Structural assessment of timber structures.
Knowns, known unknowns, and unknown unknowns

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SHATIS 22
structural health assessment of timber structures

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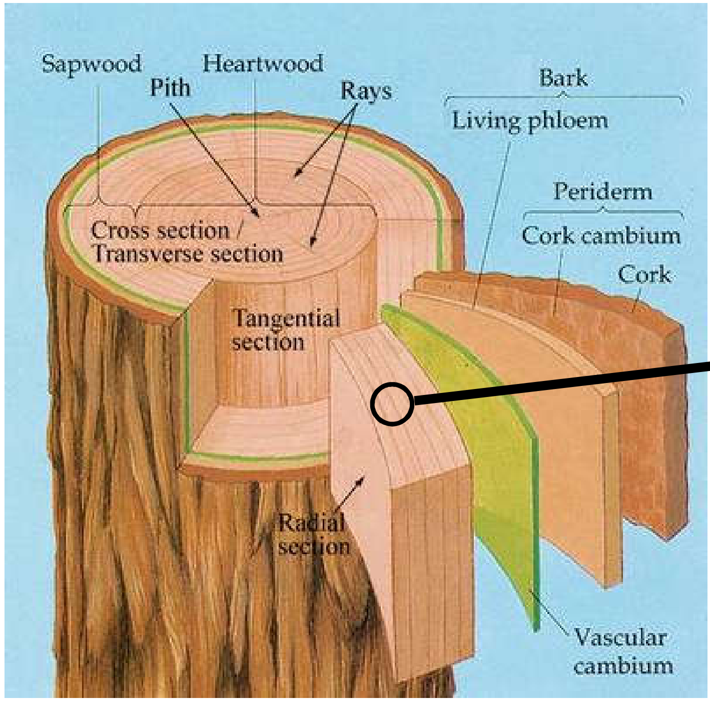
There are known knowns. There are things we know that we know. There are known unknowns. That is to say, there are things that we now know we don't know. But there are also unknown unknowns. There are things we do not know we don't know.

Donald Rumsfeld

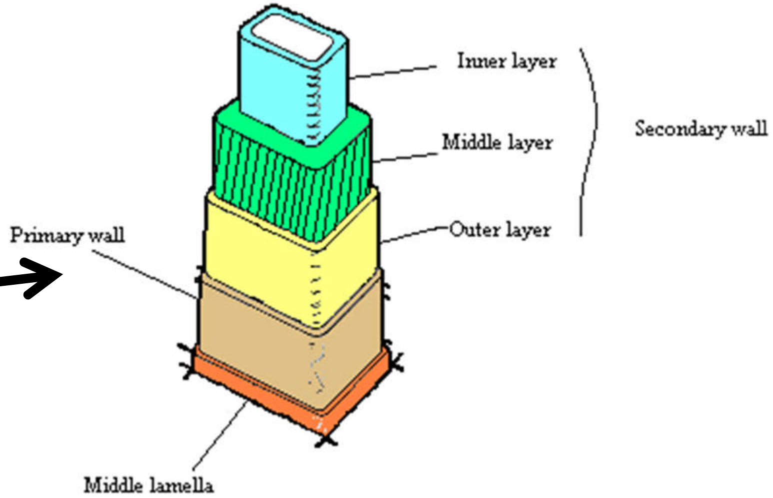
USA secretary of defense

Known knowns

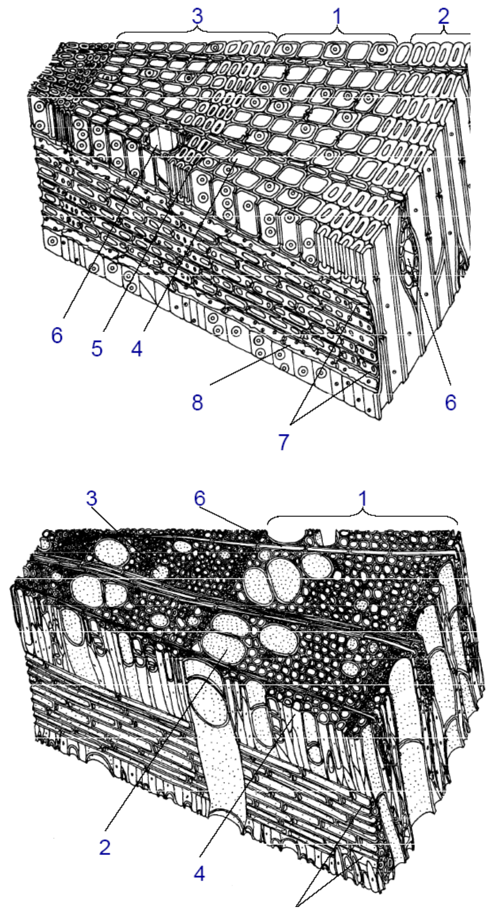
Timber is an inhomogeneous building material



Timber's principal directions structure
(source: `http://www.doitpoms.ac.uk`)



The tubular cell wall has a layered



Known knowns

- Timber is an inhomogeneous building material
- The safety and serviceability assessment of a timber structure is always dependent upon the capability to restrain the large range of properties that can be allocated to timber members

Strength grading

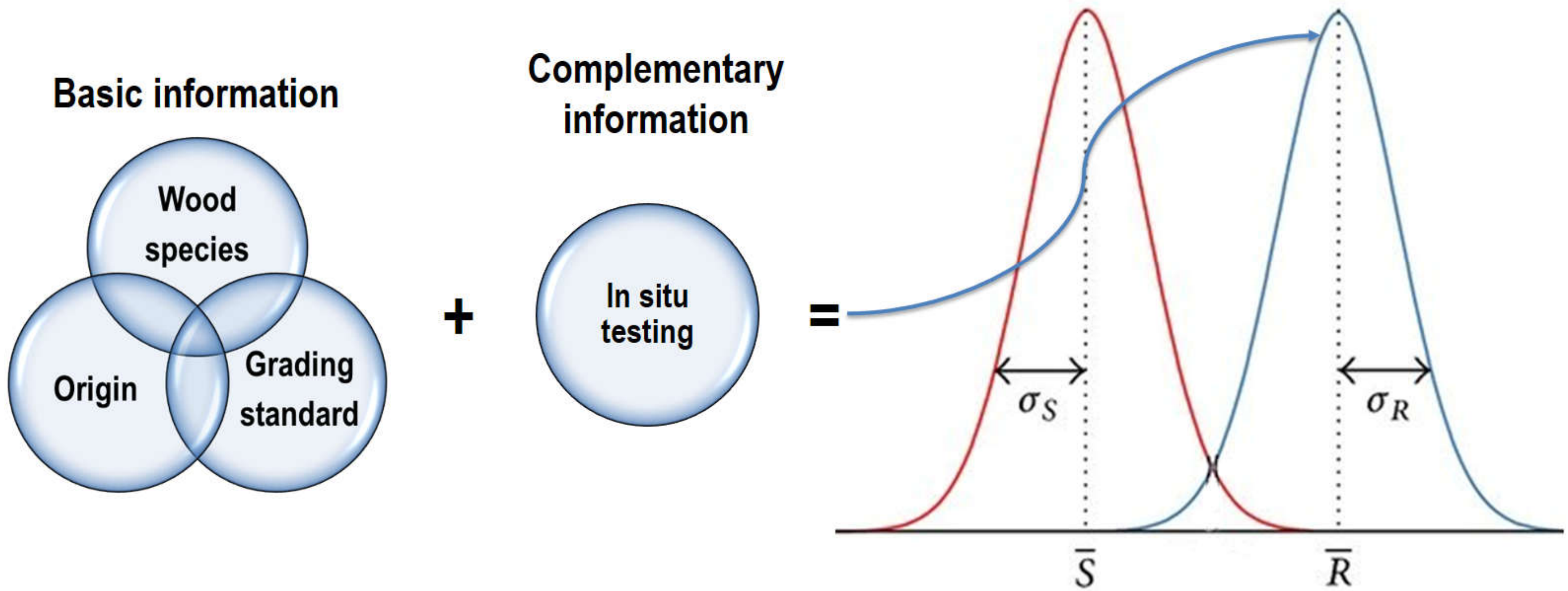
Homogenization

Known knowns

- Timber is an inhomogeneous building material
- The safety and serviceability assessment of a timber structure is always dependent upon the capability to restrain the large range of properties that can be allocated to timber members
- Structural timber members present high variability of properties being influenced by wood species, density, defects and moisture content

Wood species

WOOD SPECIES INFORMATION IS THE BASIS FOR ASSIGNING RELIABLE DESIGN VALUES TO TIMBER MEMBERS

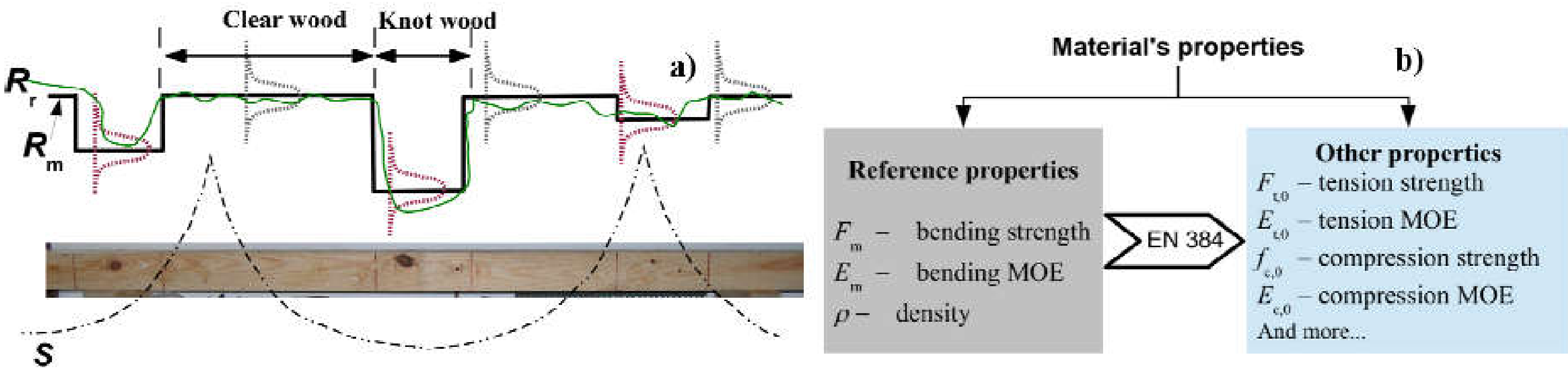


J.S. Machado, F. Pereira, T. Quilhó Assessment of old timber members: Importance of wood species identification and direct tensile test information. *Construction Building Materials*, 207 (2019), pp. 651-660.

Structural timber

Table: Coefficients of variation for clear wood and structural timber

Property	Clear wood	Structural timber
Density	10	10
Tension strength parallel to grain	25	30
Bending strength	16	25
Compression strength parallel to grain	18	20
Modulus of elasticity in bending	22	13

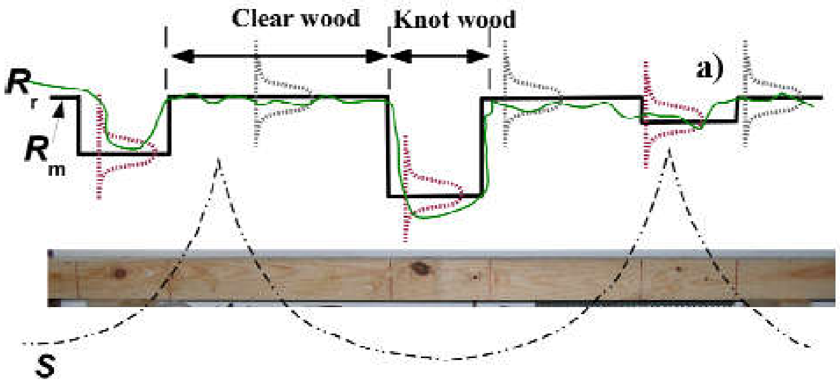


J. Machado, In situ evaluation of the reference properties of structural timber members. Use of available tools and information. *Advanced Materials Research*, 778 (2013), pp. 137-144.

