Timber Engineering and Technology

Ali Awaludin, PhD

Lab Experiment

Timber bridge test

Hokkaido, Japan

Class Instructors

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  Timber Engineering (week 1 - 5)
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Content (week 1 – 5)

- Timber Engineering: Past and Present
- Wood Properties
- Mechanical Properties and Grading Techniques
- Theory of Timber Joint
- Nailed and Bolted Joints Analysis

Content (week 1)

- Timber Engineering: Past and Present
- Wood Properties
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General Introduction

- Protection and shelter against sun, wind, rain and cold is a very basic need for mankind. Since ancient times, wood has been the most important material used for this purpose.
- Wood is extremely versatile material with a wide range of physical and mechanical properties among many species of wood.
- Wood is also a renewable resource with exceptional strength-to-weight ratio.

General Introduction

Wood properties over concrete and steel (Smith et al. 2008)

	Tensile strength	Compressive strength	Stiffness	Density
Plain concrete	-	50%	20-33%	20%
Structural steel	10-20%	5-10%	5-10%	6%

Example: compressive strength-to-weight ratio

Concrete = 30 MPa / 24 KN/m^3 = 1.25

Wood (*Cocos nucifera*) = 28 MPa / 7.9 KN/m^3 = 3.54

Wood-structure assemblies have a higher strength-to-weight ratio over those built with steel and concrete.

They are light in weight and produce a low inertia force during seismic events.

Learning From Past

Earthquake	M (Ritcher-scale)	No. of Person Killed (Approx)		No. of Wood-Frame Buildings Shaken (Estimated)
		Total	In Wood-frame Building	
Alaska, 1964	8.4	130	< 10	-
San Fernando, 1971	6.7	63	4	100,000
Edgecumbe, 1987	6.3	0	0	70,000
Saguenay, 1988	5.7	0	0	10,000
Loma Prieta, 1989	7.1	66	0	60,000
Northridge, 1994	6.7	60	20	200,000
Hyogo-Ken Nanbu (Kobe),1995	6.8	6,300	0	8,000

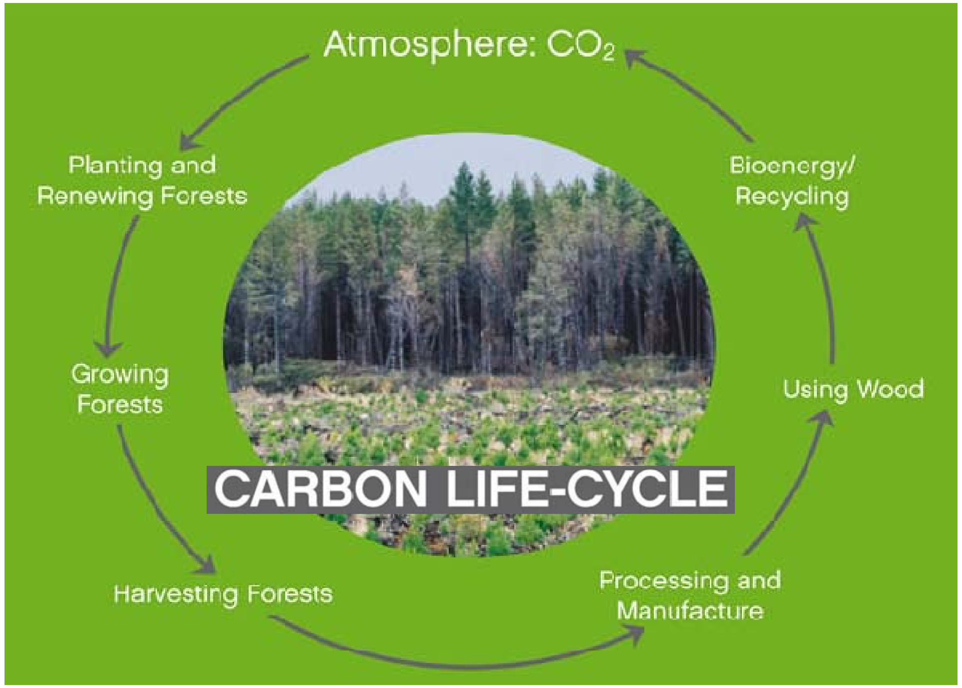
(in Toratti, 2001)

Survival timber structures are characterized by:

1. Constructed components act as a unit;
2. Symmetrical in plan;
3. Energy dissipation system found in connections.

Environmental Impact

Wood is a desirable construction material because of the energy requirement of wood for producing a usable end-product are much lower than those of competitive materials, such as steel, concrete, or plastic.



Material	Carbon released (kg/m^3)	Carbon stored (kg/m^3)
Sawn timber	15	250
Concrete	120	0
Steel	5320	0
Aluminum	22000	0

(Source: FWPRDC, 1997)

Timber Pagoda

Figure 1.2 Three storey pagoda, Yakusiji Toto, built 730 (Yasemura, 2000). (Reproduced by permission of M. Yasemura)

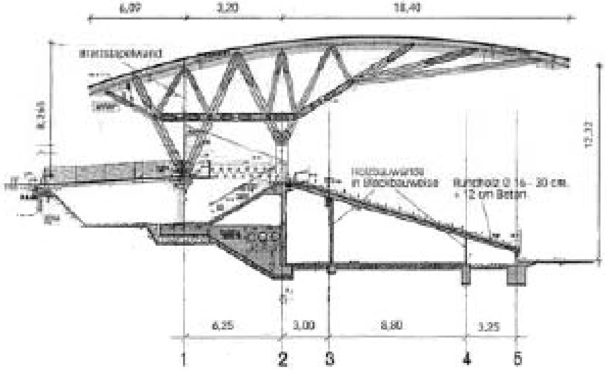
Fig.1 Main Building of ISE Shrines *photo:Y. Watanabe*

Masjid Gedhe, Yogyakarta (1773)

Courtesy Virgina Veryastuti, 2008

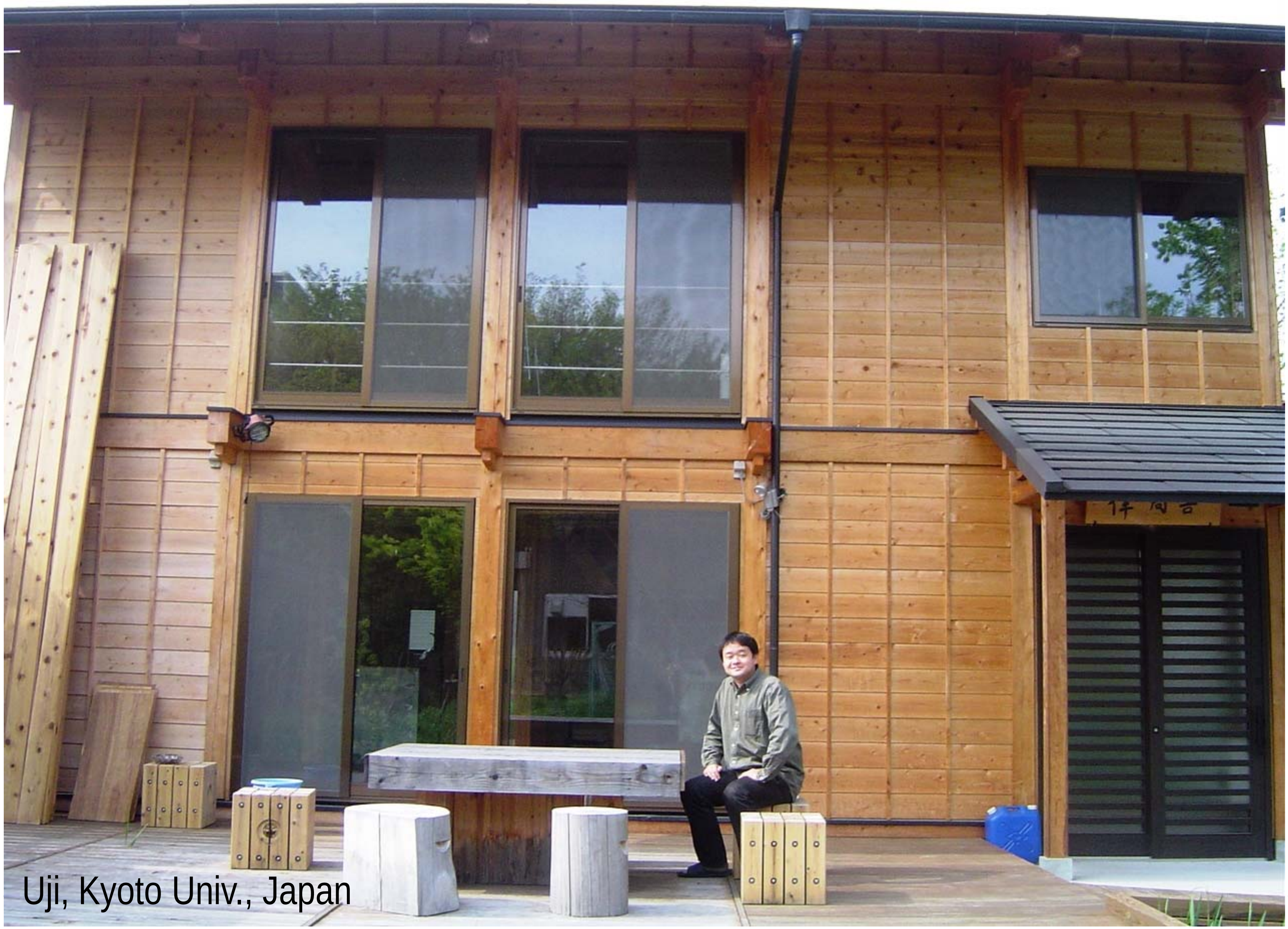
Timber Open Air Stage (1998)

The roof structure covers an area of 30 x 100 m.. The 4 highly stressed truss cantilevers (cantilever 30 m) in a distance of 25 m are in selected round wood trunks. The suspended roof structure that spans between the truss is made up of nailed boards. The different slabs as well as the inclined terraces where made of mixed wood concrete construction. The wood parts made from round conical trunks (base 32cm top 16cm) thus allowing to follow the hemispherical form of the tribune.



(in Natterer, 2009)

Two-Storey Timber House

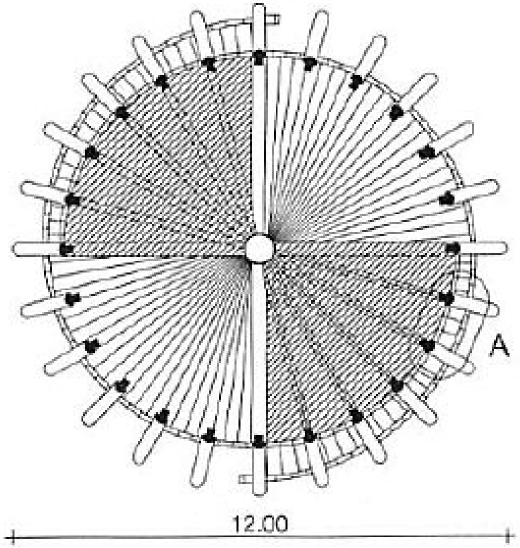


Uji, Kyoto Univ., Japan

Timber Tower Lausanne (2003)

(in Natterer, 2009)

Tower high 36 m. Observation platform at 30 m. Diameter: 12 m at base, 6m at the platform. 24 poles half round are distributed around the spiral staircase made of 20x40 cm Douglas sections. The spiral builds two independent staircases one behind the other. The upper platform and the two intermediates one are made of nailed laminated timber



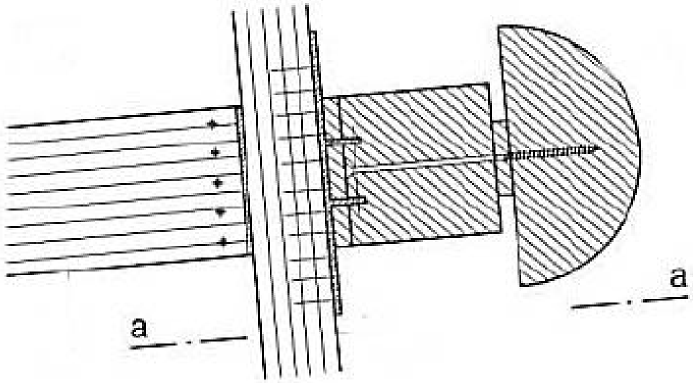
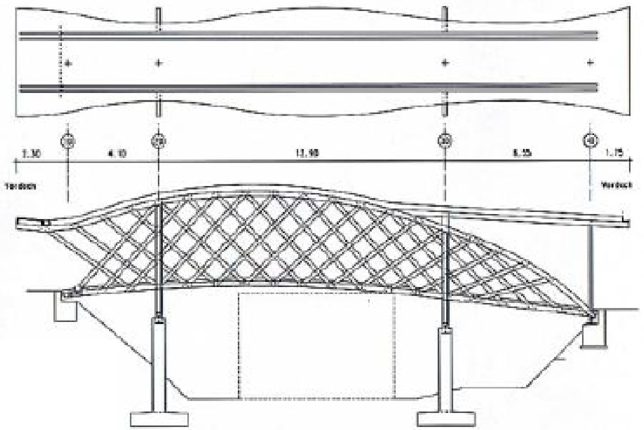


Photo: Atlas Copco

Photo: Atlas Copco

Neutraubling (D) 2001

The covered bridge have two span from 12.9 and 6.55 m and a cantilever from 4.1 m.
Under and upper chords are made of curved glue laminated timber., while the diagonals are made of boards. The bracing of the horizontal forces are achieved by rigid frames at the supporting points of the bridge



Ravine (CH) 1989

Heavy loads bridge over the "Doubs". Load: 36 t. Frame truss as main structural system. The bracing of the horizontal forces are achieved by rigid frames in the nodal points of the main structural systems upper chord. Span: 36 m, width: 4.8 m

(in Natterer, 2009)

Timber Bridge, The Netherlands (2008)

Timber Bridges

- In modern bridge construction, timber is growing popularity for foot and bicycle bridges as well as road bridges with moderate spans.
- One reason for this is environmental awareness and the trend towards the use of ecological sound materials in construction.
- A key factor for timber bridge design in durability. Preservative chemical treatment is not an attractive alternative considering environmental policies of today. However, by careful design and detailing, the wood material in a timber bridge can be kept more or less constantly dry, so that biological decay is avoided and long lifetimes can be achieved.

What is special about timber?

- Timber is an inhomogeneous building material
- Timber is only durable at certain climates
- Timber is easy to work with
- Timber is an anisotropic building material
- Timber connections are generally the weaker timber members

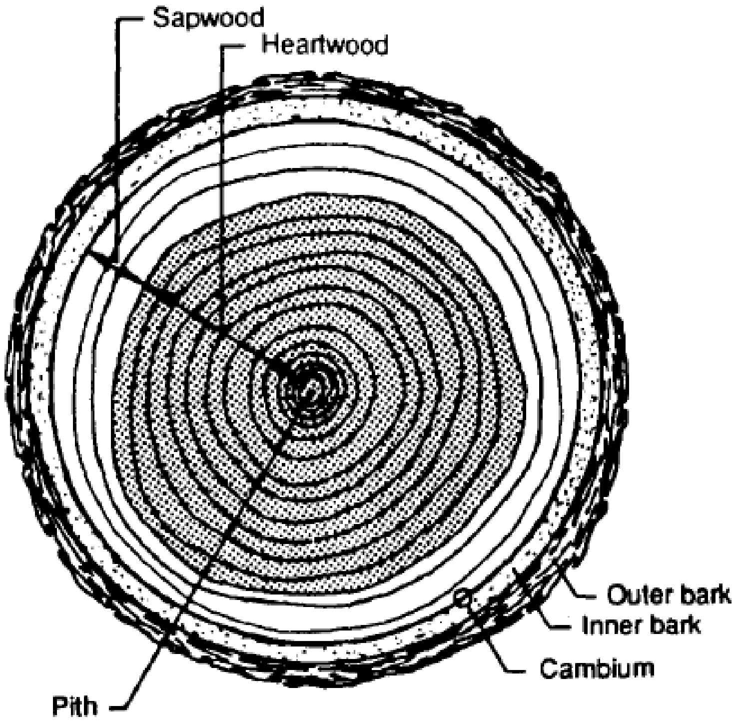
Content (week 2)

- Timber Engineering: Past and Present
- **Wood Properties**
- Mechanical Properties and Grading Techniques
- Theory of Timber Joint
- Nailed and Bolted Joints Analysis

Wood structure

Growth in trees is affected by he soil and environment al condition. Growth is accomplished by cell division. As new cell form, they are pushed either to the inside to be come wood cells or to the outside to become bark cells. As the three diameter increases, additional bark cells are pushed out ward, and the outer surface becomes cracked and ridged.

Kayu Mindi
(*Melia azedarach*)



Wood structure

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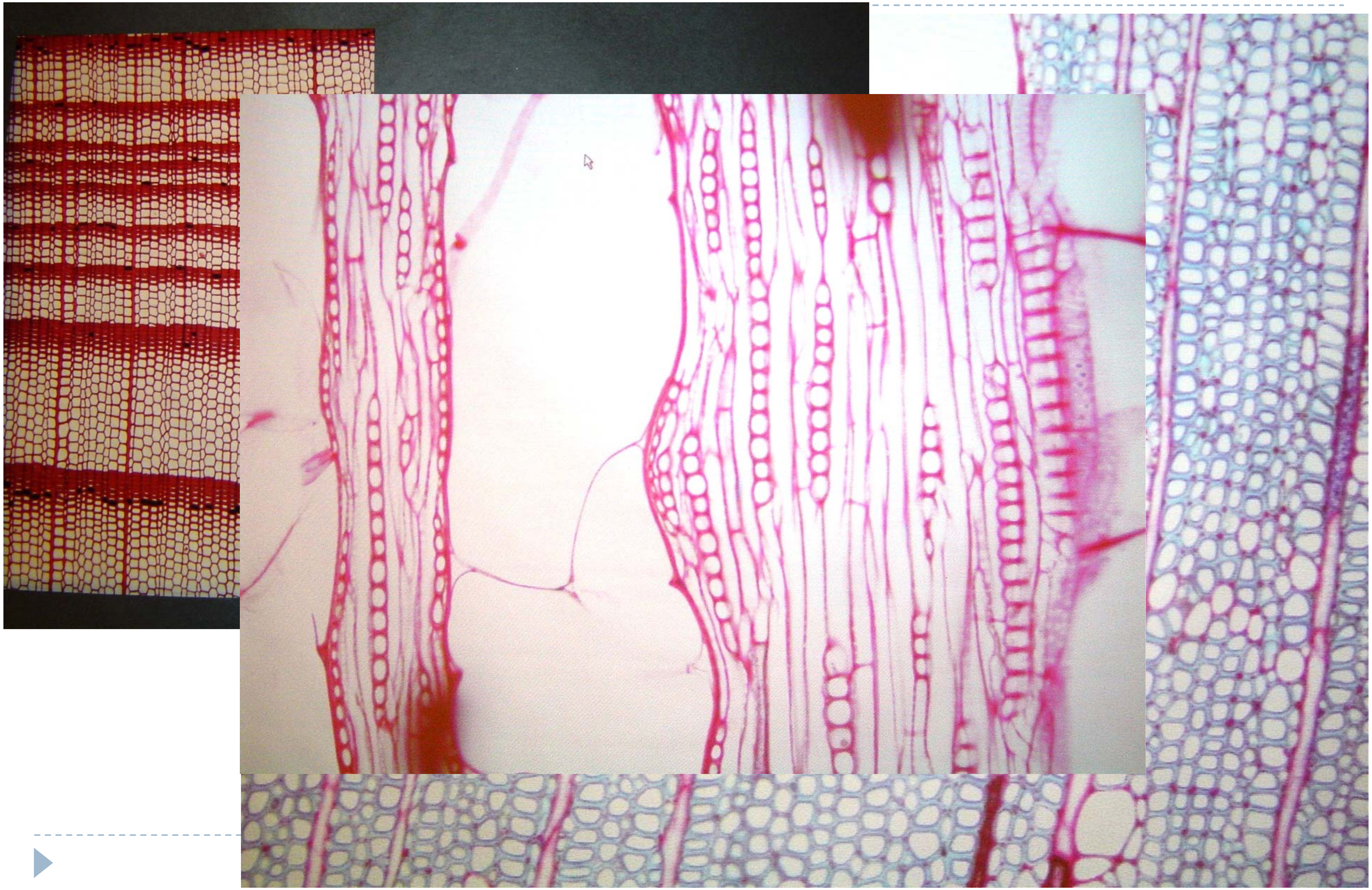
Wood structure



Wood structure

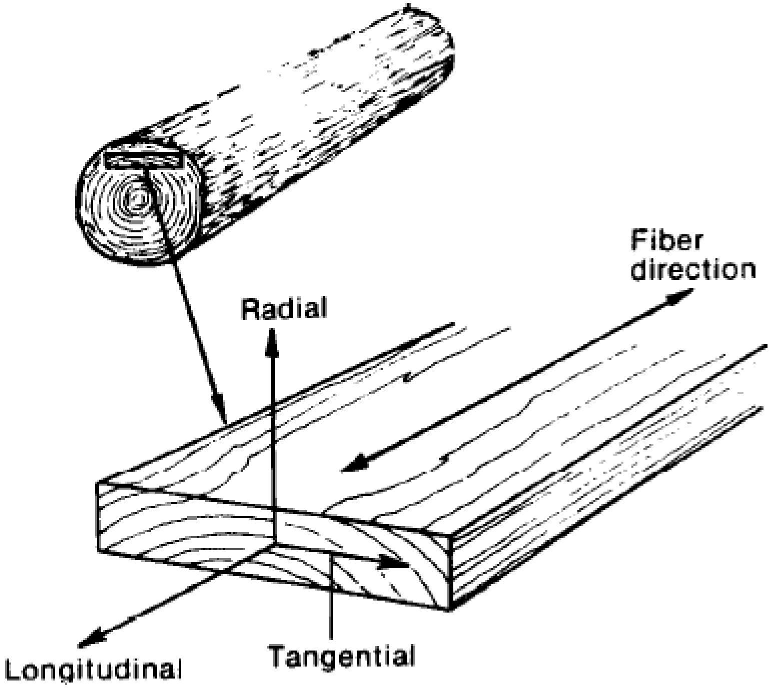
- Wood is composed of the inner sections of the trunk. The primary functions of wood are support and nutrient conduction and storage.
- Wood can be classified into two: sapwood (*gubal*) and heartwood (*teras*).
- Sapwood is located next to cambium. It functions primarily in food storage and the mechanical transport of sap. The radial thickness of sapwood is commonly 20 to 100 mm.
- Heartwood consists of an inner core of wood cells that have changed, both chemically and physically, from the cells of the outer sapwood. The cell cavities of heartwood may also contain deposits of various materials that frequently give heartwood a much darker collour.

