

TECHNICAL NOTE



A non-destructive protocol for the industrial proof-loading of tree trunks used for beams and floors

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ABSTRACT

The use of logs for construction dates back millennia but has been largely supplanted by materials such as concrete, steel, and squared timber that allow for much more flexible and efficient industrial processes. Recently, robotics and digital tools have reopened the possibility of using raw logs in modern building without relying on skilled craftsmen. However, the state of the art is still insufficient in several fields such as the mechanical characterisation and classification of tree trunks, the development of efficient and reliable log-to-log connections, the integration of finishing touches, the transmission of data between digital design tools and robots, and the design of efficient log floors. This study focused on the development of a non-destructive industrial protocol for the mechanical characterisation and classification of logs subjected to bending. The originality of the proposed methodology lies in its ability to guarantee the Ultimate Limit State (ULS), short-term Serviceability Limit State (SLS), long-term SLS and fire resistance of logs simultaneously. Developed through tests on green and dried large-scale logs, the protocol is easily transferable to industrial contexts. It also provides practical guidelines for integrating logs as load-bearing elements in construction.

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1. Introduction

1.1. The relevance of building with logs

The increase in environmental awareness over the past two decades is prompting a re-evaluation of the way natural resources are used. This has an impact on the construction sector, which is not only one of the largest producers of waste in the EU (Villoria Sáez and Osmani 2019), but also one of the main contributors to greenhouse gas emissions worldwide (International Energy Agency 2019). In this context, timber, as a renewable resource, is a material to be preferred in this sector. In fact, (i) the transformation of wood into construction products is one of the lowest producers of CO₂ across construction materials, (ii) building with timber stores CO₂ rather than releasing it into the atmosphere and (iii) there is potential for low emission recycling at the end of the building lifecycle. The condition for a sustainable approach is obviously twofold: on the one hand, systematic replanting of forests and good management according to labels such as PEFC (Programme for the Endorsement of Forest Certification), and diversified plantations to enhance biodiversity on the other hand. However, most major timber projects today are designed with beams, columns, or panels made with rectangular sections cut from trees that have inherently great natural strength for response to extreme lateral loads like storms. The transformation steps required to make timber products creates (i) waste material by extracting a rectangular section beam from a conical tree trunk, (ii) a decrease in the mechanical characteristics due to broken fibre continuity around knots (Zhang *et al.*

2024), (iii) an increased CO₂ impact, and mainly (iv), high production costs due to all required operations. The industrial production process of engineered timber begins with the sawing of the log where a large amount of material is lost, followed by drying, jointing, planing, pressing, and sanding. These steps increase the price of timber, which often decreases attractiveness compared to other building materials, thus discouraging use. Considering the aforementioned, it can be concluded that building structures with trunks is sensible, and researchers increasingly agree, as shown by the state of the art (Bukauskas *et al.* 2019). A two-part study investigated the use of roundwood, in particular small-diameter oak logs, for load-bearing timber structures (Hofmann *et al.* 2023, Schober *et al.* 2023).

Before reaching a low-cost industrial process, some scientific and technical challenges exist, including the development of equipment and protocols that allow the mechanical characterisation of logs, the development of parametric design tools capable of shaping connections between logs and sending comprehensible data to the machining tools, having tools capable of a fast machining of trunks, research to evaluate stresses in the connections despite variations in moisture and finally, a selection of the most efficient trunk-to-trunk connections suitable for industrial cutting, with as little steel as possible.

This article proposes a reliable non-destructive protocol for the mechanical characterisation of logs in bending, based on experimental tests carried out on 30 large-diameter logs. It also sets the guidelines for using logs as load-bearing elements

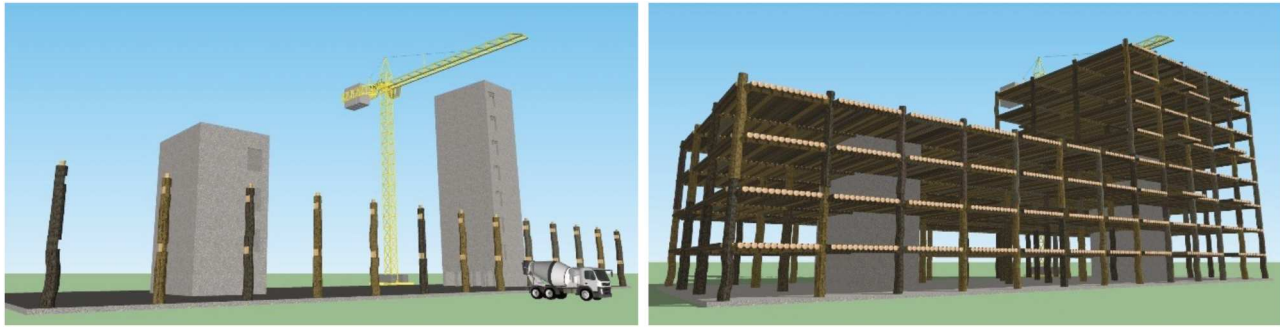


Figure 1. Load-bearing system combining a central concrete core and log floors, columns and beams.

in the practical case of building construction, such as shown in Figure 1.

1.2. Statistical-based design vs “Proof loading” design

Globally, timber design concerns mostly squared timber and follows these steps: calculation of rare ULS load case combinations, internal forces and stresses, checking the rare ULS design criteria (bending, shear, etc) with security coefficients (such as k_{mod} and γ_m for EC5), checking the SLS and fire criteria. This method is economically disadvantageous, because:

- The mean bending strength $f_{k,50\%}$ can be twice as the 5% characteristic bending strength $f_{k,5\%}$. According to (Martitegui *et al.* 2013) the distribution of bending stresses obtained on 110 Scots pine samples shows strengths ranged from 18 to 80 MPa, with $f_{k,5\%} = 26$ MPa, $f_{k,20\%} = 33$ MPa and $f_{k,50\%} = 47$ MPa. For class C30 timber, for example, NBN EN338 claims a 50% increase in modulus of elasticity when moving from the characteristic value to the mean value (from 8000 MPa to 12000 MPa).
- The discontinuity of the fibres caused by sawing logs into rectangular planks undermines the natural resistance it has taken decades to build up.
- The sawing yield of logs is relatively low (50%) (Ramage *et al.* 2017).
- The use of large-section elements requires the use of expensive engineered timber.

It is sensible to consider building with whole logs but, unfortunately, there are very few standards for classifying logs and determining their mechanical characteristics, and the guidelines that exist are incomplete and inapplicable with modern construction.

A trunk's mechanical characteristics are derived from an “average” over its entire volume and there is no formula for determining them reliably, for example on the basis of parameters such as density, diameter, number of rings or ring thickness. The challenge is to determine a loading protocol and the stop criteria (Lantsoght *et al.* 2016) without causing damage, such as local plasticity or fibre breakage, and in order to determine the load-bearing capacity of the logs before they are sent to the building site. This method, called “proof-loading”, is not yet widely discussed in the scientific literature. In other words, if the probability density function of a

log's bending strength existed (Figure 2 inspired from [Köhler 2014], dashed curve), then, after proof-loading, it would become the solid curve, since proof-loading guarantees that the probability of a lower strength than that tested is zero.

This article proposes a proof-loading protocol that provides the same degree of safety as the “statistical-based design”. The advantage of the proof-loading is that it can accurately assess the load-bearing capacity of logs in their final, ready-to-use configuration (dried, machined, treated).

1.3. Green or dried logs?

When wood loses its free water down to a moisture content of $w \leq 30\%$ of that contained within the fibres, its dimensions do not vary, as the water is replaced by air. Water bound to cellulose molecules can also be reversibly extracted when the wood dries under 30%, without altering its intrinsic properties, but with significant mechanical and dimensional variations.

To limit variations in w between the time the wood is placed on site and the time it has equilibrated with air humidity (which can also vary), it is always advisable to use wood that has a moisture content w as close as possible to its average equilibrium value with the air (in Belgium: $w = 16\%$ outdoors and $w = 10\%$ indoors). Logs can be naturally dried but this option is time consuming, sometimes taking years depending on the log size. Artificial drying is thus more appealing for industrial use of logs and several drying methods exist: artificial drying with air-conditioned hot air, heat pump drying, vacuum drying, steam drying, microwave drying, UV-infrared drying, etc. A comparison of the most commonly used drying techniques is given in (Guéritte 2014–2020) and the time required for natural drying of the first 5 cm of the log periphery is approximately 3 times longer than for kiln drying and 9 times longer than for vacuum drying. The drying method selected also implies compromises between drying speed, industrial feasibility, and cost. Finally, for the construction of a log building, three options are available:

- **Option 1**, using green logs: logs are milled and graded as soon as they arrive at the sawmill, then used without any prior drying, as is the case, for example, when rebuilding the framework of Notre Dame Cathedral in Paris. This avoids the negative environmental impact of artificial drying and reduces costs (Sehlstedt-Persson and Wamming 2010, Salas and Moya (2014). Unfortunately, the

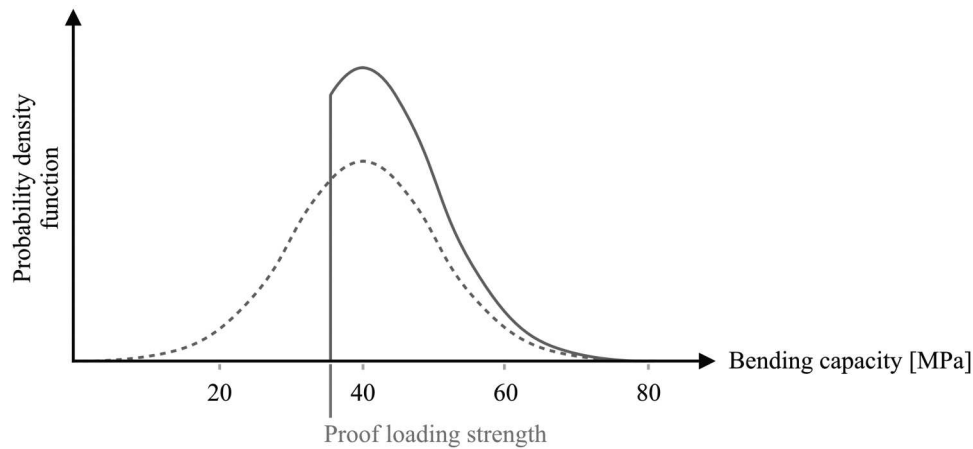


Figure 2. Density probability function of the bending capacity before and after a proof-loading.

disadvantages are numerous: (i) major dimensional variations after construction, which must be considered when designing joints, (ii) the impossibility of preservative treatment, as the wood is too damp (autoclave impregnation is ineffective above a wood moisture content of 30%) and (iii) increased risk due to the partitioning of elements that are still damp.

- **Option 2**, using fully dried wood: the elements undergo forced drying to a core moisture content of around 13%, followed by machining, preservative treatment, mechanical grading and installation. The advantages are: limited dimensional variations after placement on site, preservative treatment possible. The disadvantages are: huge drying time and cost, depending mainly on log thickness (U.S. Department of Agriculture, Forest Service, Forest Products Laboratory 1999).
- **Option 3**, using partially dried wood: this solution is a compromise between the two previous methods, and consists of drying only the periphery of the elements to below 30% moisture content, to a depth of just a few centimetres, to enable the application of a preservative treatment in this area using the osmotic autoclave process. Dimensional variations will occur after construction, but will be less pronounced than for green wood. This option is the best industrial compromise involving various factors of speed, cost and post-construction

behaviour. Kerfing (Figure 3) is recommended for “nervous” species such as *European beech*, *Douglas fir*, and *Norway spruce*, but in some cases alters mechanical behaviour (International Log Builders Association 2000). For other species, the appearance of anarchic cracking has the advantage of increasing the contact surface between the log and its environment, accelerating deep drying and promoting the penetration of preservatives.

2. State of the art of non-destructive testing of logs

2.1. Visual grading

In the timber industry, wooden elements can be classified using visual methods depending on their intended end use. Two common approaches are qualitative classification and visual strength grading, which serve different purposes.

Qualitative classification is primarily based on the external appearance of the log. It involves assessing visible features such as log curvature, diameter, taper, size and appearance of the knots, cracks, insect damage, etc. This method is used in forestry and sawmill operations to sort logs by quality classes for commercial purposes. The process is usually subjective and may vary depending on regional standards or

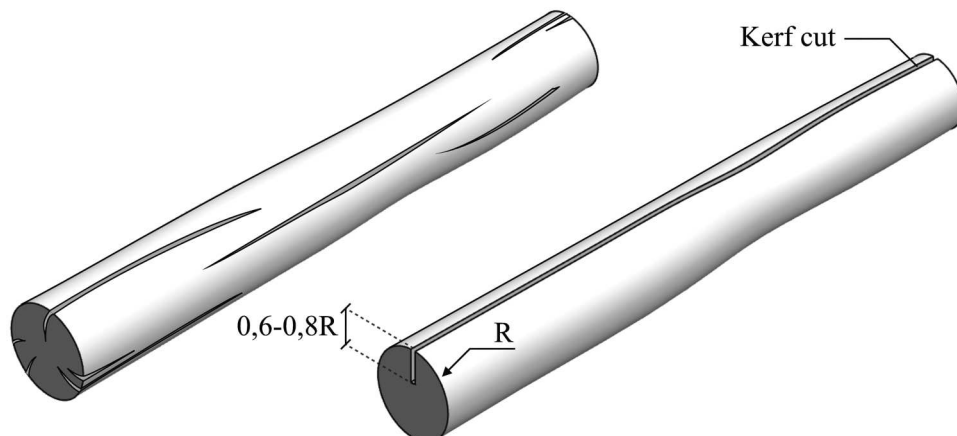


Figure 3. A kerfing in the logs to avoid drying cracks.

species-specific characteristics. While useful for value estimation and operational planning, qualitative classification does not provide a reliable indication of the log's structural performance but a general visual quality. Today, qualitative classification is strongly dependent on the experience of foresters and can therefore be highly imprecise. However, this initial sorting work, albeit rough, is the initial step in selection of logs even before they arrive at the sawmill, which also reduces unnecessary work on arrival.

