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Brief Overview of the Thermal and Mechanical Properties of Wood, Steel, and Gypsum Board for Structural Connections

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Abstract: This study outlines the essential thermal and mechanical properties of wood, steel, and gypsum board, focusing on their application in timber-steel and timber-timber connections, as well as in protected and unprotected connections involving one or more materials. These materials are widely used in structural components, serving various functions, from load-bearing to protective roles. A comprehensive summary of these materials was provided, emphasising the critical importance of understanding their properties for use in numerical simulations and other analytical methods commonly employed in structural design research. The properties of these materials significantly influence the behaviour of connections under various conditions, particularly in fire scenarios or other high-temperature environments. As such, knowledge of these properties is crucial for ensuring the accuracy of design calculations and simulations. Furthermore, selecting appropriate material properties from verified standards and documents contributes to the reliability of numerical analyses. This study aims to consolidate and present these verified properties to facilitate their application in both experimental and computational studies of structural connections.

Keywords: Thermal properties; Mechanical properties; Wood; Steel; Gypsum; Structural connections; Numerical simulations

1 Introduction

Wood elements have been explored due to their influence on civil and construction engineering regarding strength, ductility, and ability to increase global performance in use. Wooden elements are frequently used alone or combined with other materials. However, a challenge arises when such materials are exposed to extreme conditions. In design, prior analysis is crucial, following well-defined rules. In addition to analytical methodologies, experimental tests must also be carried out whenever there are no objective definitions of the behavior of these elements to different actions. Other methodologies involve the development of computational models, where prior knowledge of material properties is important.

As an example, in heavyweight timber elements, double-shear wood connections with steel fastenings are widely used to assemble different parts and assign loads [1]. Based on the application functions, the connection has different possibilities for the assembly: bolts or dowels, and steel plates together. Therefore, it is important in design to know the properties that need to be introduced for tests and simulations, where the most important thing is to determine its resistance capacity when subjected to external mechanical and/or thermal effects, such as the action of fire. The fire analysis of timber elements is highly complex since there are numerous configurations and additional materials [2]. The variability of the properties of wood and other involved materials at ambient (20°C) or higher temperatures increases this complexity. The thermal and mechanical properties have been well recognized in the literature, but the ease of compilation is essential. To develop a consistent numerical model, consistent data on the thermal and mechanical properties is needed.

Nevertheless, there is a deficiency of standardization in the described values of properties of some materials, namely wood and gypsum plasterboard, due to their composition, water content, and complexity. Therefore, delivering reliable data on the properties has great implications.

The general mechanical and thermal properties used in these types of elements were presented in this brief overview. For mechanical properties, the modulus of elasticity, Poisson ratio, and strength of steel and wood material were considered. For thermal properties, the conductivity, the specific heat, and the density of all elements necessary to use in some studies were presented. For structural and thermal analyses, it is necessary to easily obtain the properties of the materials present in the connection. To develop heat transfer models and evaluate their fire resistance, it is necessary to quantify the thermal properties at elevated temperatures. Some of these properties are outlined in Eurocode 3 (Part 1-2) for steel [3] and Eurocode 5 (Part 1-2) for wood [4]. However, the properties of gypsum board are complicated to measure because of the transient effects. This study presents an overview of the key properties of materials such as wood, steel, and gypsum, as utilised in connections, based on both published data and those investigated by the author [5–10].

2 Wood Materials

2.1 Mechanical Properties

The cellular structure of wood varies according to its volume and characteristics, with properties that remain relatively constant within species-specific limits [11]. It is a material produced from the tissue formed by woody plants with mechanical support functions. Being a naturally resistant and relatively light material, it is often used for structural purposes. It is an organic, solid material with a complex composition, where cellulose and hemicellulose fibers united by lignin predominate. To be used for different calculations, wood could be designated as an orthotropic material. Wood has exclusive and independent mechanical properties in the directions of three axes: longitudinal (L), radial (R), and tangential (T), as shown in Figure 1.

