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UNIVERSITY OF TECHNOLOGY

# TIMBER ENGINEERING - VSM196

LECTURE 15 –

MAINTENANCE AND REPAIR

FIRE & TIMBER

SPRING 2020

# Topic

- Maintenance and repair of timber structures
- Fire and timber

## Content

- Maintenance and assessment of timber structures
- Rehabilitation and reinforcement of existing timber structures
- Fire and timber
- Timber connections in fire

# Intended Learning Outcomes of this lecture

- You know procedures for maintenance and assessment of existing timber structures
- You can identify damages and critical aspects of existing timber structures
- You know possible intervention and reinforcement methods
- You are familiar with the fire behavior of timber
- You know the relevant parameters with influence on fire resistance
- You can follow the procedure in EN 1995-1-2

# General

# Wood can last for Centuries!

Borgung Church, Norway, 1200

Temple, Nikko, Japan, 1700

Kapellenbrücke, Luzern, Switzerland, 1300

# Goal: Durability

"Durability is the ability to exist for a long time without significant deterioration"

Source: Merriam-Webster's Online Dictionary

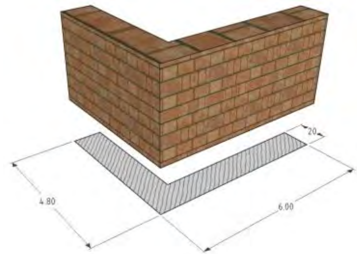
"**Durability** of a product, component, or system is **its capacity to perform** for a specified period of time **the function** for which it was intended, whether it be structural safety, serviceability or aesthetic"

Source: Foliente et al. (2002)

# Introduction

# Design of new structures

- Free adjustment of geometry
- Choice of adequate materials
- Compliance with current requirements
- Using newest technologies



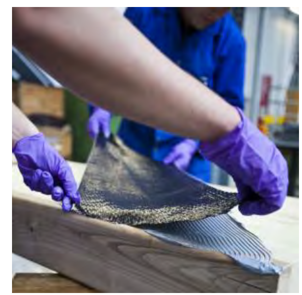


Schmölzer, proHolz Austria/LIGNUM


EUROPEAN STANDARD
NORME EUROPEENNE
EUROPÄISCHE NORM

EN 1995-1-1

Eurocode 5: Design of timber structures - Part 1-1: General
Common rules and rules for buildings


Empa

# what about existing structures?

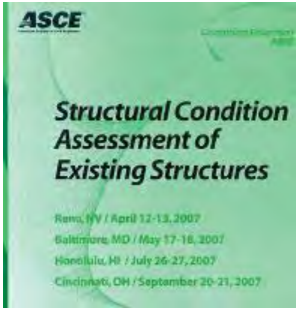
- Given geometry
- Unknown materials
- Requirements are outdated
- Old techniques

# Background and Basis

- Design of new structures
  - Eurocodes
  - Product standards
  - National guidelines


EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM
EN 1995-1-1
Eurocode 5: Design of timber structures - Part 1-1: General - Common rules and rules for buildings

- Assessment of existing structures
  - ISO 13822:2010:
    Bases for design of structures – Assessment of existing structures
  - ICOMOS (2005):
    Recommendations for the analysis, conservation and structural restoration of architectural heritage
  - National guidelines



# Obligation for Maintenance

# Maintenance Activities

Two main activities can be distinguished:

- Inspections

- Interventions

# Inspections

- Inspection before decisions are made
  - on-site non-destructive examination to establish the present condition of the structure

- **General Examination**
  - Registration of the relevant parts of the structure
- **Detailed Examination**
  - Further structural analysis under consideration of the latest findings and engineering methods

- Target:
  - Statement on structural safety
  - Statement on necessary conservation measures
  - Forecast of the development of the condition

# Interventions

A distinction is made between

- Operational interventions:
  - Monitoring
    - frequent or continuous, normally long-term, observation or measurement of structural conditions or actions
    - Required because no "safety margins" for damage or defects exist
    - Particularly necessary for structures and supporting structures large span width etc.
  - Maintenance
    - routine intervention to preserve appropriate structural performance
    - predominantly preventive character
    - should be periodically attended

# Interventions

A distinction is made between

- Operational interventions:
  - Monitoring
  - Maintenance
- Structural interventions:
  - Repair and rehabilitation
    - work required to repair, and possibly upgrade, an existing structure
    - improve the condition of a structure by restoring or replacing existing components that have been damaged.
    - Restoration of the structural safety and usability
    - e.g. renovation, restoration
    - same relevance as maintenance and repair
  - Modification
    - Adaptation to new requirements
    - is subject to the approval procedures of the building authorities
    - Depending on the effort involved, a distinction is made between: Adjustment (modernisation), reconstruction and expansion

# Proportionality of Interventions

- Comparison of the costs and benefits of maintenance aiming at an efficient use of resources

Erik Christensen

# Conservation of values

Buildings have a “value”

- Tangibles
  - Functional values
  - Economic values
  - Value of use
  - Value of the building stock

- Cultural values
  - Situation value
  - Historic-cultural value
  - Esthetical value
  - Emotional value

# Triggers For Maintenance

# Triggers For Maintenance planning

**Changes** of boundary conditions:

- Change of use (increased liveload, etc.)
- Extension of the service life
- increased requirements for the reliability of the structure
- Changes to the structure that have not yet been sufficiently investigated

# Triggers For Maintenance planning

**Doubts** as to sufficient load-bearing capacity, or
**unsatisfactory** behaviour in use:

- structure has not been monitored / inspected for a longer period of time
- a periodic inspection shows unfavourable results (decay, corrosion, deviations from the originaldesign status, construction or design errors)
- planned or unplanned exceptional loads
- similar structures do not behave satisfactorily
- Structure was exposed to an extraordinary load
- new findings on the structural behaviour or new / revised standards are available

# Updating

# Updating

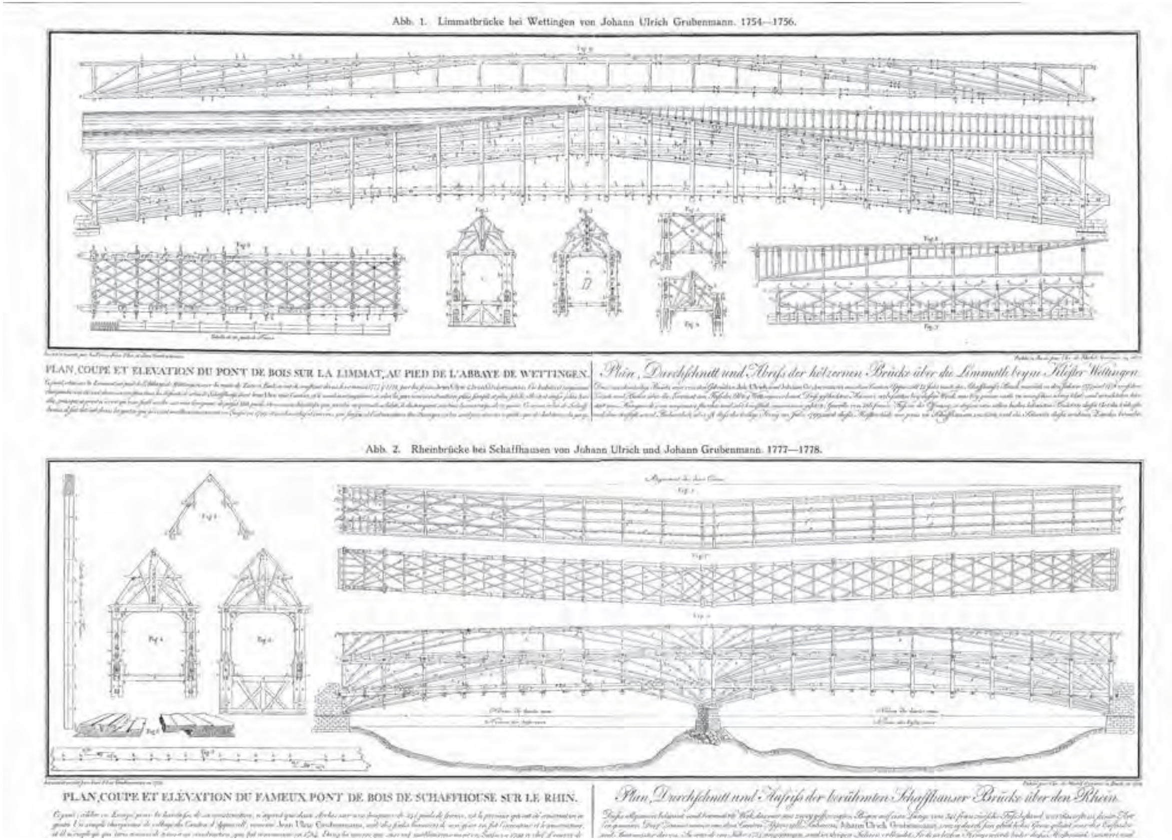


Abb. 1. Limmatbrücke bei Wettingen von Johann Ulrich Grubenmann. 1754—1756.
PLAN, COUPE ET ELEVATION DU PONT DE BOIS SUR LA LIMMAT, AU PIED DE L'ABBAYE DE WETTINGEN.
Abb. 2. Rheinbrücke bei Schaffhausen von Johann Ulrich und Johann Grubenmann. 1777—1778.
PLAN, COUPE ET ELEVATION DU FAMEUX PONT DE BOIS DE SCHAFFHOUSE SUR LE RHIN.

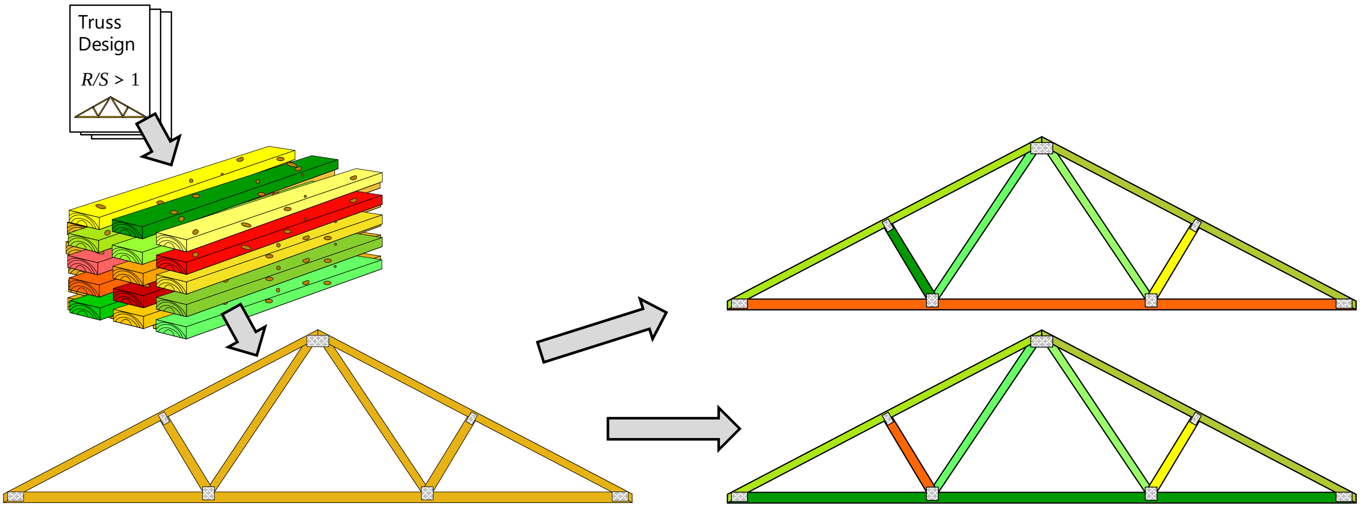
# New construction vs. maintenance

## New building

- Design, dimensioning
  - Information: general, blurred
  - Projected design values
  - Design and dimensioning

## Existing structure

- Assessment
  - many and precise information available
  - Updated design values
  - Verification



# Updating

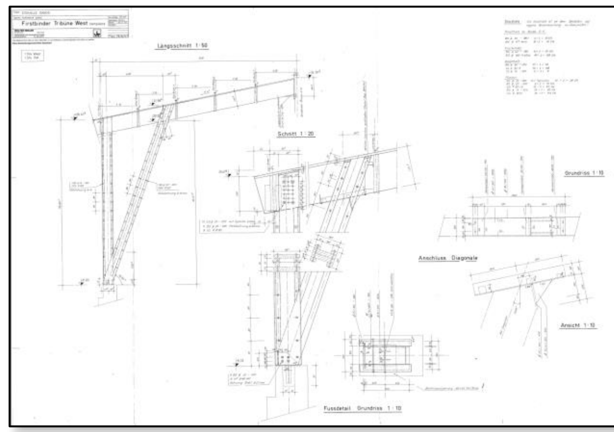
- Definition:
  Process to combine existing knowledge with new information

- Updating includes:
  - Utilization plan
  - Hazard scenarios
  - Actions
  - Geometries and dimensions
  - Structural models
  - Material properties and geotechnical conditions
  - Resistances
  - Deformation capacity
  - Model uncertainties

# Updating – Building records

Ideally, the following exist

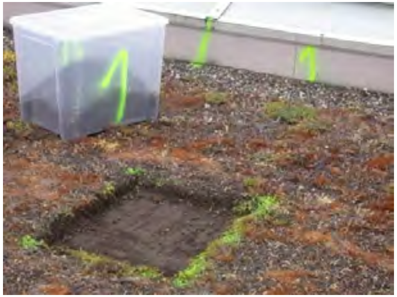
- Project documents:
    - Original drawings, design specifications, structural calculations, construction records, inspection and maintenance records, details of modifications;
- regulations and by-laws, codes of practice and standards that were used for constructing the structure;
- Utilisation plan
- Maintenance plans



# Updating Loads and Actions

# Updating Loads and Actions

- Dead loads, gravity loads, imposed loads ⇨ values according to current standards
- Grouping of actions:
  - load-controlled ( $F = m \cdot g$ ) ⇒ Dead loads
  - force controlled ($F = m \cdot a$ ) ⇒ e.g. Earthquakes, centrifugal force
  - deformation controlled ⇒ Settlements, temperature changes
- Possible reduction of partial factors
- Consider changes in local indoor and outdoor climate
  ⇨ possible changes in $k_{\mathrm{mod}}$!



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# Updating Loads and Actions

- Consider development of technological installations

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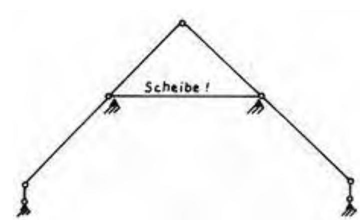
# Updating of Structural model and geometry

# Updating of structural model And geometry

- Updating of the structural model
  - select a suitable structural model, which includes the relevant influencing variables (e.g. system effect) correctly recorded
- Updating of geometric characteristics
  - Dimensions, spans, roof pitch
  - Consideration of damages and deficits



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# Updating of geometry

# Updating of Structural Model

# Updating of Structural Model

- Testing for static and dynamic properties of structure
  - Testing to better understand the properties of the structure
- Model uncertainties
  - Consider the validity and accuracy of the models
- Conversion factors
  - Influence of shape & size effect of specimens, temperature, moisture, duration-of-load effects, etc.
- Uncertainty about the condition of components
  - Adjust resistance and/or dimensions on condition of the structure

Chahud et al. (2018)

# Updating – Resistance and Deformation capacity

- Updating the load-carrying capacity
  - individual members
  - Overall behaviour of the structure
- Updating the deformation capacity
  - previous deformation behaviour
  - future deformation requirements
  - possible failure mode (ductile, brittle, progressive, etc.)
  - Possible interaction between impact and deformation!
  - Consideration of damages and deficits



# Updating – Resistance and Deformation capacity

# Updating of Material properties

# Updating of Material properties

- Study of the building documents
- Investigation of the conditions of the members
  - Check the validity of the building documents
  - Destructive and non-destructive testing
  - Ensure that tests are representative
  - Data evaluation according to the laws of statistics
  - Damages

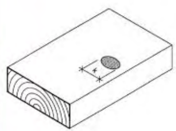
# Updating of Material properties

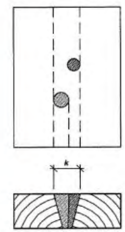
# Updating of Material properties

- Simple case:
  - Material properties are known from the old documents
- Problem:
  - Change of the design concept
  - In the past: Permissible stresses and strengths
  - Today: Semi-probabilistic design with partial safety factors (Load and resistance factored design (LRFD))
  - Different strength values $f_{\mathrm{permissible}} \neq f_{\mathrm{d}}$

# Updating of Material properties

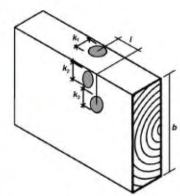
- Other case:
  - Building material properties are unknown but can be assigned
- Solution:
  - Apply current grading criteria!






