ALMA MATER STUDIORUM – UNIVERSITA' DI BOLOGNA

DEPARTMENT OF

CIVIL, CHEMICAL, ENVIRONMENTAL, AND MATERIALS ENGINEERING - DICAM

Medium-Span Timber Footbridges – A Comparative Analysis with Traditional Steel and Concrete Structures (Technical, Environmental, and Structural Aspects)

Case Study within the "Seine – Escaut Est" Project: Structural Adaptations for the 2000-Ton Navigation Standard on the Nimy-Blaton-Péronnes Canal

ANNEX 2: MECHANICAL PROPERTIES OF TIMBER

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1 MECHANICAL PROPERTIES OF TIMBER

Timber is a material whose mechanical properties are influenced by various factors. Primarily, its inherent anisotropy, derived from the natural composition of the material, plays a significant role. Additionally, the direction of load application relative to the fiber orientation, as well as the presence of defects or variability within the cross-section, further affect its structural performance.

The primary mechanical properties of timber include elasticity, strength, creep, and the influence of moisture content on mechanical behavior.

1.1 ELASTIC PROPERTIES

Timber exhibits an elastic modulus that is directly dependent on fiber orientation. Generally, the longitudinal modulus of elasticity (E_L) is significantly higher compared to the radial modulus (E_R) and the tangential modulus (E_T). This anisotropic behavior is evident in typical values for Norway Spruce (softwood):

- E_L: 12,000 N/mm²
- E_T: 420 N/mm²
- E_R: 818 N/mm²

Further consideration can be given to Poisson's ratio (ν). Timber displays different Poisson's ratio values depending on the load application direction, with ν_{LR}, ν_{LT}, and ν_{RT} ranging between 0.369 and 0.618.[1]

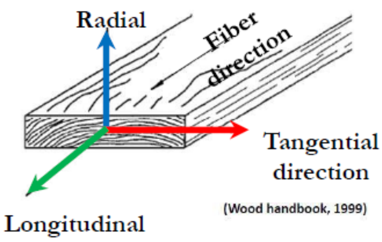

Figure 1: Representation of the Anisotropy of the Timber Material - (Wood Handbook, 2006)

	Hardwood	Softwood		Hardwood	Softwood
	Oak (white)	Norway Spruce		Oak (white)	Norway Spruce
EL	13530	12000	υ_{LR}	0.369	0.41
ET	974	420	υ_{LT}	0.428	0.55
ER	2205	818	υ_{RT}	0.618	0.6
GLR	1058	623	υ_{TR}	0.3	0.31
GLT	No data	42	υ_{RL}	0.074	0.056
GRT	No data	743	υ_{TL}	0.036	0.035

Figure 2: Indicative Values of the Elastic Properties for Different Types of Timber[2] - (Wood Handbook, 2006)

[1] (Swedish Wood, "Design of timber structures", 2022) p. 21-23
[2] Indicative values for w = 12%, determined by bending tests.

1.2 STRENGTH PROPERTIES

The strength of timber depends on the orientation of the stress relative to the fiber direction, as well as significantly on the type of stress applied (tension, compression, shear) *(Figure 3)*:

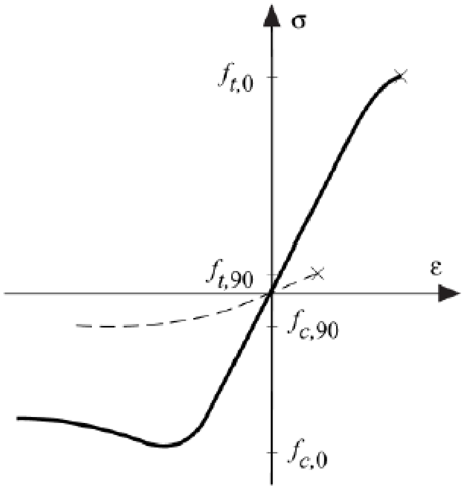

Figure 3: Stress and Strain Diagram, Longitudinal and Orthogonal Direction Comparison - (STEP 95 - Timber Engineering STEP , 1995)