Wood is a material dependent on several continuously modifying effects (moisture, soil conditions, and increasing space) with significant variation in its properties [12]. Wood, as a construction material and renewable raw material, brings many advantages in terms of ecology and cost-benefit ratio. Key mechanical properties that define wood's strength include modulus of elasticity, modulus of rupture in bending, the maximum stress in compression parallel to the grain, compressive stress normal to the grain, and shear strength parallel to the grain.

EN 338:2003 [13] presents additional strength classes like EN 384:2004 [14] and equations that form the relationships between some typical values. Due to discrepancies in the wood availability (variety, size, and combinations of species), the design and requirements of timber constructions are complicated. A strength class system groups together grades and species with comparable strength properties, which makes them compatible [13], allowing the chosen strength class to design results [13]. According to EN 384:2004 [14], each class was chosen by a number representative of the value of bending strength in newtons per square millimeter using a procedure for defining typical values of mechanical properties and density for timber types.

The mechanical advantages of wood are caused by the microstructure that is responsible for the reduced weight and high load capacity. Wood has high tensile strength and elasticity – prerequisites for use as a construction material in regions at earthquake risks. To calculate the mechanical properties, universal testing machines were used by standards. The following tables present values taken by tests conducted on small samples of wood, without concerning thread deprived of knots, etc. The moisture content was controlled, with tests performed at both green and 12% moisture content levels. For elevated moisture content, the elasticity modulus and resistance dropped significantly [12].

Table 1 presents the modulus of elasticity for selected wood types, determined primarily through bending tests rather than axial tests. This approach is commonly used when bending tests provide the only available data on elasticity for a species, either in its green state or at 12% moisture content. The modulus of elasticity evaluates the material stiffness. It was managed to express the elastic properties in tensile or compression.

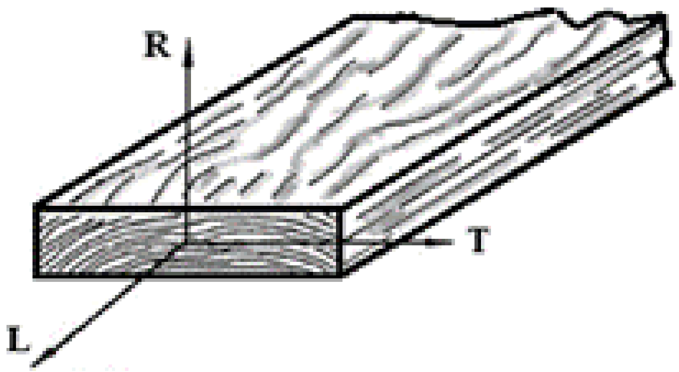

Figure 1. Different directions (L, R, and T)

Table 2 records the values of the mean tensile strength for a limited species. In the lack of adequate tensile test information, the rupture modulus was occasionally replaced for the wood tensile strength [12]. The yield stress was defined as the stress that material deforms permanently, and the ultimate tensile stress is the stress at which it fails. Tensile strength parallel to the grain is the maximum tensile stress experienced parallel to the wood grain. Reasonably limited test information was offered on the tensile strength of several types of wood parallel to the grain.

Table 1. Elasticity modulus in various timber types at green or 12% moisture content [11, 12]

Timber Types	Elasticity Modulus (MPa)	
	Green	12%
Basswood, American	7200	10100
Birch, yellow	10300	13900
Cherry, black	9000	10300
Douglas-fir Coast	10800	13400
Maple, red	9600	11300
Hemlock, western	9000	11300
Larch, western	10100	12900
Walnut, black	9800	11600
Elm, American	7700	9200
Pine, western white	8200	10100
Cedar, yellow	7900	9800
Redwood, young-growth	6600	7600
Spruce, red	9200	11100

Table 2. Mean parallel-to-grain tensile strength of selected timber types at 12% moisture content [11, 12]

Timber Types	Tensile Strength (MPa)
Beech, American	86.20
Yellow poplar	109.60
Willow, black	73.10
Douglas-fir, interior north	107.60
Maple, sugar	108.20
Hemlock, western	89.60
Larch, western	111.70
Willow, black	73.10
Elm, cedar	120.70
Redwood, young growth	62.70
Spruce, Stikla	59.30