Kvistens mått = $k$, endast om de till-sammans bildar en kvistgrupp

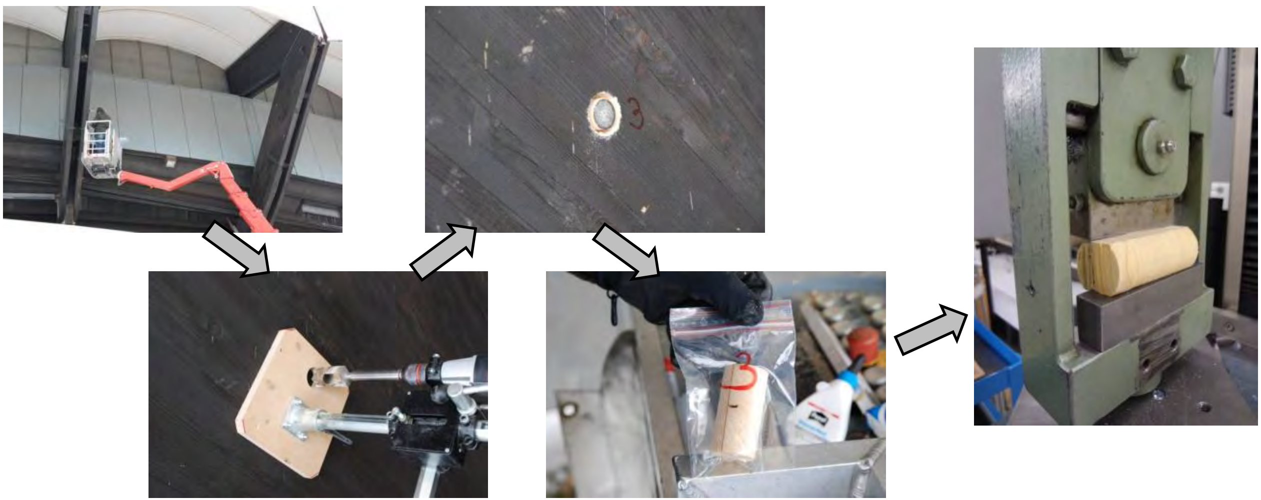

Kvistmått = $k$




Kvistgruppsmått = $k_1 + k_2 + k_3$
$l \leq l_{kc} = \min(b;\ 150\ \text{mm})$

# Updating of Material properties

- Most difficult case:
  - Building material properties are unknown and cannot be assigned
- ⇒ Values must be determined!
  - e.g. adhesive joint strength of an old glulam beam

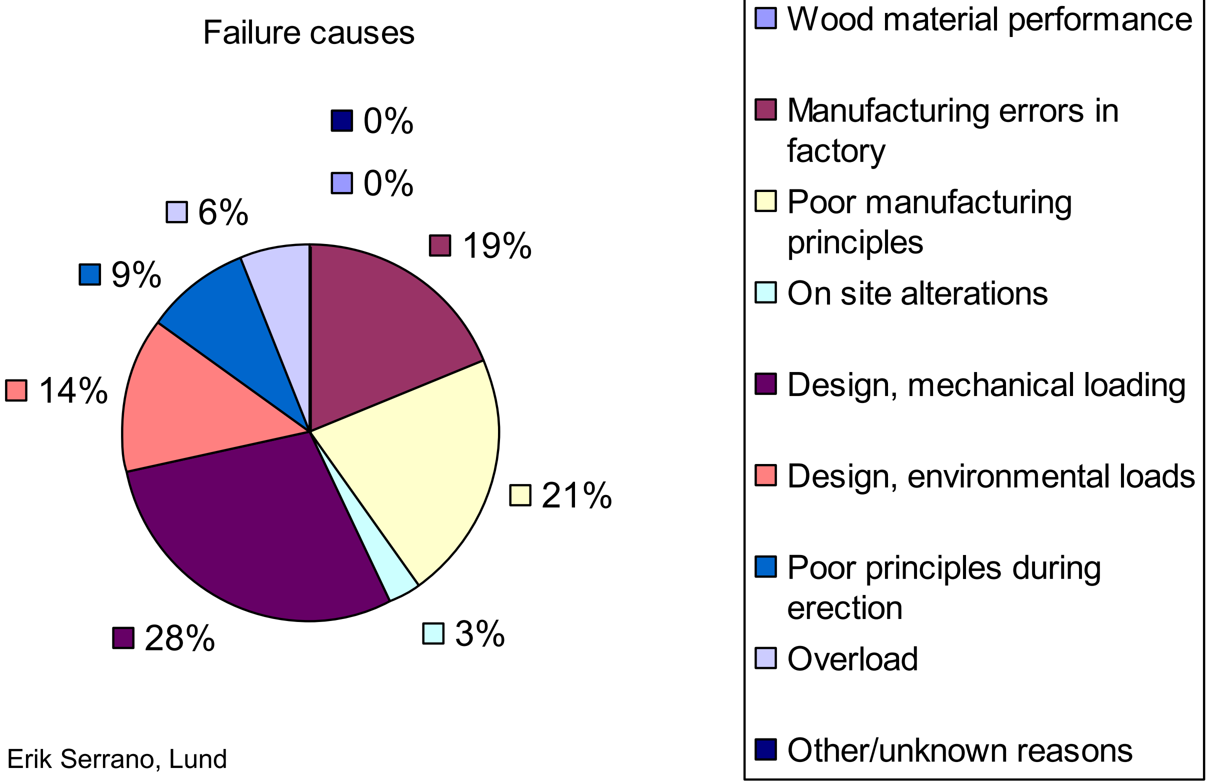


# Damages and assessment

# Updating - Damages

- Damages of the wood
- Structural damage can occur due to, among other things
  - Mechanical overloading
  - Insufficient stability
  - Strong variations of humidity
  - High moisture content (basis for biological damage)
  - Low moisture content (crack formation)
- The serviceability can be limited by, among other things
  - Excessive deflection
  - Vibrations

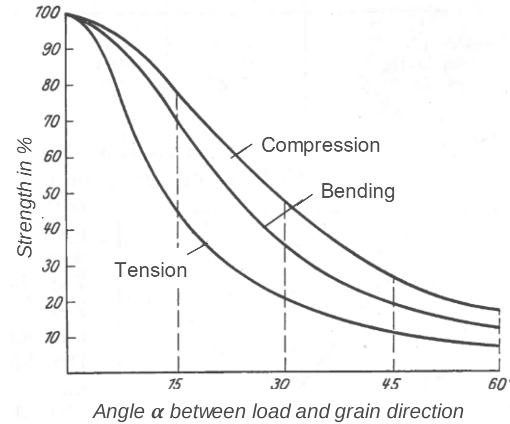
# QA and reliability for long-span wood construction

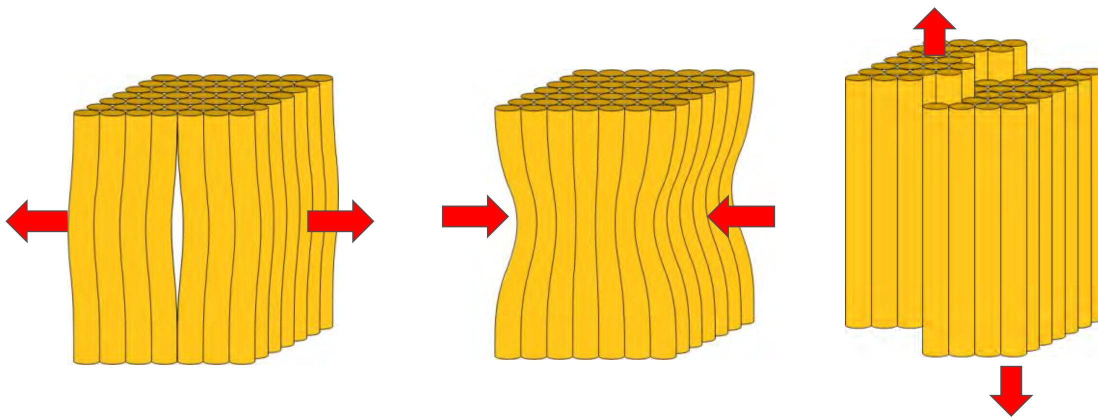



Ref: Erik Serrano, Lund

# Damages

- Mechanical damage
- Damage often occurs due to
    - Tension perpendicular to grain
    - Compression perpendicular to grain
    - Shear
- This is the case at connections!



Source: Kollmann

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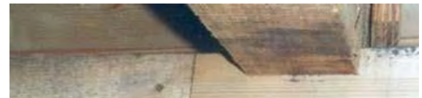
# Damages

- Tension perpendicular to the grain
    - Connections loaded perp. to grain
    - Notches
    - Holes
    - Curved/cambered beams

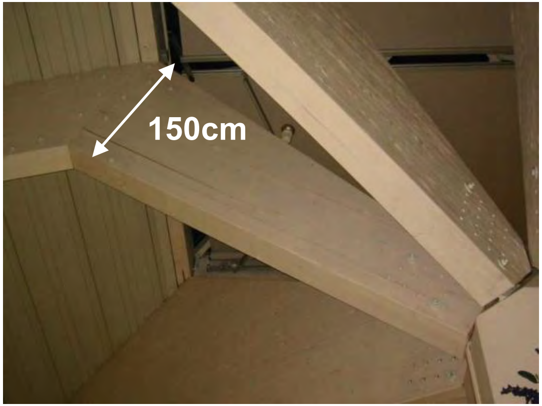
# Damages

- Compression perpendicular to the grain
  - Supports
  - Load introduction points



# Damages

- Connections
  - Important parameters:
    - Spacing and distances of fasteners
    - Height of connections
    - Damages and wood char. at the connection




# Damages

- Shear

  Critical at

  - Supports
  - Shrinkage cracks

# Damages

- Insufficient stability
  - Slender members
  - Complient connections

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# Damages

- High moisture content
  - Degradation through
  - Discolouring or decaying fungi
  - Insects

# Damages

- Insufficient serviceability
  - Large deflections
  - Vibrations

# Assessment

# Assessment process

Mapping of critical zones & sections:

- Visual assessment (external indicators for deterioration)
- Sounding
- Survey of moisture content in critical zones
- Stress-wave timing

Detailed inspection:

- Resitance drilling/Core drilling
- Acoustic tomography
- Dynamic/static load testing
- Etc.

Confirm deterioration and its extent

# Assessment of geometry

- Geometry – external
  - Effective cross section
  - Crack width
  - Crack depth

# Visual inspection

- Identification of critical zones
- External indicators for deterioration/degradation
- Sounding:
  - requires some skill
  - provides only a partial picture of the extent of decay
  - Will not detect damage in early stages ⇨ additional techniques (Sound velocity)

Awl/knife

Hammer

Brashaw (2011), USDA - FPL

# Assessment measures

- Moisture content
  - Kiln drying
  - Capacitive measurement technique
  - Measurement electrical resistance


Franke (2013)

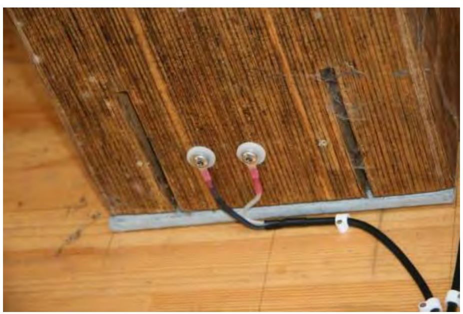
# Assessment measures

- Moisture content
  - Local measurement at critical points


Franke (2013)

# Assessment measures

- Moisture content
    - Long term measurements





Dietsch et al. (2012) & Scharmacher (2013)

# Assessment measures

- Moisture content
  - Long term measurements


Dietsch et al. (2012) & Scharmacher (2013)

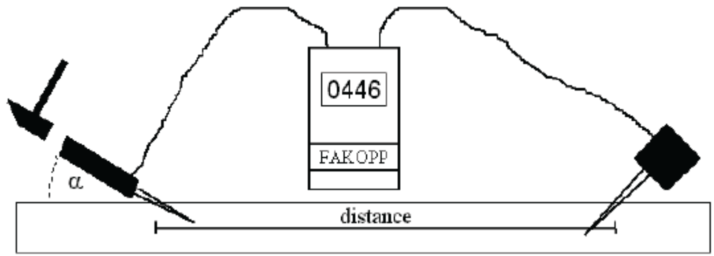
# Stress wave propagation

- Stress wave speed (Speed of flight)
- also known as ultrasonic method
- Baseline transmission times for wood species must be established or from tables

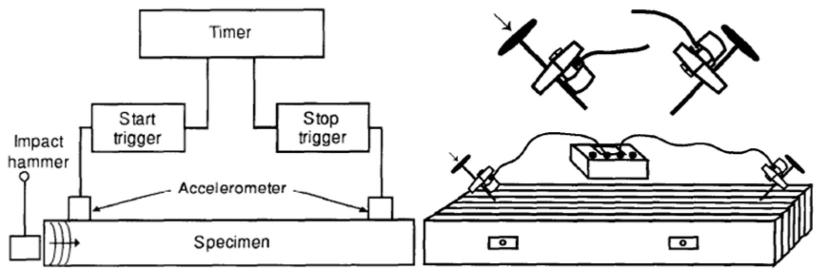
$$E_{dyn} = \rho \cdot v^2$$

- Fast and simple method
- Increase of the velocity sound by 30% results in a loss of strength of about 50%

$$\sim R^2 = 0{,}8$$




Ferenc Divos, Fakopp, Hungary



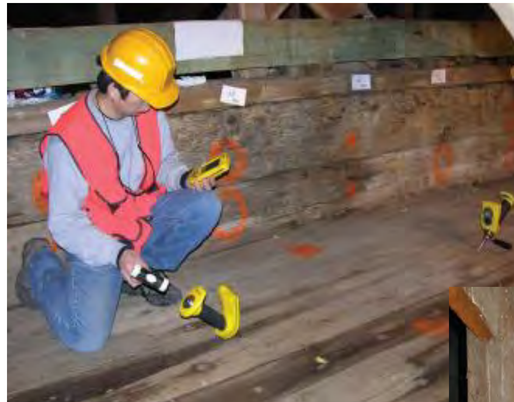

| Moisture Content (%) | Adjustment factors -18 °C (0 °F) | 3 °C (38 °F) | 27 °C (80 °F) | 49 °C (125 °F) |
|---|---|---|---|---|
| 1.8 | 0.94 | 0.95 | 0.97 | 0.98 |
| 3.9 | 0.95 | 0.96 | 0.98 | 0.99 |
| 7.2 | 0.96 | 0.98 | 1.00 | 1.01 |
| 12.8 | 0.97 | 0.99 | 1.00 | 1.01 |
| 16.5 | 0.99 | 1.01 | 1.03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

USDA – FPL – Wood handbook

# Stress wave propagation

Application:

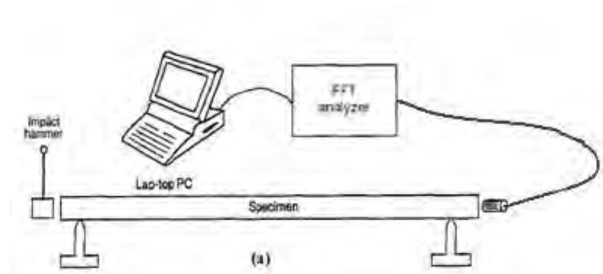
- In-situ evaluation of timber components
- Effective tool for localisation of defected members
- Detection of deterioration
- Internal cracks
- Transverse speed only for decay detection
- Often used in combination with resistance drill



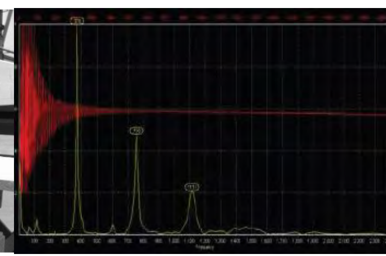
*Brashaw, Ross, Wang, Pellerin (2011, HUN)*

# Dynamic vibration tests

- Longitudinal free edge support
- Frequency and stiffness highly correlated
- vibration is induced by striking one end with the hammer and capture the electric signal via the microphone through the FFT-analyser that transforms the signal into frequency
- Resonance frequency between 5 to 9 kHz
- $E_{\text{dyn}}$ vs. $E_{\text{static}}$ ⇨ $\sim R^2 = 0{,}99$

