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Mechanical performance of glulam products made with Portuguese poplar

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Abstract

Due to its average mechanical properties, poplar, a fast-growing species, has been disfavored compared to stronger species for several decades. Wood-based products may help changing that perspective and thus, poplar has been gaining its market share for structural uses. A state-of-the-art review concerning the use of poplar to produce glued laminated products, with special focus on the use of Portuguese poplar, is presented. The Portuguese forest produces a great variety of species. The most common poplar species found in this country are *Populus x canadensis*, *P. nigra* L., and *P. alba* L. Despite its limited availability, and the market hesitation on its structural application, recent studies on poplar grown in the Portuguese forest showed its suitability for structural purposes. Glued laminated timber (GLT) beams made with this species revealed a very promising mechanical behavior. Bending strength tests evidenced a ductile behavior on more than 70% of the beams, which motivated deepening the study on the raw material used to produce those beams. To predict the mechanical behavior of such beams, a 3D numerical model was developed. The numerically predicted results were compared with the experimental ones, showing very good agreement between both approaches.

1 Introduction

The relevance of poplar, once regarded as a weed tree unwanted in timber stands, has changed, mainly in the last decades. Shortages of the usual timber raw material (e.g. pine timber) or excessive demand of timber from the market or the industry, contributed to this (Balatinecz et al. 2001; Bier 1985; Fraanje 1998). The worldwide uneven distribution of poplar, amongst plantations (about 31.4 Mha) and indigenous forests (about 54.5 Mha), has varied over time due to numerous factors, namely economic and biological ones. Despite the fact that about 98% of the poplar natural resources are concentrated in North America, Europe and Asia, currently they spread essentially over four countries: Canada with more than 39 Mha (21.8 Mha of plantations and 17.3 Mha of indigenous forests); Russian Federation with 25 Mha (indigenous forests); and USA and China with about 10 Mha each (FAO 2016). Back to the beginning of the last century, while poplar wood of good quality was abundant in Canada, there was a shortage in some European countries. This was the chance to take advantage of crossing poplar species, for example European silver poplar (*Populus alba* L.) with some Canadian native aspen (*P. tremuloides Michx.* and *P. grandidentata Michx.*) (Heimburger 1936). The timber demand in the second half of the last century, in countries like the USA, Denmark, Sweden or Norway, increased the interest in poplar wood. In addition, the easy hybridization (which in some cases can occur naturally) made the *Populus* genus the object of genetics forest studies, promoting the emergence and the investigation of several poplar hybrid clones (Beaudoin et al. 1992; Farmer 1970; Farmer and Wilcox 1968; Hernández et al. 1998; Koubaa et al. 1998; Schreiner 1959).

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The list of uses for this hardwood is rather diverse and includes pulp and paper, furniture, pallets, and biomass energy. However, its structural application raised skepticism among producers and possible buyers. Some of its intrinsic characteristics are: the susceptibility to discoloration or decay (which diminishes the value of wood), some workability problems; its lightness and softness due to a relatively low density [280–520 kg/m^3 for a moisture content of 12% (FAO 1979)]. These, together with the lack of knowledge of its mechanical properties, limited its wide acceptance for structural uses. Drying has always been a critical issue since an inappropriate drying technique could lead to warp. Distortion is the consequence of different shrinkage coefficients in different directions within each piece, and in poplar it is frequently associated with intrinsic factors like the presence of wet wood pockets, tension wood, juvenile wood or longitudinal growth stresses (Balatinecz et al. 2014; Bier 1985; Maeglin 1985). However, pressure from Alberta provincial government to use the whole forest resources at the time of harvesting, together with technological advances and the will to add value to this fast-growing species led to an increase in its use, specifically in the development of engineered wood products, such as oriented strand board (OSB), in the last decades of the XX century in North America (Morley and Balatinecz 1993). At the beginning of this century, in Northern Europe, applications other than low added-value and short life span products were also sought, by using solid and engineered poplar wood products as purlins (Fraanje 1998).

