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Application of hardwood for glued laminated timber in Europe

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Subject review

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Application of hardwood for glued laminated timber in Europe

Glued laminated timber (GLT) made of hardwood is a modern construction product developed in line with the current changes in the forestry industry. In the last decade studies on hardwoods (deciduous) such as beech, oak, chestnut and ash have been intensively conducted in Europe. The results of those studies are GLT with favourable mechanical characteristics and provisional approvals for their use in construction. This paper presents an overview of currently approved GLT made of hardwood, relevant wood species and adhesive types in their production, as well as currently applicable numerical models.

Key words:
GLT, hardwoods, adhesives for structural applications, design of timber structures

Pregledni rad

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Primjena tvrdih listača za izradu lameliranih nosača u Europi

Lijepljeni lamelirani nosači (LLN) od tvrdih listača predstavljaju suvremeni građevni proizvod razvijen u skladu s promjenama u šumarskoj industriji. U posljednjem desetljeću u Europi su se intenzivno provodila istraživanja na tvrdim listačama poput bukovine, hrastovine, pitome kestenovine i jasenovine. Rezultat su LLN povoljnih mehaničkih svojstava i privremena odobrenja za njihovu primjenu. Ovaj rad daje pregled dosad odobrenih vrsta LLN-a od tvrdih listača, vrste listača i ljepila korištena za njihovu proizvodnju, te stanje razvoja pripadajućih numeričkih modela LLN-a.

Ključne riječi:
LLN, tvrde listače, konstrukcijska ljepila, modeliranje drvenih konstrukcija

Übersichtsarbeit

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Verwendung von Hartlaubholz bei der Herstellung von Verbundträgern in Europa

Geklebte Verbundträger (LLN) aus Hartlaubholz stellen ein modernes Bauprodukt dar, das gemäß den Veränderungen in der Forstwirtschaft entwickelt wurde. In den letzten Jahrzehnten wurden in Europa intensive Untersuchungen an Hartlaubholz wie Buchenholz, Eichenholz, Edelkastanie und Eschenholz durchgeführt. Die Ergebnisse sind geklebte Verbundträger mit günstigen mechanischen Eigenschaften und vorläufigen Genehmigungen für deren Anwendung. Diese Abhandlung gibt einen Überblick über die bisher genehmigten Arten von geklebten Verbundträger aus Hartlaubholz, die Laubholzarten und die Kleber, die bei deren Herstellung verwendet werden, wie auch den Stand der Entwicklung der dazugehörigen nummerischen Modelle der geklebten Verbundträger.

Schlüsselwörter:
geklebte Verbundträger, Hartlaubholz, Kleberkonstruktion, Modellierung von Holzkonstruktionen

1. Introduction

Glued laminated timber (GLT) is a product that benefits from combined advantages of wood as natural material and controlled industrial manufacturing of construction products. Unlike natural wood, which is characterized by variations in mechanical properties due to natural growth, the process of classifying GLT members by strength class ensures uniform properties of the final product – beam. In this way, the control over quality of the construction product has been introduced, which is the basic precondition for its placement to the market. From the technical standpoint, this implies a mechanically more advantageous product, with flexible selection of shapes and sizes of cross-section, and of the element as a whole. In addition, the application of GLT members in the design of structures has enabled designers to build structures with greater spans with flat, curved, and space structures of low self-weight.

The GLT manufacturing process is carried out in full accordance with technical requirements that the product has to meet, and with close observance of current trends in the forestry industry. In the period preceding the last decade, GLT was produced almost exclusively out of coniferous wood. The main reason behind this trend was large availability of conifers in continental Europe, with large-sized timber elements that could easily be worked with. Low density, in combination with uniformity of structure and adequate distribution of mechanical properties, results in a favourable mass to strength ratio. Faster growth of coniferous trees and simpler manufacturing technology (gluing and surface treatment in particular) result in a lower raw material price and a more economical manufacturing process. However, continuous afforestation with coniferous trees and current climate changes have resulted in an increased proportion of deciduous hardwood trees in European forests [1-3]. According to recent forest management trends, spruce and pine forests are being converted into mixed forests with a high proportion of deciduous hardwood trees, beech trees in particular. In the light of the above, studies on the use of deciduous hardwood trees in GLT fabrication have been greatly intensified over the last decade [4]. In addition to their availability, deciduous hardwood species exhibit better mechanical properties compared to coniferous trees, as well as more favourable properties with regard to durability, fire resistance and aesthetics (Figure 1, Figure 2).

