Condition Assessment of Wood

Robert J. Ross, Ph.D.

USDA Forest Products Laboratory
Madison, WI

NDT Colleagues

Bob Ross, Ph.D.
Project Leader, USDA Forest Products Laboratory
608.231.9200 (rjross@fs.fed.us)

Brian Brashaw
Director, Wood Materials & Engineering Program
Natural Resources Research Institute, University of Minnesota Duluth
218.720.4248 (bbrashaw@nrri.umn.edu)

Xiping Wang, Ph.D.
Research Forest Products Technologist, USDA Forest Products Laboratory
608-231-9461(xwang@fs.fed.us)

Zhiyong Cai, Ph.D., P.E.
Project Leader, USDA Forest Products Laboratory
608-231-9446 (zcai@fs.fed.us)


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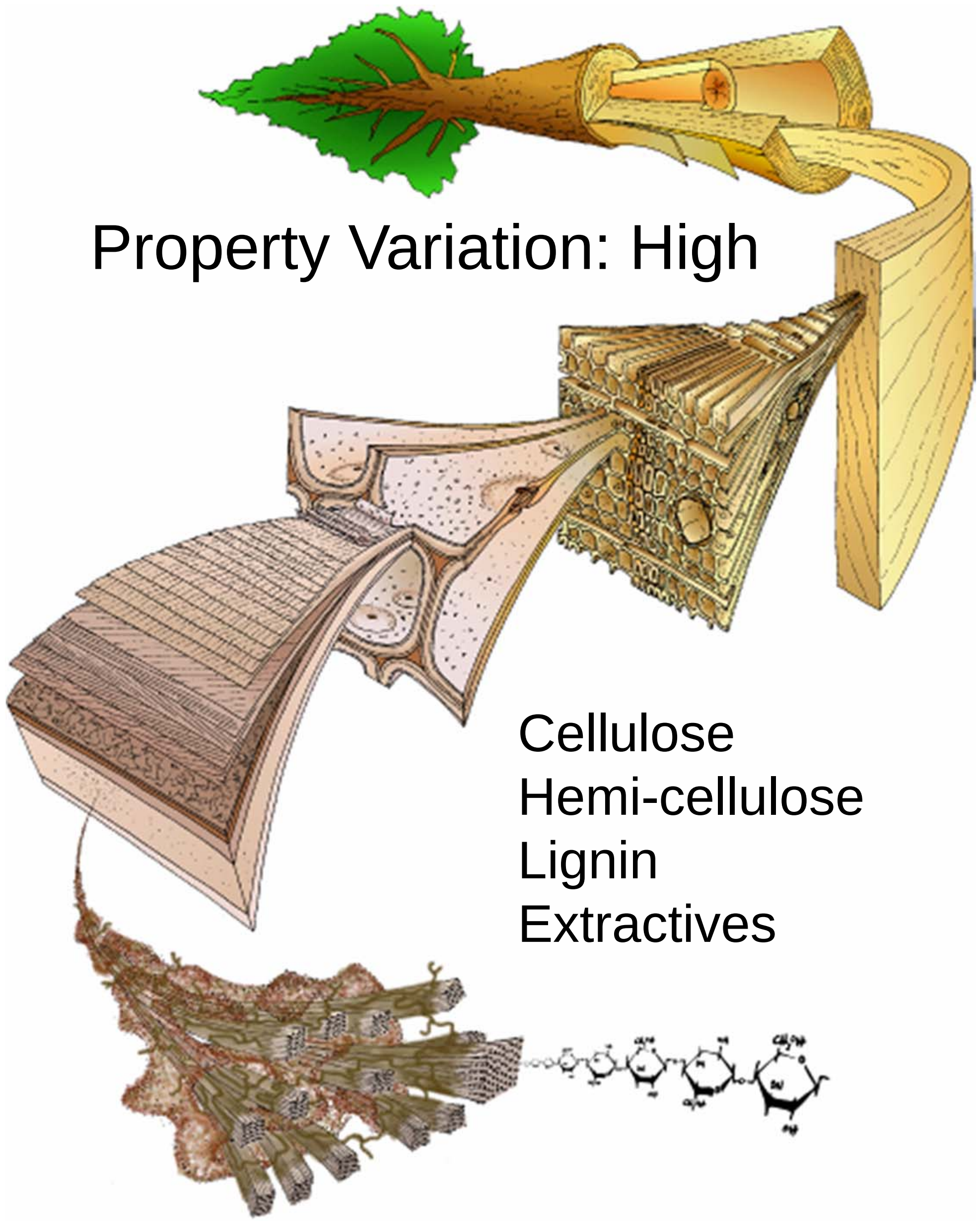
?
Thinking
Wood

Property Variation: High



Cellulose
Hemi-cellulose
Lignin
Extractives

S-diagram – U of Canterbury

Wood as an engineering material

- Advantages:
  - High strength to weight ratio
  - Good record for durability and performance
  - Good insulation against heat, sound, and electricity
  - Absorb and dissipate vibration
  - Easy repair

- Disadvantage:
  - Moisture problem

Keep It Dry!

Objective

- To present an overview of nondestructive testing (NDT) techniques for wood property evaluation
- To present an overview of methods that are used to inspect wood structures
- To present case study examples where these techniques are used

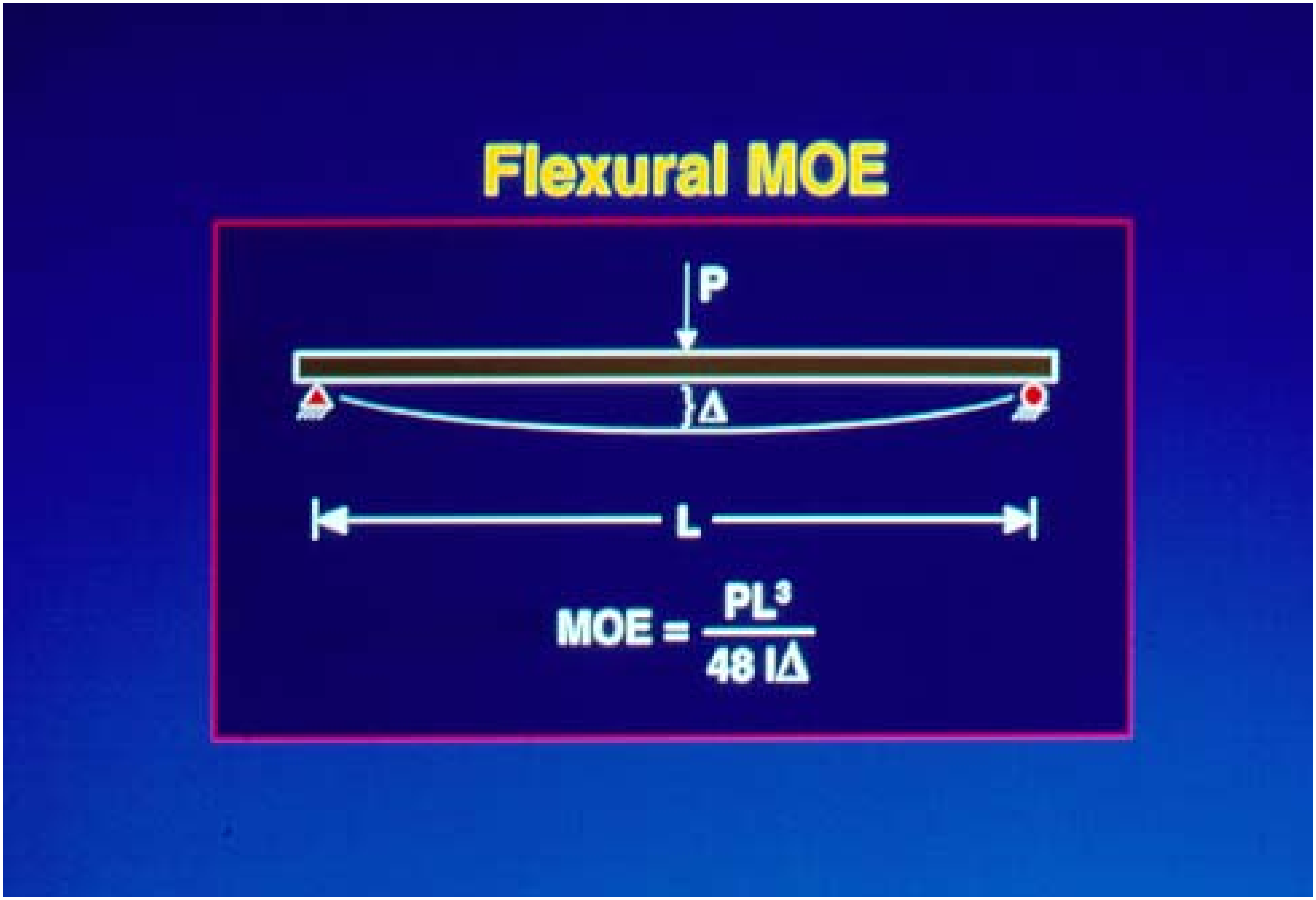
Nondestructive Evaluation of Wood

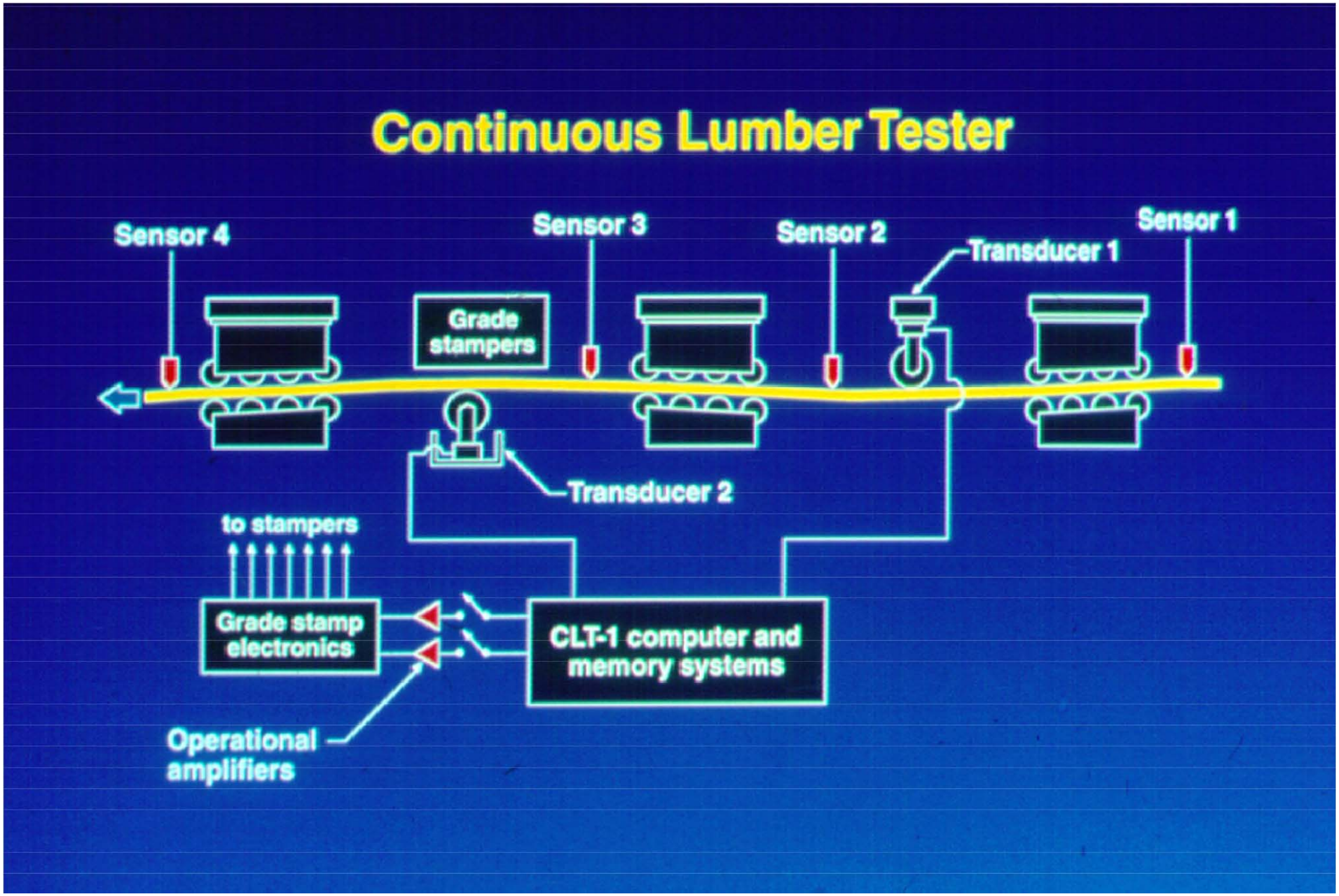
NDE Techniques

- Machine stress rating (MSR)
- Transverse vibration
- Longitudinal stress waves
- Acoustic tomography

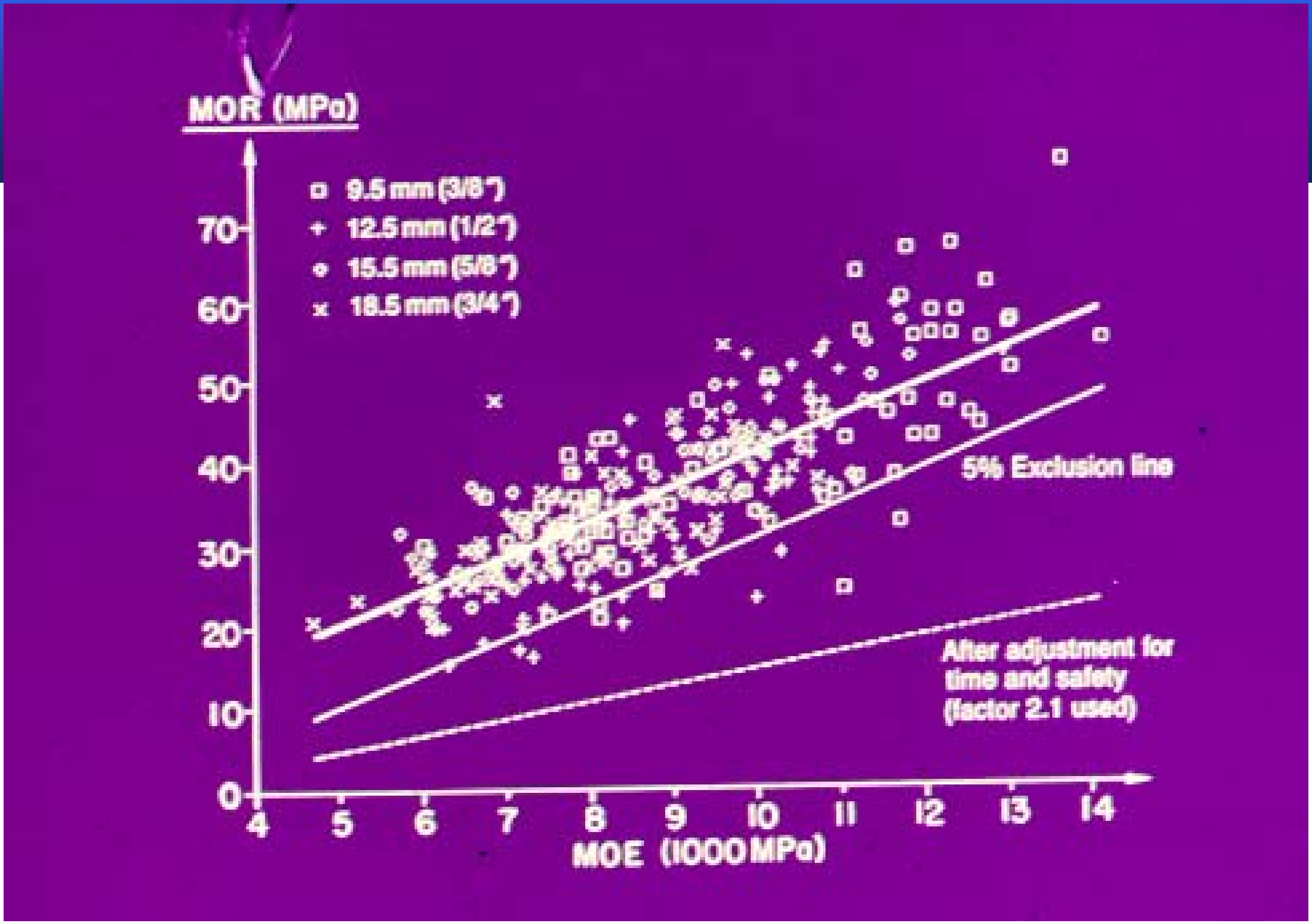
Machine Stress Rating (MSR)

- Concept - Sort lumber by MOE
- Measurement techniques
  - Static bending
- Uses/impact
  - Structural lumber,engineered components
    - Trusses, I-joists, glulam


Flexural MOE
P
Δ
L
$MOE = \frac{PL^3}{48 I\Delta}$

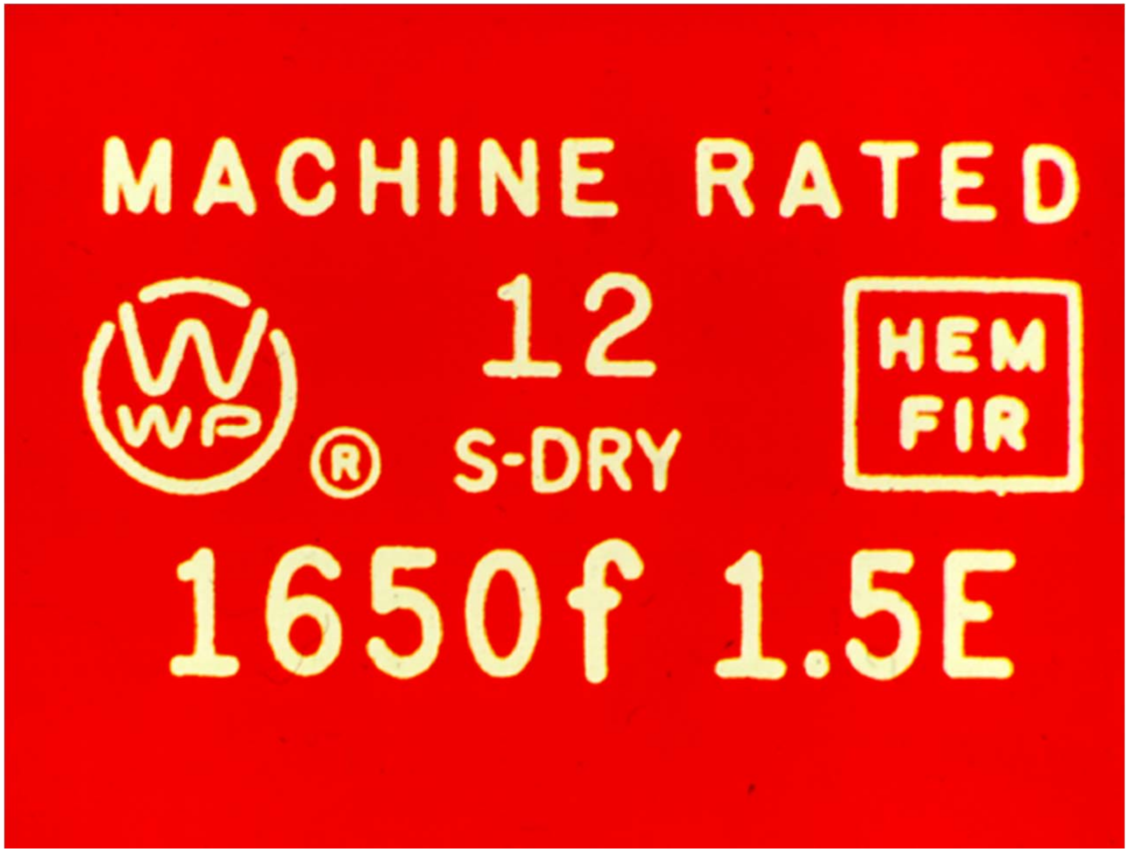

Continuous Lumber Tester
Sensor 4
Sensor 3
Sensor 2
Sensor 1
Transducer 1
Grade stampers
Transducer 2
to stampers
Grade stamp electronics
CLT-1 computer and memory systems
Operational amplifiers

HCLT by Metriguard, USA


MOR (MPa)
9.5 mm (3/8")
12.5 mm (1/2")
15.5 mm (5/8")
18.5 mm (3/4")
70
60
50
40
30
20
10
0
4
5
6
7
8
9
10
11
12
13
14
MOE (1000 MPa)
5% Exclusion line
After adjustment for time and safety (factor 2.1 used)

MSR grade stamp

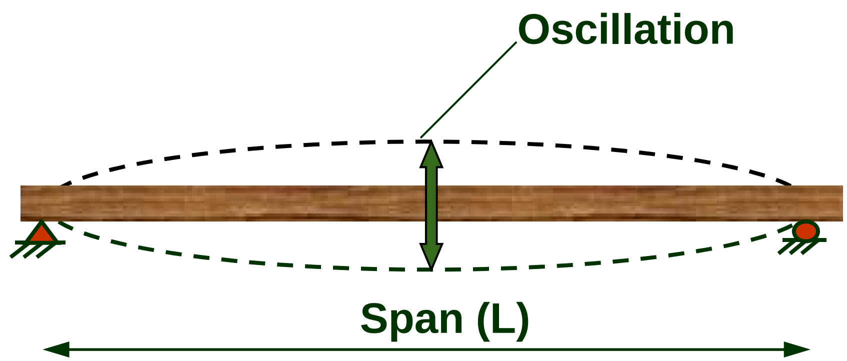
- Identity as a machine grade
- Species
- Grade level
- MC category
- Mill No.
- Supervisory agency



Transverse Vibration

- Low frequency
- Free vibration
- Bending mode
- *f*, damping capacity, MOE
- Lumber, timber, glulam beams
- Potential for structural system