Visual strength grading is a method specifically designed to predict the mechanical properties of the wood, particularly its strength and stiffness. This grading can be carried out whether a tree is still standing or has been felled, and especially when it has been squared. It involves a more systematic inspection of defects like knot size and position, slope of grain, reaction wood, and growth ring orientation. Like the qualitative classification, visual strength grading follows standardised rules depending on the species and the origin of the logs, making it more consistent and suitable for assigning structural grades to logs or sawn timber.

In addition, to prior to any formal standards, some researchers have tried to tentatively define the mechanical properties of whole timber, such as a project conducted in the 1990s in Europe (Ranta-Maunus and Tutkimuskeskus 1999), during which many trunks of small diameter and different species were tested (*Scots pine*, *Norway spruce*, *Sitka spruce*, *larch*, and *Douglas fir*) with destructive and non-destructive methods (visual grading, static bending, longitudinal stress wave and X-ray). The study presents a statistical analysis for the dependence of strength and stiffness on different factors such as density, knots, moisture content, diameter, and age to find a correlation between these parameters and the mechanical resistance.

The best-known visual grading standards for logs in Europe are:

- European standards EN1316 (for hardwoods) and EN1927 (for softwoods) for qualitative classification. The main criteria for (de)grading logs are the size and number of knots, curvature, eccentric cores and heart splits (observable only at the ends). The grading allows fair valuation of timber according to its visual quality (Class A: exceptional quality, class B: good quality, class C: common quality, class D: other logs).
- German standard DIN4074-2 governs the visual strength grading of softwood logs used for structural purposes. The grading of a log is based on the presence of defects such as insect attack, the presence of fungi, the size of growth rings, the size and position of knots and the curvature of the element. A log can thus be classified into 3 grades (III, II and I) corresponding respectively to low, normal and high strength roundwood. Another standard, DIN1052, associates a strength class with each of these three grades (Table 1). However, this table is limited to a few species. Moreover, each species can only claim one strength class.

While traditional visual grading methods – both qualitative assessments and visual strength grading – remain valuable tools for the commercial classification of logs, they must be

Table 1. Extract from the DIN1052:2008-12 standard.

Wood species	Origin	DIN 4074-2 grading	Strength classes
Spruce	Europe	III	C16
Fir	Europe	II	C24
Pine			
Larch	Germany	I	C30
Douglas			
Southern yellow pine	USA		

complemented by non-destructive techniques to support the development of predictive models of wood properties. The challenge becomes even more pronounced when irregularly shaped logs with customised machined joint details are considered.

2.2. Log grading using mechanical, electrical and dynamic methods

The literature indicates that non-destructive pre-grading results are more reliable for logs than for standing trees (Rais *et al.* 2014). Existing methods can be classified into four groups:

Group 1: mechanical methods slightly and locally alter the elements tested by isolated penetration or extraction of a piece of wood. They provide very specific and localised information, and it is necessary to take several measurements on the same individual to better characterise the whole element. These methods are mainly used on elements in service, such as power line poles, to anticipate their replacement. The resistograph is a device that measures the resistance to penetration of a drill bit (5 mm) into the trunk. Pilodyn (Simic *et al.* 2019) and Polux5 (Benoit and Sandoz 2011) propose a similar method but using a steel pin instead of a drill bit. Both methods relate penetration resistance to wood density, and indicate the presence of internal decay or degradation. The Fakopp system features a screw pull-out force sensor providing information on density and shear modulus (Cai *et al.* 2003). Other devices, such as the fractometer and the increment borer (Gao *et al.* 2017), where material is extracted, respectively measure the flexural strength and density of the sample. The resistograph is probably the most effective, as it is fast and minimally invasive (Gao *et al.* 2017). Sampling methods are time-consuming, whereas Pilodyn and the pull-off method, in addition to requiring local debarking, remain fairly superficial (<40 mm).

Group 2: electrical methods involve measuring the electrical resistance of a log using a special ohmmeter called Vitalomètre (Garrec *et al.* 1989) or Shigometer (Ostrosky and Shortle 1989). The position of the probe, its orientation, height, species and diameter are parameters that vary the measurement of electrical resistance. This method was used to monitor a spruce stand in the Vosges (France) by J.-P. Garrec *et al.* (1989). It does not allow one to determine the mechanical characteristics of the trunks, but it does allow one to evaluate, through regular measurements, the healthy or unhealthy evolution of the trees.

Group 3: ultrasonic and acoustic stress waves generated by a transmitter or a mechanical impulse. This wave may be transverse or longitudinal (Croiset *et al.* 1980) (Figure 4). Tests can be carried out on standing trees and logs.

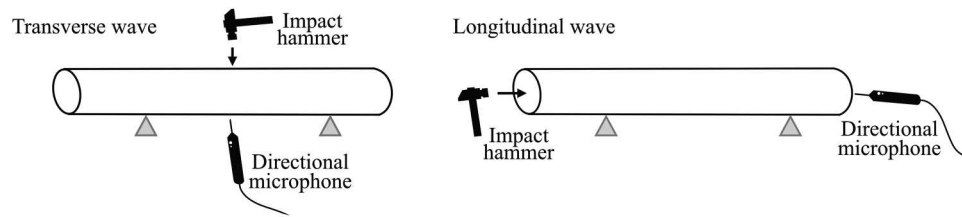


Figure 4. Bending resonance under transverse mechanical stress (left) and longitudinal resonance under longitudinal mechanical stress (right).

The dynamic “ultrasonic” method is used to obtain Young’s modulus in the longitudinal direction. Two piezoelectric probes are placed on either side of the trunk, one at each end. One sends out a high-frequency acoustic wave (15 kHz), while the other receives it. Material properties are calculated on the basis of the wave propagation speed between the two probes (distance and propagation time known). A commercial example is the Sylvestest.

The “Acoustic stress wave” method is also based on the time taken for a wave to travel through the element. The origin of the wave is different, however, as it comes from a mechanical shock such as a hammer blow. Unlike the ultrasonic method, excitation is therefore at low frequency. This method is preferred for logs due to their size, as a lower frequency dissipates energy less quickly and the signal is clearer (U.S. Department of Agriculture, Forest Service, Forest Products Laboratory 2015). Examples include: Metriguard 239A, Hitman ST300, Micro-Second Timer Fakopp.

Group 4: vibration frequency testing. With these methods, known as “Impulse excitation technique”, the vibration frequencies of the log are measured, rather than the propagation time of a wave. The overall modulus of elasticity can be determined knowing the dimensions of the log and its mass. The intensity of the excitation is proportional to the size of the log. The GrindoSonic MK7 is a commercial example for small scale and laboratory tests (Figure 5). The results of these IET tests on the same logs of this study will not be discussed in this document. Other products are used in the industry and applied directly to log measurements (Figure 6). Examples: Hitman HM220 is a manual, very fast and mobile version, whereas Hitman LG640 is the fixed, automatic version used in sawmills.

2.3. Non-destructive proof-loading protocol

The use of the NDT described above is a necessary but insufficient condition for the safe use of logs as structural elements for buildings and multi-storey buildings. They are useful because they allow for the early elimination of unsuitable logs, saving both time and money, but they are insufficient. Indeed, their accuracy is not sufficient for the level of security needed for a building, and the transformation of logs through machining and the use of specific milled joints can drastically alter their mechanical behaviour. Moreover, these methods often assume that logs have a simple, well-defined geometry and are free from defects such as drying cracks (Sandoz 2002) an assumption that is rarely true in practice.

The only sufficiently precise method for guaranteeing a log’s load-bearing capacity is therefore to carry out non-destructive bending tests on all logs used in construction, in accordance with a well-thought-out test protocol, which must provide the log’s minimum load-bearing characteristics without damaging it. This process is known as “proof-loading” or “proof-testing”.

This method is already used in industry on small-section elements, in bending or tension (Strickler and Pellerin 1971), for checking solid finger-jointed timber, or in sawmills for mechanical grading of squared timber. For logs, the number of mechanical characterisation benches globally can be counted on one hand. The New Zealand based company Unilog has developed its own bending bench to certify the strength of logs according to the NZS3605 standard that prescribes rejection of logs showing “signs of weakness” during the load test. However, it remains vague on signs of damage, stating the test “is successful if the pile carries the load

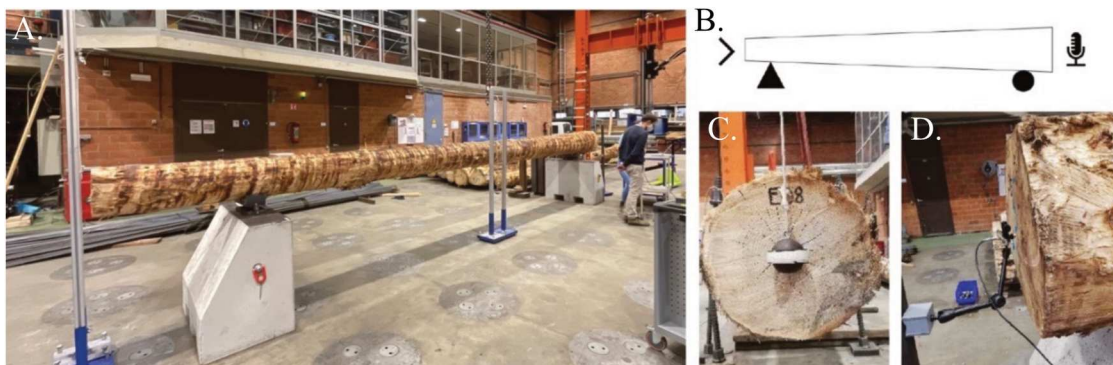


Figure 5. A Using the GrindoSonic MK7 on the lab test bench. B: Diagram of sensor position and striking zone. C: Mass on pendulum for striking. D: Microphone.



Figure 6. Left: Measuring with the Hitman HM220, middle: the Hitman HM220, Right: Sawmill use of the Hitman LG640.

without obvious signs of distress or permanent set". As another example, ISO15206 standard covers the basic requirements and test methods for wooden poles, and prescribes a 3-point bending proof-loading procedure. It also remains vague on the final result of the test and is thus insufficient: "The pole is considered to be defective if any visible sign of failure is noted during the test".

Finally, existing standards lack a rigorous definition of damage criteria and are not compatible with the safe construction of multi-storey buildings and other structures.

3. Protocol development

3.1. Equivalence between a distributed load and an actuator load

In the laboratory, four-point bending tests on beams are generally carried out with an actuator where load F is applied at two points, as shown in Figure 7. Distributed load q (kN/m) (Figure 7A) must therefore be approximated into an "actuator force", noted F (kN), such as:

- Either F and q create the same maximum bending moment at mid span with $F = \alpha qL$.
- Or F and q create the same maximum deflection δ at mid span with $F = \beta qL$.

In Figure 7B, force $F/2$ is applied at $L/4$ and $3L/4$ and:

- The two maximum bending moments are equal if $\alpha = 1$. In this case, the two maximum shear forces are also equal, such as the support reactions.
- The two maximum deflections are equal if $\beta = 0.91$.

In Figure 7C, force $F/2$ is applied at $L/3$ and $2L/3$ and:

- The two maximum bending moments are equal if $\alpha = 0.75$. In this case, the maximum shear force and support reactions of the actuator-loaded beam are 25% lower than those of the uniformly loaded beam.
- The two maximum deflections are equal if $\beta = 0.73$. The same applies for the shear force and the support reaction (27% lower).

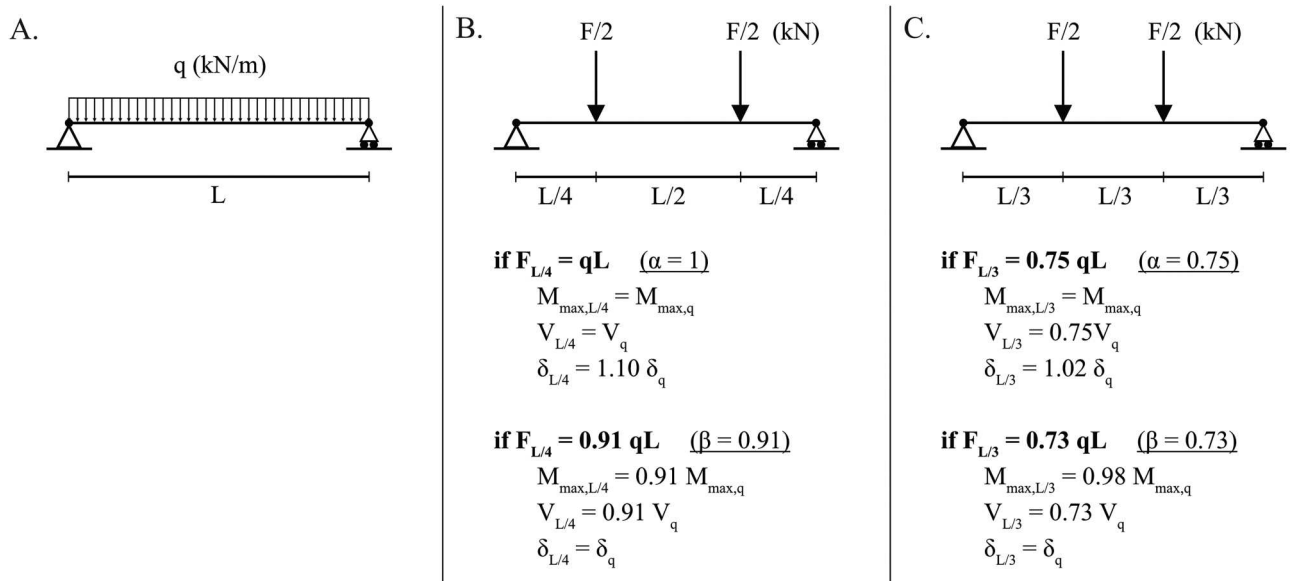


Figure 7. Equivalence between the effects of a distributed load and an actuator load.

