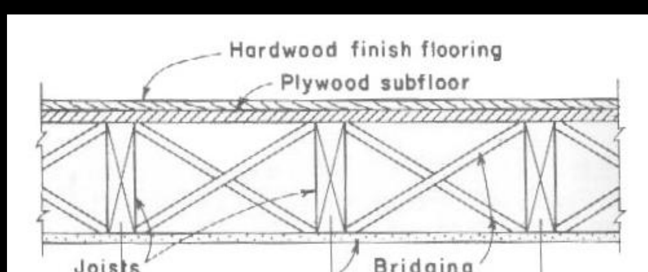
Deflection Limits

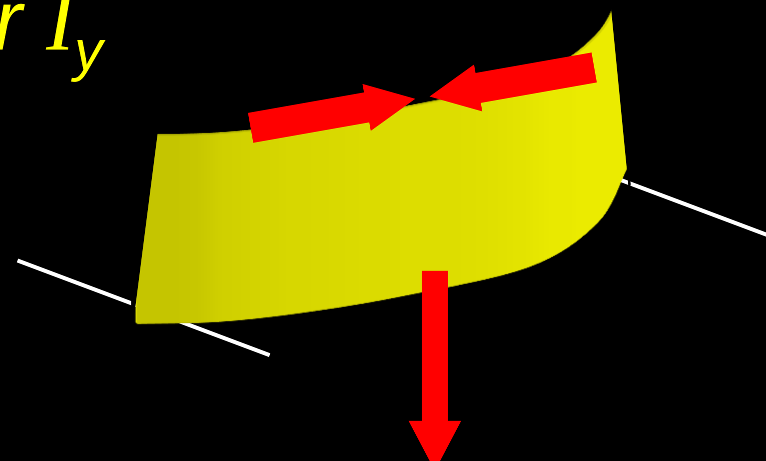
- based on service condition, severity

Use	LL only	DL+LL
Roof beams:		
Industrial	L/180	L/120
Commercial		
plaster ceiling	L/240	L/180
no plaster	L/360	L/240
Floor beams:		
Ordinary Usage	L/360	L/240
Roof or floor (damageable elements)		L/480

Lateral Buckling

- lateral buckling caused by compressive forces at top coupled with insufficient rigidity
- can occur at low stress levels
- stiffen, brace or bigger I_y

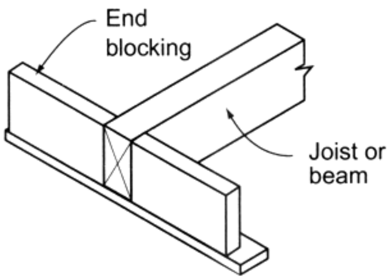
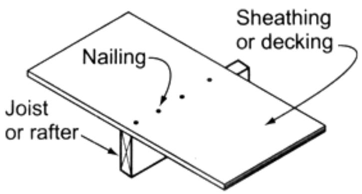
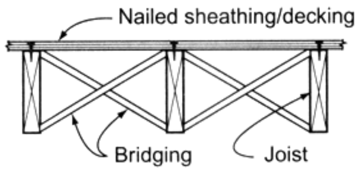
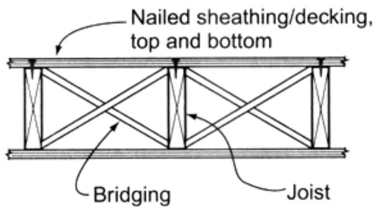




Timber Beam

Bracing

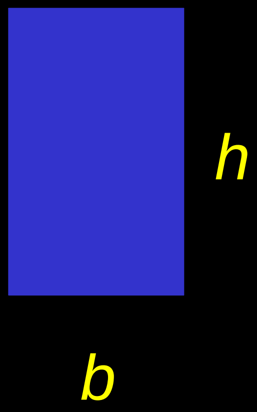
Table 9.3 Lateral bracing requirements for timber beams.