Known knowns

- Timber is an inhomogeneous building material
- The safety and serviceability assessment of a timber structure is always dependent upon the capability to restrain the large range of properties that can be allocated to timber members
- Structural timber members present high variability of properties being influenced by wood species, density, defects and moisture content
- Visual strength grading (VSG) was the 1st NDT to be developed. Other NDT and SDT methods were developed as auxiliary tools to VSG

Known knowns



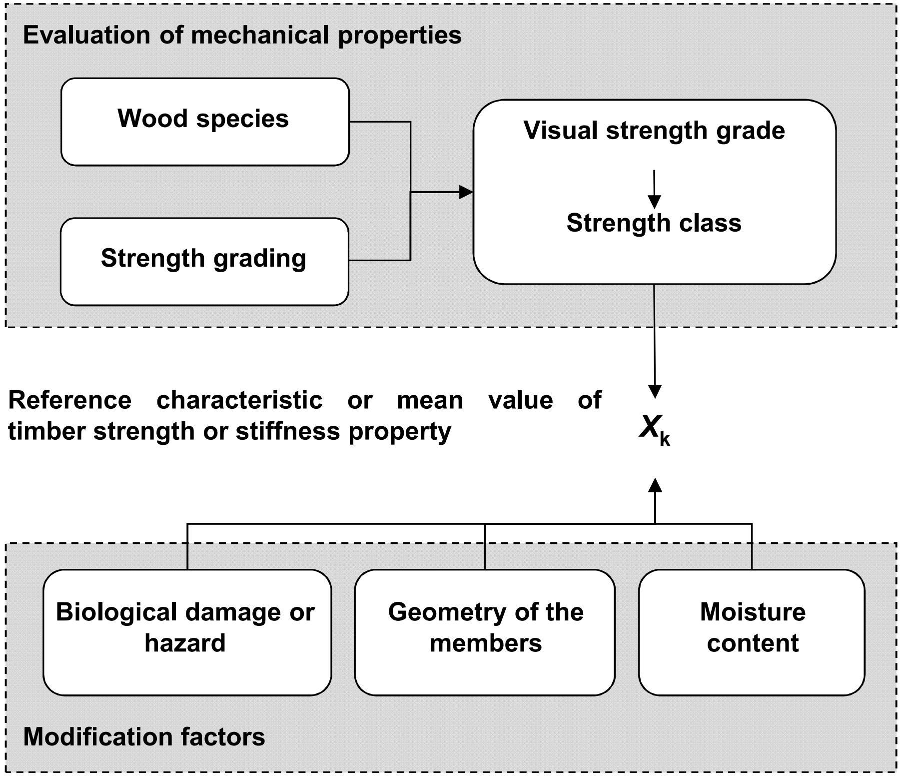


Figure: Current factors used to define the mechanical performance of timber elements onsite (adapted from Machado et al., 2011)

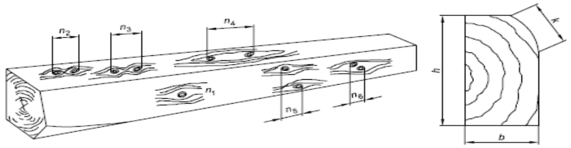
Known knowns

- The use of current grading standards for new wood is unsuitable for several reasons, among which the following can be highlighted: cross-section dimensions are usually much greater than those currently used, the reliability of applying current standards to historical timber has not been adequately verified, and some defects such as distortion and fissures, which are usually greater in large cross-section timber, hardly affect mechanical properties

Visual grading of old timber elements

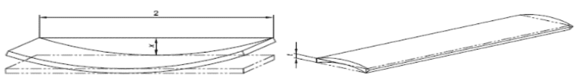
UNI 11035:2003 and UNI 11119:2004.

Grading parameters



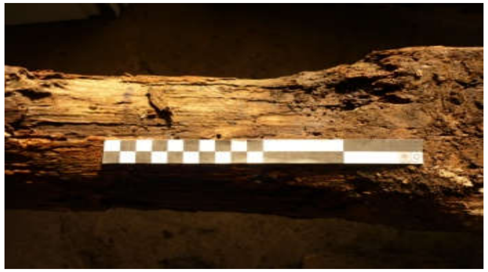
knots   wane

fiber misalignment   cracks

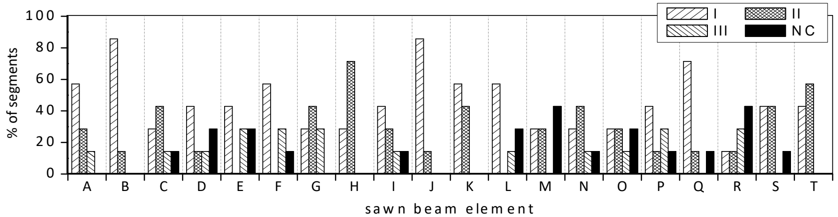


deformation

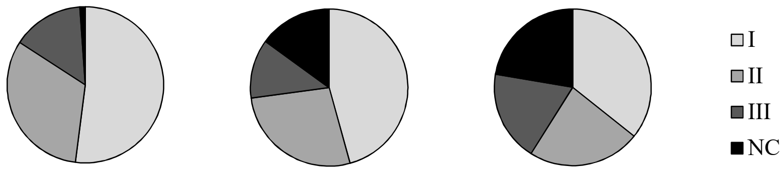
Visual inspection



Grading by segment and element



Comparison between scales



old beams   sawn beams   sawn boards

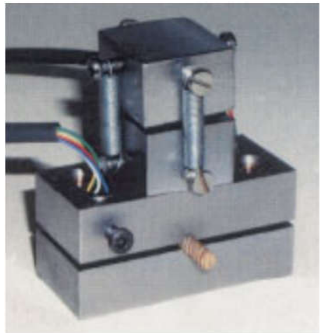
Sousa, H.S., Branco, J.M., Lourenço, P.B., Neves, L.C. (2016), Inference on stiffness and strength of existing chestnut timber members using Hierarchical Bayesian Probability Networks. *Materials and Structures*. 49(10). pp 4013-4028

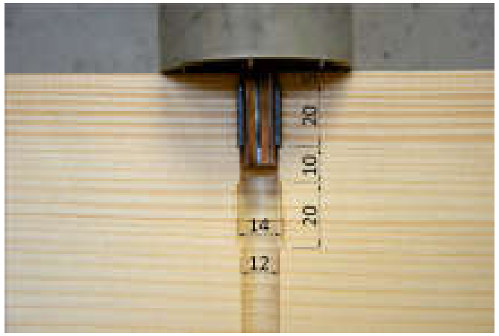
Known knowns

- The main objective when evaluating the strength of an historical timber structure should be to keep of as much of the original material as possible
- Several non and semi-destrutive testing (NDT and SDT) methods have been developed to increase the VSG accuracy
- NDT and SDT methods can be differentiated based on the type of information provided:
  - Local (limited to small volume of the element) or global (all volume of the element)
  - Direct measurement or an indirect measurement of the desired property (density, strength, stiffness)
  - Qualitative or quantitative measurements

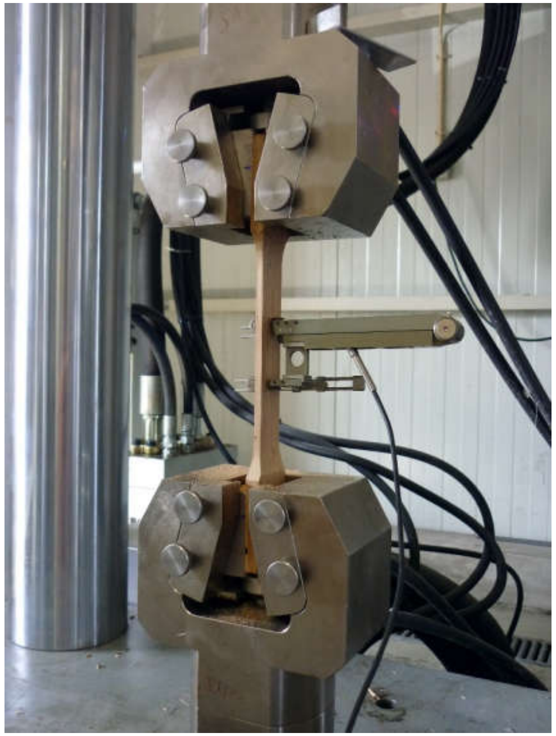
Core drilling

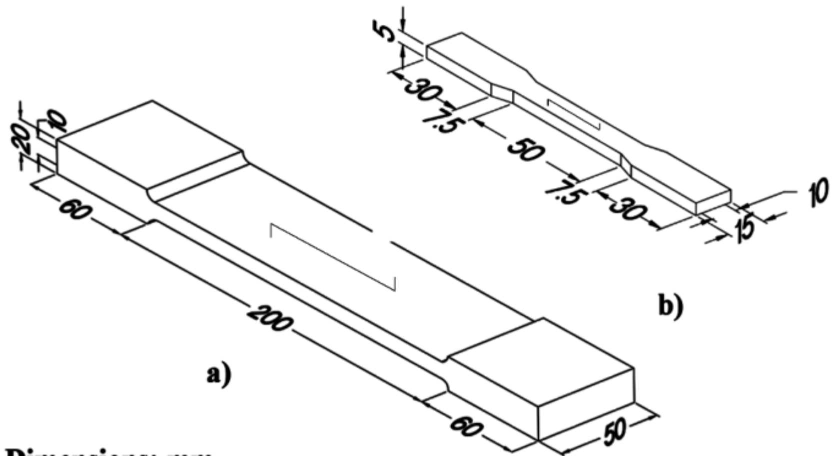
- The density is calculated by means of small cores extracted by the main piece or by correlation with other parameters, and can be used to determine the species and the quality of the material
- It should be taken several samples to have a global idea of the structure