Figure 1. GLT made of ash wood – Grandstand of Kulm Hotel in St. Moritz [5]

Figure 2. Hybrid GLT made of spruce and ash – Innerarosa carpark [5]

European standards for the design of timber structures [6, 7] provide requirements for the design and properties of glued laminated timber made of coniferous wood. However, if we wish to design GLT members made of deciduous hardwood, we will be faced with a lack of appropriate standards. However, some specific GLT products made of deciduous hard wood, and adhesives used in their production, have been provisionally approved in the scope of the European Organisation for Technical Approvals (EOTA), as an alternative for construction products that are not covered by harmonised European standards. On the national level, some EU countries have also approved application of GLT made from deciduous hardwood species. Nevertheless, additional research still needs to be undertaken for the development of uniform European standards, so that full use can be made of advantages presented by deciduous hardwoods, and to permit development of a proper quality construction product.

The aim of this paper is to draw attention of practical designers/engineers to the currently insufficiently used potential of deciduous hardwood for the manufacture of GLT members, and to place emphasis on its advantages and potential uses in construction applications. Despite undisputable mechanical advantages, the lack of practical knowledge on the production of this type of GLT, and longstanding experience in the use of coniferous wood as a reference material, are the main reasons why the potential of GLT made of deciduous hardwood has not been fully exploited. Deciduous hardwood species that are currently relevant for the fabrication of GLT members, and recent research aimed at development of the corresponding fabrication methods, are presented in this paper. As the production technology of GLT made of deciduous hardwood has not as yet been fully and unambiguously defined, its significant properties are also described. Possibilities for modelling behaviour of deciduous hardwood GLT are equally explored, and current technical approvals for the use of hardwood-based GLT in construction practice are presented.

2. Selection of deciduous hardwood for GLT production

Until recently, the GLT production in Europe was almost exclusively limited to coniferous wood species. With the proportion of more

Table 1. Mean mechanical properties of various deciduous hardwood species, and comparison with spruce [18]

Type of wood	Density at 12% water content [kg/m³]	Elastic modulus parallel to fibres [N/mm²]	Bending strength [N/mm²]	Tensil strength [N/mm²]	Compressive strength [N/mm²]	Brinell hardness [N/mm²]	
						Longitudinal	Transverse
Spruce	460	11 000	80	95	45	32	12
Beech	710	14 000	120	135	60	70	28-40
Oak	710	13 000	95	110	52	50-65	23-42
Sweet chestnut	590	9 000	80	135	49	32-39	15-23
Ash	700	13 000	105	130	50	64	28-40

Table 2. Definition of strength classes for coniferous trees and various types of deciduous hardwood by visual classification and classification by species according to HRN EN 1912 [9]

	Coniferous trees	Beech	Oak	Ash
Classification according to DIN-u 4074-1, DIN-u 4074-5 [19, 20]	S10	LS10 and more	LS10 and more	LS10 and more
Strength classes according to HRN EN 338 [21]	C24	D35	D30	D40

than 90 %, spruce and fir are the most represented types of wood used in GLT production, while the remaining species mainly include pine, larch and Douglas-fir [8].

The use of such timber as long-span girders subjected to considerable load, with architectural trends calling for slender geometry, requires – from the technical standpoint – timber with strengths greater than that of spruce and pine. A possible solution is the use of laminations made of deciduous hardwood, primarily laminations made of beech, oak, sweet chestnut, and ash-tree. The reasons for selecting these deciduous hardwood species lies in their abundance in Central Europe (beech in particular), durability (oak and sweet chestnut), and outstanding mechanical properties (Table 1). Despite these advantages, the lack of technological solutions for the fabrication of deciduous hardwood GLT has greatly postponed wider application of this type of timber. This primarily concerns the gluing technology which lacked parameters that would permit achievement of required resistance to delamination, and attainment of appropriate adhesive strength of laminations. Technological advances made over the past decade have enabled more widespread structural use of deciduous hardwood GLT, and so manufacturers are increasingly deciding to produce such laminations. Some disadvantages of deciduous hardwood GLT include: considerable self-weight, high cost, poor workability, and limited availability of large-size raw material (hardwood). However, superior mechanical properties of deciduous hardwood are also manifested in the inclusion of such hardwood into higher strength grades compared to coniferous wood, and this despite the use of equivalent criteria of visual classification (Table 2) [9, 10]. This is precisely why significant developments with regard to deciduous hardwood GLT application have been noted over the past fifteen years. Deciduous hardwood is currently used for GLT fabrication partly as a replacement for coniferous species, and partly in combination with coniferous species [11]. More information on visual classification of hardwood can be found in [12-17].