2 Poplar as raw material for engineered wood products

Engineered wood products intend to improve the "natural resource" regarding mechanical properties and performance, length and shape, at the same time minimizing waste of raw material. Development of these products increased the share of the structural applications of poplar. Besides OSB, mentioned above, poplar is used in products like laminated veneer lumber (LVL), parallel strand lumber (PSL), laminated strand lumber (LSL), oriented strand lumber (OSL), glued laminated timber (GLT), laminated scrimed lumber (scrimber), among others (Balatinecz and Kretschmann 2001; Castro and Fragnelli 2006; De Boever et al. 2007; He et al. 2016; Sheriff 1998; Van Acker et al. 2016). The manner, in which these products are obtained, includes combining timber or wood flakes, strands, veneers, or laminations, with adhesives (e.g., phenol–formaldehyde resins, usually used in OSB and plywood; or melamine-urea-formaldehyde used in GLT) and in some cases also with additives (e.g., wax, to improve water resistance; preservatives or fire retardants, among others, depending on the purpose of the engineered wood product) (American Wood Council 2018; Bolden and Greaves 2008; Forest Products Laboratory 2010; Martins et al. 2017).

GLT, also known as glulam, is part of this category and is the oldest engineered wood product made. The first records of its use date back to the early 1890s, in Europe, with its patenting in 1906 by a German master carpenter (Rinke 2015). This composite is obtained by gluing together two or more wood lamellae [about 45 mm maximum thickness (EN14080 2013)], with their grain aligned with the length direction of the structural piece. The lamellar constitution, combined with the manner in which the lamellae are coupled to each other (end-to-end, edge-to-edge, and face-to-face), allows a customized cross-section with a virtually unlimited width and height that is a multiple of the individual thickness of the lamella. A broad range of sizes and shapes, straight or curved, can be achieved with this technique. GLT production and use experienced great evolution when the synthetic adhesives developed for gluing the lamellae allowed its application in exterior environment conditions. All these characteristics make GLT suitable for numerous structural applications (APA 2017; EN 14080 2013; Forest Products Laboratory 2010; Yeh 2002).

3 Advantages of using poplar in the production of glued laminated timber beams

As explained above, poplar was not always a species of choice for structural applications. With the advent of composite and engineered wood materials, with reduced variability in the mechanical properties as compared to the natural resource, the market attitude started to change. This paper intends to present the advantages specifically concerning mechanical properties of GLT beams produced using Portuguese poplar. The use of poplar to produce glulam is not new, with the first scientific references dating back to the second half of the 1980s. According to Lepper and Keenan (1986), investigation on the use of poplar to produce GLT was a consequence of supply shortage of the usual raw material, Douglas-fir, in Canada by that time, which threatened the economic competitiveness of glued laminated timber. These authors assessed the strength and stiffness of a set of poplar (*P. tremuloides Michx.* and *P. balsamifera* L.) laminations through experimental tests, and the obtained results were used as input data to analytically model GLT beams made with this material. The strength and stiffness of those beams indicated that the species of poplar studied are suitable to produce GLT beams, but further studies were suggested. In the following years, various studies emerged concerning the use of yellow poplar (*Liriodendron tulipifera*) to produce glulam, reaching similar conclusions (Hernandez et al. 1997; Moody et al. 1993). Although yellow poplar is not of the *Populus* genus, given its similar characteristics, such as lightness, smoothness, as well as tree shape and growth rate, it is often assumed as poplar (it is usually known only by the name poplar, omitting the "yellow").

Although the following decades were not very productive regarding this topic, as Lepper and Keenan had foreseen, several studies have still been carried out since then, concerning the use of this species to produce glued laminated timber. Some other studies focused on poplar as raw material, aimed at obtaining engineered wood products with improved mechanical properties, and their overall behavior when subjected to bending, through wood treatments [preservative or hydrothermal (De Boever et al. 2016; Han et al. 2018; Marcon et al. 2018; Mirzaei et al. 2017)], as well as inner surface reinforcement, such as steel, fiber-reinforced polymers (FRP), carbon fiber-reinforced polymers (CFRP) or glass fiber-reinforced polymers (GFRP) (Cheng and Hu 2011; Lu et al. 2015; Osmannezhad et al. 2014; Tomasi et al. 2009).