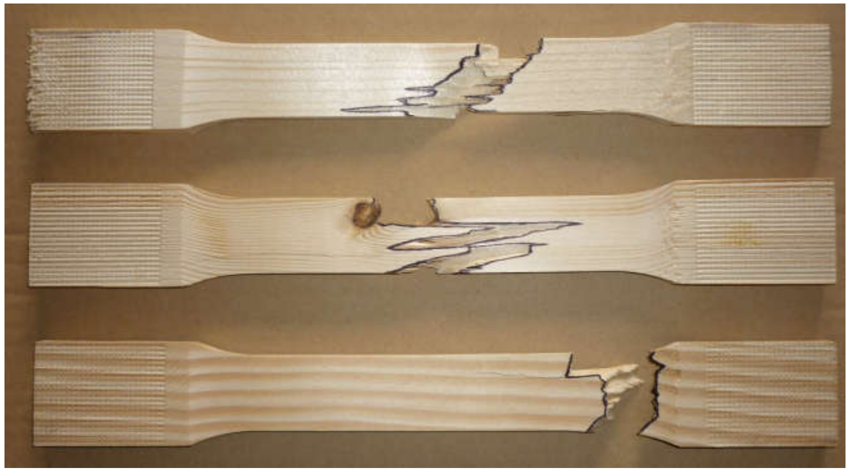


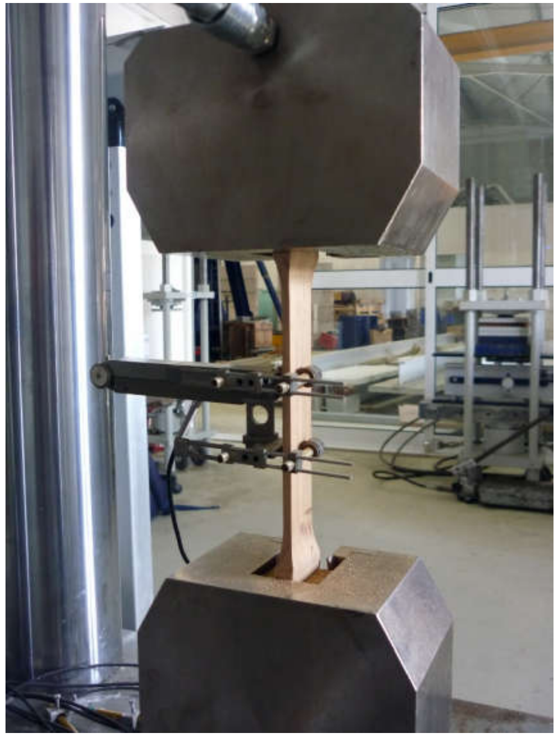


Sample extraction

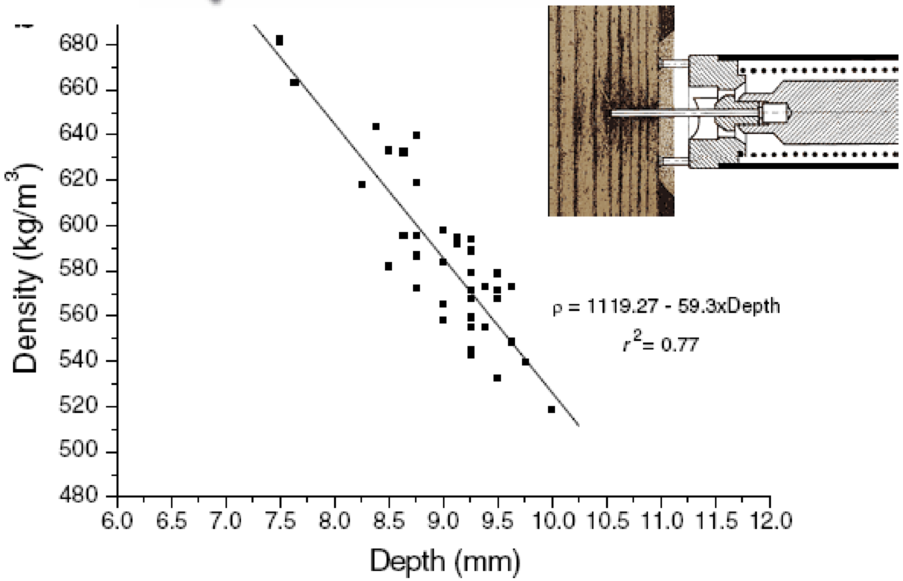


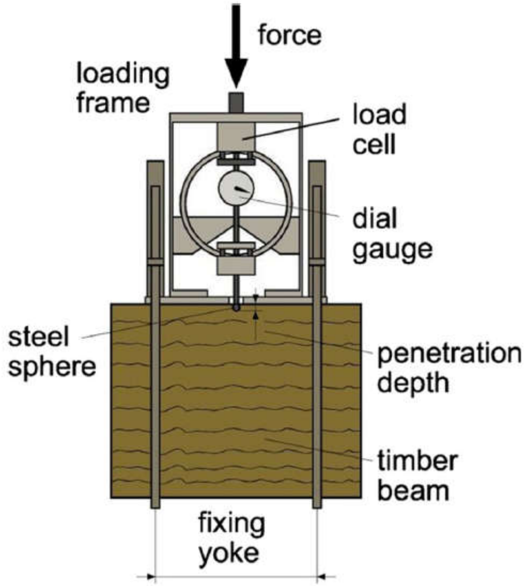


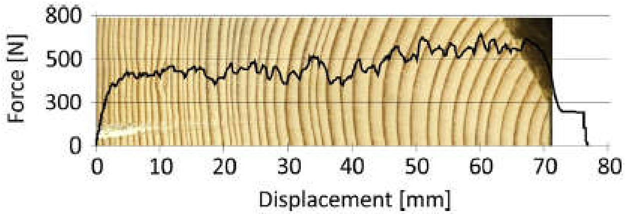


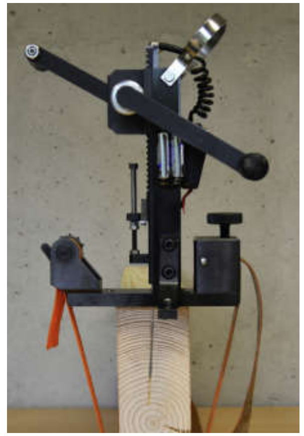


Pin penetration

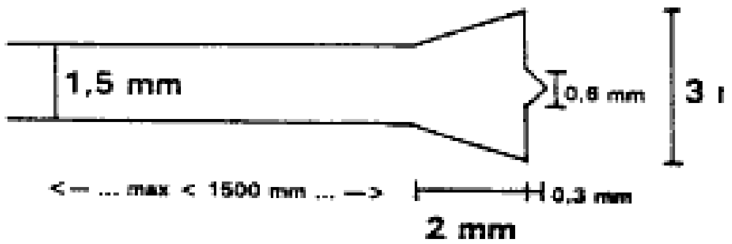


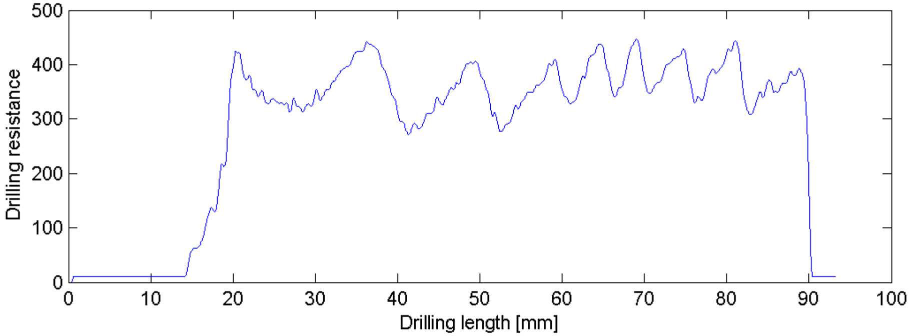


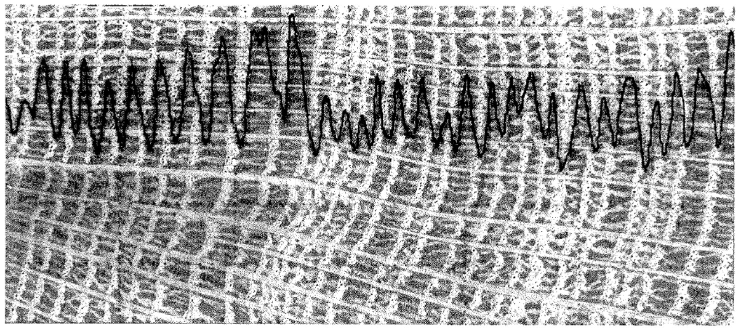


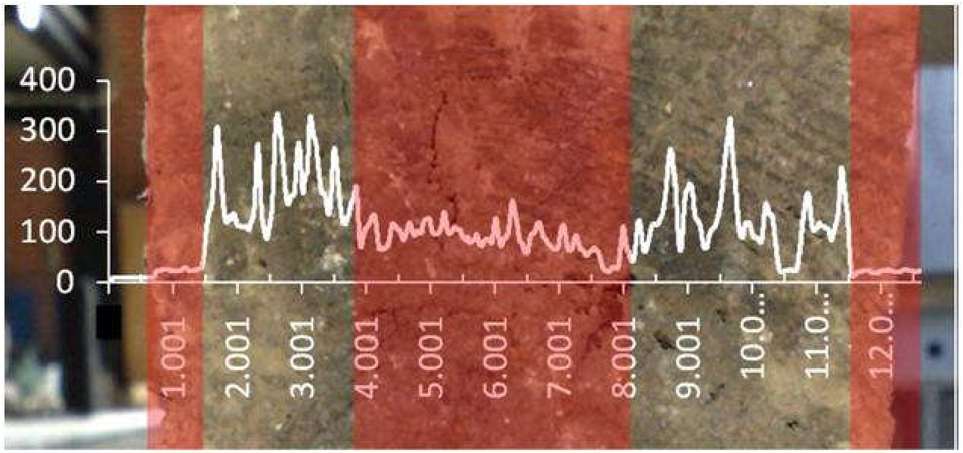


Drill resistance

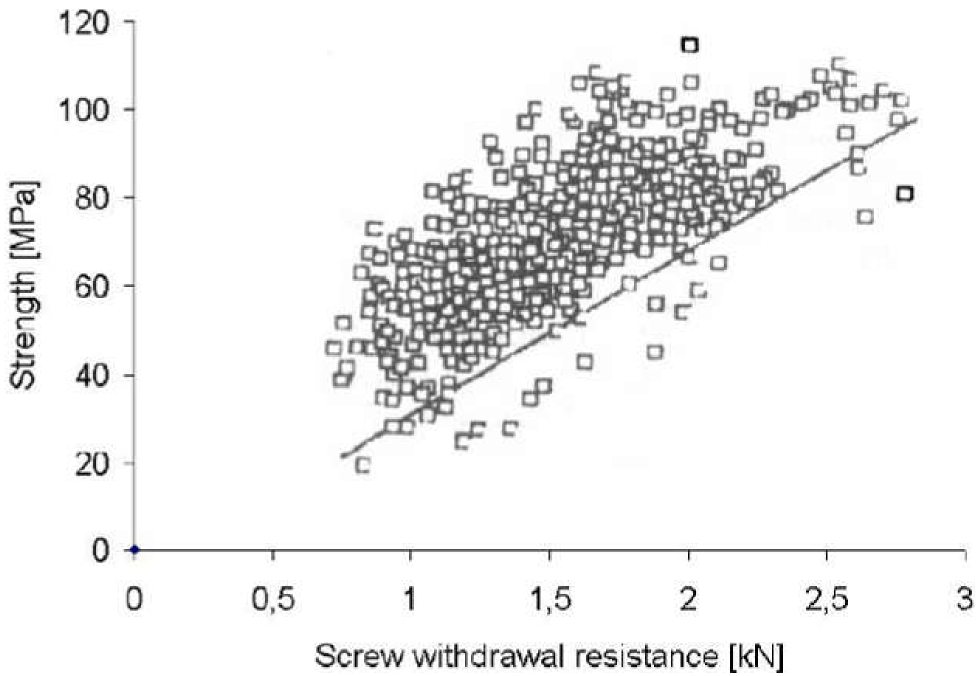




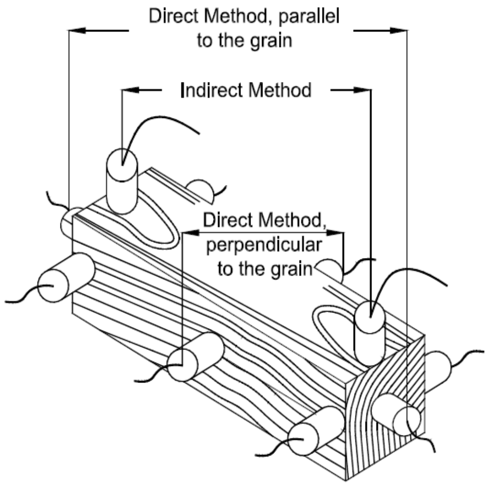




Pullout resistance

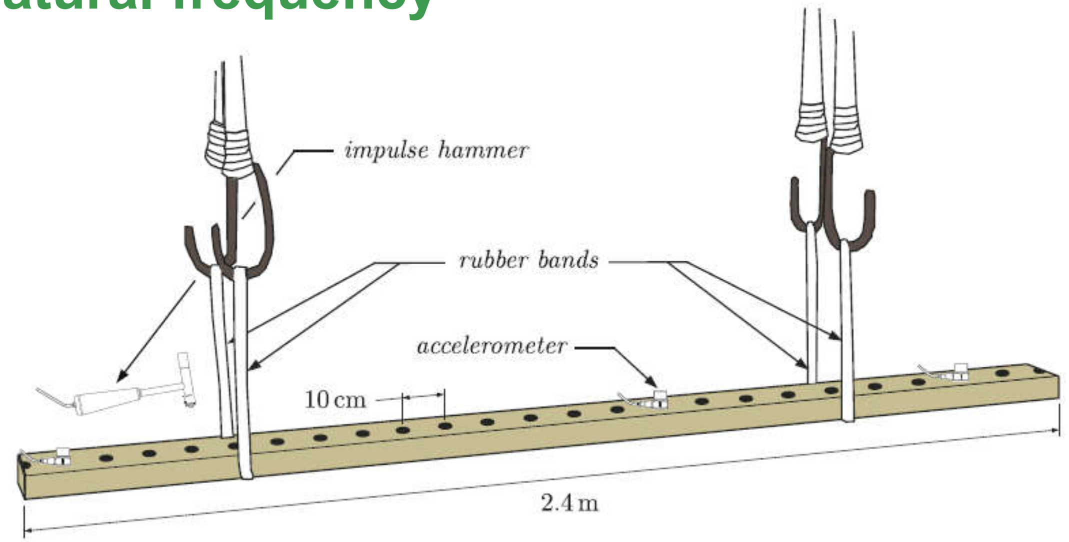


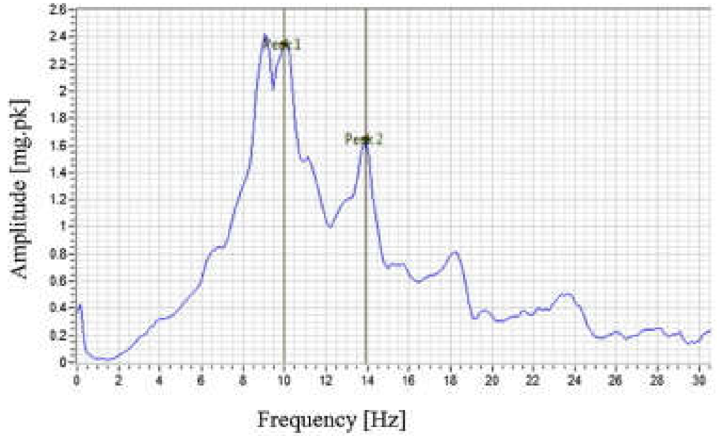
Time of flight

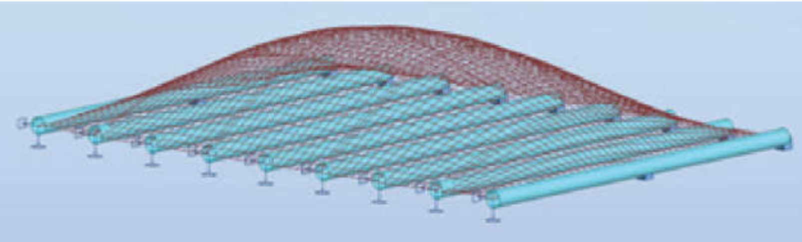


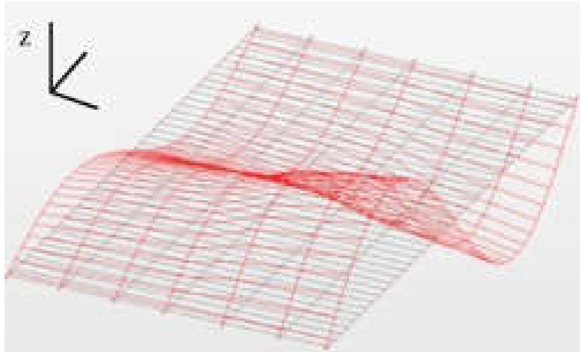
$$E_{dyn} = \rho \cdot V^2$$

Natural frequency



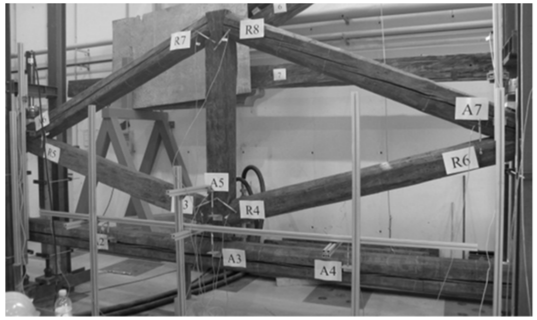


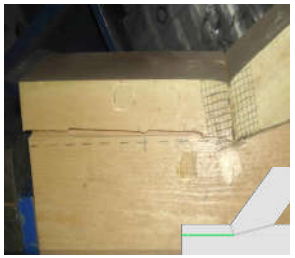
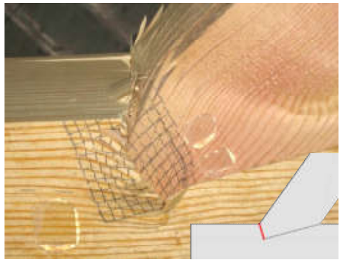




Load tests





Known unknowns

Do I need to grade all members?

Table 1 Effectiveness of NDT and SDT methods to assess structural timber

Method	Determine species	Measure MC	Locate deterioration	Quantify deterioration	Assess strength	Determine stiffness	Identify hidden details
Visual inspection			Limited				
Remote visual inspection			Limited	Limited			Yes
Species identification	Yes						
Moisture measurements		Yes					
Digital radioscopy			Yes	Limited			Yes
Ground penetrating radar		Limited	Limited				Limited
Infrared thermography		Limited	Limited				Limited
Stress waves			Limited	Limited	Limited	Estimate	
Resistance drilling			Yes	Yes	Limited		Limited
Core drilling			Yes		Estimate	Estimate	
Tension microspecimens					Estimate	Estimate	
Glueline test		Limited	Limited		Limited		
Screw withdrawal			Limited		Limited		
Needle penetration			Limited		Limited		
Pin pushing			Yes	Limited	Estimate		
Surface hardness			Limited		Limited		

M. Riggio, R.W. Anthony, F. Augelli, B. Kasal, T. Lechner, W. Muller, T. Tannert. In-situ assessment of structural timber using non-destructive techniques. *Materials and Structures*, 47 (2014), pp. 749-766

Coefficients and correlations

Table 1
Coefficients of determination between NDT/SDT methods and density.

Wood species	Method used			
	Screw withdrawal	PR	DR	CD
Abies alba Mill.		0.78 [31]		0.64 [40]