Table 3. Test results of classification

Wood Types	Rupture Modulus (MPa)	
	Green	12%
Basswood, American	34	60
Birch, yellow	57	114
Cherry, black	55	85
Douglas-fir Coast	53	85
Maple, red	53	92
Hemlock, western	46	78
Larch, western	53	90
Walnut, black	66	101
Elm, American	50	81
Pine, western white	32	67
Cedar, yellow	44	77
Redwood, young growth	41	54
Spruce, red	41	74

Table 3 provides the average modulus of rupture values for several wood types, either in green or at 12% moisture content. The rupture modulus is a low or moderate value of tensile strength for samples [12]. The modulus of rupture exhibits the maximum load-carrying capacity of a wood item in bending and is proportionate to the maximum moment assumed by the sample.

Constants (nine independent and three more dependent) are crucial to illustrate the elastic behavior of wood: Elasticity modulus (E), rigidity (G), and Poisson's ratios (μ). The elasticity modulus and the Poisson ratio are associated by the following formula:

$$\frac{\mu_{ij}}{E_i} = \frac{\mu_{ji}}{E_j}, \quad i \neq j, \quad i, j = L, R, T \tag{1}$$

The elasticity moduli, which are represented by E_L, E_R, and E_T, respectively, along the longitudinal, radial, and tangential axes of wood. These moduli are commonly acquired from compression tests. Average values of E_R and E_T, as ratios of E_L, for selected wood species, are provided in Table 4. The shear modulus represents the resistance of a material to deflection under shear stress. It is expressed by G_{LR}, G_{LT}, and G_{RT}, representing the elastic constants in the L_R, L_T, and R_T planes, respectively. Mean values of shear moduli of a limited species as a ratio to E_L are shown in Table 4.

When an item was loaded in the axial direction, the deformation normal to the direction of the load was proportional to the deformation parallel to the load alignment.

The ratio between the transverse and the axial strain is the Poisson ratio. The Poisson ratios are represented by μ_{LR}, $\mu_{RL}, \mu_{LT}, \mu_{TL}, \mu_{RT}$, and μ_{TR}. The first letter of the subscript describes the applied stress direction and the second letter the lateral deformation direction. Average values of Poisson ratios for samples of some wood types are given in Table 5. Values for μ_{RL} and μ_{TL} are a smaller amount just established than those for the other Poisson ratios. These properties vary inside and between woods [12].

Reduction factors to determine the strength and modulus of elasticity parallel to wood grain at elevated temperatures were referred to in Eurocode 5 (Part 1-2) [4], as represented in Table 6. These values should be multiplied by the local values at 20°C.

Table 4. Average elastic ratios of some timber types at 12% moisture content [11, 12]

Timber Types	E_T/E_L	E_R/E_L	G_{LR}/E_L	G_{LI}/E_L	G_{RT}/E_L
Basswood, American	0.027	0.066	0.056	0.046	..
Birch, yellow	0.050	0.078	0.074	0.068	0.017
Cherry, black	0.086	0.197	0.147	0.097	..
Douglas-fir	0.050	0.068	0.064	0.078	0.007
Maple, red	0.067	0.140	0.133	0.074	..
Hemlock, western	0.031	0.058	0.038	0.032	0.003
Larch, western	0.065	0.079	0.063	0.069	0.007
Walnut, black	0.056	0.106	0.085	0.062	0.021
Pine, western white	0.038	0.078	0.052	0.048	0.005
Redwood	0.089	0.087	0.066	0.077	0.011

Table 5. Average Poisson's ratio of some wood types at 12% moisture content [11, 12]

Wood Types	μ_{LR}	μ_{LT}	μ_{RT}	μ_{TR}	μ_{RL}
Basswood, American	0.364	0.406	0.912	0.346	0.034
Birch, yellow	0.426	0.451	0.697	0.426	0.043
Cherry, black	0.392	0.428	0.695	0.282	0.086
Douglas-fir	0.292	0.449	0.390	0.374	0.036
Maple, red	0.434	0.509	0.762	0.354	0.063
Hemlock, western	0.485	0.423	0.442	0.382	..
Larch, western	0.355	0.276	0.389	0.352	..
Walnut, black	0.495	0.632	0.718	0.378	0.052
Pine, western white	0.329	0.344	0.410	0.334	..
Redwood	0.360	0.346	0.410	0.334	..