- Tensile Strength: Timber performs well in tension parallel to the grain ($f_{t,0} \approx$ 2-3 $f_{c,0}$), but poorly in tension perpendicular to the grain ($f_{t,90} \approx 0.05\ f_{t,0}$)[3].
- Compressive Strength: Compressive strength parallel to the grain ($f_{c,0}$) is higher than perpendicular to the grain ($f_{c,90}$). Localized compression leads to apparent increases in $f_{c,90}$ due to fiber densification[4].
- Bending Strength: Timber exhibits rolling shear (perpendicular to the grain, f_r) and longitudinal shear (parallel to the grain, f_v). Longitudinal shear occurs parallel to the grain, and shear strength f_v is approximately 10% of compressive strength along the grains ($f_v \approx 0.1\ f_{c,0}$). Rolling shear is significantly lower than longitudinal shear, about half of the longitudinal shear strength ($f_r \approx 0.5\ f_v$)[5] *(Figure 4)*.

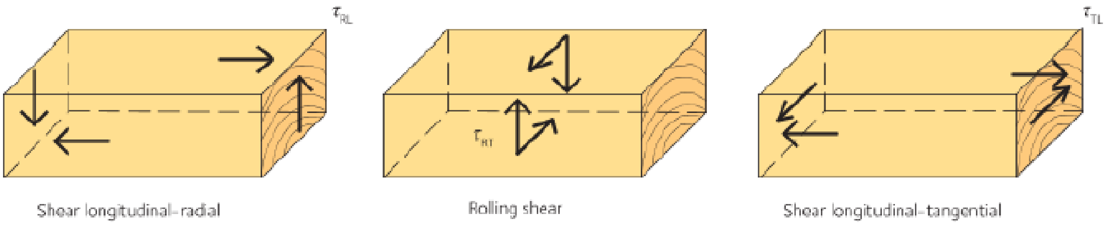

Figure 4: Longitudinal-Radial, Rolling, Longitudinal-Tangential Shear - (Swedish Wood, "Design of timber structures", 2022)

1.3 CREEP AND TIME DEPENDENT DEFORMATION

Creep refers to the time-dependent deformation of wood under sustained load. It is more pronounced in compression and bending than in tension and can lead to significant deformation over time.

[3] (Blass, H. & Sandhaas, C., 2017)
[4] (STEP 95 - Timber Engineering STEP , 1995)
[5] (Swedish Wood, "Design of timber structures", 2022)

The creep is influenced by the following factors:

- Stress level: Higher stress increases the creep *(Figure 5)*.

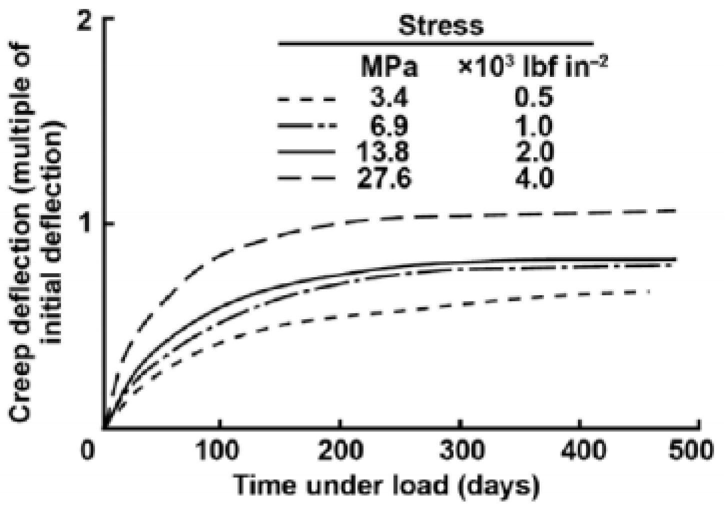

Figure 5: Influence of Different Stress Levels to the Creep Deflection - (Wood Handbook, 2006)

- Moisture content variation: Creep increases with higher moisture content and fluctuating humidity (mechano-sorptive effect)[6] *(Figure 6)*.