Picea abies (L.) H. Karst.		0.50 [60]	0.65 [49]	0.89 [430]
Pinus radiate D. Don	0.67 [61]	0.61 [61]		
Pinus pinaster Aiton	0.67 [61]	0.61 [61]	0.70 [57]	0.48 [57]
Pinus sylvestris L.	0.67 [61]	0.61 [61]		
Pinus nigra J.F. Arnold	0.67 [61]	0.61 [61]		
Castanea sativa Mill.			0.36–0.38 [62]	
Several species		0.003 [4]	0.0039 [4]	

PR – penetration resistance; DR – drilling resistance; CD – core drilling.

A. Feio, J.S. Machado, In situ assessment of timber structural members: combining information from visual strength grading and NDT/SDT methods – A review. *Construction Building Materials*, 101 (2) (2015), pp. 1157-1165

Table 2
Models used for correlating NDT/SDT methods and mechanical properties.

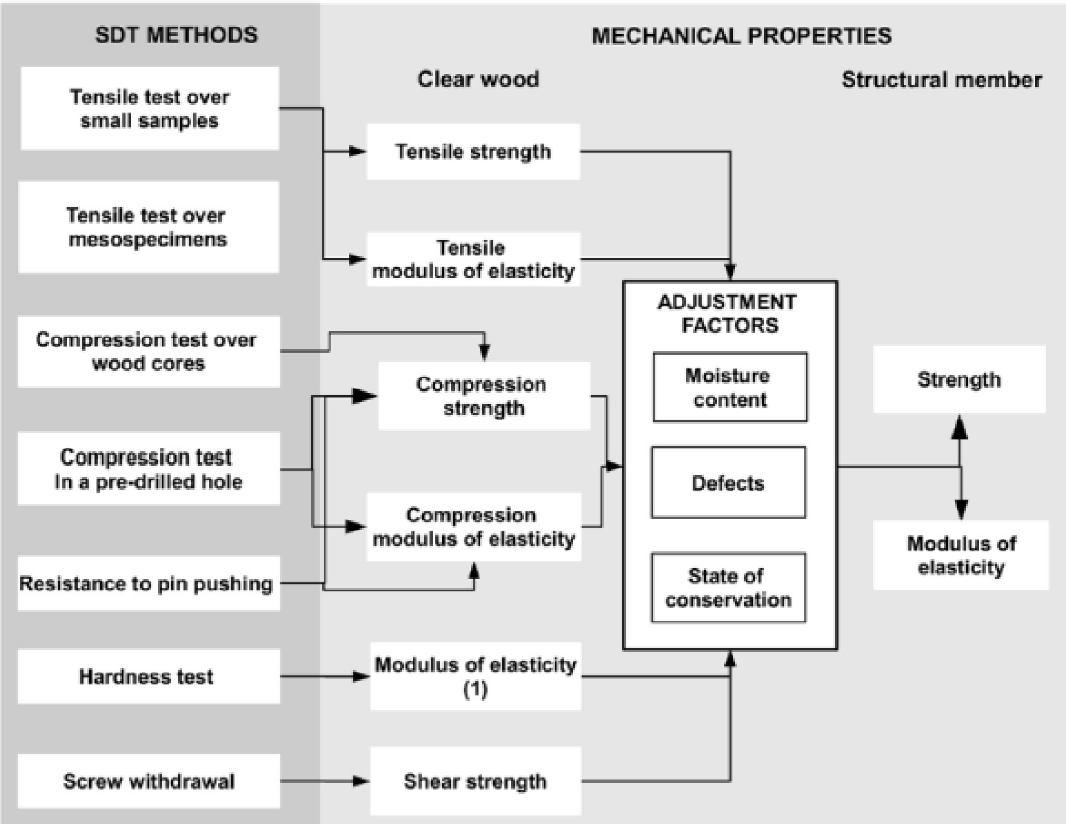
Wood species and reference	Model*	Main result
Modulus of elasticity		
Abies alba [31]	$E_m = f(v, PR)$	$E_{m,l}$ (r^2 = 0.63); $E_{m,g}$ (r^2 = 0.71)
	$E_m = f(v, PR, K)$	$E_{m,l}$ (r^2 = 0.71); $E_{m,g}$ (r^2 = 0.68)
	$E_m = f(v, PR, SoG)$	$E_{m,l}$ (r^2 = 0.69); $E_{m,g}$ (r^2 = 0.74)
	$E_m = f(v, PR, SoG, K)$	$E_{m,l}$ (r^2 = 0.83); $E_{m,g}$ (r^2 = 0.76)
Picea abies [60]	$E_m = f(\delta, A, R)$**	$E_{m,l}$ (r^2 = 0.62)
Several species [4]	$E_m = f(\delta, A, R)$**	$E_{m,l}$ (r^2 = 0.06)
Castanea sativa [32]	$E_m = f(v_v, \rho, l)$	$E_{m,g}$ (r^2 = 0.74)
	$E_m = f(E_{dyn,u}, l)$	$E_{m,g}$ (r^2 = 0.715)
	$E_m = f(v_u, \rho, l)$	$E_{m,g}$ (r^2 = 0.721)
Modulus of rupture		
Castanea sativa [32]	$f_m = f(E_{dyn,v}, K, l)$	f_m (r^2 = 0.33)
	$f_m = f(E_{dyn,u}, K, l)$	f_m (r^2 = 0.27)
	$f_m = f(E_{dyn,v}, K)$	f_m (r^2 = 0.19)
Pinus pinaster [68]	$f_m = f(E_{dyn,u}, \delta)$	f_m (r^2 = 0.50)

f (...) – regression model; E_m – bending modulus of elasticity; $E_{m,l}$ – local modulus of elasticity; $E_{m,g}$ – global modulus of elasticity; v – stress wave velocity; PR – penetration resistance; SoG – slope of grain; K – knots dimension; δ – Correction factor function of the size of defects; A – coefficient function of the wood species; R – load force; v_v – vibrational velocity; ρ – density; l – length of the test piece; $E_{dyn,u}$ – dynamic modulus of elasticity (ultrasonic); $E_{dyn,v}$ – dynamic modulus of elasticity (vibrational analysis); f_m – bending strength.

* Details of the way to measure each variable can be found in the original work.