Table 6. Reduction factor for strength and relative elasticity modulus for wood material at elevated temperatures [4]

Temperature (°C)	Reduction Factor			Relative Modulus of Elasticity	
	Compression	Tension	Shear	Tension	Compression
20	1	1	1	1	1
100	0.25	0.40	0.65	0.50	0.35
300	0	0	0	0	0

2.1.1 Glulam

According to the definition in EN 1194:1999 [15], a structural component modelled by bonding jointly wood laminations with the parallel grain was defined as glued laminated timber (glulam). Glulam is a technologically advanced product intended for the construction of structures and composed of different wood species. This structural wood has high strength and stability and is, therefore, frequently used in large structures. It is an extremely versatile architectural material, as it allows for a wide variety of shapes as well as structures with large spans.

Glulam presents several advantages over alternatives such as reinforced concrete or steel, including providing more economical solutions, faster implementation, lightness, and architectural versatility. It also offers ease of integration with other materials such as plasterboard, insulation, finishes, tiles, and masonry. Additionally, it facilitates the industrialization and prefabrication of building components, delivers enhanced fire resistance, serves as a thermal insulator, and contributes to aesthetic and structural benefits due to its high strength.

In this brief overview, five wood classes in homogeneous glulam were considered for application in connections. The density of these wood classes ranges between 370 and 480 kg/m³ [16].

The types of glued laminated wood are GL20H, GL24H, GL28H, GL30H, and GL32H, which are frequently applied in building engineering. EN 1194:1999 [15] lists eight strength classes for homogeneous glulam and combined glulam.

The strength classes of glulam are determined based on wood classifications. They were nominated by GLxh as homogeneous lay-up, meaning that all the laminations are of the equivalent grade and species, or GLxc as combined, where the cross-section comprises inner and outer laminations of different strength classes [17]. The label GL indicates that it is laminated glued wood; the number describes its resistance to bending. To conclude, the letter H or C differentiates the kind of beam, homogeneous or combined, correspondingly. The properties of the chosen glulam are specified in Table 7 [16].

Table 7. Mechanical properties for homogeneous glulam [16]

Strength Class	GL20H	GL24H	GL28H	GL30H	GL32H
Rupture modulus in static bending $(\mathrm{N/mm^2})$	20	24	28	30	32
Average parallel-to-grain tensile strength $(\mathrm{N/mm^2})$	16	19.2	22.3	24	25.6
Modulus of elasticity $(\mathrm{N/mm^2})$	8400	11500	12600	13600	14200
Density $(\mathrm{kg/m^3})$	370	420	460	480	480

2.2 Thermal Properties

Thermal material properties are fundamental to studying steady and unsteady thermal analysis due to real conditions like fire situations. The emissivity of the wood material was assumed to be equal to 0.8 [4].

Thermal conductivity measures the heat flow ratio across the material thickness submitted to a temperature grade. The wood conductivity is presented in Table 8.

The specific heat of wood varies on various factors, but it is independent of material density or species [4]. The specific heat values are shown in Table 9, as indicated in Eurocode 5 (Part 1-2) [4].

Wood is used in extensive conditions, and it is established by the moisture content in use [11].

The density of wood is typically derived from the average attributes of the species, though this value should be regarded as an approximation due to the inherent variability of wood.

The density coefficient of wood, as shown in Table 10, corresponds to a moisture content of 12% (ω), as indicated in Eurocode 5 (Part 1-2) [4].

The density variation with the temperature of the five wood classes (GL20H, GL24H, GL28H, GL30H, and GL32H) is presented in Table 11.

The presented values were acquired according to Table 10 by considering the respective density in Table 7.