Wood structure

Growth rings vary in width depending on species and site conditions. Rings formed during dry seasons are thinner than those formed when growing conditions are more favorable. It is commonly believed that the age of tree may be determined by counting these rings. However, this method can lead to errors because abnormal environmental condition can cause tree to produce multiple-growth increments or even prevent growth entirely for a period.

Kayu Mahoni (*Melia azedarach*)

Wood physical properties



Directional properties

Because of the orientation of the wood fibers and the manner in which a tree increases in diameter as it grows, properties vary along three mutually perpendicular axes: longitudinal, radial, and tangential.

Although most wood properties differ in each of these three axis directions, differences between the radial and tangential axes are relatively minor when compared to difference between the radial or tangential axis and the longitudinal axis.

Wood physical properties

- The moisture content of wood is defined as the weight of water in wood given as a percentage of oven-dry weight.
- In living trees, moisture content may vary from 25% to more than 250%.
- Water exists in wood either as bound water (in cell wall) or free water (in the cell cavity).
- When wood dries, most free water separates at a faster rate the bound water. The moisture content at which the cell walls are still saturated but virtually no water exists in the cell cavities is called the fiber saturation point (FSP).
- Wood is a hydroscopic material that absorbs moisture in a humid environment and loses moisture in a dry environment. Under constant temperature and humidity, wood reaches an equilibrium moisture content (EMC). Change of moisture content can be retarded by coating

Wood physical properties

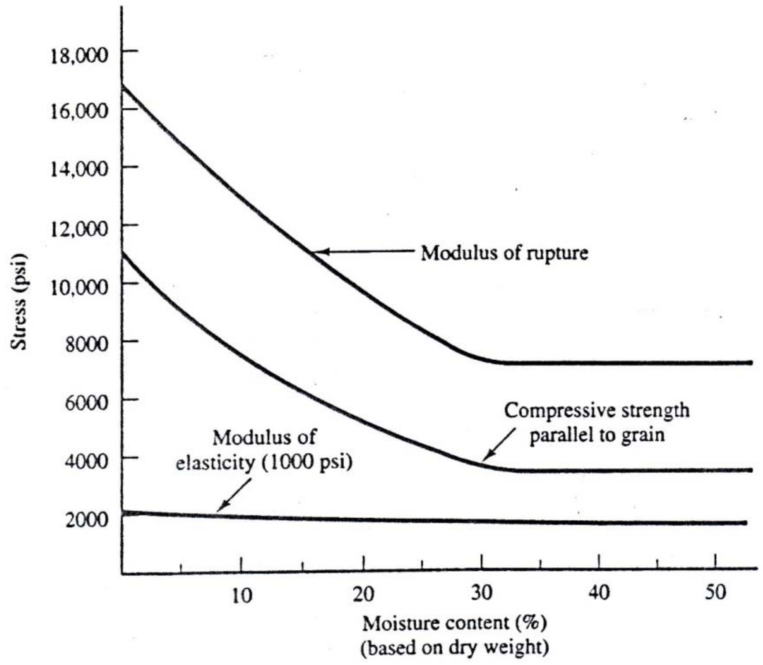
- Above FSP, wood will not shrink or swell from changes in moisture content.
- However, wood changes in dimension as moisture content varies below FSP.
- This dimensional changes may result in splitting, checking, warping.
- Dimensional changes in the longitudinal direction between FSP and oven-dry are between 0.1 and 0.2% and are of no practical significance.
- The combine effect of shrinkage in the tangential and radial axes can distort the shape of wood pieces. Tangential shrinkage (varying from 4.4% to 7.8% depending on species) is twice that of radial shrinkage (from 2.2% to 5.6%).
- The phenomenon of dimensional stability and EMC must be understood, recognized, and considered in good timber design.

Wood physical properties

Splitting caused by large moisture evaporation

Kayu Sengon (*Paraserianthes falcataria*)

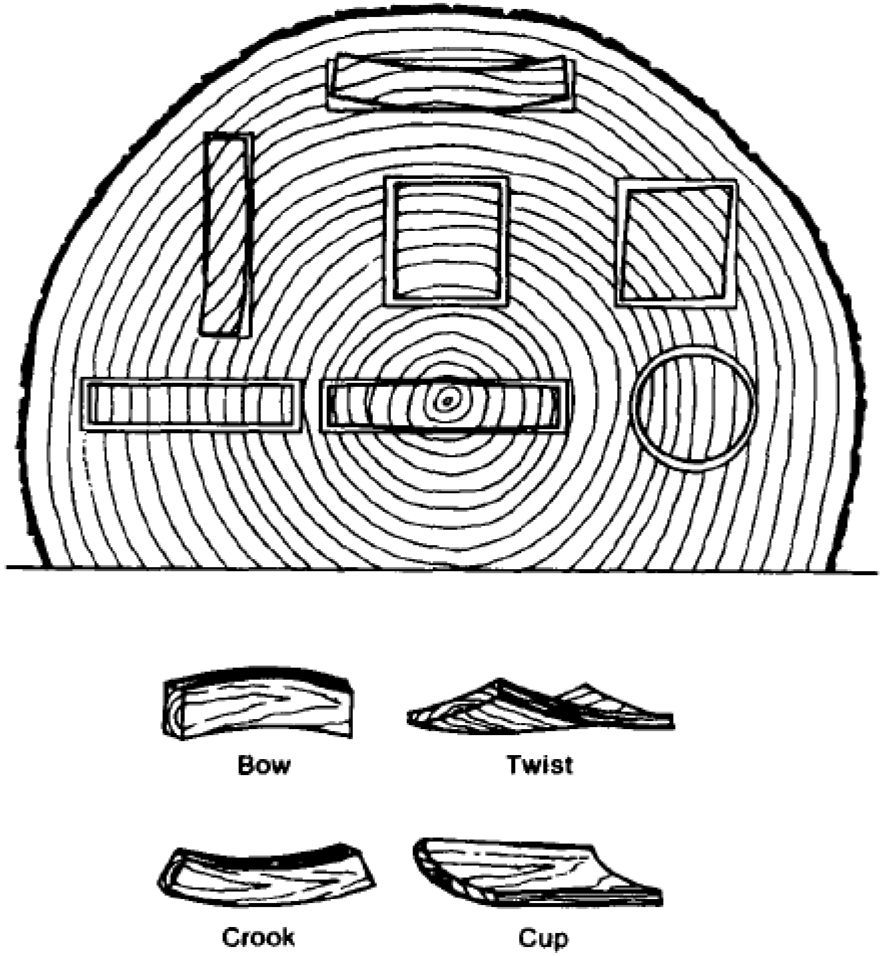
Wood physical properties



Effect of moisture content on strength

(in Somayaji , 1995)

Shrinkage and distortion of wood



Wood physical properties

- Density of a material is the mass per unit volume at some specified condition. Wood density depends on two factors: weight of the wood structure and moisture retained in the wood.
- Specific gravity is a relative measure of the amount of wood substance contained in a sample of wood. It is dimensionless ratio of the weight of an oven-dry volume.
- In research activities, specific gravity may be reported on the basis of both weight and volume oven-dry.
- For many engineering application, the basis for specific gravity if generally the oven-dry weight and volume as a moisture content 12%.

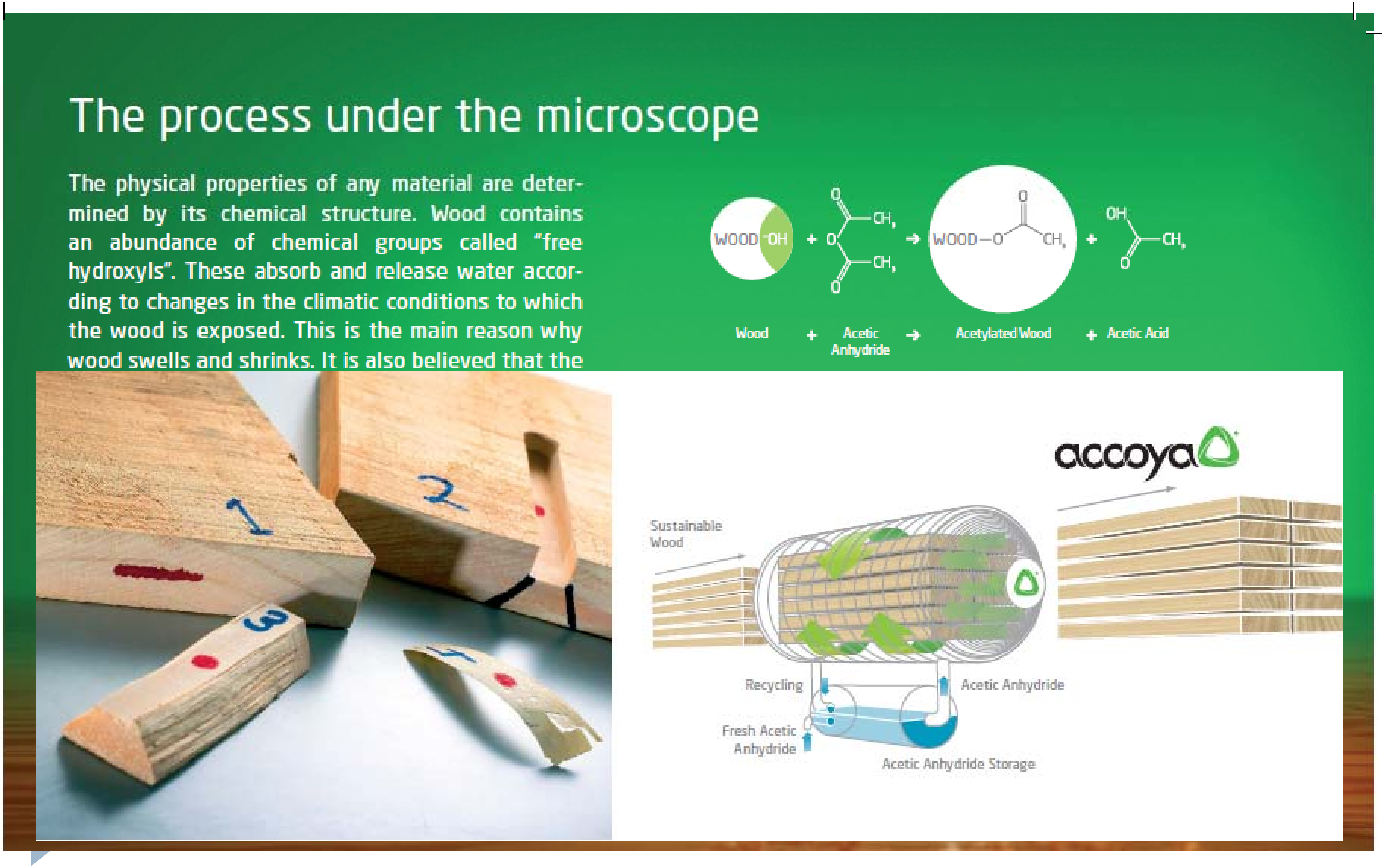
Wood physical properties

- Wood decay fungi and wood-destroying organism require oxygen, appropriate temperature, moisture and a food source.
- Wood will not decay if kept dry (MC less than 20%). On the other extreme, if continuously submerged in water at sufficient depths, wood will usually not decay.
- To avoid problems with decay where moisture content cannot be controlled, the engineer or designer can use either naturally durable species or treated timbers.
- In general, sapwood has little resistance to deterioration.
- For heartwood, natural durability depends on species. In some species, the sugars present in the cell are concerted to highly toxic extractive that are deposited in the wood cell walls.

Wood treatment

Wood-destroying organism, Termite

Wood treatment



The process under the microscope

The physical properties of any material are determined by its chemical structure. Wood contains an abundance of chemical groups called “free hydroxyls”. These absorb and release water according to changes in the climatic conditions to which the wood is exposed. This is the main reason why wood swells and shrinks. It is also believed that the

Wood thermal properties

- Under appropriate conditions, wood will undergo thermal degradation or pyrolysis.
- Timber will gradually produce a char layer from the residue of wood combustion. This char acts as a thermal insulator.
- On heavy timbers, this char layer will eventually inhibit combustion by establishing a thermal barrier between the uncharred and the heat of the fire.
- Heavy timber is virtually self-extinguishing, but steel, which has a thermal conductivity 100 times that of wood, will absorb heat until it reaches a temperature at which it yields under structural load without actually burning.

Wood physical properties

Strength loss under elevated temperature

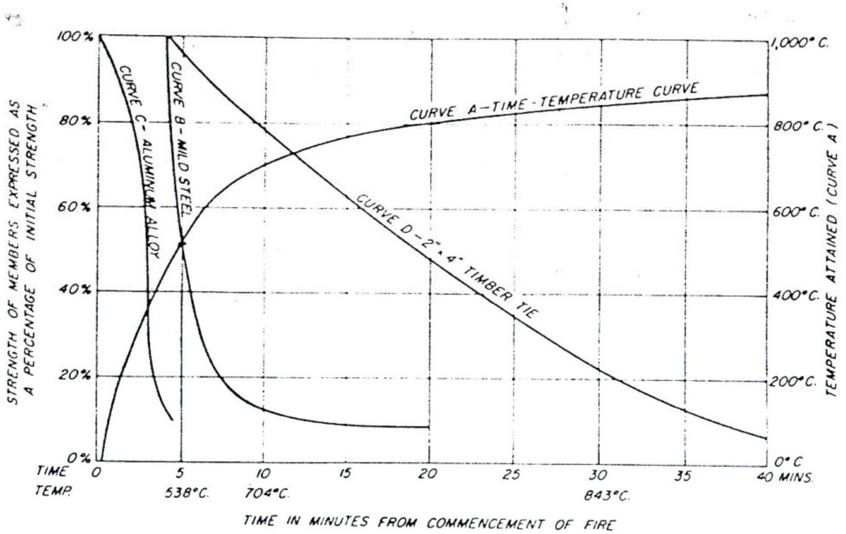


Figure 8.3. Strength loss of timber, steel, and aluminum in fire. (Photograph courtesy of U.S. Forest Products Laboratory.)

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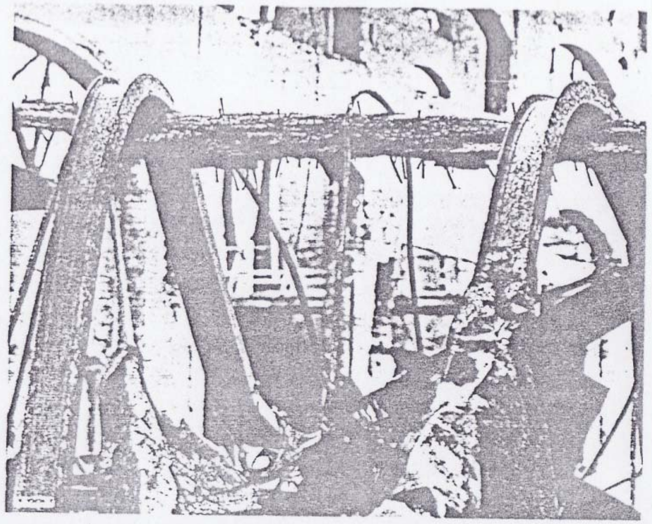

Figure 8.4. Lumber supports collapsed steel I-beams in a burned-out structure. (Photograph courtesy of U.S. Forest Products Laboratory.)

(in Kubler, 1980)

Engineered Wood Products

- Plywood

Manufactured from thin sheets of cross-laminated veneer and bonded under heat and pressure with strong adhesives, plywood has been one of the most ubiquitous building products for decades.

- Oriented Strand Board (OSB)

OSB is manufactured from waterproof heat-cured adhesives and rectangularly shaped wood strands that are arranged in cross-oriented layers, similar to plywood. This results in a structural engineered wood panel that shares many of the strength and performance characteristics of plywood. Produced in huge, continuous mats, OSB is a solid panel product of consistent quality with no laps, gaps or voids.

Engineered Wood Products

- Glued Laminated Timber (Glulam)

Glulam is a stress-rated engineered wood product comprised of wood laminations, or "lams," specifically selected and positioned in the timber based on their performance characteristics, and bonded together with durable, moisture-resistant adhesives. Glulam components can be a variety of species, and individual "lams" are typically two inches or less in thickness.

- Cross Laminated Timber (Cross-lam, X-lam)

It is made of layers of solid timber, alternating grain direction at 90 degrees (where Glue-laminated timber is layered with the grain). The exterior layers' grains run lengthways giving optimum strength.

Content (week 3)

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Grading principle: bending

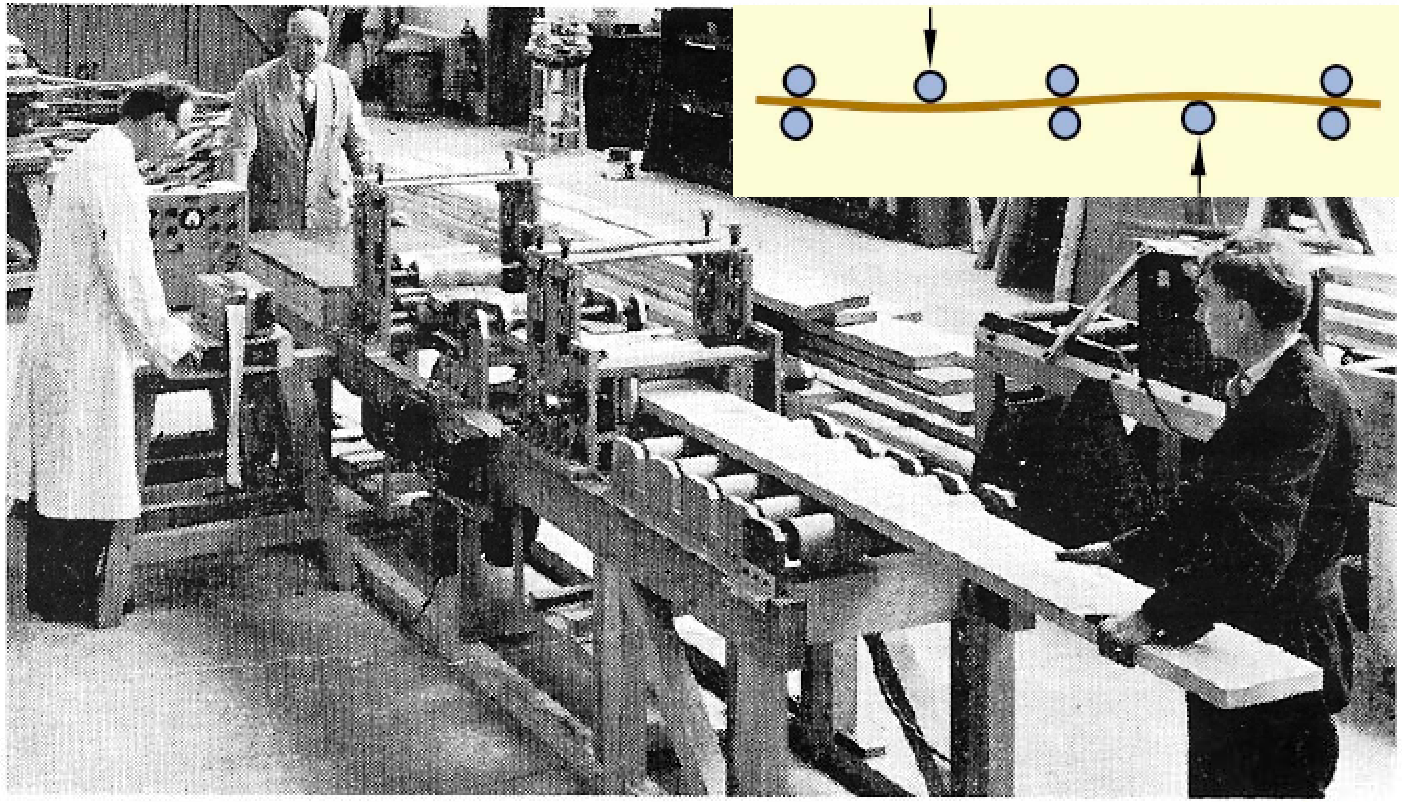
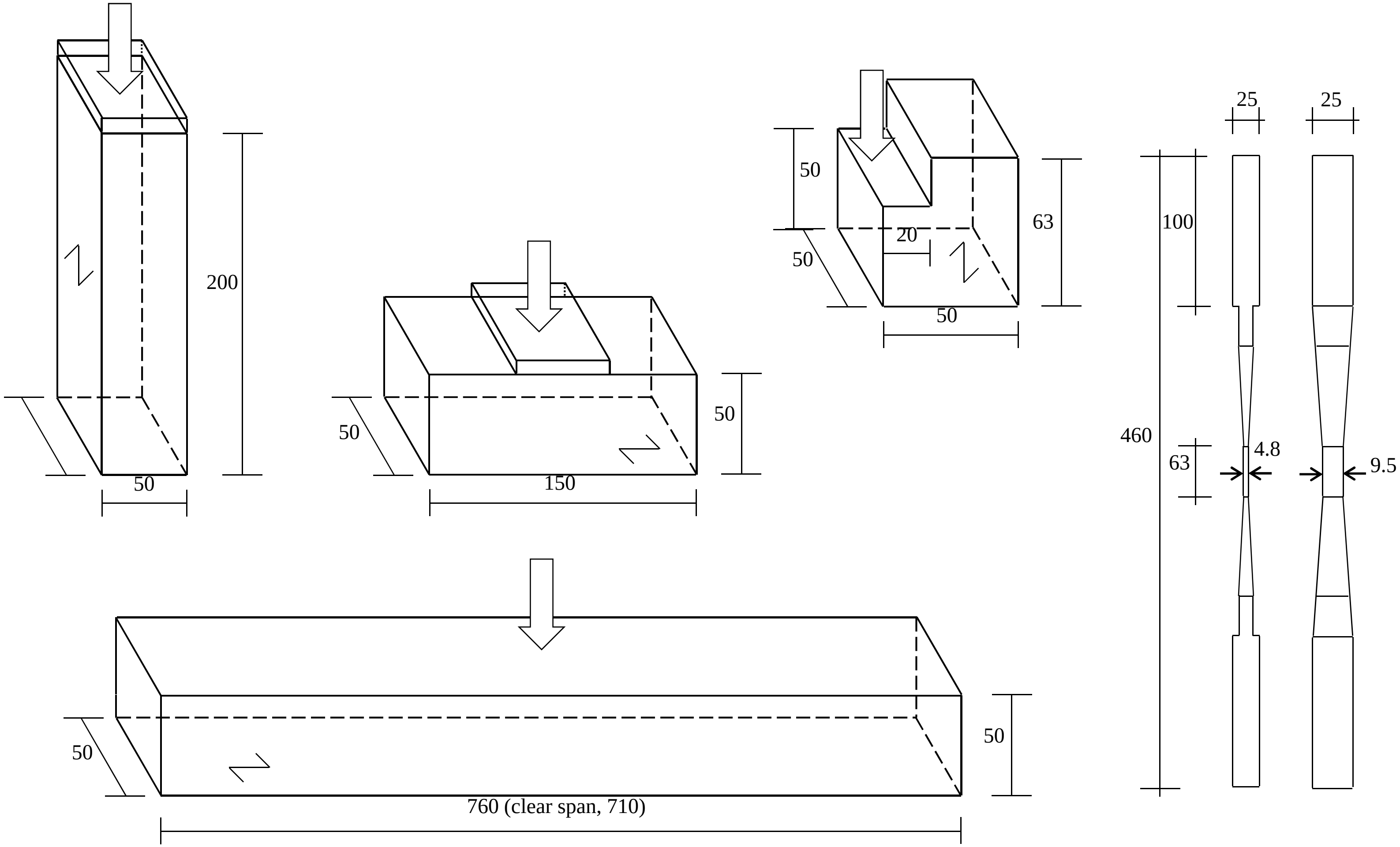


Figure 1.—Experimental model of Princes Risborough stress-grading machine. 1962

Lumber grading

- The majority of sawn lumber is graded by visual inspection, and material graded in this way is known as visually graded structural lumber. Knots; grain direction; growth rings; wood-destroying organism; splitting; etc.
- A small percentage is machine stress rated by subjecting each piece of wood to a non-destructive test. As lumber comes out of the mill, it passes through a series of rollers. In this process, a bending load is applied about the minor axis of the cross section, an the modulus of elasticity of each piece is measured.