Beam theory

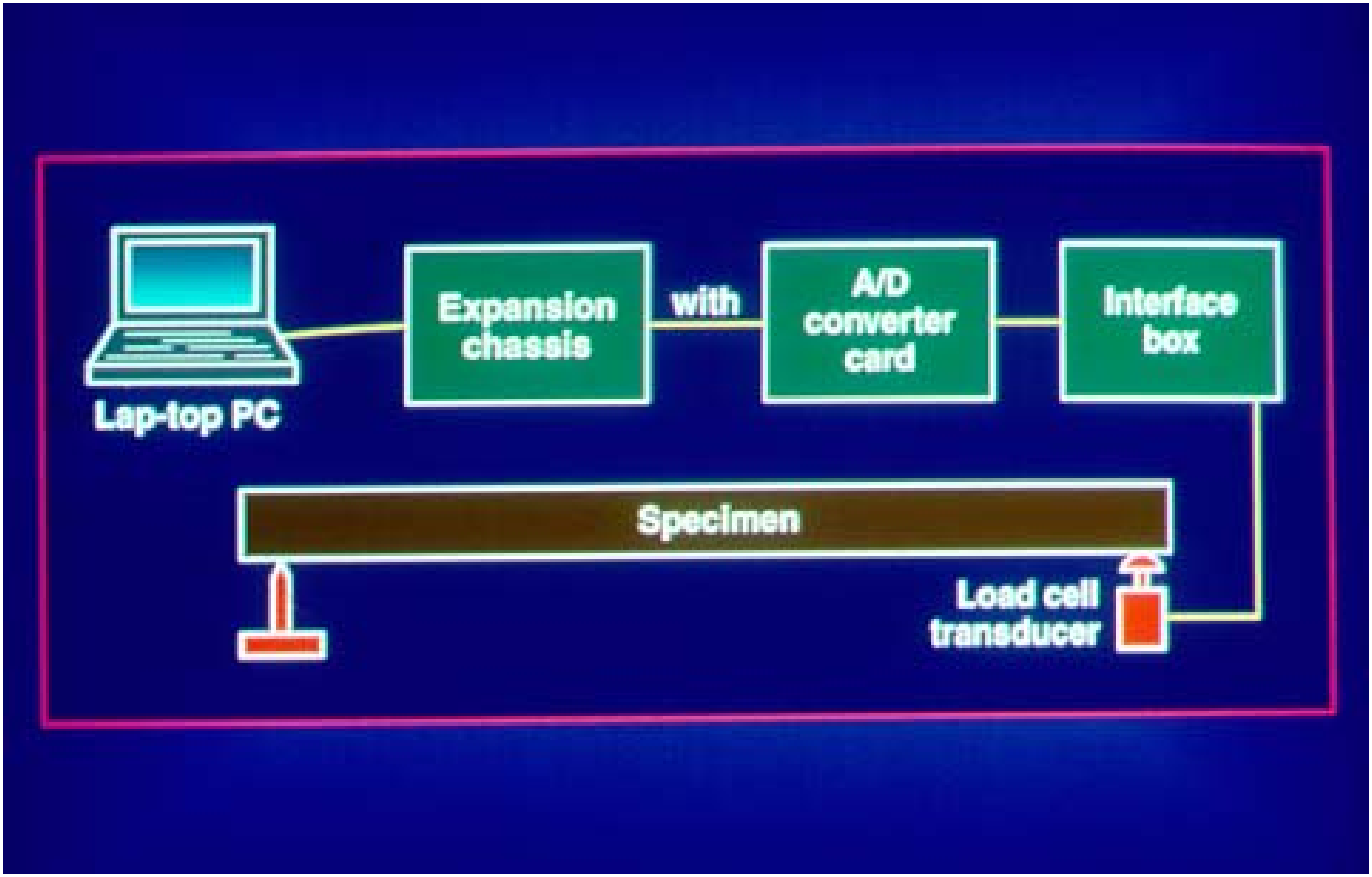


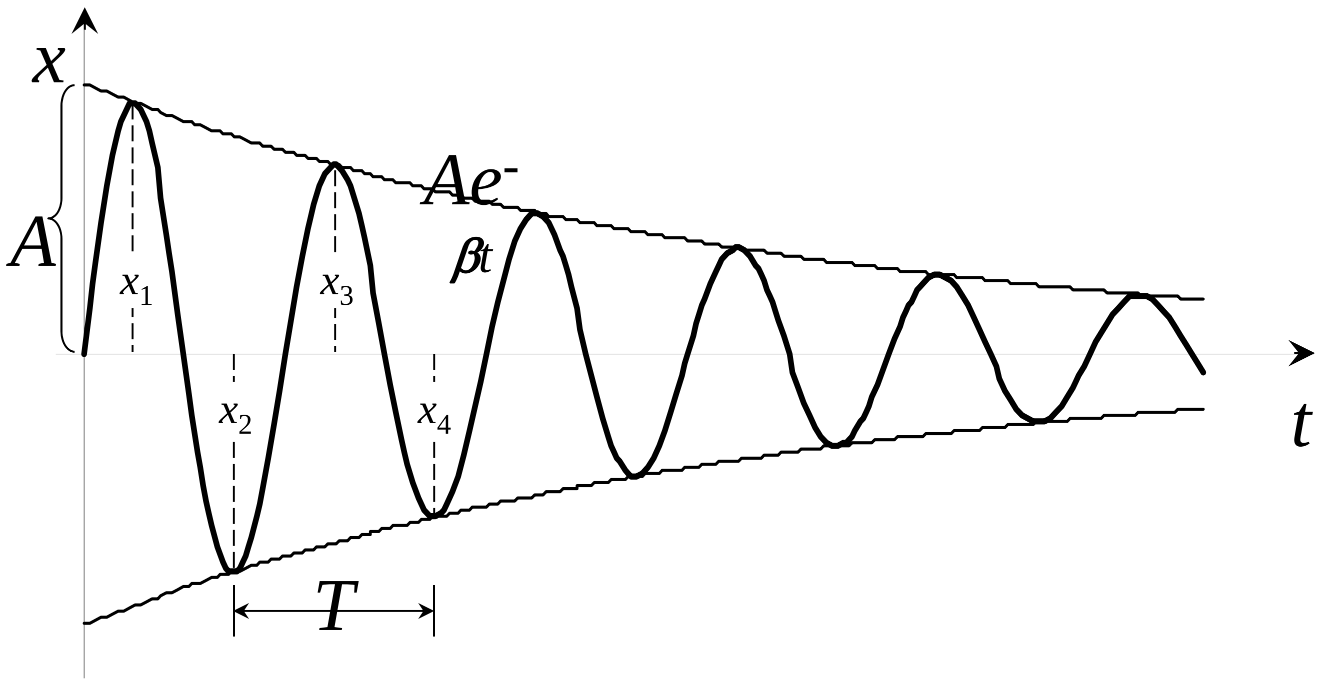
- Timoshenko beam theory (shear considered)

$$EI\frac{\partial^4 r}{\partial x^4}+\rho A\frac{\partial^2 r}{\partial t^2}-\rho I\left(1+\frac{E}{\beta G}\right)\frac{\partial^4 r}{\partial x^2 \partial t^2}+\frac{\rho^2 I}{\beta G}\frac{\partial^4 r}{\partial t^4}=0$$

- Euler beam theory (neglecting shear)

$$E=\left(\frac{f_n}{C_n}\right)^2\frac{mL^3}{I}$$


Lap-top PC
Expansion chassis
with
A/D converter card
Interface box
Specimen
Load cell transducer



x
A
x_1
x_2
x_3
x_4
Ae-
βt
T
t

How it Works!

Commercial Transverse Vibration Systems

- “E” Computer
  (Metriguard, Inc)

- Dyna MOE
  (Qualtim, Inc.)

Experimental work – Structural Inspection

- **Hypothesis** – Deterioration of wood structures caused by any organism or overloading reduces strength and stiffness of wood components, and thus could affect the dynamic behavior of the system.

- **Goal** - Develop cost-effective and accurate NDE methods for assessing the condition of wood structures based on analysis of fundamental frequency of the superstructure and determine the global stiffness of the system.

Longitudinal Stress Waves

- “sound waves”, “acoustic waves”

- Impact-induced
- Axial mode
- C, density → MOE
- Lumber, large timber, poles, logs
- **In-place condition assessment**

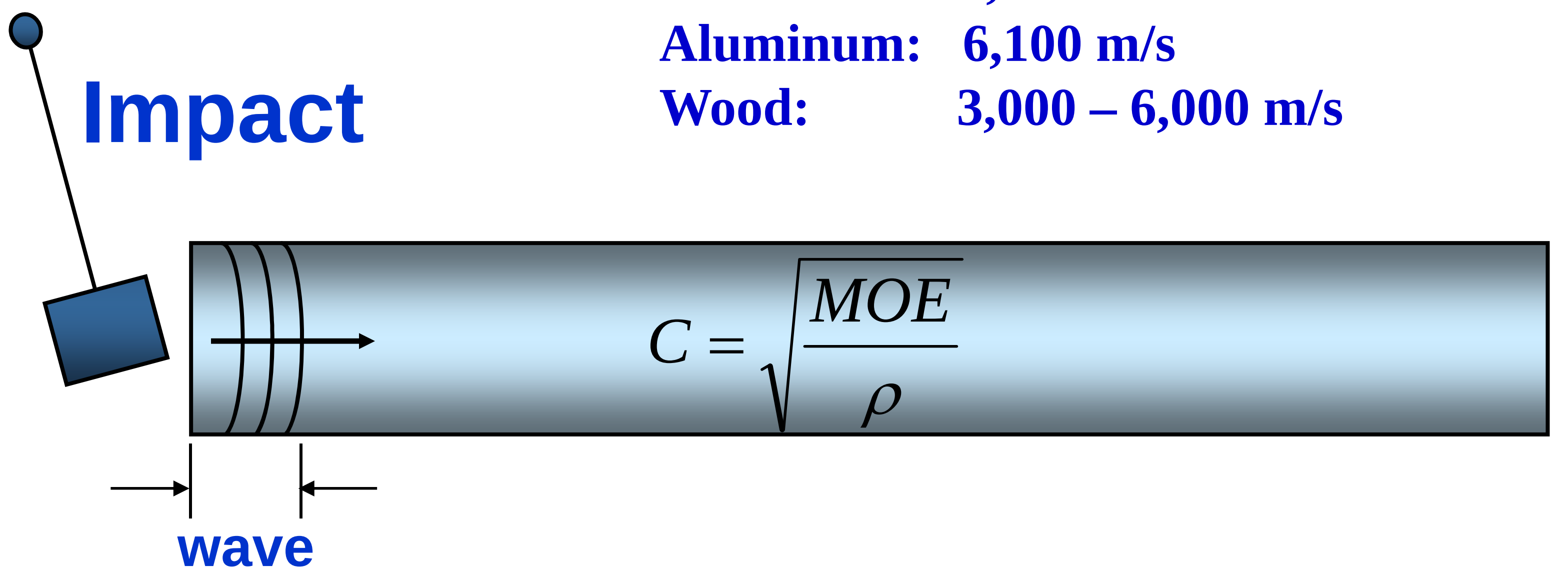
Elastic wave theory

Sound speed in different materials:

Steel: **5,800 m/s**

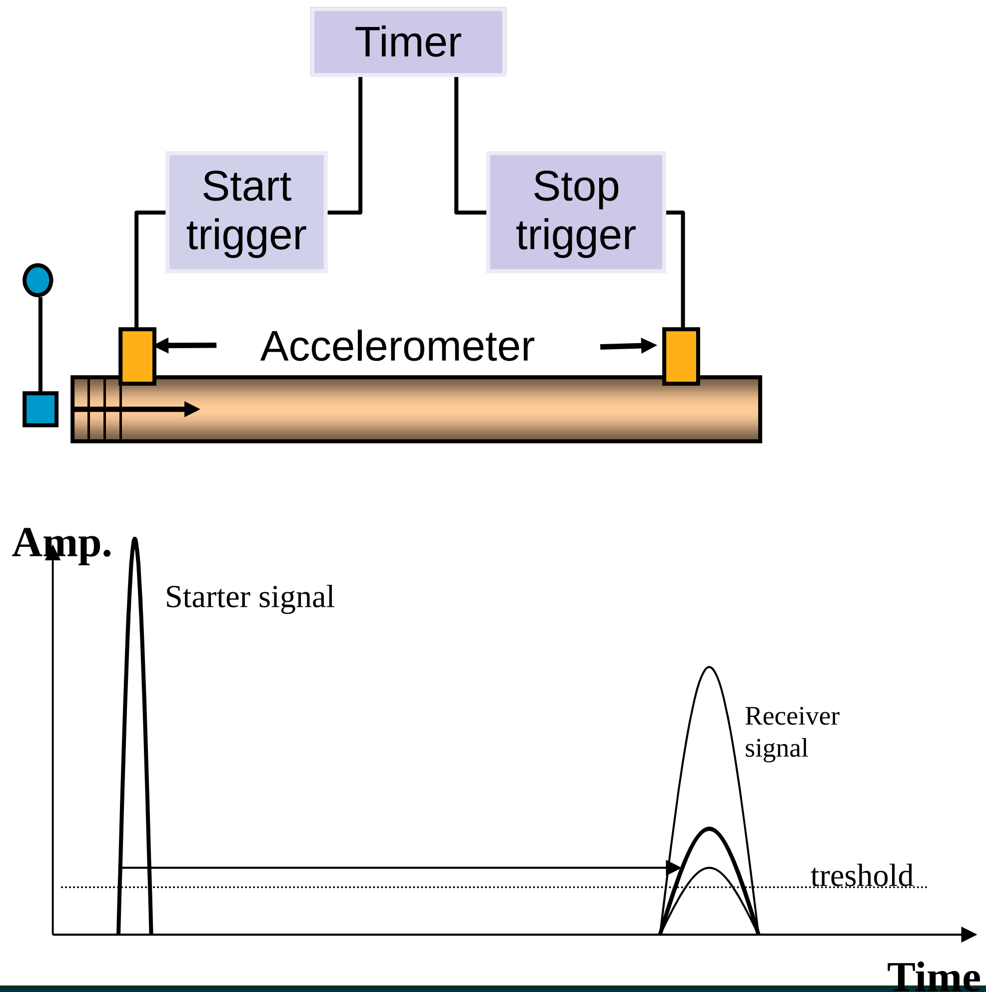
Aluminum: **6,100 m/s**

Wood: **3,000 – 6,000 m/s**

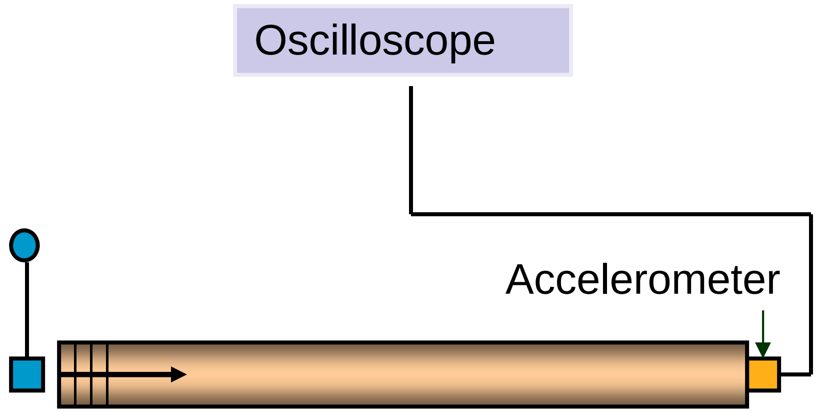


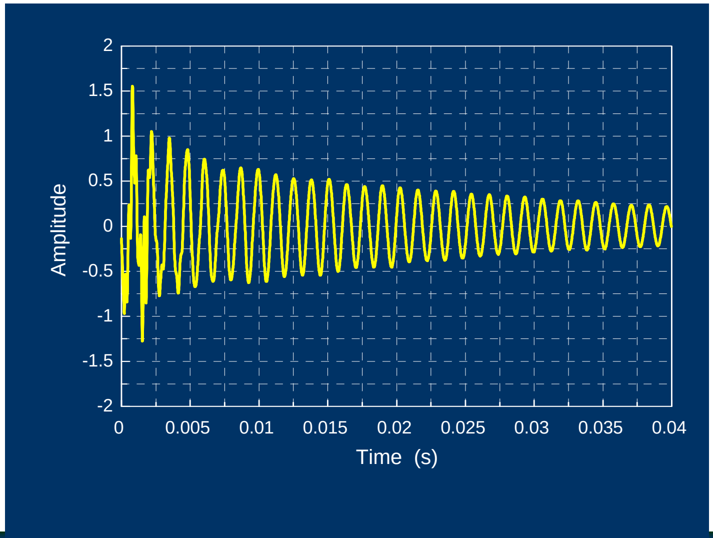
$$MOE = C^2 \rho$$

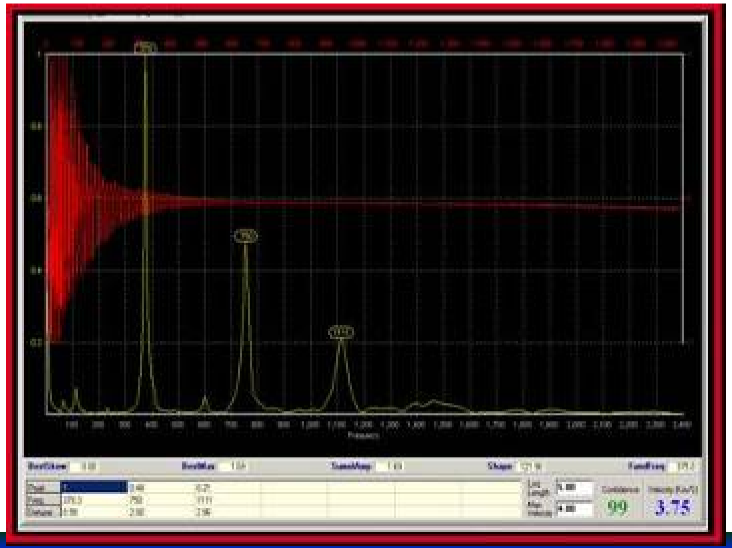
Pitch-catch system



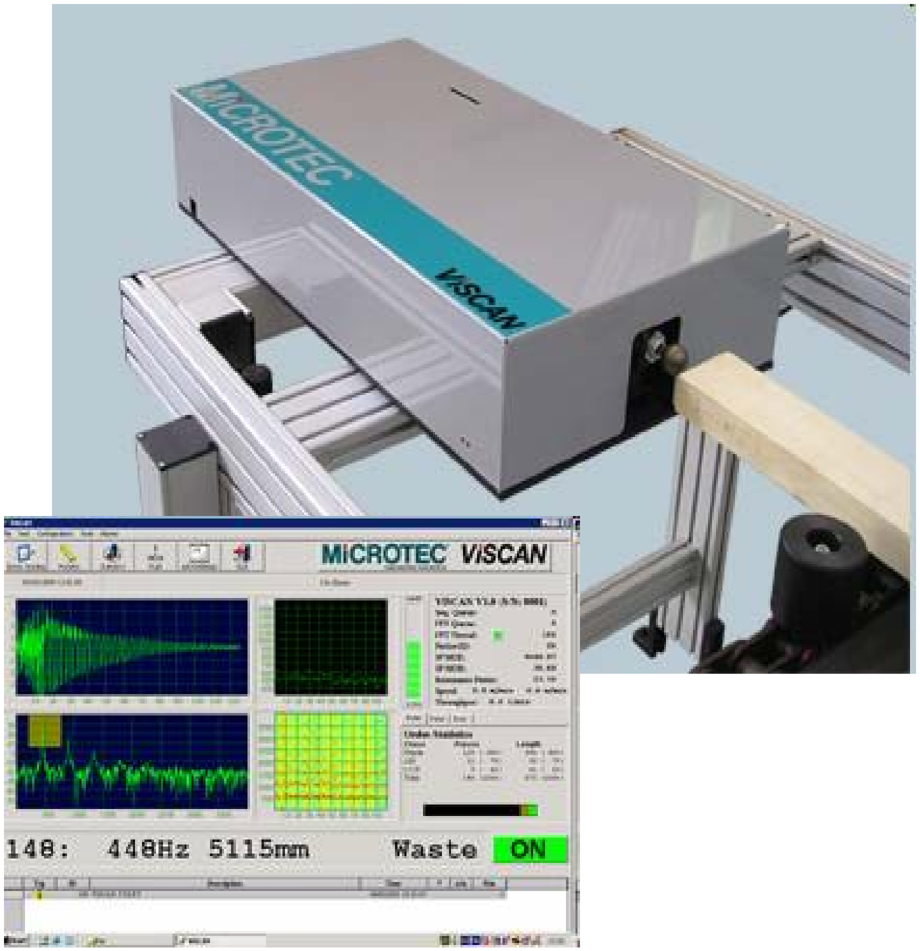
Resonance system





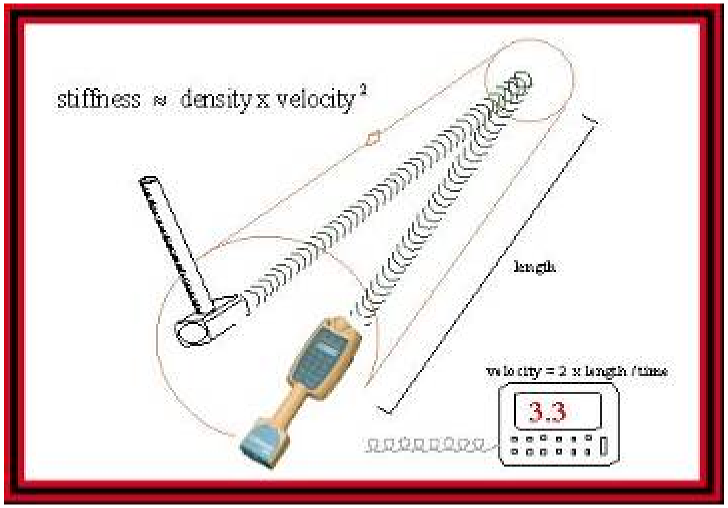


Online lumber grader



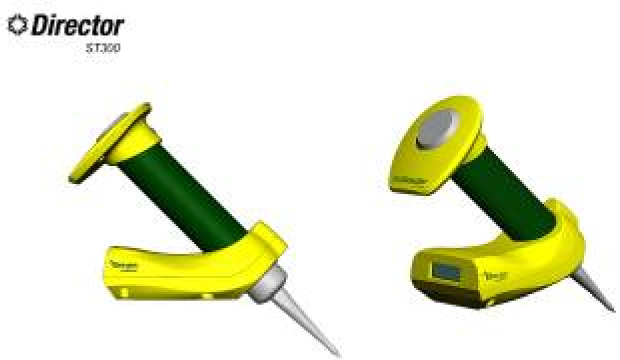
Director HM200

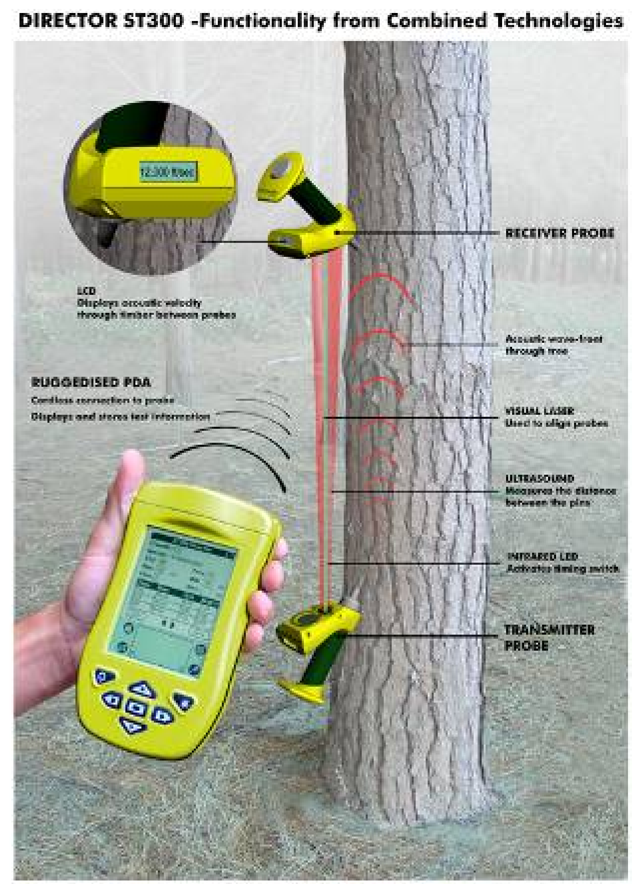
- fibre-gen,New Zealand
- www.fibre-gen.com



Director ST 300

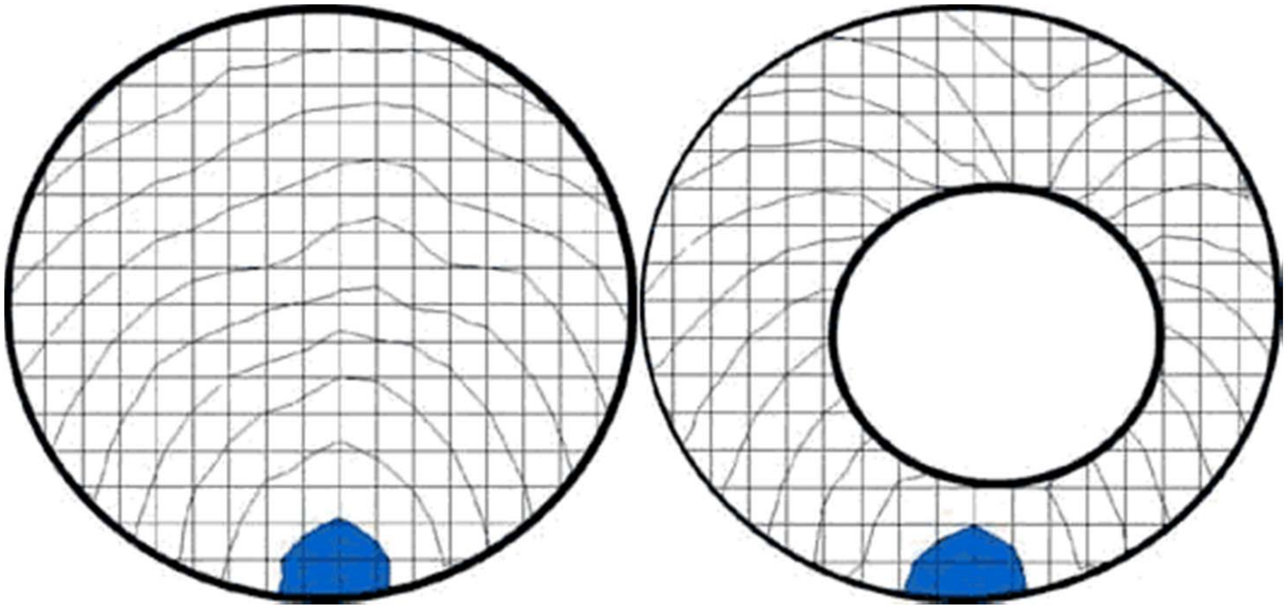
- fibre-gen, New Zealand
- www.fibre-gen.com





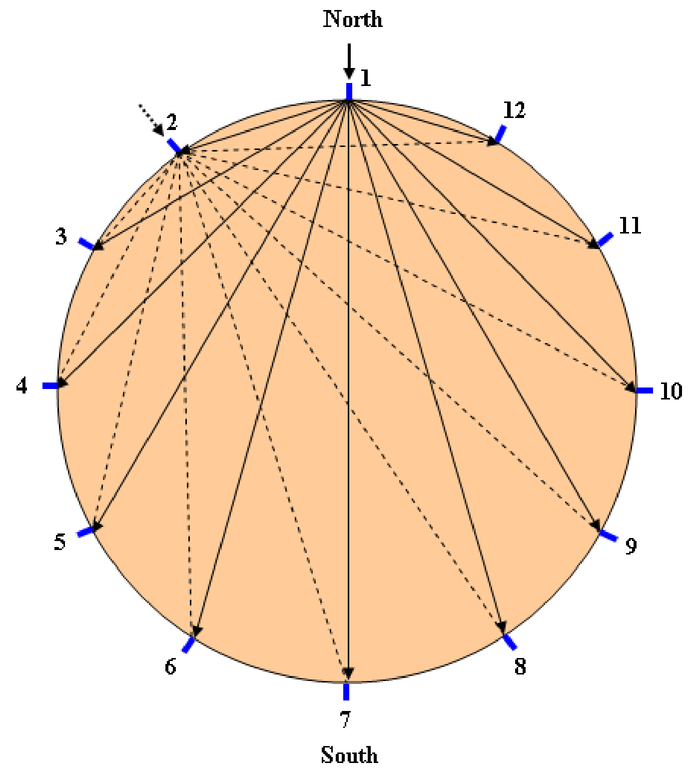
Acoustic Tomography

- Concept: Acoustic wave propagation is adversely affected by wood deterioration caused by any organism.