Many standards (such as NBN EN14251) impose loads placed at $L/3$ and $2L/3$. In this case, the shear force and support reactions are 25% lower than those of the uniformly loaded log, and the log under testing is therefore in a more favourable situation than when placed in real conditions. Figure 7C, which is more in line with standards, is preferred to determine the protocol based on laboratory tests, while Figure 7B should be preferred for an industrial protocol that must reproduce real-life conditions as closely as possible, even though it does not comply with certain standards applicable in certain countries.

3.2. Description of the test set-up and extent of laboratory tests

Ten logs from 3 different species were tested (Table 2):

Populus tremula L. – European aspen – (poplar)
Tsuga heterophylla (Raf.) Sarg. – western hemlock – (tsuga)
Picea abies (L.) Karst – Norway spruce – (spruce)

Table 2. Summary of the bending tests.

WOOD Specie	Number of logs tested	Diameter ϕ (cm)	Length L (cm)	(L/ ϕ)	Loads position
European aspen (Poplar)	10	35–37.3	700–746	20	$L/3$
Western hemlock (Tsuga)	10	35–37.5	700–750	20	$L/3$
Norway spruce (Spruce)	10	36.3–41.7	617–709	17	$L/3$

Figure 8 shows the test bench, in which the log supports (spaced apart by L) and the two points of application of the actuator can be moved for each log, in order to maintain a constant L/ϕ ratio within the same batch of logs (ϕ taken at half length). Each log was tested as follows:

- Undried logs: bending test in the undried state, with visual grading (according to European and German standards) and characterisation with an IET non-destructive method between the different loading stages (GrindoSonic MK7).
- Return to the sawmill for kiln drying for 3 weeks according to the option 3 explained in section 1.3.
- Dried logs: second bending test (IET GrindoSonic MK7 before the test only).

Each bending test consists of several loading and unloading cycles to verify both the repeatability and convergence of the force-displacement response, and the non-damage status (detailed in section 3.3).

The actuator is bolted to the reaction frame and has a mechanical fork joint at the connection to the distribution beam. This fork joint ensures that the force applied to the cylinder is equally distributed between the two load application points on the log. The load application devices and lower log supports have been machined into a “V” shape to accommodate and stabilise debarked logs during loading (Figure 8).

3.3. General principle of the proof-loading

As part of a construction project, the data required for proof-loading must come from the structural engineer in charge, and are as follows:

- The span L needed for the log.
- The uniformly distributed load q_{ULS} (kN/m) applied on the log under ULS rare load combinations.
- The maximum allowed value $\delta_{ST,max}$ (mm) of the short-term deflection created by the uniformly distributed load $q_{SLS,ST}$ (kN/m) under SLS short-term combinations (Typically $\delta_{ST,max} = \dots L/500 \dots L/300 \dots$). The maximum allowed value $\delta_{LT,max}$ (mm) of the long-term deflection created by the uniformly distributed load $q_{SLS,LT}$ (kN/m) under SLS long-term combinations (Typically $\delta_{LT,max} = \dots L/150 \dots L/300 \dots$).
- Fire resistance requirements, in particular the time t_{req} required for fire resistance and the distributed load q_{fi} (kN/m) that the log must be able to withstand in the event of fire (ULS accidental combinations).

From data sets, one can calculate:

- $F_{ULS}^{project} = \alpha \mu q_{ULS} L$ the force in the actuator that creates the same bending moment than μq_{ULS} with the same degree of safety as the Eurocodes “statistical” approach based on design criteria (section 1.2, with $\mu = \gamma_m/k_{mod}$ if one considers EC5).
- $F_{SLS,ST}^{project} = \beta q_{SLS,ST} L$ the force in the actuator that creates the same deflection than $q_{SLS,ST}$.
- The ratio $\omega = q_{SLS,LT}/q_{SLS,ST}$ (>1).
- The ratio $\theta = q_{fi}/q_{ULS}$ (<1).
- The maximum allowed carbonisation depth d_{ef} (with $d_{ef} = (\beta_n t_{req} + 7)$ if one considers EC5).

The challenge is to develop a protocol that guarantees the load-bearing capacity of the logs and that can highlight the preliminary signs of damage (local plasticisation, fibre breakage). It is important to distinguish between:

- The industrial protocol, which can be used quickly and cost-effectively by a company developing an industrial bending bench to implement it.
- The laboratory protocol, which helped define the industrial protocol and which differs in the number of cycles performed and loading speed, are discussed in section 5.

The general principle of the protocol, illustrated in Figure 9, is based on a 4-point bending test with controlled displacement (the actuator’s displacement is imposed), and consists of 3 steps:

- Subjecting the log to a 1st set of loading-unloading cycles (noted SLS1) until $F_{SLS,ST}^{project}$.
- Subjecting the log to the theoretical force $F_{ULS}^{project}$.
- Subjecting the log to a 2nd set of loading-unloading cycles (noted SLS2) until $F_{SLS,ST}^{project}$.

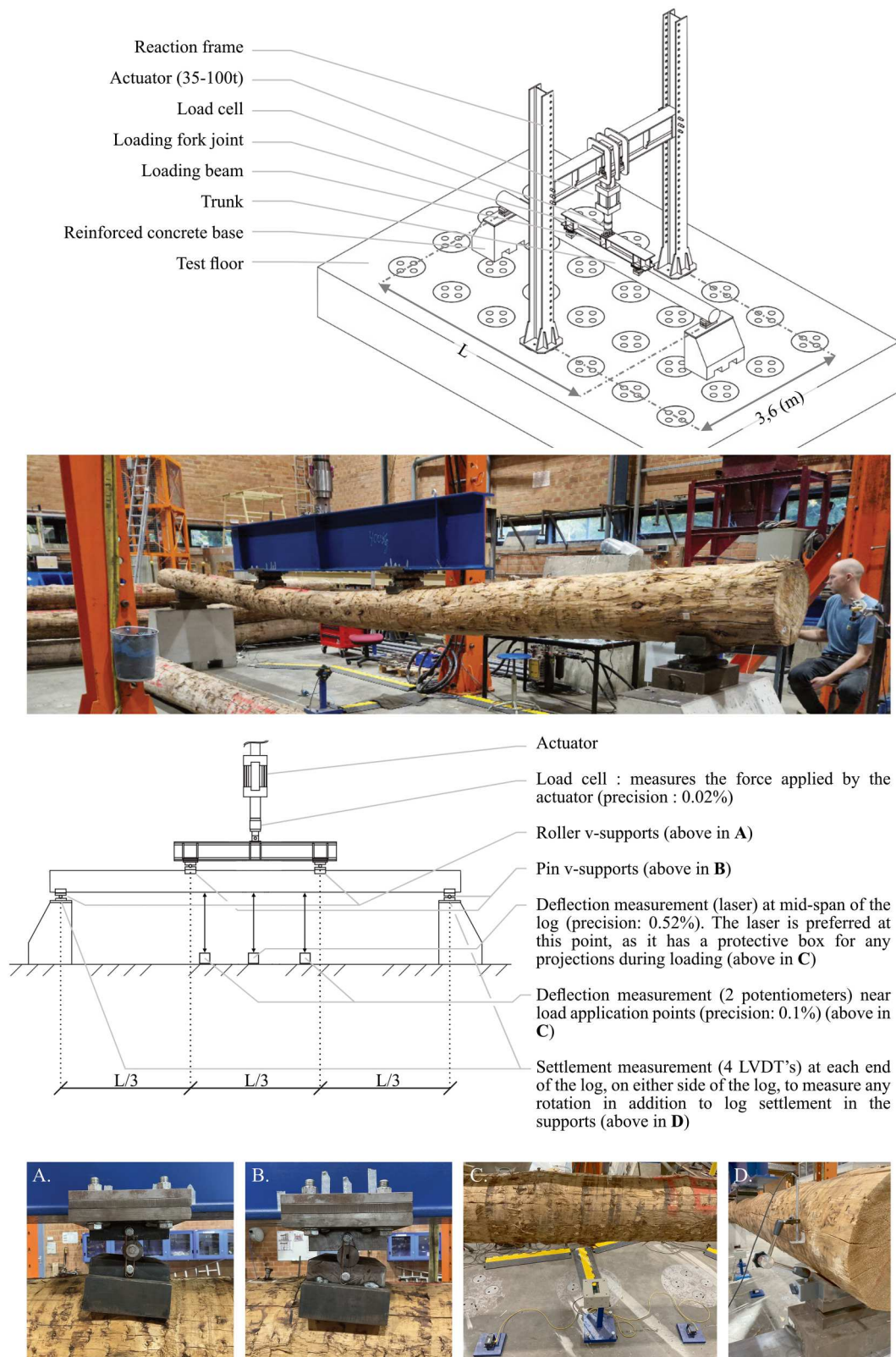


Figure 8. Above: Lab bending bench. Below: A: roller v-supports, B: Pin v-supports, C: Potentiometers and laser for deflection measurements, D: LVDT for settlement at support to correct the deflection.

This approach was chosen for two reasons: on the one hand, it enables one to check whether the project short-term SLS, long-term SLS, ULS and fire criteria are met (sections 3.4, 3.5, 3.6 and 3.8) and, on the other hand, one can check that no damage of the log occurs (section 3.7).

Non-destructive tests (IET, see Figure 6) were carried out after cycles 4 and 6 for the “undried state” only. As these tests required the removal of the steel loading beam, cycles 5 and 7 can be considered as set-up cycles, as the distribution beam and log were brought into contact again.

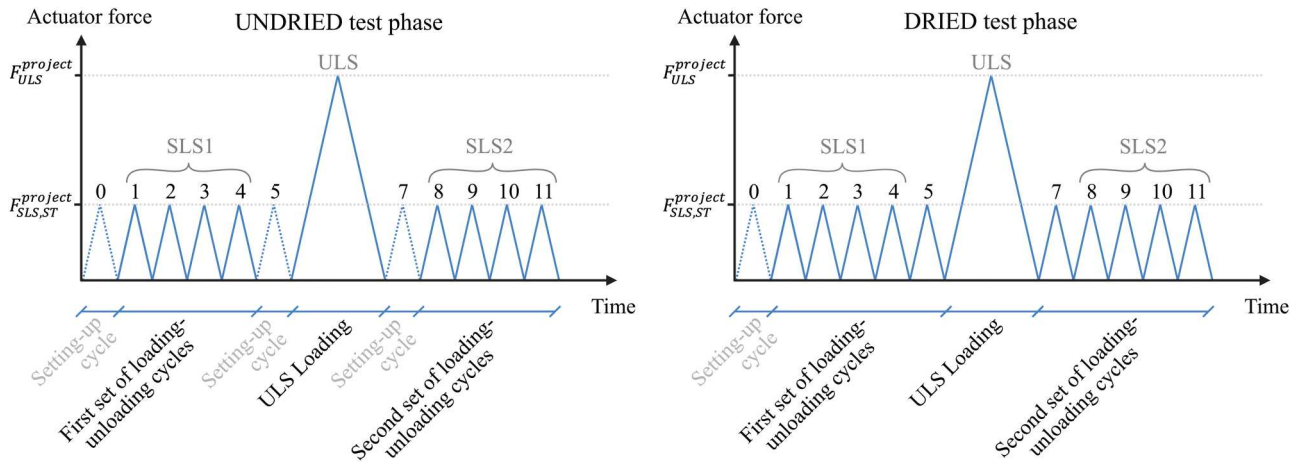


Figure 9. General principle of the proof-loading protocol for the “undried state” (left) and “dried state” (right).

3.4. Checking the SLS_{ST} short-term deflection criterion

The short-term deflection criterion is respected if, for all of the SLS1 and SLS2 cycles, the maximum deflection δ at mid-span is such that $\delta < \delta_{ST,max}$ (Figure 10) (in particular the final deflection).

3.5. Checking the SLS_{LT} long-term deflection criterion

The ratio $\omega = q_{ELS,LT}/q_{ELS,CT} > 1$ depends on the characteristics of the project, and is a datum assumed to be known before the bending test.

The long-term deflection criterion should only be considered if $\omega(\delta_{ST,max}/\delta_{LT,max}) \geq 1$. Otherwise, the short-term criterion is more demanding, and it alone should be considered.

The long-term deflection criterion is inevitably the result of a calculation artifact enables one to deduce, from a short-term test, behaviour of which the effects will appear after several years. In reality, the long-term load is a “mathematical” load and does not correspond to any reality that may occur. It would therefore be senseless to apply this load to the log during a test. Instead, it should be interpreted as follows: “in the long term and for the same load, the deflection will be greater by a factor of ω ”. The factor ω will “mathematically” transform a “short term” loading test into a “long term” loading test, by multiplying each abscissa displacement by the value of ω (Figure 11).

The long-term deflection criterion is respected if, for all of the SLS1 and SLS2 cycles, the maximum deflection δ at mid-span is such that $\omega\delta < \delta_{LT,max}$ (in particular the last one). This is shown in Figure 11A,B where the loading curves of two trunks arbitrarily named A and B both fulfil the short-term criteria but only trunk A satisfies the long-term criteria (Figure 11A) but not trunk B (Figure 11B).

3.6. Checking the ULS criterion

For cycle n°6, the force in the actuator is $F_{ULS}^{project} = \mu\alpha q_{ULS}L$, as shown in Figure 9.

Non-rupture of the element under this loading is not a sufficient condition for validation of the log, as it does not guarantee that invisible or inaudible damage has not occurred during the test. Signs of damage (local plasticisation or fibre breakage) must therefore be adequately detected, either during the application of $F_{ULS}^{project}$, or during the second set of SLS cycles that follow. This is discussed in section 3.7.