To produce a GLT beam, a homogenous or combined cross-section can be assembled. The second option, also known as combined glulam, is only suitable for horizontally laminated members. When the element is subjected to bending stresses, the outer lamellae will be the ones subjected to higher compressive (upper lamella) and tensile (lower lamella) stresses, thus those will be the ones requiring a higher timber grade, while the inner lamellae will be of a lower grade. This is a procedure particularly efficient and economical concerning the flexural response of the GLT beam (Forest Products Laboratory 2010). Following this reasoning, some studies focused on the use of various species in the same cross-section, aiming to balance an improved structural response with reasonable weight, cost and/or performance (e.g., Castro and Paganini 2003). The use of poplar in these combinations allows taking advantage of characteristics that, in a section of solid poplar wood, could be seen as disadvantages. One example is the material's lightness when using poplar in the inner lamellae in combination with heavier stronger species, like, for instance, Eucalyptus [e.g. *Eucalyptus grandis* (Castro and Paganini 1999)]. On the other hand, positioning the poplar lamellae on the compression side and the stronger species on the lamellae subjected to tension will induce the development of deformations on the most compressed lamella outside the elastic domain, associated with a ductile behavior (Del Senno et al. 2003). Additionally, the ratios between modulus of elasticity and density and between strength and density of poplar species, 24.8 and 0.13, respectively, result in a higher structural efficiency ratio when compared with other species such as pine (20.3, 0.10) (Martins 2018). Relatively to the structural efficiency of Eucalyptus (24.5, 0.13), similar values were obtained for poplar, despite having a density less than half the density of Eucalyptus (Martins 2018). This is another advantage, especially concerning the behavior of the GLT beam under dynamic actions (Del Senno et al. 2003).

In Portugal, given the limited availability of this raw material, only recently, some studies took place, like those by Hodoušek et al. (2017) and Martins et al. (2017, 2019). Those studies investigated poplar grown in the Portuguese forest, specifically *P. x Canadensis*, *P. nigra* L., and *P. alba* L. showing its suitability for structural purposes. In the study by Martins et al. (2019), the authors produced and tested eighteen GLT beams. Bending strength mechanical tests evidenced a ductile behavior in two-thirds of the produced set of beams. This led to deepening the study on the material used to produce those beams, with the aim to analyze their mechanical properties (Monteiro et al. 2019). Therefore, more poplar GLT beams were produced and tested, and from the tests' remnants, several samples were collected to perform a mechanical characterization, in tension and in compression, of clear wood specimens. Furthermore, these tests showed a significantly ductile behavior associated with compression parallel-to-grain, suggesting potential advantages associated with the use of these species for the production of GLT beams.

4 Mechanical behavior of glulam beams subjected to bending

In general, timber is assumed as a brittle material when subjected to bending, since it usually fails under tension efforts. The ductile behavior in timber structures is associated only with steel connections. However, this is not completely true since wood under compression may present a ductile behavior. Pirinen (2014) states that this behavior is a consequence of some factors at the wood structure level, specifically the inelastic buckling deformations of the cell walls, which also depends on the angle between the compressive ultimate load and the grain directions. When the grain and compression load have the same direction, there is a strain-hardening following the elastic phase. Regarding the radial and the tangential compression, slight hardening and almost perfectly plastic behavior occur, respectively. In the latter case, the ultimate strain is essentially limited by splitting when wood deforms, due to tension perpendicular-to-grain.