** Hardness test by Piazza and Turrini.

Reference material properties



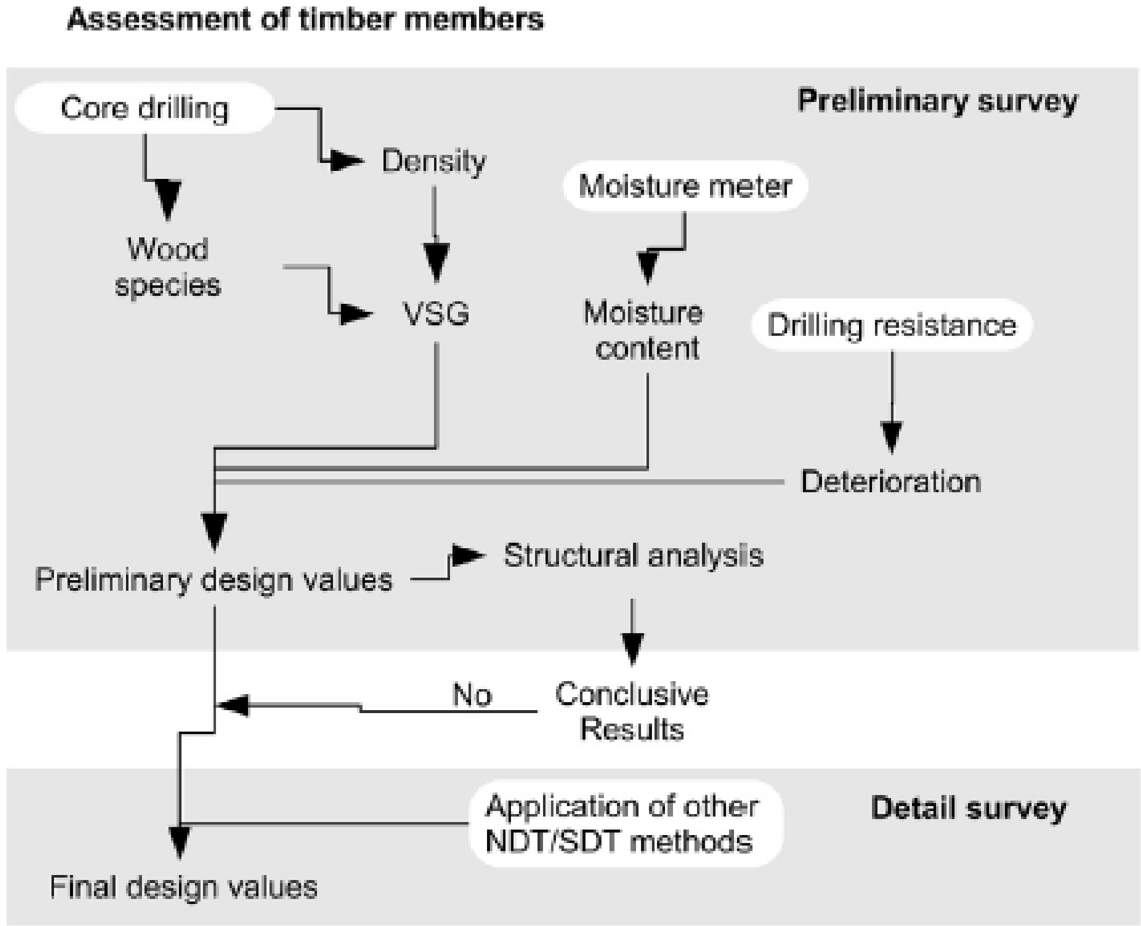
(1) Effect of defects is already taken into account

Reference Material Properties		Other Material Properties	
R_m =	bending strength	$R_{t,0/90}$ =	tension strength
E_m =	bending MOE	$E_{t,0/90}$ =	tension MOE
ρ_{den} =	density	$R_{c,0/90}$ =	compression strength
		$E_{c,0/90}$ =	compression MOE
		R_v =	shear strength
		G_v =	shear modulus
		$R_{h,0/90}$ =	embedding strength

M. Kloiber, M. Drdacky, J.S. Machado, M. Piazza, N. Yamaguchi, Prediction of mechanical properties by means of semi-destructive methods: a review. *Construction Building Materials*, 101 (2) (2015), pp. 215-1234

Preliminary survey

A. Feio, J.S. Machado, In situ assessment of timber structural members: combining information from visual strength grading and NDT/SDT methods – A review. *Construction Building Materials*, 101 (2) (2015), pp. 1157-1165



Carpentry joints



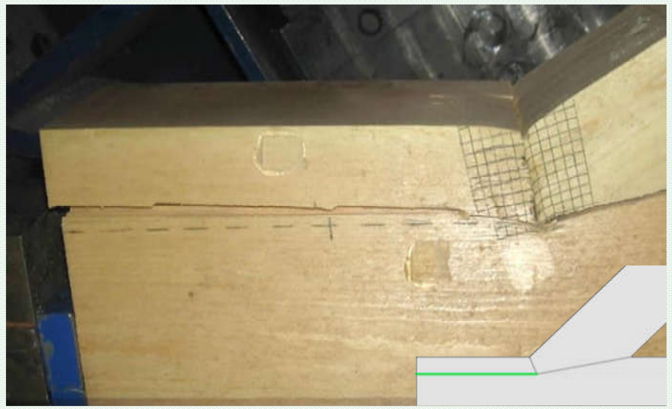


Branco, J.M., Descamps, T. (2015), Analysis and strengthening of carpentry joints. *Construction and Building Materials*. 97: 34–47.

Carpentry joints (NEW) – Failures modes

Brittle Failure Mode

- Joint strength ↘↘ 0 kN after yield point.
- Collapsing of the joint (rupture).

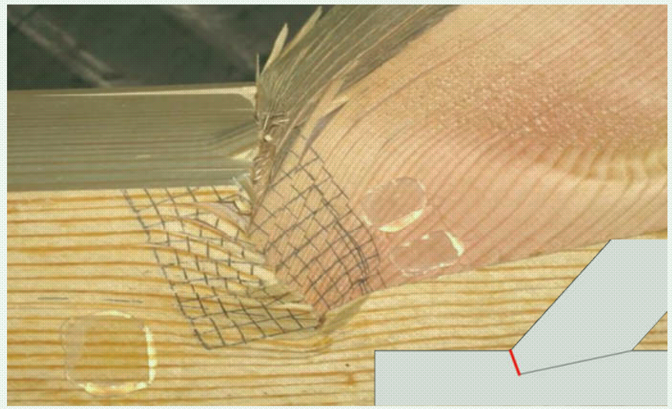


Shear crack at the heel depth along the grain in the tie beam.

VS

Ductile Failure Mode

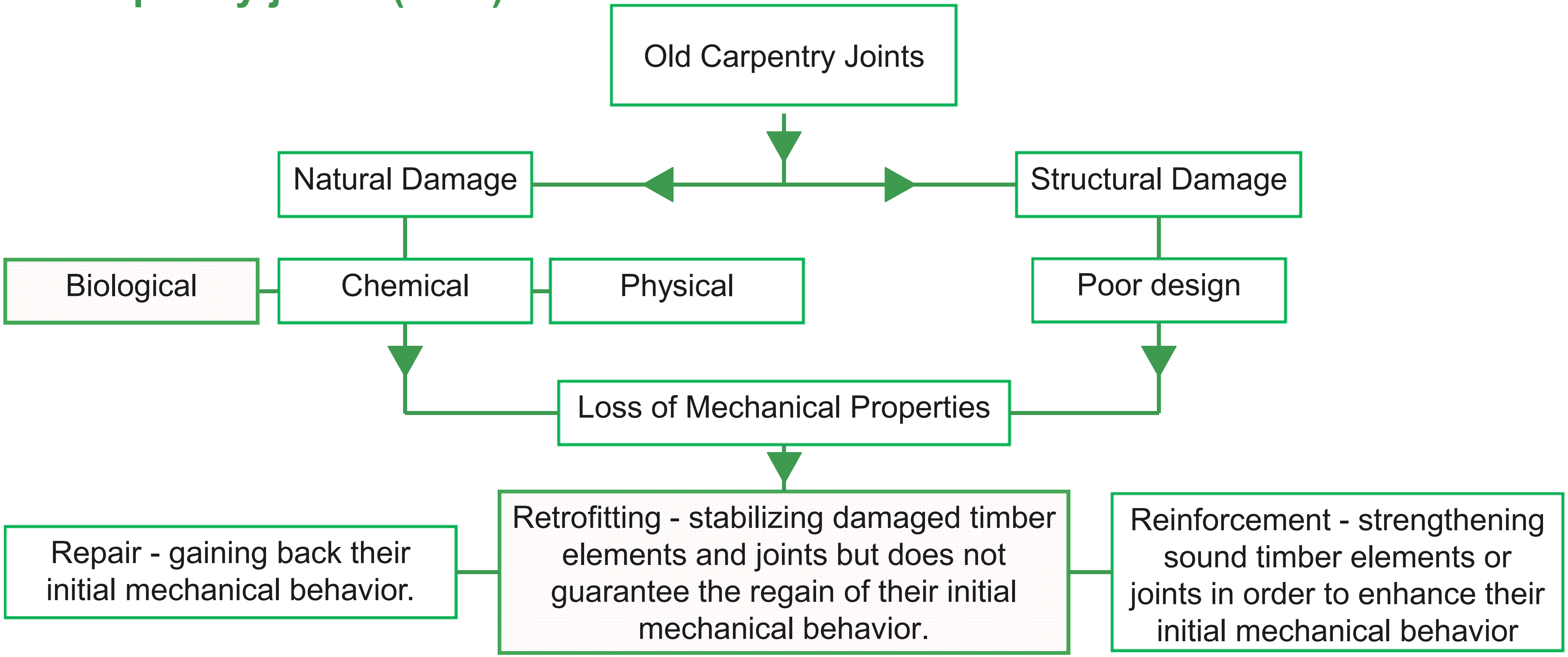
- Joint strength ≅ C after yield point.
- High deformation of the joint (yielding).



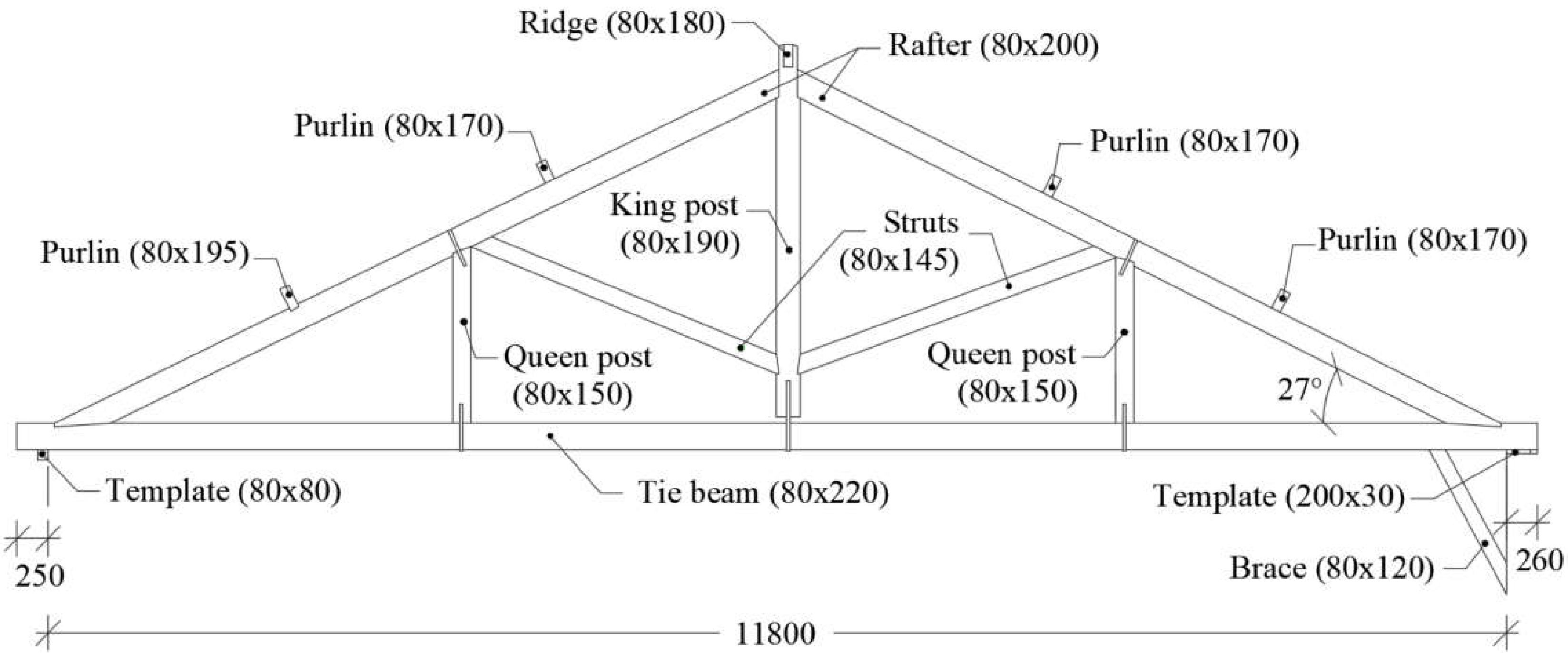
Crushing at the front-notch surface in the rafter and tie beam.