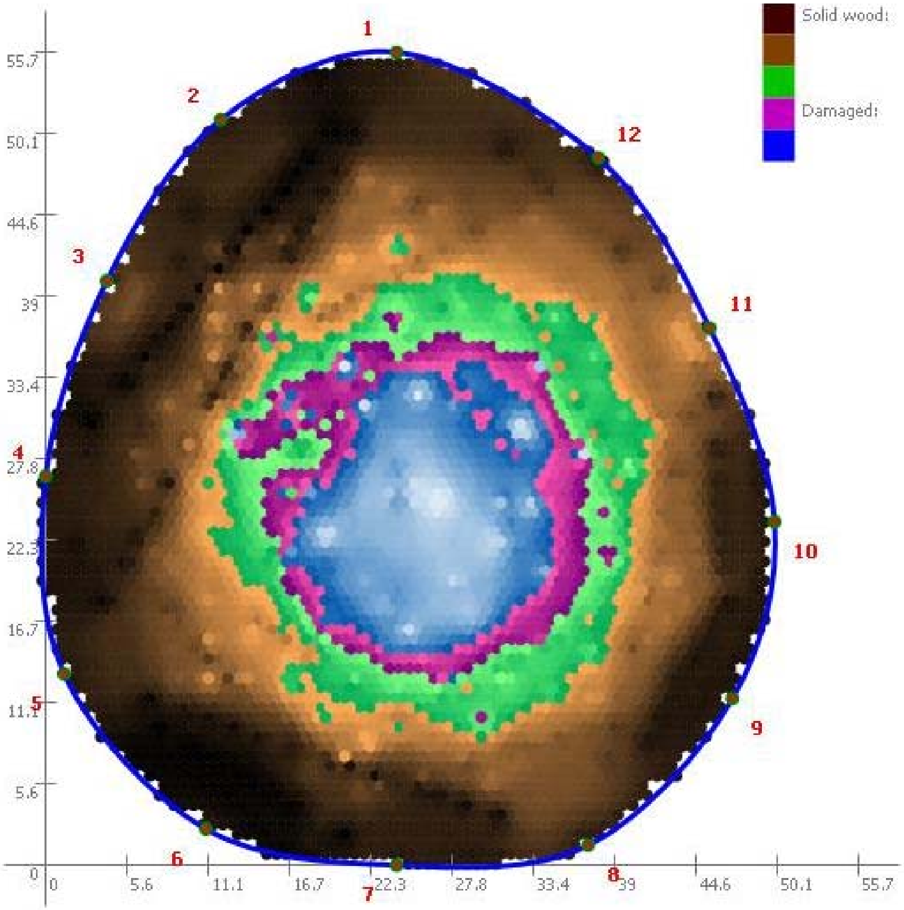
Application

- Decay detection in live trees, pilings, utility poles.
- Typically 6 to 32 acoustic sensors are placed around the stem at the level to be tested. A hammer tap on a sensor generates stress waves propagating through the tree, which are received and measured by all the other sensors.
- A software records the transit time data, calculates the velocities at different paths, and generates a two dimensional velocity distribution (tomogram) of the cross section.
- Decay or cavity appear on the tomogram image.



Tomogram - Picus

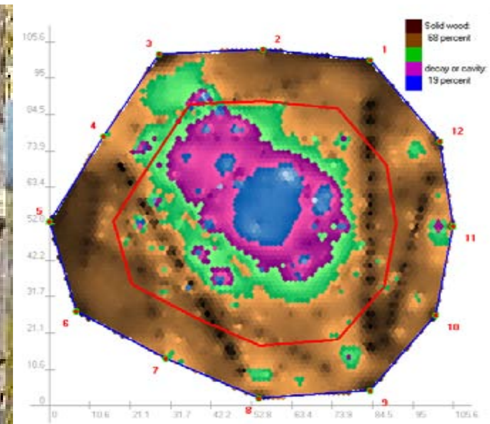
- In application, colors indicate physical conditions
- Brown represents sound wood
- Green, purple, blue indicate increasing degree of decay

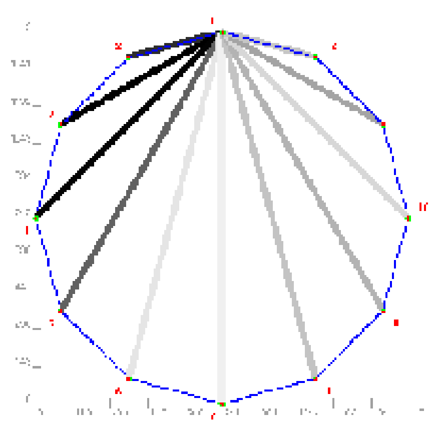


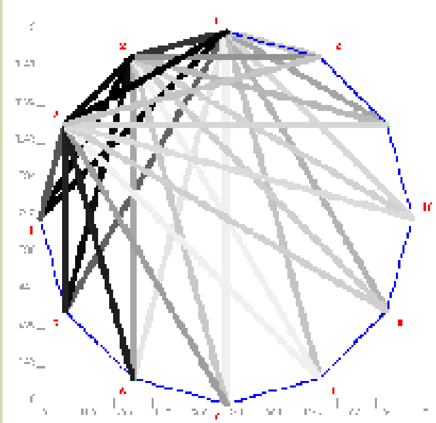
Acoustic tomography systems

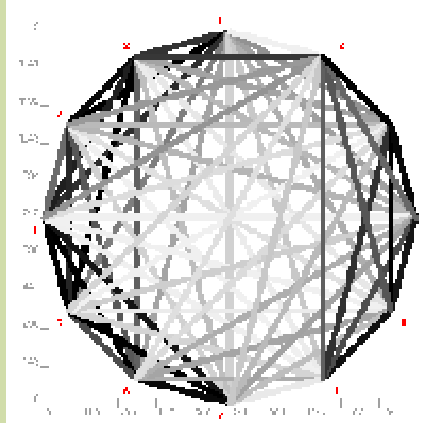
- PICUS Sonic Tomograph, Germany
- FAKOPP 2D Timer, Hungary
- ARBOTOM ®, Germany

PICUS SONIC Tomograph









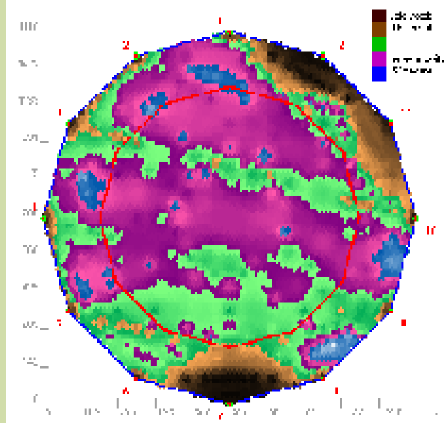
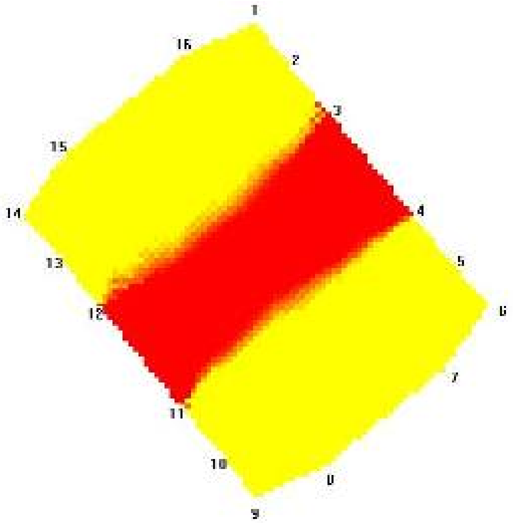


Image source is www.tree-test.com

Mast Inspection of U.S. Brig Niagara

Fakopp Acoustic tomograph



ARBOTOM®

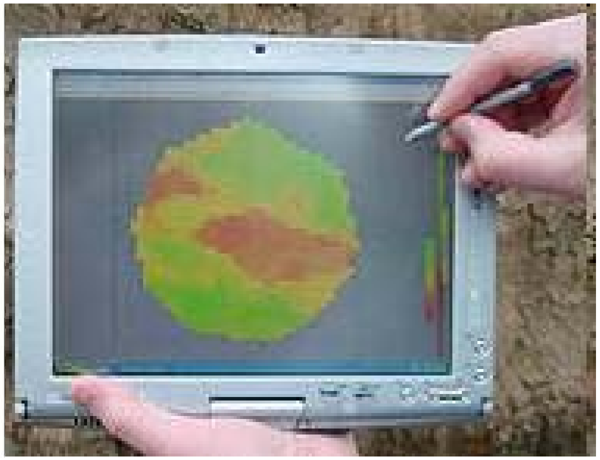
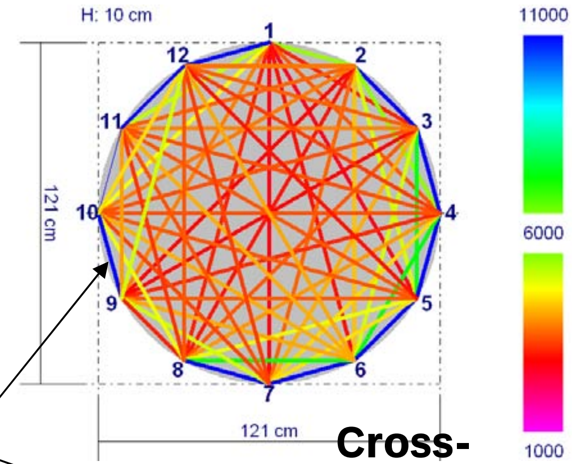


Image source:www.rinntech.de

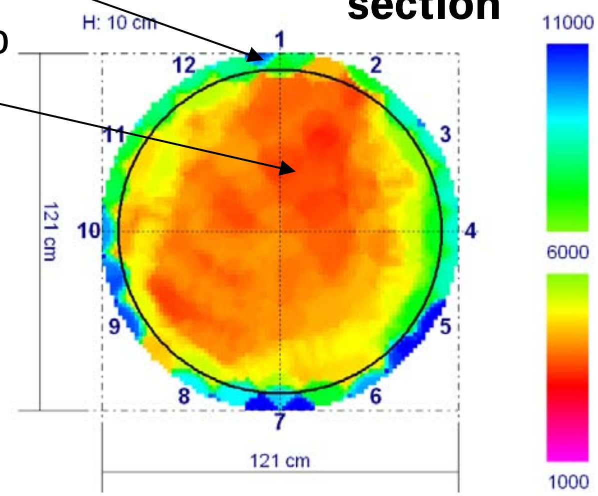
Arbotom® at concrete = PICOTOM

Testing of new and old concrete, steel and compound structures in order to find cracks and other signals of beginning or further decay.
The stress wave speed was shown to be a significant measure for identifying damages even in early stages – on a non-destructive way.



Strong shell but missing connection to the weak central part.

Cross-section



In-Place Assessment Methods

What to look for

- Species
  - Species ID
- Quality/Property
  - Grade stamp
  - Visual characteristics
  - Properties
- Condition
  - Mechanical and biological damages
  - Fire and chemical damages

Historical documents

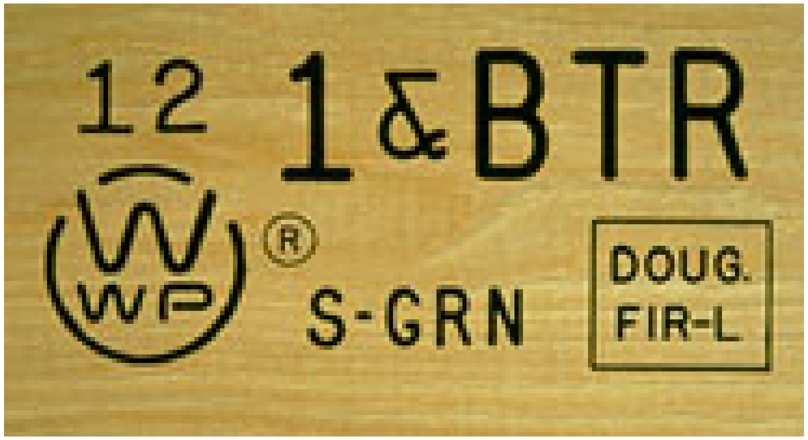
- Design and construction drawing
- Records of structural modifications
- Uses of structure
- Extreme environment conditions
  - Earthquake
  - Hurricane
  - Tornado

Species Identification

- Visual Examination
- Microscopic Examination
  - Wood samples
  - University or extension specialists
  - USDA FPL
    - Wood Anatomy Research Center

Quality – Grade level

- Grading Rules
  - Visual grading rules
  - Machine grade or product stamps
- Visual Characteristics
  - Knots
  - Slope of grain
  - Warp
  - Check/split
  - Decay



SEL STR
S-GRN
DOUG. FIR-L
MILL 10
DENSE NO.1
2050 f PARA 124-bb
S-GRN
DOUG FIR
WC LB
MC 15
1550f
NLGA
No 1
S-GRN
HEM-F
00
SPIB
No.2 MG
MC 15
1550f
7
MILL 10
WC LB
2100 f 1.8E
MSR
HEM-FIR
S-DRY
STAND D.FIR
CFI
MILL 10
NO. 1
S-DRY
WC LB
SPIB No.1 KD 7
2050
DOUG FIR

Condition Assessment
- Conventional Inspection Methods

- External Deterioration
  - Visual
  - Probing
- Internal Deterioration
  - Sounding
  - Drilling and Coring
  - Stress Wave Timing
  - Moisture Meters

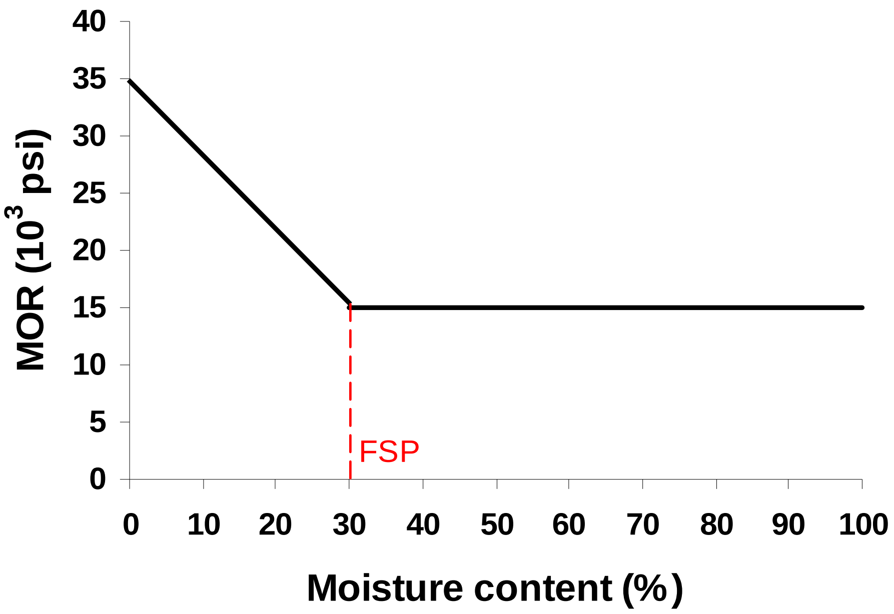
Inspection Equipment

Visual Inspection

- Look for the obvious
  - Foundation failure (sloping floor, cracks in walls, other evidence of settlement)
  - Signs of distress (collapsed, failed members, excessive deflections)
  - Missing members
  - Fruiting bodies
  - Sunken faces or localized surface depressions
  - Staining or discoloration
  - Plant or moss growth in splits, cracks
  - Insect damage
  - Fire damage

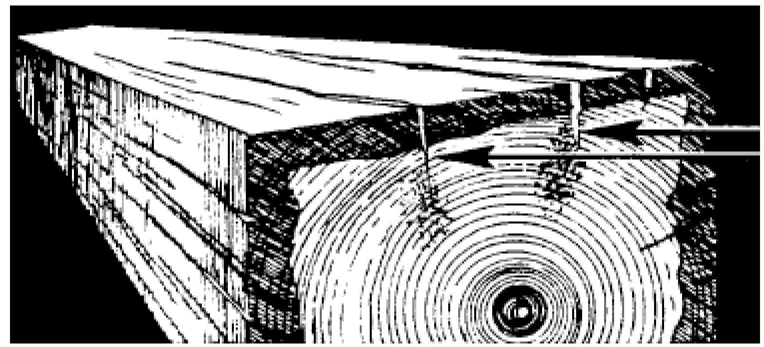
Fiber saturation point (FSP)

- Water exists in two forms in wood
  - Free water (cell cavities)
  - Bond water (chemically bonded within the cell walls)
- FSP (30%) - the point at which the cell cavities no longer contain water, but the cell walls are completely saturated with bond water.
- As MC drops below the FSP, the physical and mechanical properties of wood begin to change as a function of MC



Corrosion of metal fastener

- Fasteners lose thickness or cross-section
- Chemical by-product attacks the wood





Circled areas show mold fungi growing on wooden beams



I-01

Obvious Concerns

Probing

- Use an awl or knife to probe areas of suspected decay or insect damage
  - A splintered break reveals sound wood
  - A brash break indicates decayed wood
  - Use caution on water softened versus decayed wood

Sounding

- Old and commonly used technique
  - Requires some skill
  - Provides only a partial picture of the extent of decay
  - Will not detect decay in early stages
- Verify using additional techniques

Moisture Meter

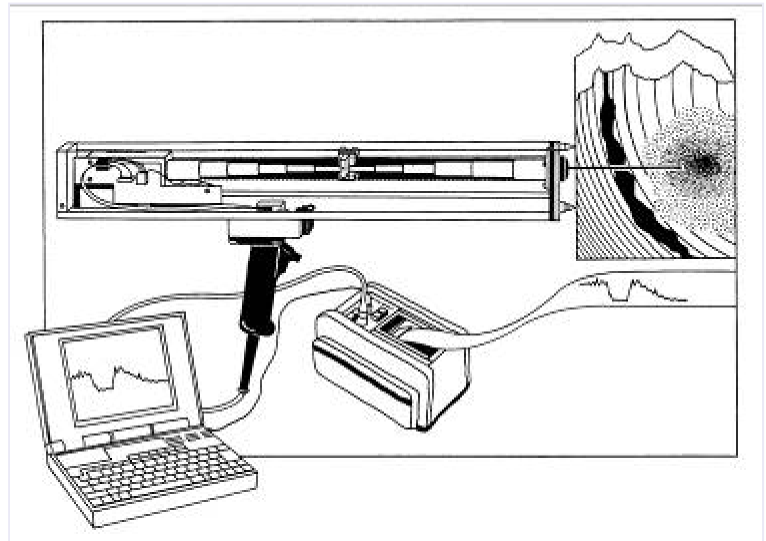
- Moisture content is indicative of the potential for decay
- Recommended as an initial check
- Sound wood
  - Interior moisture content 6-12%
  - Exterior moisture content 10-20%
- Potentially decayed wood
  - Moisture content (20-30%)

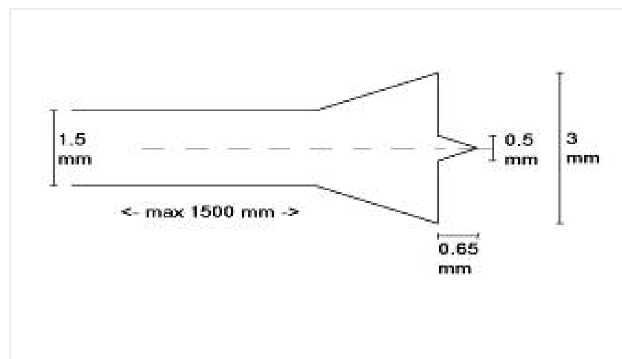
Coring

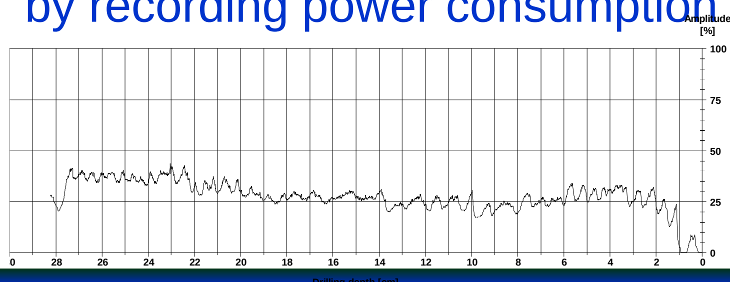
- Use a forestry increment borer
  - Determine voids
  - Allows for analysis of the core sample for presence of decay
  - Potential species ID
  - Determine preservative penetration
- Replug with treated wood dowel

Resistance Micro-Drilling - Resistograph®

- Locate decay and termite damage
- Concept:
  - Drill resistance is well correlated to wood density
  - Measure the relative resistance as a rotating drill bit is driven into the wood.
  - Display relative density profile
- Measurement system:
  - Micro-drill (special needle)
  - Relative resistance is measured by recording power consumption

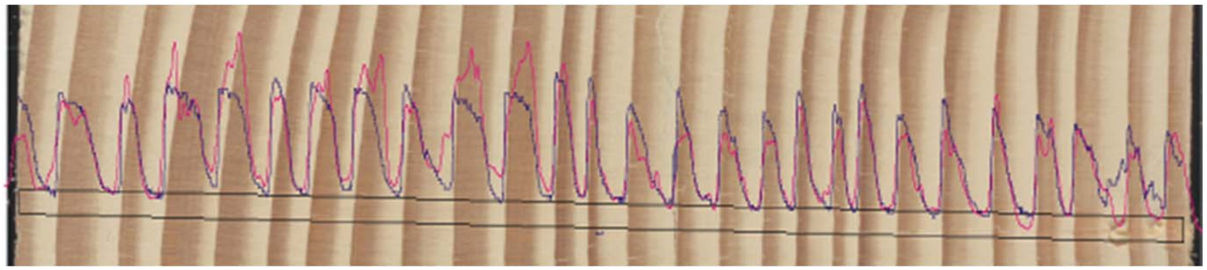




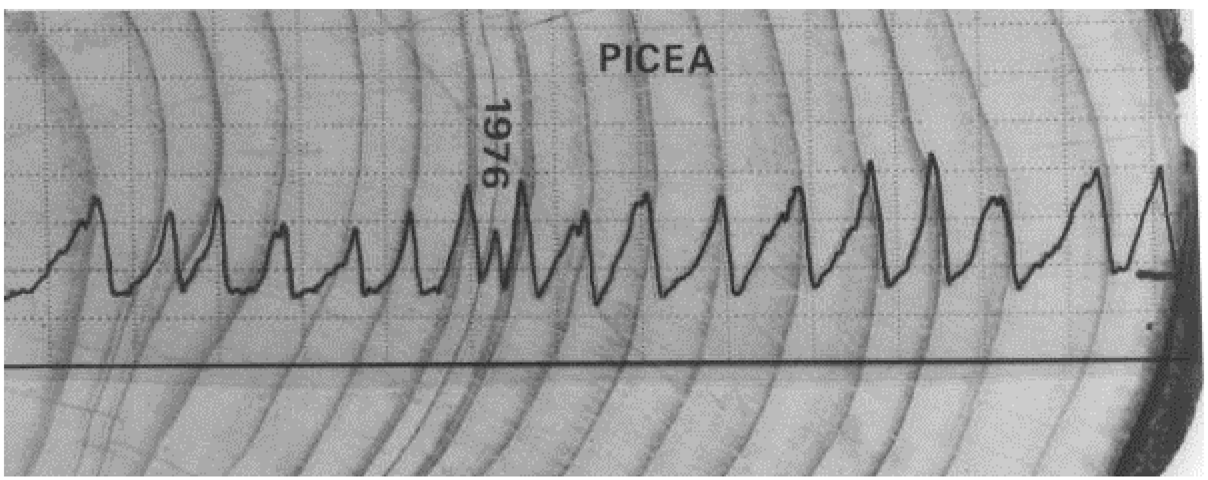


Profiles of intact wood

Drill-resistance profiles show annual rings and density variations



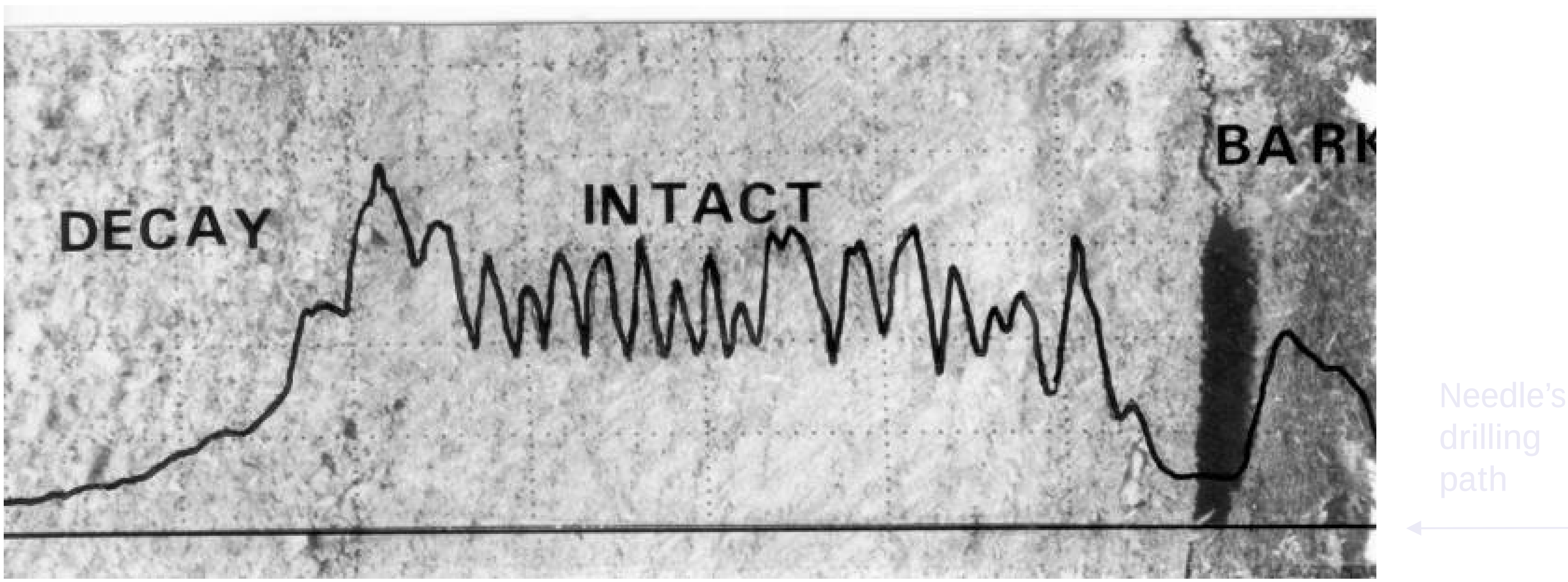
Drill-resistance and grey scale profile of fir (Abies alba Mill.)
including compression wood.