Beam Depth/ Width Ratio	Type of Lateral Bracing Required	Example
2 to 1	None	
3 to 1	The ends of the beam should be held in position	
5 to 1	Hold the compression edge in line (continuously)	
6 to 1	Diagonal bracing should be used	
7 to 1	Both edges of the beam should be held in line	

Design Procedure

1. Know F_{all} for the material or F_U for LRFD

2. Draw V & M, finding M_{max}



3. Calculate $S_{req'd}$ $\left(f_b \leq F_b \right)$

4. Determine section size

$$S = \frac{bh^2}{6}$$

Beam Design

4*. Include self weight for M_{max}

– and repeat 3 & 4 if necessary

5. Consider lateral stability

Unbraced roof trusses were blown down in 1999 at this project in Moscow, Idaho.

Photo: Ken Carper

Beam Design

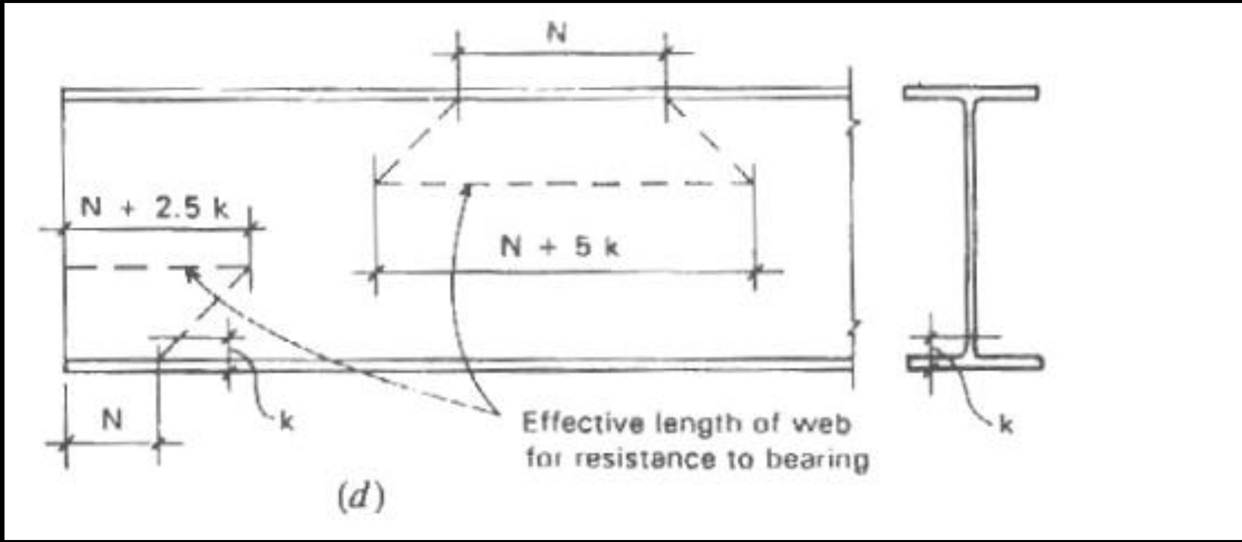
6. Evaluate shear stresses - horizontal

- $\left(f_v \leq F_v \right)$
- *rectangles and W's* $$f_{v-\max} = \frac{3V}{2A} \approx \frac{V}{A_{web}}$$
- *general* $$f_{v-\max} = \frac{VQ}{Ib}$$