Clear-wood tests (ASTM D143-94)



Strength properties

- The modulus of elasticity (E) are determined from bending rather than from an axial test. E_L includes an effect of shear deformation; E_L from bending test can be increased by 10% to remove this effect approximately.
- Possion's ratio: The ratio of transverse to the axial strain. The Poisson's ratios are denoted by μ_{LR}, μ_{RL}, μ_{LT}, μ_{TL}, μ_{RT}, μ_{TR}. The first letter of the subscript refers to direction of applied stress, and the second letter to direction of lateral deformation. Poisson's ratios vary within and between wood species and are affected by moisture content and specific gravity.
- Modulus of rigidity or shear modulus indicates the resistance to deflection of a member caused by shear stresses. The three moduli of rigidity denoted by G_{LR}, G_{LT}, G_{RT}. As with moduli of elasticity, the moduli of rigidity vary within and between wood species and are affected by moisture content and specific gravity.

Strength properties

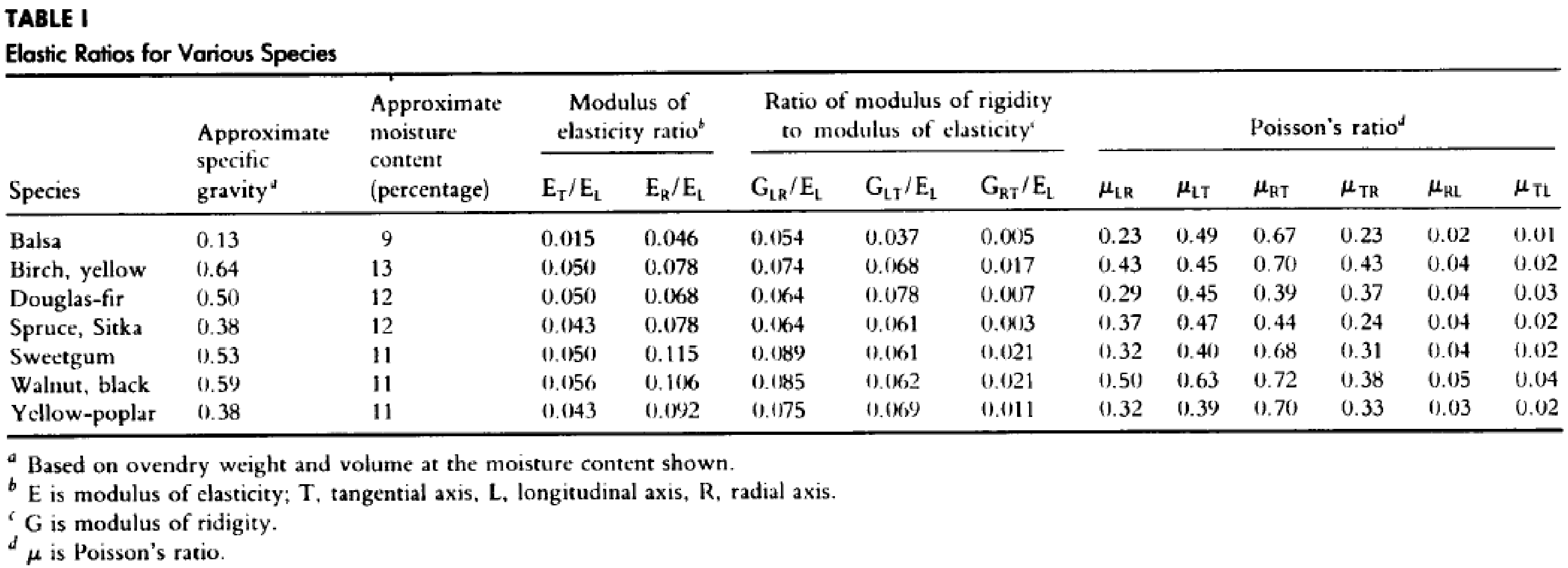


TABLE I

Elastic Ratios for Various Species

Species	Approximate specific gravity[a]	Approximate moisture content (percentage)	Modulus of elasticity ratio[b]		Ratio of modulus of rigidity to modulus of elasticity[c]			Poisson's ratio[d]					
			E_T/E_L	E_R/E_L	G_{LR}/E_L	G_{LT}/E_L	G_{RT}/E_L	μ_{LR}	μ_{LT}	μ_{RT}	μ_{TR}	μ_{RL}	μ_{TL}
Balsa	0.13	9	0.015	0.046	0.054	0.037	0.005	0.23	0.49	0.67	0.23	0.02	0.01
Birch, yellow	0.64	13	0.050	0.078	0.074	0.068	0.017	0.43	0.45	0.70	0.43	0.04	0.02
Douglas-fir	0.50	12	0.050	0.068	0.064	0.078	0.007	0.29	0.45	0.39	0.37	0.04	0.03
Spruce, Sitka	0.38	12	0.043	0.078	0.064	0.061	0.003	0.37	0.47	0.44	0.24	0.04	0.02
Sweetgum	0.53	11	0.050	0.115	0.089	0.061	0.021	0.32	0.40	0.68	0.31	0.04	0.02
Walnut, black	0.59	11	0.056	0.106	0.085	0.062	0.021	0.50	0.63	0.72	0.38	0.05	0.04
Yellow-poplar	0.38	11	0.043	0.092	0.075	0.069	0.011	0.32	0.39	0.70	0.33	0.03	0.02

[a] Based on ovendry weight and volume at the moisture content shown.

[b] E is modulus of elasticity; T, tangential axis, L, longitudinal axis, R, radial axis.

[c] G is modulus of ridigity.

[d] μ is Poisson's ratio.

Hardwood:

Walnut, black; Yellow-poplar; Birch, yellow; Balsa; Sweetgum; Oak; Aspen; Ash, white; Maple; Elm; Alder, red; Hackberry.

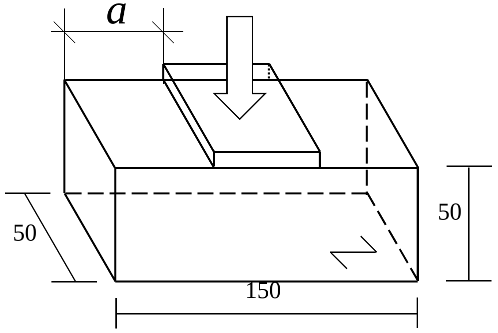
Softwood:

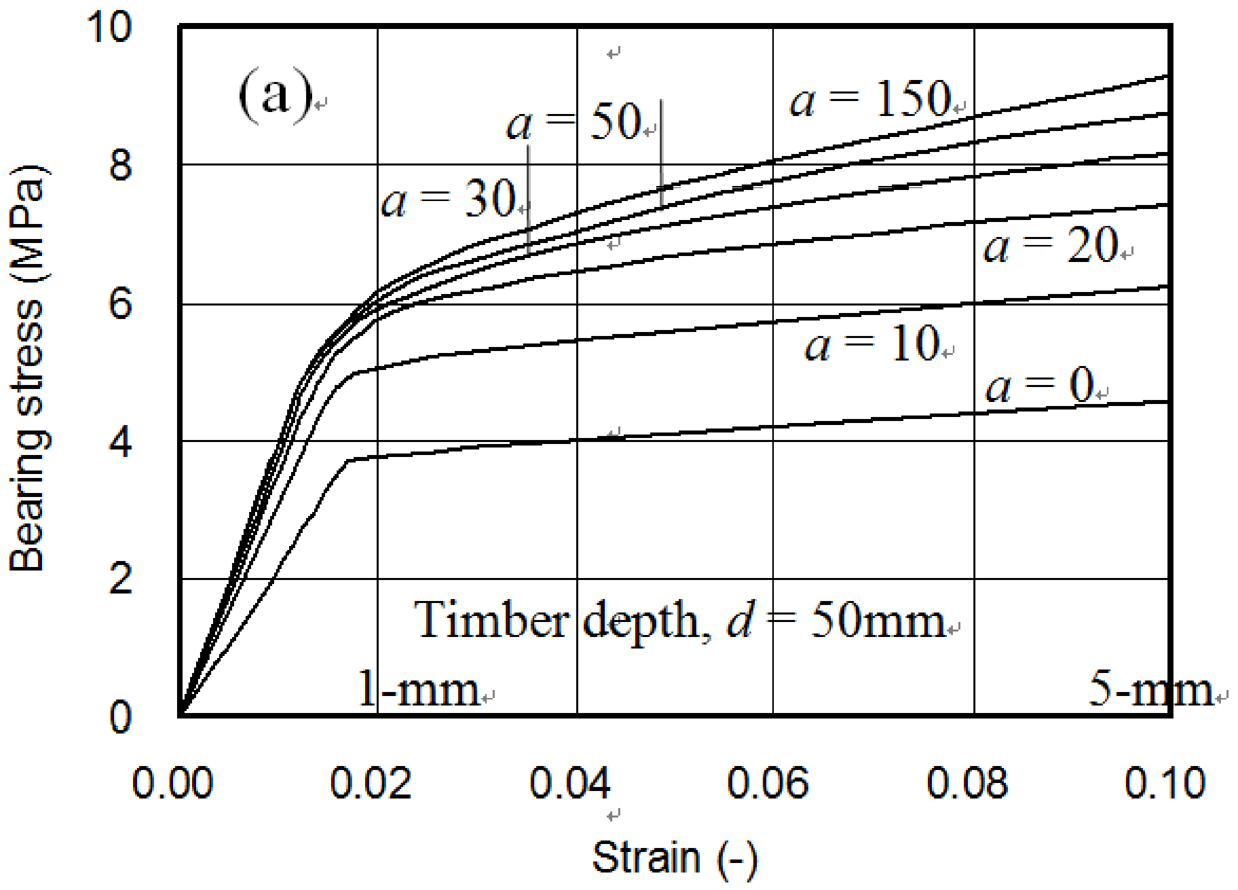
Douglas-fir; Spruce, Sitka; SPF (spruce, (white) pine, (Douglas) fir); Hemlock; Larch; Redwood.

Strength properties

- Modulus of Rupture (MOR): The maximum load-carrying capacity of a member in bending and is proportional to maximum moment borne by the specimen. Bending stresses are induces when a material is used as beams, such as in a floor or rafter system.
- Compressive strength parallel to grain: Maximum stress sustained by a compression-parallel-to-grain specimen having a ratio of length to the least dimension of less than 11.
- Compressive strength perpendicular to grain: Stress at proportional limit. There is no clearly defined ultimate stress for this property. Once the hollow cell cavities collapsed, wood is quite strong because no void space exists.

Strength properties

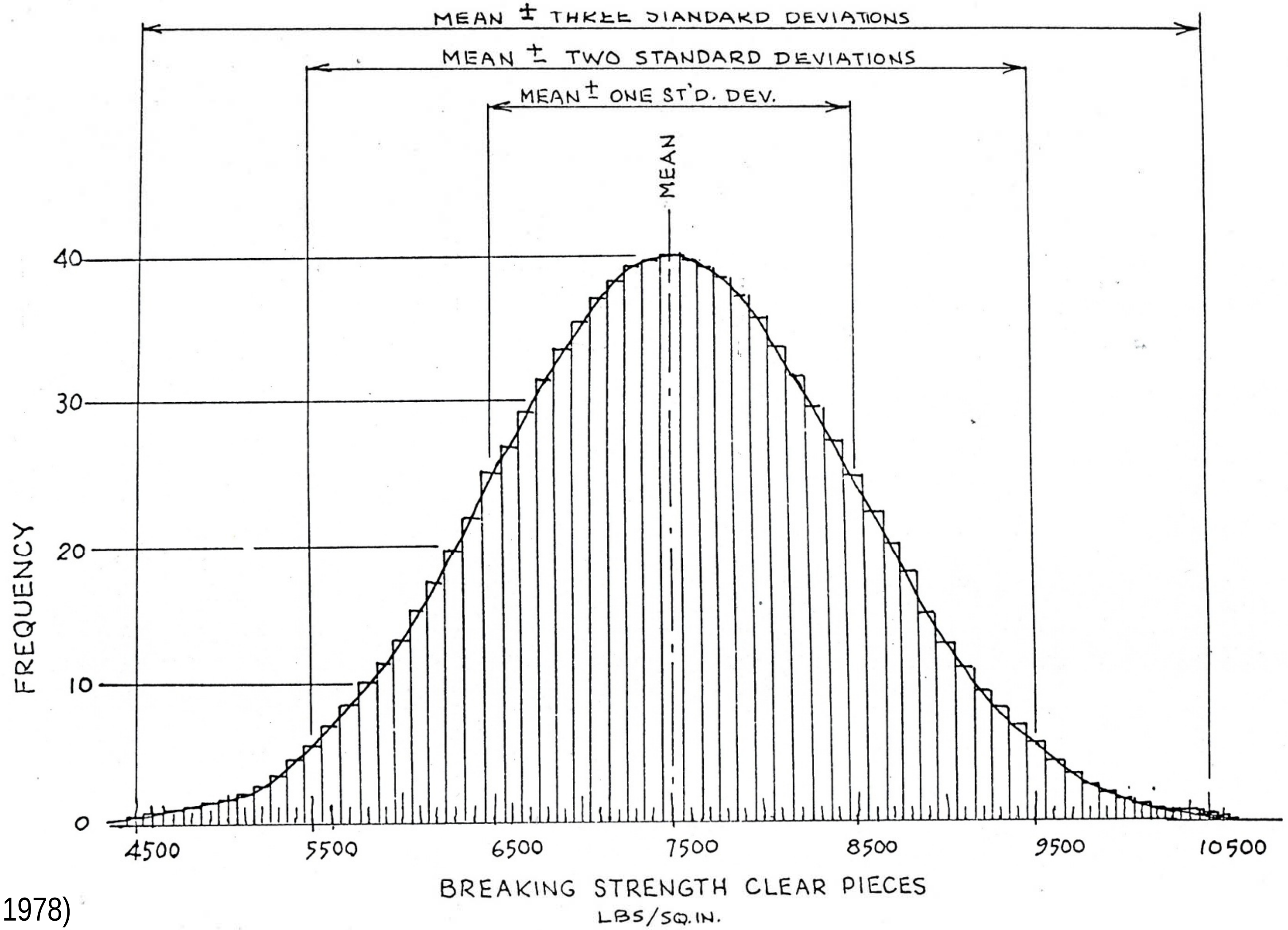




Strength properties

- Tensile strength parallel to grain: Maximum tensile stress sustained in direction parallel to grain. Wood is very strong in tension parallel to grain. Failure occurs by a complex combination of two modes: cell-to-cell slippage and cell wall failure.
- In contrast, wood is relatively weak when loaded in tension perpendicular to grain. Stresses in this direction act perpendicular to the cell length and produce splitting or cleavage along the grain. Design situation that induce this stress should be avoided.
- Shear strength parallel to grain: Ability to resist internal slipping of one part upon another part along the grain. When used as a beam, wood is exposed to compression stress on one surface of the beam and tensile stress on the other. This opposition of stress results in a shearing action termed as horizontal shear.

Characteristic values



(in Hoyle, 1978)

Characteristic values

- Discrepancies between a design and its performance may arise out of a poor understanding of the variability of the material.
- Wood, like all other materials, displays a characteristics variability. In its simple form, one might consider the frequency distribution.

Exclusion level	Number of STD	Exclusion value
50%	0	Mean
20%	0.68	Mean – 0.68xSTD
10%	1.28	Mean – 1.28xSTD
5%	1.65	Mean – 1.65xSTD
2.5%	1.96	Mean – 1.96xSTD
1%	2.33	Mean – 2.33xSTD
0.1%	3.00	Mean – 3.00xSTD

RSNI-2002 strength class

Machine stress rate at MC of 15%

Strength class	E_w	F_b	$F_{t//}$	$F_{c//}$	F_v	$F_{c\perp}$
E26	25000	66	60	46	6.6	24
E25	24000	62	58	45	6.5	23
E24	23000	59	56	45	6.4	22
E23	22000	56	53	43	6.2	21
E22	21000	54	50	41	6.1	20
E21	20000	50	47	40	5.9	19
E20	19000	47	44	39	5.8	18
E19	18000	44	42	37	5.6	17
E18	17000	42	39	35	5.4	16
E17	16000	38	36	34	5.4	15
E16	15000	35	33	33	5.2	14
E15	14000	32	31	31	5.1	13
E14	13000	30	28	30	4.9	12
E13	12000	27	25	28	4.8	11
E12	11000	23	22	27	4.6	11
E11	10000	10	19	25	4.5	10
E10	9000	18	17	24	4.3	9

RSNI-2002 strength class

- The modulus of elasticity (E_w) given in the previous table can be estimated by this following equation,

  $$E_w = 16500 G^{0.7}$$

  where *G* is specific gravity at MC equals to 15%.

- Specific gravity in the above equation can be evaluated using wood specimen at *m*% MC (*m* should not exceed 30%).

  1. Compute moisture content, *m*%;
  2. Compute density at *m*% MC, ρ in kg/m^3;
  3. Calculate specific gravity at *m*% MC;

  $$G_m = \frac{\rho}{\left[1000\left(1 + m/100\right)\right]}$$

RSNI-2002 strength class

- 3. Calculate specific gravity at *m*% MC;

$$G_m = \frac{\rho}{\left[1000\left(1 + m/100\right)\right]}$$

- 4. Calculate basis specific gravity (G_b);

$$G_b = \frac{G_m}{\left(1 + 0.265aG_m\right)};\ a = \frac{30 - m}{30}$$

- 5. Lastly, define specific gravity at 15% MC as

$$G = \frac{G_b}{\left(1 - 0.133G_b\right)}$$

Example: given that W_i = 1.6 gr, W_f = 1.3 gr, and V_i = 2 cm^3; compute *G*?