Concerning GLT beams, the general consideration of a linear behavior until failure remains. From the studies using poplar species to produce GLT beams, some focused on the numerical modeling. Different goals led to different approaches by the authors, namely concerning the way in which wood mechanical behavior was modeled. Aiming at obtaining a numerical model capable of predicting the mechanical behavior of these beams, studies using other wood species were also considered, to gather as much information as possible. In general, authors sought for describing the GLT beams behavior, considering the effect of several parameters (e.g., defects, finger joint connections, delamination, combination of species), and/or sought for their mechanical properties (Frese et al. 2010a, b; Frese and Blaß, 2005, 2007; Gao et al. 2015; Kandler et al., 2015; Kessel and Guenther 2006; Serrano et al. 2001), with focus on the elastic phase. Some of the studies (like Frese et al. 2010a, b; Frese and Blaß, 2005, 2007; Kandler et al., 2015, 2018) followed a common approach: to establish equations able to estimate properties such as bending strength, based on the mechanical properties of the lamellae that constitute them, the mechanical properties of the finger joints, and the cross-section dimensions.

There are, however, some studies, like the ones by Čizmar et al. (2014), Del Senno et al. (2004) and Tomasi et al. (2009), which looked into the ductile capability of GLT beams, with the latter two focusing on the combination of poplar with other species in the cross-section, with poplar lamellae located in the compression zone. The three works sought to define the constitutive law of timber beams in bending, listing some of the existing approaches to do so, either for the elastic phase, or the post-elastic phase, considering ductility.

5 Numerical analysis

5.1 Input data

A set of twenty-one poplar GLT beams was produced and their bending properties, namely modulus of elasticity (local, $E_{m,l}$ and global, $E_{m,g}$) and bending strength parallel to grain (f_m), were obtained. Raw material, assembly process, mechanical properties and the mechanical test details, as well as the quality control of the glue lines, can be found in Martins et al. (2019) and Monteiro et al. (2019). Each beam had a 92 × 120 mm^2 (width × height) cross-section, composed of five lamellae, 24 mm thick. The length of the beams was 2300 mm or 2400 mm, depending on the minimum length of the lamellas. The lamellae order within a beam cross-section was set based on each lamella`s dynamic modulus of elasticity (E_{dyn_l}) trying to have the outer ones (the ones subjected to the highest stresses) with the highest values of E_{dyn_l} and the central one with the lowest values of E_{dyn_l}, thus, increasing stiffness from the center to the exterior layers. The moisture content of the glulam beams, determined by the oven-drying method, following BS EN 13183-1 (2002), ranged between 13.2% and 14.9%, with an average value of 14.1%. Beams were experimentally tested in four-point static bending tests (for more information see Martins et al. 2019), following EN 408 (2012). The average local modulus of elasticity was 12,607 MPa (ranging between 9461 MPa and 17,786 MPa) and the average global modulus of elasticity was 10,533 MPa (ranging between 8610 MPa and 13,401 MPa). An experimental average value of bending strength of 55.3 MPa was found (with a coefficient of variation, COV, of 17.9%) at the ultimate deformation (average value of 68.7 mm, COV = 32.9%). The load–deflection curves obtained are shown in Fig. 1. This allows identifying two sets concerning the behavior of the beams: a tendentially elastic behavior (Fig. 1a); and a non-linear behavior, where the ductile phase can be clearly identified (Fig. 1b). More than two-thirds of the sample fell in the latter set. Taking into account the common assumptions concerning the ductile behavior in timber structures, this is undoubtedly a very interesting and promising behavior, concerning the use of GLT structural elements made from Portuguese poplar.

The first group of beams [plotted in Fig. 1a)] is identified by lower values of strain, as compared with the mean maximum strain values obtained in the same study for poplar in tension parallel-to-grain, 0.683%, having a mean bending strength of 42.9 MPa (COV = 12.0%) and mean ultimate