Beech and oak are hardwood species that are most frequently encountered in Europe. **Beech** (*Fagus sylvatica*) is a very hard and heavy type of wood that can easily be worked with and is characterised by high strength (Table 1). It is dried slowly as it is prone to splitting during the drying process but, after drying, it reacts well to gluing and so satisfactory results can be achieved if an appropriate gluing technology is applied [22]. Beech is distinguished from other wood species by an extremely high susceptibility to shrinkage and swelling (Table 3). Significant stress levels can occur already at slight change in moisture, which is why individual laminations must be as thin as possible when used to produce GLT. Lamination sizes of up to 40 mm in thickness and 240 mm in width are normally allowed for other wood species, while in case of beech the durability of strength of the glued joint is achieved by laminations of up to 30 mm in thickness and up to 160 mm in width [23]. This aspect must especially be taken into account when beech is combined with other species of wood. In addition, in contact with moisture, beech exhibits low durability, which is why it can be used for beams exposed to external influences only after special treatments (Table 4). Despite this deficiency, because of its wide availability, high strength [24], and good gluing characteristics, beech has so far been the most widely studied deciduous hardwood species with regard to GLT production [25, 26]. From the technical standpoint, production of beech-based GLT has a considerable potential as strength classes of GL40 and GL48 can easily be attained.

Table 3. Shrinkage coefficient of various deciduous hardwood species, and comparison with spruce wood [28, 29]

Type of wood	Variation in size at 1% change in moisture content [%]		
	Radial	Tangential	Average
Spruce	0.16	0.32	0.24
Beech	0.20	0.40	0.30
Oak	0.16	0.32	0.24
Sweet chestnut	0.16	0.32	0.24
Ash	0.18	0.32	0.26

Table 4. Durability classes for various deciduous hardwood species and comparison with spruce wood [30]

Type of wood	Wood decay fungi	Wood-boring beetles	Termites	Treatability of heartwood*
Spruce	Slightly durable (4)	Not durable (S)	Not durable (S)	Difficult - Extremely difficult to treat (3-4)
Beech	Not durable (5)	Not durable (S)	Not durable (S)	Easily treated (1v**)
Oak	Durable to slightly durable (2-4)	Durable (D)	Moderately durable (M)	Extremely difficult to treat (4)
Sweet chestnut	Durable (2)	Durable (D)	Moderately durable (M)	Extremely difficult to treat (4)
Ash	Not durable (5)	Not durable (S)	Not durable (S)	Moderately easy to treat (2)
*ease with which a wood can be penetrated by a liquid; **unusually high level of variability				

Some companies already have a fully developed technology for the production of beech-based GLT [23]. Also, the authors of a recently published study on the use of deciduous hardwood in GLT have concluded that beech is currently the most suitable specie [27].

Oak (lat. *Quercus petraea, Quercus robur*) is a very hard and heavy wood that can easily be worked with. It exhibits medium to high strength values (Table 1). Due to its availability and durability (Table 4), it has been a traditional construction material which, when properly processed and protected, can last up to 500 years [31]. It dries slowly, and is prone to splitting, especially in early stages of the drying process. When used in the fabrication of GLT, a special attention must be paid to gluing, as a satisfactory level of integrity of cross section cannot be achieved with most adhesives that are successfully used for conifers [32]. Some of the factors contributing to this property are its high density, surface acidity and much greater tannin content and shear modulus compared to conifers. Compared to spruce, oak wood is characterized by much higher strength (although not as high as beech wood), but this is accompanied by a greater weight and more complex manufacturing technology. This is why its main attributes are durability and high aesthetical appeal. Because it is durable in contact with water, oak GLT is a preferred material in the construction of edestrian bridges [33, 34].

Sweet chestnut (lat. *Castanea sativa*) is characterized by good workability and medium strength (Table 1). Because of its availability and durability (Table 4), it has been a traditional building material, most often used in the Mediterranean area. Although its tensile strength is comparable to that of beech wood, very low stiffness of this wood reduces its bending strength considerably (Table 1). It reacts good to gluing. Although GLT products made of sweet chestnut are commercially available, not enough research has as yet been conducted to justify its wider application in engineering [35-39].