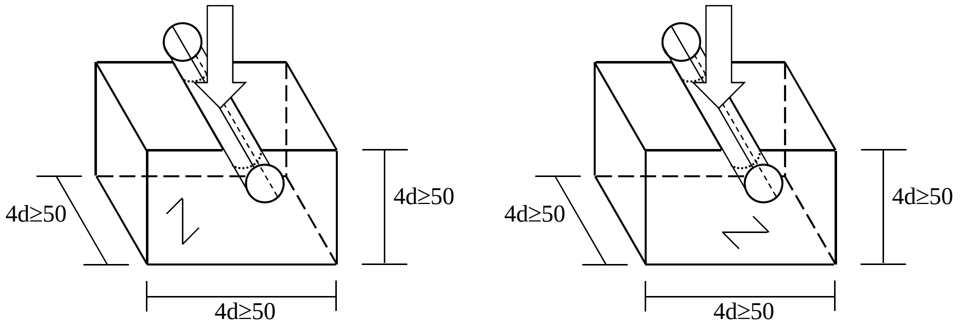
European strength class

	Softwood												Hardwood					
	C14	C16	C18	C20	C22	C24	C27	C30	C35	C40	C45	C50	D30	D35	D40	D50	D60	D70
MOR	14	16	18	20	22	24	27	30	35	40	45	50	30	35	40	50	60	70
$E_{0,mean}$	7000	8000	9000	9500	10000	11000	11500	12000	13000	14000	15000	16000	10000	10000	11000	14000	17000	20000
ρ_{mean}	350	370	380	390	410	420	450	460	480	500	520	550	640	670	700	780	840	1080

	Softwood												Hardwood					
	C14	C16	C18	C20	C22	C24	C27	C30	C35	C40	C45	C50	D30	D35	D40	D50	D60	D70
$F_{t,0,k}$	8	10	11	12	13	14	16	18	21	24	27	30	18	21	24	30	36	42
$F_{t,90,k}$	0.4	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
$F_{c,0,k}$	16	17	18	19	2.0	21	22	23	25	26	27	29	23	25	26	29	32	34
$F_{c,90,k}$	2.0	2.2	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3.1	3.2	8	8.4	8.8	9.7	10.5	13.5
$F_{v,k}$	1.7	1.8	2.0	2.2	2.4	2.5	2.8	3.0	3.4	3.8	3.8	3.8	3.0	3.4	3.8	4.6	5.3	6.0
G_{mean}	0.44	0.5	0.56	0.59	0.63	0.69	0.72	0.75	0.81	0.88	0.94	1.0	0.6	0.65	0.7	0.88	1.06	1.25

Dowel bearing strength

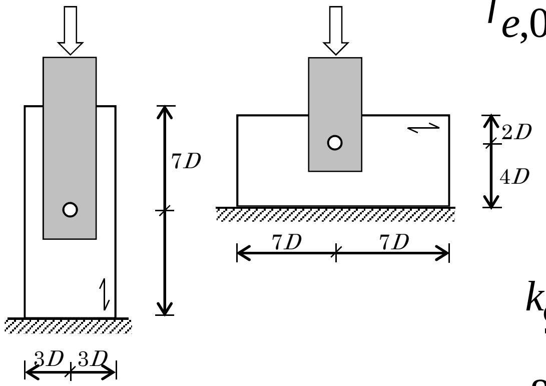
ASTM D5764 (half-hole test)



$$f_{e,0} = 77.25G \qquad f_{e,90} = 212G^{1.45}d^{-0.5}$$

$$f_{e,\alpha} = \frac{f_{e,0}\,f_{e,90}}{\left(f_{e,0}\sin^2\alpha + f_{e,90}\cos^2\alpha\right)}$$

EN 383 (full-hole test)

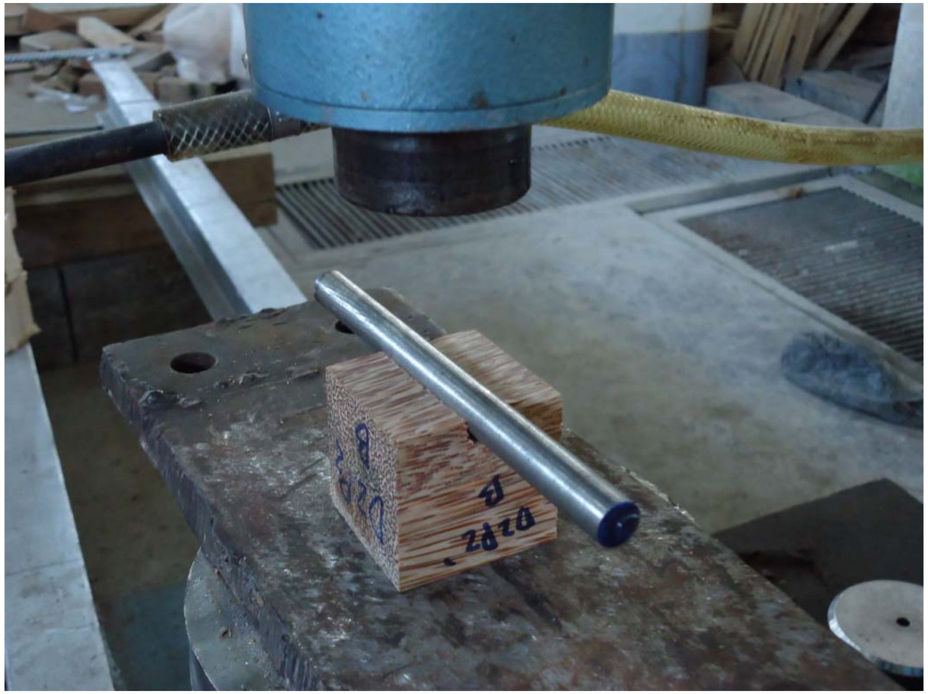


$$f_{e,0} = 82(1-0.01d)G$$

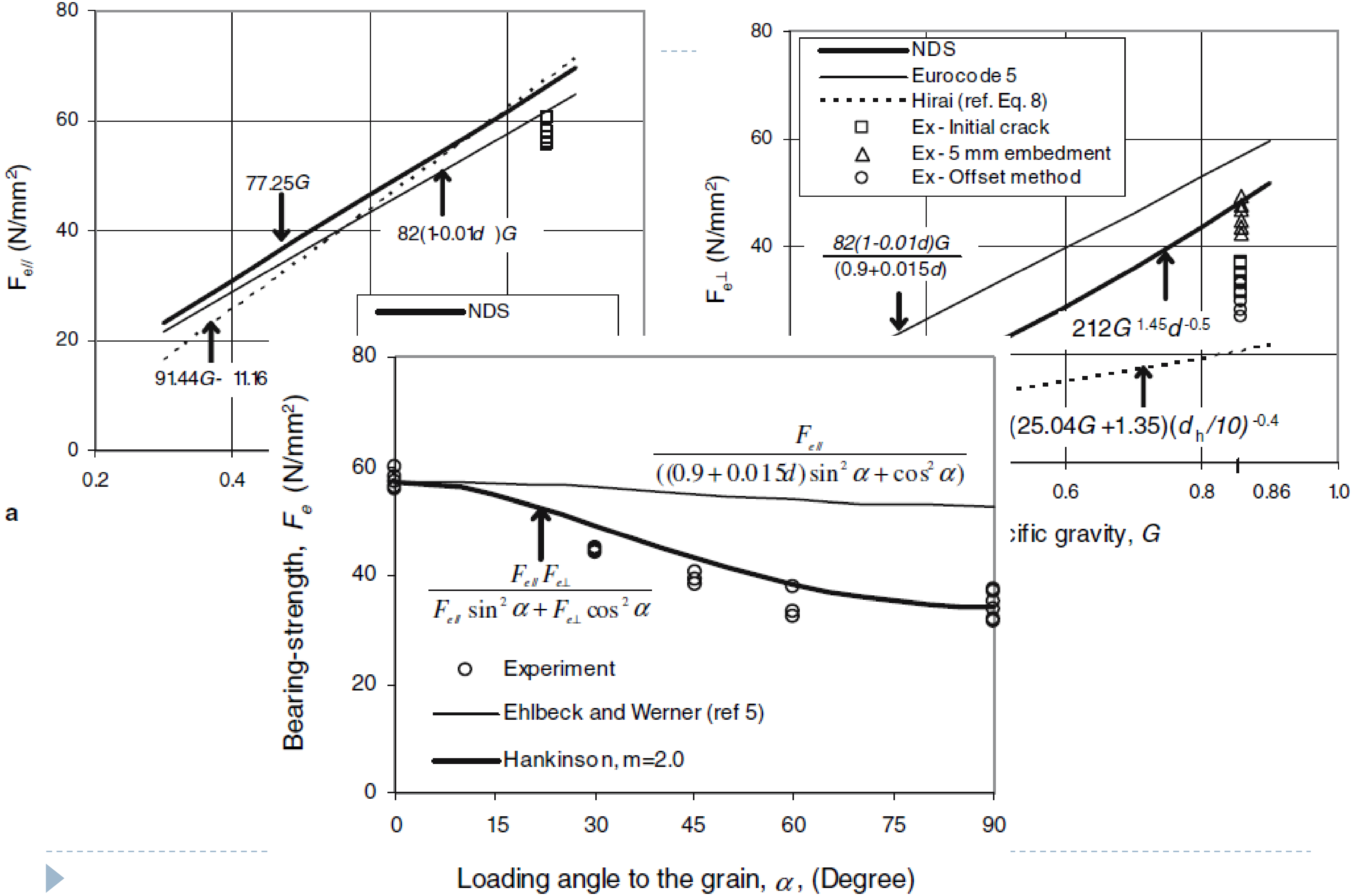
$$f_{e,90} = \frac{f_{e,0}}{k_{90}}$$

$$k_{90} = 0.9 + 0.015d$$

$$f_{e,\alpha} = \frac{82(1-0.01d)G}{\left(k_{90}\sin^2\alpha + \cos^2\alpha\right)}$$



Dowel bearing strength



Load duration factor

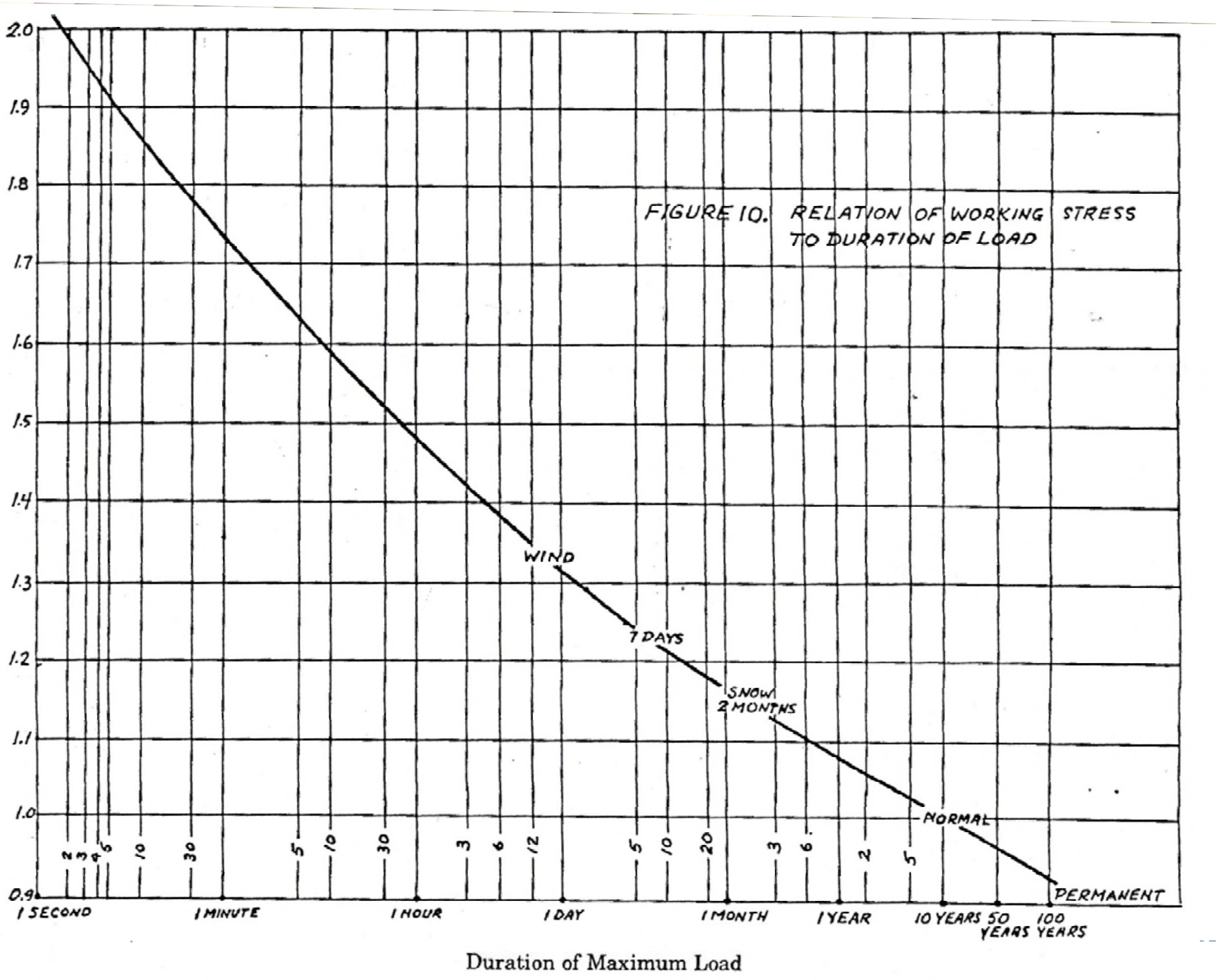


FIGURE 10. RELATION OF WORKING STRESS TO DURATION OF LOAD

Load duration factor

- Ordinarily one might assumed that if a structure is proof tested to the full service loading without any evidence of instability or failure, it could be relied upon to carry that load indefinitely. In the case of wood structures this assumption can be false, because the strength properties of wood are time-dependent.
- Clear wood (defect-free specimen) strength values are for a very special condition of loading, i.e., zero to ultimate, in five minutes. This is called “short-term” loading.
- Allowable stress for short-term loading is 164% of the 10-year load strength, and 182% of the permanent load strength (100-year).

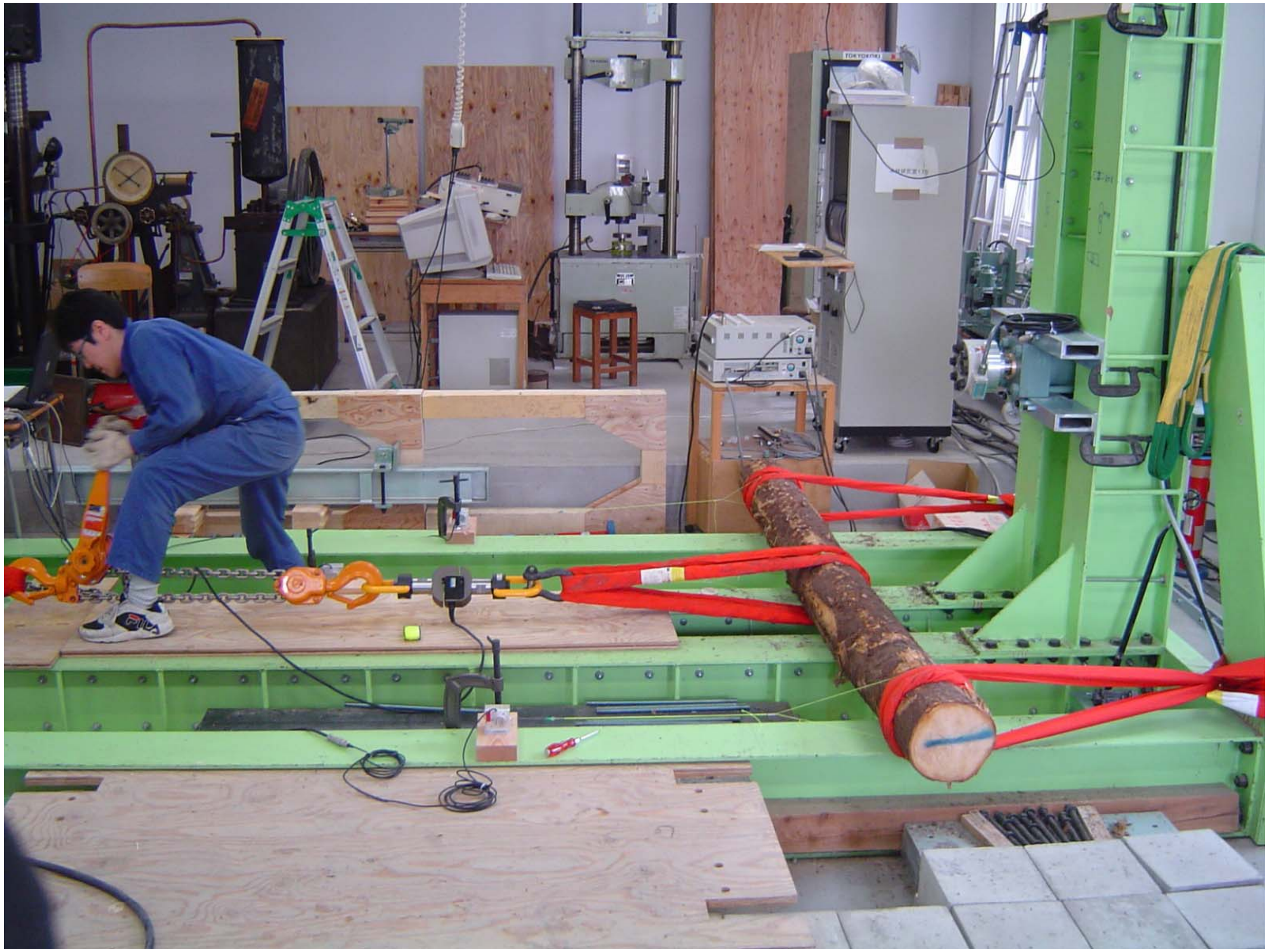
Load duration adjustment factor (RSNI-2002)

Loading combination	λ
1.4D	0.6
1.2D + 1.6L + 0.5(L_a or H)	0.7; 0.8; 1.25 (depends the source of L)
1.2D + 1.6(L_a or H) + (0.5L or 0.8W)	0.8
1.2D + 1.3W + 0.5L + 0.5(L_a or H)	1.0
1,2D ± 1.0E + 0.5L	1.0
0.9D ± (1.3W or 1.0E)	1.0

- Allowable stress for short-term loading is 170% of the 50-year load strength.

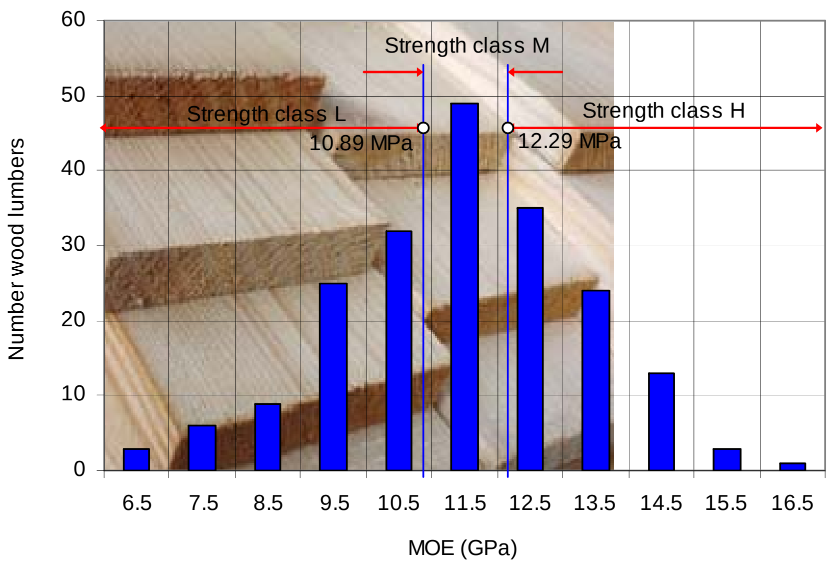
$$1/1.7=0.6$$

Tree Grading

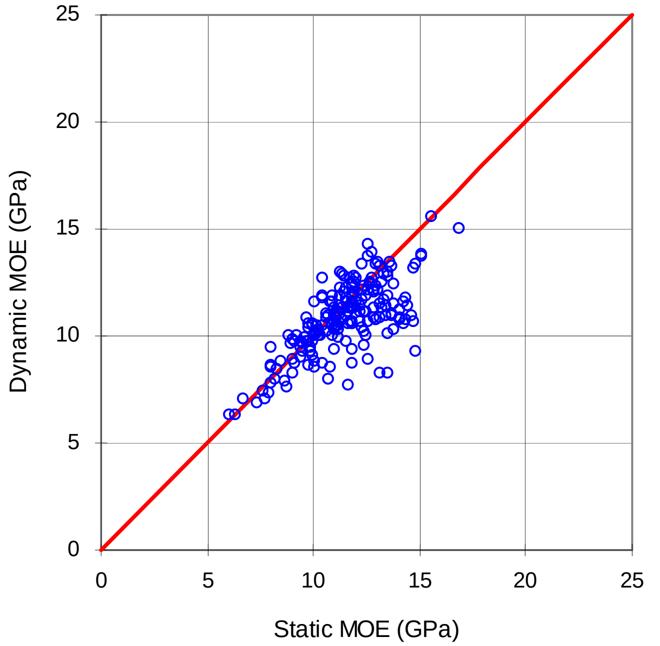


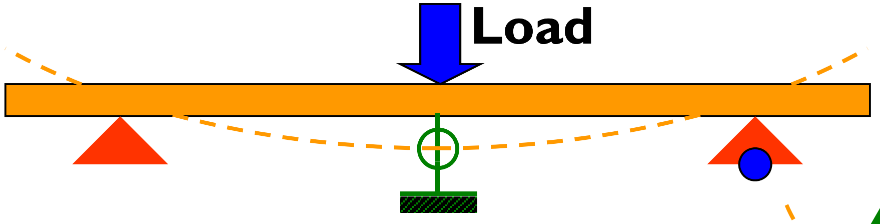
Static, Dynamic Modulus of Elasticity

MOE Distribution from 200 wood lumbers

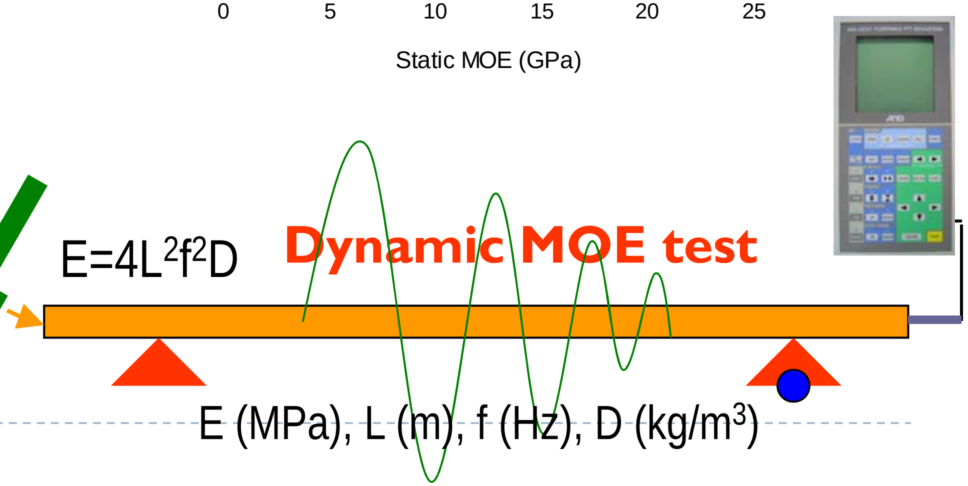


Comparison between static and dynamic MOE





Static MOE test



$E=4L^2f^2D$

Dynamic MOE test

E (MPa), L (m), f (Hz), D (kg/m^3)

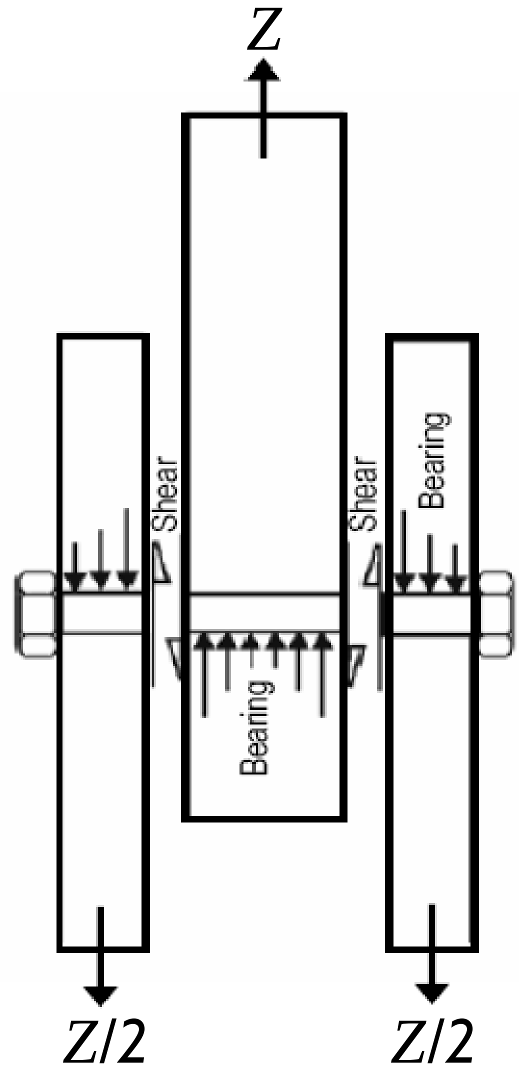
Content (week 4)

- Timber Engineering: Past and Present
- Wood Properties
- Mechanical Properties and Grading Techniques
- Theory of Timber Joint
- Nailed and Bolted Joints Analysis

Timber connections

- Timber joints play an essential role on static and dynamic performances of wooden structures.
- The ability to transfer load over a period of time, or during a seismic event, has a direct effect on the safety, reliability, and durability of timber structures.
- For many timber designers, bolts are still the first choice due to the fact that bolts are relatively easy and quick to install and require no surface preparation.
- Although easily installed, bolted connections are extremely complex regarding the response mechanism to various loadings, mainly inherent to the anisotropic and variable characteristics of the surrounding wood.