Beam Design

7. Provide adequate bearing area at supports

$$f_p = \frac{P}{A} \le F_p$$



Beam Design

8. Evaluate torsion

$$\left(f_v \leq F_v \right)$$

- circular cross section

$$f_v = \frac{T\rho}{J}$$

- rectangular

$$f_v = \frac{T}{c_1 ab^2}$$

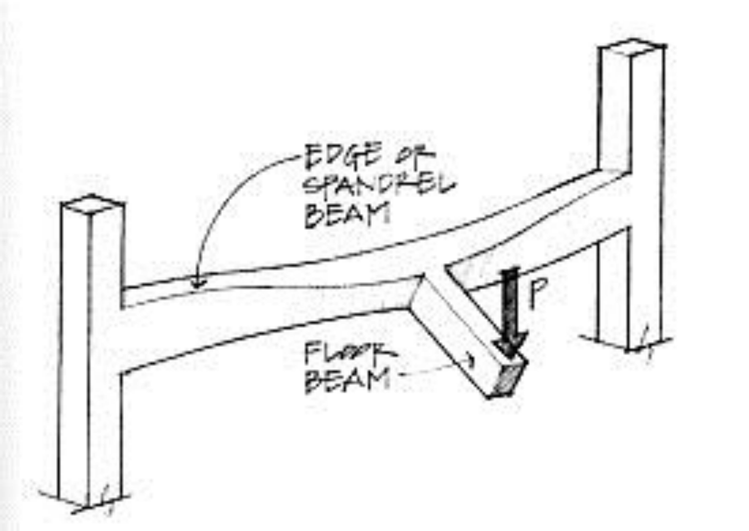
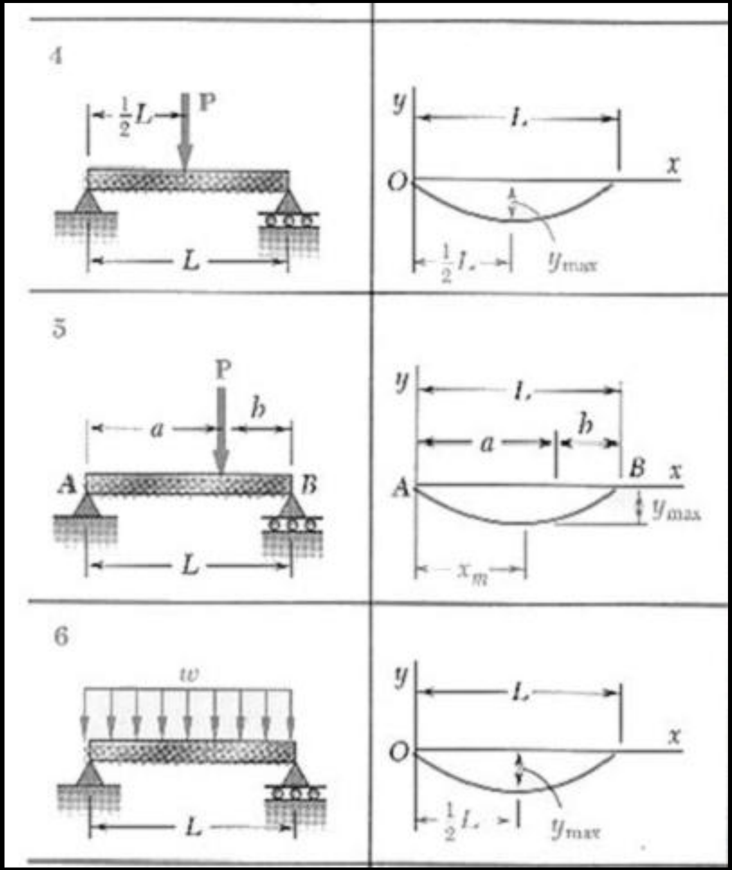


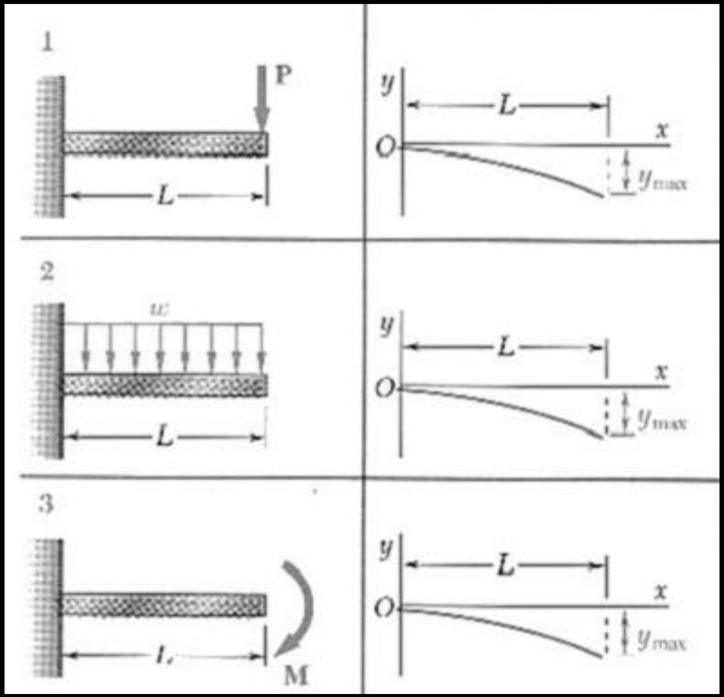
TABLE 3.1. Coefficients for Rectangular Bars in Torsion