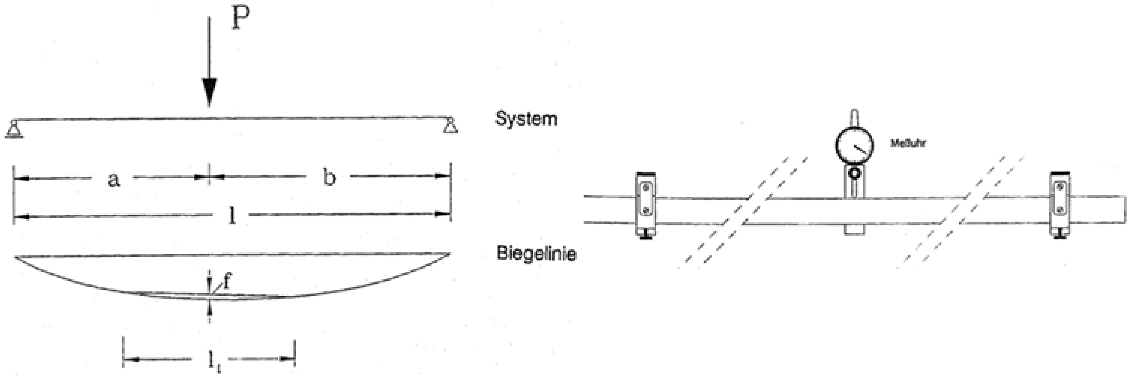



$$E = 4 \cdot \rho \cdot f^2 \cdot L^2$$



Ferenc Divos, Fakopp, Hungary

# In-situ static load test




Görlacher (1991)

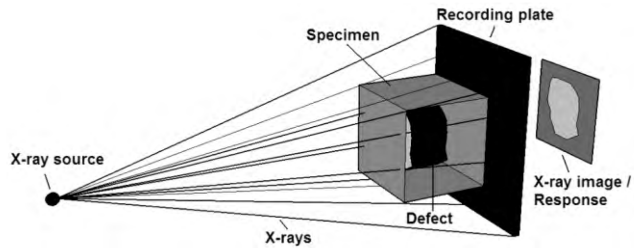
$$\Delta_f = \frac{P \cdot {l_1}^3}{48 \cdot EI} \cdot (-0.5 + 6 \cdot a/l \cdot b/l \cdot l/l_1 + s \cdot E/G \cdot (h/l_1)^2)$$

- Determination of E-modulus (stiffness)
- Relatively high correlation coefficients (0.7-0.8)
- Relative deformation since the purely simply supported state is never reached on-site

# X-Ray measurement

Background X-rays:

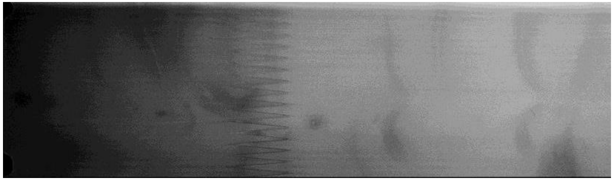
- X-rays are absorbed by materials (exponential decrease)
- Variations in density well visible from X-ray images
- Water (0.15 cm$^{-1}$) / material ⇨ attenuation coefficient
- For a given material: density and thickness must be corrected for MC
- Energy level up to 150 keV(P)





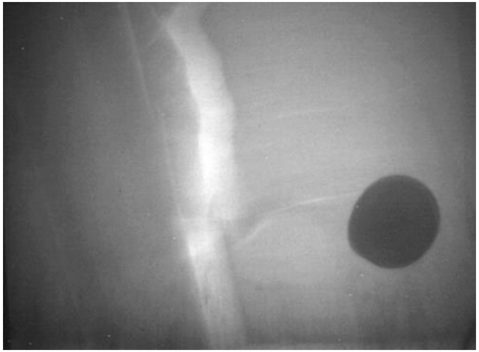
# Applications

## Delaminations in glulam / finger joints



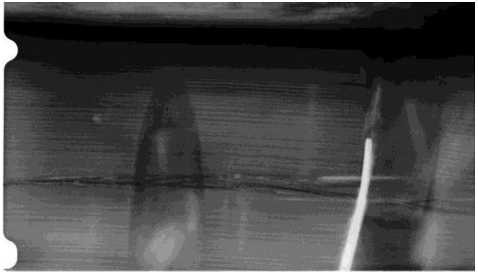
*NCPTT (2005)*

## Fracture of truss chord



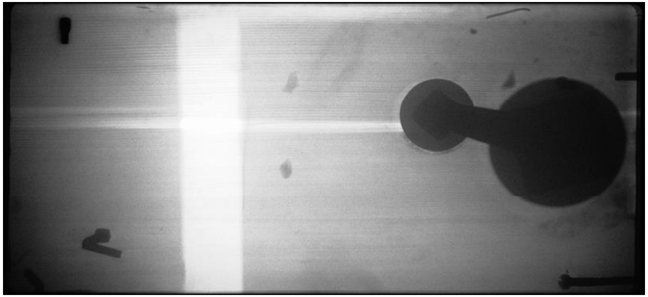
*NCPTT (2005)*

## Hidden geometry



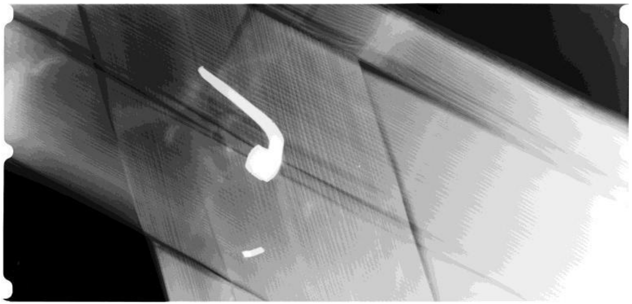
*NCPTT (2005)*

## Fracture/splitting in connection

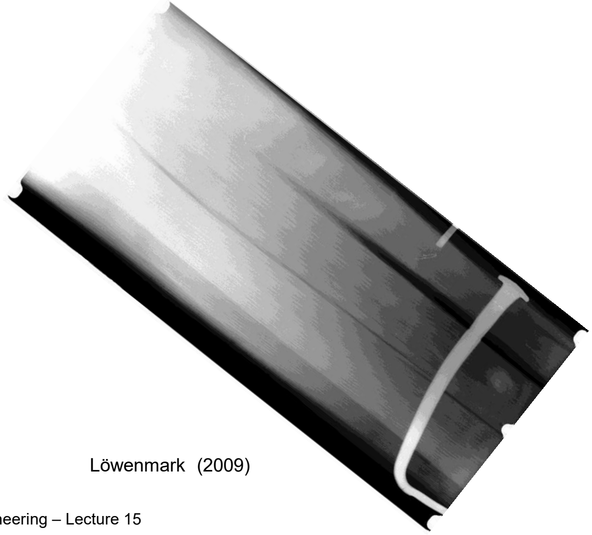


*NCPTT (2005)*

# Corrosion of metal fastener

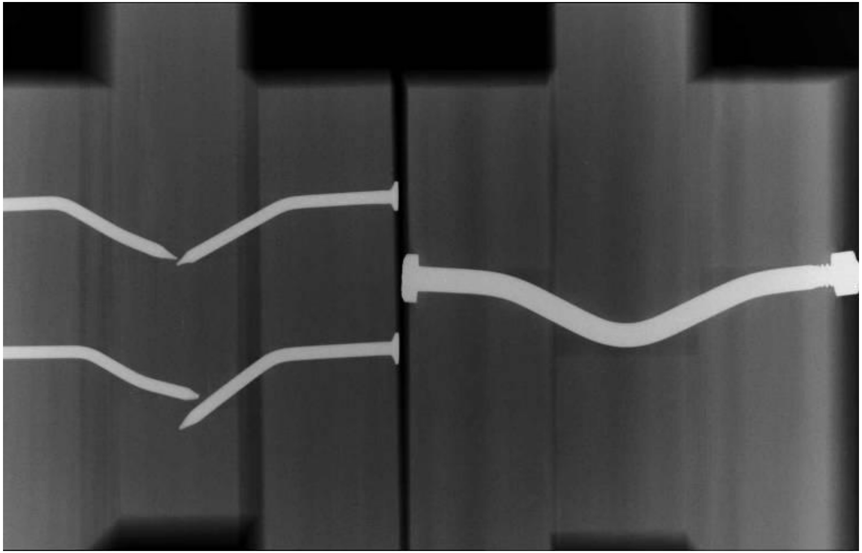


Löwenmark (2009)



Löwenmark (2009)

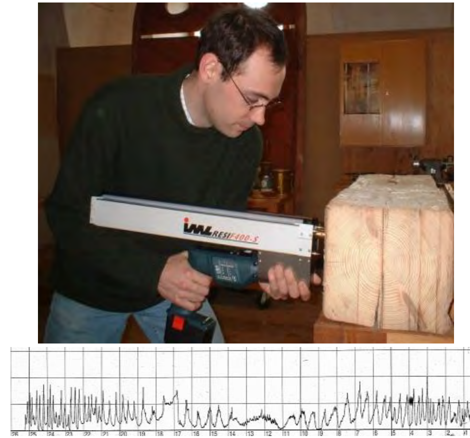
# Failure modes of fasteners



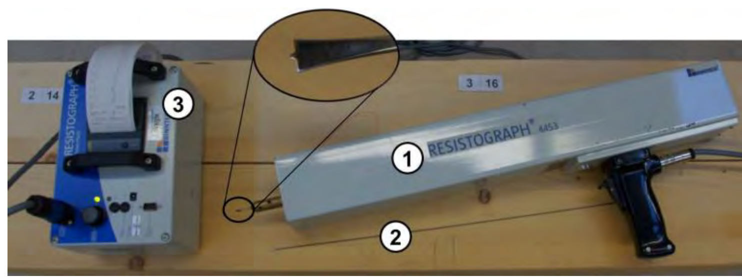
NCPTT (2005)

# Resistance drilling / Resistograph®

- small diameter needle-like drill
- drilling resistance is proportional to the relative variations in density, i.e. that decreasing drilling resistance is followed by decreased torque of the drill
- Resistance Measure (RM) parameter was implemented that allowed the comparison between the density of the drilling resistance and mechanical and physical properties of the timber
- RM ⇨ integral of the area of the drilling diagram divided by the length of the drilled perforation



Hasenstab (2009)



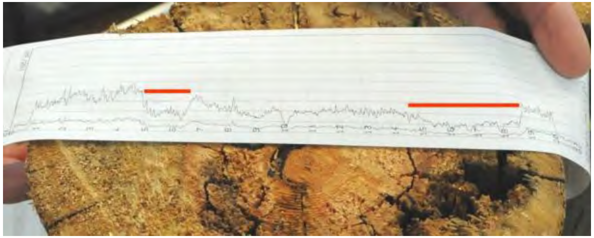

Scharmacher (2013)

# Resistance drilling / Resistograph®

Applications:

- Determination of local density
- Annual ring width
- Extent of deterioration
- Often used in combination with additional techniques, e.g. stress wave timing, X-ray
- Correlations for density ~0.98

Scharmacher (2013)

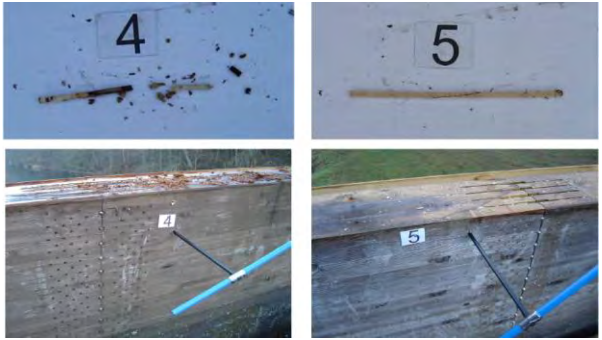


# Core drilling

- Hollow drill (increment borer)
  - Presence of decay/voids
  - Determination of wood species
  - Age of tree

Core extraction of probe

Brashaw (2011)




Tannert / Müller / Vogel (2010); University Appl. Sciences Biel

Replug with treated wood dowel or epoxy

# Choice of intervention

# Interventions

- Immediate safety interventions:
  - Restriction of use
  - immediate structural measures (supports etc.)
  - Intensified monitoring
  - Decommissioning and shut-off
  - Alarm / evacuation

# Interventions

- Additional safety interventions:
  - Restriction of use, Limitation the remaining service life
  - Limiting imposed loads
  - Monitoring of the load bearing behaviour
  - permanent or periodic monitoring
  - Warning and safety systems
  - Preparation of emergency measures, Alarm dispositions, evacuation plans

# Principle of Proportionality

- important basis: remaining service life
- Comparison of costs and benefits
- Efficiency of the safety-related intervention measures concerning:
  - safety requirements of the individual and society
  - Availability of the structure / plant
  - Extent of damage to persons, property and environment
  - Preservation of cultural value
- Include demolition costs in the analysis

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# Proportionality of Intervention

- Comparison of the costs and benefits of maintenance aiming at an efficient use of resources

Erik Christensen

# Interventions

# Interventions

- Goal:
  - Restoring structural safety

- Possible interventions
  - Repair of members
  - Replacement of members
  - Reinforcement
  - Reduction of action effects
  - Reduction of loads

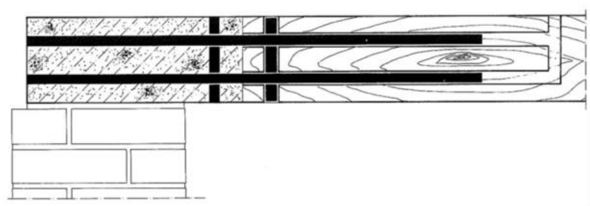
# Interventions

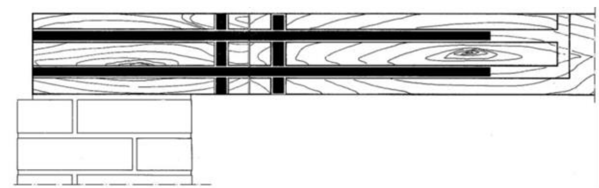
- Criteria for selection of interventions
  - Cause of damage / hazard scenario
  - Accessibility of the members
  - Cross sections, age of the structure
  - Existing climate conditions
  - Optical requirements
  - Material procurement (delivery dates, availability)
  - Dates, duration of interventions
  - Proportionality

# Interventions – Repair of crack

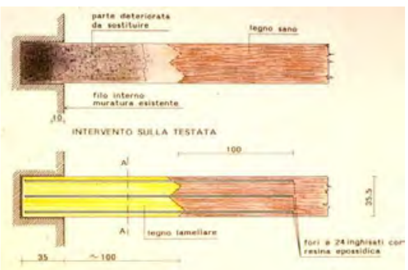
- Procedure
  - Cleaning the crack
  - Closing the crack
  - Drilling the holes for injection
  - Injecting
  - Closing the holes
  - Testing the glued joint

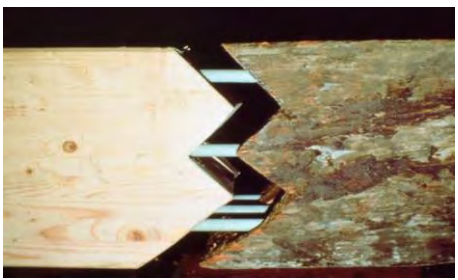
# Interventions – Replacement





Paul (1989)



Cestari (1989)

# Interventions – Replacement

Smedley (2012)

# Interventions – Replacement

Paul (1989)

# Interventions – Replacement and addition

- Replacement and addition of bracing

Merzaghi (2013a)

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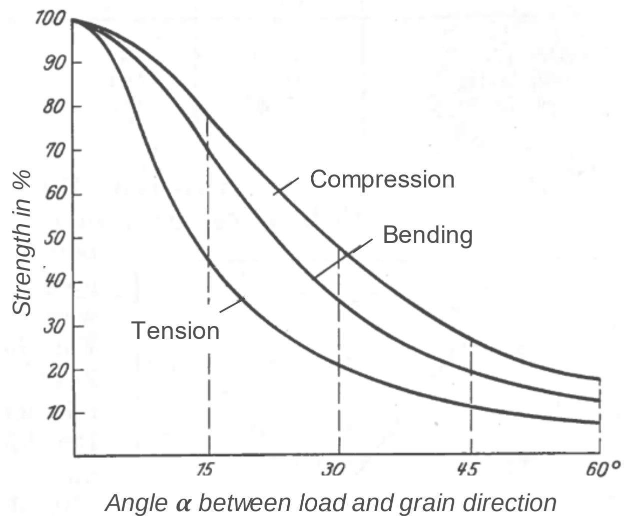
# Interventions – Reinforcement