Table 8. Thermal conductivity of wood [4]

Temperature $(^{\circ}\mathrm{C})$	**Thermal Conductivity** $(\mathrm{W/mK})$
20	0.12
200	0.15
350	0.07
500	0.09
800	0.35
1200	1.50

Table 9. Specific heat of wood [4]

Temperature $(^{\circ}\mathrm{C})$	**Specific Heat** $(\mathrm{J/kgK})$
20	1530
99	1770
110	13600
120	13500
130	2120
200	2000
250	1620
300	710
350	850
400	1000
600	1400
800	1650
1200	1650

Table 10. Density ratio of wood [4]

Temperature $(^{\circ}\mathrm{C})$	**Density Ratio**
20	$1+\omega$
99	$1+\omega$
120	1
200	1
250	0.93
300	0.76
350	0.52
400	0.38
600	0.28
800	0.26
1200	0

Table 11. Density of wood classes (GL20H, GL24H, GL28H, GL30H, and GL32H)

Temperature $(^{\circ}\mathrm{C})$	**GL20H** $(\mathrm{kg/m^3})$	**GL24H** $(\mathrm{kg/m^3})$	**GL28H** $(\mathrm{kg/m^3})$	**GL30H** $(\mathrm{kg/m^3})$	**GL32H** $(\mathrm{kg/m^3})$
20	414.4	470.4	515.2	537.6	537.6
99	414.4	470.4	512.2	537.6	537.6
120	370	420	460	480	480
200	370	420	460	480	480
250	344.1	390.6	427.8	446.4	446.4
300	281.2	319.2	349.6	364.8	364.8
350	192.4	218.4	239.2	249.6	249.6
400	140.6	159.6	174.8	182.4	182.4
600	103.6	117.6	128.8	134.4	134.4
800	96.2	109.2	119.6	124.8	124.8
1200	0	0	0	0	0

2.3 Wood under Fire

The primary challenges for the calculation of the wooden strength subjected to fire are thermal degradation and charring depth development. When wood structures are subjected to elevated temperatures, a char layer forms on the surface, which eliminates the material's strength but acts as an insulating barrier that protects the core from further heat exposure. The charring rate is constant and essentially depends on the density and moisture content of wood properties [18–20].

The wood density reduces with the material degradation produced by the pyrolysis process in the presence of elevated temperatures. The pyrolysis process generally begins at temperatures of 280 to 300°C [18–20]. The charred zone has no real resistance, reducing the resistance of the effective cross-section. On the other hand, the charring depth depends on the time of fire exposure. The verification of these parameters provides the evaluation of their load-bearing capability. The speed at which wood burns is known in various standards and building codes (average value of 0.7 mm/min). The wooden structural element burns from the outside in at a known rate, leaving the unburned inner section intact. Therefore, when calculating firewood elements, the effective section method is used, that is, the resistant section corresponds to the unburned part. This justifies the statement that wood has greater fire resistance than steel. Steel has high thermal conductivity, thus affecting its resistant properties with increasing temperature. Therefore, in practice, whenever the fire action is present in construction, the metallic elements are inserted into wooden elements so that the wood protects the steel, preventing its temperature from rising (wood is a poor thermal conductor) to values that call into question its mechanical properties.

This is a general theory for exposure to standard fire and it is done on the assumptions of one-dimensional heat transfer, which holds for items used in buildings. After fire exposure, the wood cross-section is shown in Figure 2, representing different zones: An outside part of the wood that is charred; a layer with a thickness that is defined by pyrolysis, where the wood is chemically changed by fire but is not yet entirely decomposed; and the core that comprises the integral wood.

The high weakness of wood, due to the fire conditions or at high temperatures, needs a demanding analysis. Nevertheless, when compared with other constructive materials, wood material presents good resistance to high temperatures due to its low temperature inside the cross-section. But in general, when wood material is used in buildings, fire-protective surfaces are normally mandatory, and the protection required can be established by applying standards and procedures. The analysis of connections exposed to fire can be not easy due to their complexity and variability. For these components, glulam components were proposed to withstand fire class R60 or R30, which means that they retain their stability during a fire in 60 and 30 minutes [21]. There are wood connections that can resist fire better than others. Wooden components made from glulam with large cross-sections (strong dimensions) have high fire stability [20]. However, the fire penetration is slow because of the carbon layer which forms insulation and prevents the heat flow from the fire area to the pyrolysis zone, which then creates fire protection. In buildings with high fire protection conditions, connections with steel plates and screws are frequently used [20]. Easy rules from Eurocode 5 (Part 1-2) [4] were used to analyse the fire capability of the wood element. The char layer is the distance between the outside surface of the initial item and the position of the char line, shown as the position of the 300°C isotherm, and must be determined from the time of fire exposure and the related charring rate [4].