a/b	c_1	c_2
1.0	0.208	0.1406
1.2	0.219	0.1661
1.5	0.231	0.1958
2.0	0.246	0.229
2.5	0.258	0.249
3.0	0.267	0.263
4.0	0.282	0.281
5.0	0.291	0.291
10.0	0.312	0.312
∞	0.333	0.333

Beam Design

9. Evaluate deflections





$$y_{max}(x) = \Delta_{actual} \leq \Delta_{allowable}$$

Decking

- across beams or joists
- floors: 16 in. span common
  - ¾ in. tongue-in-groove plywood
  - 5/8 in. particle board over ½ in. plywood
  - hardwood surfacing
- roofs: 24 in. span common
  - ½ in. plywood

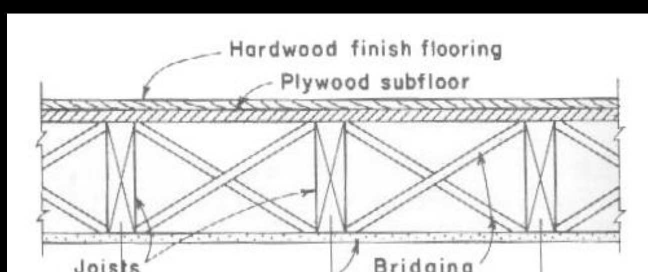
Joists & Rafters

- *allowable load tables (w)*
- *allowable length tables for common live & dead loads*
- *lateral bracing needed*
- *common spacings*

TABLE 5.5 Allowable Spans in Feet and Inches for Floor Joists

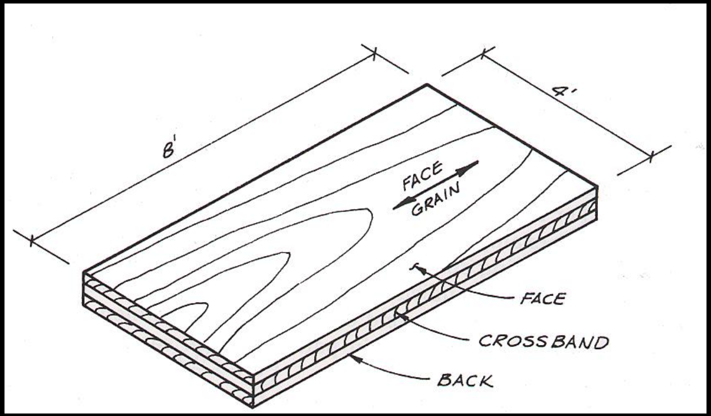
DESIGN CRITERIA:
Deflection — For 40 psf (1.92 kN/m²) live load.
Limited to span in inches (mm) divided by 360.
Strength — Live load of 40 psf (1.92 kN/m²) plus dead load of 10 psf (0.48 kN/m²) determines the

Joist Size (in)	Spacing (in)	Modulus of Elasticity, *E*, in 1,000,000 psi × 0.00689 for N/mm²		
× 25.4 for mm		1.3	1.4	1.5
2 × 6	12.0	10-0	10-3	10-6
	16.0	9-1	9-4	9-6
	19.2	8-7	8-9	9-0
	24.0	7-11	8-2	8-4
2 × 8	12.0	13-2	13-6	13-10
	16.0	12-0	12-3	12-7
	19.2	11-3	11-7	11-10
	24.0	10-6	10-9	11-0
2 × 10	12.0	16-10	17-3	17-8
	16.0	15-3	15-8	16-0
	19.2	14-5	14-9	15-1
	24.0	13-4	13-8	14-0
2 × 12	12.0	20-6	21-0	21-6
	16.0	18-7	19-1	19-6
	19.2	17-6	17-11	18-4
	24.0	16-3	16-8	17-0
F_b	12.0	993	1,043	1,092
	16.0	1,093	1,148	1,202
	19.2	1,161	1,220	1,277
	24.0	1,251	1,314	1,376