3.7. Damage detection and log rejection criteria

Based on lab tests carried out according to the protocol shown in Figure 9, three rejection criteria are proposed. The first loading cycle, noted cycle n°0, always shows a lower loading

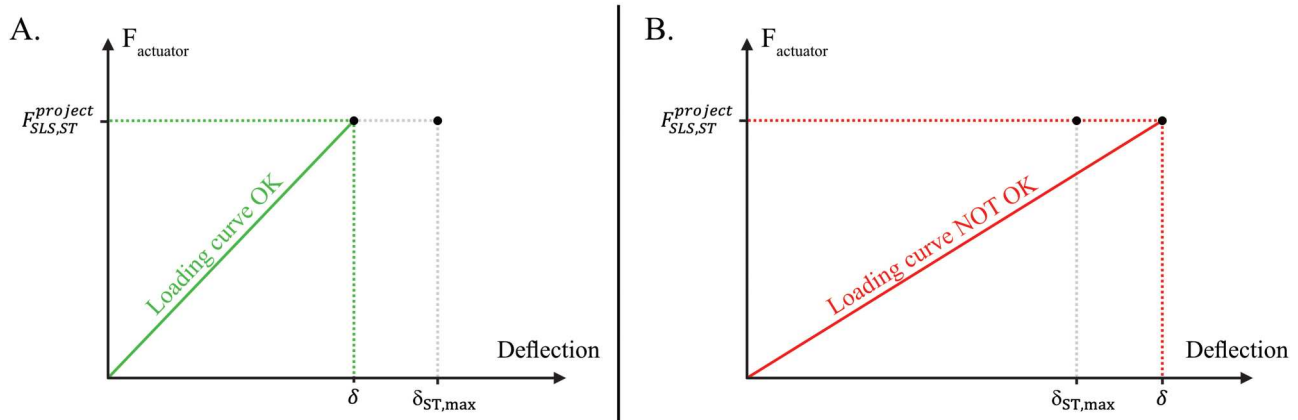


Figure 10. Principle of the short-term deflection criterion, the criterion is respected in 10A unlike in 10B, where the criterion is not met

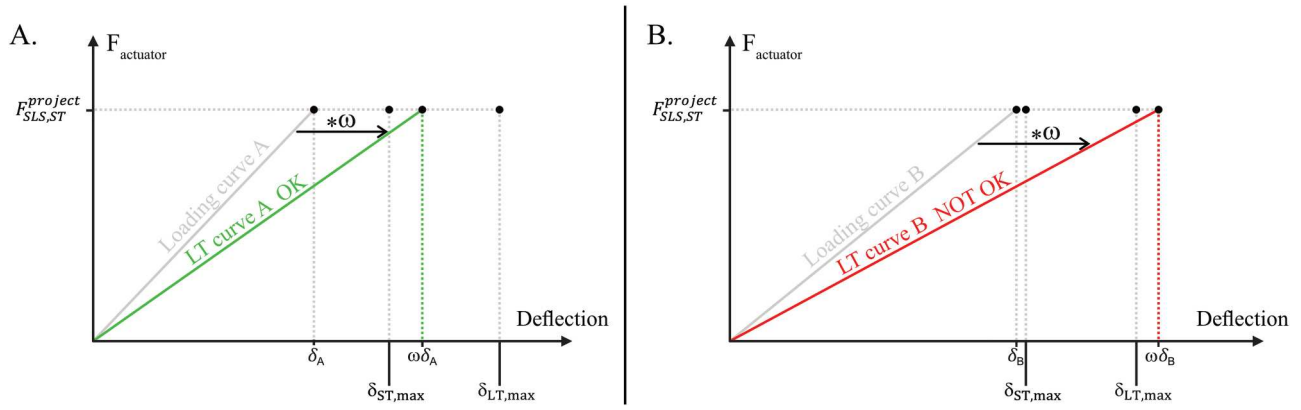


Figure 11. Principle of the long-term deflection criterion, the criterion is respected in 11A but not in 11B.

than the following ones, reflecting the correct positioning and contact of the log with its supports. One therefore considers cycle n°1 and not cycle n°0 as the reference for Figure 13 and Figure 14.

For the laboratory tests that were carried out on the 30 logs, there was no real construction project behind them and therefore no project loading value $F_{SLS,ST}^{project}$ as considered in section 3.3 and Figure 8. The cycles of SLS1 and SLS2 were therefore all pushed to reach a deflection of $L/350$ and can therefore each theoretically correspond to a different force in the actuator. However, this does not alter the principle of the rejection criteria n°2 and n°3 illustrated in Figure 13 and Figure 14 below: the variation of force ΔF observed in the lab (for a constant maximum deflection $L/350$) is the equivalent to a variation in measured deflection $\Delta \delta$ observed in industrial conditions (for a constant maximum actuator force $F_{SLS,ST}^{project}$).

Rejection criterion n°1: noticeable jumps in the force-displacement curve (Figure 12) of ULS cycle (n°6). The test campaign revealed that, on all logs, audible cracks appeared during ULS loading, indicating that some fibres were breaking. The majority of these cracks are related to peripheral fibres and are undetectable on the test force-displacement response graphs, and therefore benign. However, for the tested log

T07, much noisier cracking is reflected in curve jumps on the test curve. In order to reject logs exhibiting such jumps during the test, it is necessary to impose that the force-displacement response of a log is a strictly increasing monotonic function for each loading and unloading rise of its cycles.

Rejection criterion n°2: this rejection criterion concerns the absence of stiffness convergence during the second set of SLS cycles (Figure 13). If the log deflections δ obtained during the second set of load-unload cycles are highly variable or do not converge towards the same value, this indicates that the ULS loading has irreversibly modified the stiffness and that the log is damaged. However, this situation has never been observed on any of the logs tested, with behaviour similar to that shown in Figure 13 (left), where the force peaks (i.e. the deflection δ for the industrial protocol) converge towards a value very close to that of cycle n°1. Figure 13 (right) illustrates a similar test, but in which each set of SLS cycles comprises 50 load-unload cycles instead of five. It leads to the same conclusion.

Rejection criterion n°3: too great a discrepancy between the respective average stiffnesses of SLS1 and SLS2. Two cases can occur: after ULS loading, either a loss of stiffness such that the SLS criteria detailed in sections 3.4 and 3.5 are no longer met (Figure 14, left), or a loss of stiffness that still satisfies the SLS criteria, but is deemed too great, as it reflects

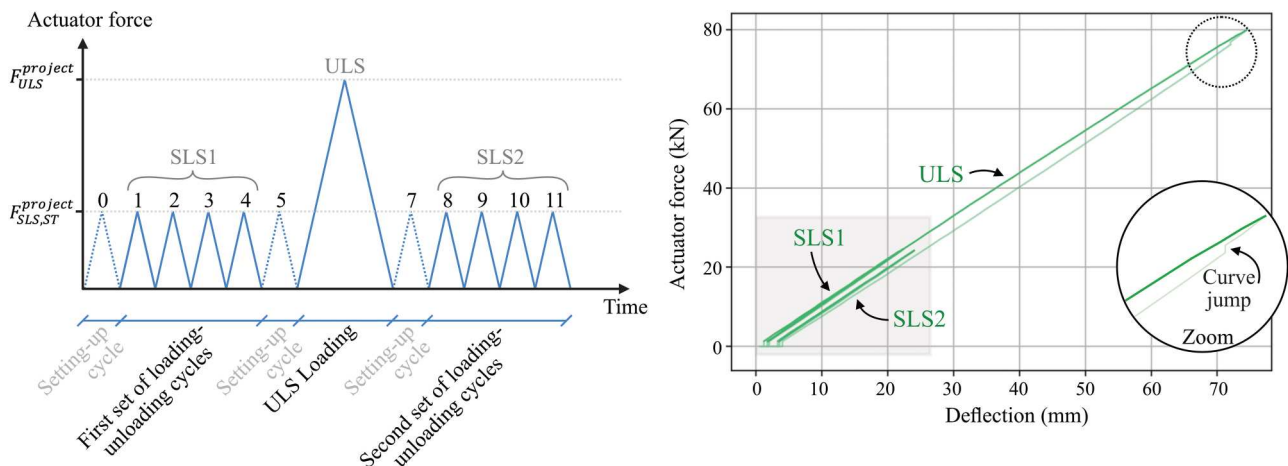


Figure 12. Left: General principle of the bending laboratory protocol, Right: Force-displacement response of Tsuga for log T07 in the undried state, where curve jumps could be observed during cycle 6.

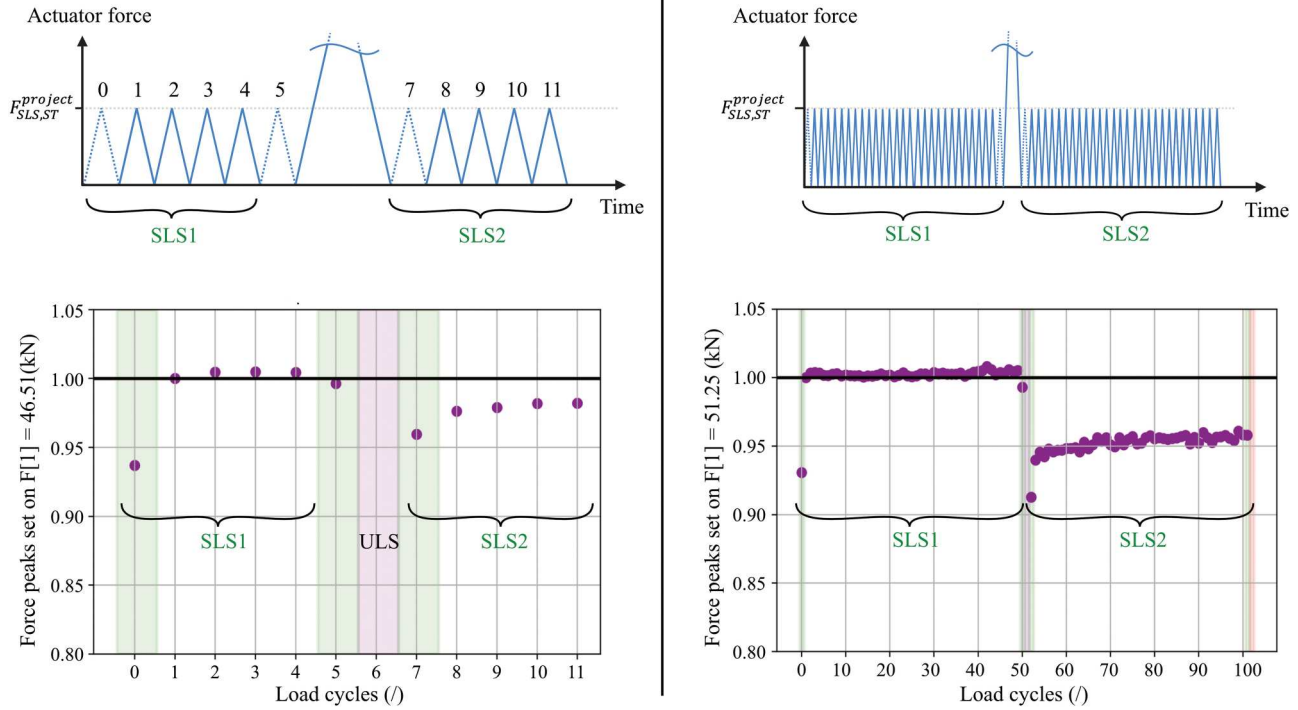


Figure 13. Evolution of actuator force peaks to achieve the required short-term deflection. Left: results for spruce log no. 7 in the undried state. Right: results for spruce log no. 4 in the undried state, tested with 50 cycles in each set.

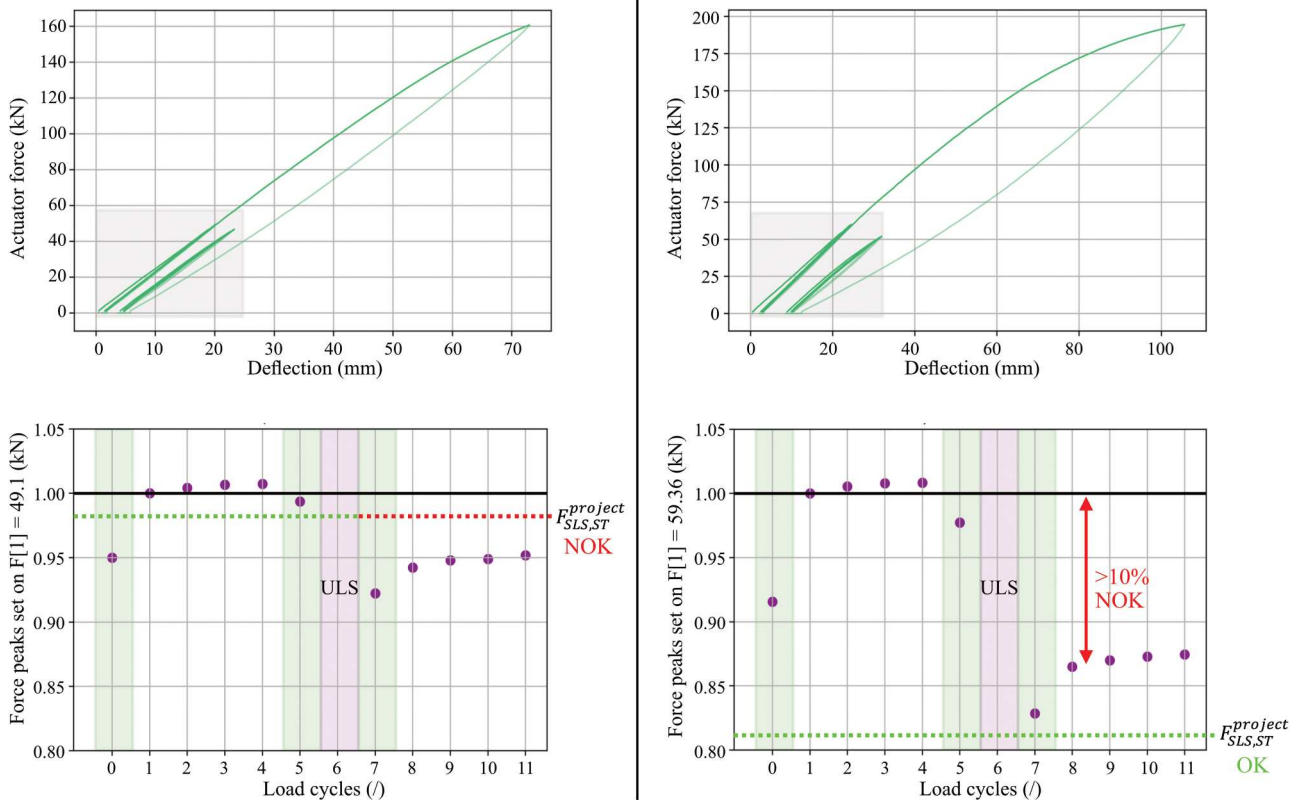


Figure 14. Illustrations of two cases of rejection involving a reduction in stiffness after ULS loading. These loading values ($F_{SLS,ST}^{project}$) are fictitious, as the load case to be satisfied is not linked to any existing project. Undried test phase, on the left, spruce log no. 6; on the right, spruce log no. 5.

damage (Figure 14, right). This damage should be confirmed by the high non-linearity of the SLS loading curve. A log could be downgraded if this loss exceeds 10%. The choice of this arbitrary 10% stiffness reduction as third rejection criterion strikes a balance between the current lack of normative guidance in the standards cited in 2.3, the precision of the proof loading in industrial conditions and structural safety. Until a larger experimental dataset is available to refine this approach, this conservative strategy remains a justified and responsible choice.