Drill-resistance profile of an intact spruce (narrow ring = dry year 1976).

Frank Rinn 2005

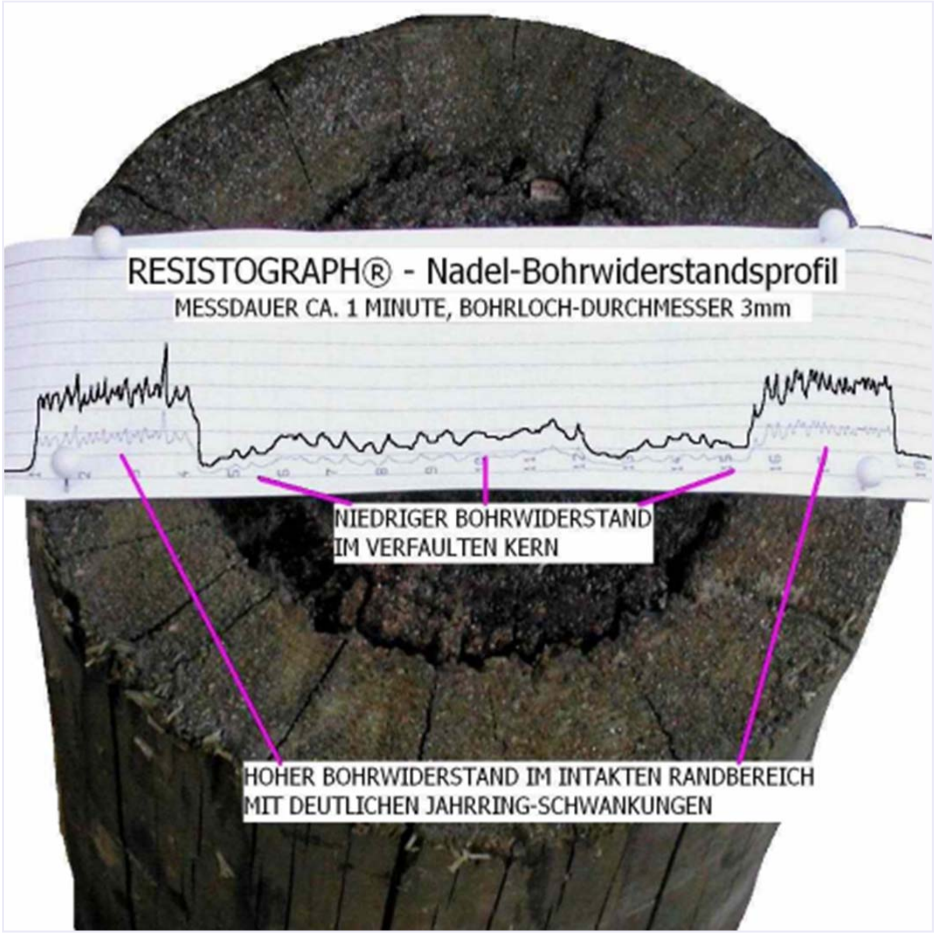
Bark, intact tree rings and decay



- Intact wood => high wood density => high drill resistance
- Decay => lower density => lower drill resistance => low profile values
- Even differences between hard late wood and soft early wood zones of tree rings are visible

Frank Rinn 2005

Internal decay



Frank Rinn 2005

Resistograph Tools

IML, Inc.

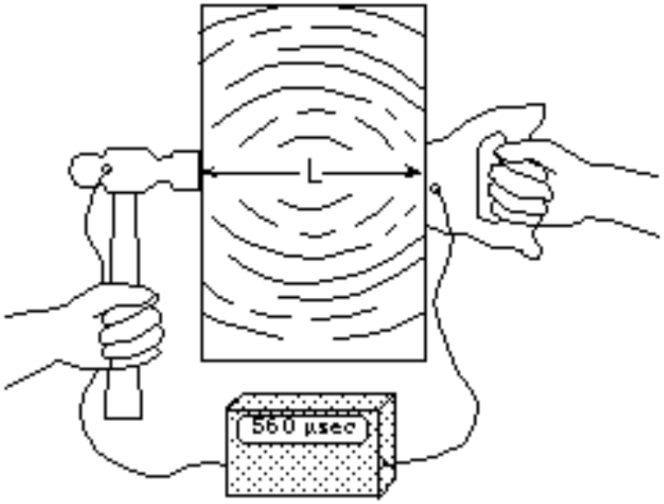
- Kennesaw, GA
- www.imlusa.com
- Email: Info@imlusa.com

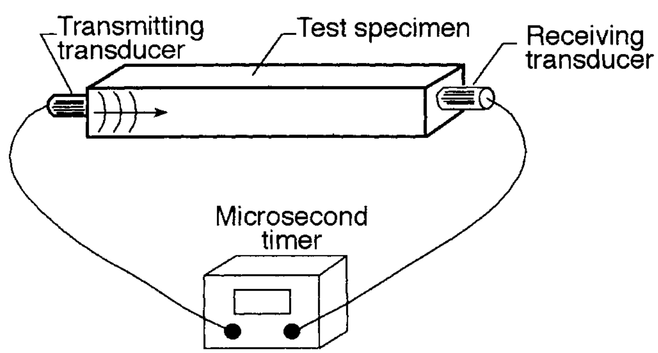
Rinntech, Inc.

- Haidolborg, Germany
- www.rinntech.com
- Email: infor@rinntech.com

Stress Wave Timing

- Stress wave is induced into wood perpendicular to grain.
  - ➢ Impact
    - – Accelerometer monitors waves and starts timer
    - – Backside accelerometer monitors the waves arrival and stops the clock
    - – Timer displays transit time or velocity
  - ➢ Ultrasound





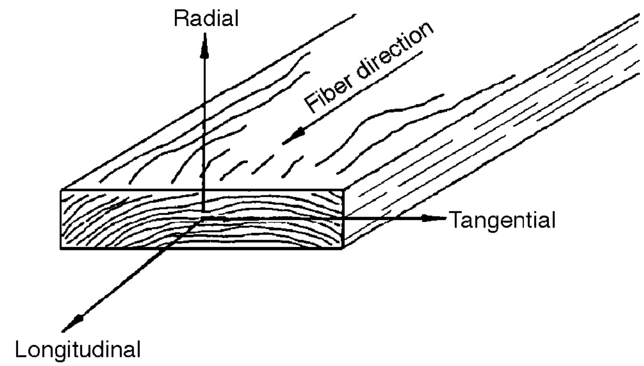
Concept and limitations

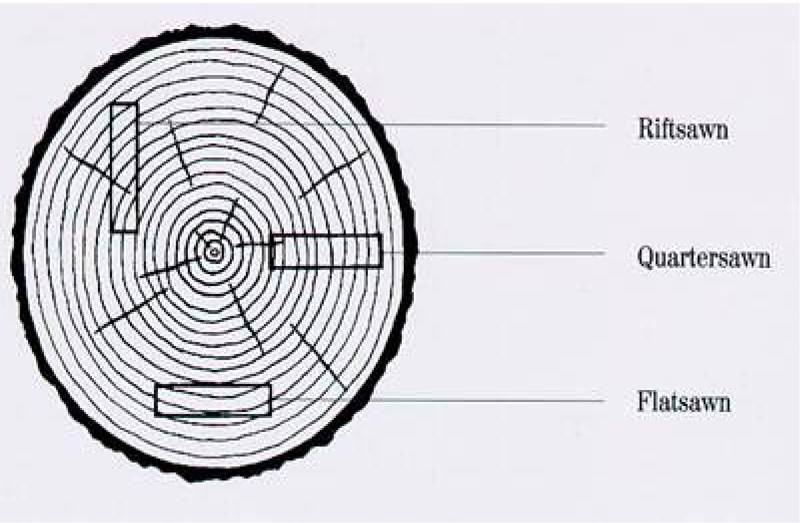
- Concept
  - Stress wave velocity is sensitive to presence of degradation in wood members
  - Stress wave travels faster through sound wood than it travels through decayed wood

- Limitations
  - Require to access both sides of the member
  - Effective in large solid timbers or glulam members (>3.5 in.)

Stress Wave Basics

- Wood is anisotropic, therefore stress waves travel at different speeds in different directions
- Douglas fir 12% MC
  - Longitudinal ≈ 60 μs/ft
  - Radial ≈ 195 μs/ft
  - Tangential ≈ 234 μs/ft
  - Riftsawn ≈ 290 μs/ft





Decay Effect on Stress Waves

- Sound Douglas fir
  - 200 - 300 µs/ft
- Incipient decay
  - 300 - 400 µs/ft
- Moderate
  - 400 - 500 µs/ft
- Severe decay
  - > 500 µs/ft

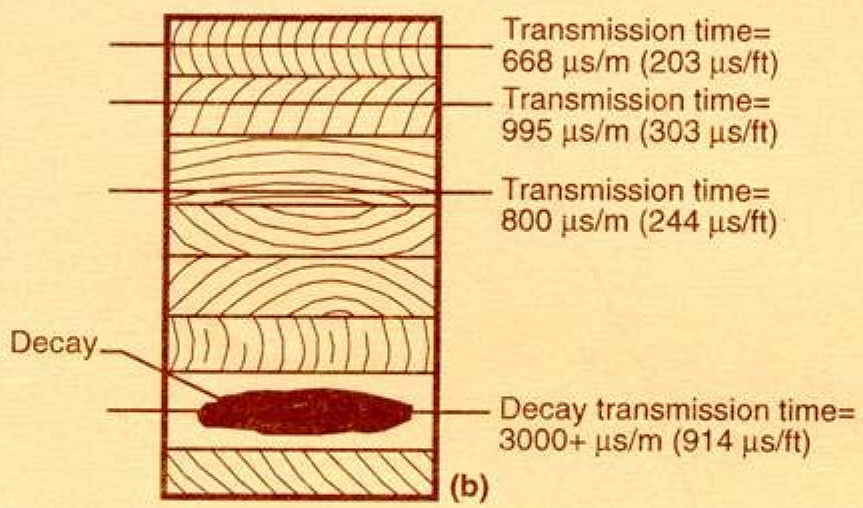
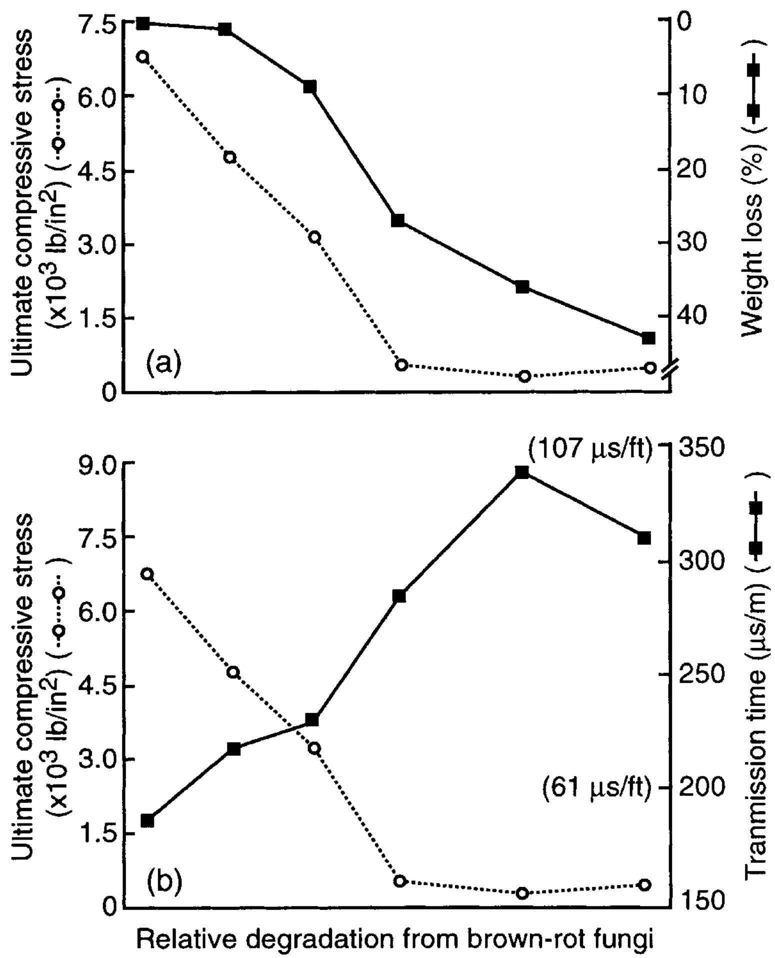
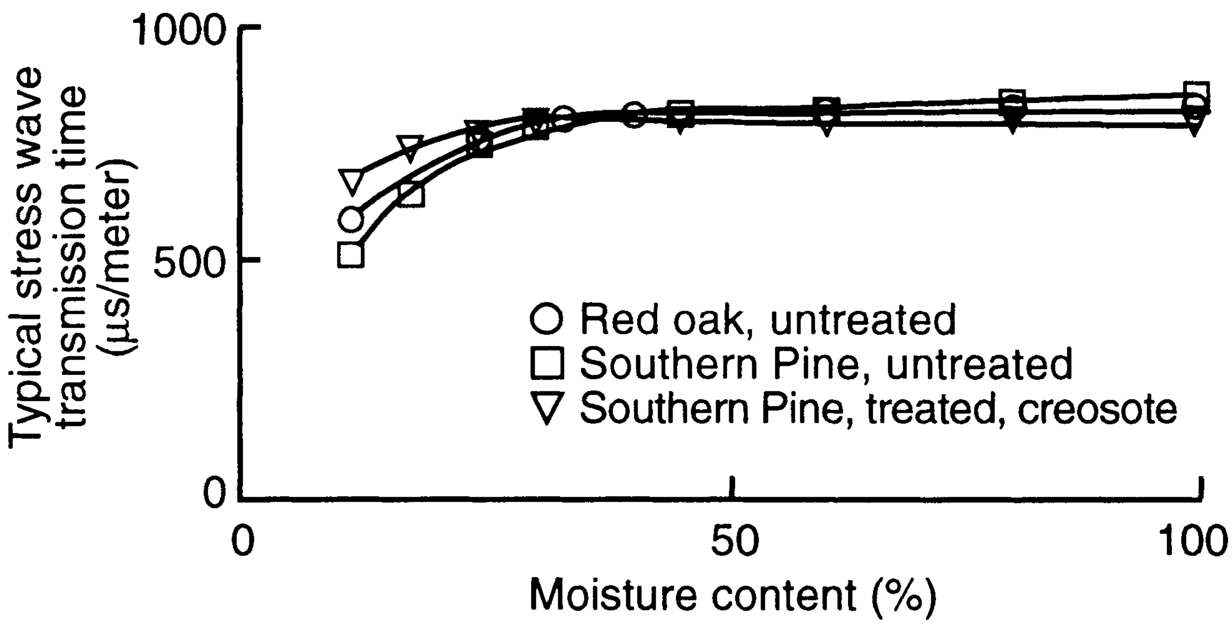


Figure 3—Transverse stress wave paths and transmission times: (a) timber, (b) glulam beam.

Relationship between stress wave transmission time and fungal degradation



Moisture effect



Stress wave transmission time adjustment factors for temperature and moisture content for Douglas-fir

Moisture Content (%)	Adjustment factors			
	-18 °C (0 °F)	3 °C (38 °F)	27 °C (80 °F)	49 °C (125 °F)
1.8	0.94	0.95	0.97	0.98
3.9	0.95	0.96	0.98	0.99
7.2	0.96	0.98	1.00	1.01
12.8	0.97	0.99	1.00	1.01
16.5	0.99	1.01	1.03	1.05
23.7	1.05	1.07	1.09	1.14
27.2	1.07	1.10	1.12	1.17

Procedures

- Establish baseline transmission times for wood species, sizes of members
- Establish testing pattern
- Stress wave scan in likely decay areas and connections
- Follow-up with drilling/coring in questionable areas

Stress wave equipment

- Metriguard Model 239A Stress Wave Timer
  - Metriguard Inc., Pullman, WA

- Sylvatest Duo
  - Concept Bois Technologie, Switzerland

Stress wave equipment

- James “V” Meter
  - James Instruments, Chicago, IL

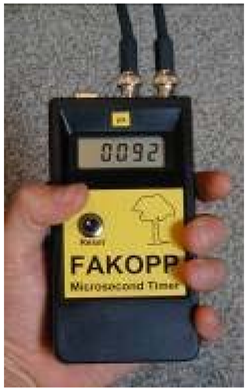
- Fluke Scopemeter w/ Columbia accelerometers

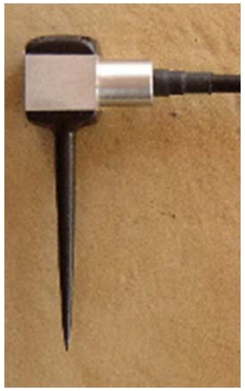
Stress wave equipment

- Impulse Hammer (Electronic hammer)
  - IML USA
  - www.imlusa.com

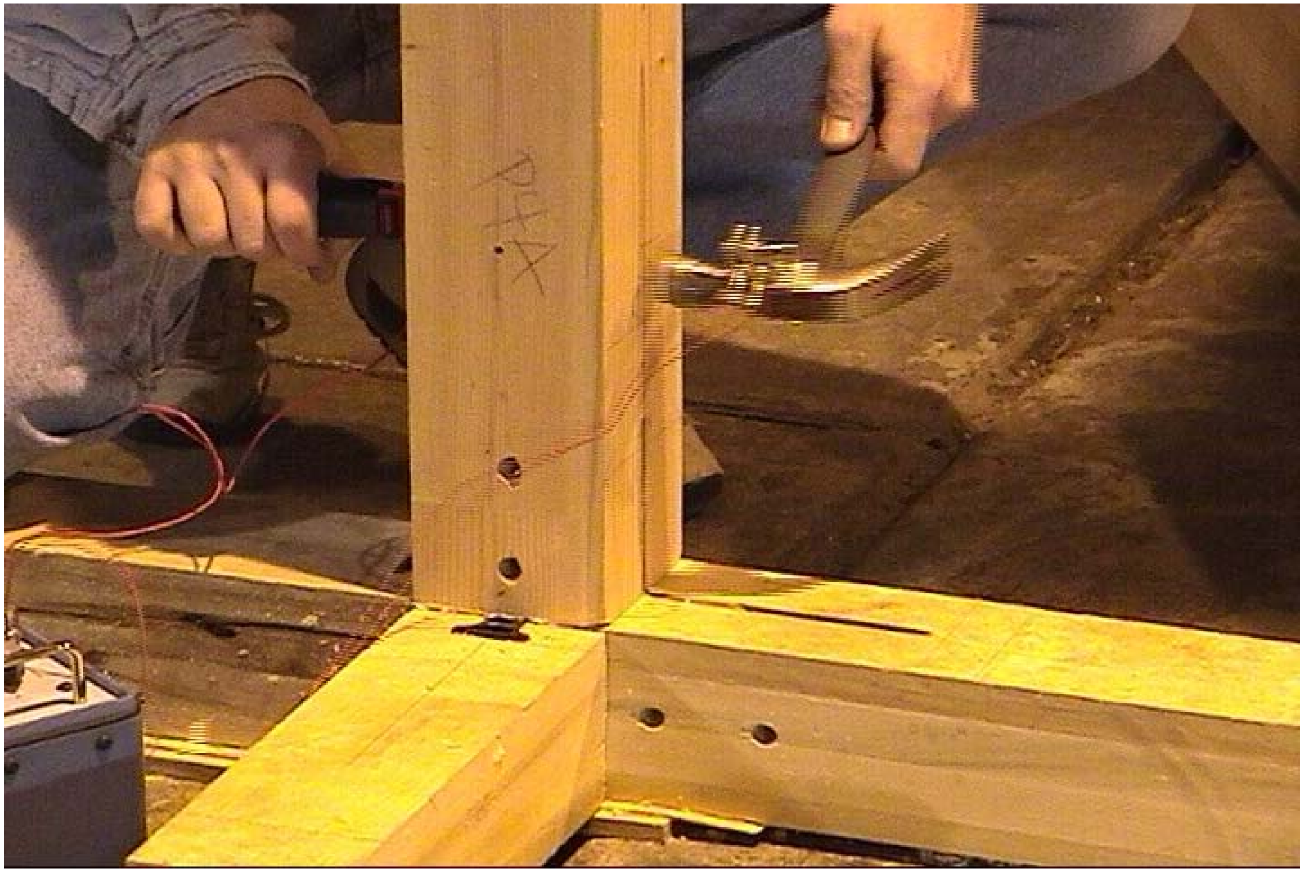
Stress wave equipment

- FAKOPP Microsecond Timer
  - FAKOPP Enterprise, Hungary
  - www.fakopp.com





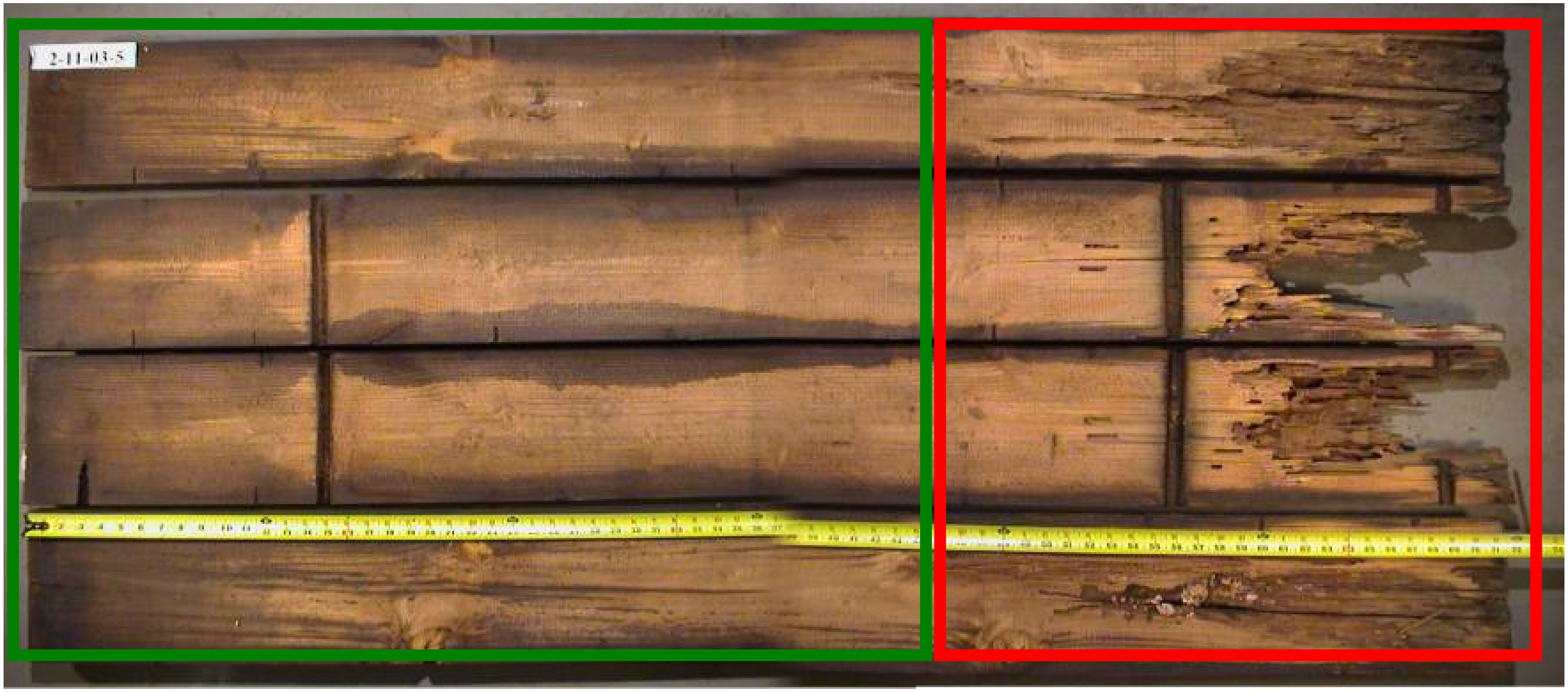
Impact stress wave (Metriguard 239A)