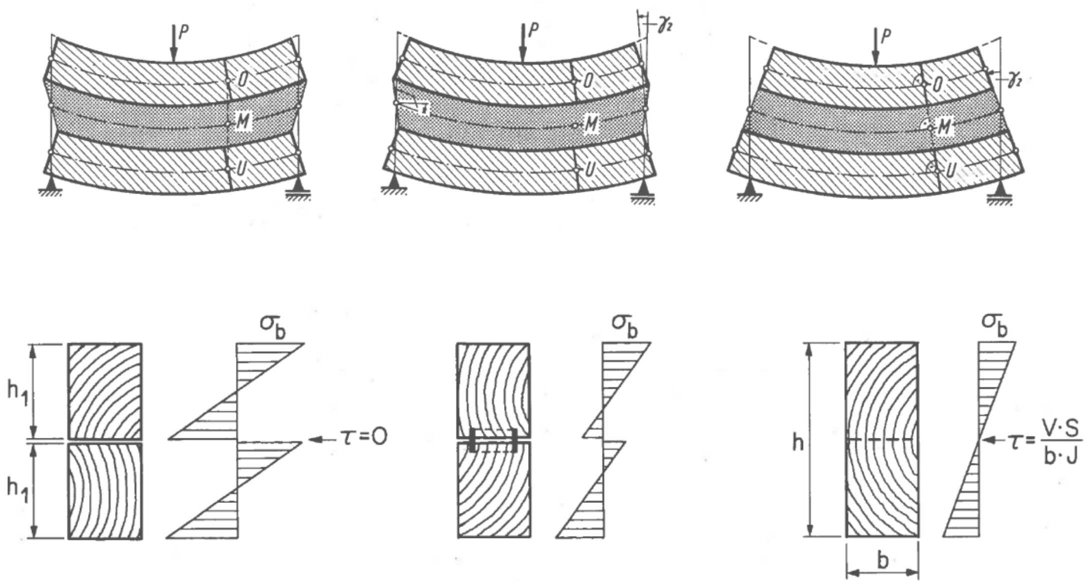
- Reinforcement according to loading conditions
  - Bending
  - Tension (mostly perpendicular to grain)
  - Compression (mostly perp. to grain)
  - Shear
  - (Deflection)




Kollmann

# Interventions – Reinforcement

- Bending reinforcement



# Interventions – reinforcement

- Bending reinforcement
  - Additional lamella

Widmann (2014)

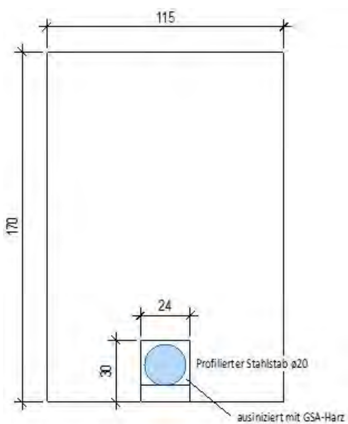
# Interventions – reinforcement

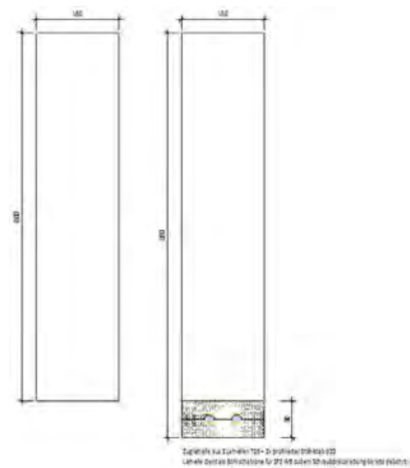
- Bending reinforcement
  - Curved beam


Merzaghi (2013b)

# Interventions – reinforcement

- Bending reinforcement
  - Optimization:
    By using additional lamellas or elements of high stiffness, the stresses in the timber can be reduced!



# Interventions – reinforcement

- Bending reinforcement
  - Timber Bridge in Sims, Switzerland
    - Reduction of deflection by 20%
    - First CFRP Reinforcement in Switzerland!

Baier (2013)

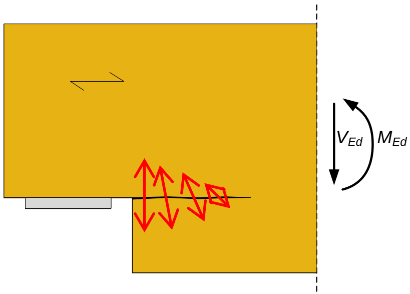
# Interventions – reinforcement

- Bending reinforcement
  - External reinforcement

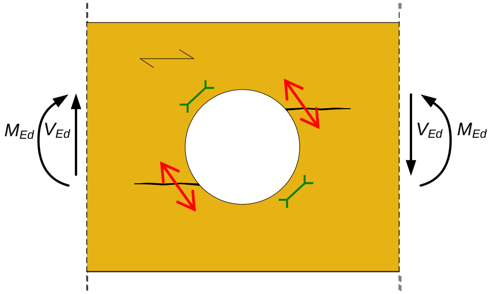

SFS (2013)

# Interventions – reinforcement

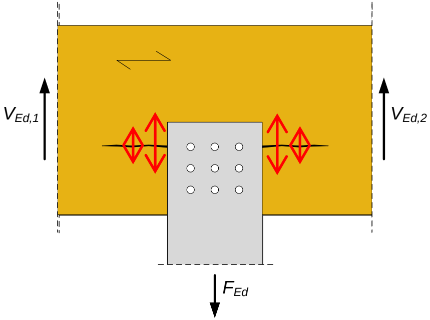
- Notch



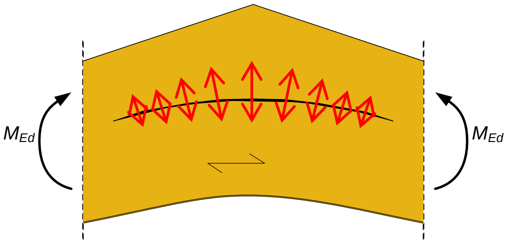

- Hole




- Connection perp. to grain




- Curved beams

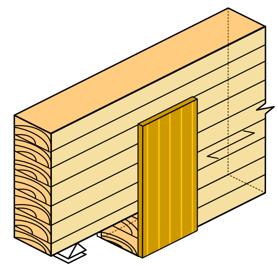


# Interventions – reinforcement

- Notched beams
    - Internal, dowel-type reinforcement:
        - fully threaded screws according to EN 14592 or European Technical Assessment
        - screwed-in threaded rods with wood screw thread according to European Technical Assessment
        - glued-in threaded or ribbed steel rods

# Interventions – reinforcement

- Notched beams
  - Plane, external reinforcement may be applied:
    - glued-on plywood according to EN 13986
    - glued-on structural laminated veneer lumber according to EN 14374
    - glued-on laminations made of either structural solid timber according to EN 14081-1 or plywood according to EN 13986 or structural laminated veneer lumber according to EN 14374
    - pressed-in punched metal plate fasteners

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# Interventions – reinforcement

- Holes in beams
  - Reinforcement:

Brunauer (2015)

# Interventions – reinforcement

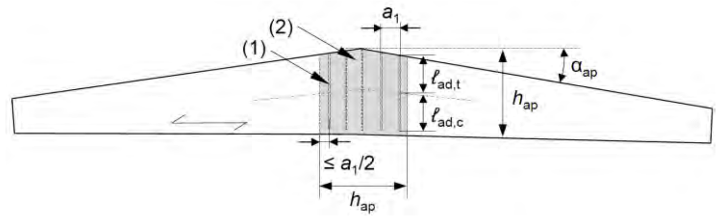
- Curved and cambered beams

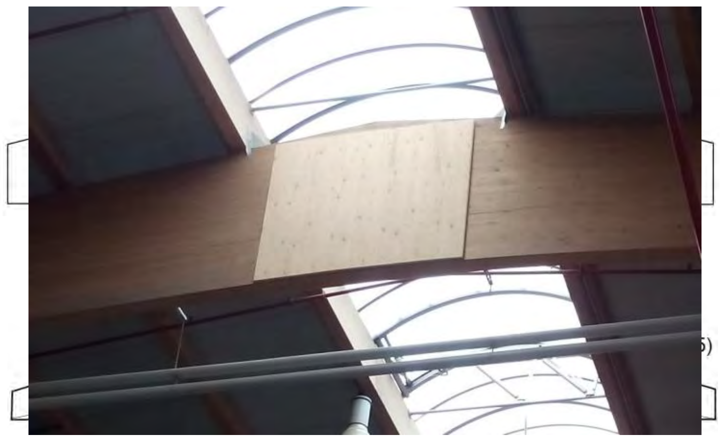
# Interventions – reinforcement

- Curved and cambered beams
  - Force on reinforcement:

$$F_{t,90,Ed} = k_{ka} \cdot \sigma_{t,90,d} \cdot b \cdot a_1$$

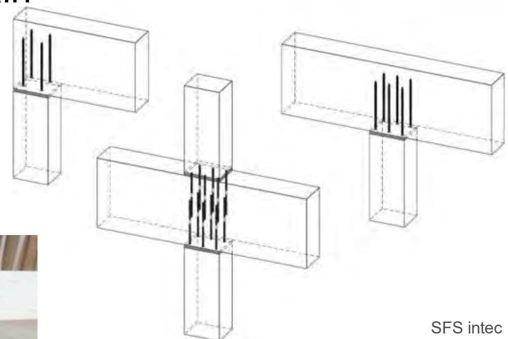
  - Where:
  - $k_{ka} = 1.0$ for curved beams & in inner quarters
  - $k_{ka} = 0.67$ in outer quarters



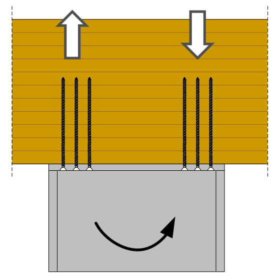



# Interventions – reinforcement

- Compression reinforcement perp. to grain
  - Bonded-in rods
  - Screws

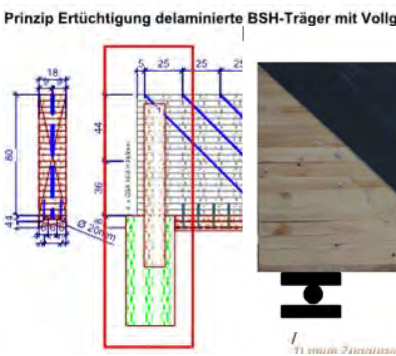


SFS intec



# Interventions – reinforcement

- Shear reinforcement
  - Bonded-in rods
  - Screws/Threaded rods
  - Plywood
  - FRP lamellas




Kübler and Bühler (2014)
Merzaghi (2013a)

Source: A. Frangi, ETH

# Fire and timber

# Behaviour of materials under high temperatures

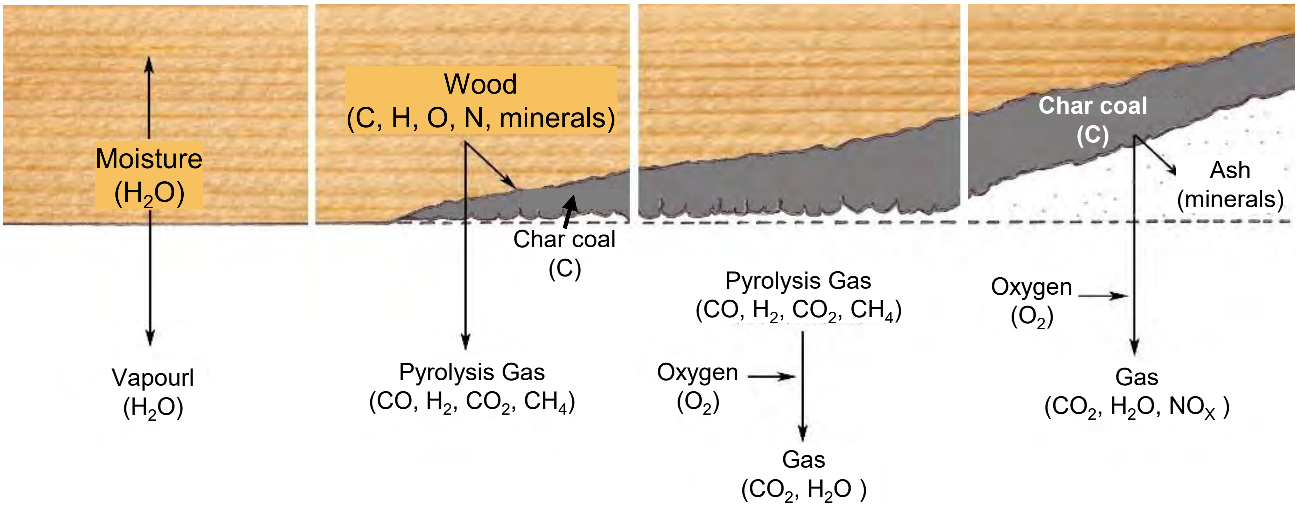
## Concrete

## Steel

## Timber

Source: A. Frangi, ETH

# Combustion of wood




| Drying | Pyrolysis | Combustion of gases from pyrolysis | Combustion of char coal |
|---|---|---|---|
| $\approx 100°C$ | $200 - 500°C$ | $400 - 1200°C$ | from $600°C$ |

Source: Klippel, Schmid, ETH

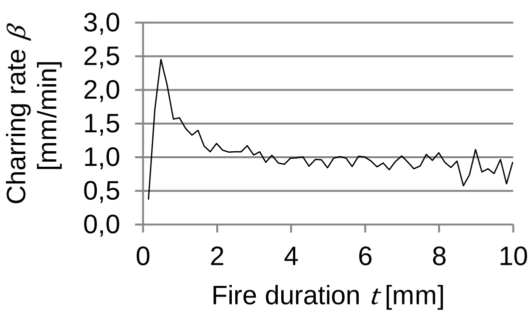
# Consideration of cumbustion in design

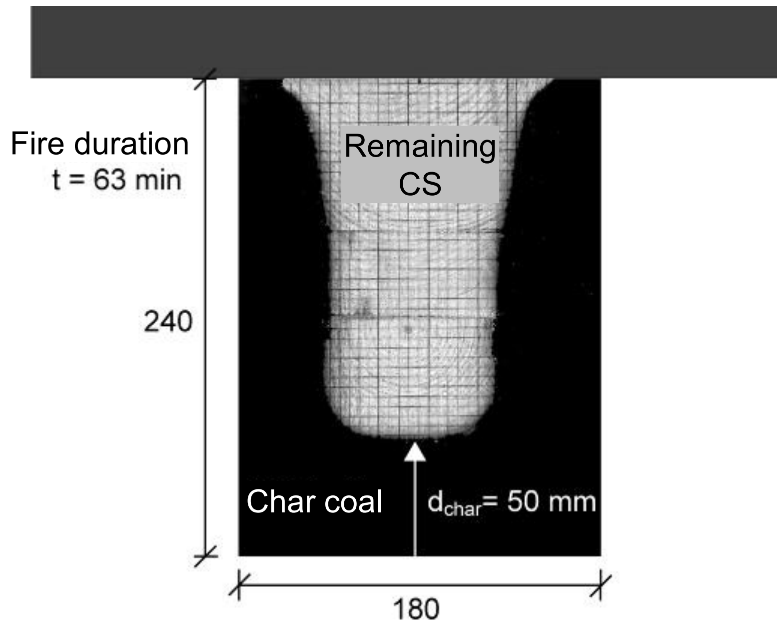
- Charring rate $\beta$ :
  Char thickness in dependency of fire duration

$$\boxed{\beta = \frac{d_{char}}{t}}$$

- Example:

$$\beta = \frac{d_{char}}{t} = \frac{50mm}{63\text{min}\, mm/\text{min}}$$

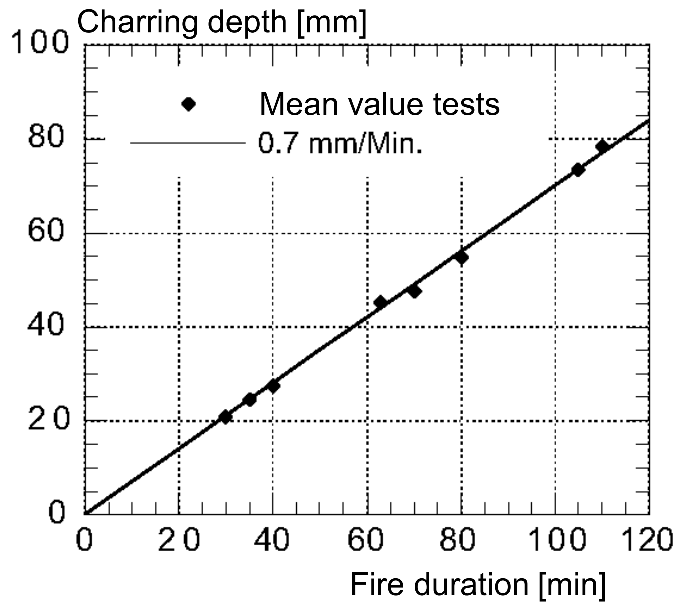



Source: A. Frangi, ETH

# Charring rate

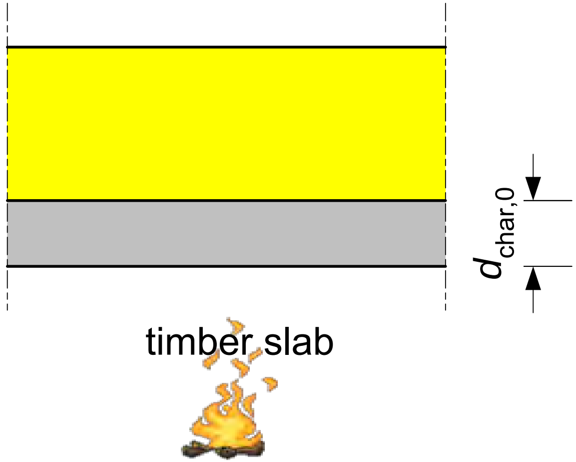
- depending on the temperature load
  - almost constant over time under ISO standard fire exposure
- depending on the type of wood
  - for spruce: $\beta \approx 0{,}7\, mm/min$
- Influence of wood moisture and density low