Engineered Wood

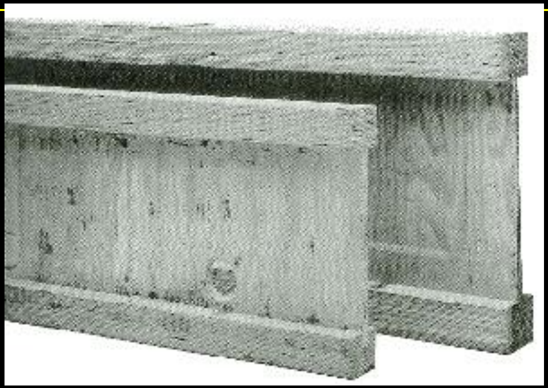
- *plywood*
  - *veneers at different orientations*
  - *glued together*
  - *split resistant*
  - *higher and uniform strength*
  - *limited shrinkage and swelling*
  - *used for sheathing, decking, shear walls, diaphragms*



Engineered Wood

- glued-laminated timber
  - glulam
  - short pieces glued together
  - straight or curved
  - grain direction parallel
  - higher strength
  - more expensive than sawn timber
  - large members (up to 100 feet!)
  - flexible forms

Engineered Wood



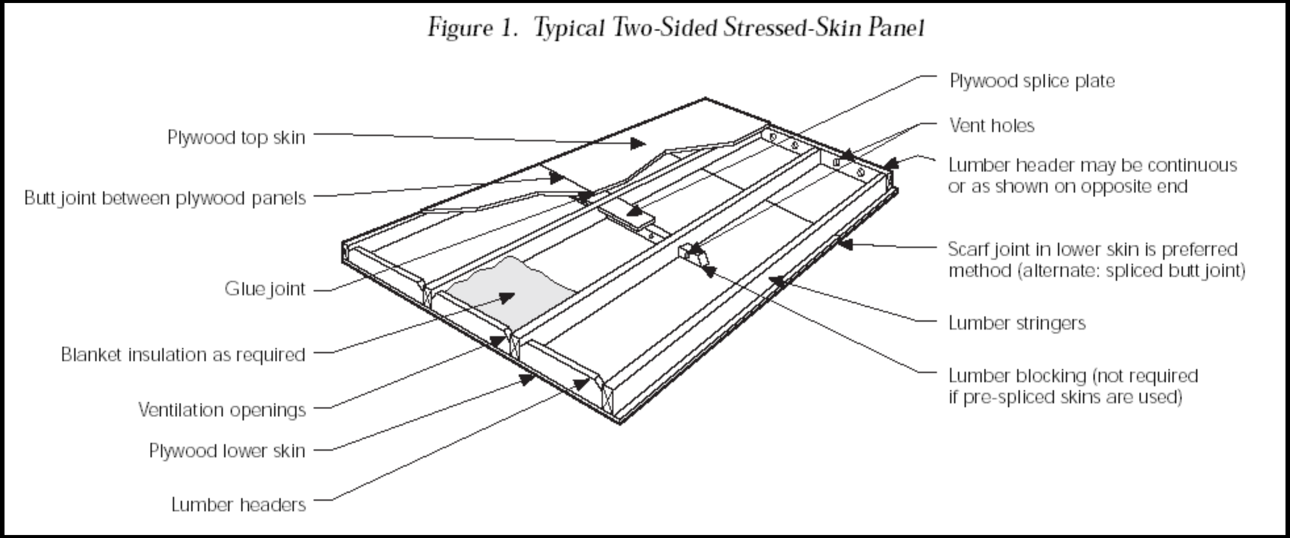
- *I sections*
  - *beams*

- *other products*
  - *pressed veneer strip panels (Parallam)*
  - *laminated veneer lumber (LVL)*