Ultrasound (Sylvatest Duo)

Timber Specimen

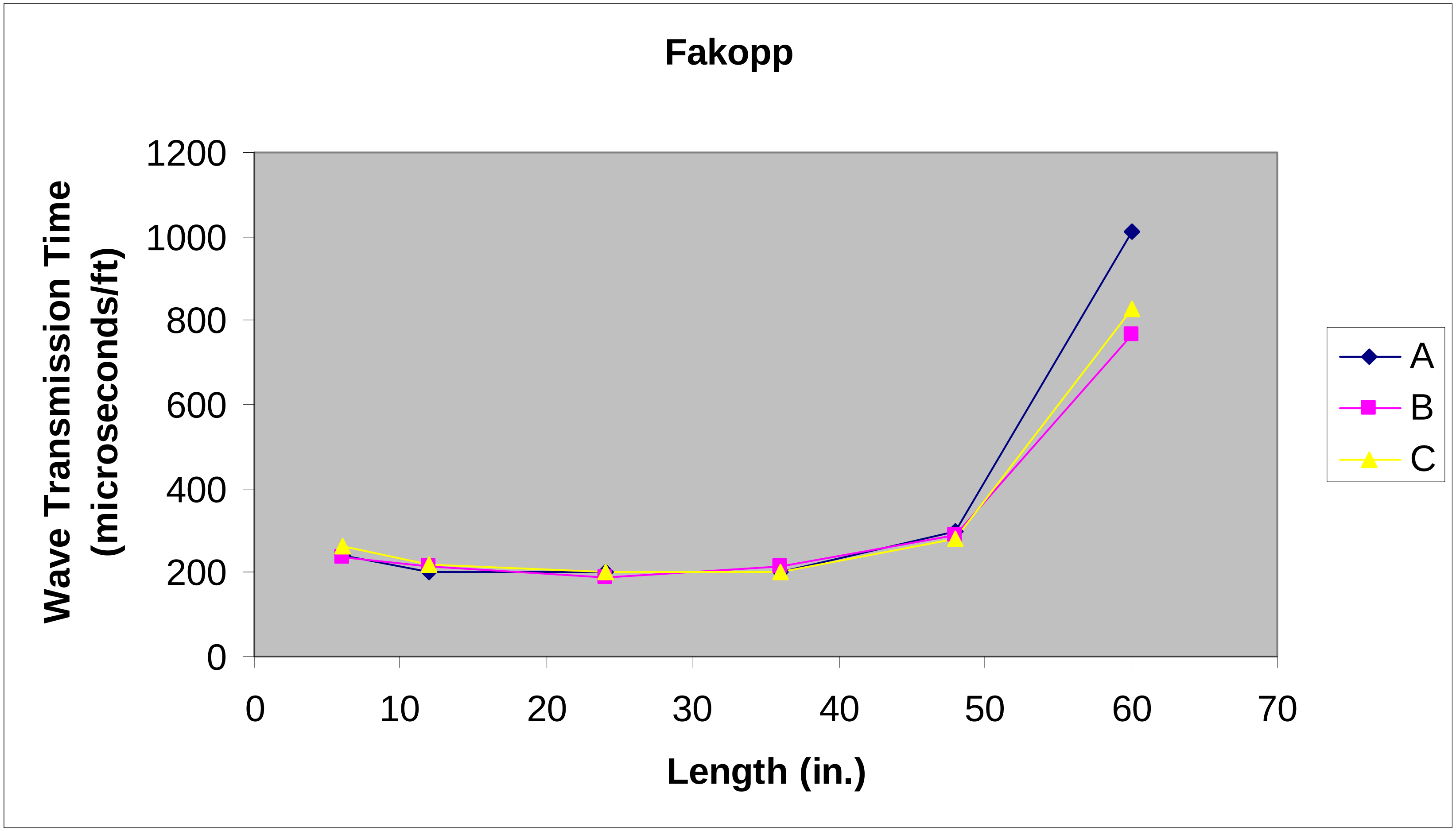
Sliced Timber Specimen



SOUND WOOD

DECAY

Fakopp Microsecond Timer



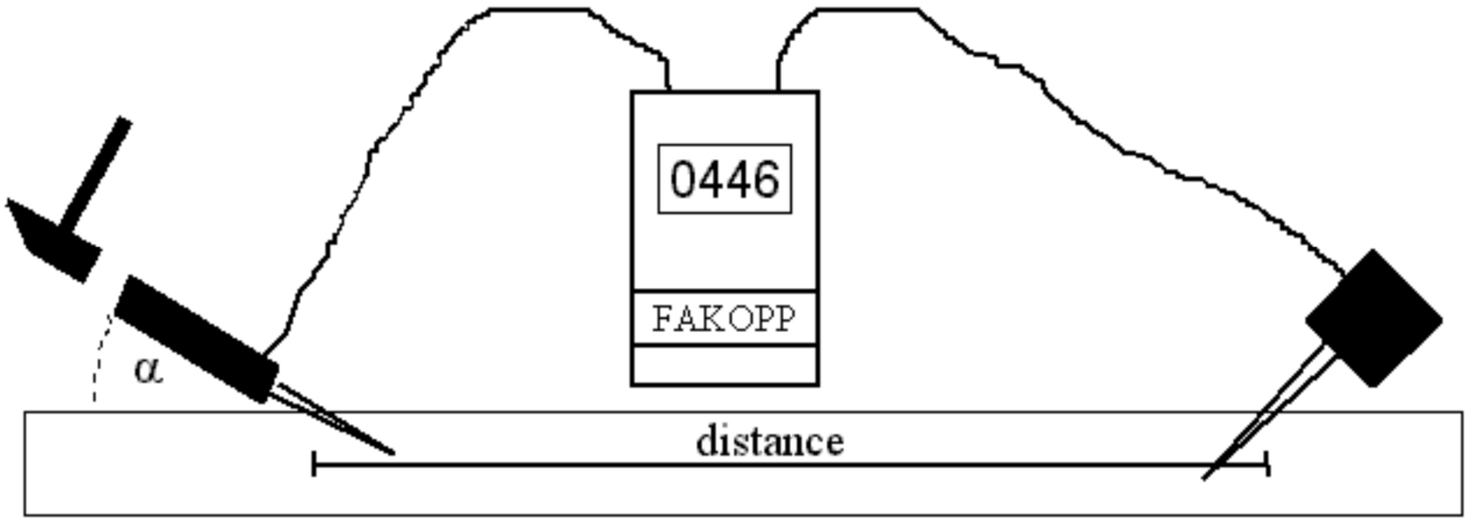
Fakopp Microsecond Timer

	Stress Wave Transmission Times (microseconds/ft)			
Species	Sound Wood	Moderate Decay	Severe Decay	Splits
Douglas fir	130-260	300-400	500+	300-700
Western red cedar	160-300	300-400	500+	300-500
Southern yellow pine	220-250	No results to report		
White pine	230-325	No results to report	500+	No results to report

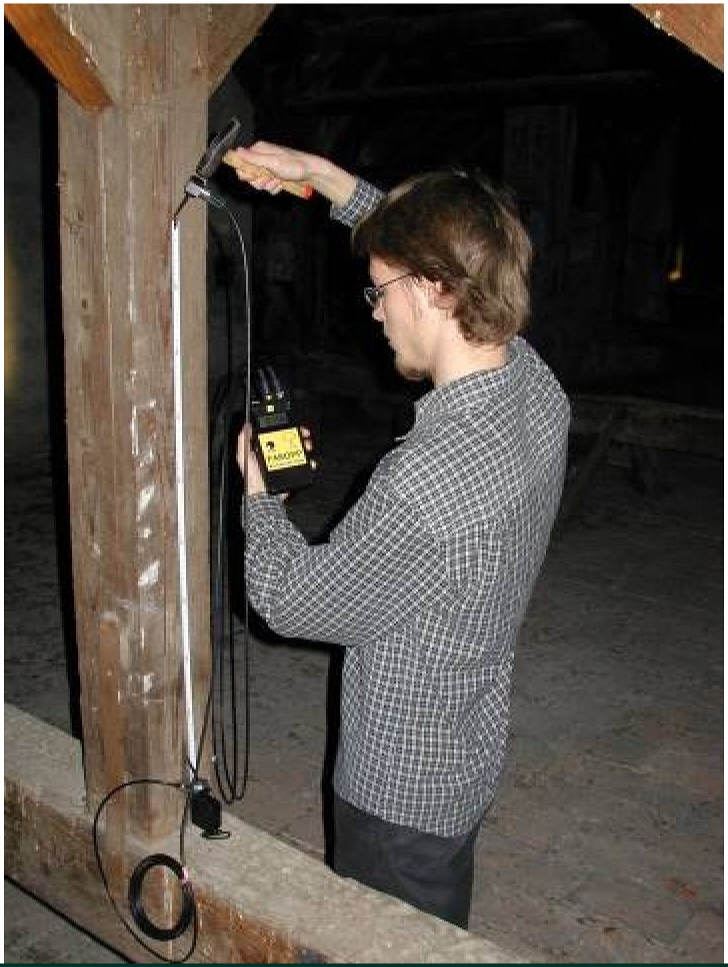
Prediction of Residual Strength of Structural Members

- Possible NDE prediction parameters:
  - Stress wave speed (V)
  - Screw withdrawal resistance (F)

Determine stress wave speed in a wood member



(Ferenc Divos, University of Western Hungary)



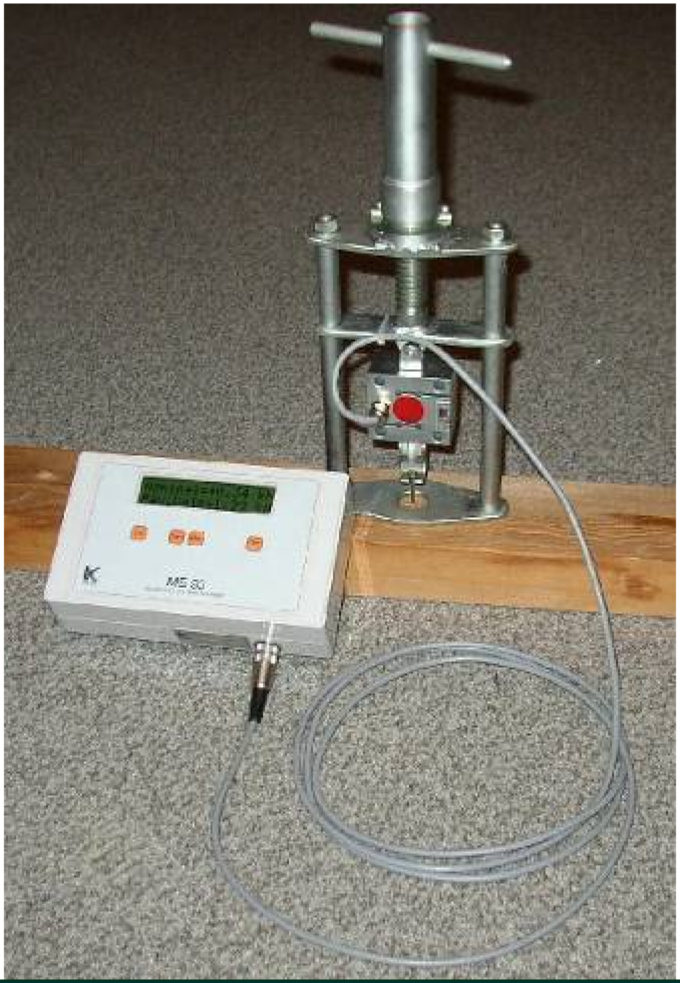
Screw withdrawal resistance

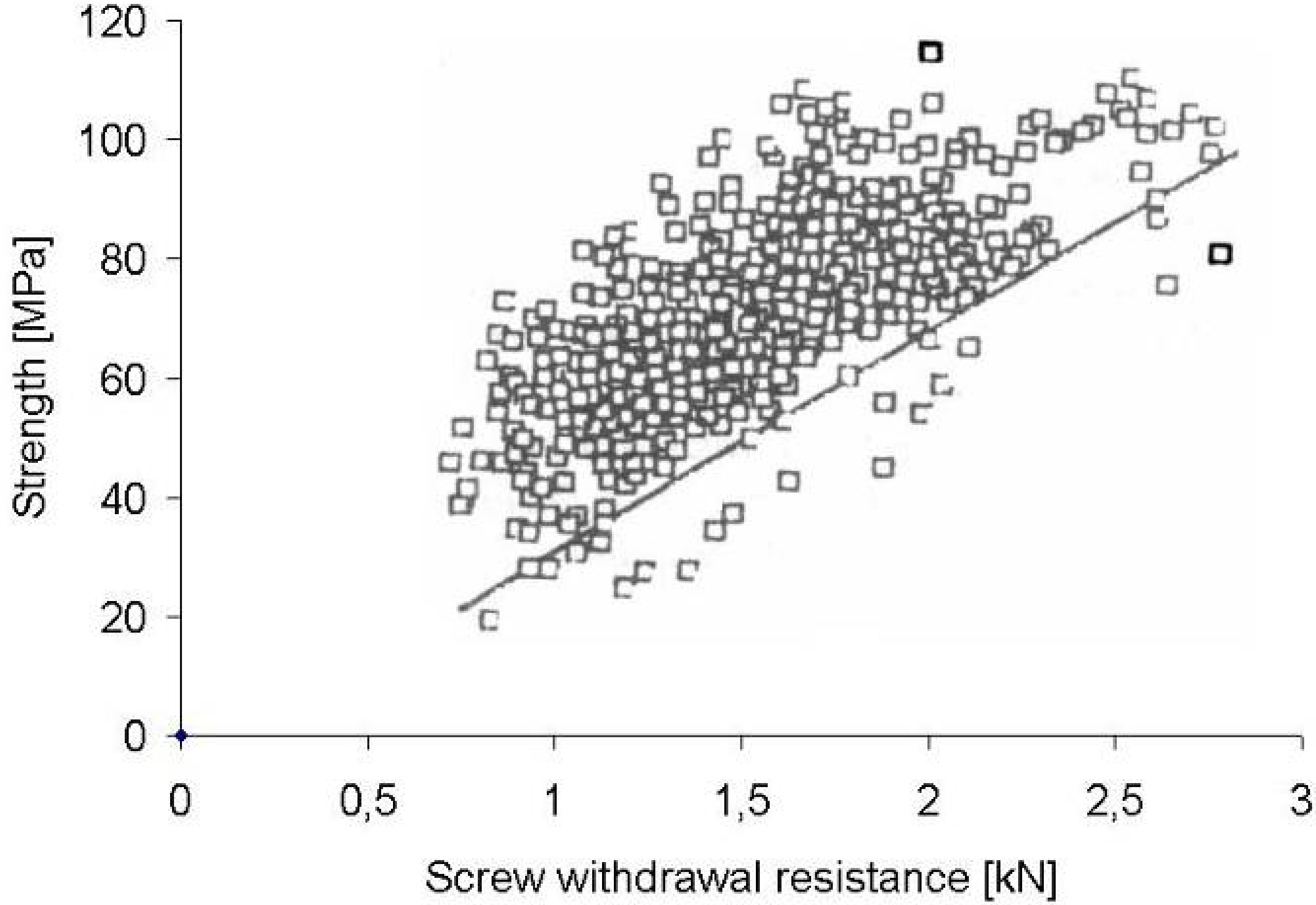
- **Concept:** the force a screw probe requires to pull out from wood is correlates to the density and bending strength of the wood

- **Applications:** wood structural members, plywood sheathings.

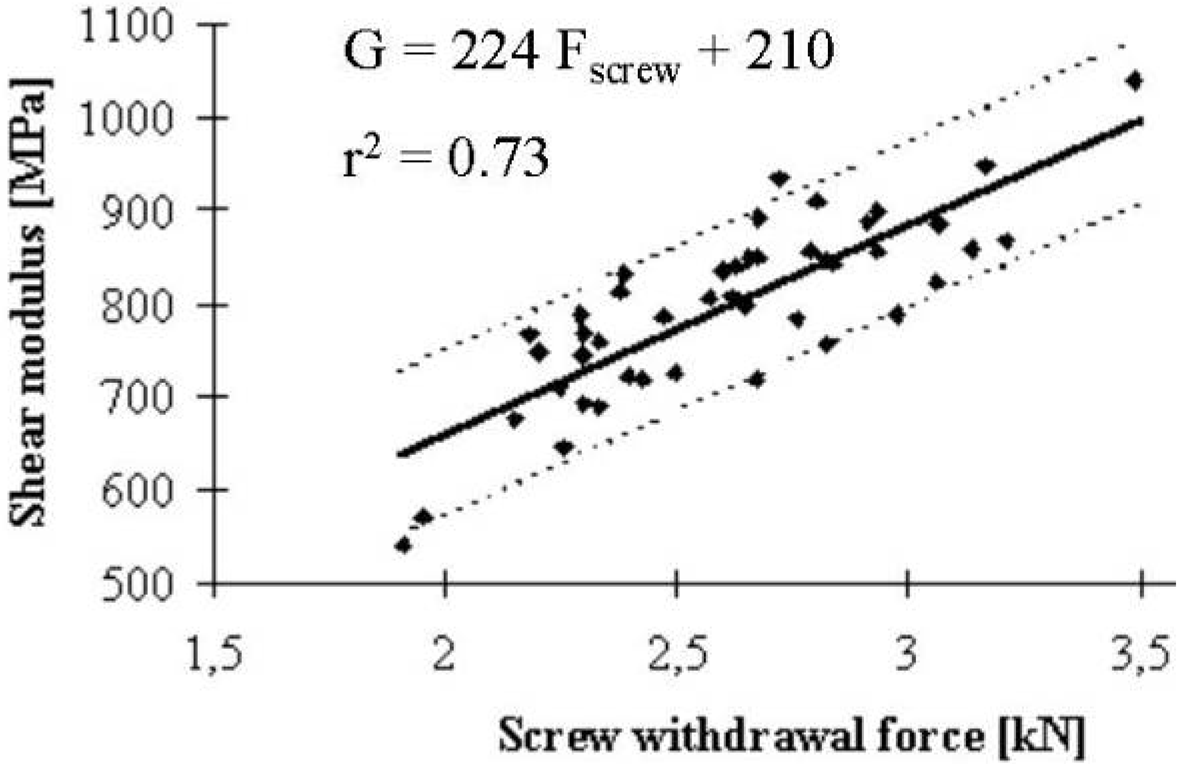
Screw withdrawal meter
(Fakopp Enterprise, Hungary)

- Withdrawal mechanics
  - Screw diameter: 4 mm
  - Thread length: 18 mm.
- Force transducer
- Transducer amplifier
- Display unit
- Implementation
  - A 2.7 mm diameter hole is made in the wood member, perpendicular to the surface, to accommodate the screw.
  - The screw is slowly (0.2 - 0.4 mm/s) pulled out, and
  - The maximum force value is displayed and recorded by the instrument.





120
100
80
60
40
20
0
Strength [MPa]
0
0,5
1
1,5
2
2,5
3
Screw withdrawal resistance [kN]



$G = 224\ F_{screw} + 210$
$r^2 = 0.73$
Shear modulus [MPa]
1100
1000
900
800
700
600
500
1,5
2
2,5
3
3,5
Screw withdrawal force [kN]

Formulation of strength predictor

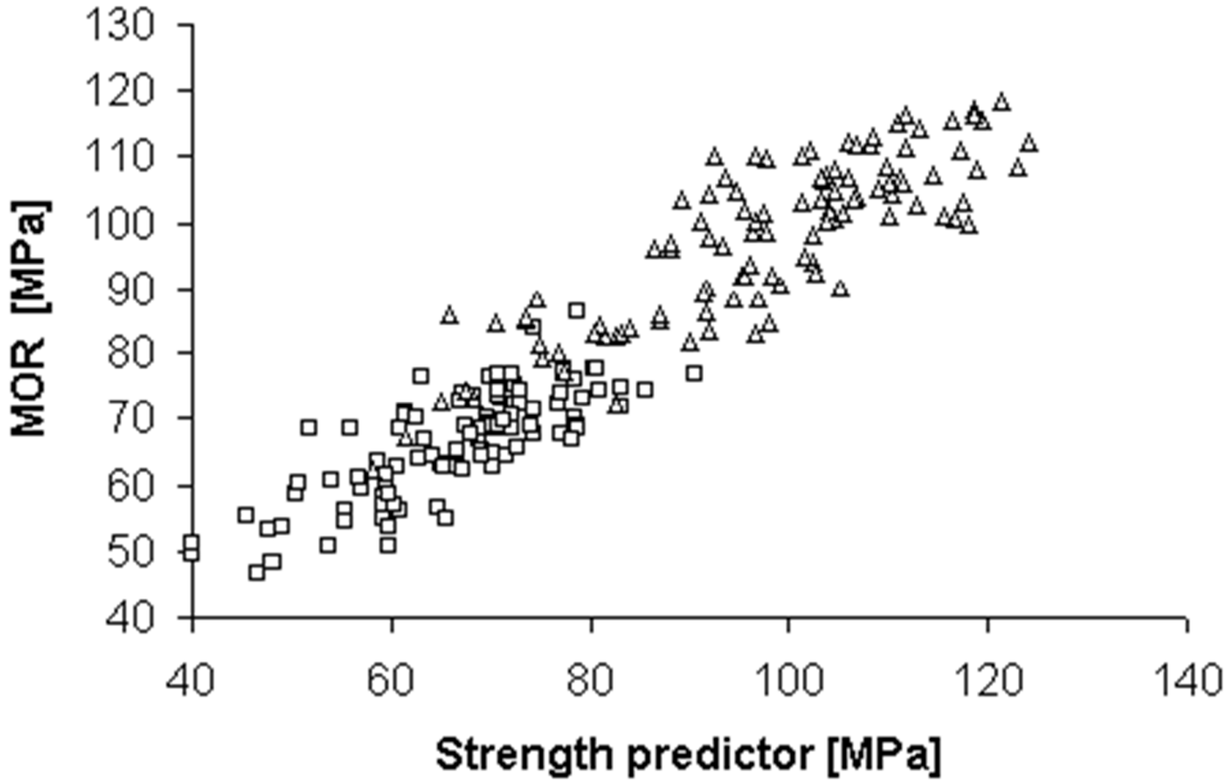
- The fundamental strength predictor:

$$MOE = V^2 \rho \qquad \rightarrow \qquad MOR$$

- Screw withdrawal force (F) is correlated with density ρ.