Source: A. Frangi, ETH

# Charring rate in EN 1995-1-2

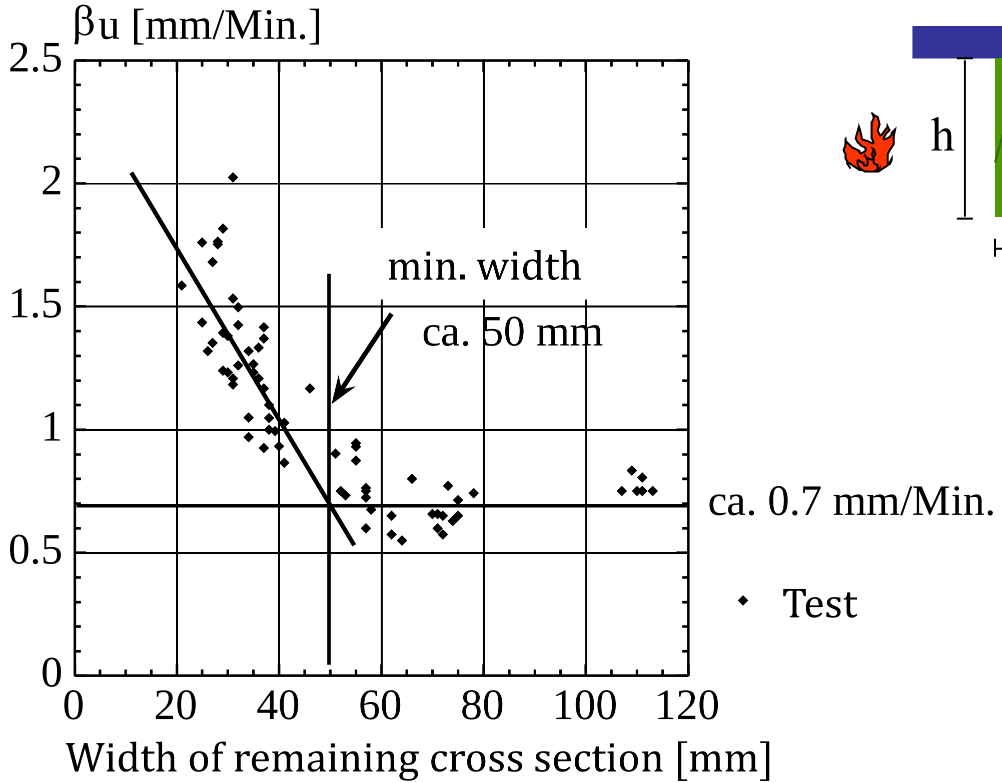
- Charring rate for one-dimensional charring

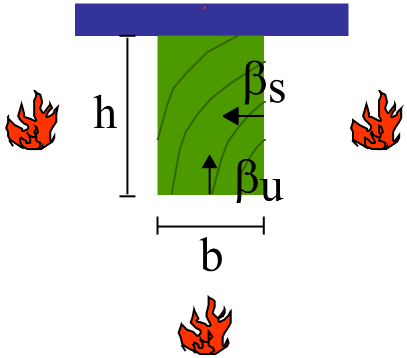



$$d_{char,0} = \beta_0 \cdot t$$

Source: A. Frangi, ETH

# Charring rate

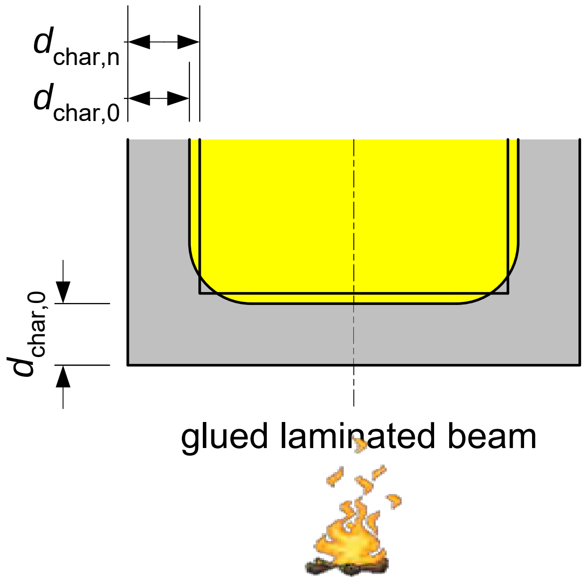



Source: A. Frangi, ETH

# Charring rate in EN 1995-1-2

- Notional charring rate
    - magnitude of which includes for the effect of corner roundings




$$d_{char,n} = \beta_n \cdot t$$

Source: A. Frangi, ETH

# Charring rate in EN 1995-1-2

**Table 3.1 – Design charring rates $\beta_0$ and $\beta_n$ of timber, LVL, wood panelling and wood-based panels**

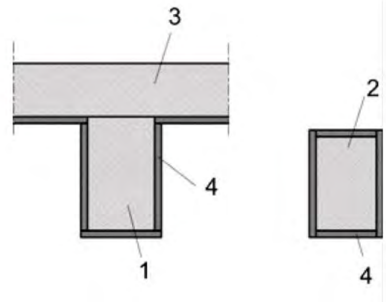
| | $\beta_0$<br>mm/min | $\beta_n$<br>mm/min |
|---|---|---|
| **a) Softwood and beech**<br>Glued laminated timber with a characteristic density of ≥ 290 kg/m$^3$<br>Solid timber with a characteristic density of ≥ 290 kg/m$^3$ | <br>0,65<br>0,65 | <br>0,7<br>0,8 |
| **b) Hardwood**<br>Solid or glued laminated hardwood with a characteristic density of  290 kg/m$^3$<br>Solid or glued laminated hardwood with a characteristic density of ≥ 450 kg/m$^3$ | <br>0,65<br>0,50 | <br>0,7<br>0,55 |
| **c) LVL**<br>with a characteristic density of ≥ 480 kg/m$^3$ | 0,65 | 0,7 |
| **d) Panels**<br>Wood panelling<br>Plywood<br>Wood-based panels other than plywood | <br>0,9[a]<br>1,0[a]<br>0,9[a] | <br>–<br>–<br>– |

[a] The values apply to a characteristic density of 450 kg/m$^3$ and a panel thickness of 20 mm; see 3.4.2(9) for other thicknesses and densities.

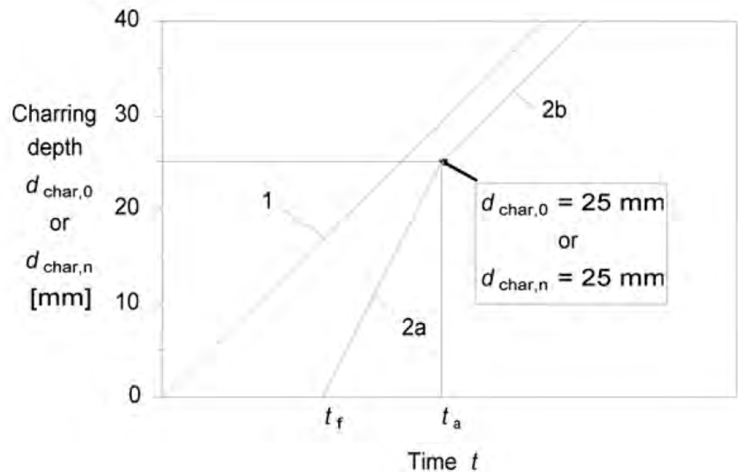
Source: A. Frangi, ETH

# Fire resistance of timber members

- Unprotected timber members
  - Verification of residual cross-section
- Timber members protected from fire exposure
  - Verification of residual cross-section and different fire phases




Key:
1 beam
2 column
3 deck
4 cladding




Key:
1 Relationship for members unprotected throughout the time of fire exposure for charring rate $\beta_n$ (or $\beta_0$)
2 Relationship for initially protected members after failure of the fire protection
2a After the fire protection has fallen off, charring starts at increased rate
2b After char depth exceeds 25 mm charring rate reduces to the rate shown in table 3.1

Source: A. Frangi, ETH

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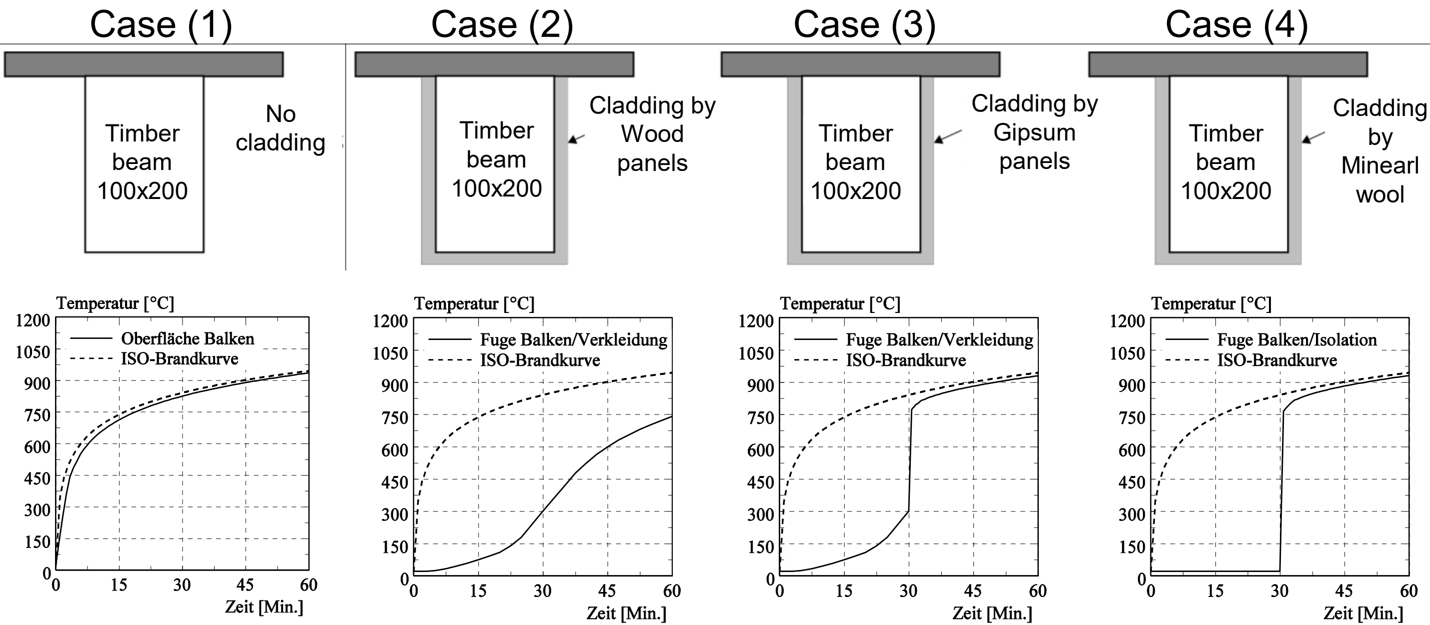
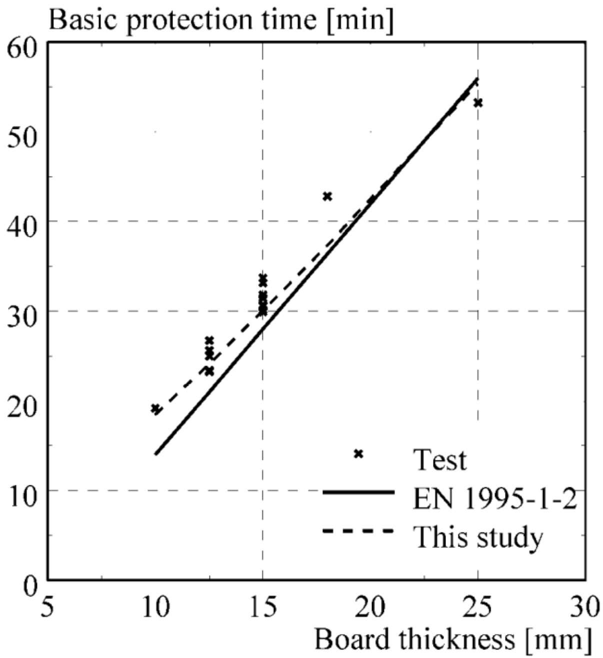
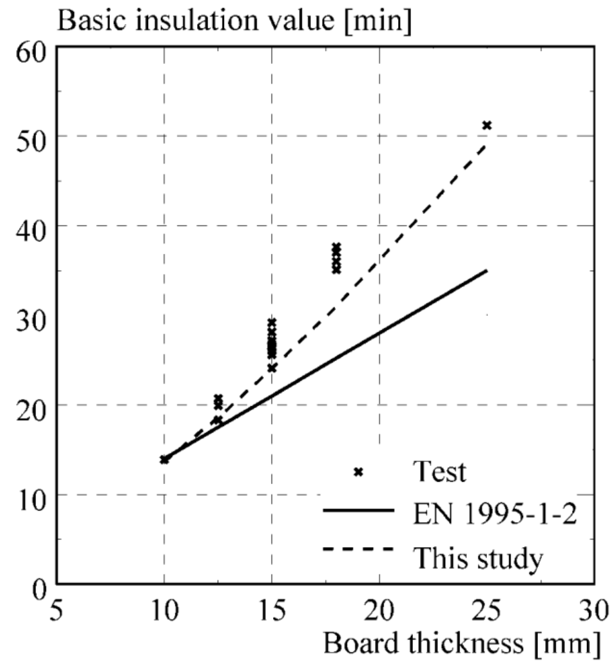
# Impact of cladding