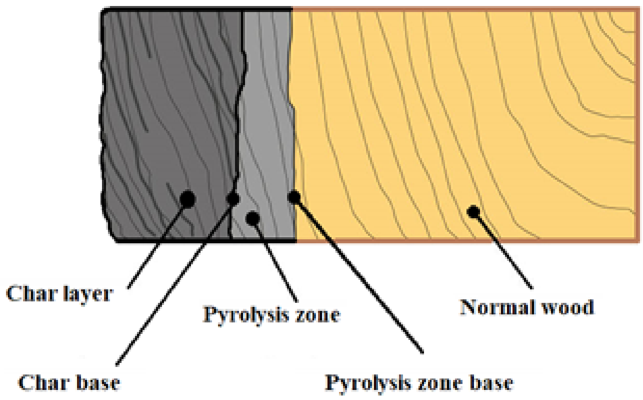

Figure 2. Damage zones in the wood cross-section

3 Steel Materials

3.1 Mechanical Properties

The elastic constants used for the steel elements in connections are shown in Table 12, as mentioned in Eurocode 3 (Part 1-1) [22]. Yield strength and ultimate tensile strength for structural steel elements were mentioned in Eurocode 3 (Part 1-1) [22]. Table 13 lists the nominal values used in the studied connections, based on element thickness and steel grade at 20°C.

Table 12. Properties of steel [22]

Elasticity Modulus (MPa)	**210000**
Poisson ratio	0.3

Table 13. Some nominal values for steel [22]

EN 10025-2 [23] and Steel Grade	**Steel Nominal Thickness $\leq 40(\text{ mm})$**		**$40 <$ Steel Nominal Thickness $\leq 80(\text{mm})$**	
	Yield Strength (MPa)	**Ultimate Tensile Strength (MPa)**	**Yeld Strength (MPa)**	**Ultimate Tensile Strength (MPa)**
S 235	235	360	215	360
S 275	275	430	255	410
S 355	355	510	335	470
S 450	440	550	410	550

Table 14. Reduction factors to use for carbon steel at high temperatures [3]

Steel Temperature $(^{\circ}\text{C})$	**Reduction Factor**		
	Effective Yield Strength	**Proportional Limit**	**Slope of the Linear Elastic Range**
20	1.000	1.000	1.000
100	1.000	1.000	1.000
200	1.000	0.807	0.900
300	1.000	0.613	0.800
400	1.000	0.420	0.700
500	0.780	0.360	0.600
600	0.470	0.180	0.310
700	0.230	0.075	0.130
800	0.110	0.050	0.090
900	0.060	0.0375	0.0675
1000	0.040	0.0250	0.0450
1100	0.020	0.0125	0.0225
1200	0.000	0.0000	0.0000

The mechanical properties at high temperatures should be calculated by applying the reduction factors for the determination of the stress-strain curve [3], as represented in Table 14. The reduction factors applied to steel at high temperatures are related to the mechanical properties at 20°C.

3.2 Thermal Properties

As referred to in Eurocode 3 (Part 1-2), there are some expressions for steel thermal properties calculation [3]. The steel density is constant and equivalent to 7850 kg/m^3 [3]. The material emissivity related to the material surface is equal to 0.7 for carbon steel and 0.4 for stainless steel [3].

The thermal conductivity of steel λ_a (W/mK) must be calculated from Eqs. (2) and (3) [3].

For 20$\leq$ θ_a $\leq$800°C:

$$\lambda_a = 54 - 3.33 \times 10^{-2}\theta_a \tag{2}$$

For 800$\leq$ θ_a $\leq$1200°C:

$$\lambda_a = 27.3 \tag{3}$$

The specific heat of steel C_a(J/kgK) must be resolved from the following expressions [3]:

For 20≤ θ_a ≤600°C:

$$C_a = 425 + 7.73 \times 10^{-1}\theta_a - 1.69 \times 10^{-3}\theta_a^2 + 2.22 \times 10^{-6}\theta_a^3 \tag{4}$$

For 600≤ θ_a ≤735°C:

$$C_a = 666 + \frac{13002}{738 - \theta_a} \tag{5}$$

For 735≤ θ_a ≤900°C:

$$C_a = 545 + \frac{17820}{\theta_a - 731} \tag{6}$$

For 900≤ θ_a ≤1200°C:

$$C_a = 650 \tag{7}$$

where, θ_a is the temperature (°C) in steel material.