Branco J.M., Verbist, M.P., Descamps, T., Design of Three Step Joint Typologies: Review of European Standardized Approaches. *Engineering and Structures*. (2018) 174: 573-585.

Carpentry joints (OLD)

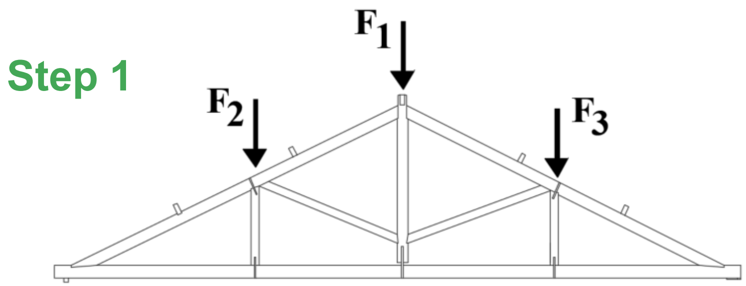


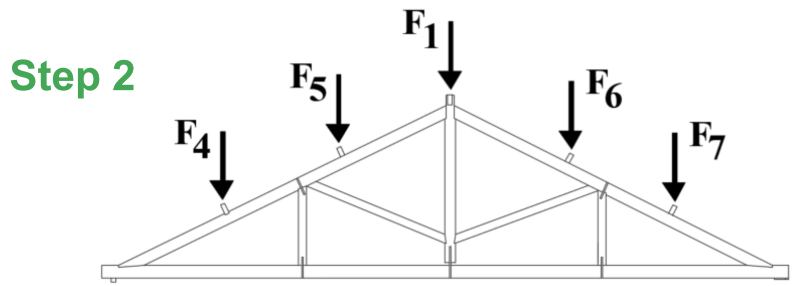
Field tests – Overall and local (joints) behaviour

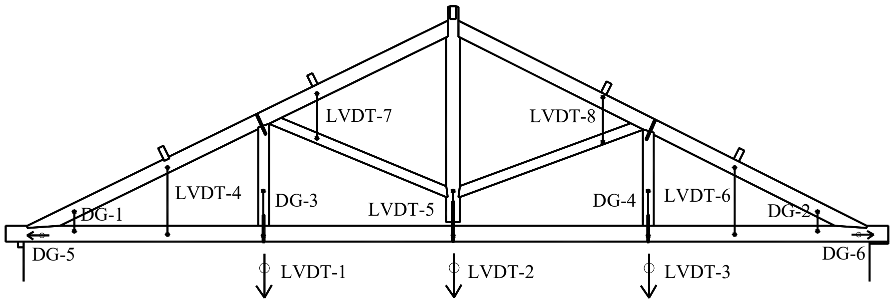


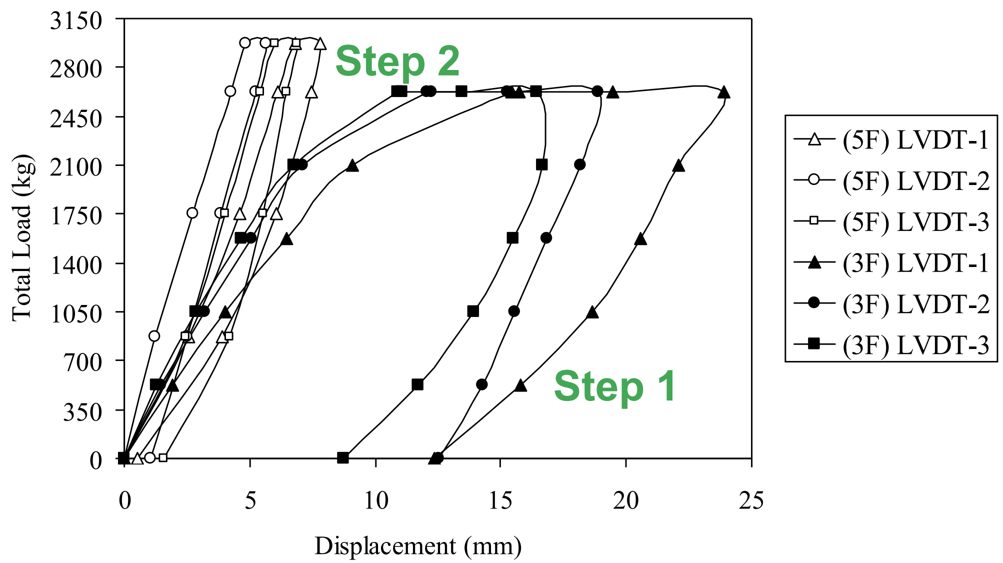
Branco J.M., Varum H., Matos F.T., On-site full-scale tests of a timber queen-post truss. *International Journal of Architectural Heritage*. (2018) 12:545-554.

Field tests – Assessment of the joints response

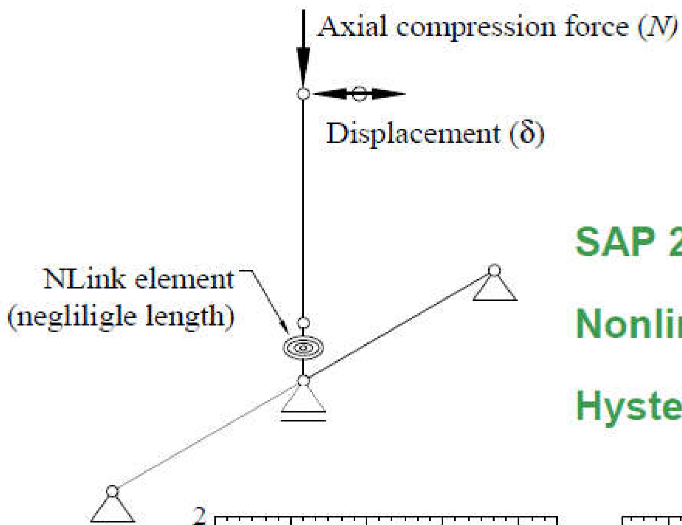








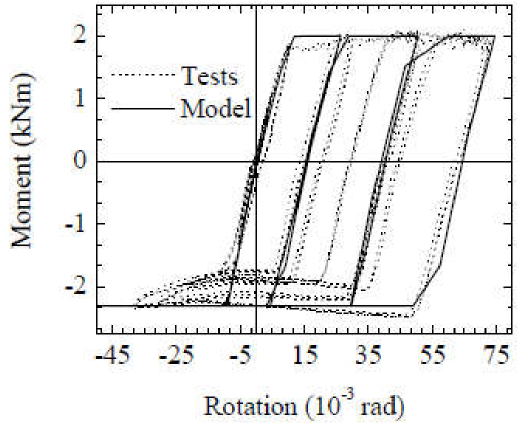
Semi-rigid modelling of joints

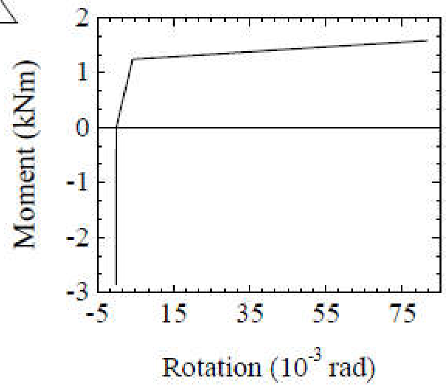


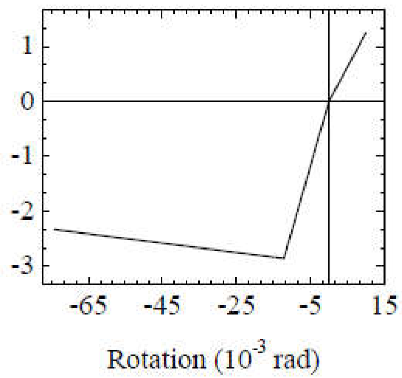
SAP 2000

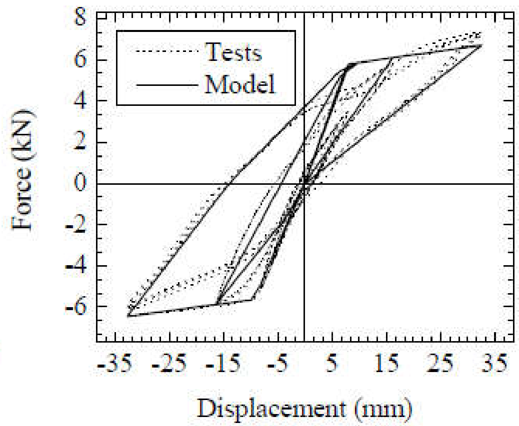
Nonlinear behaviour

Hysteretic rules

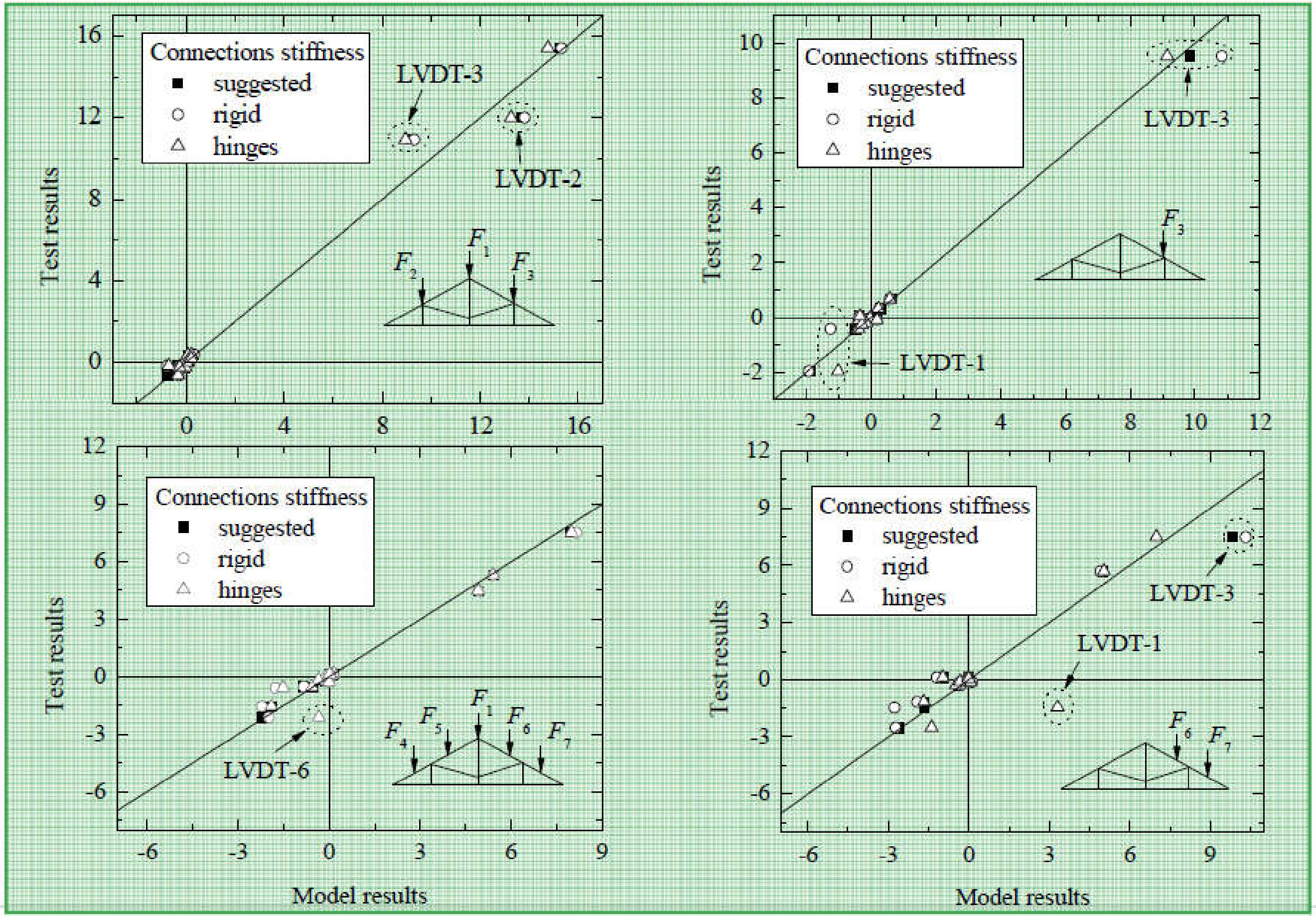








Field tests – Connections stiffness



Unknown knowns

Unknown knowns

- To support expert's decision, NDT and SDT methods were developed as auxiliary tools to VSG for the allocation of more reliable (meaning closest to the real value) mechanical characteristics to structural timber members in situ. However several shortcomings explains why their applications is limited and the final decision is still based solely on expert's opinion and application of a simplified set of visual rules.