Source: A. Frangi, ETH

# Examples of protection behaviour of Gipsum panels



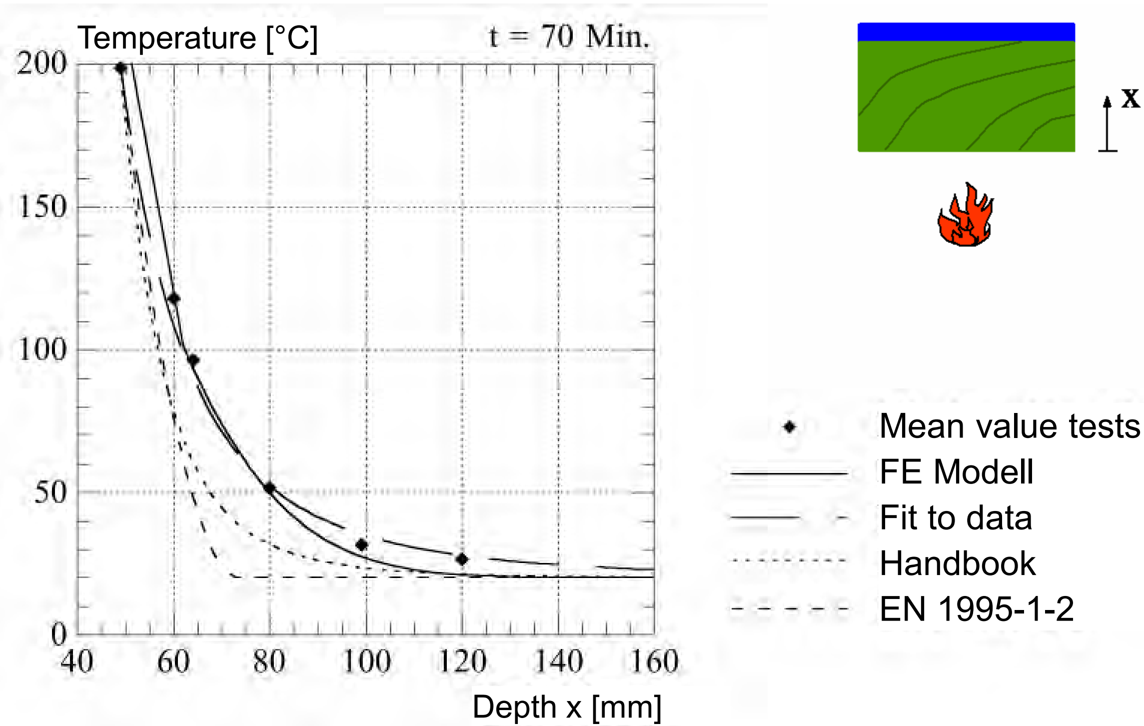




$$t_{prot,0} = 30 \cdot \left(\frac{h_p}{h_{p,ref}}\right)^{1.2} \quad with\ h_{p,ref} = 15mm$$

$$t_{ins,0} = 24 \cdot \left(\frac{h_p}{h_{p,ref}}\right)^{1.4} \quad with\ h_{p,ref} = 15mm$$

Source: A. Frangi, ETH

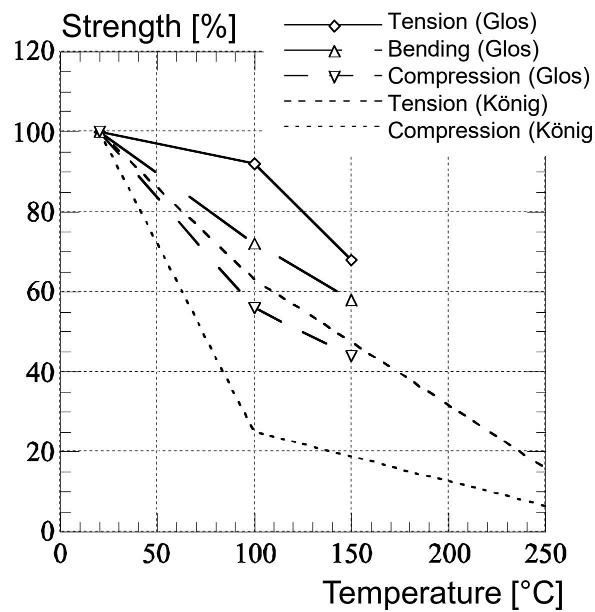
# Temperature in a timber member




Source: A. Frangi, ETH

# Impact of temperature on strength

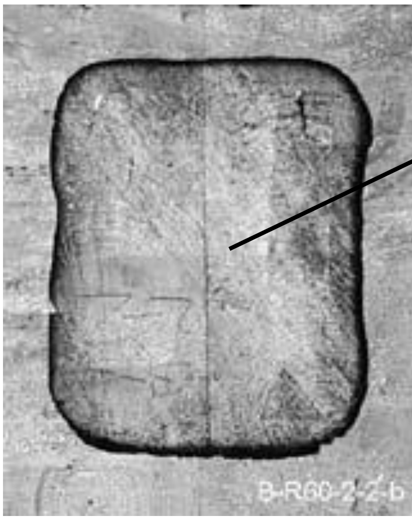
- Highly dependent on the test method
- Strong influence of moisture content changes in the timber cross-section
- Strength decrease only close to the combustion zone




Source: A. Frangi, ETH

# Strength of timber in fire

- Charcoal layer protects the inner wood from heat



Source: proHolz, Austria

Remaining cross-section

- "cold"
- Good strength

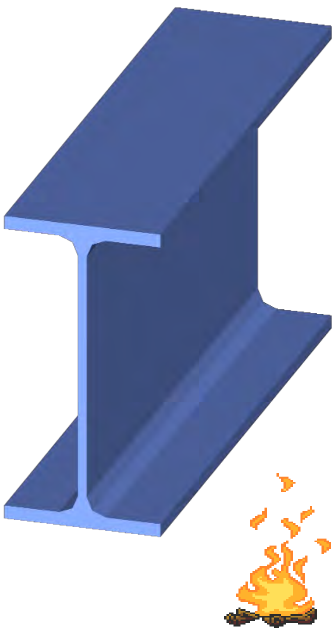
**<u>Steel</u>**

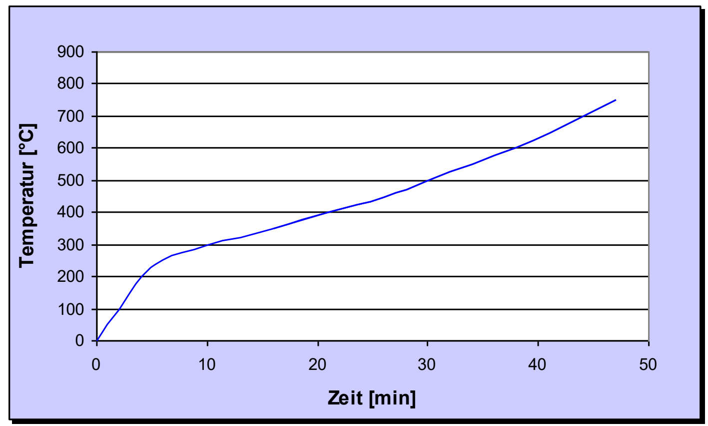
Non-combustible but quick heat transfer

Source: A. Frangi, ETH

# Intrumescent paint

- when exposed to heat, from approx. 200°C (depending on the product) the coating foams up and forms a solid, compact, heat-insulating foam






Source: A. Frangi, ETH

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# Intrumescent paint

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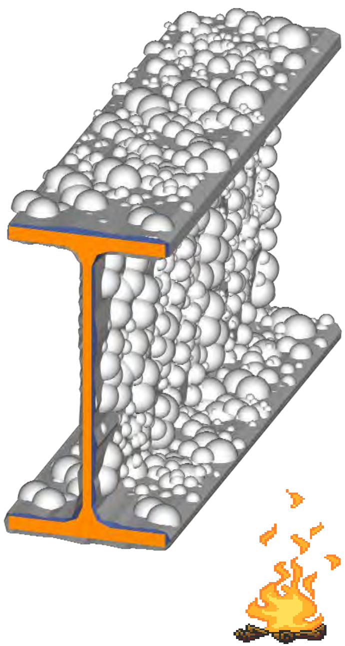

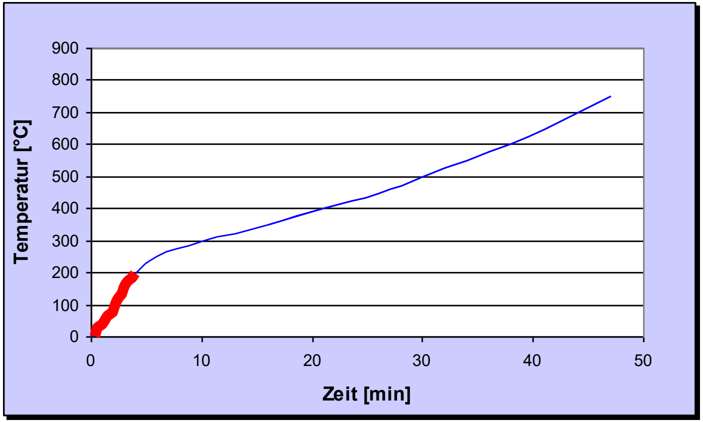


Source: A. Frangi, ETH

# Intrumescent paint

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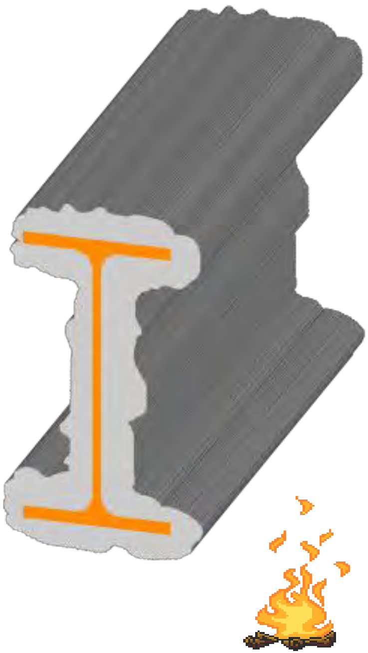
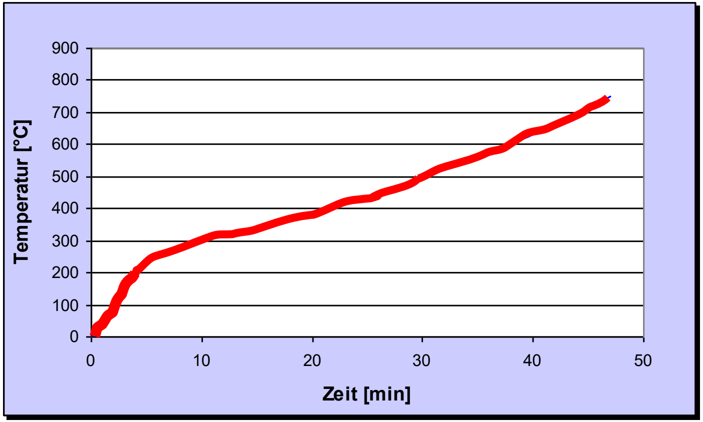





Source: A. Frangi, ETH

# Fire protection systems forming an insulating layer

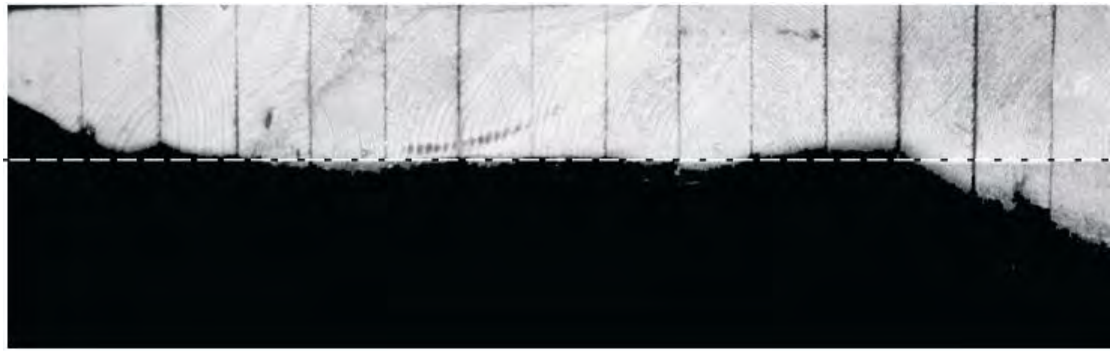
- “Modern manmade intumescent materials applied to steel structural elements are in essence an attempt to replicate what timber does naturally.”

Source:
Paper “Overview of design issues for tall timber buildings”, I. Smith, A. Frangi, SEI 2/2008

Source: A. Frangi, ETH

# Fire resistance of timber members

- General considerations
  - Choice of massive cross-sections



Source: A. Frangi, ETH

# Fire resistance of timber members

- General considerations
  - Choice of massive cross-sections
  - Increasing cross-sections by charring depth

Source: A. Frangi, ETH

# Fire resistance of timber members

- General considerations
  - Choice of massive cross-sections
  - Increasing cross-sections by charring depth
  - Covering the cross sections with non-combustible insulating materials

SP ≈ 600°C SP > 1000°C SP ≈ 600°C SP > 1000°C

Source: A. Frangi, ETH

# Verification in EN 1995-1-2

- Same verifications as for normal temperature, but with
  - the design values of the actions according to EN 1990
  - the strengths according to EN 1995-1-2
- Verification of structural safety in case of fire

$$E_{d,fi} \leq R_{d,fi}$$

- For simplification, in timber construction for residential and office buildings $E_{d,fi} \approx 0{,}6 E_d$ may be assumed

Source: A. Frangi, ETH

# Verification in EN 1995-1-2

- Design value of the resistance in case of fire $R_{d,fi}$

$$f_{d,fi} = k_{mod,fi} \frac{f_{20}}{\gamma_{M,fi}}$$

20 %
Fraktile value
of strength

modification faktor
(Impact of temperature)

Partial factor = 1.0

$$f_{20} = k_{fi} \, f_k$$

e.g. $k_{fi} = 1{,}25$ for solid timber

$k_{fi} = 1{,}25$ for glulam

Source: A. Frangi, ETH

# Verification in EN 1995-1-2

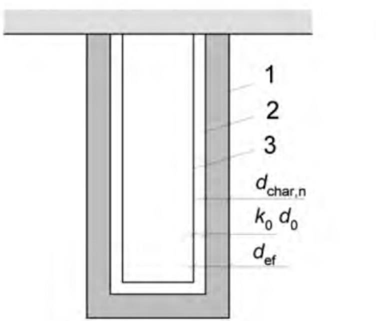
- Reduced cross-section method

$$d_{ef} = d_{char,n} + k_0 \cdot d_0$$

$$d_0 = 7mm$$

$$k_{\mathrm{mod},\,fi} = 1.0$$

$$f_{d,fi} = f_{20} = k_{fi} \cdot f_k$$



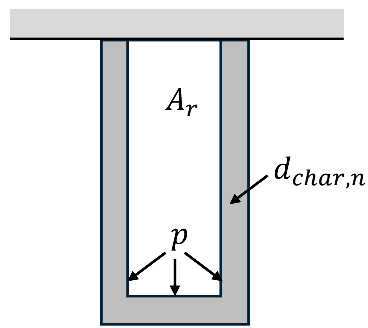

Key
1 Initial surface of member
2 Border of residual cross-section
3 Border of effective cross-section

- Reduced property method

$$d_{char,n} = \beta_n \cdot t$$

$$k_{\mathrm{mod},\,fi} = f(p/A_r)$$

$$f_{d,fi} = k_{\mathrm{mod},\,fi} \cdot f_{20} = k_{\mathrm{mod},\,fi} \cdot k_{fi} \cdot f_k$$




Source: A. Frangi, ETH

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# Verification in EN 1995-1-2

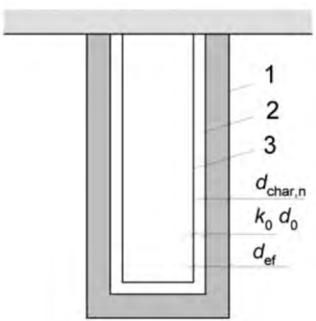
- Reduced cross-section method

$$d_{ef} = d_{char,n} + k_0 \cdot d_0$$

$$d_0 = 7mm$$

$$k_{\text{mod},fi} = 1.0$$

$$f_{d,fi} = f_{20} = k_{fi} \cdot f_k$$



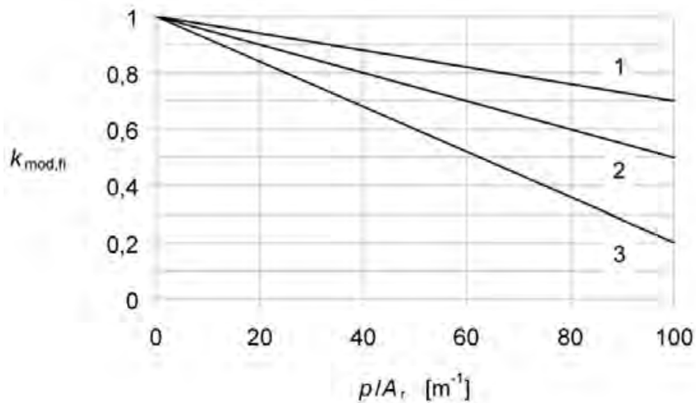

Key
1 Initial surface of member
2 Border of residual cross-section
3 Border of effective cross-section

- Reduced property method

$$d_{char,n} = \beta_n \cdot t$$

$$k_{\text{mod},fi} = f(p/A_r)$$

$$f_{d,fi} = k_{\text{mod},fi} \cdot f_{20} = k_{\text{mod},fi} \cdot k_{fi} \cdot f_k$$




Key:
1 Tensile strength, Modulus of elasticity
2 Bending strength
3 Compressive strength