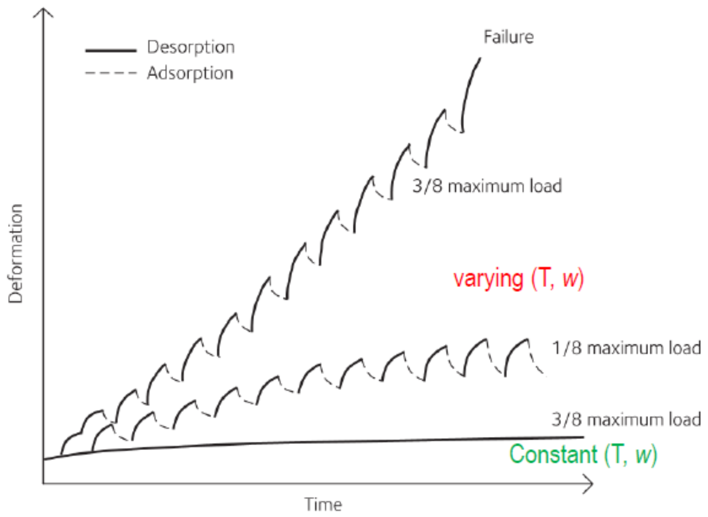

Figure 6: Mechano-Sorptive Effect[7] - (Swedish Wood, "Design of timber structures", 2022) - (Hearmon and Paton, 1964)

Cyclic moisture content has an impactive effect on the creep. Moreover, moisture content infects strengths properties *(Figure 7, Figure 8)*.

[6] (Swedish Wood, "Design of timber structures", 2022)
[7] Reference of maximum load on short-term in constant climate.

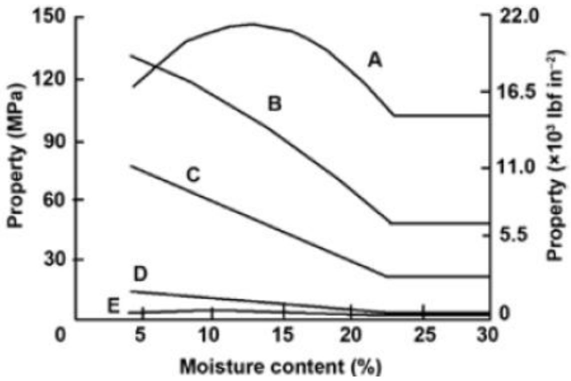

Figure 7: Effect of Moisture Content on Wood Strength Properties[8] - (Wood Handbook, 2006)

Property	Change
Compressive strength parallel to the grain	6%
Compressive strength perpendicular to the grain	5%
Bending strength	4%
Tensile strength parallel to the grain	2.5%
Tensile strength perpendicular to the grain	2%
Shear	2.5%
Modulus of elasticity (MOE) parallel to the grain	1.5%

Figure 8: Change in the Properties of Clear Wood with a One Percent Change in Wood Moisture (w=12%) - (Blass, H. & Sandhaas, C., 2017)

- Temperature: Creep deformation is accelerated by higher temperatures.
- Material stiffness: Lower elastic modulus E correlates with higher creep.
- The presence of knots and adhesives in engineered wood products affects creep performance.

It is therefore important to understand that while the load remains constant over time, the shape changes due to creep deformation. Additionally, creeping results in an instantaneous deformation upon load application, followed by a progressive increase over time (*Figure 9*).

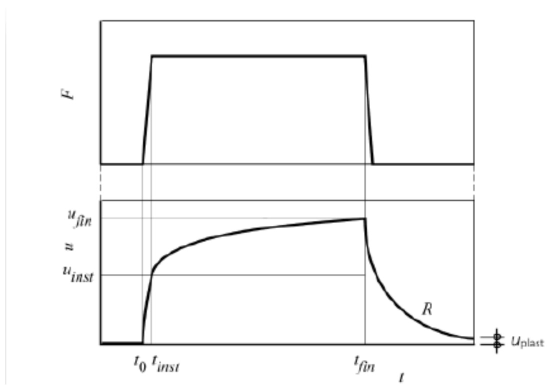

Figure 9: Relationship between Applied Load Over Time and Deformation Over Time - (STEP 95 - Timber Engineering STEP , 1995)

[8] A) Tension parallel to grain; B) Bending; C) Compression parallel to grain; D) Compression perpendicular to grain; E) Tension perpendicular to grain.

1.4 DEFECTS AND VARIABILITY

Defects such as knots, resin pockets and cracks significantly reduce both strength and stiffness: Knots disrupt grain direction, leading to localized stresses concentration; variability within and between species also affects mechanical properties.