Lateral resistance of a bolted joint

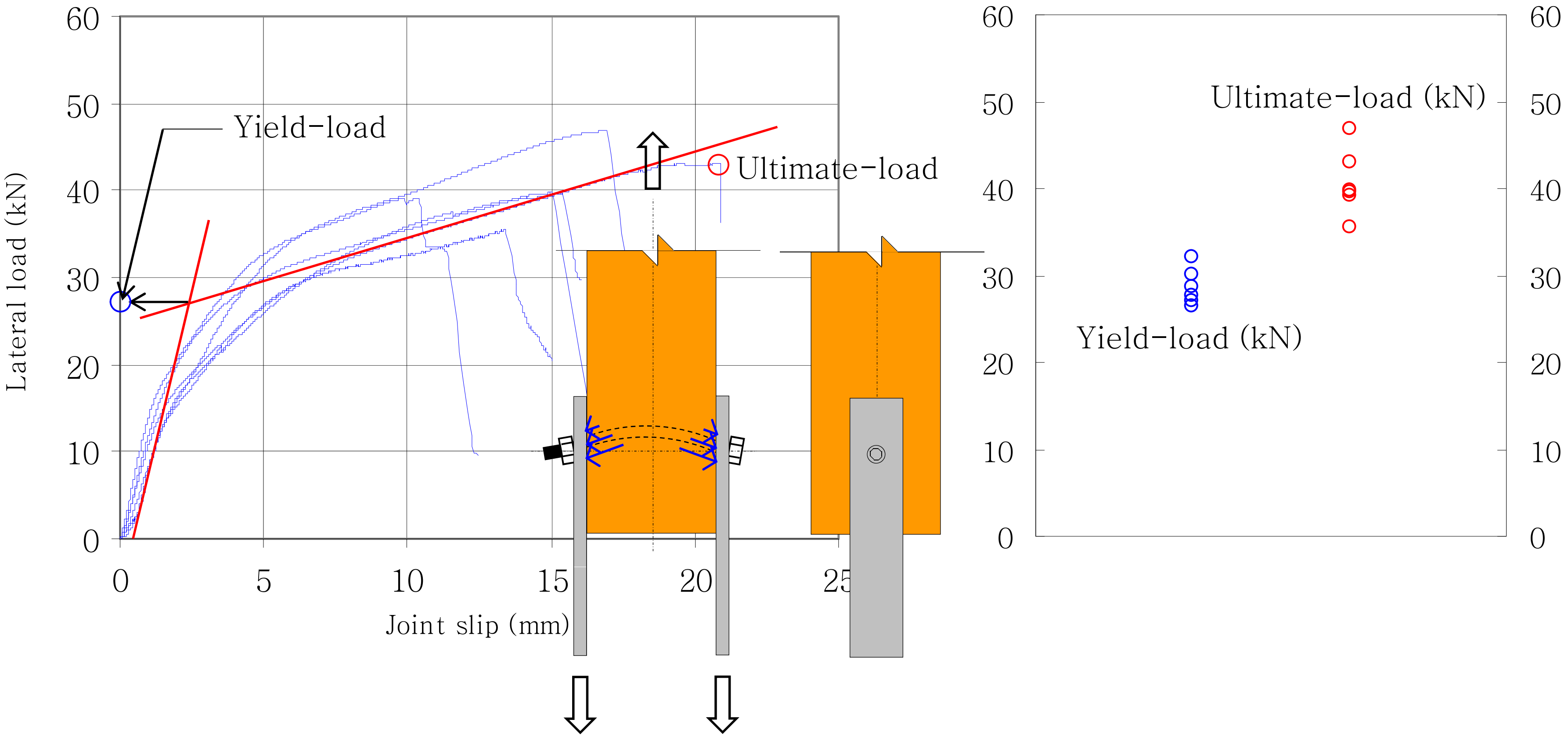


- ❑ Load carrying capacity (*Z*) of bolted timber joint can be evaluated using: Yield theory; Beam on elastic foundation theory; or Spring model based fracture mechanic approach.

- ❑ The yield theory gives relatively simple formulation and is adopted by many design standards such as: NDS of U.S.; Eurocode; Canadian code; Japanese code; and others.

- ❑ The yield theory does not take fastener axial force into consideration so that it naturally underestimates the joint strength.

Steel-wood-steel joints

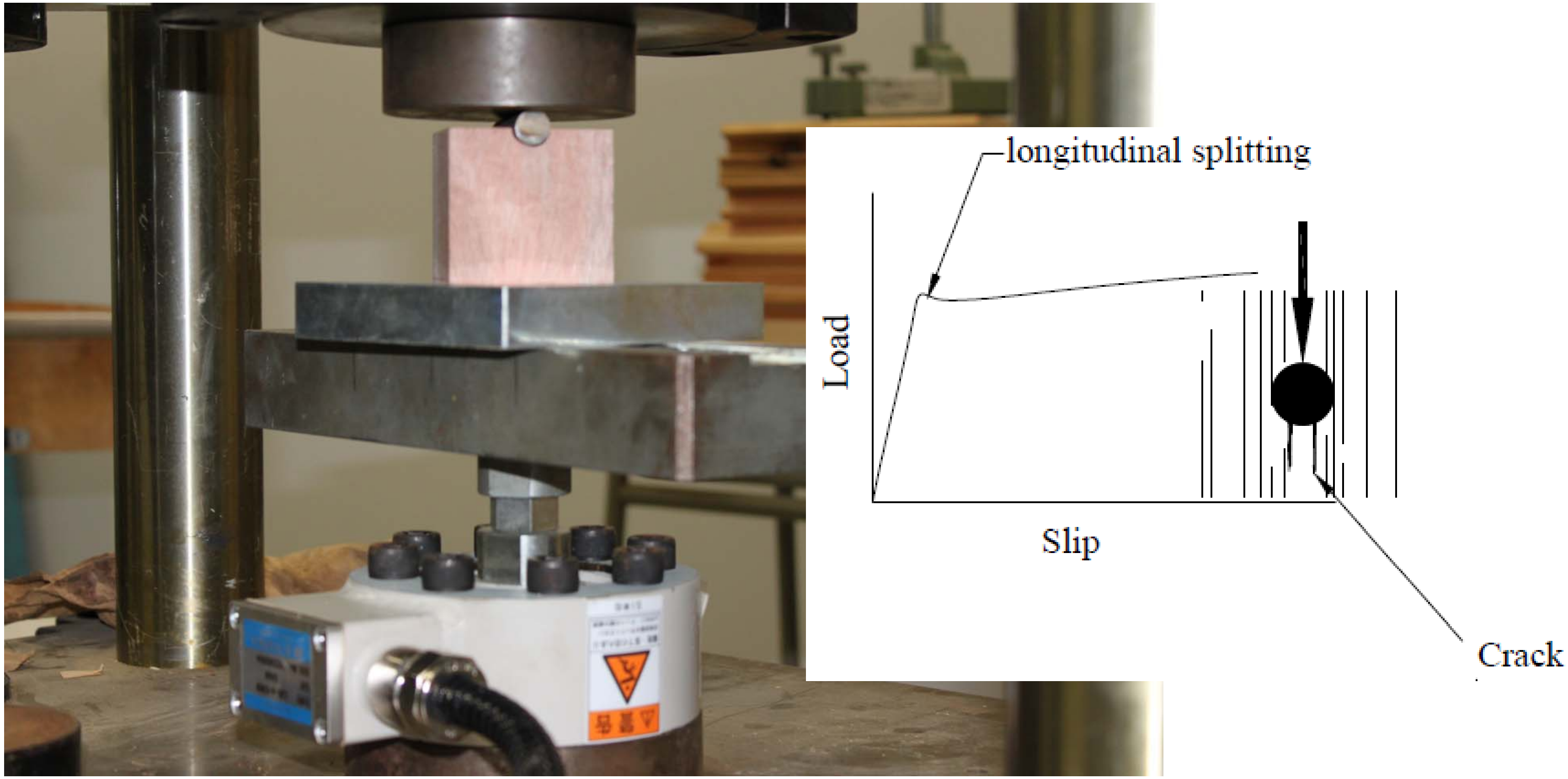


Fastener secondary axial force is well indicated by the slope of final stiffness of experimental load-slip curves. Some researchers associated this mechanism as “rope” or “cable” effect.

Joint yield load

- In the late 1940's Johansen utilized basic mechanics to predict yield load of a single-dowel type joint.
- Yield model based on Johansen's yield theory is often referred to European Yield Model (EYM).
- The yield theory provides an analysis method to predict the strength of dowel-type connections such as bolted, drift-pinned, or nailed joints.
- The analysis is derived based on equilibrium equation resulting the free body diagram of a dowel in wood member.
- Both wood member and fastener were assumed to behave perfectly rigid-plastic, ignoring the strain-hardening effect.

Embedding test



Dowel bending yield moment

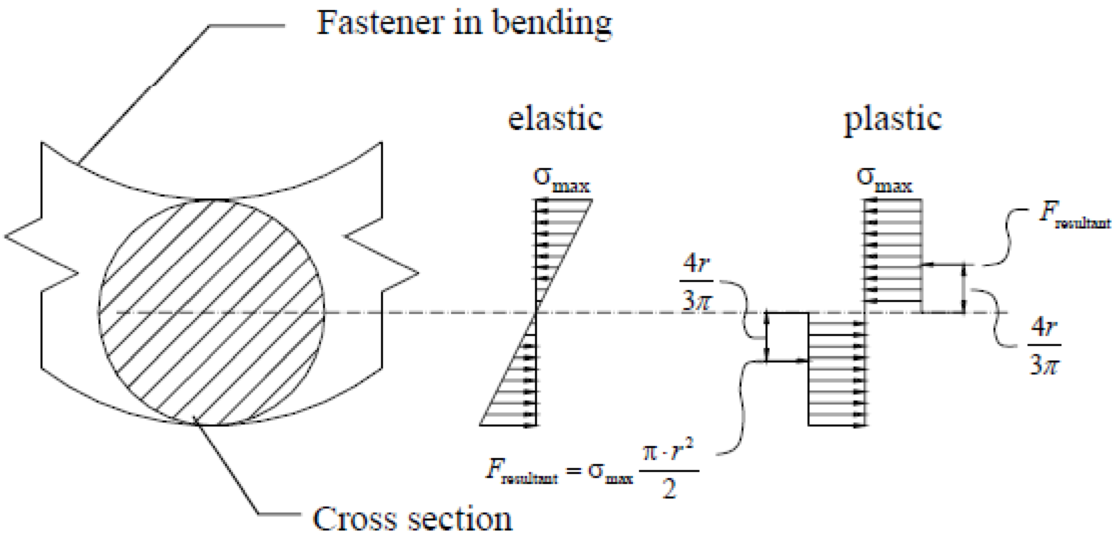


Figure 2.1: Illustration of elastic and plastic bending capacity of the faste

Elastic bending moment:

$$M_{el} = \sigma_{\max,\text{elastic}} \cdot \frac{\pi \cdot d^3}{32}$$

Plastic bending moment:

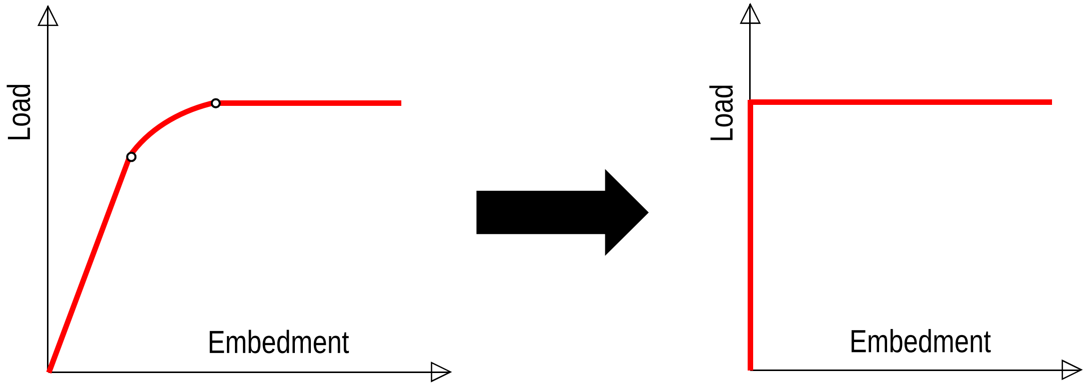
$$M_{pl} = \sigma_{\max,\text{plastic}} \frac{2 \cdot \pi \cdot r^2}{2} \cdot \frac{4 \cdot r}{3 \cdot \pi} = \sigma_{\max} \cdot \frac{d^3}{6}$$

Joint failure mode

- The yield theory assumed that the load carrying capacity of a dowel-type joints is attained when either:

  1) The dowel bearing (embedding) strength of the wood beneath the dowel is exceeded; or

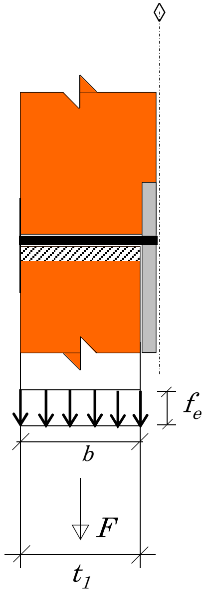
  2) one or more plastic hinges develop in the dowel.
- Based on these assumption, a series of failure modes was postulated.



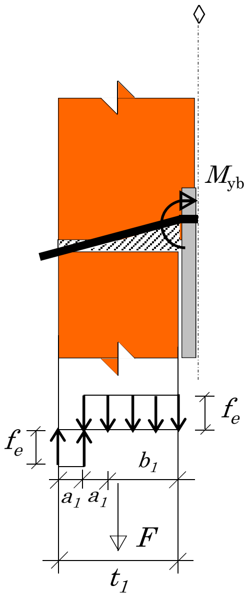
Rigid-plastic material model

Joint yield load

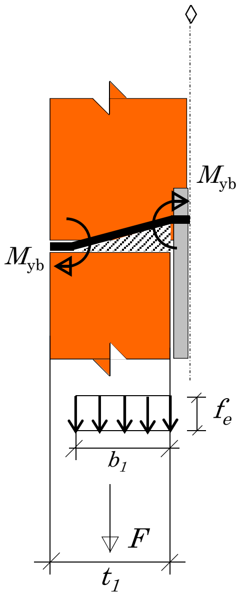
A. Wood-steel-wood Joint (Inserted steel plate timber joint)



$$F = f_e t_1 d$$



See next slide!!



$$2M_y = f_e b_1 d \frac{1}{2} b_1$$

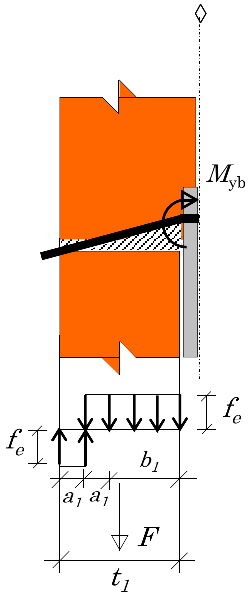
$$b_1 = \sqrt{\frac{2M_y}{f_e d}}$$

$$F = f_e d b_1$$

$$F = \sqrt{4M_y f_e d}$$

Joint yield load

A. Wood-steel-wood Joint (Inserted steel plate timber joint)



$$f_e a_1 d\left(b_1+\frac{3}{2}a_1\right)+M_y-f_e d\,\frac{1}{2}\left(b_1+a_1\right)^2=0$$

$$\text{Let: } 2a_1+b_1=t_1;\ \text{or } a_1=\frac{\left(t_1-b_1\right)}{2}$$

$$\left(b_1+\frac{3}{2}a_1\right)=\frac{1}{4}\left(b_1+3t_1\right);\quad \left(b_1+a_1\right)=\frac{1}{2}\left(b_1+t_1\right)$$

$$f_e d\,\frac{1}{2}\left(t_1-b_1\right)\frac{1}{4}\left(b_1+3t_1\right)+M_y-f_e d\,\frac{1}{8}\left(b_1+t_1\right)^2=0$$

$$b_1^2+2b_1t_1-\left(t_1^2+\frac{4M_y}{f_e d}\right)=0;\quad b_1=t_1\left(\sqrt{2+\frac{4M_y}{f_e d t_1^2}}-1\right)$$

$$F=f_e d b_1=f_e d t_1\left(\sqrt{2+\frac{4M_y}{f_e d t_1^2}}-1\right)$$

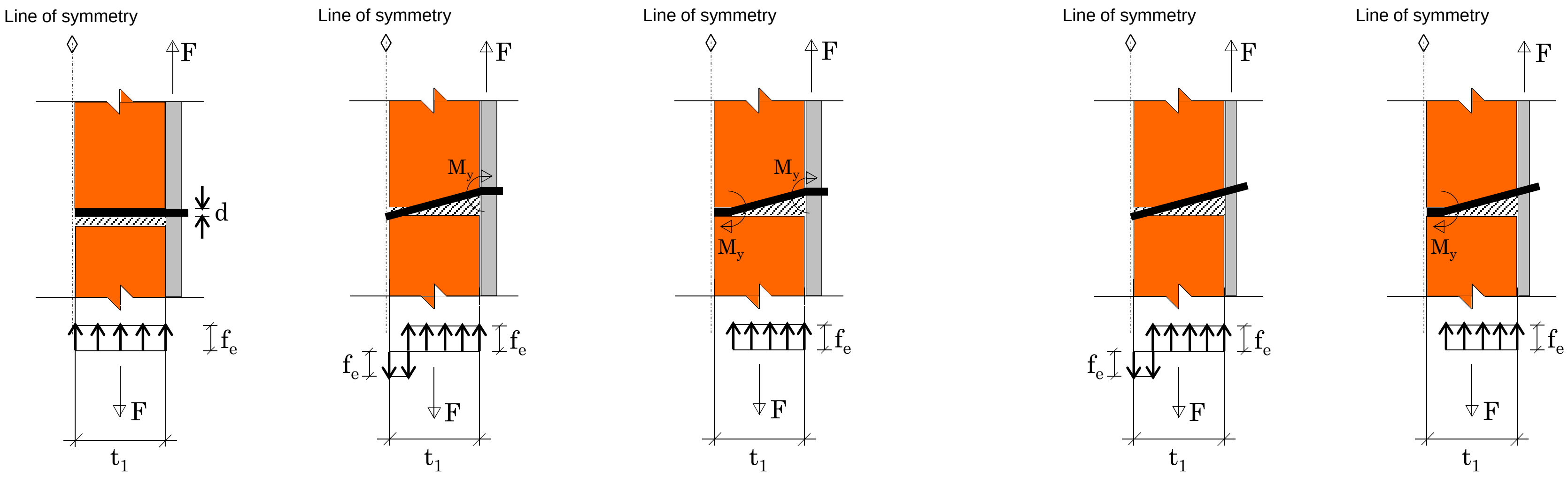
Joint yield load

Homework
(due date, next week)

B. Steel-wood-steel joint

Thick steel plate ($t_s \geq d$)