# Requirements in fire situation

- Requirement on Load-capacity "R”
- Requirement on fire compartments "EI”
  - no failure of smoke tightness through cracks, holes or other openings large enough to allow the passage of fire in the form of flames or hot gases (smoke tightness requirement and integrity "E")
  - no failure of the thermal insulation due to temperature increase on the side facing away from the fire beyond agreed limits (requirement of thermal insulation "I")


Source: A. Frangi, ETH

# Tightness of structures forming fire compartments

- Burning through after 50 minutes of exposure to fire of an uncovered deck of board stacks

Source: A. Frangi, ETH

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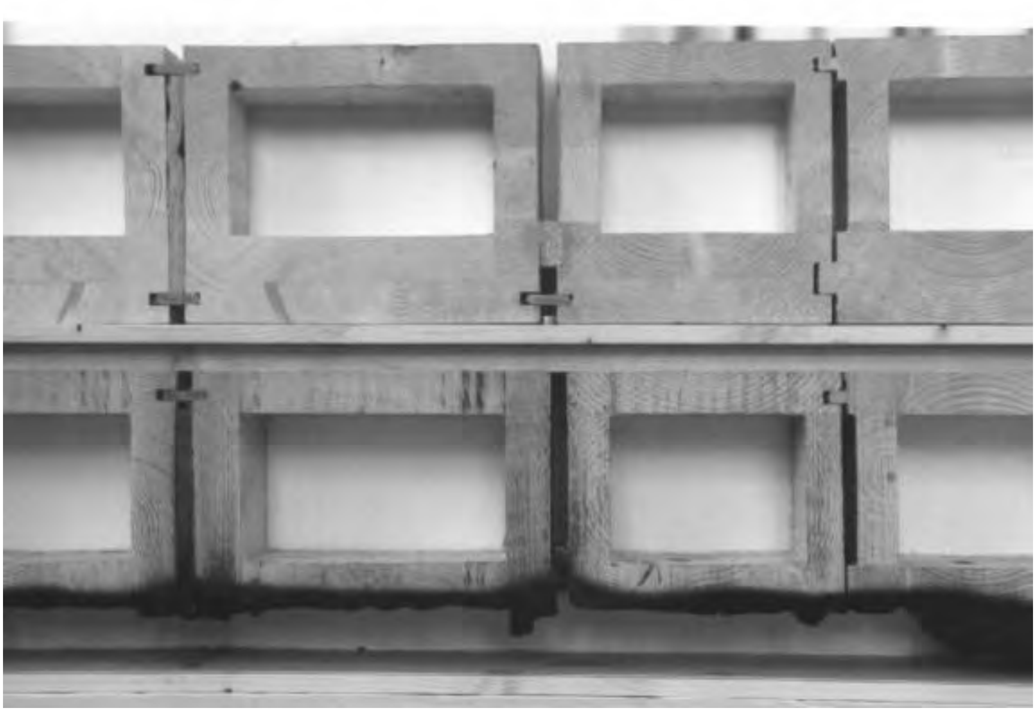
# Tightness of structures forming fire compartments

- Residual cross section after 60 minutes exposure to fire



Source: A. Frangi, ETH

# Tightness of structures forming fire compartments

- General considerations
  - Close gaps
  - Fill cavities
  - Multi-layer construction
  - Covering, planking, cladding

- Favourable components in case of fire
  - Timber-concrete-composite
  - Plane, massive timber elements

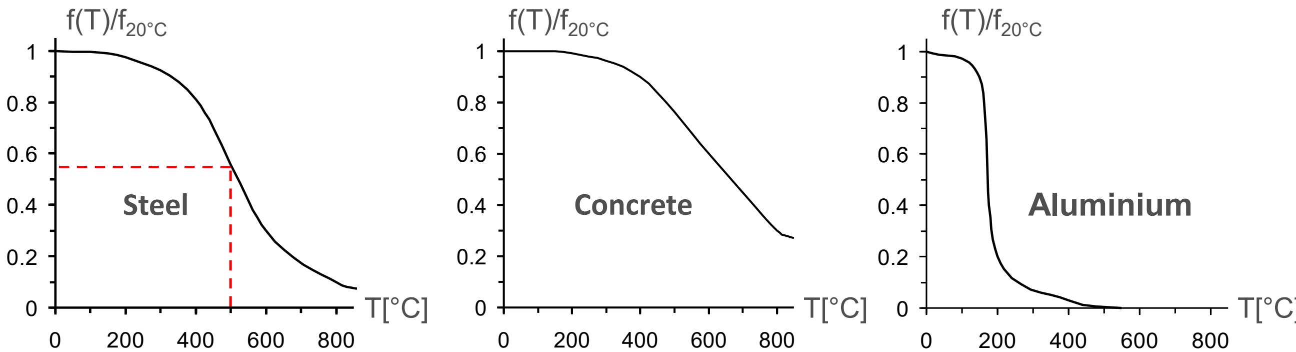
Source: A. Frangi, ETH

# Integrity of wall

Source: A. Frangi, ETH

# Timber Connection in Fire

# Comparison of material behaviour




- Loss of strength at high temperatures


Remaining cross-section

Source: proHolz, Österreich

Timber:

- Reduction of cross section
- Rounding of corners

Source: A. Frangi, ETH

# Connections in fire - General considerations

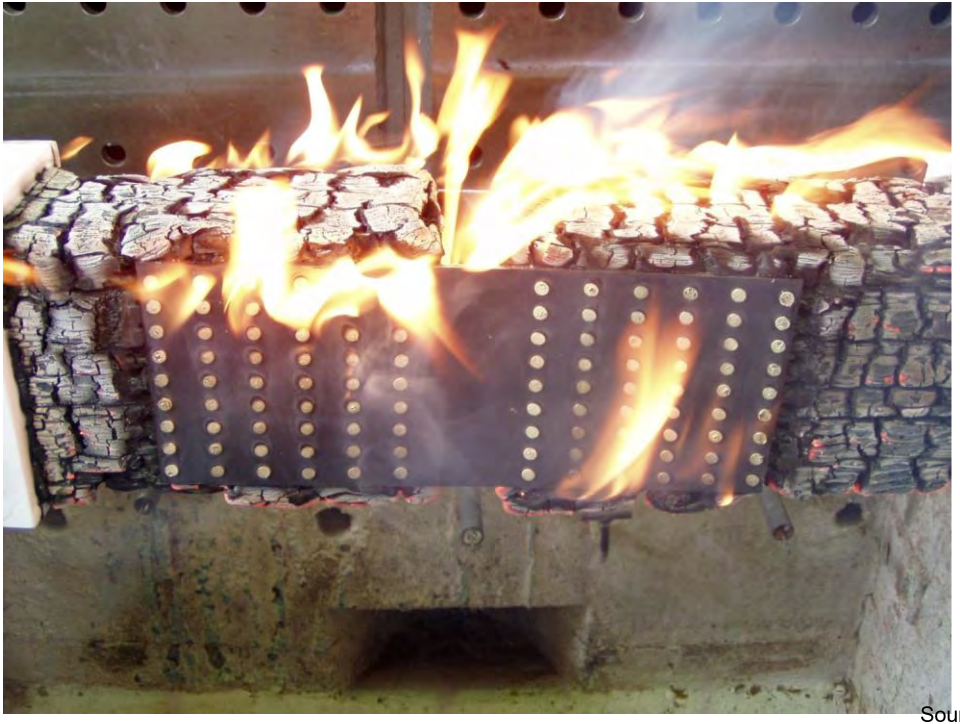
- Connections with steel parts
  - Avoid or cover external steel parts
  - Larger edge and end distances; minimum timber thickness
  - Keep slots for metal sheets narrow, so that they are fully filled
  - Countersink sheet metal / fasteners
  - Protect screw heads from the temperature

- Benefitial impacts on connections in fire
  - Increase spacing and distances
  - Cladding
  - Over dimensioning

Source: A. Frangi, ETH

# Connections in fire

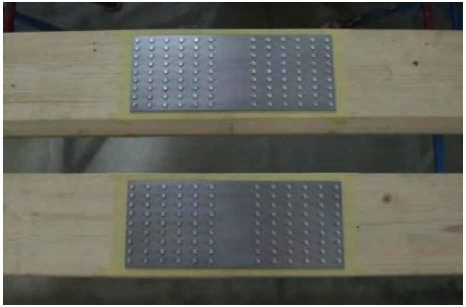
- Behaviour of connections with external nailed steel plates



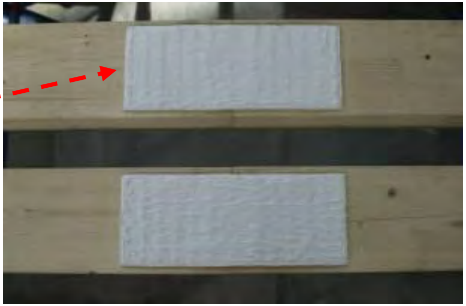
Source: A. Frangi, ETH

# Tests on connections with external nailed steel plates

- Test program
  - 5 tests at room temperature according to EN 26891
  - 8 tests under ISO - standard fire stress



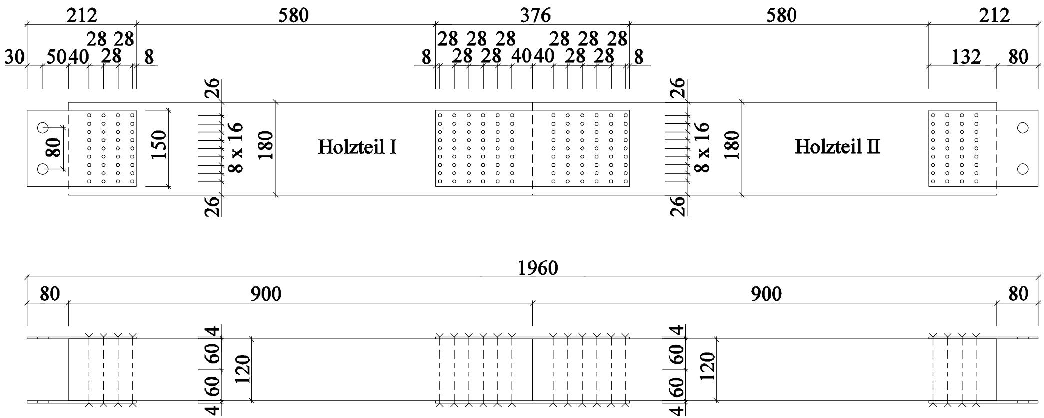
- Test parameters of the fire tests
  - Load level (30 and 15 % of $F_{cold}$)
  - 4 tests with fire protection coating SIKA Pyroplast Steel D



Source: A. Frangi, ETH

# Tests on connections with external nailed steel plates

- Specimens




Source: A. Frangi, ETH

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# Tests on connections with external nailed steel plates

- Results
    - unprotected: Fire resistance 13 minutes (average)
    - protected:  Fire resistance 32 minutes (average value); R30
    - Increased burn-up under the steel sheets
    - strong deformations of the grooved nails
    - Foaming of the coating uneven

Source: A. Frangi, ETH

# Tests on connections with external nailed steel plates

- Observations

Source: A. Frangi, ETH

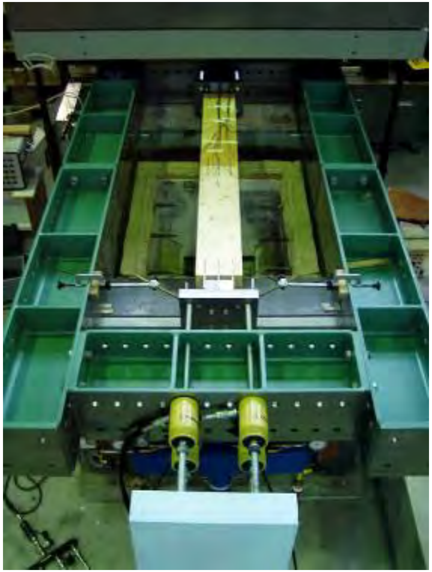
# Connections in fire

- Behaviour of connections with multiple slotted in plates

Source: A. Frangi, ETH

# Tests on connections with multiple slotted in plates

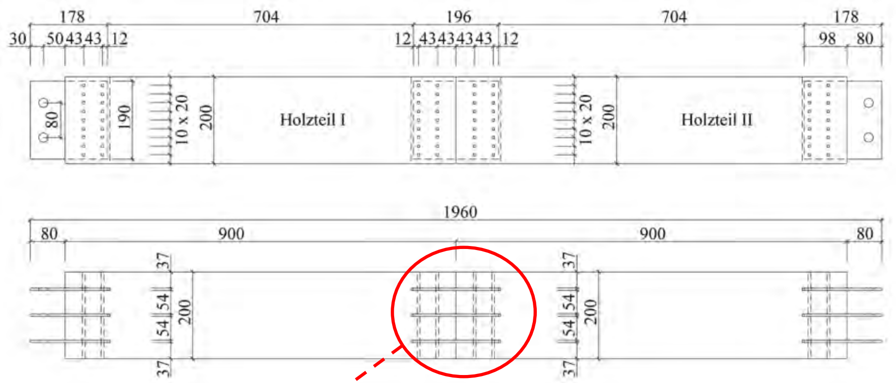
- 26 Tests
- Fire tests R30 and R60
- Test parameters
  - Load during the fire test ($0{,}3F_u$, $0{,}15F_u$, $0{,}075F_u$)
  - Number of dowels, geometry (9x2, 9x3, 3x3 and 4x2 dowels)
  - Dowel diameter (6.3 mm or 12 mm)
  - Increased timber dimensions
  - Cladding of the joint