To mitigate the impact of these factors, the implementation of the grading process and the reprocessing (creation of engineered wood products) is useful.

The grading is implemented using two primary methods:

- Visual grading: Assesses specific visible characteristics of timber, such as the presence of nature knots, the orientation of grains, the width of natural rings and the occurrence of cracks. These features directly influence the mechanical and physical properties of wood, and grading ensures that timber with a specific visible defect is either appropriately classified or excluded based on its intended structural application.
- Mechanical grading: This method employees non-destructive machine testing, particularly focusing on the modulus of elasticity (MOE) determined via static bending tests. These mechanical assessments are critical for accurately estimating the performance of timber in structural context.

The grading process is essential for addressing the inherent heterogeneity of wood, variations within and between species, and the impacts of defects, including knots, cracks, resin pockets and more. By identifying and categorizing timber based on these properties, grading ensures efficient use of material and the reliability of wood in structural applications. It also forms the foundation of defining timber strength classes, such as those detailed in standards like NBN EN 338 (2016), ensuring compatibility with structural engineering requirements and norms *(Figure 10)*.

	Class	C14	**C16**	**C18**	C20	C22	**C24**	C27	**C30**	C35	C40	C45	C50
Strength properties in N/mm²													
Bending	$f_{m,k}$	14	**16**	**18**	20	22	**24**	27	**30**	35	40	45	50
Tension parallel	$f_{t,0,k}$	7,2	**8,5**	**10**	11,5	13	**14,5**	16,5	**19**	22,5	26	30	33,5
Tension perpendicular	$f_{t,90,k}$	0,4	**0,4**	**0,4**	0,4	0,4	**0,4**	0,4	**0,4**	0,4	0,4	0,4	0,4
Compression parallel	$f_{c,0,k}$	16	**17**	**18**	19	20	**21**	22	**24**	25	27	29	30
Compression perpendicular	$f_{c,90,k}$	2,0	**2,2**	**2,2**	2,3	2,4	**2,5**	2,5	**2,7**	2,7	2,8	2,9	3,0
Shear	$f_{v,k}$	3,0	**3,2**	**3,4**	3,6	3,8	**4,0**	4,0	**4,0**	4,0	4,0	4,0	4,0
Stiffness properties in kN/mm²													
Mean modulus of elasticity parallel bending	$E_{m,0,mean}$	7,0	**8,0**	**9,0**	9,5	10,0	**11,0**	11,5	**12,0**	13,0	14,0	15,0	16,0
5 percentile modulus of elasticity parallel bending	$E_{m,0,k}$	4,7	**5,4**	**6,0**	6,4	6,7	**7,4**	7,7	**8,0**	8,7	9,4	10,1	10,7
Mean modulus of elasticity perpendicular	$E_{m,90,mean}$	0,23	**0,27**	**0,30**	0,32	0,33	**0,37**	0,38	**0,40**	0,43	0,47	0,50	0,53
Mean shear modulus	G_{mean}	0,44	**0,50**	**0,56**	0,59	0,63	**0,69**	0,72	**0,75**	0,81	0,88	0,94	1,00
Density in kg/m³													
5 percentile density	ρ_k	290	**310**	**320**	330	340	**350**	360	**380**	390	400	410	430
Mean density	ρ_{mean}	350	**370**	**380**	400	410	**420**	430	**460**	470	480	490	520

NOTE 1 Values given above for tension strength, compression strength, shear strength, char. modulus of elasticity in bending, mean modulus of elasticity perpendicular to grain and mean shear modulus have been calculated using the equations given in EN 384.

NOTE 2 The tension strength values are conservatively estimated since grading is done for bending strength.

NOTE 3 The tabulated properties are compatible with timber at moisture content consistent with a temperature of 20 °C and a relative humidity of 65 %, which corresponds to a moisture content of 12 % for most species.

NOTE 4 Characteristic values for shear strength are given for timber without fissures, according to EN 408.

NOTE 5 These classes may also be used for hardwoods with similar strength and density profiles such as e.g. poplar or chestnut.

NOTE 6 The edgewise bending strength may also be used in the case of flatwise bending.