Thin steel plate ($t_s \leq d/2$)



$$F = f_e t_1 d$$

$$F = f_e d t_1 \left(\sqrt{2 + \frac{4M_y}{f_e d t_1^2}} - 1 \right)$$

$$F = 2\sqrt{M_y f_e d}$$

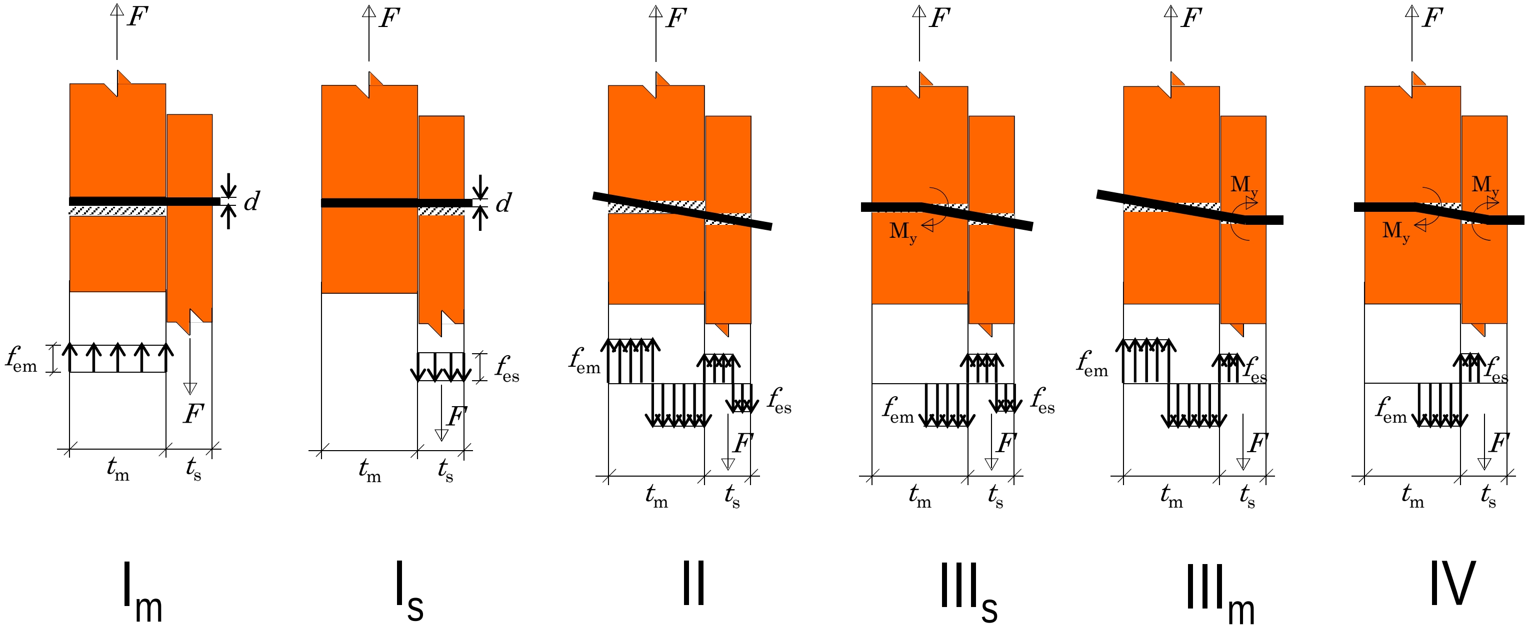
$$F = \left(\sqrt{2} - 1 \right) f_e t_1 d$$

$$F = \sqrt{2M_y f_e d}$$

Joint yield load

Homework
(due date, next week)

C. Wood-to-wood Joint



Joint yield load

$\mathrm{I_m} \quad \Longrightarrow \quad F = f_{em} t_m d$

$\mathrm{I_s} \quad \Longrightarrow \quad F = f_{es} t_s d$

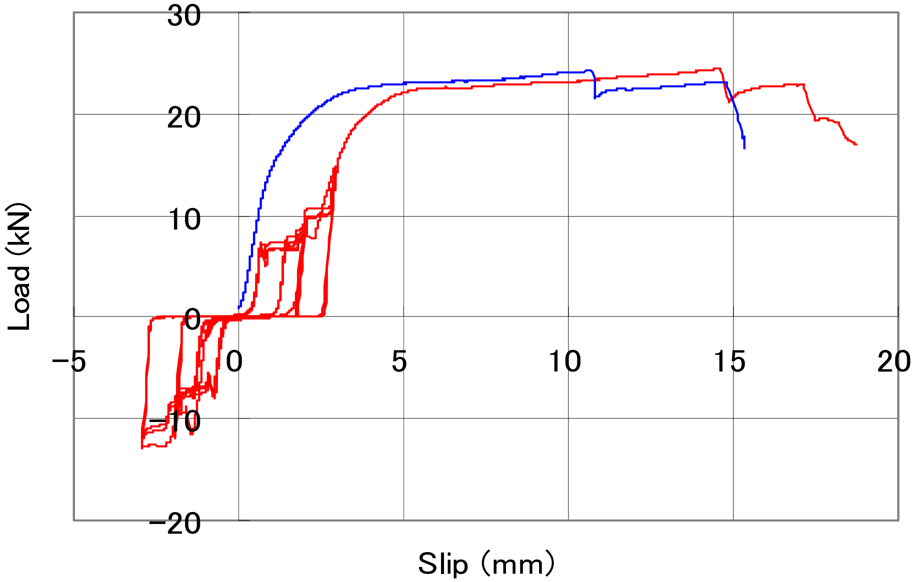
$$\mathrm{II} \quad \Longrightarrow \quad F = \frac{f_{es} t_s d}{1+\beta}\left\{\sqrt{\beta + 2\beta^2\left[1+\frac{t_m}{t_s}+\left(\frac{t_m}{t_s}\right)^2\right] + \beta^3\left(\frac{t_m}{t_s}\right)^2} - \beta\left(1+\frac{t_m}{t_s}\right)\right\}$$

$$\mathrm{III_s} \quad \Longrightarrow \quad F = \frac{f_{es} t_s d}{2+\beta}\left\{\sqrt{2\beta(1+\beta)+\frac{4\beta(2+\beta)M_y}{f_{es} t_s^2 d}}-\beta\right\}$$

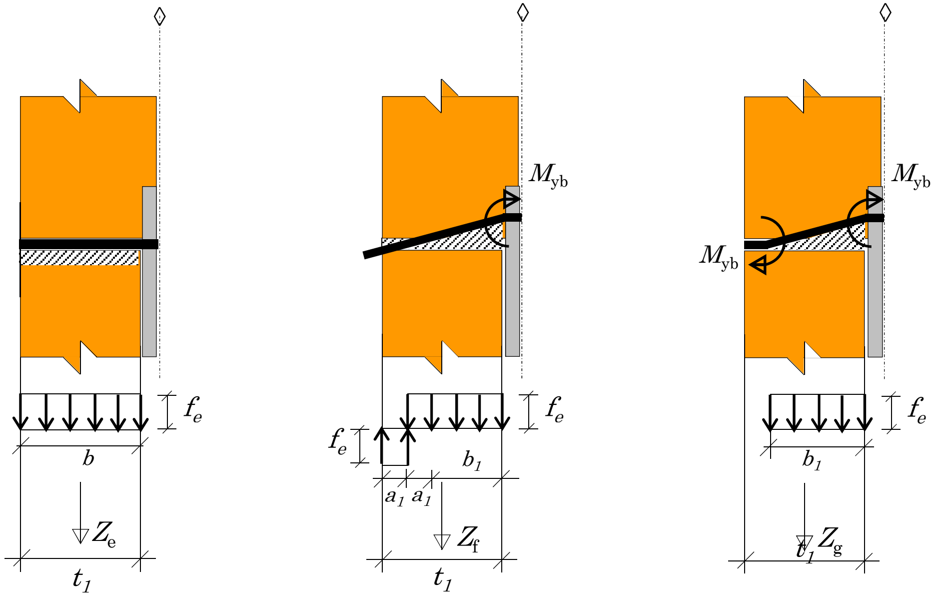
$$\mathrm{III_m} \quad \Longrightarrow \quad F = \frac{f_{es} t_m d}{1+2\beta}\left\{\sqrt{2\beta^2(1+\beta)+\frac{4\beta(1+2\beta)M_y}{f_{es} t_m^2 d}}-\beta\right\}$$

$$\mathrm{IV} \quad \Longrightarrow \quad F = \sqrt{\frac{2\beta}{1+\beta}}\sqrt{2M_y f_{es} d}$$

Joints with inserted plate



Example



Material properties:

$f_e = 26.62\ \text{N/mm}^2$

$t_1 = 47\ \text{mm}$

$D = 12\ \text{mm}$

$f_y = 413\ \text{N/mm}^2$

$M_{yb} = f_y D^3/6 = 118{,}944\ \text{Nmm}$

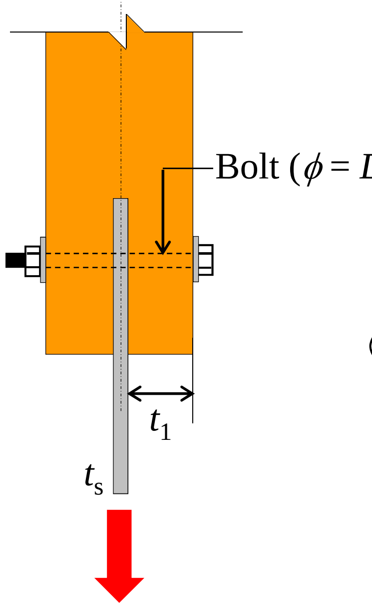
Lateral load:

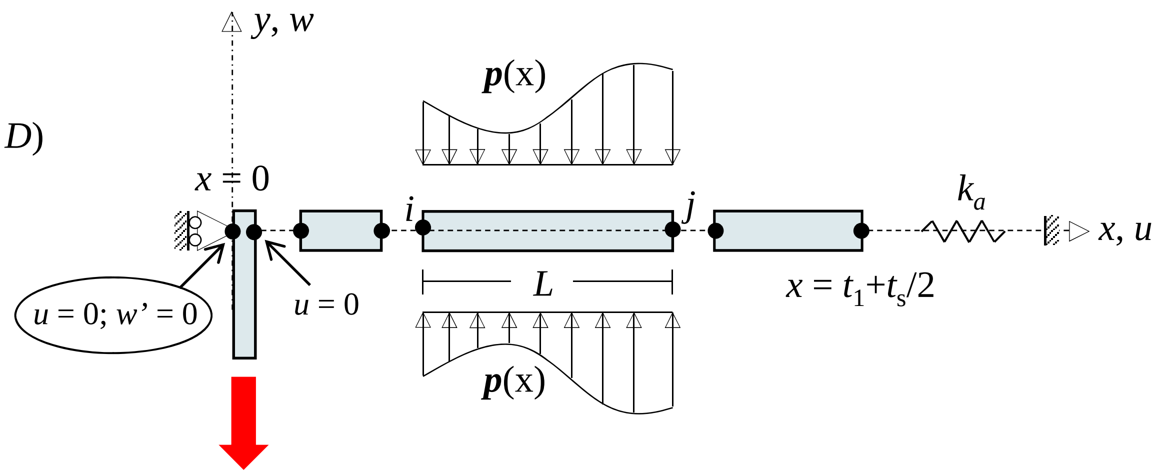
$$Z_e = f_e t_1 D = 30.03\ \text{kN}$$

$$Z_f = f_e D b_1 = f_e D t_1 \left(\sqrt{2 + \frac{4M_{yb}}{f_e D t_1^2}} - 1 \right) = 19.08\ \text{kN}$$

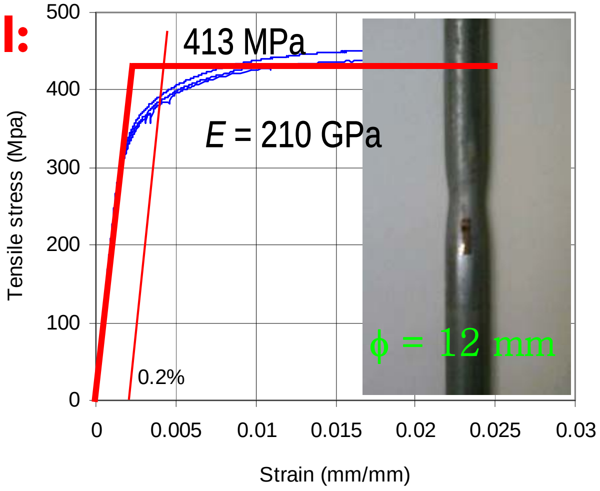
$$Z_g = \sqrt{4M_{yb} f_e D} = 24.66\ \text{kN}$$

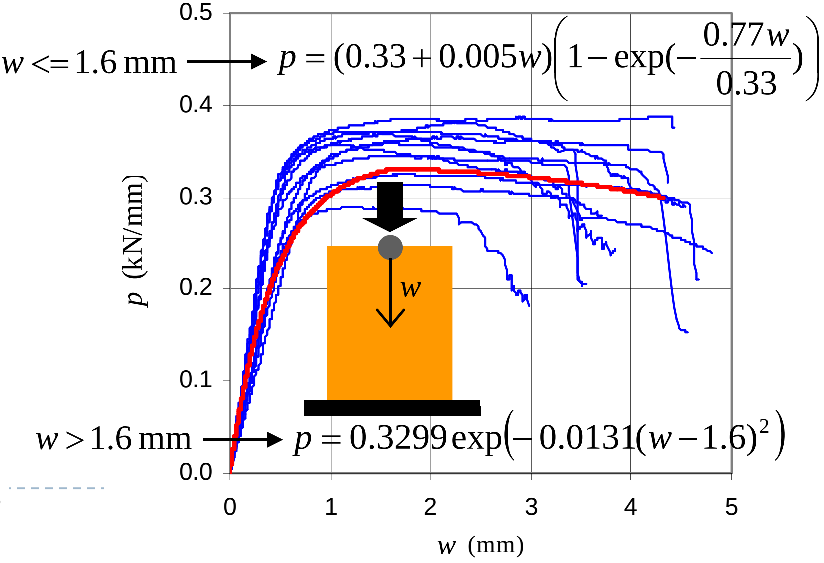
Beam on elasto-plastic foundation model





Material model:

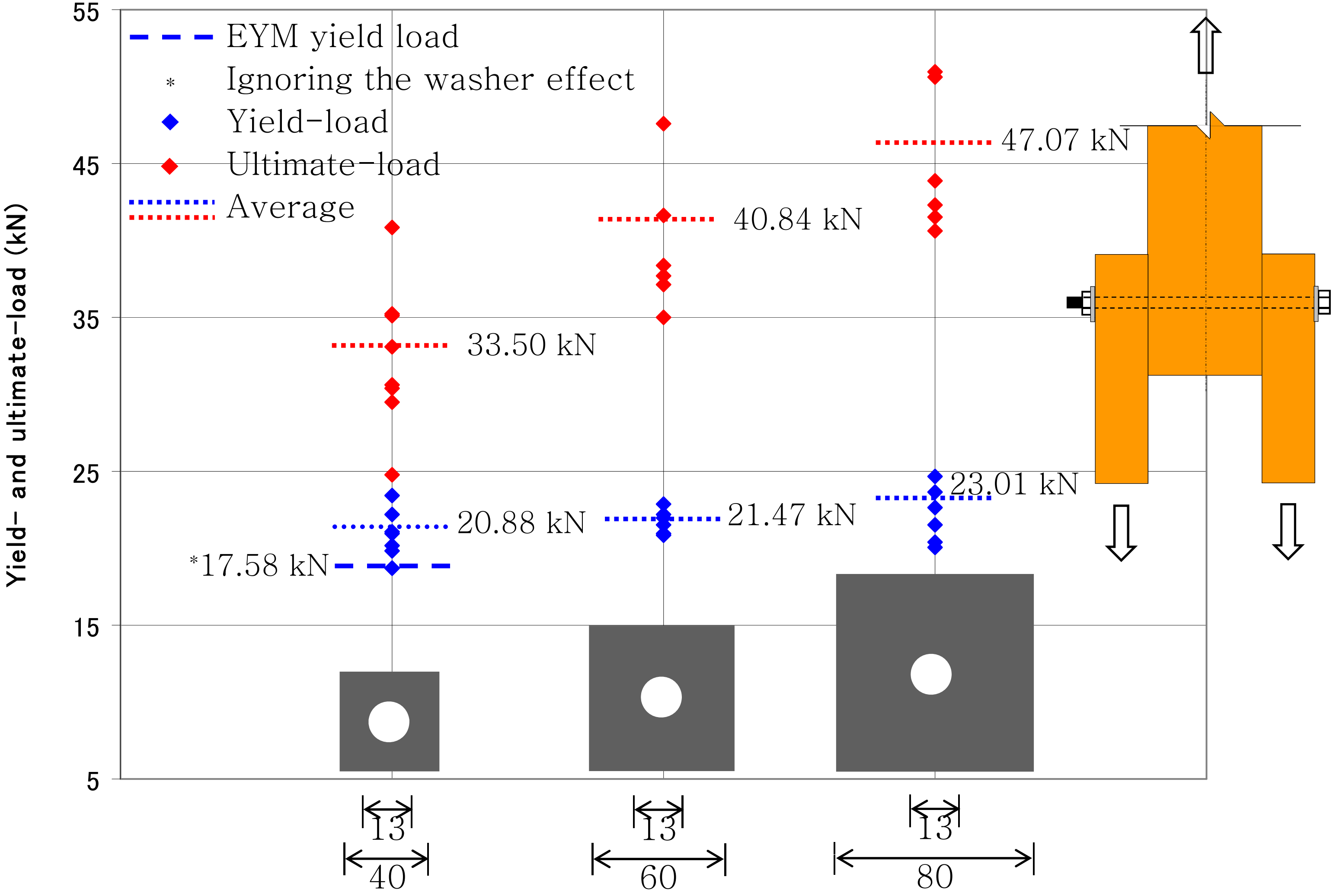




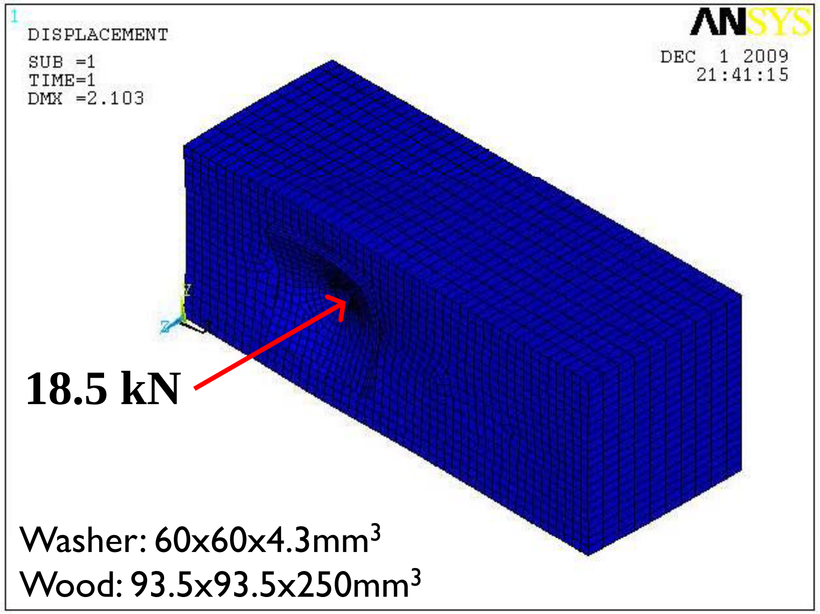
$w <= 1.6$ mm → $p = (0.33 + 0.005w)\left(1 - \exp(-\frac{0.77w}{0.33})\right)$

$w > 1.6$ mm → $p = 0.3299\exp\left(-0.0131(w-1.6)^2\right)$

Effect of washer dimension

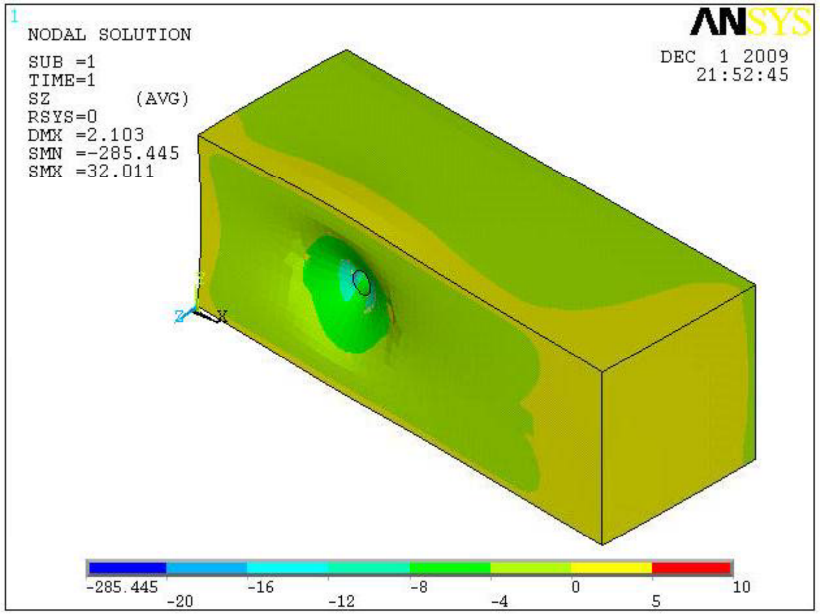


FE-Model of washer embedment



Washer: 60x60x4.3mm^3

Wood: 93.5x93.5x250mm^3



Material properties:

1. Wood member (*Picea jezoensis*) ⟶ *Anisotropic plasticity model*

Ex	4720	MPa	νxy	0.37
Ey	378	MPa	νyz	0.47
Ez	236	MPa	νxz	0.42
Gxy	337	MPa		
Gyz	33.7	MPa		
Gxz	317	MPa		