- *wood fibers*
  - *Hardieboard: cement & wood*

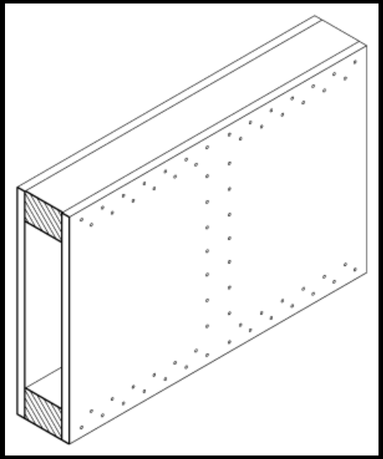
Timber Elements

- *stressed-skin elements*
  - *modular built-up "plates"*
  - *typically used for floors or roofs*



Timber Elements

- *built-up box sections*
  - *built-up beams*
  - *usually site-fabricated*
  - *bigger spans*

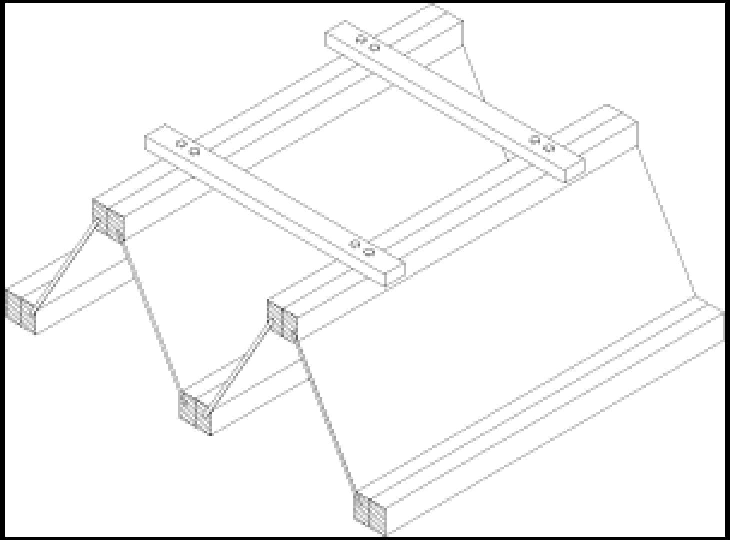


Timber Elements

- trusses
  - long spans
  - versatile
  - common in roofs

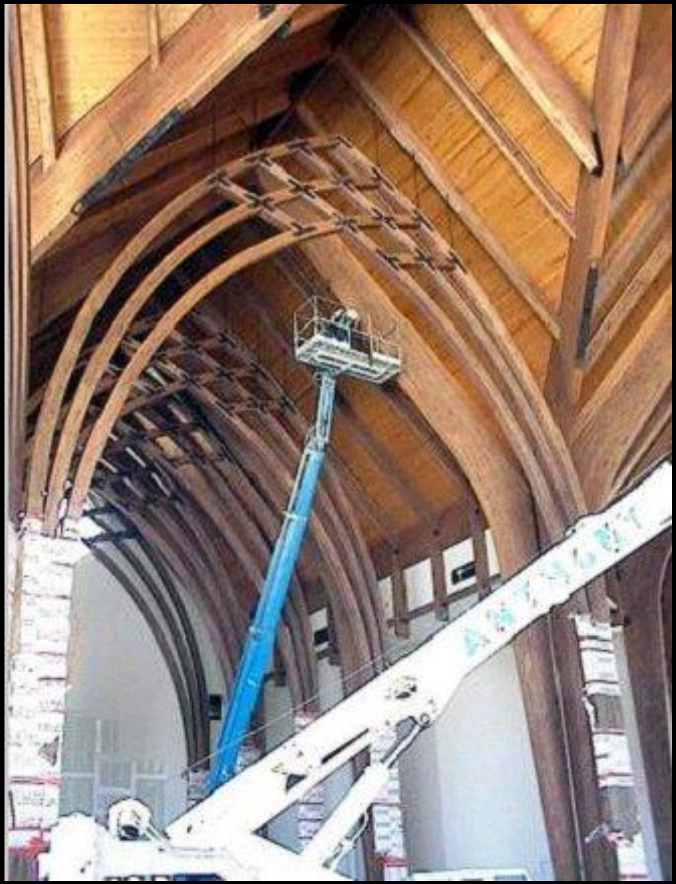
Timber Elements

- *folded plates and arch panels*
  - *– usually of plywood*



Timber Elements

- arches and lamellas
  - arches commonly laminated timber
  - long spans
  - usually only for roofs