*An **unknown known** is information that an individual or organization has in its possession but whose existence, relevance or value has not been realized.*

Degradation & Aging

J.S. Machado, P.B. Lourenço, P. Palma, Assessment of the structural properties of timber members in situ – a probabilistic approach, in: *SHATiS'11 International Conference on Structural Health Assessment of Timber Structures*, Lisbon, 2011.

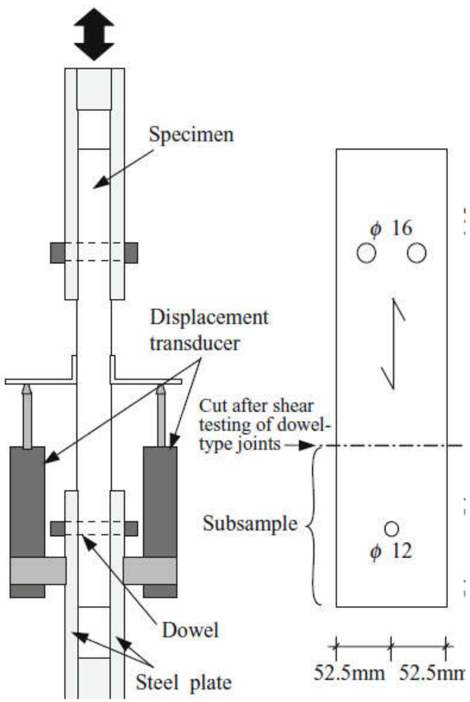
In the case of timber member in situ, other factors affecting material properties should also be taken into consideration. A conservation factor linked to the degradation by fungi or insects with implication in the reduction of the material properties (k_{con}) and an aging factor that attends to physical and mechanical deterioration of the timber materials due to time in service (k_a). Thus Eq. 1 becomes Eq. 2.

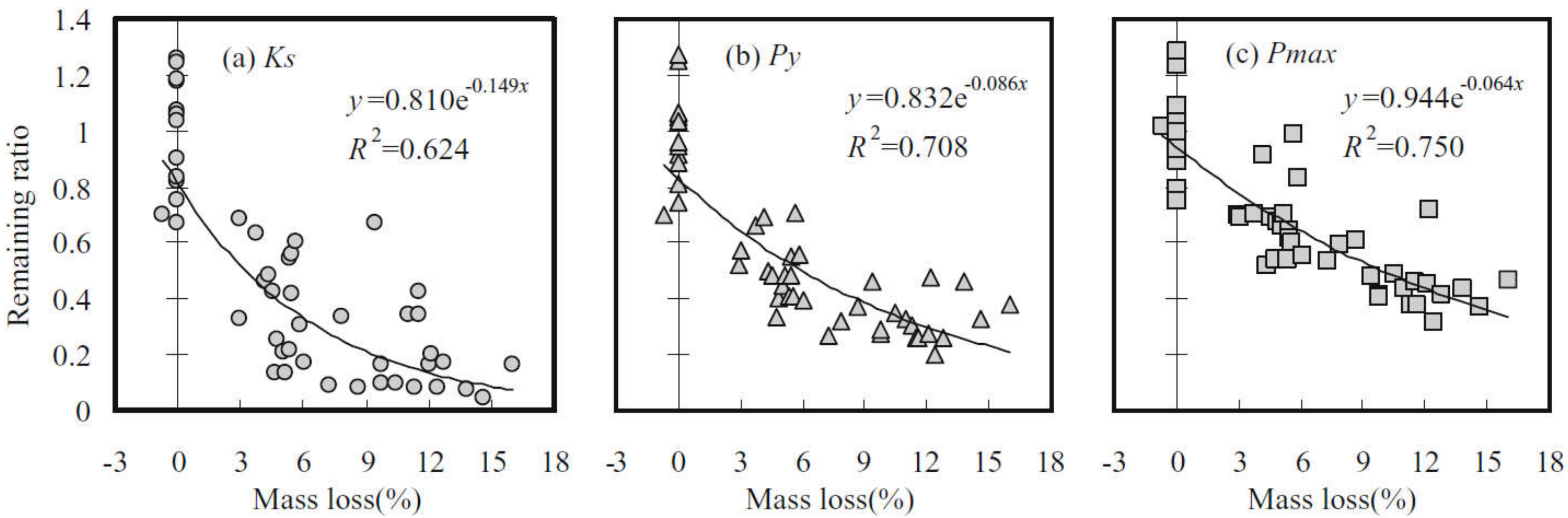
$$X_d = \frac{k_1}{\gamma_M} \cdot X_k \cdot k_h \cdot k_{con} \cdot k_a \quad (2)$$

where k_{con} = reduction of wood properties due to conservation status, k_a = reduction of wood properties due to time in service (aging factor).

The Eurocode 5 factors in Eq. 2, are generally taken as constants, dependent on the worst situation to which the members are exposed while in service. The other two factors (k_{con} and k_a) are more difficult be define, because the way in which the degradation of the wood material by fungi or insects leads to the deterioration of the mechanical performance of structural elements is left to the judgment of the expert evaluating the structure. As regards aging, a long discussion exists about the need to consider this factor for structural members (gross cross-section). From the experience with white pine timber, Suter (1982) suggested a value of 0.9 for k_a.

Decay on dowel-type joints

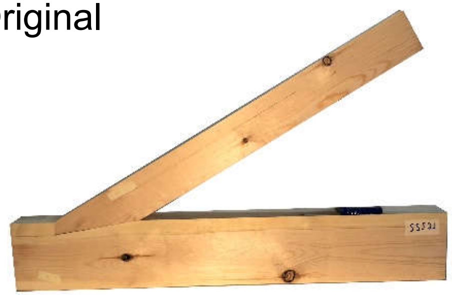


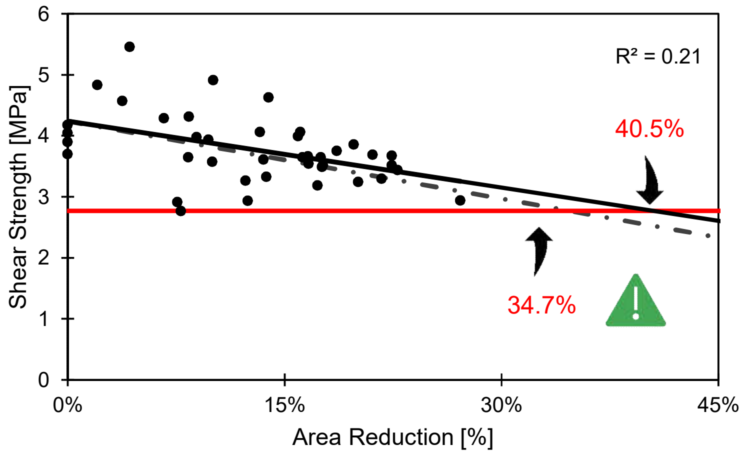


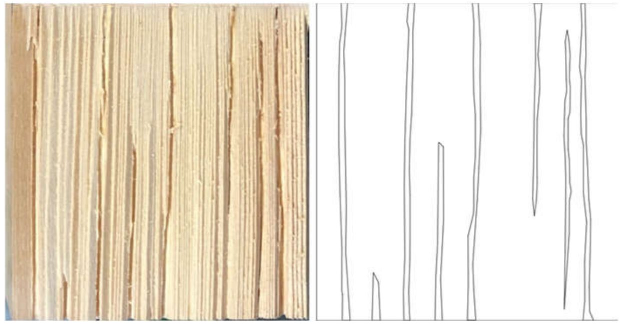
K. Sawata, T. Sasaki, S. Doi, Y. Iijima, Effect of decay on shear performance of dowel-type timber joints. *J Wood Science*, 54 (2008), pp. 356-361.