- Formulated strength predictor:

$$MOR' = aFV^2 + b$$



(Ferenc Divos 2004)

Strength prediction models

- Softwood

$$MOR' = 0.809FV^2 + 26.8$$

- Hardwood

$$MOR' = 1.258FV^2 + 36.9$$

- Units
  - MOR' – MPa
  - F – KN
  - V – Km/s

(Ferenc Divos 2004)

Inspection of Wood Structures

- Historic Wood Ships
- School Gymnasium
- Trestle
- Timber Bridge

Historic Wood Ships

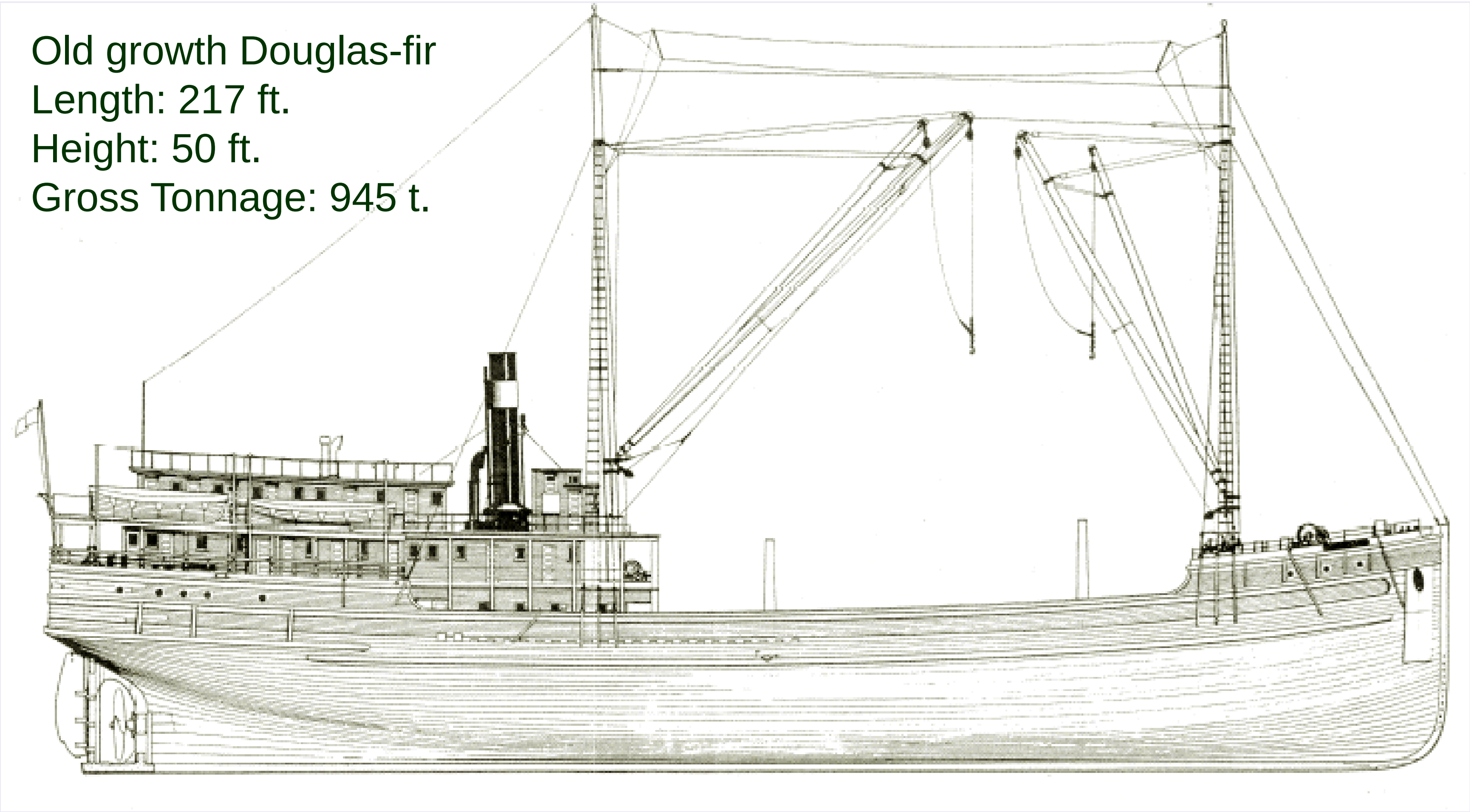
California

Wapama
- A Historic Steam Schooner

Built in 1915
Designed for lumber trade and coastwise service
In-service thru 1945
Declared as a NHL in 1984

Profile View - Starboard

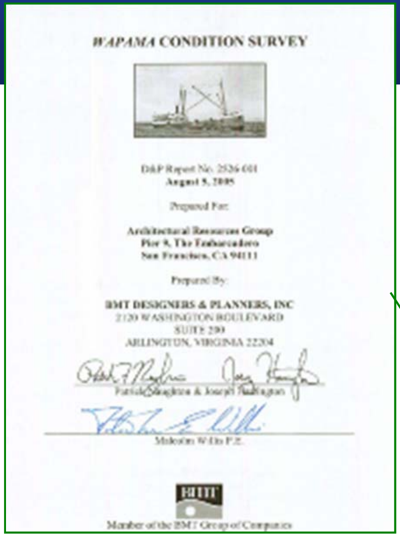
Old growth Douglas-fir
Length: 217 ft.
Height: 50 ft.
Gross Tonnage: 945 t.



National Historic Landmark

Currently placed on a barge at Richmond Reserve Shipyard
in Richmond, California

Inspection Planning



***WAPAMA* CONDITION SURVEY**

D&P Report No. 2526-001
August 5, 2005

Prepared For:

Architectural Resources Group
Pier 9, The Embarcadero
San Francisco, CA 94111

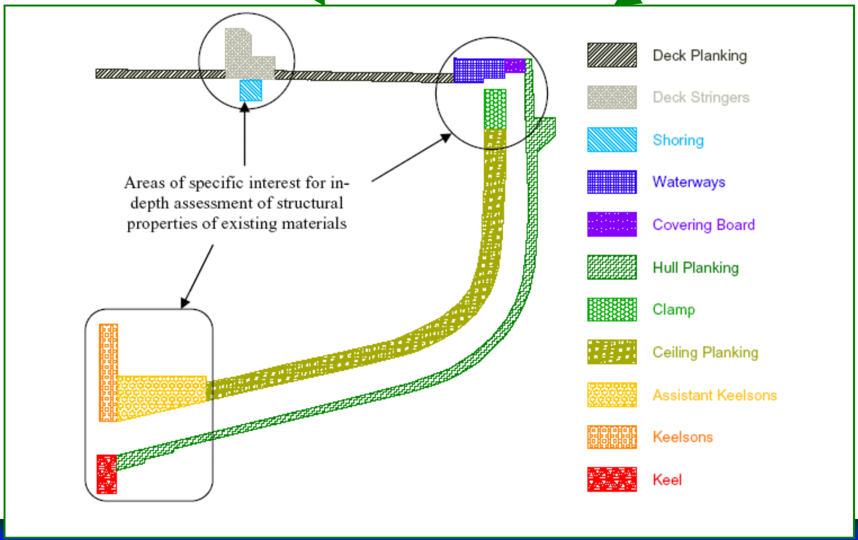
Prepared By:

BMT DESIGNERS & PLANNERS, INC
2120 WASHINGTON BOULEVARD
SUITE 200
ARLINGTON, VIRGINIA 22204

Patrick Slaughter & Joseph Hadfington

Malcolm Willis P.E.

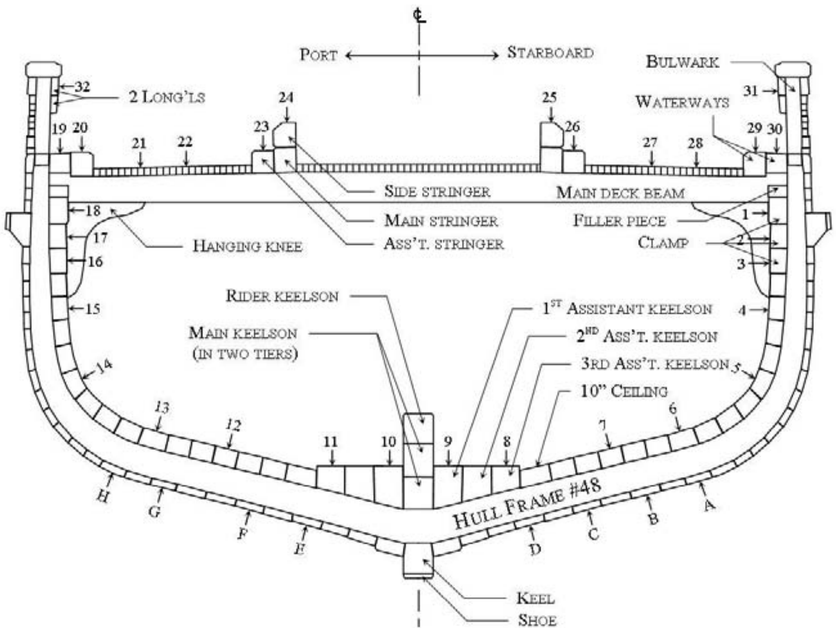
Member of the BMT Group of Companies



Inspection Focus

- Nondestructively determine the internal physical condition of the key structural elements of the vessel that are difficult to assess by visual inspection.

  - **Keelsons/Assistant keelsons**
  - **Keel**
  - **Ceiling planks**
  - **Hull frames**
  - **Clamps**
  - **Main deck beams/stringers**
  - **Waterways**
  - **Hanging knees**

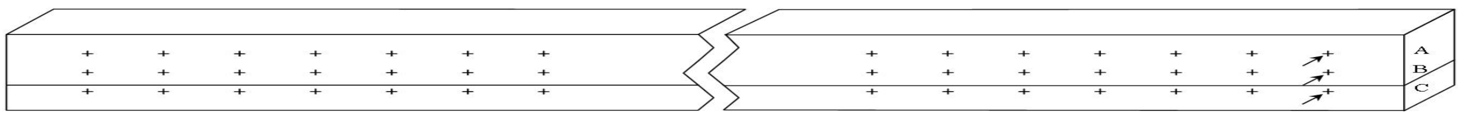


Inspection Methods

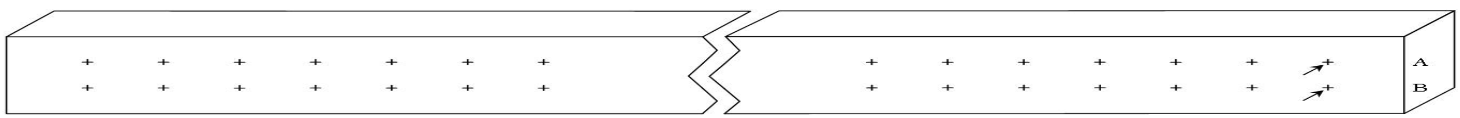
- Stress wave timing
- Resistance micro-drilling
- Moisture examination

Key Longitudinal Strength Members

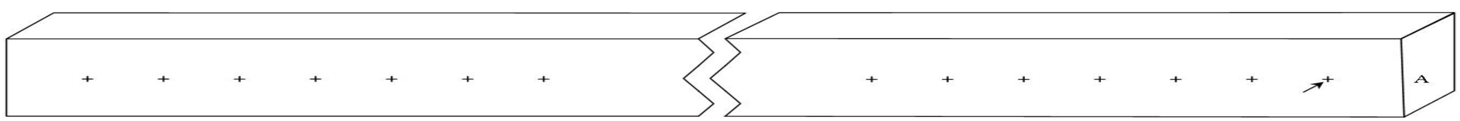
- Stress wave scanning



Keelson

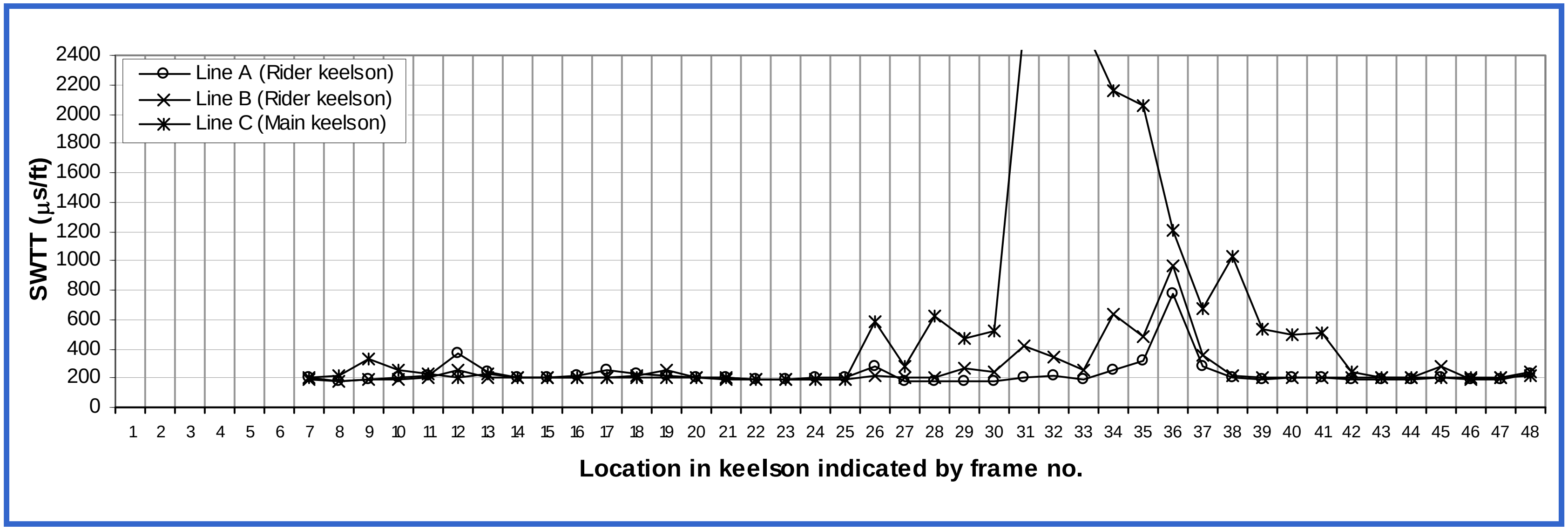


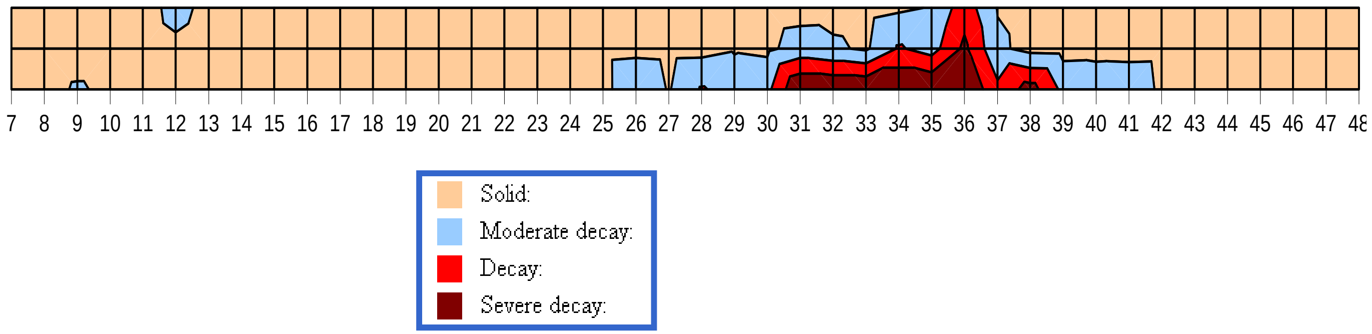
Keel



Main deck stringer, beam

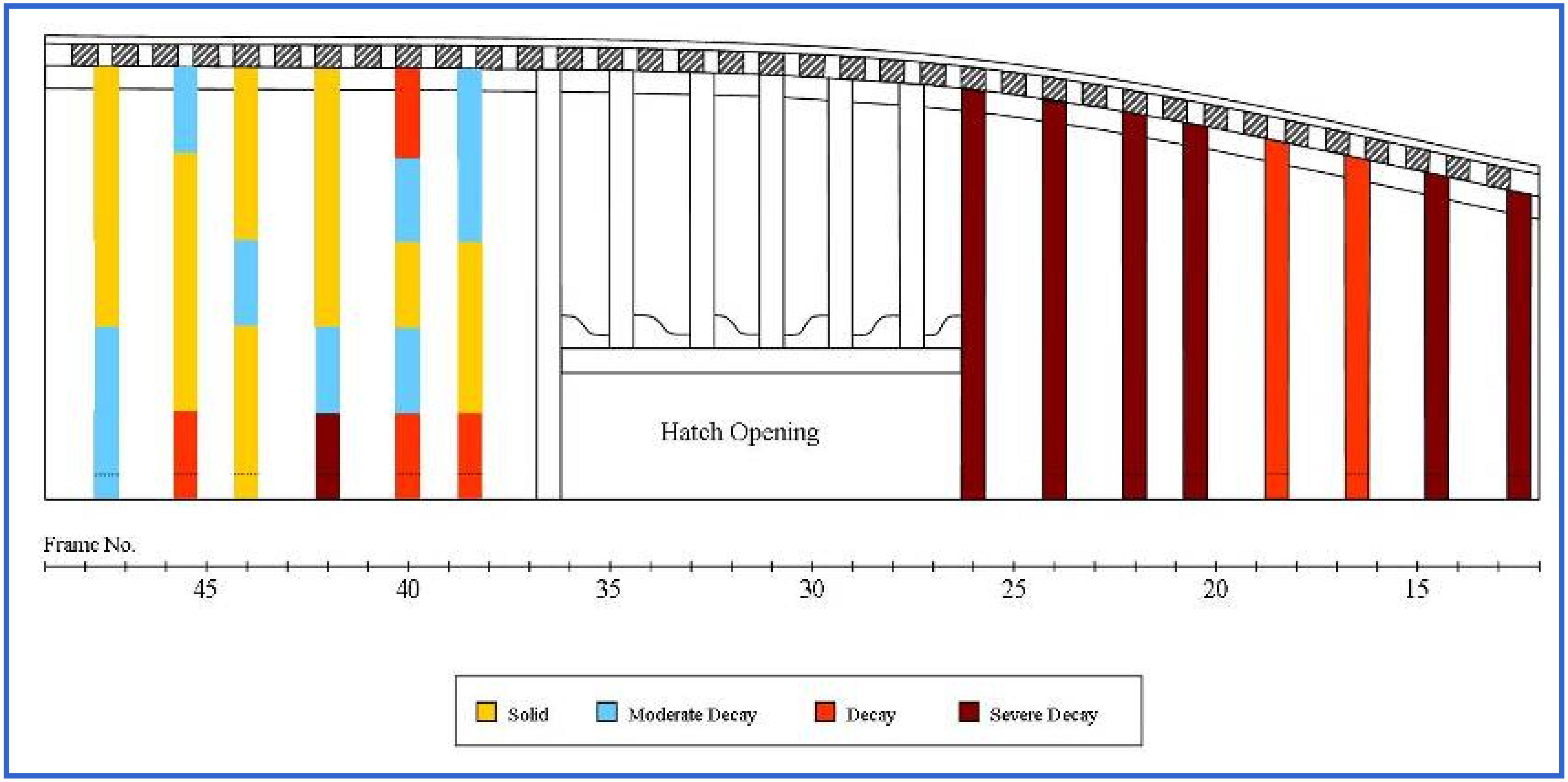
Keelsons
- Summary of stress-wave data



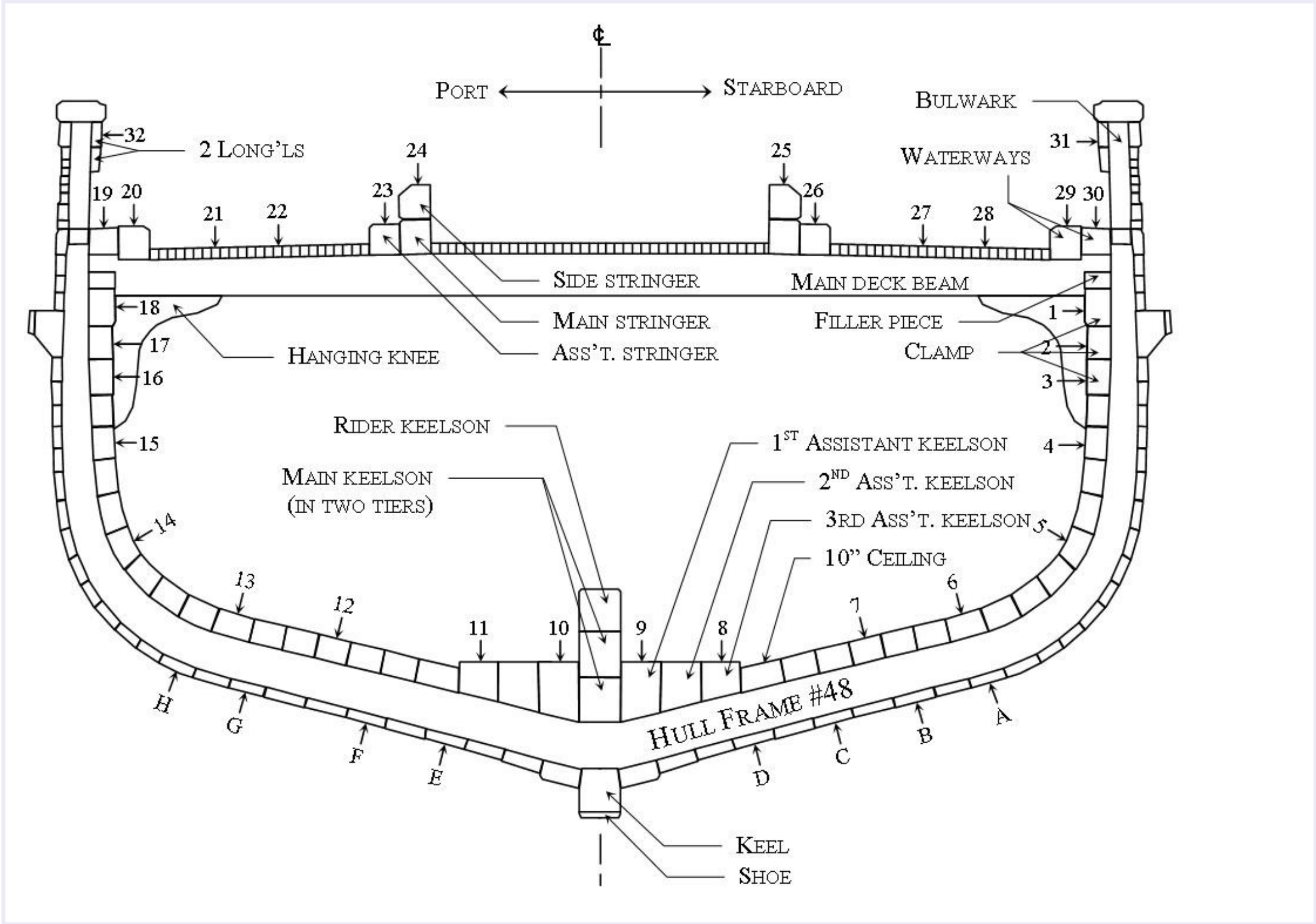


Main deck beams

- Summary of stress-wave data



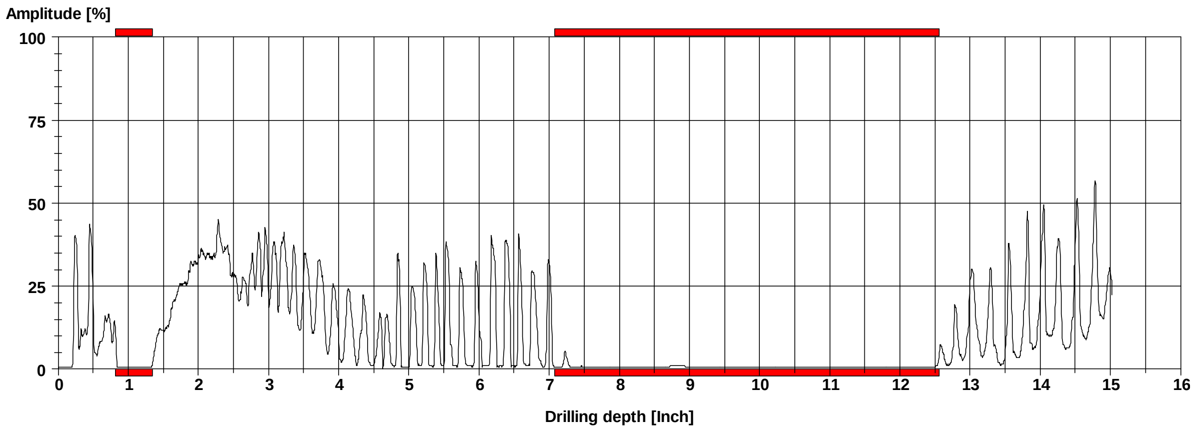
Resistance micro-drilling
- Typical hull-framing test locations