Ash (lat. *Fraxinus excelsior*) is a heavy and hard wood characterized by good workability and high strength (Table 1). It can be seen in Table 1 that, due to its strength, ash wood is the main competitor to beech wood while, unlike beech wood, its shrinkage coefficient corresponds to that of spruce wood (Table 3). The above data shows that ash wood is subjected to lower stresses with regards to weather changes and that it can be combined more easily with spruce wood [40, 41]. Despite good mechanical properties, the greatest flaw of ash-based GLT is the lack of an appropriate gluing technology, which is already in place for beech wood [7]. Current research has insufficiently addressed this area, and so ash wood is mainly used in Switzerland whose construction regulations are more liberal compared to Germany for instance. It should also be noted that, due to spread of the phytopathogenic fungus *Chalara fraxinea*, a considerable dieback of ash trees has been observed in most European countries [42-44], which is why it can be expected that great quantities of this raw material – coming from sanitary felling – will soon be available at the market. Other relevant botanical species of deciduous trees that are used in the fabrication of GLT are: birch [45], poplar, flooded gum (*Eucalyptus grandis*), and black locust [46]. Despite their abundance in European forests, detailed studies on their use have not as yet been made. The above discussion clearly shows that deciduous hardwood exhibits mechanical properties that are more favourable when compared to coniferous species (Figure 3).

Figure 3. GLT made of beech and spruce of equivalent flexural stiffness [47]

Their drawback is complicated and hence more expensive drying process, workability, and gluing technology that is more demanding compared to that used for conifers. A possibility for making use of mechanical advantages of deciduous hardwood, while at the same time achieving savings in the fabrication of GLT, involves combing hardwood laminations with conifer-wood laminations (Figure 4). Conifer wood is placed in the central zone of the beam, where lower stress occurs, while deciduous hardwood is placed in the external zone at the height equalling one sixth of the beam height, where highest stress occurs [40, 47]. It should also be noted that mechanical characteristics of wood, being a natural material, equally depend on the locality from which the wood originates. In this respect, many papers point to considerable differences in properties of some species of deciduous hardwood in the context of geographical setting [14, 48-50].

Figure 4. Hybrid GLT made of beech and spruce [47]

3. Gluing GLT made of deciduous hardwood

It has been known for a long time that adhesive types and gluing technologies that are successfully used for making conifer-based GLT do not provide satisfactory results when used for gluing deciduous hardwood species [51-53]. Density of deciduous hardwood is generally higher compared to conifer wood, and hence it exhibits lower porosity levels, which is why adhesive penetrates more slowly through its structure and has shorter penetration depth. In addition, deciduous hardwood is more susceptible to moisture absorption, swelling, and shrinkage. Variable external conditions thus cause greater stress values in deciduous hardwood GLT layers compared to the values for conifer wood, which can lead to splitting and delamination.

Four types of adhesives are nowadays dominantly used for gluing structural wood members: phenol-resorcinol formaldehyde glue (PRF), melamine-urea formaldehyde glue (MUF), emulsion polymer isocyanate glue (EPI), and polyurethane glue (PUR). Characteristics of glued connections of deciduous hardwood are usually estimated via resistance to delamination [54] and via longitudinal tensile shear strength [55]. Unsatisfactory resistance to delamination is the greatest challenge for glued lamellas made of deciduous hardwood species. The delamination testing procedure involves several cycles of impregnation of laminated samples immersed in water in the impregnation chamber under high pressure and vacuum, which is followed by their drying at an elevated temperature. The temperature, drying conditions, and number of cycles, depend on weather conditions to which the connection is to be exposed (type I and type II). In this way, stresses simulating variable external conditions are applied to the glued lamellas, and then the long-term stability of this section is analysed. The results are presented in the form of percentage of the total delamination length to the total nominal length of the glued lines [54]. The reasons why deciduous hardwood species have difficulties in meeting requirements of this test can be defined as a combination of poor penetration of adhesive, greater susceptibility to shrinkage and swelling, and higher elastic modulus and strength when compared to conifer species.