4 Gypsum Materials

4.1 Mechanical Properties

Gypsum is a natural mineral or sedimentary rock material rarely used as a structural member. Gypsum board is an ideal material used in protected connections, as well as in wall and ceiling lining constructions. The core is incombustible, providing good fire protection, and has a paper lining on all sides. The porosity is the major parameter that determines the strength and durability of this material [24]. This is a popular material due to the low maintenance in use. Different values of mechanical and physical properties can be obtained from the laboratory, function of the material characteristics, compiled by manufacturers or researchers. According to the Gypsum Association, the compressive strength according to ASTM C473 Standard [25] at 20°C varies between 2400 and 2750 kPa. According to referenced tested boards by Petrone et al. [26], compressive strength is in the range of 3.02 to 8.14 MPa, while the elastic modulus is between 2130 and 4161 MPa. The comparison relating compression tests executed in longitudinal and transversal directions generally focuses on minor differences. The orthotropic behavior is therefore limited to tension tests [26].

The mechanical properties at elevated temperatures are also not perfectly established. Limited data are available on the modulus of elasticity and strength, with some studies reporting data for gypsum up to 140°C [27]. The results presented in Table 15 suggest that the strength and stiffness of gypsum reduce to zero by 120°C, where gypsum becomes brittle. The presented ratios can be multiplied by the properties at 20°C.

Table 15. Strength and modulus of elasticity ratio [27]

Temperature (°C)	Strength Ratio (%)	Modulus of Elasticity Ratio (%)
20	1	1
50	0.42	0.79
100	0.42	0.79
120	0	0

4.2 Thermal Properties

Gypsum plasterboards are composed of a non-combustible gypsum core, integrally wrapped in a coating. They can be used in applications that require direct mechanical fixing to wooden or metal structures, or by fixing using suspension elements or adhesive glues. The gypsum plasterboards offer fire resistance, adapting to the maximum fire reaction classes required for certain applications. These materials are applied to ceilings, partitions, and coatings of dry spaces. The main advantages are ease of installation, fire resistance, and energy efficiency. Gypsum plasterboard is extensively used in civil construction to provide passive fire protection. Passive fire protection continues inactive in the coating structure until a fire appears. To achieve fire protection and life security, the structural integrity is preserved for a time during the fire, restraining the fire spread and its outcomes [28, 29]. The core of the fire resistance of gypsum plasterboards keeps in low thermal conductivity and water content evaporation, which absorbs a significant amount of heat, delaying temperature rise through the system.

Thermal properties of gypsum are also temperature-dependent, and among them, thermal conductivity has a critical influence, with a wide range in literature. The variety of thermal properties (density, specific heat, and conductivity) influencing the fire protection ability of different products of gypsum is considerable [28, 29]. Using the bibliography [28–31], it is possible to find the gypsum thermal properties studied by different authors.

In this work, two different gypsum types were presented [28–31], and considered in connection applications [5–10]. Type A is a regular gypsum suitable for decoration in interior dry construction systems, and type F is a fire-retardant gypsum. Type F is a fire-resistant plasterboard with an increased core adhesion at high temperatures with mineral fibres and/or other additives, and with a face to which suitable gypsum plasters or decoration may be applied [32]. The material properties of gypsum considered as constant take the following values: the specific heat is 950 J/kg°C, the thermal conductivity of solid dried gypsum is equal to 0.19 W/m°C and the density is equal to 889 kg/m^3 [27, 32]. The gypsum emissivity was considered equal to 0.8 [28, 33].

For temperature-dependent thermal properties, Table 16, Table 17, and Table 18 present the specific heat, thermal conductivity, and mass loss of each gypsum type.

The specific heat considering the different chemical reactions during heating exhibits two endothermic reactions of the gypsum: Dehydration and calcium-magnesium carbonate decomposition [28]. Most of the decomposition of the gypsum takes place at 100°C.