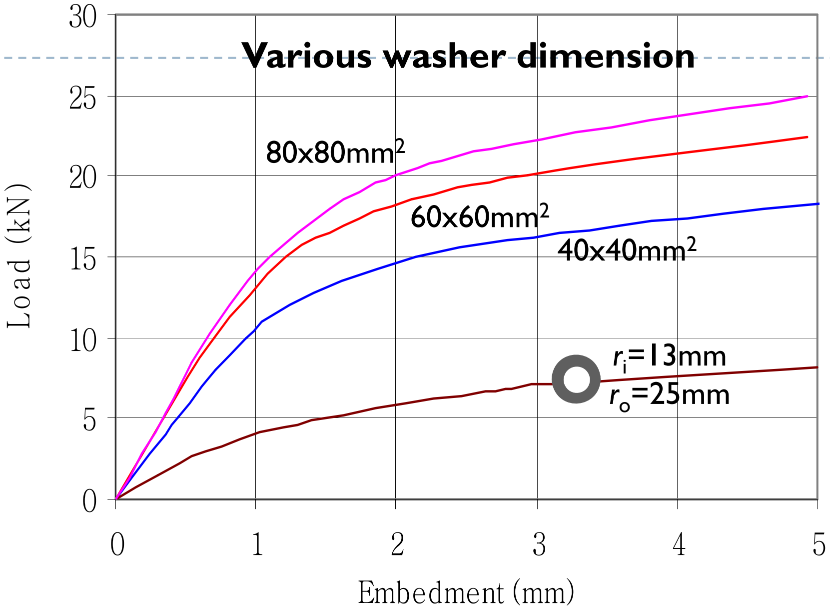
Et±x	140	MPa	Gtxy	10	MPa
Et±y	11	MPa	Gtyz	1	MPa
Et±z	7	MPa	Gtxz	9.5	MPa
σ±x	18	MPa	τxy	4.08	MPa
σ±y	3.73	MPa	τyz	0.93	MPa
σ±z	3.72	MPa	τxz	3.09	MPa