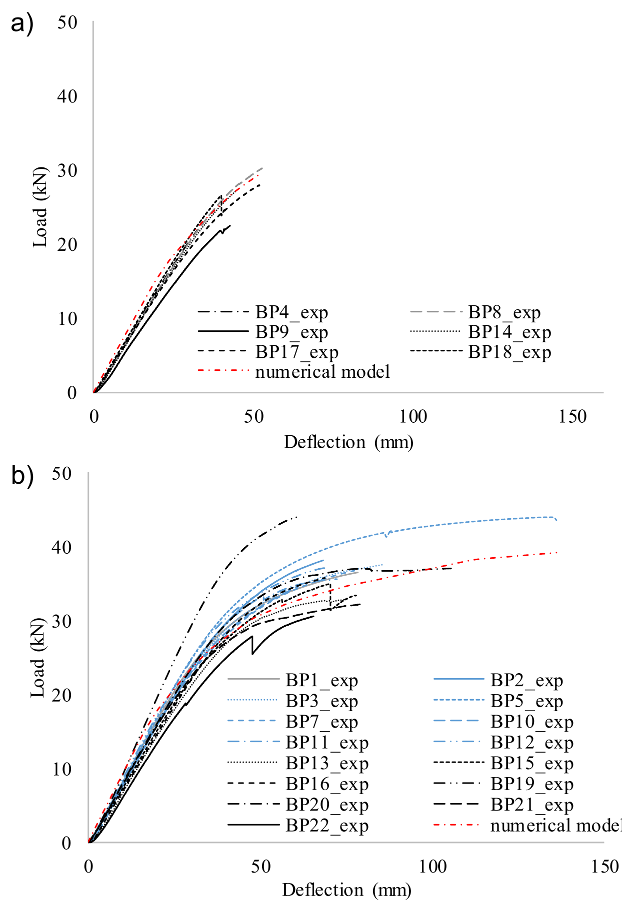

Fig. 1 Experimental and numerical load–deflection curves **a** linear; and **b** non-linear behavior sets of beams

deformation of 44.3 mm (COV = 17.0%). Expressive differences to these results were found for the non-linear behavior set (plotted in Fig. 1b), with a mean bending strength of 60.3 MPa (COV = 10.1%), and a significantly higher mean ultimate deformation of 78.5 mm (COV = 24.0%). Amongst the beams of this group, significant deformation was observed in four beams (BP3, BP5, BP20, and BP21), approaching their mechanical behavior to elastic-perfectly plastic.

Aiming at a better understanding of the material associated with this behavior, thus enabling selecting the appropriate material to produce the GLT beams, clear wood specimens were tested in tension and in compression parallel-to-grain. From the beams previously tested in bending until failure, the undamaged clear wood parts of the upper and the lower lamellae were used to produce twenty compression and twenty tension test specimens. The compression test specimens were quadrangular prisms of $20 \times 20 \times 120$ mm^3 (width x thickness x length). For tension tests, a thinner longer specimen was used, with a configuration similar to that used by Brites et al. (2012) (with a central cross-section of 5×10 mm^2 (thickness × width). Further details can be found in Monteiro et al. (2019). Linear elastic behavior was found for all specimens tested in tension, whereas non-linear ductile behavior was found in compression tests. The data collected from both sets of tests allow obtaining a stress–strain curve, which characterizes the typical (mean) behavior of the Portuguese poplar wood, as found in Monteiro et al. (2019). Figures 2 and 3 show the histograms for the distribution of tension and compression specimens regarding their density and their tensile or compressive strength, respectively. The mean density of the two samples of specimens are similar. However, the tensile strength range of variation (70.3 MPa, COV 25.3%) was larger than the range of variation of compressive strength (9.6 MPa, COV 8.5%). Figure 4 presents the correlation between density and tensile and compressive strength.

5.2 Numerical modelling

Aiming at obtaining a numerical model able to predict adequately the behavior of GLT beams in bending, a three-dimensional model was developed using Abaqus CAE (Simulia 2017) software. The GLT beam considered intentions to simulate those produced with the Portuguese poplar species as presented in Martins et al. (2019) subjected to a static bending test, as described in Sect. 5.1. A 3D solid finite element continuum and hexahedral (C3D8R) was chosen. This kind of element is a height-node brick element with reduced integration, hourglass control, and first-order interpolation.