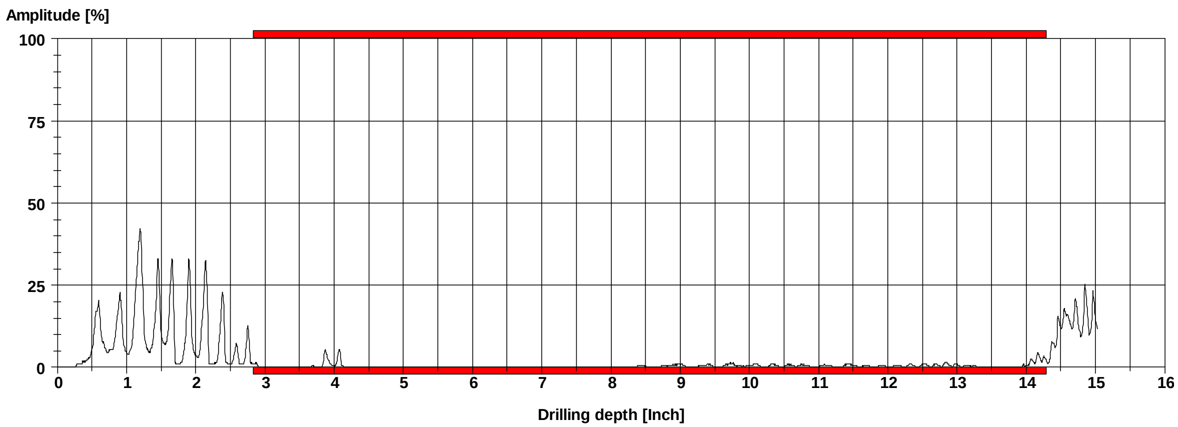
Resistance micro-drilling

Inside thru ceiling

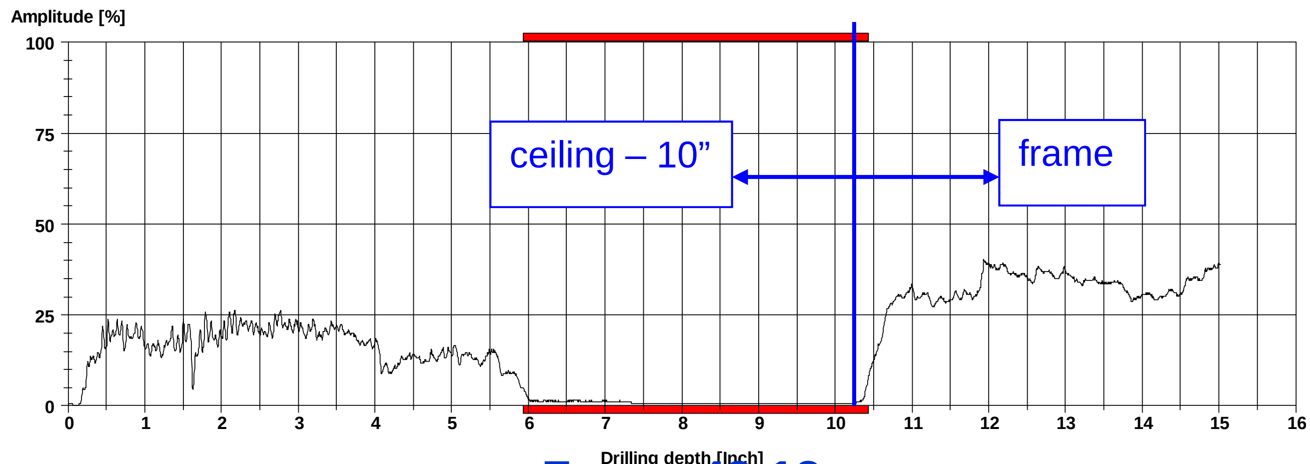
Outside thru hull



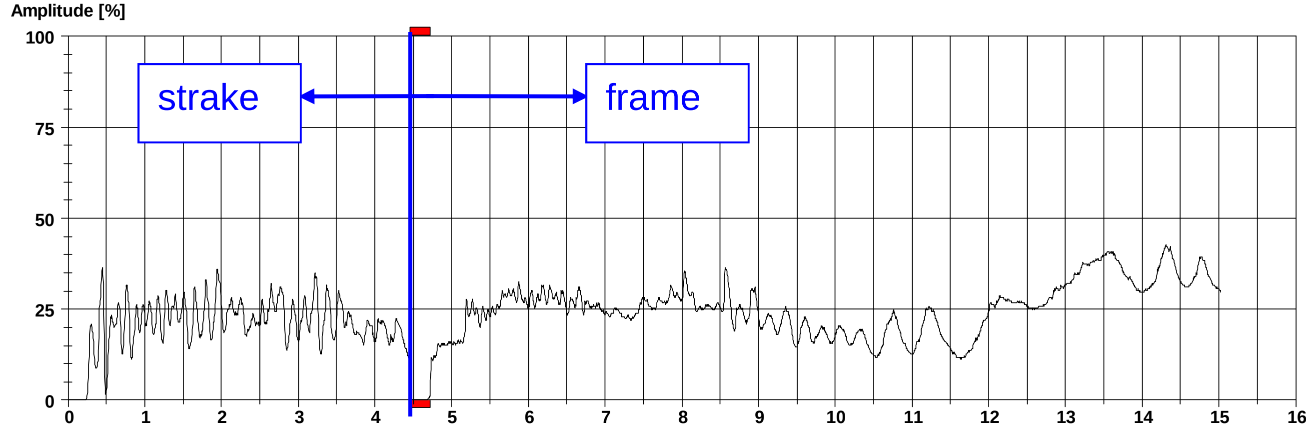
Main deck beam



Main Keelson



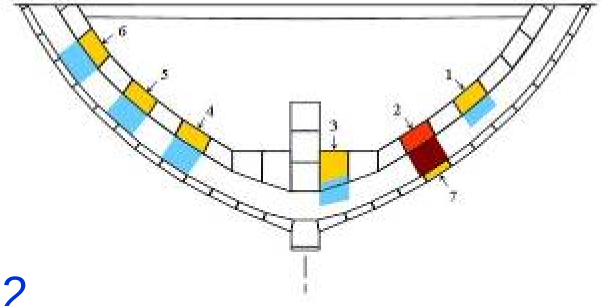
Frame 48-12



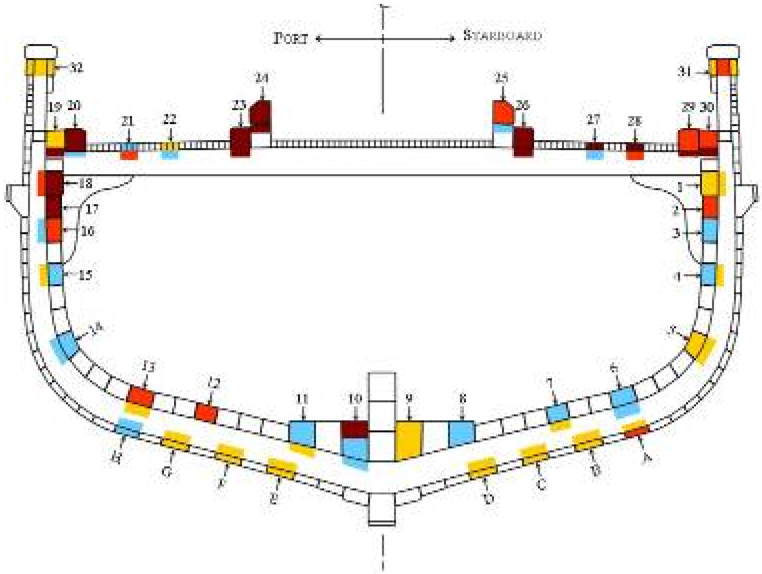
Frame 48-F

Hull Assembly

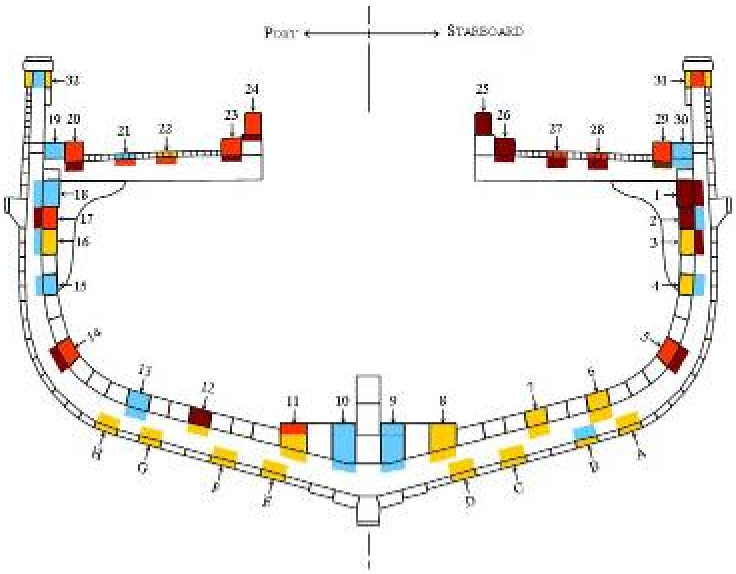
Frame #8



Frame #32

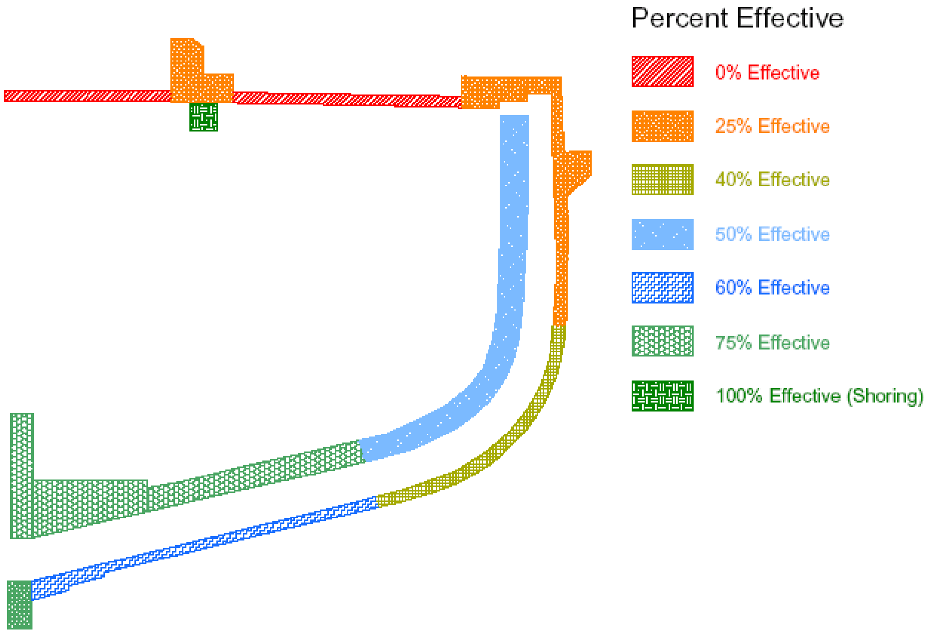


Frame #48



Significance of NDE Inspection

- The findings of this inspection will assist the structural analysis phase of the WAPAMA restoration process.



CA Thayer
- A historic lumber schooner

- Built in 1895
- Declared a NHL in 1986
- San Francisco Maritime National Historic Park
- Serve as a floating exhibit providing a marine heritage educational platform, hosting an environmental living program to primary school children.
- Inspected in 2002
- Repair 2004 - 2006


28
27
26
25
24


38
37
36
35

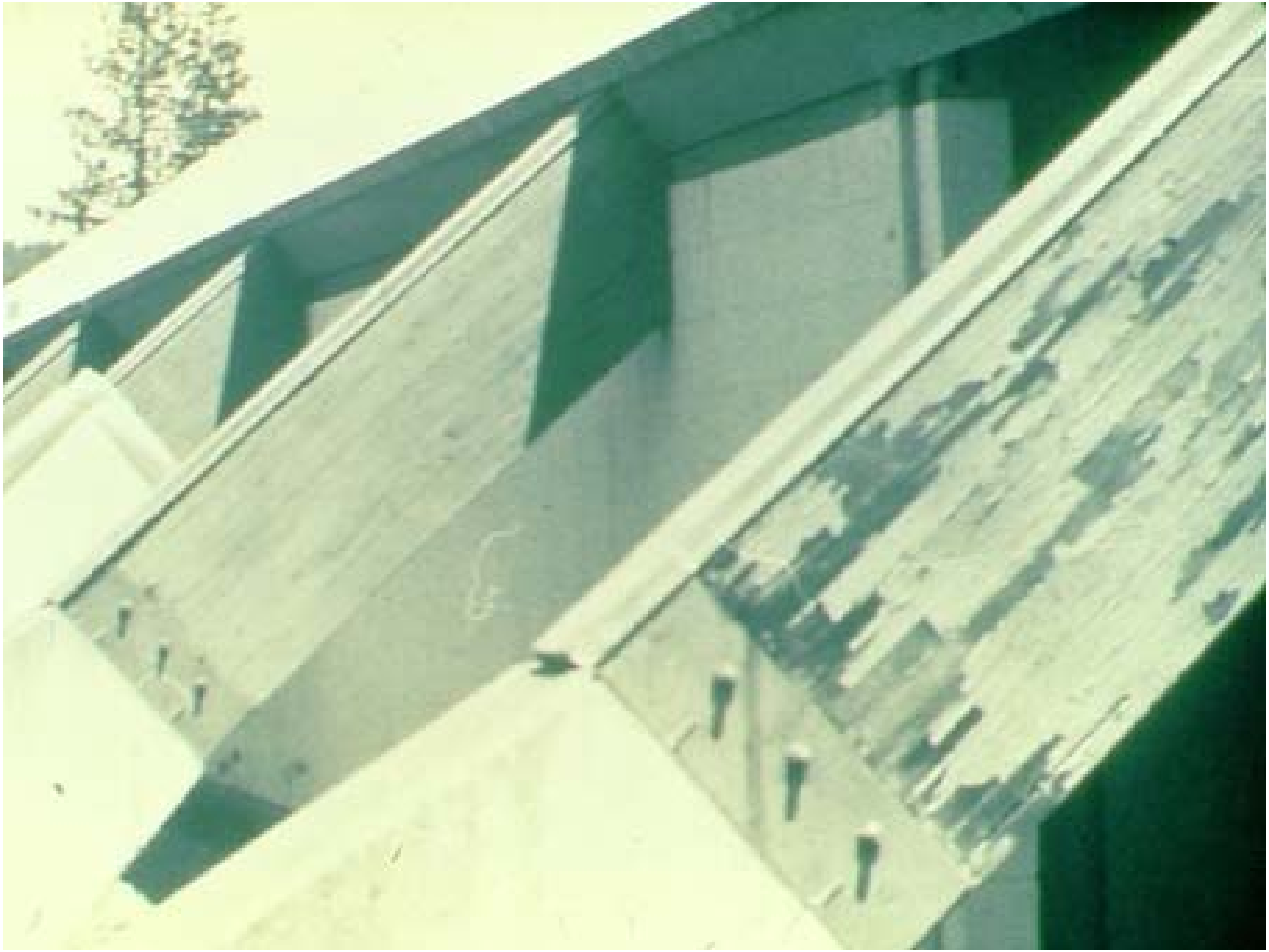

Lumber Schooner C. A. Thayer

School Gymnasium

Idaho

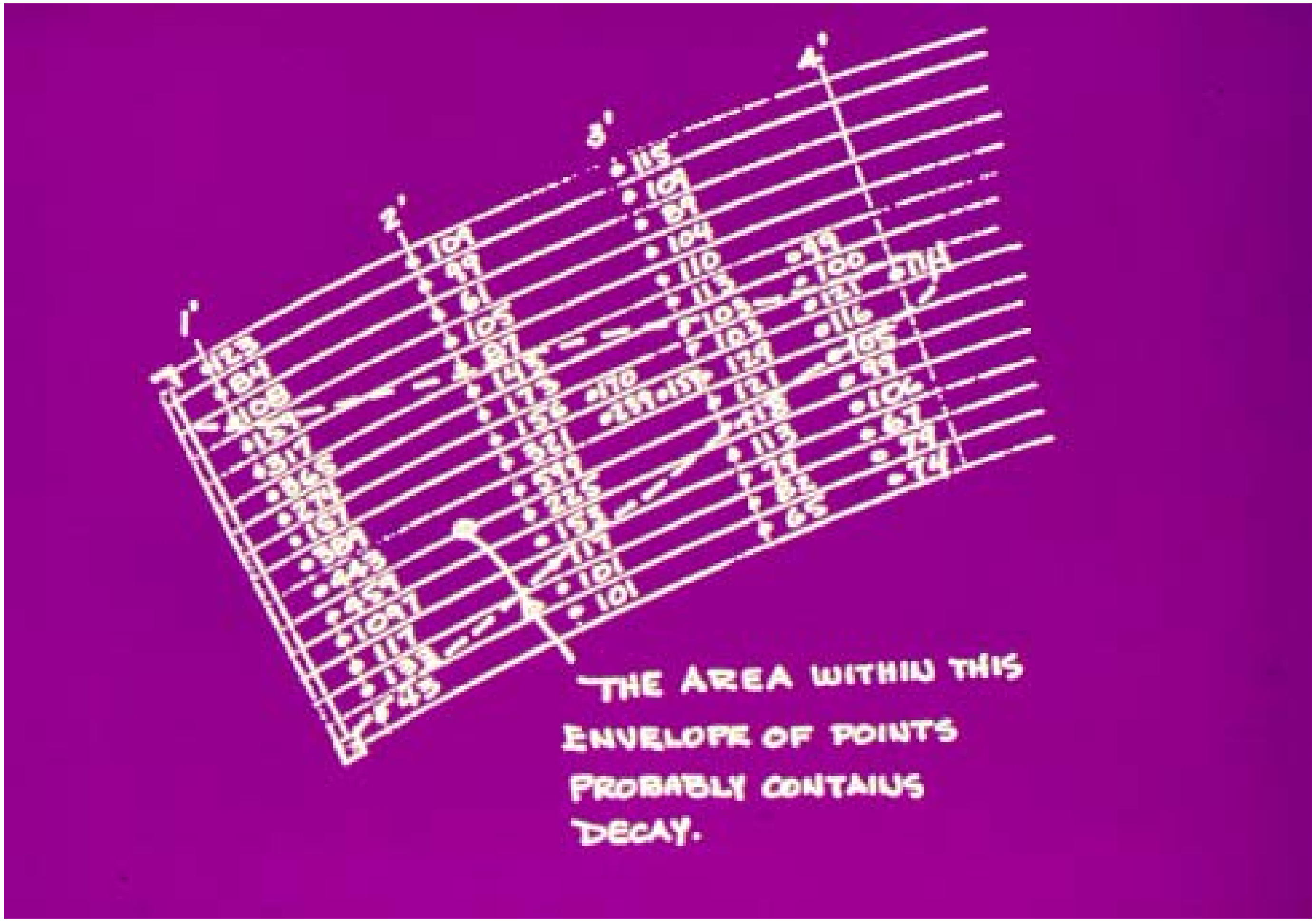
Rathdrum School Gymnasium

- Main support structure:
  - Laminated barrel arches
- Problem area:
  - Arch end was exposed to the weather and rest on concrete foundation
  - Heavy non-breathing paint
- Decay indication:
  - Cracking and peeling of paint
- Inspection:
  - Locate decay



- Establish how far from the arch ends that the decay had progressed
- Replace those ends of the arches with structurally sound material

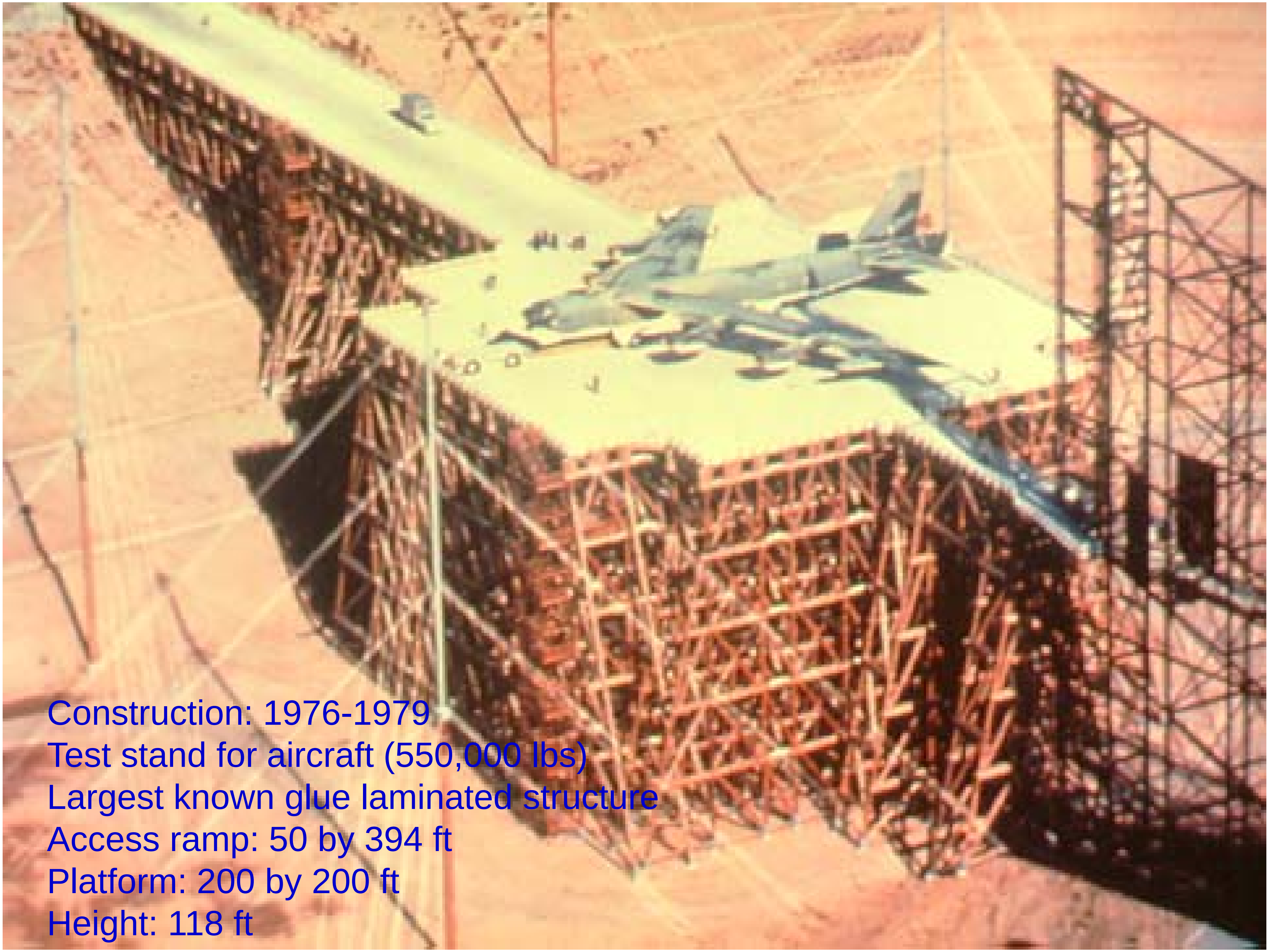
Inspection diagram showing stress wave travel time (μs)