Figure 10: Strength Classes for Softwood Based on Edgewise Bending Tests - Strength, Stiffness and Density Values - (NBN EN 338: Structural timber - Strength classes, April, 2016)

2 PHYSICAL PROPERTIES

The physical properties of timber play a crucial role in determining its structural applications and assessing durability. The key physical properties to be analyzed include density, hygroscopic behavior, and thermal properties, along with other additional physical characteristics that may be considered non-essential for the specific case study.

2.1 DENSITY

Timber exhibits a wide range of densities (with values varying from 160 to 1040 kg/m^3) depending on the species, with typical values for softwoods of 400-550 kg/m^3, and for hardwood of 600-700 kg/m^3.

The density values can be generally compared to the other materials ones, like steel (7850 kg/m^3) and concrete (2500 kg/m^3): It is easy to understand how the density values of the timber are significantly lower compared to the ones of the other materials, bringing to the conclusion that the timber is a lighter material.[9]

2.2 HYGROSCOPIC BEHAVIOUR

Timber absorbs and releases moisture based on the environmental conditions.

The equilibrium moisture content is around w=12% at standard conditions (20°C and 65% of relative humidity). This behavior contributes to dimensional changes (shrinkage and swelling only for w<25% or 30%) and it is not observed in the same way in materials like concrete and/or steel.

When the moisture content exceeds the FSP (Fiber Saturation Point), typically 30-200%, timber properties change significantly[10].

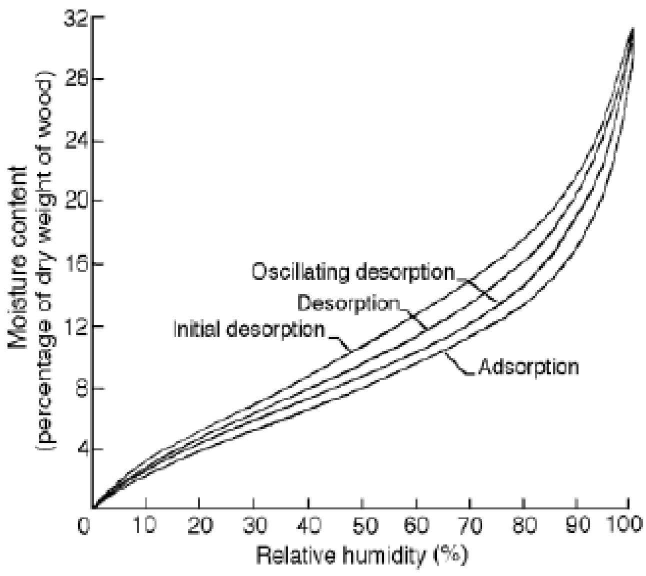

Figure 11: Moisture Content - Relative Humidity Relationship for Wood Under Absorption and Various Desorption Conditions - (Simpson, w. & TenWolde, A., 2010)

[9] (NBN ISO 13061-2:2023. Physical and mechanical properties of wood - Test methods for small clear wood specimens - Part 2: Determination of density for physical and mechanical tests, October, 2014)
[10] (Simpson, w. & TenWolde, A., 2010)

2.3 THERMAL PROPERTIES

Timber presents low thermal conductivity, making it an excellent insulator, reducing costs for temperature regulations:

- Thermal Conductivity (w=12%): 0.10-0.14 W/mk.
- Heat Capacity: Varies from 1.2 kJ/kgK (w=0%) to 1.7 kJ/kgK (w=20%).
- Thermal Expansion Coefficient (oven dry): In the case of parallel to the grain α_L = 3.1E-6 to 4.5E-6 K^{-1}; in the case of radial and tangential directions, 5-10 times α_L[11].

2.4 FIRE RESISTENCE

Timber chars at a consistent rate when exposed to fire (starting at 300°C). It is a material classified at Euro-class D for fire reaction, meaning it ignites relatively easily.

The timber behavior when exposed to fire is predictable, and the charring formation creates a protective layer that slows combustion:

- Charring rate: 0.6-0.8 mm/min for softwoods, 0.4-0.7 mm/min for hardwoods.
- Charring Depth Calculation: Based on exposure duration and material properties.[12]

3 STRUCTURAL APPLICATIONS OF TIMBER

The selection of timber products is a critical aspect of structural design, as different processing methods influence mechanical performance, dimensional stability, and application feasibility.