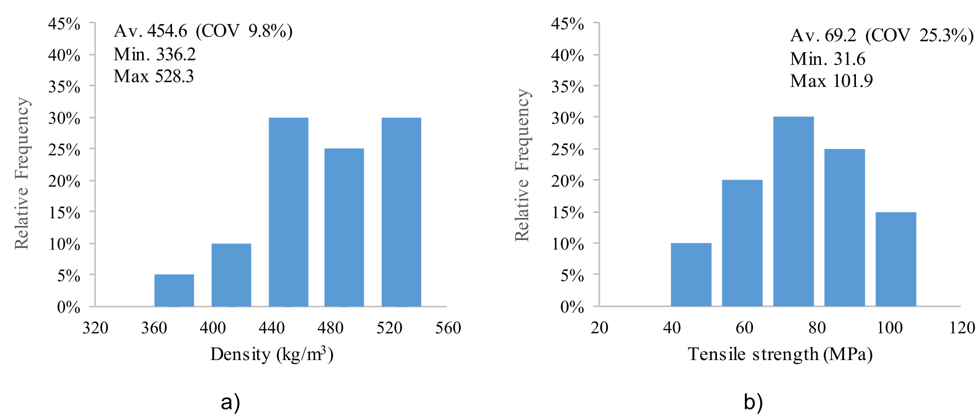

Fig. 2 Distribution of tension specimens as a function of their: **a** density; and **b** tensile strength

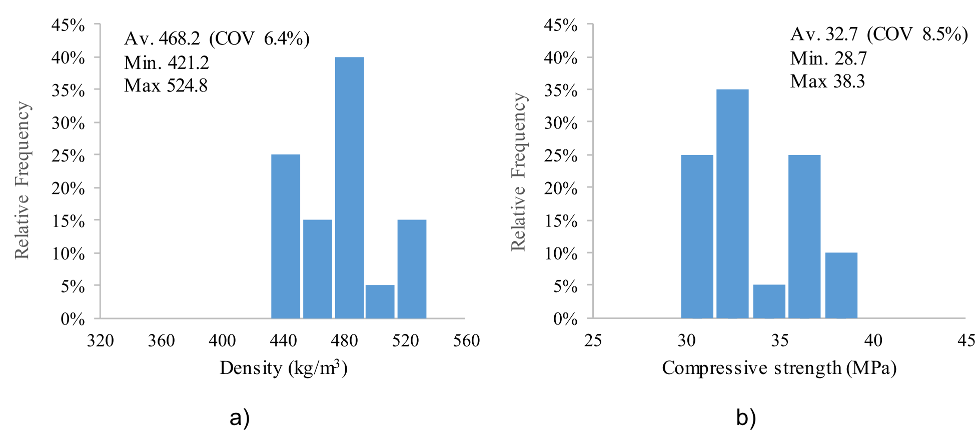

Fig. 3 Distribution of compression specimens as a function of their: **a** density; and **b** compressive strength

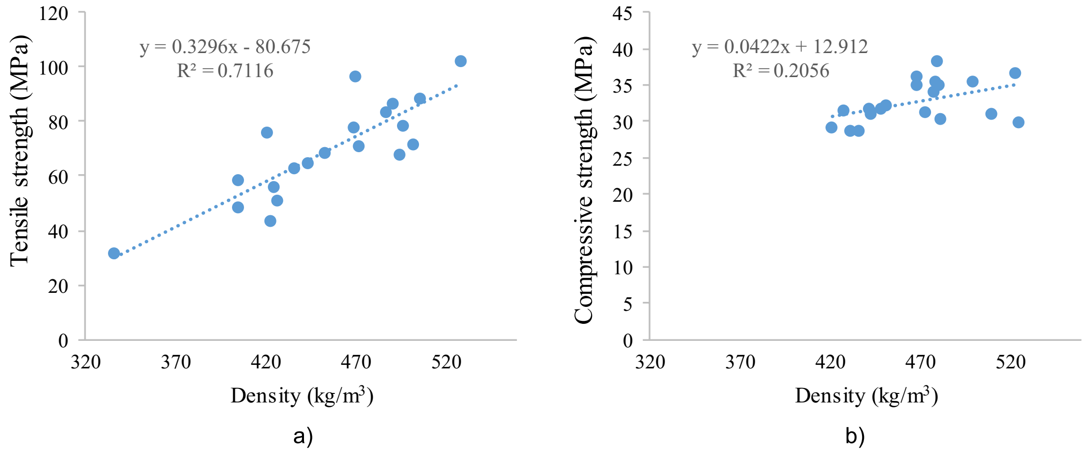

Fig. 4 Correlation between density and: **a** tensile strength; and **b** compressive strength