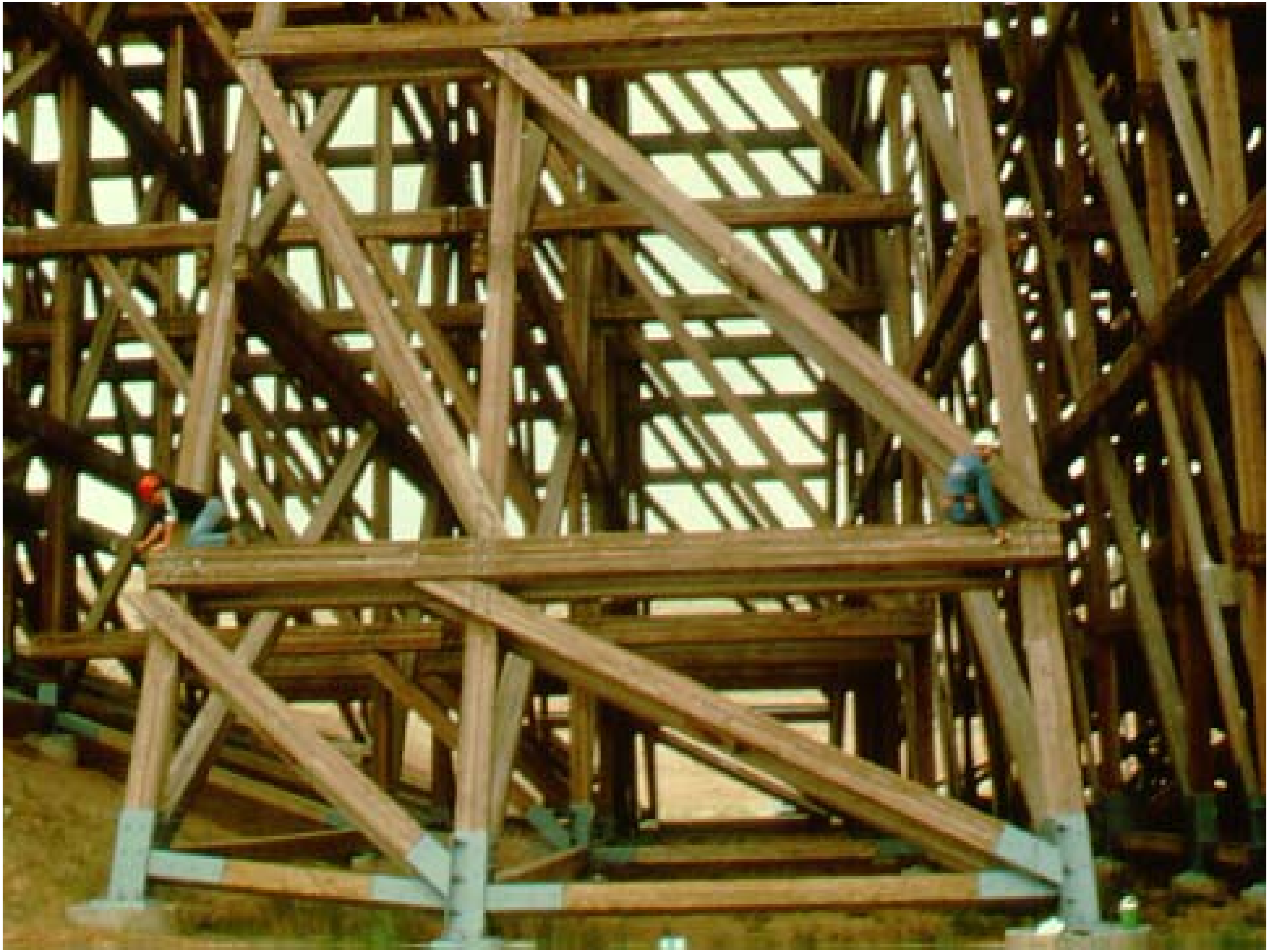
Trestle

Kirtland Air Force Base

New Mexico



Construction: 1976-1979
Test stand for aircraft (550,000 lbs)
Largest known glue laminated structure
Access ramp: 50 by 394 ft
Platform: 200 by 200 ft
Height: 118 ft



484 glulam members tested (5% of the total structural members)

Conclusions

- The structural framework of TRESTLE showed only slight decrease in rated strength
- The exposed deck system was degraded 18 percent below the average of the structural framework members

Recommendations

- Replacement of some decking material
- OK to increase loads to accommodate alternate aircraft

Timber Bridge

Maryland

Timber bridge -Gaithersburg, Maryland

- Constructed in 1946
  - Nail-laminated deck sitting on steel girders in a 3-span configuration
- Deck replaced in 2000
- Recent concerns
  - Significant checking in the timber substructure
  - Uncertainty about their significance within the load rate analysis

Focus of inspection

- Two timber pier bent supports
  - Timber columns 12x12
  - Base beam 12x12
  - Cap beam 12x12
  - Diagonal bracing

Mapping deep checks & splits

Determine the extent of checks and splits

Stress wave timing and resistance micro-drilling

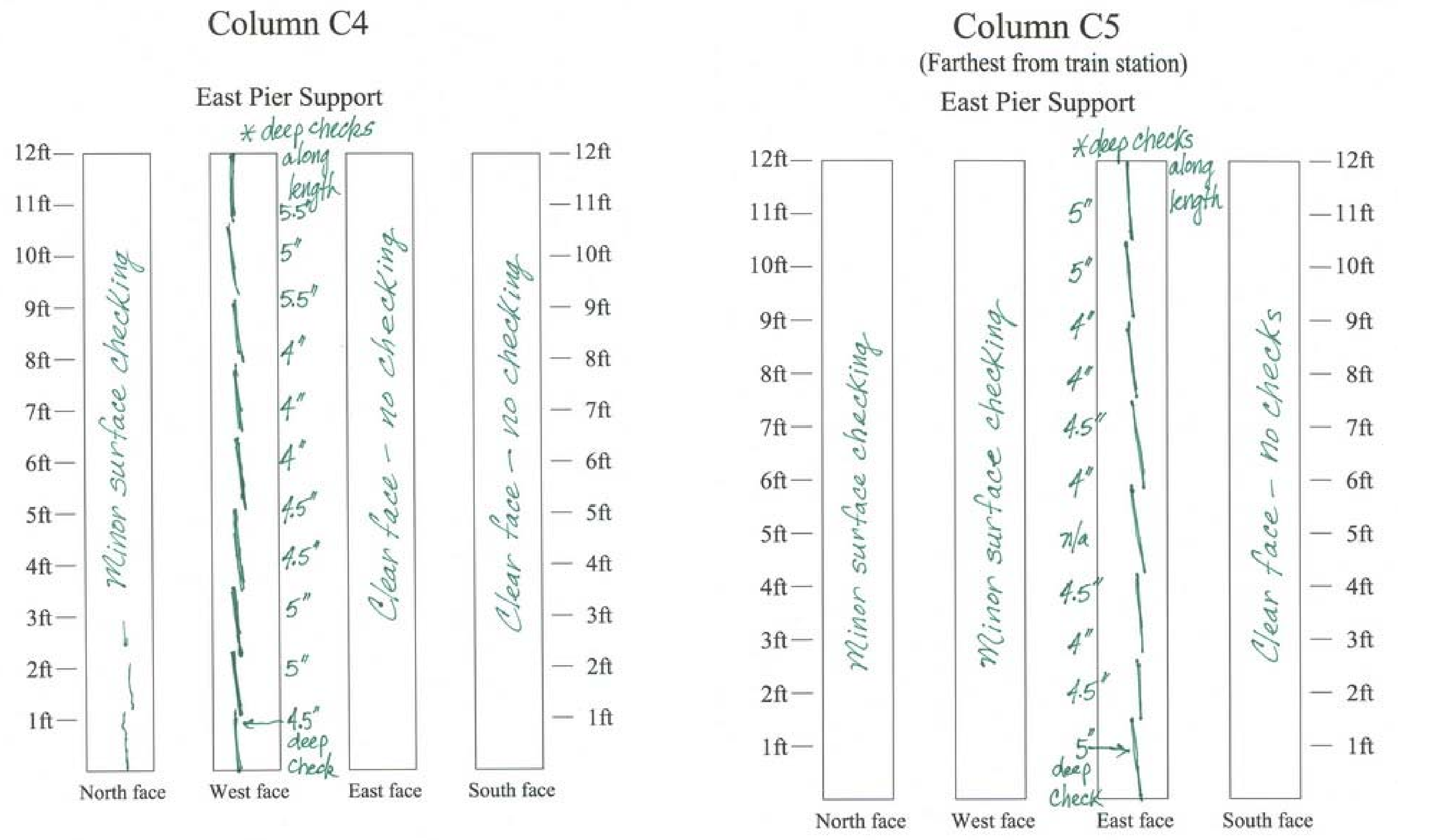
Check moisture content

- Electrical resistance meter

Removing core samples

- Density measurement
- Species identification
- Decay detection

Maps of checks and splits in timber columns



Summary of moisture content

		No.	Location	MC (%)
West Pier	Column 1	1	1 ft above base beam	11
	Column 4	4	2.5 ft above base beam	12
	Column 5	5	1 ft above base beam	10.5
	Base beam	2 3	topside measurement, between C1-C2 Side face measurement, between C2-C3	14 23
East Pier	Cap beam	11 12 13 14 15 16 17 18 19	taken from west face, near C3 taken from west face, near C4 taken from west face, near C5 taken from topside, near C3 taken from topside, near C4 taken from topside, near C4 taken from east face, near C3 taken from east face, near C4 taken from east face, near C5	14 14.5 11 14 23 13 13 10 11
	Column 3	1	1 ft from underside of cap beam	9
	Column 4	2	1 ft from underside of cap beam	10.5
	Column 5	3	1 ft from underside of cap beam	11.5
	Base beam	4 5 6 7 8 9 10	mid height under C1 mid height between C1-C2 mid height under C2 mid height under C4 topside near C4 topside near C5 mid height under C5	11 12.5 10.5 12.5 8.5 12 13

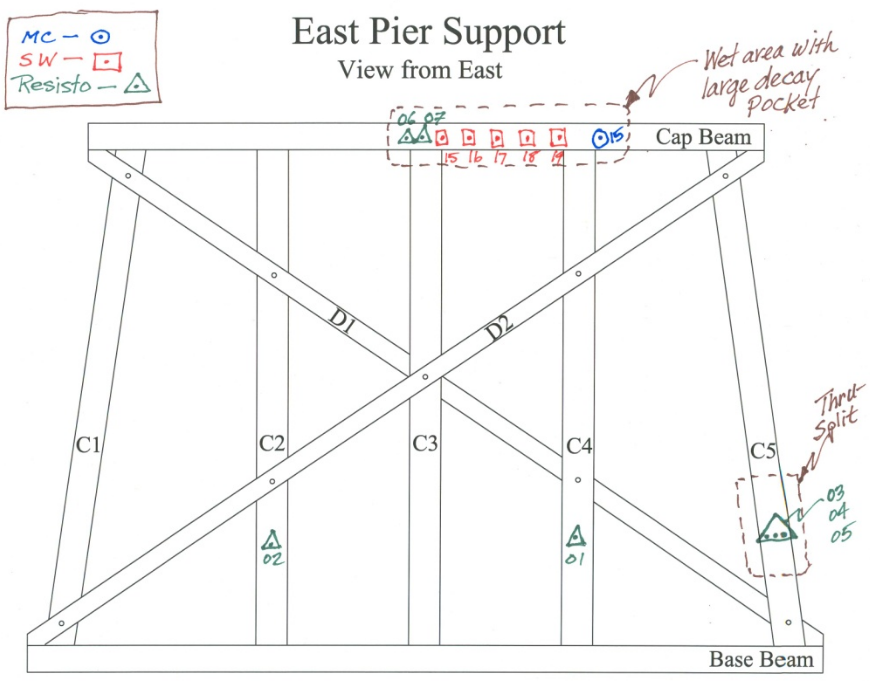
Determination of MOE of timber columns

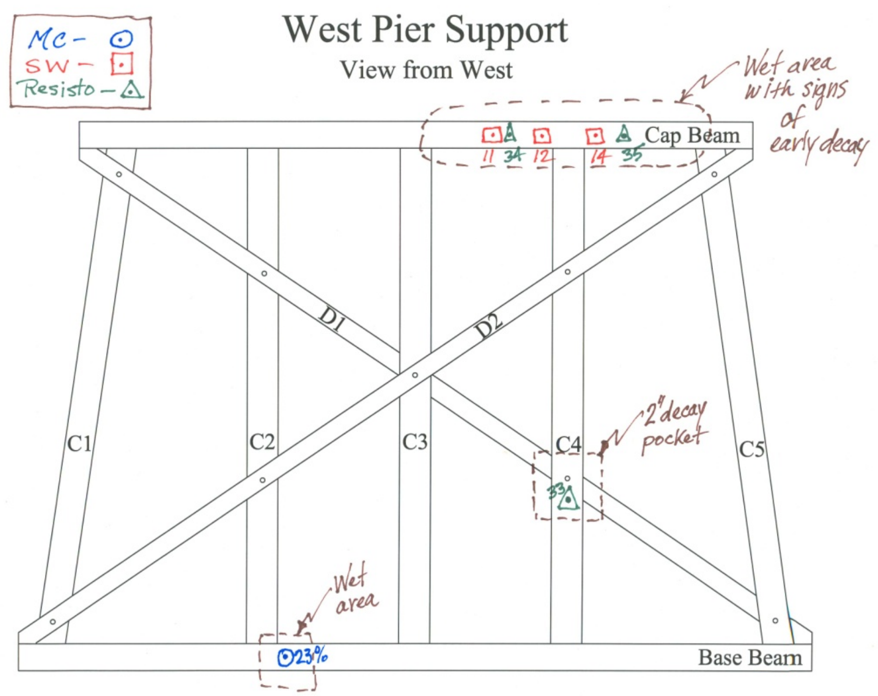
	Column	Transmission time (m-sec / ft)	Predicted Static MOE* (x 10^6 lb/in.^{2})
East Pier	C3	63	1.70
	C4	59	1.93
West Pier	C2	64	1.64
	C3	63	1.70
	C4	58	2.00

Deficiency of connection

- End splitting propagated through the connection region and compromises the integrity of the connection.

Summary of key findings





Recommendations

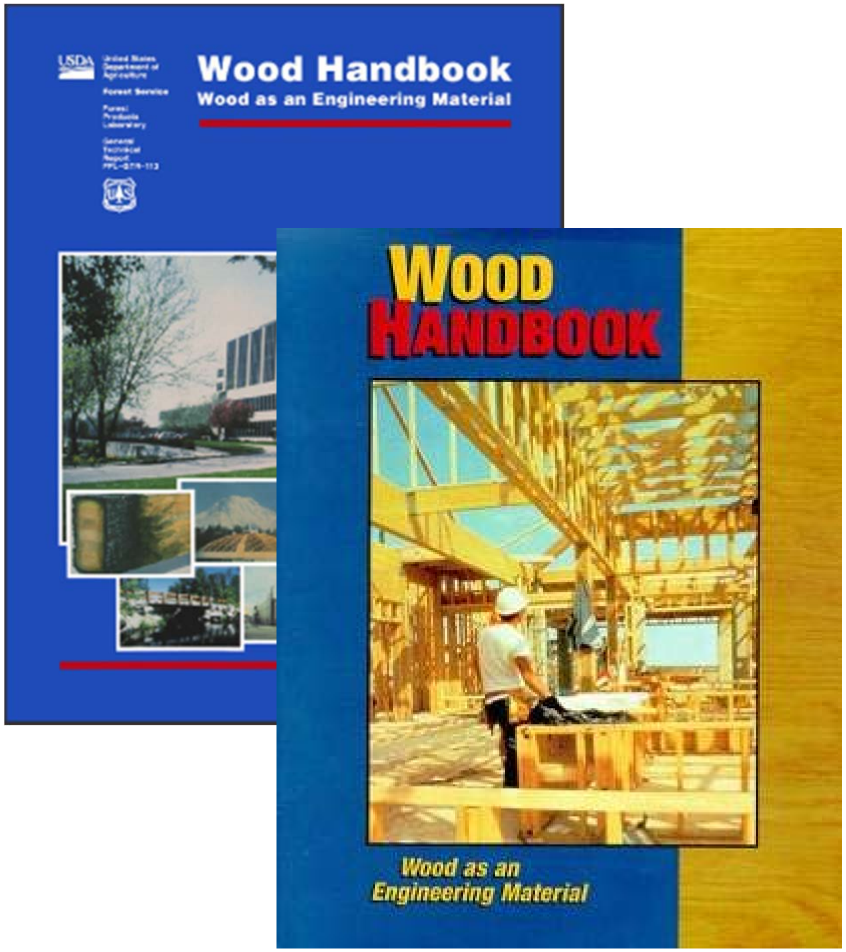
- Columns
  - Two columns (thru-split and decay) were recommended to be replaced.

- Cap beams
  - Significant internal decay pockets
  - Recommend to replace

- Diagonal bracing
  - End splitting in the vicinity of connections
  - Replace to ensure lateral stability

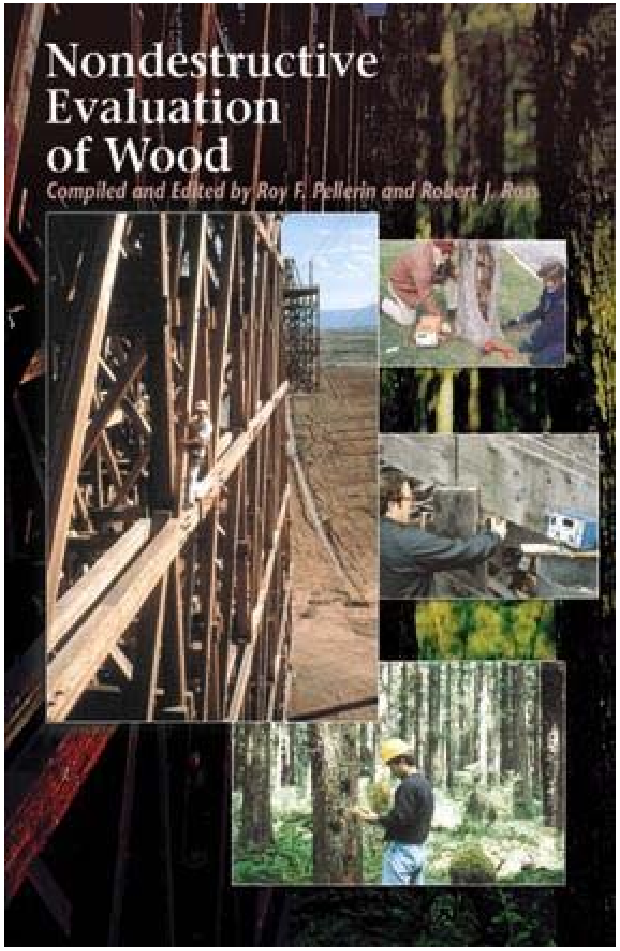
Sources of Information

USDA Wood Handbook



- USDA Forest Products Lab
  - www.fpl.fs.fed.us
  - Go to publications section
- Forest Products Society
  - www.forestprod.org

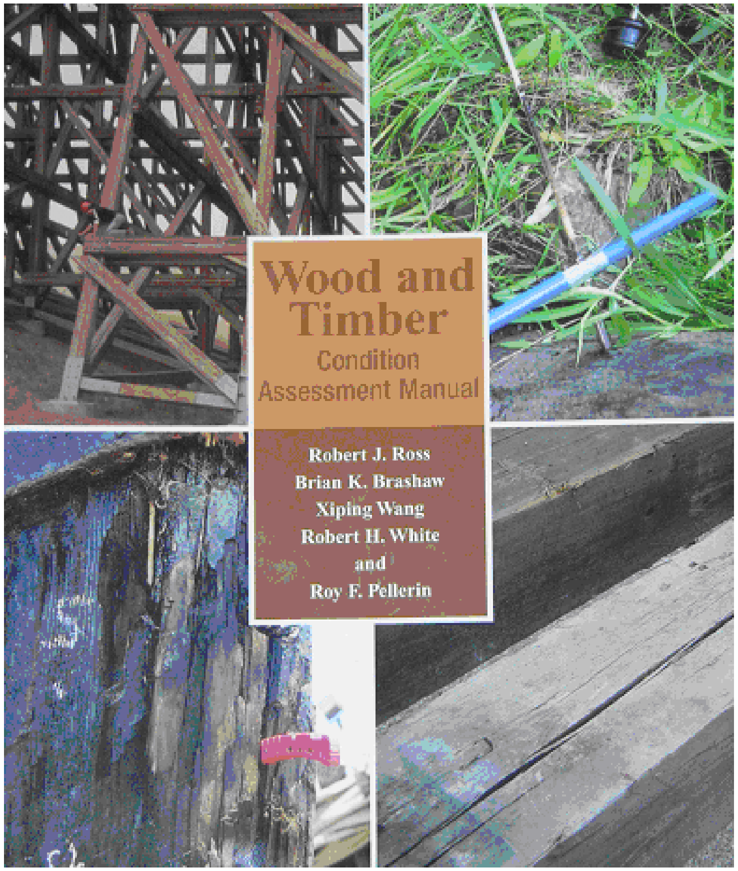
Nondestructive Evaluation of Wood



- By Roy F. Pellerin and
  Robert J. Ross
- A synthesized source of information on NDE of wood
- Contents:
  - Part I- Fundamental concepts
  - Part II- Application

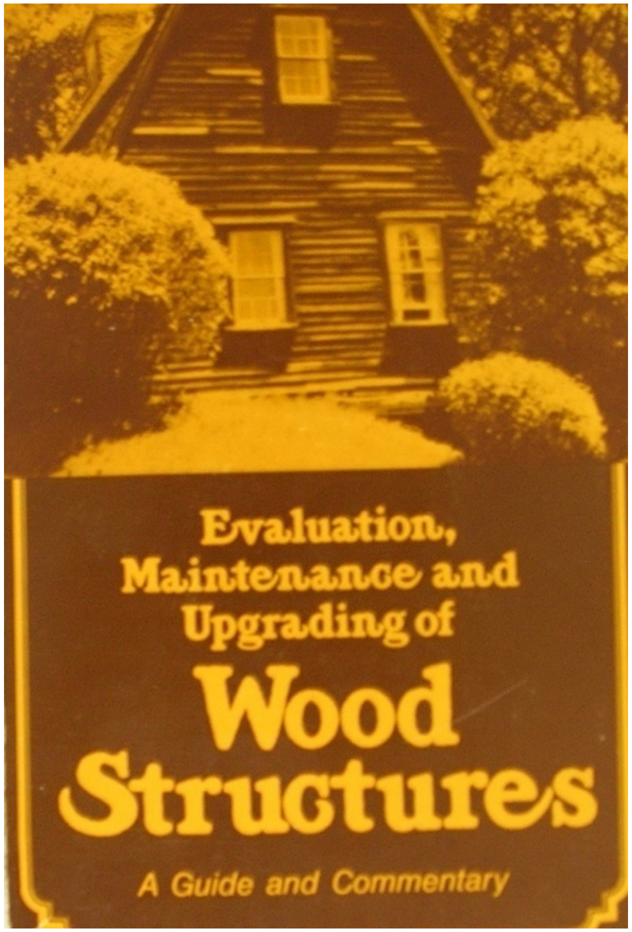
Wood and Timber Condition Assessment Manual

- *Forest Products Society*
  - Visual inspection
  - Coring
  - Drilling
  - Stress wave timing
  - Post-fire assessment
  - Case studies
  - Sample report



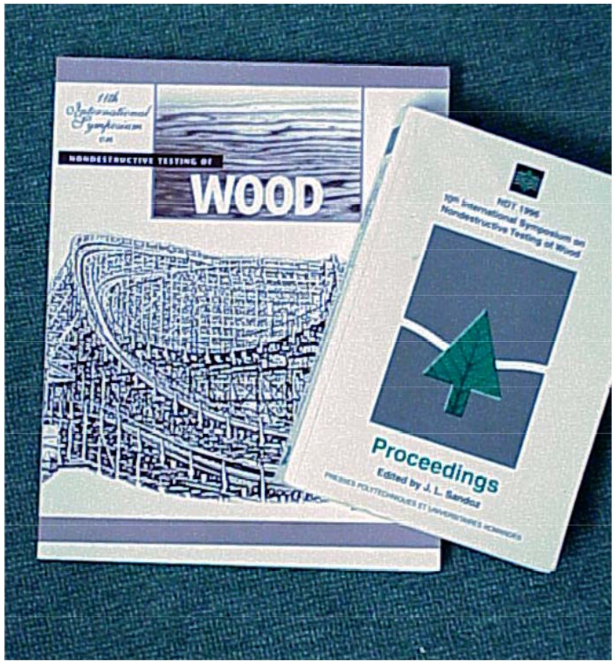
Evaluation, Maintenance and Upgrading of Wood Structures

- Inspection
- Evaluation
- Methods of repair
- Maintenance



International Symposium Series on Nondestructive Testing (NDT) of Wood

- Since 1963
- Over 600 presentations, papers, posters
- Technologies: from simple mechanical tests to ultrasound/acoustics, x-ray, γ-ray, etc.
- Trees, logs, lumber, veneer, composites, etc.
- **Structural condition assessment**



Thanks !