Structural timber is available in various technological solutions, providing specific responses to requirements for load resistance and durability. These solutions are closely related to the aspects discussed in the previous subsections, as they depend on the material's properties and anisotropy, which are modified according to the type of engineered timber used. This process leads to the development of high-performance structural materials.

The following section presents a detailed description of the different types of structural timber materials under analysis. For each typology, a brief yet comprehensive overview of its properties and characteristics is provided, along with practical examples.

3.1 SOLID WOOD PRODUCTS

It represents the simplest form of timber product, directly derived from trees with minimal processing. In its definition we can find the following categories:

- Roundwood: It features continuous annual rings, has minimal mechanical processing and is naturally shaped to resist compression (no weak axis). As a material advantage, it presents minimal surface area exposed to environmental conditions, reducing susceptibility to degradation. On the other hand, it has a limitation in the difficulties in creating joints and being prone to shrinkage cracks (which can be mitigated by adding grooves - *Figure 12*).

[11] (Swedish Wood, "Design of timber structures", 2022)
[12] (Swedish Wood, "Design of timber structures", 2022)

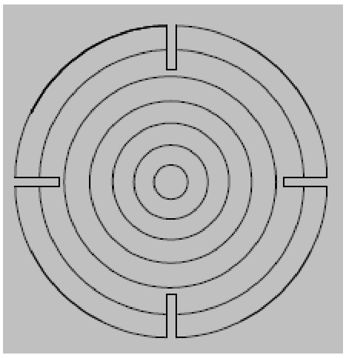

Figure 12: Roundwood with Grooves to Reduce Shrinkage Cracks (Continuous Annual Rings) - (José Gouveia Henriques, 2024)

- Sawn Timber: Economical material due to the low level of processing required, exhibits high variability in mechanical properties and great susceptibility to dimensional changes. It presents some dimensional limitations for structural applications, in lengths (maximum of 6-8 meters) and in cross-section (maximum 100x300 mm).
- Structural Finger Joined Timber (FST): Solid wood produced by joining shorter pieces of timber using adhesives to create longer elements (13 meters - *Figure 13*). It also presents an improved dimensional stability by drying wood to 15% ± 3% moisture content before joining.

Figure 13: Example of FST Connection - (José Gouveia Henriques, 2024)

The mechanical properties of this family of solid wood products are directly described and governed by standards like NBN EN 338[13], which defines strength classes, divided in tables in function of the type of material and classifying it as C = softwood, and D = hardwood.

3.2 ENGINEERED TIMBER PRODUCTS

To overcome the limitations of solid wood, various engineered timber products have been developed:

- Glued Laminated Timber (GLT): Timber element composed of several layers of lamellae glued together, creating a very versatile engineered wood product. The lamellae present a thickness that can vary between 15 to 50 mm, and a length between 1.5 to 5 meters. A GLT cross-section can go up to 2 meters in height and the total length of the element can reach up to 40 meters (with limitations in transportation logistics)[14] (*Figure 14*).

[13] (NBN EN 338: Structural timber - Strength classes, April, 2016)
[14] (The Glulam Handbook Volume 1, Facts about glulam, Swedish Wood, Edition 1, 2024)

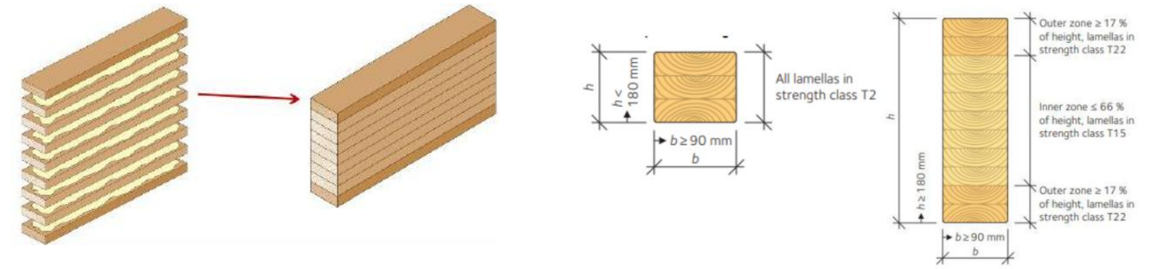

Figure 14: GLT Lamellas Composition of a General Element - (The Glulam Handbook Volume 1, Facts about glulam, Swedish Wood, Edition 1, 2024)

The GLT elements present a smaller dimensional and mechanical properties variation due to better defect distribution (*Figure 15*). It allows the optimization of material usage, by combining different strength classes; moreover, it can be produced in various shapes, including curved, tapered or cambered beams (*Figure 16*).