Approximate Depths

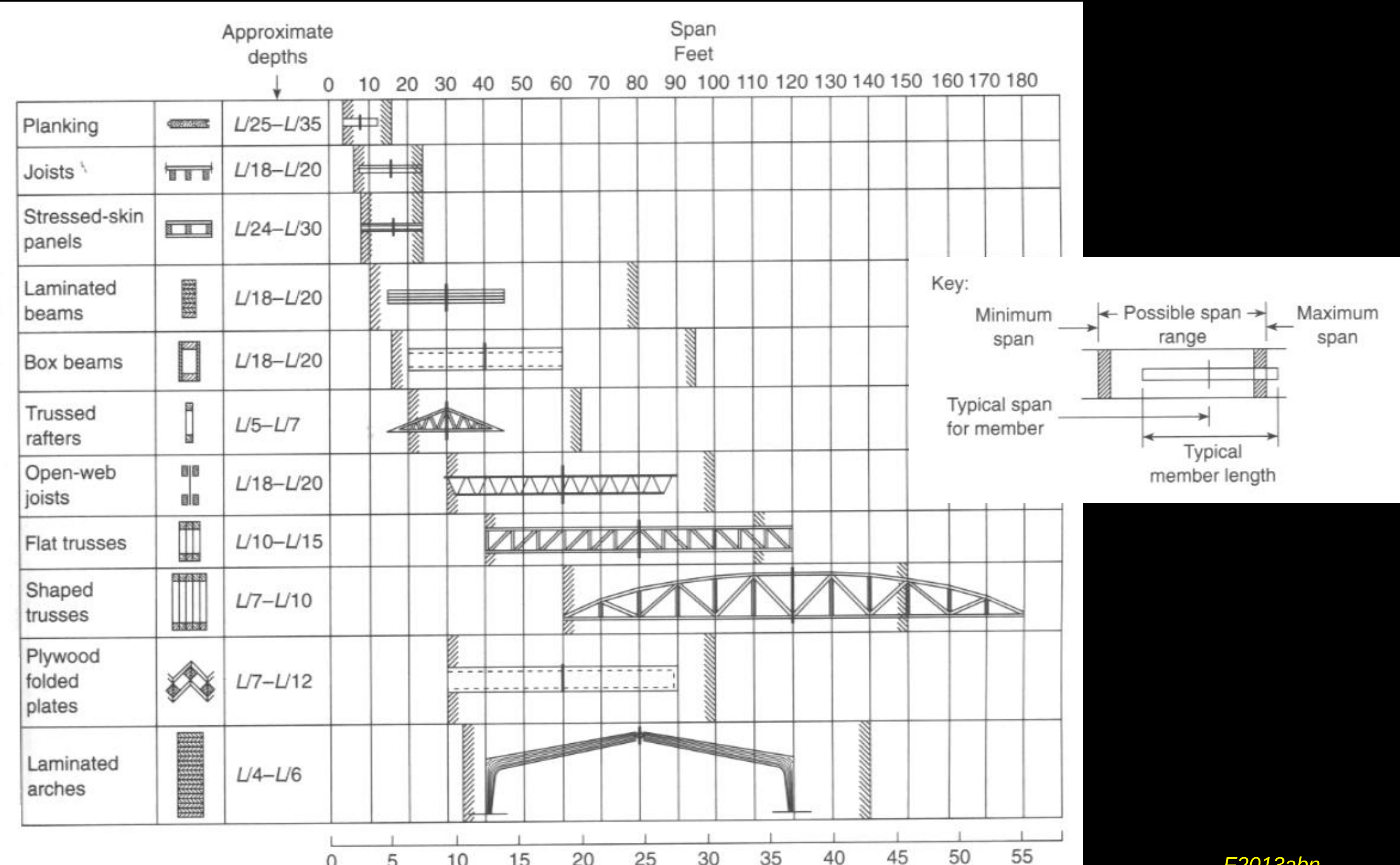


FIGURE 15–3 Approximate span ranges for timber systems.

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