3.8. Checking the ULS fire criterion

As it is impossible to use the force-displacement curve directly to verify the fire resistance criterion applied to a log where part of the cross-section has been reduced by fire (Figure 15), it is necessary, as with the long-term deflection criterion, to go through a “mathematical” verification.

The flexural modulus of a circular section of diameter ϕ is $\pi\phi^3/32$. The flexural modulus of a circular section whose diameter is reduced due to fire by a value $2d_{ef}$ is equal to $W_{ULS} = \pi(\phi - 2d_{ef})^3/32$. This d_{ef} value is a project data, assumed to be known before the proof-loading (see section 3.3).

For the same bending moment, the maximum stress increases in a ratio $\xi = \phi^3/(\phi - 2d_{ef})^3$ as the cross-section is reduced by d_{ef} . During a test on a log, its diameter ϕ can be measured at mid span and the ratio ξ can be calculated from the project data (d_{ef}). The ratio between the load $\theta = q_{fi}/q_{ULS}$ depends on the characteristics of the project, and is therefore assumed to be known before proof-loading. Its value varies from one project to another, but is very often between 0.55 and 0.75.

For the ULS calculation, the “statistical-based” design criteria for bending is:

$M_{ULS}/W_{ULS} \leq k_1 f_{mk}$, with $k_1 = k_{mod}/\gamma_m$ if one considers the Eurocode 5, with $\gamma_m = 1.3$.

For the fire calculation, the “statistical-based” design criteria for bending is:

$\xi\theta M_{ULS}/W_{ULS} \leq k_2 f_{mk}$, with $k_2 = k_{fi} = 1.25$ if one considers the Eurocode 5.

Therefore, the fire criterion in bending is respected if $\xi\theta k_1 \leq k_2$.

The same reasoning should also apply for the shear criterion, though it is probably always irrelevant, and the compression perpendicular to the grain at the supports.

From the above equation, Table 3 gives the minimum diameters ϕ_{min} required for 60, 90, and 120 minutes fire resistance,

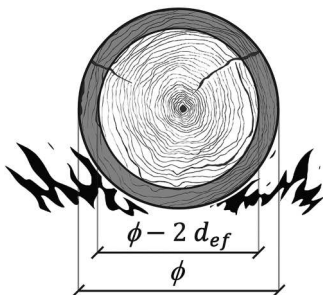


Figure 15. Cross-section reduction due to wood carbonisation.

Table 3. Minimum diameters for fire ratings R60, R90 and R120 for usual θ values.

ϕ_{min} (cm)	θ	Fire resistance		
		R60	R90	R120
	0.55	32	45	59
	0.65	35	50	66
	0.75	39	56	73

for $\beta_n = 0.8$ (mm/min), $k_{mod} = 0.8$ (/) and for, respectively, $\theta = 0.55$, $\theta = 0.65$, $\theta = 0.75$ (/).

3.9. Summary of the proof-loading protocol

Based on the above developments, the proof-loading protocol can be summarised as shown in Figure 16, in which one has already incorporated the considerations from section 5 to make the protocol more applicable to an industrial test machine (in particular, three cycles for each SLS set instead of five).

4. Results of the lab tests on logs

The scope of the lab tests is described in section 3.2. As explained in section 3.7, the laboratory protocol is outside the context of a real building project for which $q_{SLS,ST}$ and thus $F_{SLS,ST}^{project}$ is known. This is why it was decided that the deflection δ would systematically be pushed to L/350 for each SLS1 and SLS2 cycle:

- Taking a value that is too severe (e.g. L/500) would correspond to a very low deflection, a low actuator force for the slenderness under consideration, and therefore to a too light loading situation in which the detection of damage due to ULS loading is less easily detectable.
- Taking a value that is too lax (e.g. L/300) would correspond to a project that is not very demanding in terms of permissible deflections. What's more, this high deflection would correspond to a high actuator force, and therefore to a situation in which element failure could occur before the end of the ULS cycle, preventing a comparison between the two sets of loading-unloading cycles.

Similarly, $F_{ULS}^{project}$ is not known for the lab protocol and was taken equal to $3.25 F_{L/350}$ (The value of 3.25 is an upward estimation coming from

$$\mu\gamma_Q \cong (1.3/0.6)*1.5$$

if one considers the Eurocode specifications).

4.1. Experimental determination of a log's average modulus of elasticity

In order to study the influence of the number of cycles and the loading speed (sections 5.1 and 5.2), it is necessary to define the stiffness of a log, which can be expressed:

- Either directly from experimental data, using the ratio between the force in the actuator and the deflection at mid-span, expressed in kN/m (or kN/mm), which does not allow comparisons between the wood material of several logs of different lengths and diameters.
- Or from experimental and geometric data, by calculating an average modulus of elasticity E (MPa) based on the formula

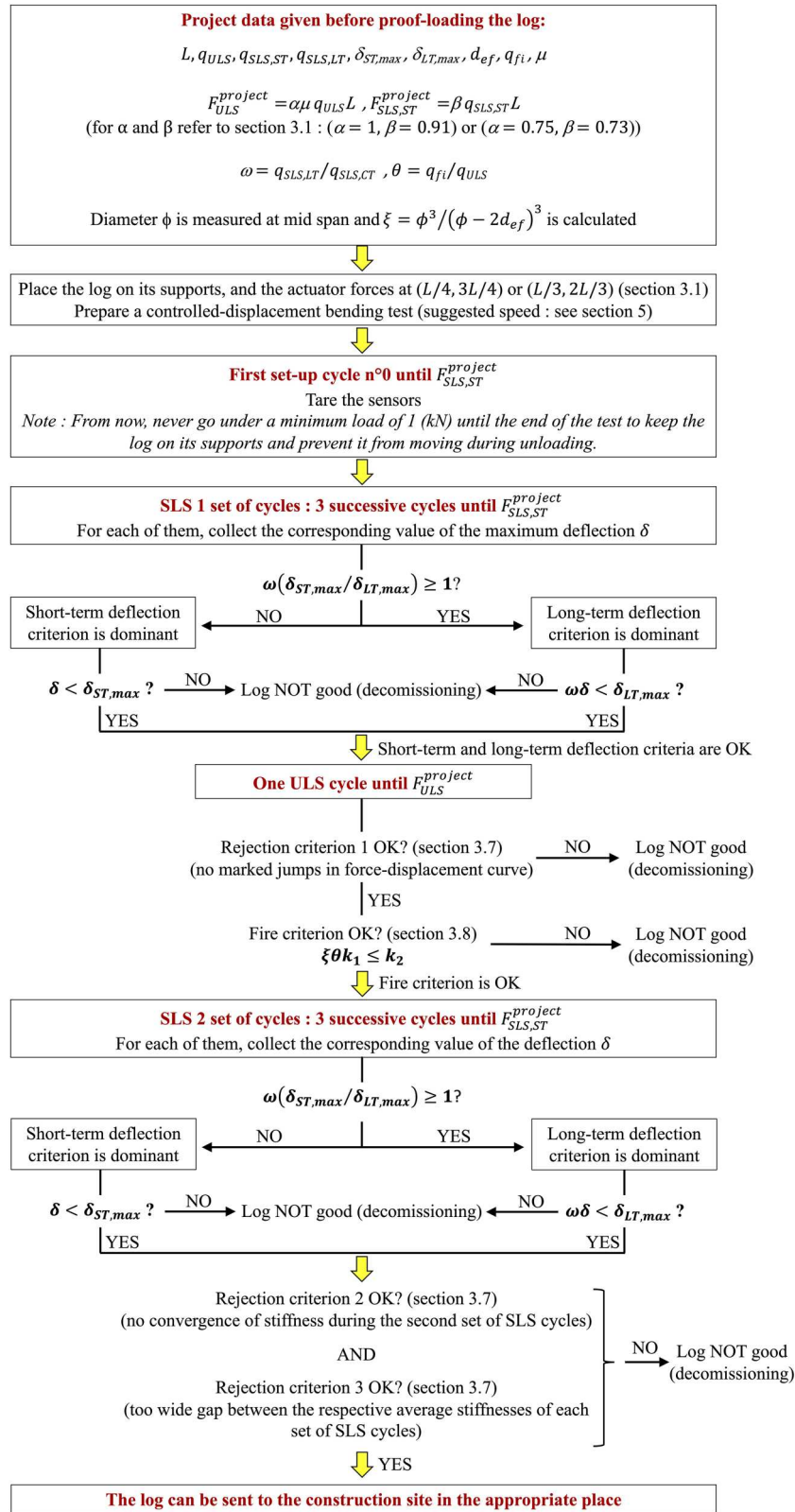


Figure 16. Summary of the definitive proof-loading protocol.

for the deflection δ of a beam with a cross-section considered to be circular and constant, created by a total actuator force F , and calculated from the average diameter ϕ measured at mid-span. Following EN408, for a 4-point test with a load $F/2$ applied at $L/3$ and $2L/3$, the modulus of elasticity is given by (with an error of less than 1% if the

hypothesis $G = 650$ (MPa) is taken):

$$E = \frac{0.723L^3}{\left(2\frac{\delta}{F}\phi^4 - \frac{0.472L\phi^2}{G}\right)}$$

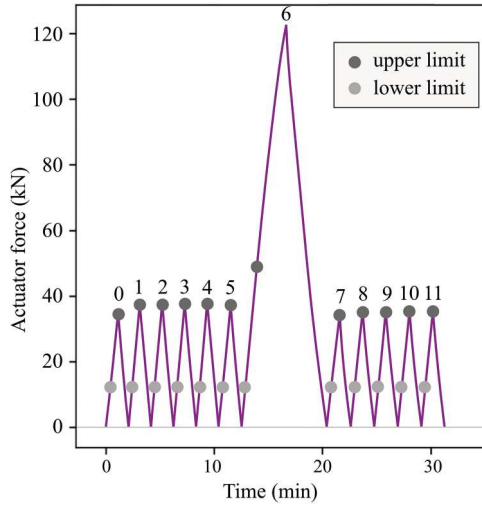


Figure 17. Upper and lower limits used to calculate Young's modulus of the logs.

The pairs of points (δ, F) considered for the above formula are derived from the test curve. During the ULS loading between the two sets of SLS cycles, failure is rarely reached and the $0.1 F_{ULS}$ and $0.4 F_{ULS}$ limits are considered for calculating E (see dots in Figure 17). For SLS cycles, which never reach $0.4 F_{ULS}$, the modulus of elasticity is calculated between $0.1 F_{ULS}$ and the maximum force reached during the corresponding SLS cycle. Table 4 and Table 5 show the moduli of elasticity calculated by this method for all the tests carried out.

4.2. Summary of laboratory tests on 30 logs

Table 4 and Table 5 concern respectively the undried and dried states of tests and provides:

- Log geometry: total length L_{tot} , distance L between supports, median diameter ϕ , slenderness $\lambda = L/\phi$, volumetric mass which is calculated by considering the volume of a perfect cylinder with the median diameter of the log. Assimilating the log to a cylinder rather than a truncated cone leads to a small error in the volume of 0.75% for a tree taper of 1 (cm/m).
- Moisture content measured by a resistive method using a spiked moisture metre where the two spikes are used as electrodes. The measurement is an average of three measurements taken respectively at mid-span ($L/2$) and at the two load application points ($L/3$ and $2L/3$).
- Relative and absolute deflection ($L/350$ in our case) imposed during SLS cycles.
- Loading speed. A single speed is used for the "undried state" (for both SLS and ULS loading), while 3 SLS speeds are used for the "dried state" (discussed in 5.2 and illustrated in Table 6). The ULS cycle is always performed at the lowest speed to enable comparisons with previous tests.
- The averages $F_{SLS1,mean}$ and $F_{SLS2,mean}$ of the actuator peaks obtained for SLS1 and SLS2 cycles set.
- F_{ULS} peak actuator force during ULS loading.
- F_{rupt} peak actuator force during the failure.