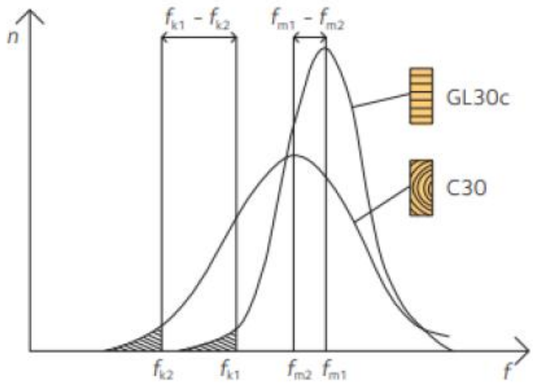

Figure 15: Distribution of the Material - Comparison between GL30c and C30 - (The Glulam Handbook Volume 1, Facts about glulam, Swedish Wood, Edition 1, 2024)[15]

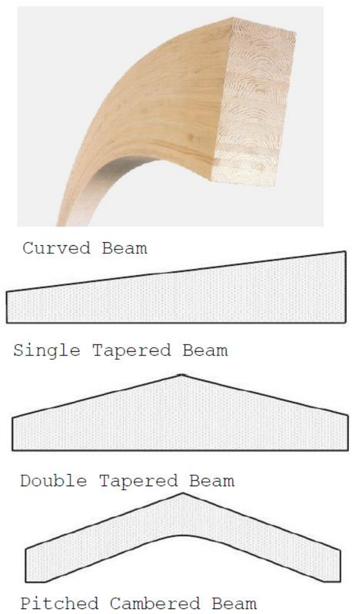

Figure 16: Example of Different Shapes of the GLT Technical Solution - (Porteous J. & Kermani A., 2013)

[15] The GL30c presents a more optimal distribution of the material, with a consequence of better mechanical properties: The variability is lower, and the curve is less spread.

The field of applications of this technology are very vast: Commonly it is used in structural applications, such as beams and arches, due to its strength, durability and ability to be shaped for specific needs.

- Cross Laminated Timber (CLT): Engineered wood product composed of layers of boards or planks glued together with each layer oriented at 90° to the next – following a cross wise disposition. This type of solution presents different dimensional limitations, in particular each board/plank presents a maximum thickness (*t*) of 60mm and a maximum width (*b*) of 300mm; the CLT panels, instead, present a maximum width (*B*) up to 4.8 meters, a length (*L*) up to 30 meters and a maximum number of layers (*n*) up to 25 (*Figure 17*).

Figure 17: CLT Panel Dimensions References - Scheme of the Different Dimensional Limitations - (José Gouveia Henriques, 2024)

This type of engineer wood presents a moisture requirement very detailed: Boards must have a moisture content between 8% and 15% and variations between adjacent boards must not exceed 5%. The final moisture content should ideally match the equilibrium state of the finished structure. The properties of the CLT elements are defined by certified manufacturers. The timber used for CLT is strength graded according to EN 1408[16].

3.3 OTHER WOODEN BASED PRODUCTS FOR CONSTRUCTION

The objective of *Annex 2* is to provide a detailed specification of the properties and possible applications of timber as a structural material directly related to the design of a footbridge. Only a brief mention is made of other structural elements that could be considered in construction but are not directly implemented in the design of the analyzed structure. This inclusion is solely for the sake of completeness in the computational evaluation.

- Laminated Veneer Lumber (LVL): Consists of thin veneer layers bonded in parallel or orthogonal orientations. The high degree of processing ensures superior strength, reduced variability, and enhanced mechanical properties[17].
- Plywood and oriented Strand Board (OSB): These panel-based products provide economical solutions for sheathing and load distribution applications. OSB, classified by EN 300, includes structural grades OSB2, OSB3, and OSB4, with moisture resistance varying accordingly[18].

[16] (José Gouveia Henriques, 2024)
[17] (LVL Handbook Europe , 2019)
[18] (José Gouveia Henriques, 2024)

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