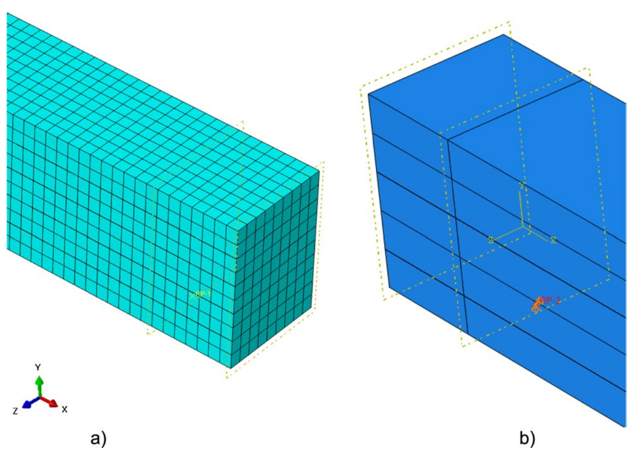

Fig. 5 Numerical model details: **a** mesh; **b** boundary conditions

It has three degrees of freedom per node, each one corresponding to a translation in each of the three directions (x, y, and z). To obtain an efficient mesh, as regards to accuracy versus computing time, a mesh with approximately 12 mm (half thickness of each lamella) was adopted (Fig. 5a). For the sake of simplicity, the contact interaction between adjacent lamellae was considered as rigid. This was achieved through connection nodes between the surfaces of both lamellas, assuming a Master–Slave relation, with the dominant surface (Master) corresponding to the lamella with a higher E_{dyn_l} (Fig. 5b). Concerning the test layout, a four-point bending test configuration was adopted, as the experimental tests performed by Martins et al. (2019). Therefore, a pinned support with no translations was associated with one of the supports, and a second one was defined using a pinned support with all the translations blocked but the one parallel to beam longitudinal axis. The load procedure defined in the model followed the procedure adopted in the experimental test, as well as the loading conditions recommended in EN 408 (2012). Therefore, an imposed displacement of 100 mm was assumed on each load position. For cases, where the ultimate deformation of the beams exceeded 100 mm, a displacement of 200 mm was modeled.

Table 1 Poplar elastic constants

Modulus of elasticity		Shear modulus		Poisson coefficients	
Longitudinal, E_L	E_{dyn_l}	G_{LR}/E_L (%)	7.55	ν_{LR}	0.331
				ν_{LT}	0.406
E_R/E_L (%)	8.75	G_{LT}/E_L (%)	6.05	ν_{RT}	0.789
				ν_{TR}	0.311
E_T/E_L (%)	4.50	G_{RT}/E_L (%)	1.10	ν_{RL}	0.037
				ν_{TL}	0.019

To model the material's mechanical behavior, three parameters were taken into account: (1) density, (2) elastic behavior, and (3) plastic behavior. Wood is an anisotropic material. Nevertheless, simplified approaches modeled it as orthotropic, with three axes of symmetry, defined by the three main directions: longitudinal (L), radial (R) and tangential (T). Aiming at defining the elastic phase of the material behavior, three properties were considered, namely: (1) modulus of elasticity (E), (2) shear modulus (G), and (3) Poisson coefficients (υ). The definition of these elastic constants passed through an iterative procedure; details thereof can be found in Martins (2018). The values adopted are listed in Table 1, wherein E_{dyn_l} corresponds to the values obtained experimentally for the longitudinal dynamic modulus of elasticity (detailed information can be found in Martins 2018). The numerical definition of the wood behavior, in tension and in compression, was based on five stress–strain pairs, corresponding to the values of 10%, 50%, 70%, 90% and 100% of the maximum strength of each specimen, in tension and