- The theoretical value of the maximum stress due to ULS loading:

$$\sigma_{ULS} = \frac{16 LF}{3 \pi D^3}$$

- The average Young's moduli $E_{SLS1,mean}$ and $E_{SLS2,mean}$ for the two sets of cycles SLS1 and SLS2 (see 4.1).
- The presence or absence of sharp jumps in the force-displacement curve (see section 3.7/rejection criterion no. 1).
- Average damage due to SLS loading (see 3.7/rejection criterion no. 3), with $\Delta F_{SLS,mean}$ and Young's modulus reduction $\Delta E_{SLS,mean}$ obtained as follows:

$$\Delta F_{SLS,mean} = \frac{F_{SLS1,mean} - F_{SLS2,mean}}{F_{SLS1,mean}}$$

$$\Delta E_{SLS,mean} = \frac{E_{SLS1,mean} - E_{SLS2,mean}}{E_{SLS1,mean}}$$

5. Lab Protocol vs industrial protocol

The laboratory protocol as shown in Figure 9 (right) and tested on the 30 logs takes an average of 120 minutes per log, with approximately:

- 60 minutes for set-up (instrumentation)
- 2 minutes for the setting-up cycle n° 0
- 2 minutes for each cycle n° 1-2-3-4-5 (10 minutes).
- 7 minutes for the ULS cycle n° 6.
- 2 minutes for each cycle n° 7-8-9-10-11 (10 minutes).
- 30 minutes for the unset-up

This "laboratory" version of the protocol would ideally be shortened to 10–15 minutes, instead of 120 minutes for the final industrial version, to reduce costs. Sections 5.1–5.3 deal respectively with the number of SLS1 and SLS2 cycles required, the loading/unloading speed, and the possibility of downgrading logs using the NDT method even before the protocol is carried out.

5.1. Reducing the number of cycles for SLS1 and SLS2

A study of the variation in force F over the cycles is carried out here, based on the following formulae where i and j are the number of the cycle under consideration, and cycles n°4 and n°11 are used as references as they are the last cycles performed in the SLS set to which they belong:

- Force variation during the set SLS1 : $F = \frac{F_{cycle 4} - F_{cycle i}}{F_{cycle 4}}$
- Force variation during the set SLS2 : $F = \frac{F_{cycle 11} - F_{cycle j}}{F_{cycle 11}}$

Figure 18 shows the values of ΔF for all 30 logs tested in the undried (UD) and dried (D) state.

Figure 18 shows that, whichever cycle number is considered, the variation in force measurement fluctuates between – 0.5% and 1.7%, which is of the order of magnitude of the measurement accuracy of industrial machines. There is no fundamental difference in modulus variation between SLS1 and SLS2,



Table 4. Summary of the bending tests on 30 logs, undried state.

UNDRIED test phase	Geometry			Volumic mass		Moisture	Test parameters			Actuator force			Stress	Young modulus		Rejection criteria				
	L _{tot} (cm)	L (cm)	φ (cm)	λ (°)	m (kg/m³)		w (%)	δ _{ST,max}		V (mm/s)	F _{SL1,mean} (kN)	F _{SL2,mean} (kN)		F _{ULS} (kN)	σ _{ULS} (MPa)	E _{SL1,mean} (MPa)	E _{SL2,mean} (MPa)	n°1	n°3	
								L/r	(mm)										ΔF _{SL2,mean} (%)	Damage ΔE _{SL2,mean} (%)
Poplar	P01	1,000	700	35.0	20	782	27.7	350	20.0	0.308	25.4	25.1	82.5	22.9	10,380	10,280	/	0.9%	1.0%	
	P02	800	700	35.0	20	740	29.2	350	20.0	0.308	24.6	24.3	80.1	22.2	10,120	9,910	/	1.3%	2.1%	
	P03	800	746	37.3	20	694	27.7	350	21.3	0.328	25.5	25.1	83.2	20.3	9,170	9,010	/	1.5%	1.7%	
	P04	800	700	35.0	20	774	29.7	350	20.0	0.308	26.2	25.7	85.3	23.6	10,790	10,500	/	1.9%	2.7%	
	P05	800	700	35.0	20	695	24.8	350	20.0	0.308	24.3	23.7	78.8	21.8	9,940	9,710	/	2.5%	2.3%	
	P06	800	700	35.0	20	751	21.1	350	20.0	0.308	24.6	24.2	79.8	22.1	10,070	9,840	/	1.6%	2.3%	
	P07	800	700	35.0	20	731	25.9	350	20.0	0.308	26.9	26.6	87.3	24.2	11,210	11,040	/	1.0%	1.5%	
	P08	800	700	35.0	20	713	27.4	350	20.0	0.308	26.1	25.7	84.9	23.5	10,760	10,590	/	1.4%	1.6%	
	P09	800	700	35.0	20	781	26.9	350	20.0	0.308	27.1	26.9	88.3	24.5	11,240	11,090	/	0.7%	1.3%	
	P10	800	700	35.0	20	743	27.1	350	20.0	0.308	24.9	24.7	80.9	22.4	10,210	10,080	/	0.8%	1.3%	
Tsuga	T01	851	700	35.0	20	547	28.1	350	20.0	0.308	15.8	15.6	51.4	14.2	6,240	6,120	/	1.0%	1.9%	
	T02	848	726	36.3	20	606	18.5	350	20.7	0.319	30.8	30.5	100.4	25.9	12,080	11,900	/	1.3%	1.5%	
	T03	848	750	37.5	20	545	21.6	350	21.4	0.330	22.1	22.0	71.7	17.3	7,810	7,800	/	0.4%	0.1%	
	T04	850	750	37.5	20	585	15.7	350	21.4	0.330	23.7	23.6	77.3	18.7	8,300	8,200	/	0.8%	1.2%	
	T05	847	750	37.5	20	673	21.2	350	21.4	0.330	23.2	23.0	75.4	18.2	8,260	8,240	/	0.6%	0.2%	
	T06	851	726	36.3	20	635	28.5	350	20.7	0.319	21.4	21.2	69.7	17.9	8,090	7,970	/	1.1%	1.5%	
	T07	851	726	36.3	20	675	22.2	350	20.7	0.319	24.6	24.2	80.0	20.6	9,400	9,240	yes	1.5%	1.7%	
	T08	850	750	37.5	20	625	17.5	350	21.4	0.330	22.6	22.5	73.6	17.8	8,020	7,980	/	0.5%	0.5%	
	T09	850	750	37.5	20	564	23.2	350	21.4	0.330	31.6	31.1	102.9	24.8	11,530	11,360	/	1.7%	1.5%	
	T10	851	750	37.5	20	685	24.2	350	21.4	0.330	24.3	24.1	79.0	19.1	8,550	8,490	/	0.7%	0.7%	
Spruce	E01	706	649	38.2	17	486	28.0	350	18.6	0.336	41.0	39.5	133.7	26.4	10,820	10,360	/	3.8%	4.3%	
	E02	701	649	38.2	17	619	24.9	350	18.6	0.336	45.5	43.8	148.2	29.3	12,160	11,600	/	3.6%	4.6%	
	E03	677	617	36.3	17	651	27.8	300	20.6	0.319	37.6	35.2	122.6	26.8	9,230	8,590	/	6.4%	6.9%	
	E04	801	709	41.7	17	592	24.0	350	20.3	0.367	51.4	48.8	167.8	27.8	11,080	10,830	/	5.0%	2.3%	
	E05	712	649	38.2	17	670	38.1	300	21.6	0.336	59.7	51.7	194.5	38.5	13,700	11,410	/	13.4%	16.7%	
	E06	747	649	38.2	17	672	26.0	350	18.6	0.336	49.3	46.5	160.8	31.8	13,040	12,220	/	5.7%	6.3%	
	E07	806	682	40.1	17	574	25.8	350	19.5	0.353	46.7	45.6	151.9	27.3	11,080	10,890	/	2.4%	1.7%	
	E08	788	709	41.7	17	638	26.7	350	20.3	0.367	54.2	51.3	176.3	29.3	11,940	11,170	/	5.3%	6.4%	
	E09	811	682	40.1	17	646	27.2	350	19.5	0.353	47.0	45.5	152.9	27.4	11,240	10,900	/	3.2%	3.0%	
	E10	664	617	36.3	17	605	28.9	300	20.6	0.319	48.0	42.1	156.2	34.2	12,160	10,300	/	12.3%	15.3%	

Table 5. Summary of the bending tests on 30 logs, dried state.

DRIED test phases	Volumic mass m (kg/m ³)	Moisture w (%)	Test parameters		Actuator force			Stress		Young modulus			Rejection criteria			Comparison Dried-Undried ΔF _{SL2,mean} (%)
			v (mm/s)	F _{SL1,mean} (kN)	F _{SL2,mean} (kN)	F _{ULS} (kN)	F _{rupt} (kN)	σ _{ULS} (MPa)	σ _{rupt} (MPa)	E _{SL1,mean} (MPa)	E _{SL2,mean} (MPa)	Marked curve jumps	n°3			
													ΔF _{SL2,mean} (%)	ΔE _{SL2,mean} (%)	Damage	
Poplar	P01	/	0.308	0.616	0.924	/	/	/	128.0	/	35.5	/	/	/	/	/
	P02	499	12.4	0.308	0.616	0.924	24.2	24.1	78.9	21.9	30.3	9.870	9.880	0.7%	-0.1%	-1.0%
	P03	474	11.7	0.328	0.656	0.985	24.9	24.6	81.0	19.8	33.8	9.020	8.820	1.1%	2.2%	-2.2%
	P04	526	13.2	0.308	0.616	0.924	25.8	25.2	84.1	23.4	36.7	10.740	10.450	2.0%	2.7%	-2.0%
	P05	/	/	0.308	0.616	0.924	/	/	/	/	/	/	/	/	/	/
	P06	517	12.5	0.308	0.616	0.924	23.3	23.3	75.9	96.1	26.6	9.510	9.460	0.1%	0.5%	-3.8%
	P07	500	13.0	0.308	0.616	0.924	26.4	26.2	85.8	151.1	23.8	10.950	10.790	0.6%	1.5%	-1.6%
	P08	472	13.3	0.308	0.616	0.924	25.4	25.4	82.7	111.8	22.9	10.420	10.450	-0.1%	-0.3%	-1.3%
	P09	539	12.6	0.308	0.616	0.924	26.1	26.0	85.0	148.5	23.6	10.960	10.820	0.3%	1.3%	-3.5%
	P10	504	12.3	0.308	0.616	0.924	23.9	23.7	78.1	133.1	21.6	9.780	9.610	0.8%	1.7%	-4.0%
Tsuga	T01	/	0.308	0.616	0.924	/	/	/	/	/	/	/	/	/	/	/
	T02	507	14.3	0.319	0.639	0.958	31.4	31.4	102.0	26.3	43.8	12.220	12.170	-0.2%	0.4%	3.1%
	T03	422	14.2	0.330	0.660	0.990	22.2	22.1	72.3	138.8	17.4	7.830	7.810	0.5%	0.3%	0.6%
	T04	469	13.5	0.330	0.660	0.990	23.8	23.5	77.5	125.1	18.7	8.490	8.350	1.2%	1.6%	-0.3%
	T05	419	15.3	0.330	0.660	0.990	23.0	22.9	75.1	123.4	18.1	8.240	8.210	0.4%	0.4%	-0.3%
	T06	437	13.9	0.319	0.639	0.958	21.2	21.0	68.9	119.2	17.8	7.980	7.890	0.9%	1.1%	-1.0%
	T07	488	14.2	0.319	0.639	0.958	24.2	22.8	78.8	116.1	20.3	9.160	8.530	6.0%	6.9%	-6.4%
	T08	471	15.0	0.330	0.660	0.990	23.0	23.0	75.2	122.0	18.2	8.140	8.120	0.0%	0.2%	2.3%
	T09	471	13.4	0.330	0.660	0.990	31.1	30.7	101.2	147.2	24.4	11.220	11.040	1.1%	1.6%	-1.1%
	T10	/	/	0.330	0.660	0.990	/	/	/	145.1	/	35.0	/	/	/	/
Spruce	E01	406	11.7	0.336	0.672	1.008	42.0	40.9	136.7	189.3	27.0	11.040	10.770	2.6%	2.4%	3.5%
	E02	546	11.1	0.336	0.672	1.008	46.9	46.0	152.8	209.5	30.2	12.340	12.100	1.9%	1.9%	4.7%
	E03	515	10.0	0.319	0.639	0.958	33.1	32.0	107.7	/	23.6	9.370	9.010	3.1%	3.8%	-9.9%
	E04	/	/	0.367	0.734	1.101	/	/	/	213.3	/	35.4	/	/	/	/
	E05	547	12.3	0.336	0.672	1.008	50.6	47.8	165.0	241.9	32.6	13.930	13.100	5.4%	6.0%	-8.1%
	E06	523	11.7	0.336	0.672	1.008	49.0	48.0	159.3	221.8	31.5	12.890	12.560	2.0%	2.6%	3.0%
	E07	/	/	0.353	0.706	1.059	/	/	/	/	/	/	/	/	/	/
	E08	521	11.9	0.367	0.734	1.101	55.5	54.3	180.5	245.6	30.0	12.190	11.920	2.1%	2.2%	5.5%
	E09	515	13.2	0.353	0.706	1.059	45.9	45.5	149.7	244.1	26.9	11.470	11.320	0.8%	1.3%	0.0%
	E10	485	11.9	0.319	0.639	0.958	42.9	40.8	139.9	198.0	30.6	12.560	11.730	5.0%	6.6%	-3.4%

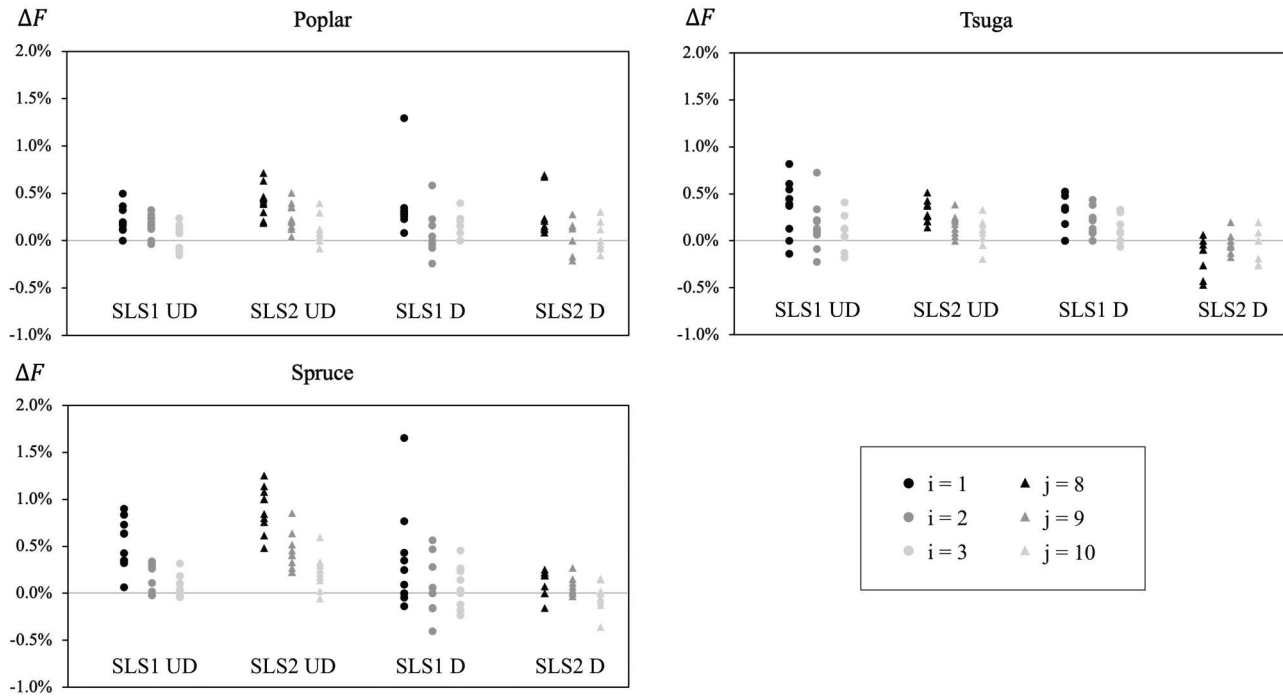


Figure 18. Influence of the number of cycles per SLS loading-unloading set (UD = undried state, D = dried state).

between the undried and dried state, or whatever the type of wood considered. It can therefore be concluded that each SLS1 and SLS2 set could contain only 2 or 3 cycles.