The thermal conductivity of gypsum is moderately complex because of moisture and radiation occurrence. Table 17 represents these values from two types of gypsum plasterboard.

Table 16. Specific heat [34]

Temperature ($^\circ$C)	**Specific Heat**	
	Regular Gypsum (J/kg$^\circ$C)	**Fire Retardant Gypsum** (J/kg$^\circ$C)
50	951	884
100	3911	4362
150	933	823
200	422	396
250	274	216
300	30	31
350	-602	-543
400	-302	-249
450	-297	-237
500	-367	-298
550	-275	-243
600	7	-13

Table 17. Thermal conductivity [34]

Temperature ($^\circ$C)	**Thermal Conductivity**	
	Regular Gypsum (W/m$^\circ$C)	**Fire Retardant Gypsum** (W/m$^\circ$C)
28	0.355	0.355
242	0.217	0.217
444	0.240	0.240
596	0.267	0.267
780	0.285	0.285
918	0.232	0.232
918	0.323	0.323
1016	0.518	0.518

The density of gypsum is affected by mass loss, which remains largely unchanged up to 100°C. Between 100°C and 160°C, moisture evaporation causes a 15-17% reduction in mass, after which the density stabilizes.

Table 18 gives these values which allow the calculation of density depending on temperature.

4.3 Fire Protective Thickness with Gypsum Plasterboard

For fire resistance, the wood connections need to be protected using, for example, gypsum plasterboard. The panel thickness was calculated according to Eqs. (8) to (11) to the minimum value to delay the charring rate based on Eurocode 5 (Part 1-2) [4].

For protected connections, steel plates are the side items that may be considered insulated, involving the edges of the plate. In this type of fastener, fire protection should be calculated according to Eurocode 3 (Part 1-2) [3].

Table 18. Mass loss [34]

Temperature (°C)	Mass Loss	
	Regular Gypsum (%)	Fire Retardant Gypsum (%)
40	100.10	100.10
100	99.50	99.50
140	90.50	91.10
200	85.50	86.30
240	85.40	86.30
300	85.40	86.30
340	85.40	86.30
400	85.30	86.30
440	85.40	86.30
500	85.40	86.30
540	85.40	86.20
600	85.10	85.90
640	84.60	85.50
700	82.00	83.00
740	79.80	80.80
800	79.60	80.80
840	79.60	80.80
900	79.60	80.90
940	79.60	80.90
1000	79.40	80.90

In the studied connections, isolating materials such as boards, glulam, and type F gypsum plasterboard, were selected to protect the steel-to-wood connections.

For connections with isolating material, the Eurocode 5 (Part 1-2) [4] provides two alternatives: Gypsum or wood-based panels. For each one, the fire-protecting panel thickness h_p was calculated using Eqs. (8) to (11), respectively, for gypsum type A or H:

$$t_{ch} \geq t_{req} - 0.5t_{d,fi} \tag{8}$$

$$h_p = \frac{t_{ch} + 14}{2.8} \tag{9}$$

For gypsum type F:

$$t_{ch} \geq t_{req} - 1.2t_{d,fi} \tag{10}$$

$$h_p = \frac{t_{ch} + 14}{2.8} \tag{11}$$

The value t_{ch} denotes the delay of the beginning of the charring rate due to protection; the fire resistance time $t_{d,fi}$ is given to the fastener in use and t_{req} characterizes the needed time for fire resistance.

5 General Conclusion

Several studies were produced and published by the author using these selected materials in the study of different connections [5–10]. Numerical simulations are very relevant for testing resistance. The materials used have the greatest relevance in the results obtained. For this reason, this study shows typical material properties, which are easy to use in numerical models, particularly when it is necessary to consider materials exposed to fire. With the correct use of materials, the best approximate behaviour of the connections or other elements was obtained. In addition, it is possible to determine just how fast the decrease in the wood cross-section size is when it is subjected to a critical level of temperatures, as well as to verify the use of insulating materials that can delay this effect.

Data Availability

Data supporting these conclusions are available in the manuscript or upon request.

Conflicts of Interest

No conflict of interest.

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