Table 2 Numerical mechanical behavior of wood

Stress %	Tension		Compression	
	Stress (MPa)	Strain (%)	Stress (MPa)	Strain (%)
10%	6.9	0.065	3.3	0.030
50%	34.6	0.333	16.3	0.160
70%	48.4	0.470	22.9	0.248
90%	62.2	0.609	29.4	0.360
100%	69.2	0.683	32.7	0.456
90%_d	–	–	33.0	2.418

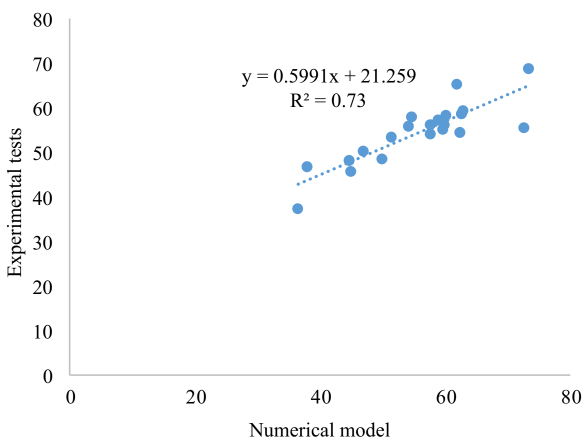

Fig. 6 Numerical *vs.* experimental bending strength results

in compression, respectively. Aiming at considering the ductile behavior in compression, an extra stress–strain pair was defined, corresponding to 90% of the maximum stress value (90%_d) in the descending branch (see Table 2).

As already shown in Fig. 1, two sets of beams with different behavior were identified: one, composed of 6 beams, with linear elastic behavior up to failure (BP4, BP8, BP9, BP14, BP17, and BP18), and a second one, of 15 beams, with non-linear behavior. In addition to the experimental curves, these figures also present two numerical curves representative of the two types of behavior. For the first set of beams, a predicted mean bending strength of 46.3 MPa (COV = 9.9%) was obtained, and for the second set, a value of 57.9 MPa (COV = 7.2%) was found. In general, there is a very good agreement between numerical and experimental results (Fig. 6), concerning the maximum tensile stress of the GLT beam, with a mean absolute error of 7.3% and a coefficient of determination, R^2, of 0.73. As for the maximum compressive stress values, in 81% of the beams, predicted compressive stresses were higher or very close to the mean experimental values of clear wood tests (33.0 MPa). This work is described in detail by Monteiro et al. (2019).

6 Conclusion

This study focuses on addressing the use of Portuguese poplar timber to produce GLT. Twenty-one GLT beams, composed of *Populus x canadensis*, *P. nigra L.,* and *P. alba L.*, were produced and subjected to static bending tests. The mechanical behavior of the poplar under tension and under compression was also analyzed. In addition, a 3D numerical model was developed and each individual beam was modeled. The following conclusions stand out:

- More than 70% of the beams showed a clear ductile behavior, with a mean bending strength of 60.3 MPa (COV = 10.1%), and a mean ultimate deformation of 78.5 mm (COV = 24.0%). From those, more than 25% approach their mechanical behavior to elastic-perfectly plastic.
- A linear elastic behavior was found for all the clear wood specimens tested in tension, while in compression tests non-linear ductile behavior was found. Although the mean density of the two samples of specimens was similar, the tensile strength range of variation (70.3 MPa, COV 25.3%) was larger than the range for the compressive strength (9.6 MPa, COV 8.5%).
- In general, there is a very good agreement between numerical and experimental results, with a mean absolute error of 7.3%, concerning the maximum tensile stress, which corresponds to a coefficient of determination of 0.73.

These results prove that ductile behavior in timber structures may also be associated with the timber elements, which is a very interesting finding. The numerical model and its agreement with the experimental results are a good starting point for the development of a tool capable of predicting the mechanical behavior of such beams without the need to perform destructive tests.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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