5.2. Increasing the loading/unloading speed

Various standards such as [NBN EN408, NBN EN14251] prescribe test speeds for round or squared timber. Based on these standards, but also on fracture tests carried out in parallel with this study involving spruce logs, the loading and unloading speeds considered for the 30 logs tested is based on the formula below:

$$v_0 = 88.10^{-5} \phi$$

This formula gives a speed of 0.35 mm/s for a diameter of 400 mm. The speeds applied for each log are given in Table 4.

It is relevant to determine the influence of loading speed on the results, which was conducted for the logs in the dried state (Table 5), according to a protocol incorporating 3 loading speeds for each of the SLS1 and SLS2 cycles (Figure 19), with:

- A first loading with 5 cycles at speed $v_0 = 88.10^{-5} \phi$.
- Idem with speed $2v_0$.
- Idem with speed $3v_0$.

Figure 20 shows the variation in mean modulus measured during loading cycles performed at speeds $2v_0$ and $3v_0$ compared with the mean modulus measured during cycles performed at speed $2v_0$, for both SLS1 and SLS2. The deviation never exceeds 1.1%. However, the ISO 15206 standard on basic requirements and test methods for wood poles stipulates

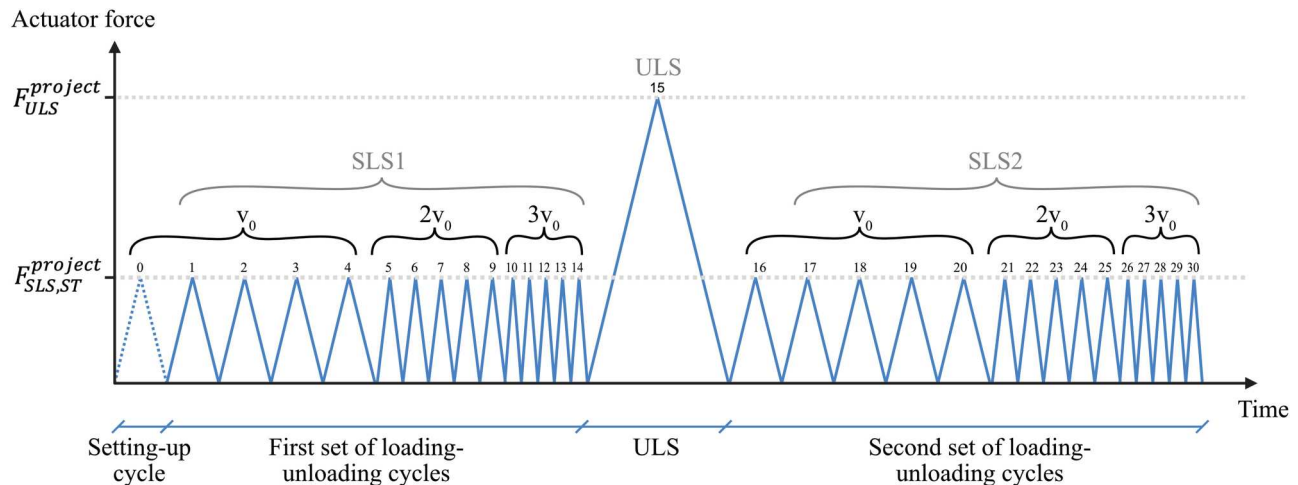
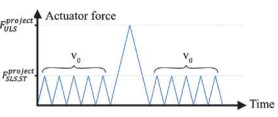
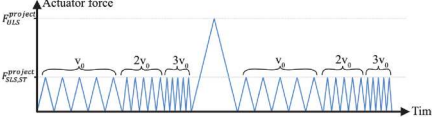
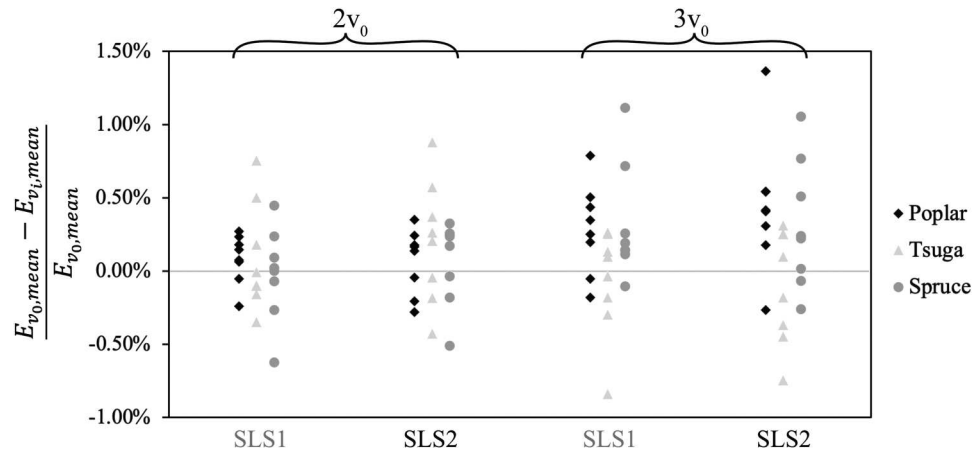


Figure 19. Lab protocol with different loading/unloading speeds

Table 6. Summary of loading protocols used for the different logs tested.

Test phases	Undried	Poplar	Single speed	
		Tsuga		
		Spruce		
	Dried	Poplar	Various speed	
		Tsuga		
		Spruce		

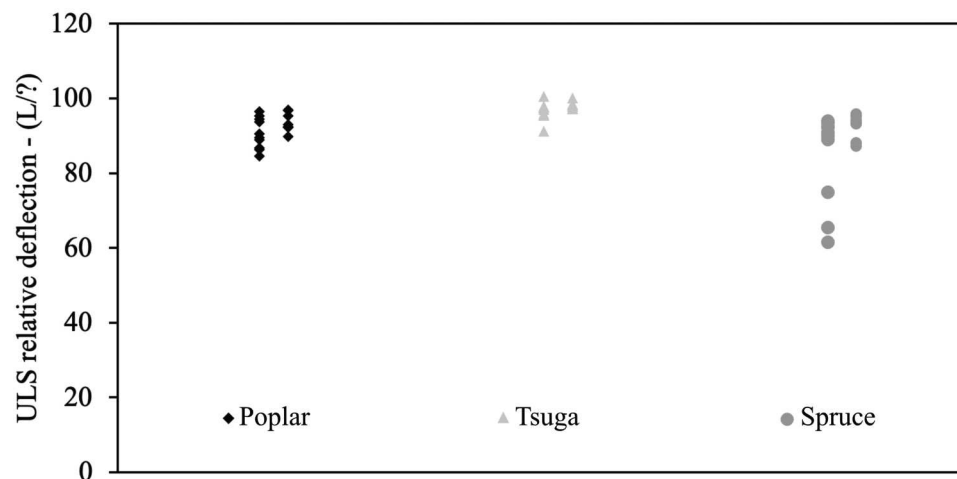
**Figure 20.** Variation in average Young's modulus measured with speeds $2v_0$ and $3v_0$ compared with that measured with speed v_0 for the dried batch test.

an accuracy of 1% for force and deflection measurements, as well as for the position of supports and load points. New Zealand standard NZS 3605, which deals with the proof-loading of round timber elements for use in construction, imposes an accuracy of 5% for force and 1% for the position of loads and supports. Furthermore, the NBN EN14251 standard for round timber also imposes an accuracy of 1% on deflection and force measurements during a bending test. It can be concluded that the loading and unloading speeds in an industrial process can be pushed to $3v_0$.

5.3. Criteria for downgrading logs using the NDT method before application of the protocol

Figure 21 shows the value of the deflection at mid-span of the 30 tested logs under ULS load (cycle 6 in Figure 17 or cycle 15 in Figure 19), expressed as a fraction of the span L (calculated with the classical formulas used for deflections). Figure 21 shows that the ULS deflection is always between $L/100$ and $L/60$.

The results of the same 30 tests are seen in Figure 22, indicating the reduction in ULS mean stiffness between SLS2 and SLS1 as a function of relative ULS deflection. The figure

**Figure 21.** Deflection at mid span of logs under ULS load, undried state on the left and dried state on the right, expressed as a fraction of the span L , for the 30 tests carried out.

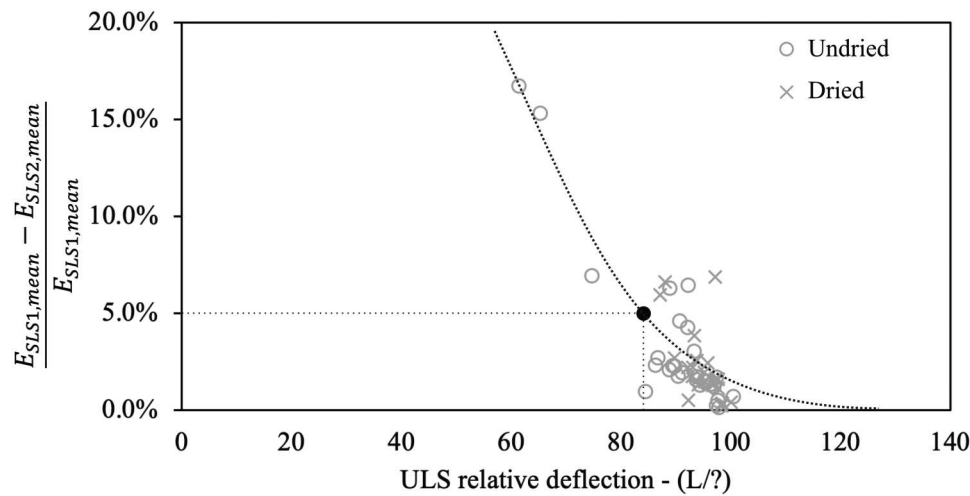


Figure 22. Reduction in stiffness between SLS2 and SLS1 as a function of the relative deflection under ULS load for all species combined.

shows that a reduction of more than 5%, indicative of probable damage due to the ULS loading, occurs for ULS deflections greater than $L/85$. In the case of this campaign, this is equivalent to downgrading 3 out of 30 logs.

This conclusion, valid also for dried logs, makes it possible to avoid testing logs unnecessarily, as follows:

- Determine an approximate modulus of elasticity of the log using NDT equipment (section 2.2) and before any transformations as debarking, canting, drying, machining and proof-loading.
- Calculate the theoretical deflection related to the ULS load.
- Check whether this deflection is greater than $L/85$, and if so, downgrade the log.

5.4. Conclusion : time saving

Finally, with the above comments in sections 5.1, 5.2 and 5.3, the duration of an industrial protocol becomes:

- 5 minutes for set-up (instrumentation is implemented permanently on the proof-loading bending machine)
- 1 min for the setting-up cycle n°0.
- 2 minutes for the first set of 3 cycles SLS1.
- 2 minutes for the ULS cycle.
- 2 minutes for the second set of 3 cycles SLS2.
- 3 minutes for the unset-up.

The final protocol as shown in Figure 9 (right) could take 15 minutes per log, with approximately 7 minutes for the test itself with a reduction of the number of cycles and the speed pushed to $3v_0$. In addition, 8 minutes are necessary to place the log on the bending bench, and to remove it after the test. The primary time constraint associated with the proof-loading process is that its total duration must remain shorter than the time required for machining the logs. Machining represents the most time-consuming individual transformation step in the production process, typically taking between 30 and 45 minutes depending on the complexity of the cuts and handling time. If this condition is met, proof loading can be completed before the machining of the subsequent log is finished, thereby ensuring that it does not delay the overall production workflow.

6. Discussion

6.1. About the protocol and the tests results

The laboratory protocol is based on a constant deformation even though the final protocol discussed will be based on a constant applied force. This is because a lab setting and construction site differ and therefore some data is unknown, such as the ULS and SLS loads or maximum allowed deflections. However, by loading up to an imposed deflection of $L/350$, more data could be collected and there is no fundamental difference between the two approaches. However, for both it is always recommended to use displacement-controlled loading, which is safer than force-controlled loading in the event of log failure. The lab tests enabled to develop the future industrial protocol with the forces were applied at $L/3$ as discussed in section 3.1, but future tests to carry out similar tests with forces applied at $L/4$ may have some interest.