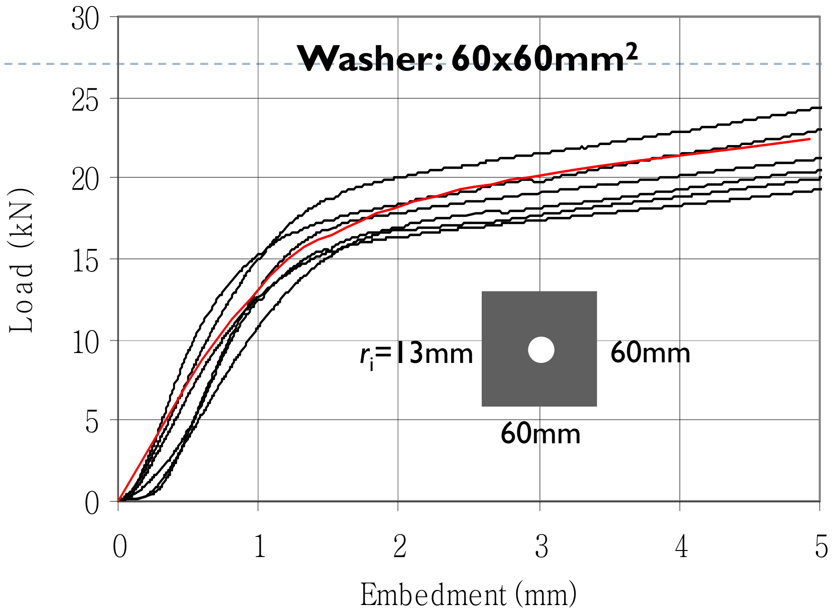
2. Steel plate

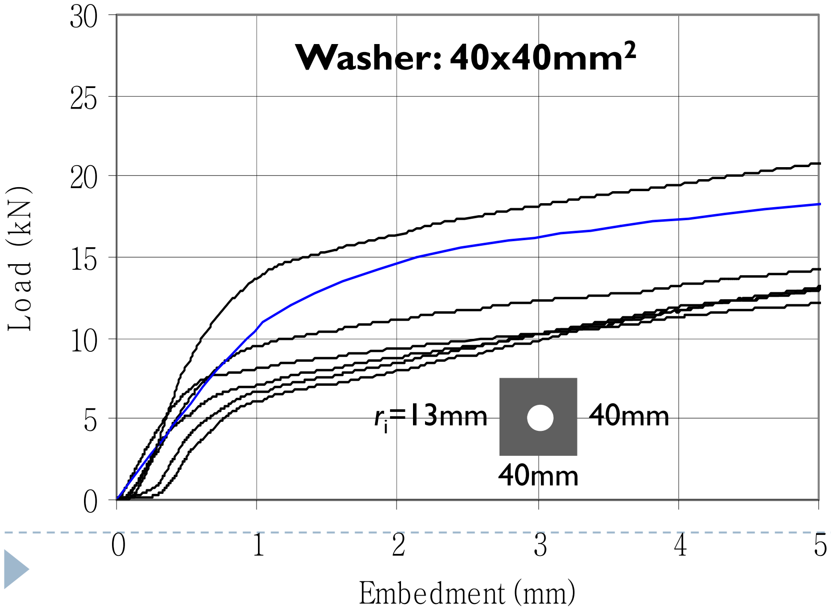
E	195.4	GPa	σ_{yield}	308.7	MPa	ν	0.3

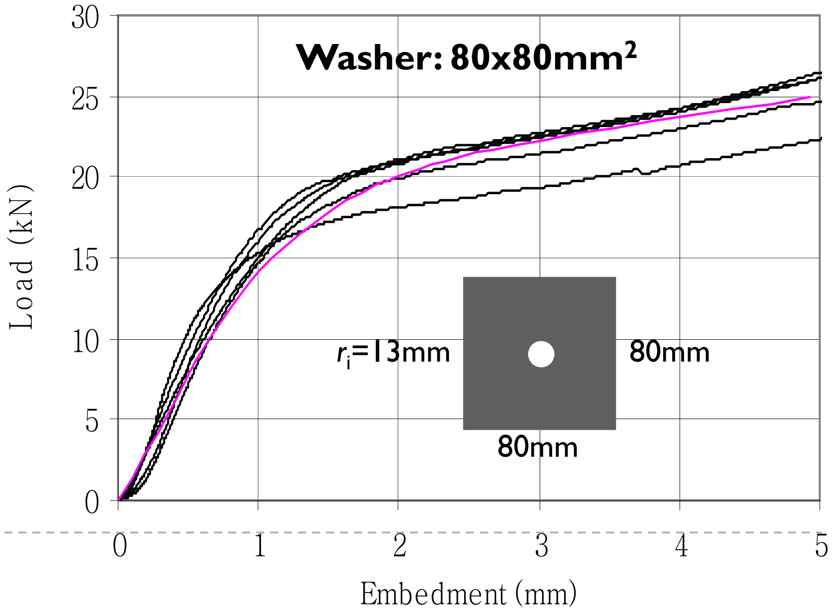
Elasto-plastic model

FE-Analysis vs. Test results

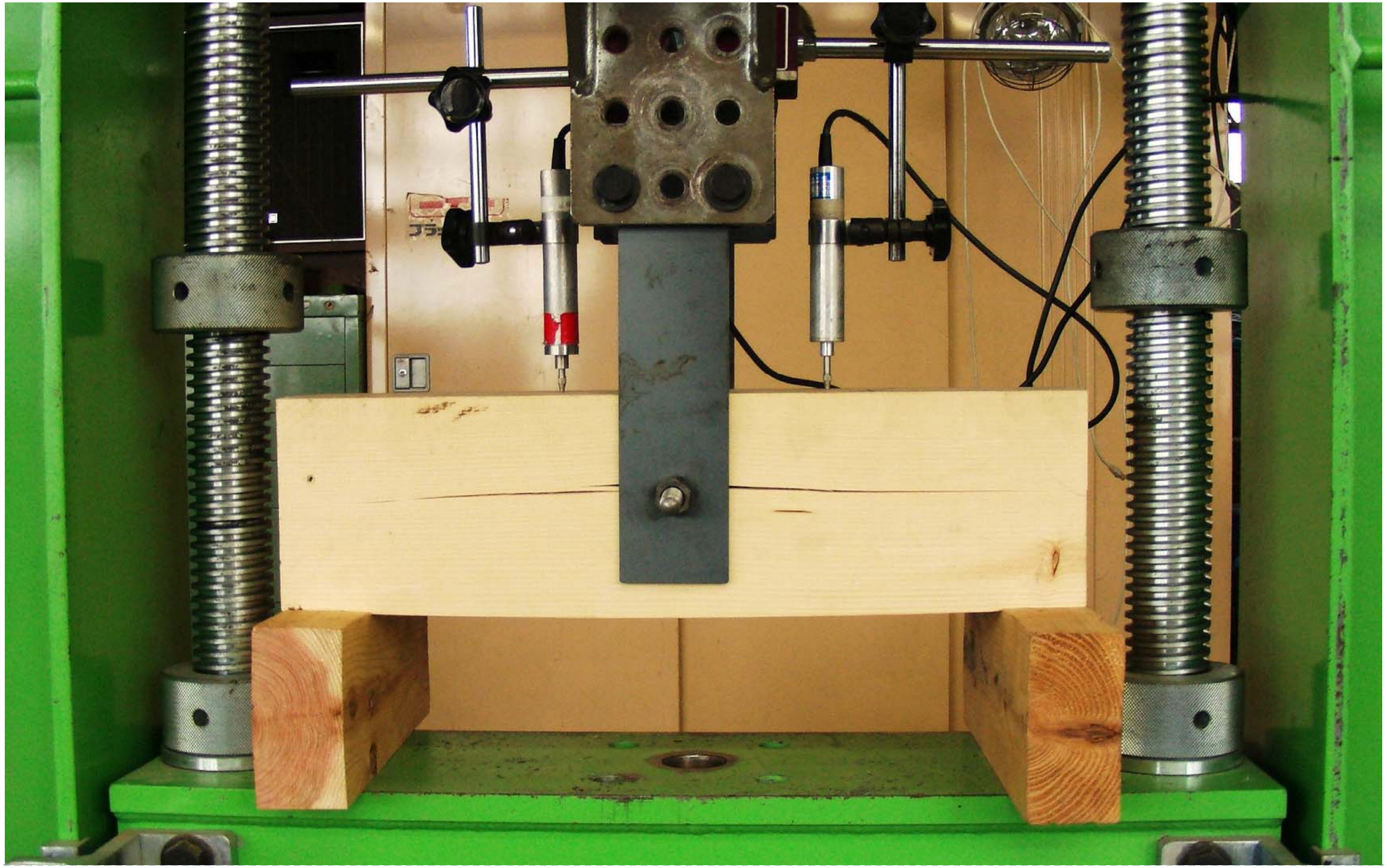




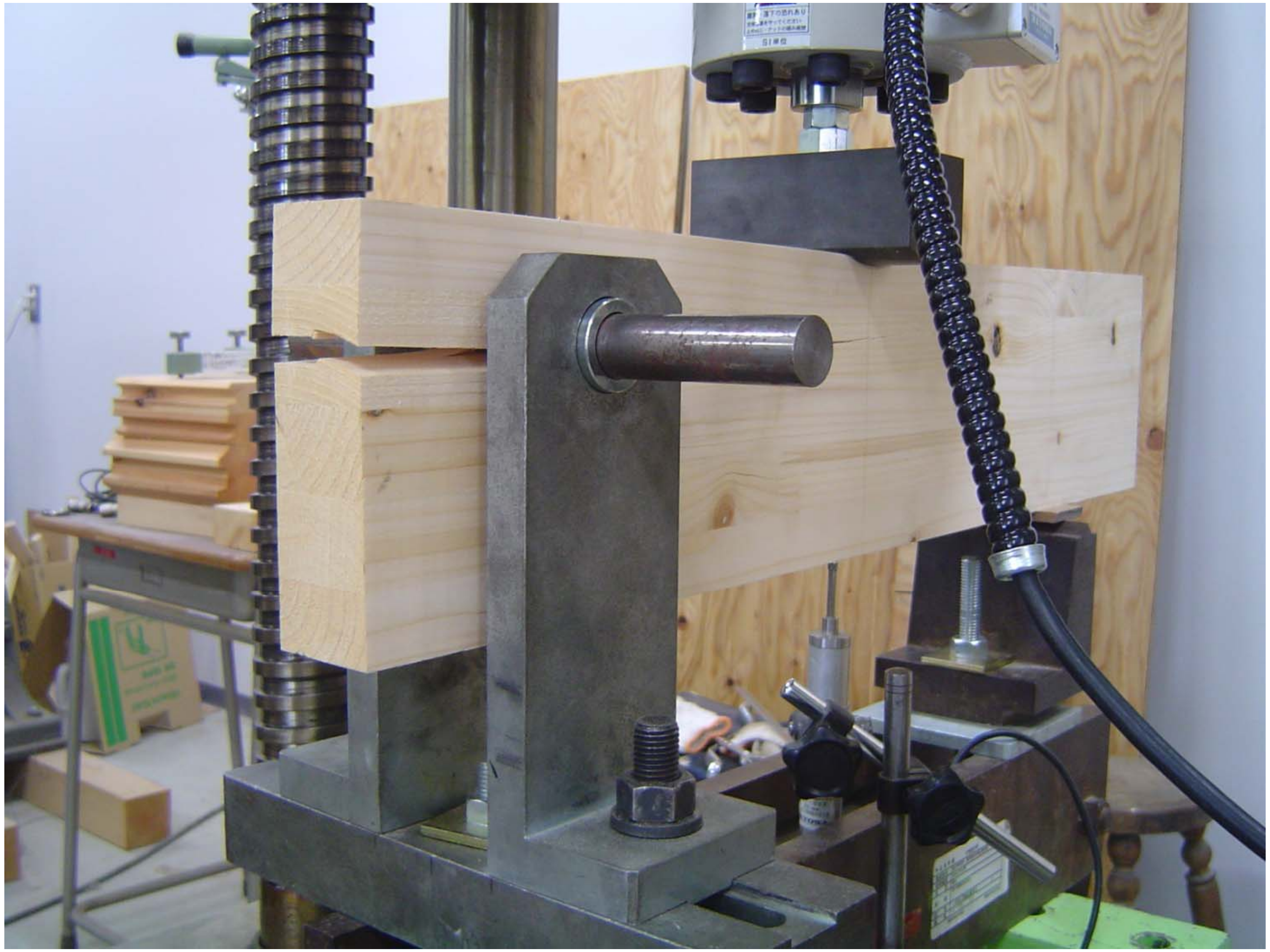




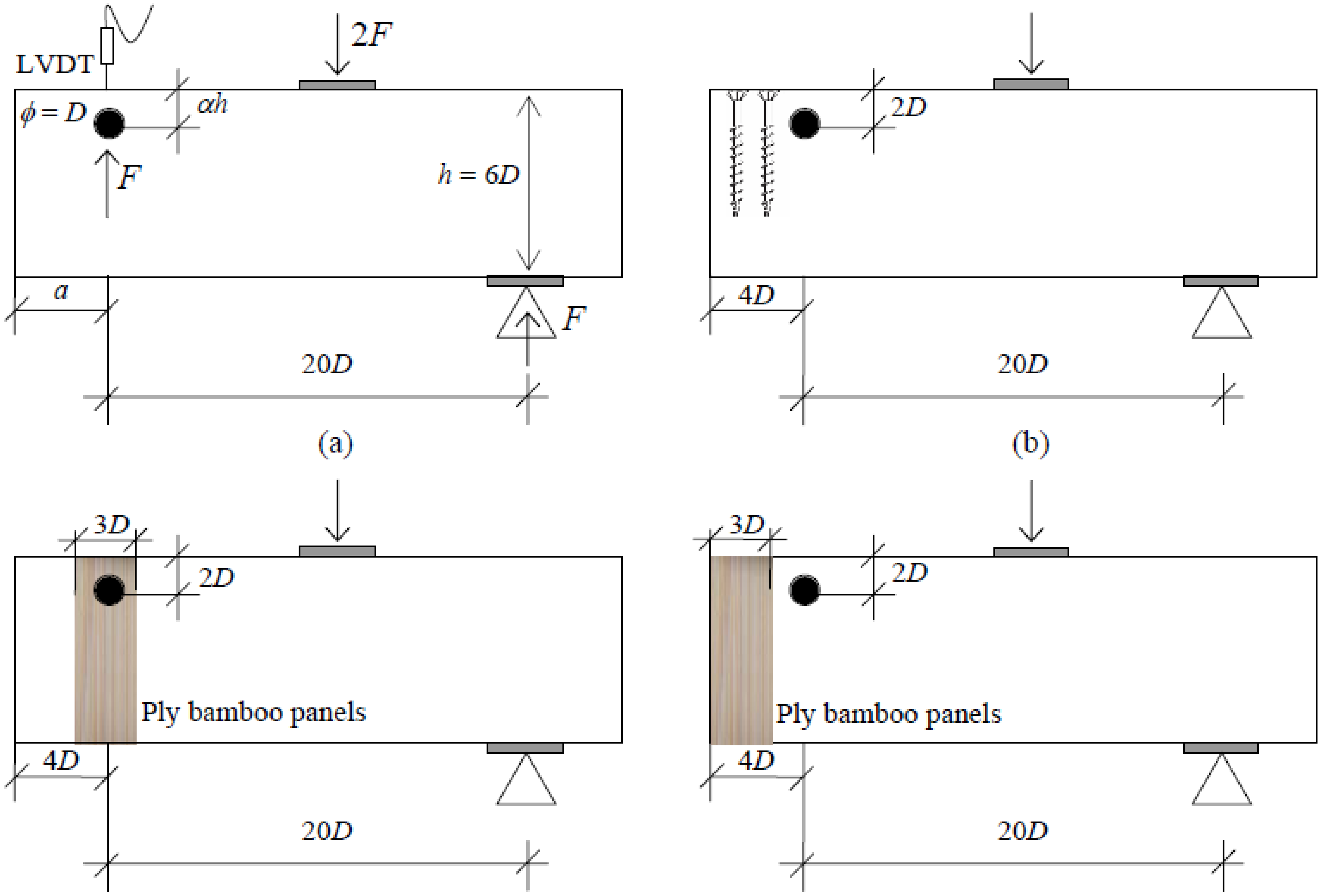
Splitting



Splitting

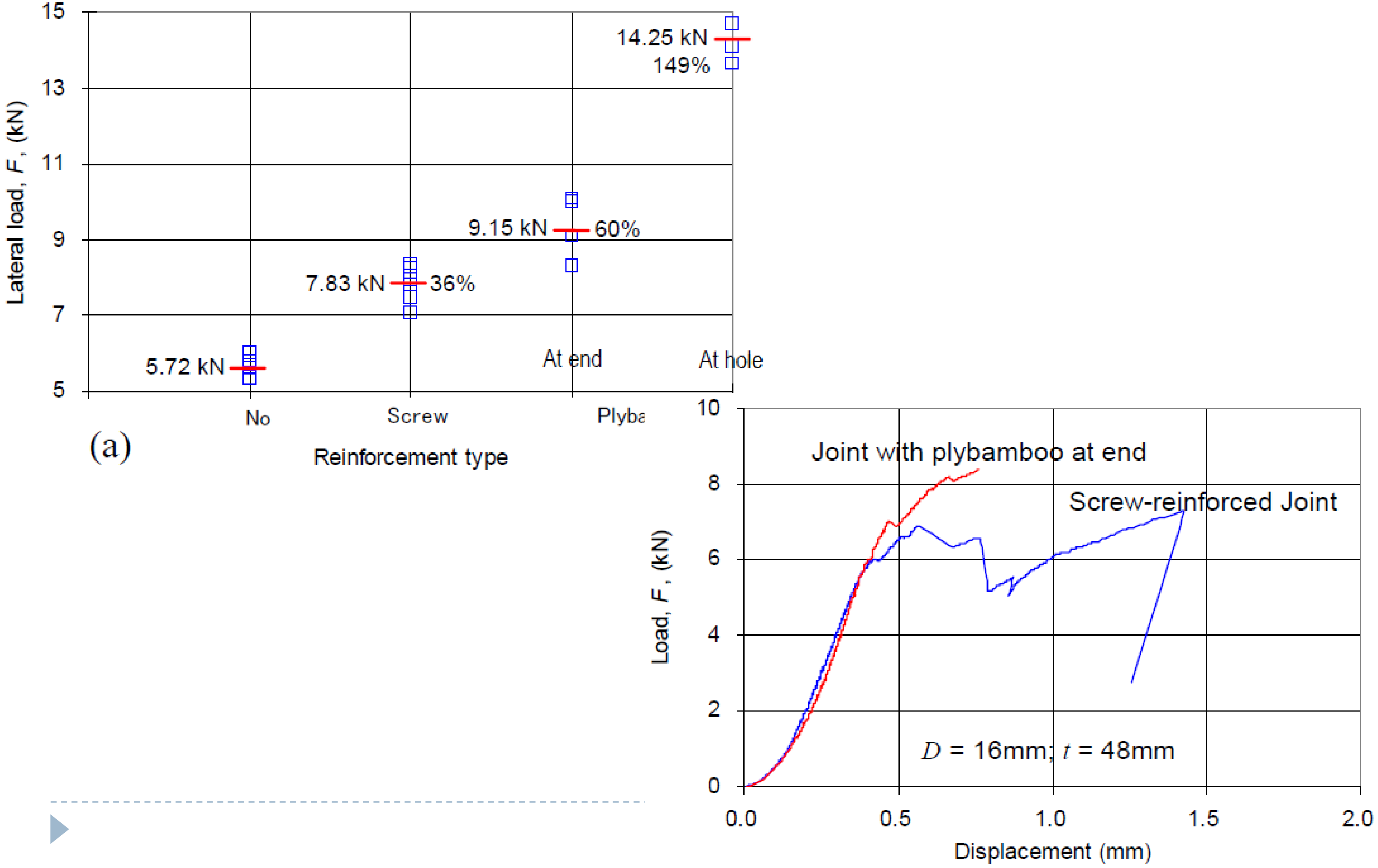


Splitting

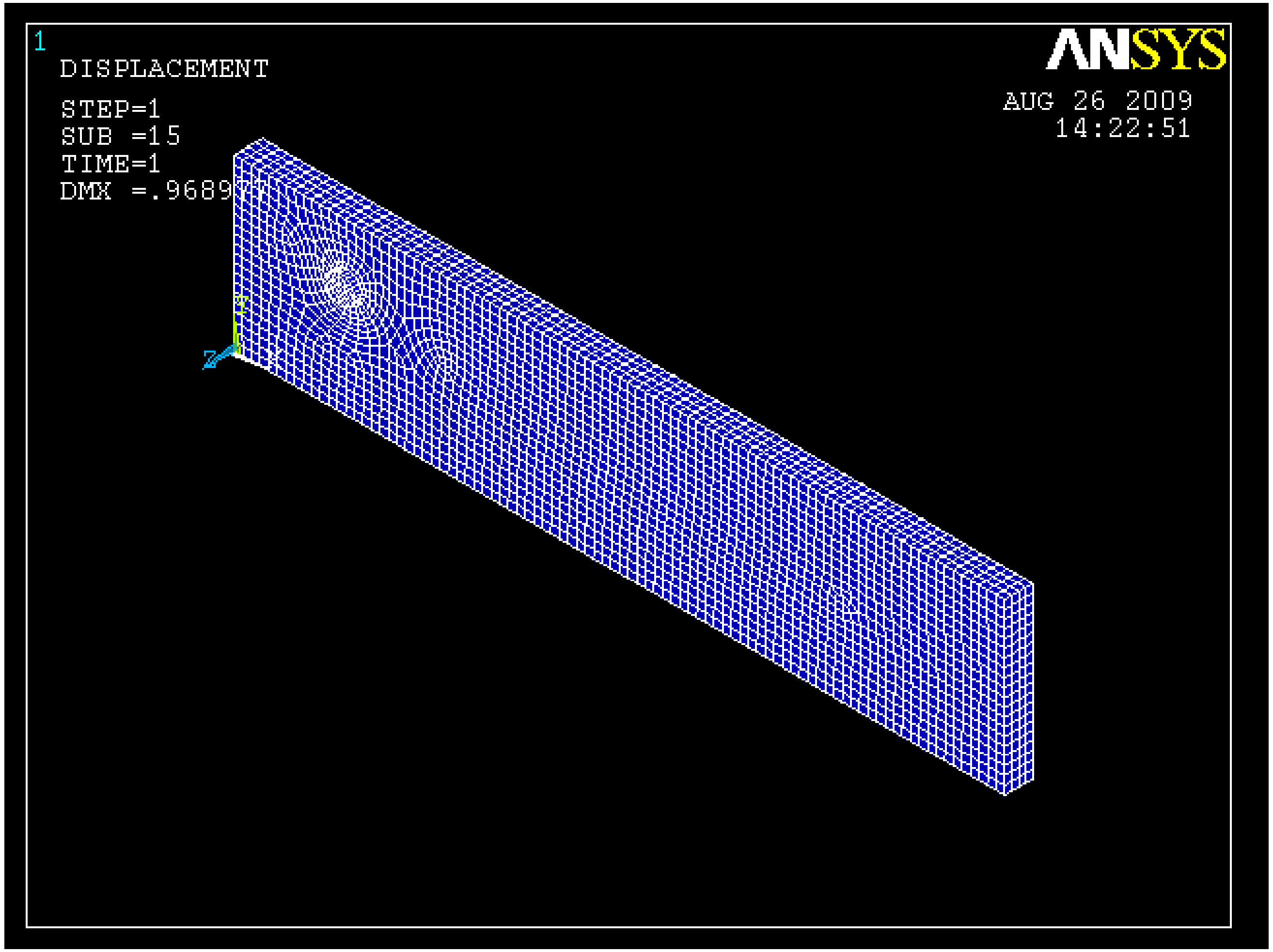


(a) (b) (c) (d)

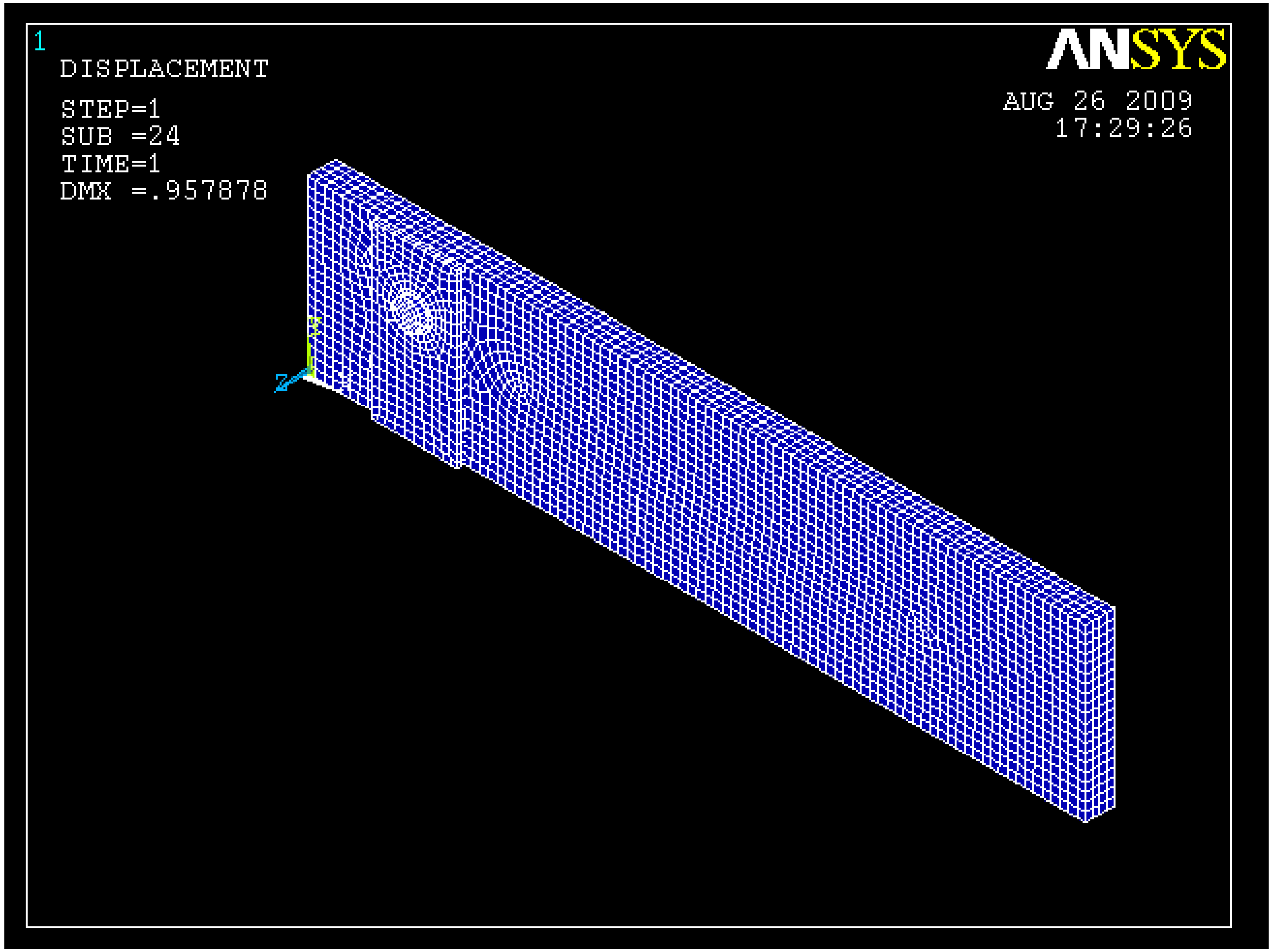
Splitting


(a)
Lateral load, F, (kN)
15
13
11
9
7
5
5.72 kN
7.83 kN
36%
9.15 kN
60%
14.25 kN
149%
At end
At hole
No
Screw
Plyba
Reinforcement type
Load, F, (kN)
10
8
6
4
2
0
Joint with plybamboo at end
Screw-reinforced Joint
D = 16mm; t = 48mm
0.0
0.5
1.0
1.5
2.0
Displacement (mm)

Splitting


1
DISPLACEMENT
STEP=1
SUB =15
TIME=1
DMX =.9689
ANSYS
AUG 26 2009
14:22:51
Y
Z

Splitting


1
DISPLACEMENT
STEP=1
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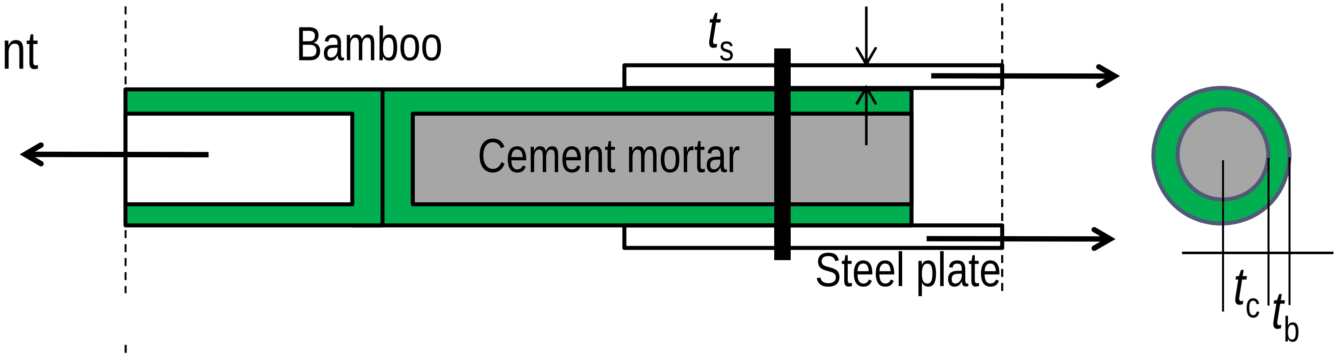
TIME=1
DMX =.957878
ANSYS
AUG 26 2009
17:29:26
Y
Z

Bamboo joint with cement mortar

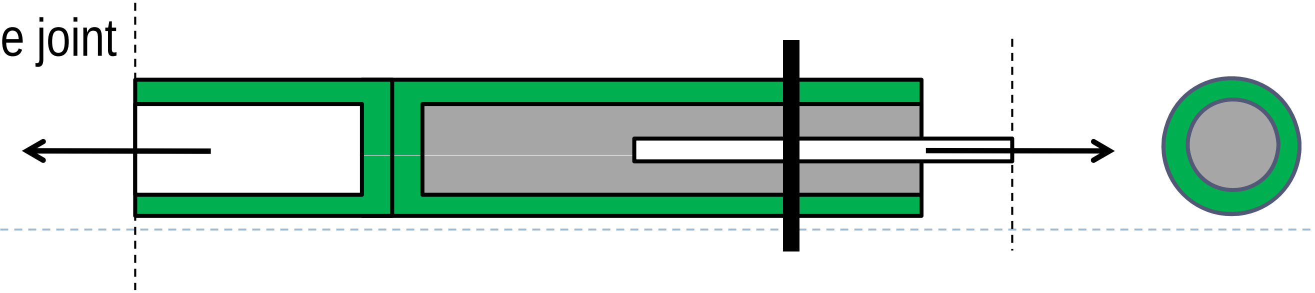
Homework (due date, two weeks after)

1. Derive the yield load formulation.
2. Calculate the yield load of Joint A, given: f_{eb} = 44-MPa, f_{ec} = 12-MPa, d = 12-mm, t_b = 9-mm, t_c = 35-mm, t_s = 5-mm

A. Steel side plate joint



B. Inserted steel plate joint



Content (week 5)

- Timber Engineering: Past and Present
- Wood Properties
- Mechanical Properties and Grading Techniques
- Theory of Timber Joint
- Nailed and Bolted Joints Analysis

Nailed Joints designed to SNI-5 (2002)

$$Z_u = \lambda \phi_z Z'$$

Loading combination	λ
1.4D	0.6
1.2D + 1.6L + 0.5(L_a or H)	0.7; 0.8; 1.25 (depends the source of L)
1.2D + 1.6(L_a or H) + (0.5L or 0.8W)	0.8
1.2D + 1.3W + 0.5L + 0.5(L_a or H)	1.0
1,2D ± 1.0E + 0.5L	1.0
0.9D ± (1.3W or 1.0E)	1.0

Compression	ϕ_c	0.90
Tension	ϕ_t	0.80
Connection	ϕ_z	0.65
Bending	ϕ_b	0.85
….		

Nailed Joints designed to SNI-5 (2002)

Yield mode	Lateral resistance per shear plane
$\mathrm{I_s}$	$Z = \dfrac{3{,}3 D t_s F_{es}}{K_D}$
$\mathrm{III_m}$	$Z = \dfrac{3{,}3 k_1 D p F_{em}}{K_D (1 + 2R_e)}$ $k_1 = (-1) + \sqrt{2(1 + R_e) + \dfrac{2F_{yb}(1 + 2R_e)D^2}{3F_{em}\, p^2}}$
$\mathrm{III_s}$	$Z = \dfrac{3{,}3 k_2 D t_s F_{em}}{K_D (2 + R_e)}$ $k_2 = (-1) + \sqrt{\dfrac{2(1 + R_e)}{R_e} + \dfrac{2F_{yb}(1 + 2R_e)D^2}{3F_{em}\, t_s^2}}$
IV	$Z = \dfrac{3{,}3 D^2}{K_D}\sqrt{\dfrac{2F_{em}F_{yb}}{3(1 + R_e)}}$

p is point side penetration

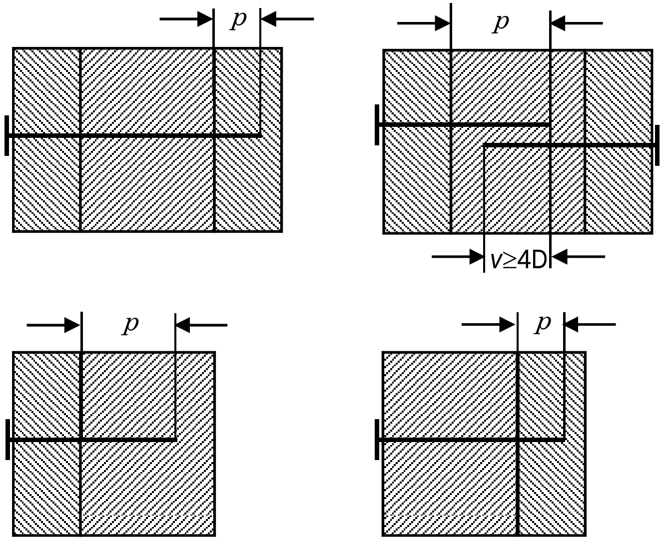
$R_e = F_{em}/F_{es}$

K_D is nail diameter factor

$K_D = 2.2$ for $D \leq 4.3$ mm;

$K_D = 0.38D + 0.56$ for $4.3 \leq D \leq 6.4$ mm;

$K_D = 3.0$ for $D \geq 6.4$ mm.



Nailed Joints designed to SNI-5 (2002)

	Wood specific gravity						
	0.40	0.45	0.50	0.55	0.60	0.65	0.70
F_e (N/mm^2)	21.21	26.35	31.98	38.11	44.73	51.83	59.40

Nail	Diameter (mm)	Length (mm)	Length/Diameter
CN-50	2.8	51	18
CN-60	3.1	63	20
CN-75	3.4	76	22
CN-90	3.8	89	23
CN-100	4.2	102	24
CN-110	5.2	114	22

Nailed Joints designed to SNI-5 (2002)

Nail diameter	Bending yield strength F_{yb}
$\leq$ 3.6 mm	689 N/mm^2
3.6 mm < $D \leq$ 4.7 mm	620 N/mm^2
4.7 mm < $D \leq$ 5.9 mm	552 N/mm^2
5.9 mm < $D \leq$ 7.1 mm	483 N/mm^2
7.1 mm < $D \leq$ 8.3 mm	414N/mm^2
D > 8.3 mm	310 N/mm^2

Correction factor

1. Point side penetration (C_{d})
2. End grain (C_{eg})
3. Inclined nailing (C_{tn})
4. Diaphragm action (C_{di})

$$Z' = C_d C_{di} C_{tn} C_{eg} Z$$

Nailed Joints designed to SNI-5 (2002)

1. Point side penetration (C_d)

   $C_\text{d} = 1.00$ for $p \geq 12D$;

   $C_\text{d} = p/12D$ for $6D \leq p \leq 12D$;

   $C_\text{d} = 0.00$ for $p \leq 6D$.

2. End grain (C_eg)

   $C_\text{eg} = 0.67$

3. Inclined nailing (C_tn)

   $C_\text{tn} = 0.83$

4. Diaphragm action (C_di)

   Frame to plywood connection (e.g. Floor or wall), $C_\text{di} = 1.20$

   Otherwise $C_\text{di} = 1.00$

Nailed Joints designed to SNI-5 (2002)

Design examples:

Awaludin, A., Introduction to timber connection design (*Dasar-dasar perencanaan sambungan kayu*), 2005

Bolted Joints designed to SNI-5 (2002)

$$Z_u = \lambda \phi_z Z'$$

Loading combination	λ
1.4D	0.6
1.2D + 1.6L + 0.5(L_a or H)	0.7; 0.8; 1.25 (depends the source of L)
1.2D + 1.6(L_a or H) + (0.5L or 0.8W)	0.8
1.2D + 1.3W + 0.5L + 0.5(L_a or H)	1.0
1,2D ± 1.0E + 0.5L	1.0
0.9D ± (1.3W or 1.0E)	1.0

Compression	ϕ_c	0.90
Tension	ϕ_t	0.80
Connection	ϕ_z	0.65
Bending	ϕ_b	0.85
….		

Bolted Joints designed to SNI-5 (2002)

A. Two-member joint

Yield mode	Lateral resistance per shear plane
$\mathrm{I_m}$	$Z = \dfrac{0{,}83 D t_m F_{em}}{K_\theta}$
$\mathrm{I_s}$	$Z = \dfrac{0{,}83 D t_s F_{es}}{K_\theta}$
II	$Z = \dfrac{0{,}93 k_1 D t_s F_{es}}{K_\theta}$
$\mathrm{III_m}$	$Z = \dfrac{1{,}04 k_2 D t_m F_{em}}{(1 + 2R_e) K_\theta}$
$\mathrm{III_s}$	$Z = \dfrac{1{,}04 k_3 D t_s F_{em}}{(2 + R_e) K_\theta}$
IV	$Z = \left(\dfrac{1{,}04 D^2}{K_\theta}\right)\sqrt{\dfrac{2 F_{em} F_{yb}}{3(1 + R_e)}}$

Bolted Joints designed to SNI-5 (2002)

B. Three-member joint

Yield mode	Lateral resistance per shear plane
I_m	$Z = \dfrac{0{,}83 D t_m F_{em}}{K_\theta}$
I_s	$Z = \dfrac{1{,}66 D t_s F_{es}}{K_\theta}$
III_s	$Z = \dfrac{2{,}08 k_3 D t_s F_{em}}{(2 + R_e) K_\theta}$
IV	$Z = \left(\dfrac{2{,}08 D^2}{K_\theta}\right)\sqrt{\dfrac{2 F_{em} F_{yb}}{3(1 + R_e)}}$

$$R_t = t_m / t_s$$

$$R_e = F_{em} / F_{es}$$

$$K_\theta = 1 + (\theta / 360^\circ)$$

$$k_1 = \frac{\sqrt{R_e + 2R_e^2\left(1 + R_t + R_t^2\right) + R_t^2 R_e^3} - R_e(1 + R_t)}{(1 + R_e)} \quad k_2 = (-1) + \sqrt{2(1 + R_e) + \frac{2F_{yb}(1 + 2R_e)D^2}{3F_{em}t_m^2}} \quad k_3 = (-1) + \sqrt{\frac{2(1 + R_e)}{R_e} + \frac{2F_{yb}(2 + R_e)D^2}{3F_{em}t_s^2}}$$

Bolted Joints designed to SNI-5 (2002)

Embedding strength (F_e)

$$F_{e//} = 77{,}25G \quad F_{e\perp} = 212G^{1{,}45}D^{-0{,}5} \quad F_{e\theta} = \frac{F_{e//}F_{e\perp}}{F_{e//}\sin^2\theta + F_{e\perp}\cos^2\theta}$$

Embedding strength (F_e) in N/mm^2 for 12.7-mm bolt

Specific gravity	Loading angle to the grain (degree)									
	0	10	20	30	40	50	60	70	80	90
0.50	38.63	37.75	35.42	32.37	29.27	26.57	24.45	22.95	22.07	21.77
0.55	42.49	41.61	39.28	36.17	32.97	30.13	27.87	26.27	25.32	25.00
0.60	46.35	45.48	43.15	40.01	36.73	33.79	31.42	29.72	28.70	28.36
0.65	50.21	49.36	47.04	43.89	40.56	37.53	35.06	33.28	32.21	31.85
0.70	54.08	53.23	50.95	47.81	44.45	41.35	38.81	36.96	35.84	35.47
0.75	57.94	57.12	54.87	51.76	48.39	45.25	42.65	40.75	39.59	39.20
0.80	61.80	61.00	58.81	55.73	52.38	49.22	46.59	44.63	43.44	43.04
0.85	65.66	64.89	62.75	59.74	56.41	53.26	50.60	48.62	47.41	47.00
0.90	69.53	68.78	66.71	63.77	60.49	57.36	54.70	52.70	51.48	51.06
0.95	73.39	72.67	70.67	67.82	64.61	61.52	58.87	56.88	55.64	55.22
1.00	77.25	76.56	74.65	71.89	68.77	65.74	63.12	61.14	59.91	59.49

Bolted Joints designed to SNI-5 (2002)

Correction factor

1. Group action (C_g)
2. Geometric (C_Δ)

$$Z' = C_g C_\Delta Z$$

See following examples for more clear explanation:

Awaludin, A., Introduction to timber connection design (*Dasar-dasar perencanaan sambungan kayu*), 2005