Carpentry joints - Beetle attack

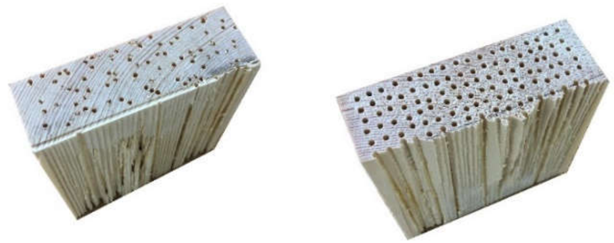
Original



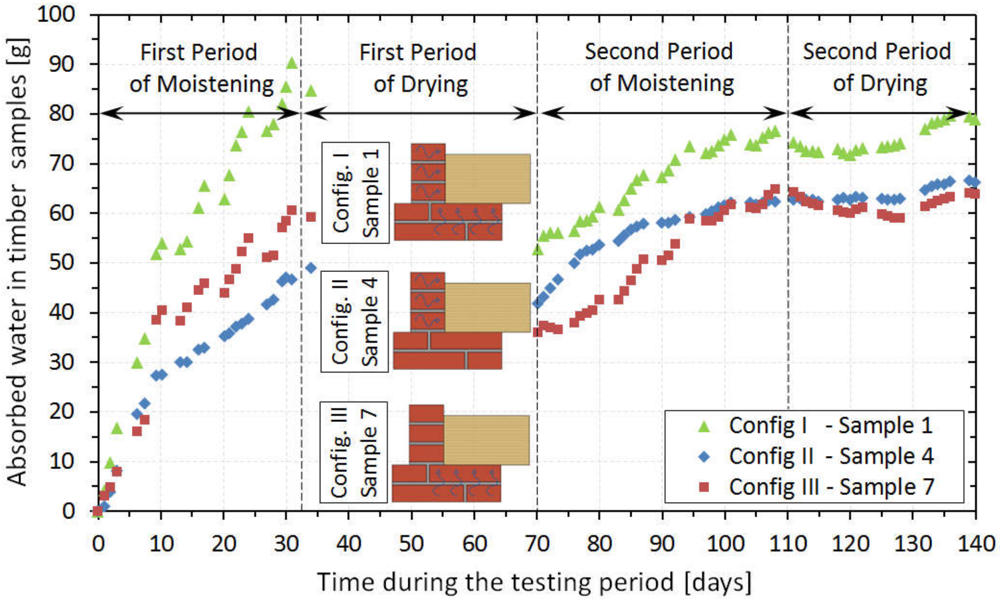


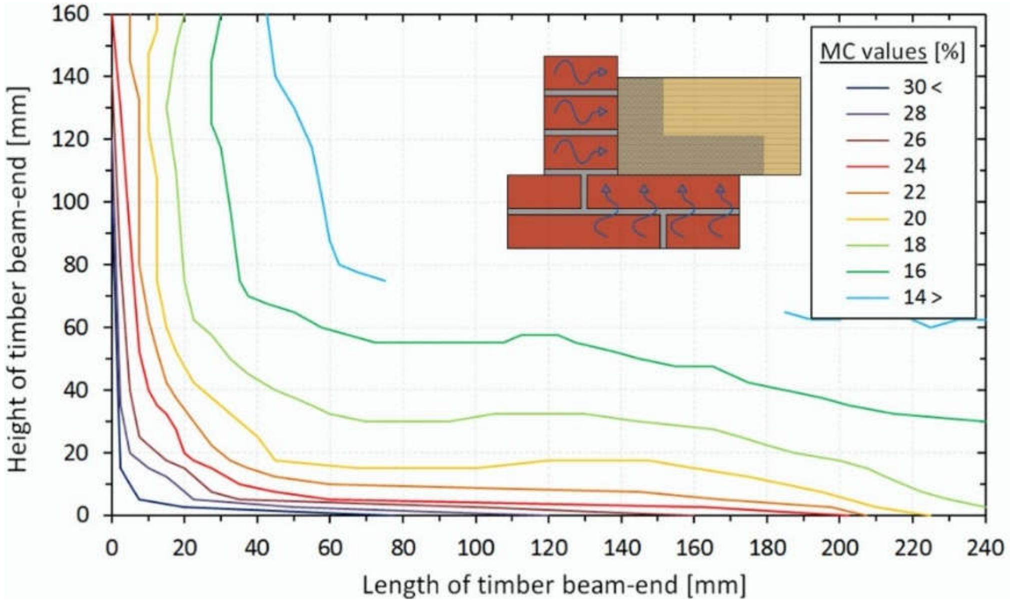


Residual



Moisture propagation & Fungi





L. Nunes, M. Verbist, D. F. Lima, J.M. Branco, Preliminary testing of moisture propagation at timber beam-ends in contact with wet masonry, in: *ICMB'21 1st International Conference on Moisture in Buildings,* UCL London, 28-29 June 2021.

Unknown unknowns


Designed by pngtree

Unknown unknowns

- **Visual inspection is the first step to a full diagnostic of an existing structure.**
- **Work focused on the mechanical survey of elements and joints for structural analysis purposes.**
- **Future actions and interventions are result of present diagnostic.**

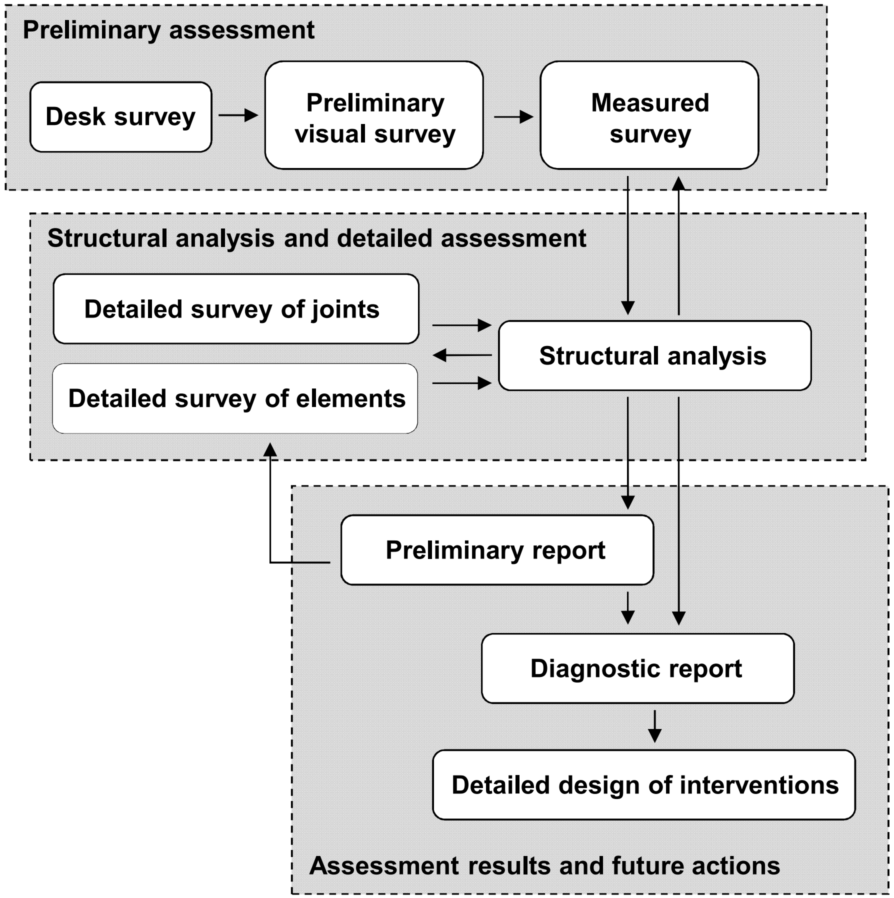
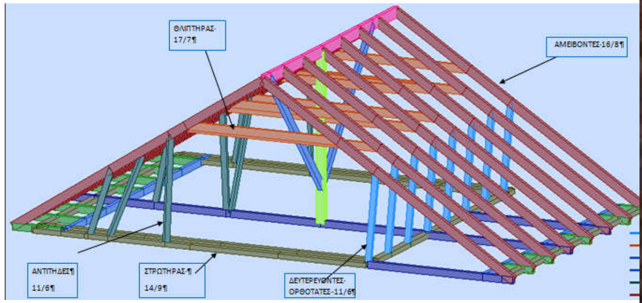
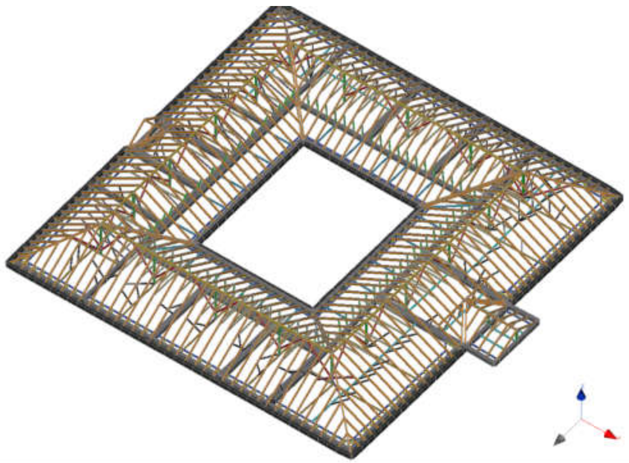


Figure: Assessment and planning of interventions in historic timber structures (adapted from Cruz et al., 2013)






LOADS TRANSFERD TO TRANSVERSAL WALL
LOADS TRANSFERD TO THE TIE-BEAM

Unknown unknowns

Experimental tests and NDT correlations

material properties

clear wood

↓

higher strength
higher stiffness

Visual inspection and NDT results

structural scale effects

defects / decay

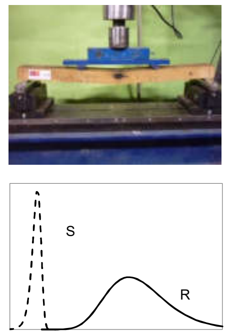
↓ **size, length, concentration**

lower mechanical properties

Definition and variation of mechanical properties

- **bending stiffness**
- **bending strength**
- **density**

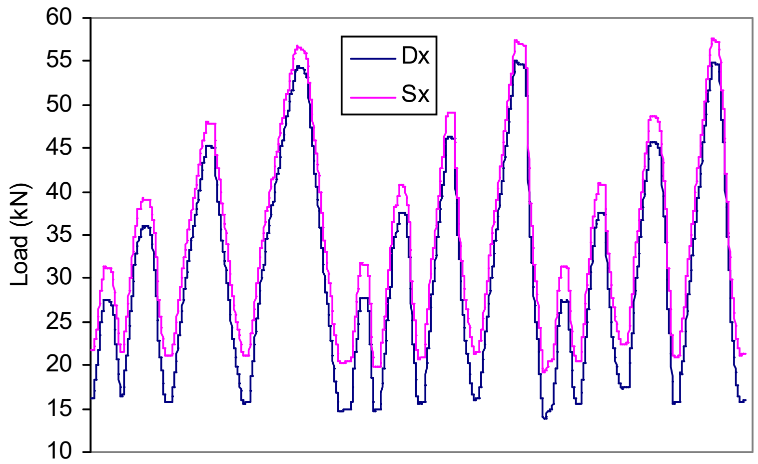
→ **Structural Assessment**

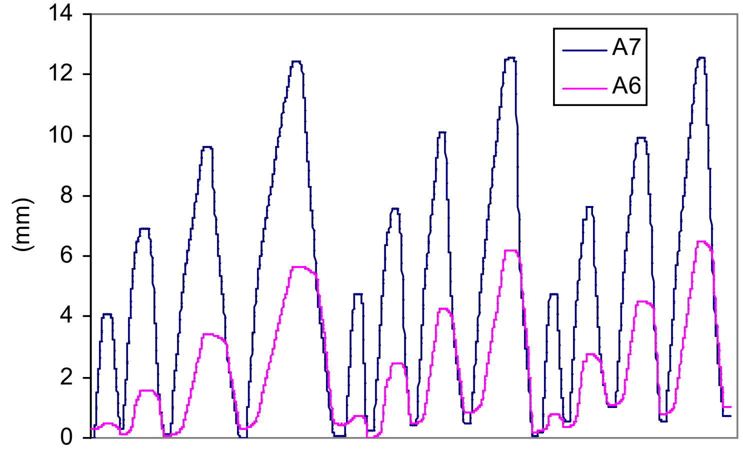


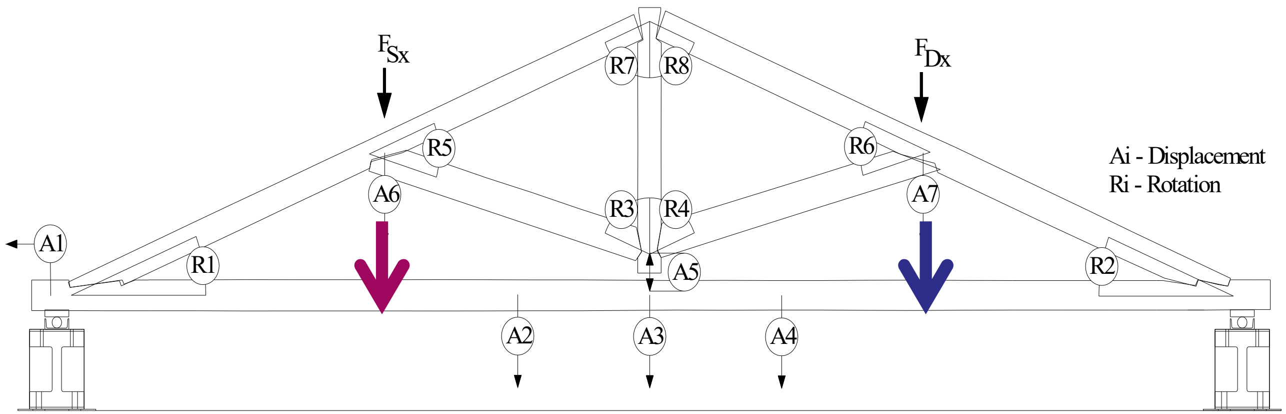
King-post truss – Load tests

Branco, J.M., Piazza, M., Cruz, P.J.S. (2010), Structural analysis of two king-post timber trusses. Nondestructive evaluation and load-carrying tests. *Construction and Building Materials*. 24 (3), 2010, 371-383. URL: http://hdl.handle.net/1822/13995.

King-post truss – Response (global)







Unknown unknowns

- In the assessment of existing timber structures the uncertainty can be considered as epistemic (the errors are only due to our incapacity to get the necessary information, to deal with human errors or to apply the correct test methods).

Structural assessment of timber structures.

Knowns, known unknowns, and unknown unknowns

Obrigado!

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SHATIS 22

structural health assessment of timber structures

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University of Minho