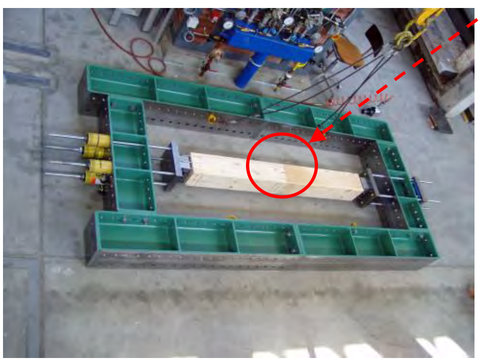


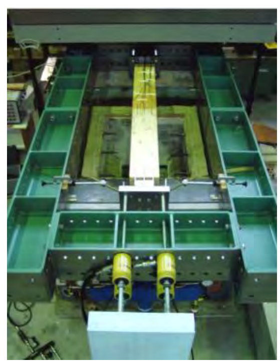
Source: A. Frangi, ETH

# Tests on connections with multiple slotted in plates

- Specimens and setup



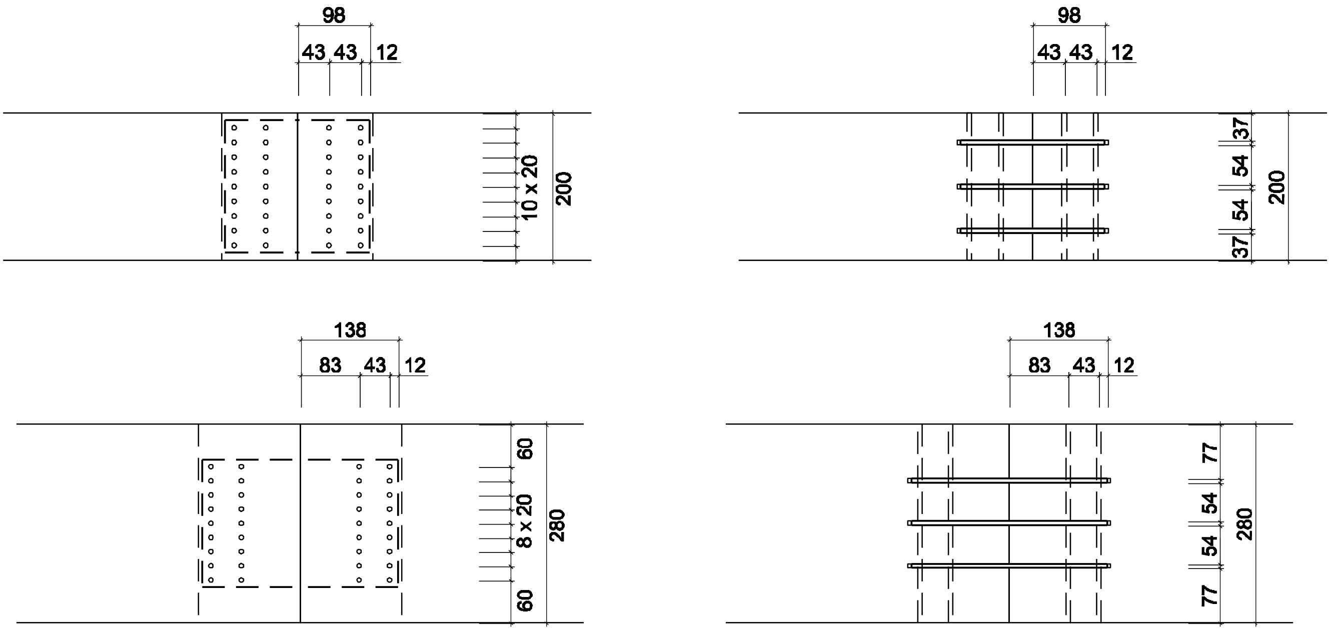





Source: A. Frangi, ETH

# Tests on connections with multiple slotted in plates

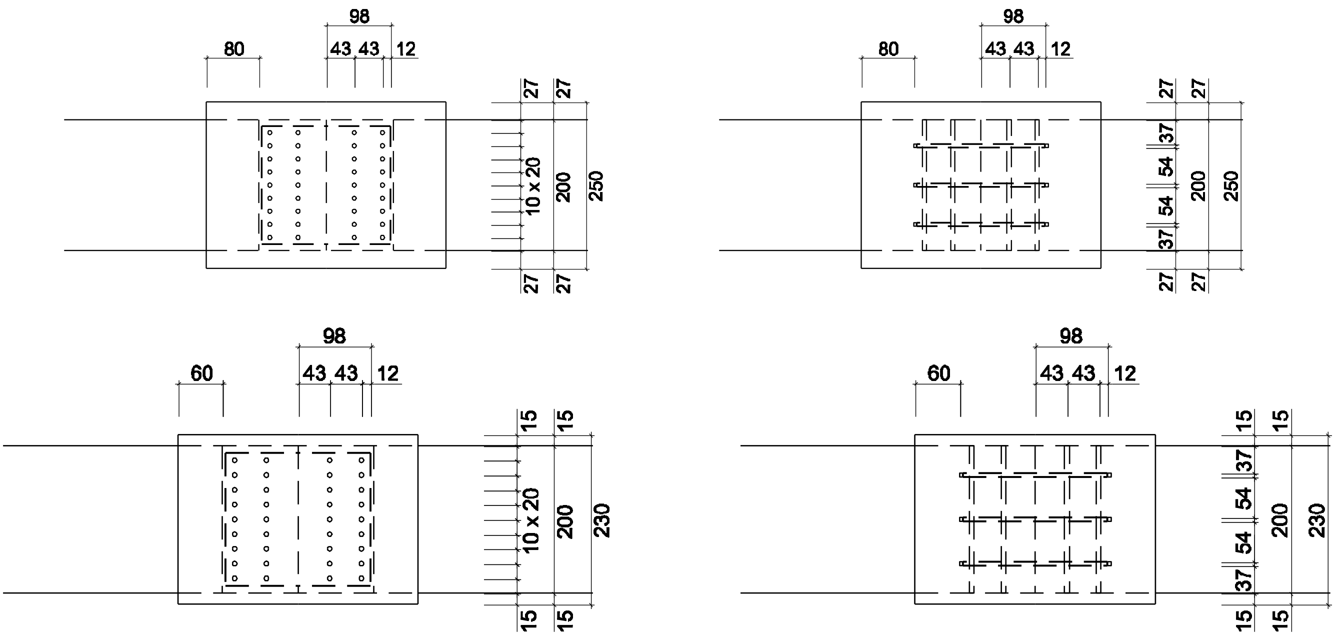
- Specimens R60: Increased dimensions




Source: A. Frangi, ETH

# Tests on connections with multiple slotted in plates

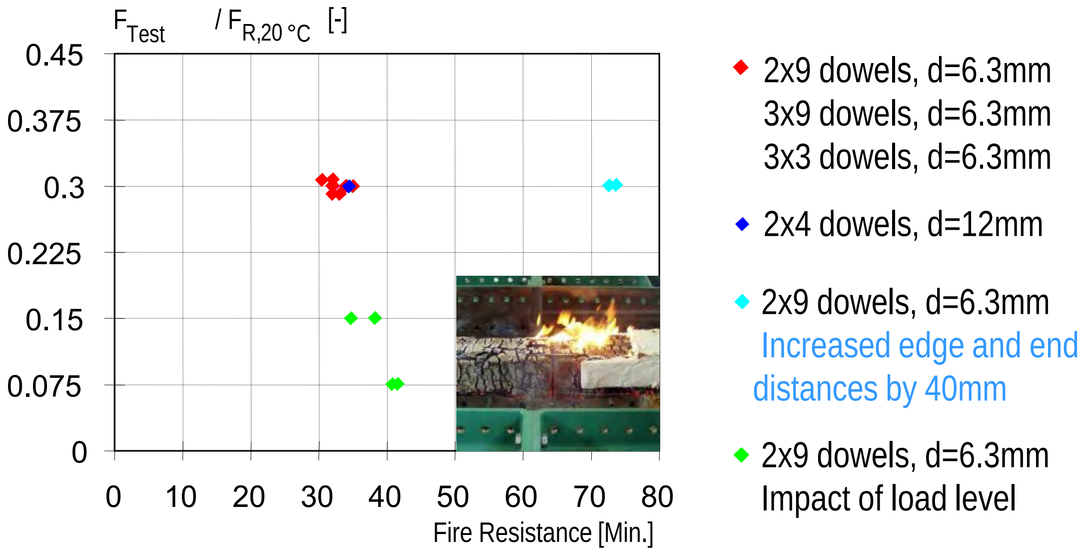
- Specimens R60: Cladding with Gipsum and Wood panels




Source: A. Frangi, ETH

# Tests on connections with multiple slotted in plates

- Results




Source: A. Frangi, ETH

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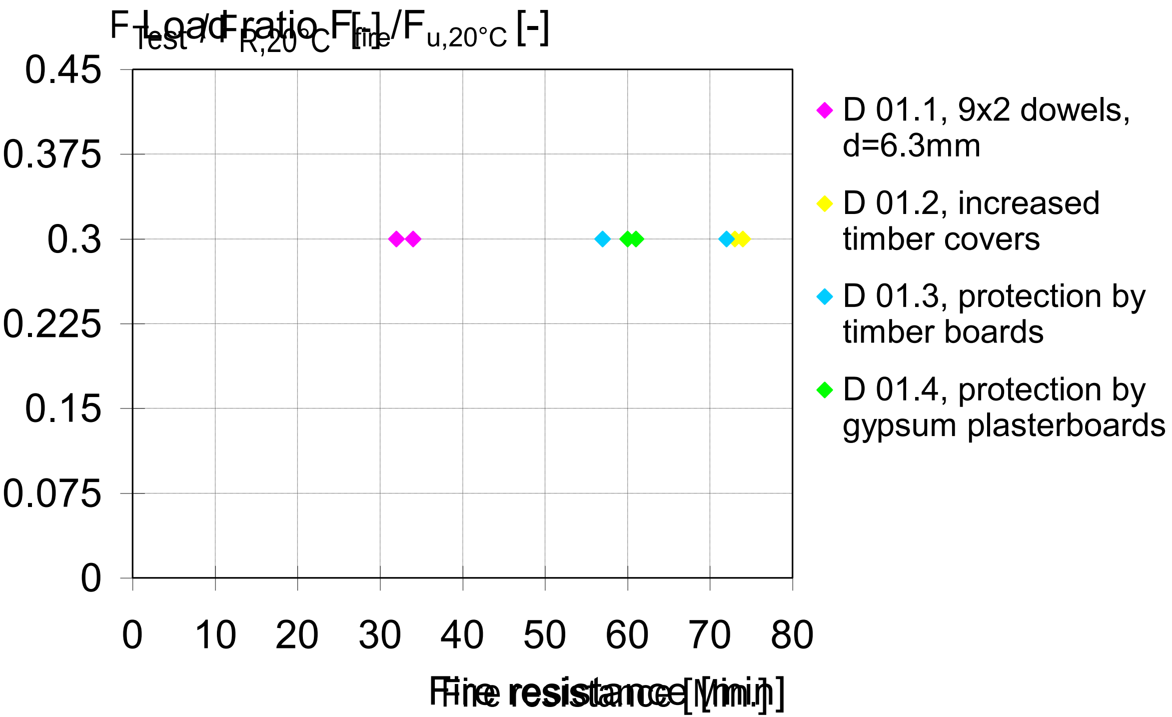
# Tests on connections with multiple slotted in plates

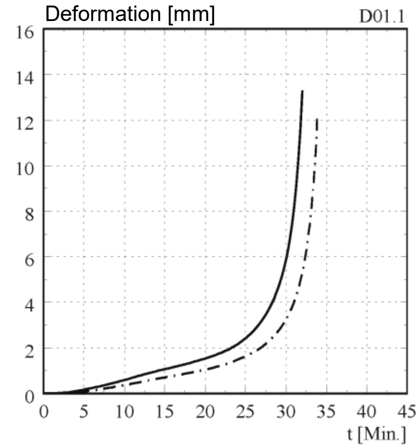
- Results




Source: A. Frangi, ETH

# Tests on connections with multiple slotted in plates

- Results - observations




Source: A. Frangi, ETH

# Large scale testing

# Large-scale natural fire test

- Project SOFIE of the IVALSA Institute, Trento, in Tsukuba (Japan), 6 March 2007
- Timber structures made of cross laminated timber
- Several fire tests on wall and ceiling components
- Large-scale natural fire test on a 3-storey timber building

Source: A. Frangi, ETH

# Project SOFIE

- Wall layup

- Fire load = 790 $MJ/m^2$

Source: A. Frangi, ETH

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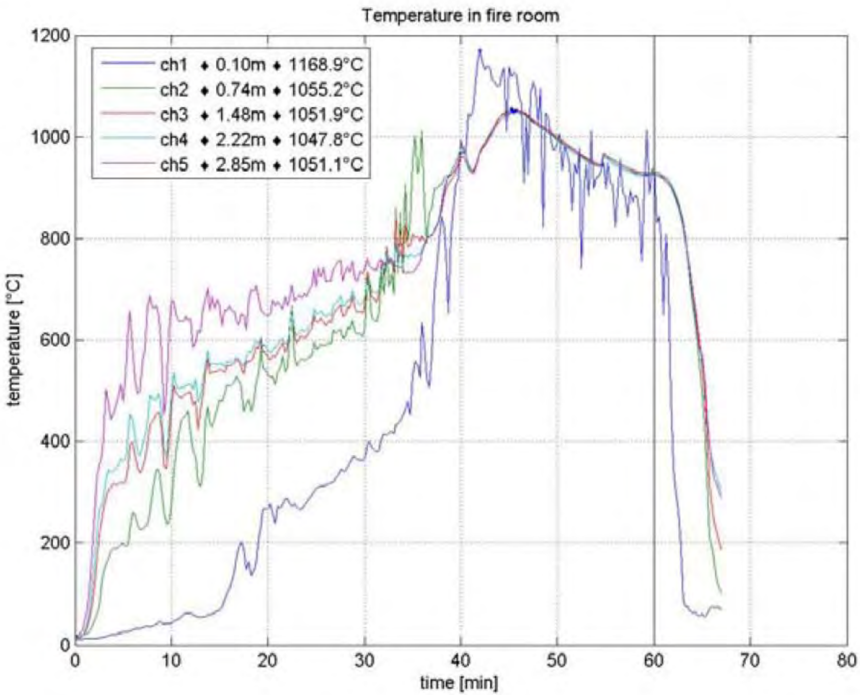
# Project SOFIE

Source: A. Frangi, ETH

# Project SOFIE

- Temperatures




Comment:
Both windows only broken completely after 36 minutes

Source: A. Frangi, ETH

# Project SOFIE

- spread of fire: no burning through from the lower to the upper floor

Source: A. Frangi, ETH

# Observations from large scale tests

- Combustible surfaces
  - Great influence on fire intensity
- Sprinkler system
  - Fire extinguished in a short time
  - No fire spread over the facade
- Fire compartmentation
  - No burn-through even with flammable insulation, provided that it is adequately protected
- Detailing
  - Great influence on fire safety
  - Massive timber shows good robustness in case of fire

Source: A. Frangi, ETH

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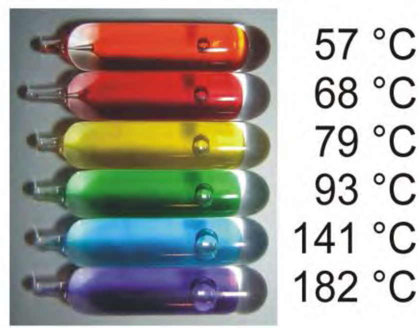
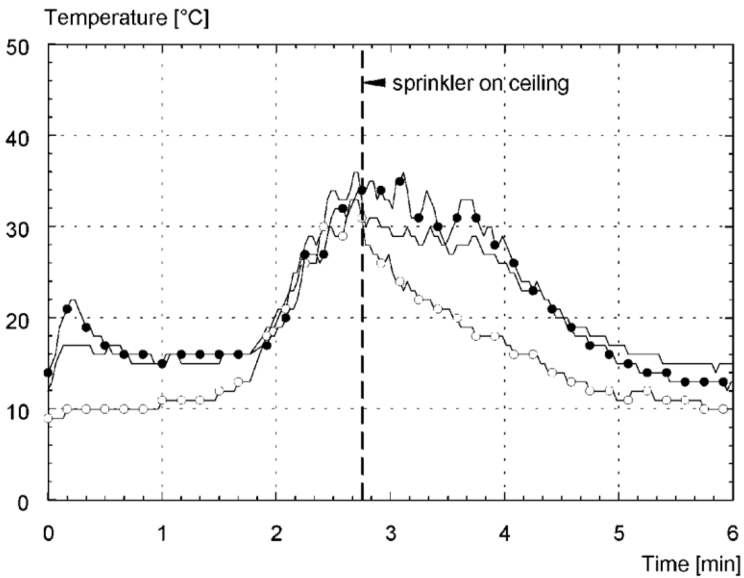
# Solutions

# Fire sprinkler



# Effect of sprinklers

- Fast response (RTI value=35-50m$^{0.5}$s$^{0.5}$)
- Response temperature
  - Ceiling sprinkler: 57°C or 68°C
  - Wall sprinkler: 68°C



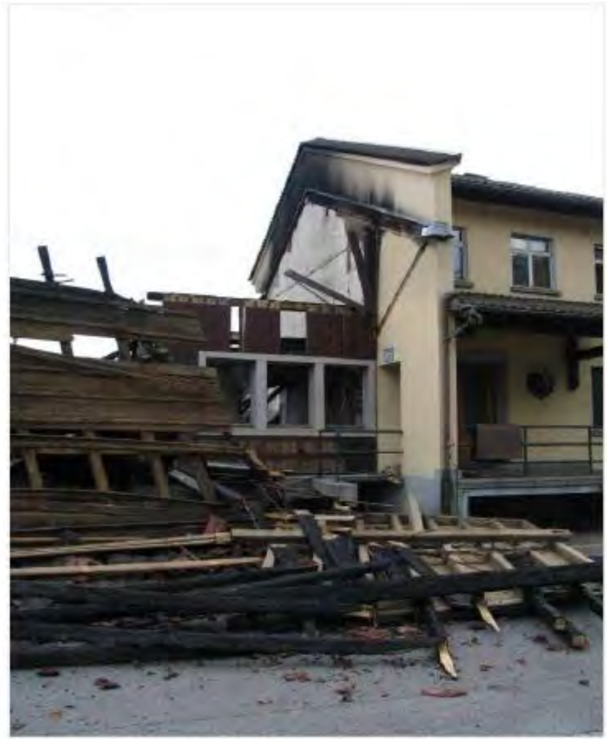

Source: A. Frangi, ETH

# Fire sprinkler - effect

Source: A. Frangi, ETH

# Fire sprinkler - arrangement

# Fire walls



Source: A. Frangi, ETH

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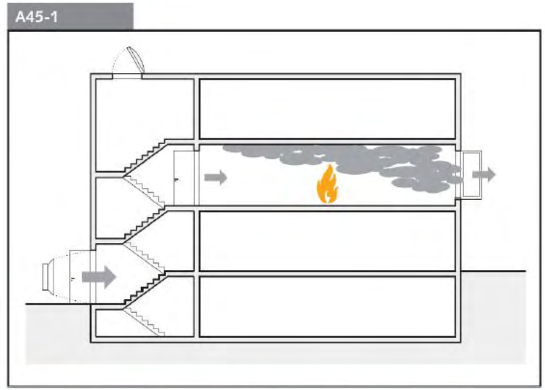
# Escape routes


Source: M. Klippel, ETH

# Escape routes

This should be avoided!

Source: M. Klippel, ETH

# Escape routes



This should be avoided!

Source: M. Klippel, ETH

AVANCEZ

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