The verification procedures prescribed by the standards cited in Section 2.3 (ISO15206 and NZS3605) are primarily focused on bending performance, but specifically for elements intended to function as piles or poles, rather than for beams used in buildings. Both standards define proof loading based on the verification of a characteristic strength value, typically established through prior destructive testing on representative samples. In contrast, our approach is oriented toward the individual assessment of each specimen, which likely explains why the standards require only a single loading/unloading cycle for verification. Both impose visual rejection criteria, such as prohibitive indentations, cracks, or excessive knots. NZS3605 also specifies a minimum density requirement. However, since our goal is to evaluate elements in their final machined configuration – including extensive modifications near support zones – some of these selection criteria become less relevant within the scope of our protocol. In addition, unlike the ISO standard, NZS 3605 specifies that the proof load must be reached within 3–30 s, followed by a 15-second hold before unloading. Our methodology involves multiple loading cycles, both to potentially detect damage evolution and to provide the level of safety which is required for a building or multi-storey building.

Both standards further state that no signs of weakness, distress, or permanent set should be observed during proof testing, though they do not define or quantify these signs explicitly. Regarding the three rejection criteria (RC) developed in 3.7. (i) RC1: the noticeable jump in the force-displacement curve for the tested Tsuga log T07 in the “undried state” was not observed again in the “dried state”. Even if the breakage of certain fibres is undeniable, this criterion could be reconsidered, as the log showed no particular signs of weakness during its second proof-loading (dried), (ii) RC2: both dried and undried test phases show a convergence of results. This criterion has therefore never been observed. Also, the number of cycles and loading speed do not appear to be constraining parameters, (iii) RC3: as this criterion is not linked to a real project, it is difficult to evaluate its application in the laboratory conditions. Nevertheless, the greatest reduction in stiffness has been recorded for the three spruce logs (E03, E05, E10) loaded at L/300 instead of L/350. Linking this loading approach to a deflection criterion therefore seems relevant and varies from NZS3605 proof-testing standard, which imposes characteristic stresses.

Regarding the loading response, the logs tend to have a slight drop in stiffness after undergoing the ULS loading. This observation is valid for the undried and dried proof-loading even if this reduction of stiffness is less marked in the dried state.

The results of the same logs between the undried and dried phases shows a small variation, depending on the species. The batch of poplar shows an average reduction in stiffness (−2.4%), while the batch of tsuga seems negligibly affected (−0.4%), though the spruce shows an opposite trend with an increase (+3.3%). According to the literature, a gain in mechanical properties after the drying process was expected (U.S. Department of Agriculture, Forest Service, Forest Products Laboratory 1999). This seems to apply to squared sections, where the cross-section will tend to deform rather than split. The reduction in inertia due to the reduction in overall diameter and the appearance of cracks is therefore not offset by the gain in mechanical properties. Since logs are not systematically stiffer after drying, this makes it all the more worthwhile to test elements in their final configuration when dried and machined.

Finally, the results obtained could be compared with the values of the EN338 standard establishing strength classes for general use for timber in design codes as informative

approximation. The tested logs clearly fall outside the scope of this standard due to several factors, including their irregular geometry, non-standard cross-section, non-uniform moisture content, and the use of proof testing but there is currently no equivalent standard applicable to round timber that would allow a direct classification based on the same parameters. Figure 23 (left) shows the stresses reached during ULS loading (black) and the failure stress (grey). Along ULS proof loading, poplar would be predominantly classified in grade C18, C16 for tsuga and C24 for spruce. It is important to note that the failure stresses are much higher than the proof loading stresses. Nevertheless, the young's moduli measured during the tests, confirm the previous allocation of species batches to strength classes: poplar in C18, tsuga in C16 and spruce in C24. In this study, the focus is deliberately placed on bending strength and modulus of elasticity (MOE) rather than on density, due to the non-uniform distribution of moisture throughout the log. The pre-drying process did not fully dry the logs to their core, resulting in an artificially high apparent density, which would not accurately reflect the mechanical performance under standard conditions.

6.2. Log preparation before proof loading

A log floor contains primary beams that support smaller diameter secondary beams with two possible extremes, knowing that all intermediate situations between these two extremes are possible:

- Secondary beams are arranged on top of the primary beams (Figure 24A).
- Secondary beams are arranged in such a way that all the top fibres are aligned in the same plane (Figure 24B).

In modern industrialised construction, it is unthinkable for the upper floor level to vary according to the different geometries of the beams, as this makes floor finishing very difficult. The logs must therefore be canted (where a beam is sawn lengthwise, or parallel to the grain) in such a way as to achieve a straight, horizontal upper plane, as illustrated in Figure 24C,D.

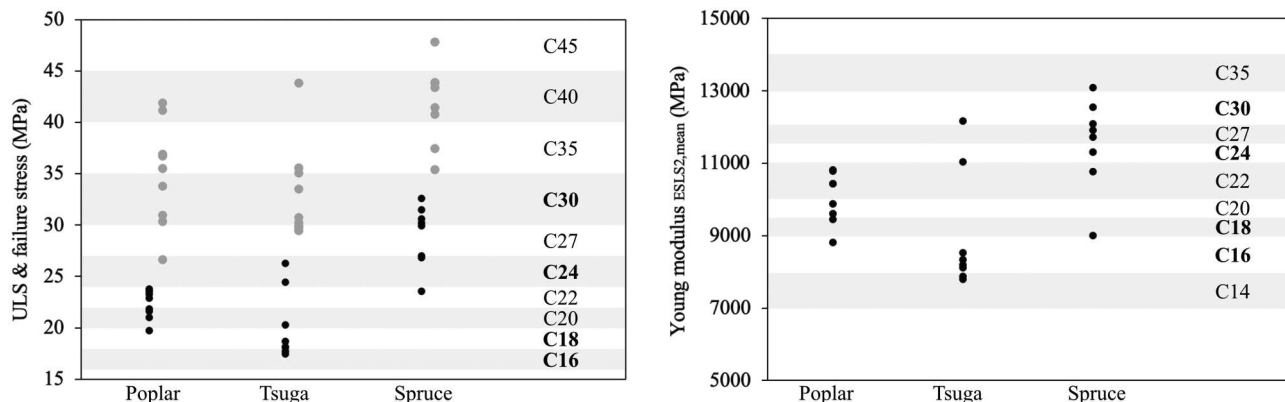


Figure 23. Bending results during the dried test phase shown with EN338 grades, on the left the ULS (black) and failure stresses (grey), on the right the Young modulus.

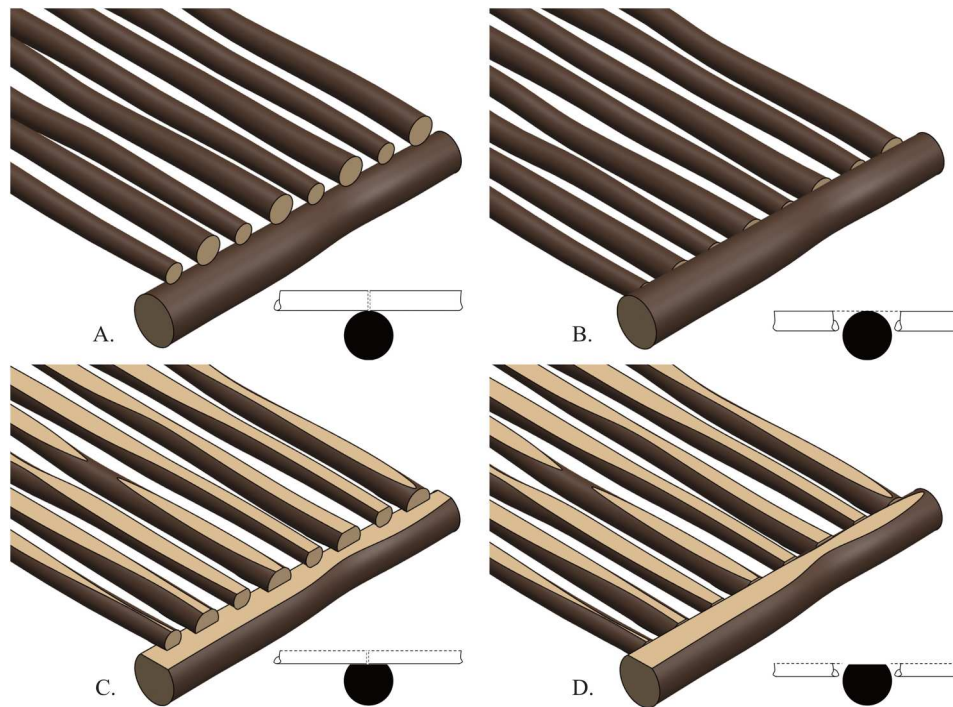


Figure 24. A and B show scenarios where beams are not canted at the top, which makes it very difficult to complete the floor finishing. Examples C and D show examples of beams that are canted at the top.

This canting has two further advantages: it provides a reference plane for milling the assemblies, and it promotes faster drying. Finally, an efficient way of preparing logs for proof loading consists of the 8 steps illustrated in Figure 25. Step 1 is detailed in section 5.3 and concerns the first NDT tests (section 2.2). The proof loading can only be carried out effectively on logs that have been completely machined in accordance with the construction project: if machining is carried out after mechanical characterisation, there is a risk of weakening the log without this being detected or quantified. Step 6 involves the machining of logs using, for example, a robotic arm according to the design office's drawings: cut-outs for column-column, beam-column and beam-floor connections. Logs that pass proof loading (step 8) can then be delivered to the site, while the others have to be discarded, and processed into other products despite having been dried and machined.

At the start of a project, the sawmill must order the number of logs required, based on a pre-dimensioning by the design office and a bill of lading with the mechanical and geometric characteristics required of each log. Depending on timber harvesting habits in a given country, the sawmill can also anticipate and build up its log stock. An increase in the order is necessary (probably of the order of 10-15%) in order to anticipate the fact that a certain number of logs will be downgraded by proof-loading. Excluded elements are cut or kept in stock for future projects or non-structural uses.

In order to reduce the risk of logs being downgraded during proof-loading and to avoid unnecessary preparation, it is advisable to plan three preliminary steps before step 1 shown in Figure 25:

- Designers can determine with a certain degree of certainty the minimum cross-section required for each log according

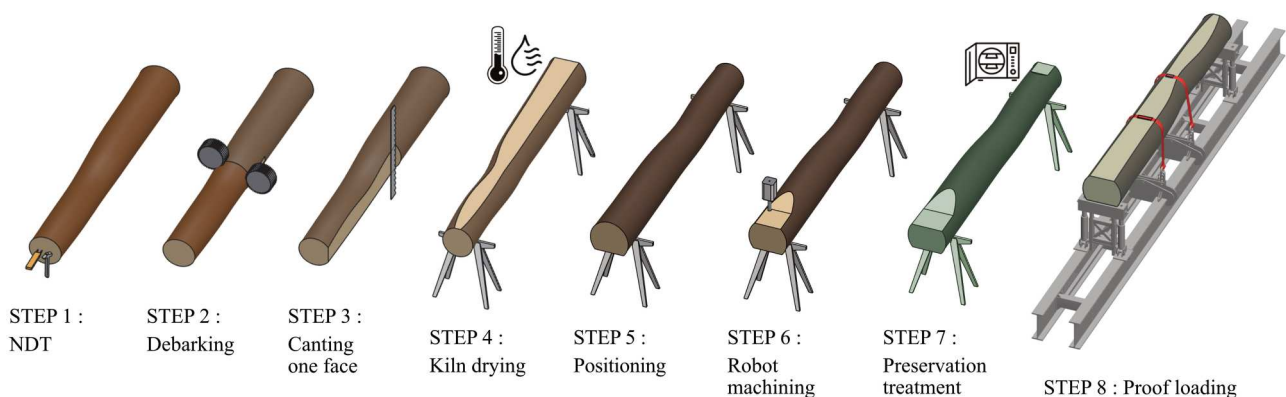


Figure 25. Preparing logs before the proof loading.

to its position in the structure, produces draft plans, and draw up an approximate list of the logs required for the project. This work can be facilitated by the existence of charts produced by the sawmill, based on its experience in proof-loading.

- The sawmill orders the logs from the forester on the basis of the design office's list, increasing their number by a certain percentage to compensate for the logs that will be excluded by proof-loading. A visual pre-classification of logs in the forest must be imposed on the forester, according to standards and specifications to be communicated to him (see 2.1).

7. Conclusion

This article proposes a protocol for the mechanical characterisation of logs in bending, which can be applied to an industrial machine in a sawmill or even directly on construction sites. The protocol enables verification of whether a log complies with the rare ULS and accidental ULS criteria (fire) in bending, as well as the short-term and long-term SLS deformation criteria. It is supported by experimental tests on 30 large logs of 3 different species, tested both in the green state and after being placed in a kiln. The lab tests provided a foundation from which to verify the relevance of the proposed rejection criteria and to refine the proposed protocol so that it can be applied in industry. The analysis of the lab test results has also enabled the determination of how NDT-type preliminary tests can be applied to logs prior to proof-loading in order to speed up the industrial process by avoiding its application to low quality logs. The protocol does not consider shear strength, but this criterion is never dominant for bending beams in normal use, unless the logs are heavily cut at ends. In this particular case, it will be necessary to carry out a check using the usual "standard" ULS shear criterion, deducting an estimated timber strength class from the ULS cycle of the proof-loading and the diameter of the log (Figure 24). The same reasoning can be applied to the verification of the compression criterion perpendicular to the fibres at the supports. The authors focused on the strength of logs used as beams. The protocol developed must be adapted for logs used as columns or as elements subjected to both bending and compression, which is outside the scope of this article and requires further experimental testing with larger-capacity cylinders.

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