Parameters that can influence the strength of an adhesive connection are quite numerous, and are dependent on the type of wood, preparation of adhesive, size of lamellas, type of adhesive, gluing procedure, and exposure to external influences. Scientists from the Munich Technical University have recently succeeded in demonstrating that beech wood can successfully pass the delamination test according to [54] if the above mentioned parameters are adequately selected. Thus, the key parameter is the closed assembly time, i.e. the time period between surface contact of lamellas after placement of adhesive and application of pressure [22]. During the assembly time of less than 45 minutes a good but shallow penetration of glue has been registered. The viscosity of glue increases with an increase in assembly time, which has proven to be crucial for its deeper penetration. By selecting MUF glue and closed assembly time of between 45 minutes and 75 minutes, the delamination percentage was reduced to within the allowable 5 %. As to other beech wood parameters, it would be important to note the influence of coloured heartwood on delamination of the glued surfaces, but not on the tensile shear strength [56-58]. In the case of deciduous hardwood, tensile shear strength tests have not pointed to significant dependence on the above parameters, which confirms the theory that the longitudinal shear strength of contact surfaces is dominantly dependent on hydrothermal conditions [59-61].

In comparison with beech wood, which is characterized by a diffuse porous structure, the oak, ash and sweet chestnut wood is characterised by a less homogeneous ring-shaped porous structure. In addition, wood properties that are significant for the glue hardening process, such as pH value, water absorption, and extract content, vary by individual type of wood [57]. In some studies focusing of the quality of glued oak wood connections, significant differences have been noted even within the same type of glue [53, 62]. German Construction Institute issued in 2012 the first approval for the use of a commercial MUF glue for gluing hardwood of beech, oak, sweet chestnut and birch [63]. This approval also specifies key parameters such as preparation of surface, application procedure, closed assembly time, duration of the pressure, etc. After that, several other commercial types of adhesives have been approved for gluing beech, oak, and sweet chestnut [46]. However, the technology that would meet resistance to delamination requirements has still not been developed for ash wood. In recent studies focusing on ash wood, tests were conducted with various surface treatment types, adhesive types, mix ratios, and closed assembly times [8, 60, 64, 65].

4. Modelling behaviour of GLT made of deciduous hardwood

Due to the lack of databases or technical specifications for the calculation of standardised GLT made of hardwood, and considering the absence of design models that would describe characteristics of such GLT members, the emphasis of research conducted so far has been placed on the conduct of experiments. Development of design models would enable valuation of GLT bending strength based on mechanical properties of laminations and finger joints. Models developed so far are mostly adequate for the description of conifer-based GLT. According to [6], a typical bending strength of homogeneous GLT made of conifer wood and poplar wood can be defined according to the following expression:

$$f_{m,g,k} = -2.2 + 2.5 f_{t,o,l,k}^{0.75} + 1.5\left(f_{m,j,k} / 1.4 - f_{t,o,l,k} + 6\right)^{0.65} \quad (1)$$

where $f_{t,o,l,k}$ is the characteristic tensile strength of a lamination, while $f_{m,j,k}$ is the characteristic bending strength of the finger joint. Nevertheless, this expression is valid only if

$$1.4 f_{t,o,l,k} \leq f_{m,j,k} \leq 1.4 f_{t,o,l,k} + 12 \quad (2)$$

which is typical for conifer wood. The expression (2) introduces a limitation according to which the tensile strength at the joints must not be lower than the tensile strength of the lamination. In the case of deciduous hardwood, the finger joint strength to lamination strength ratio reduces with an increase in lamination strength and so the requirement from expression (2) is not always fulfilled. A study conducted using the oak-made GLT [66] revealed that the tensile strength potential of material can be used only until class T30, while beyond this class the finger joint tensile strength to lamination strength ratio falls much below the value of one. When modelling GLT with finite elements, mechanical properties of laminations and finger joints are described statistically. Elastic modulus and strength vary locally along each lamination, while laminations also differ according to global properties. Scientists from Stuttgart University have recently presented a stochastic model for predicting bending strength of oak-made GLT. The model was calibrated with experimental data and implemented in the context of the extended finite element method (xFEM) [67]. The extended FEM enables estimation of the occurrence and propagation of cracks and, depending on fracture energy, the cracks open at laminations and at finger joints. In other numerical analyses, such as those presented in [68-70], the dependence of finger joint geometry on

Table 5. Properties of deciduous hardwood GLT species currently approved in Germany and Europe [47]

Type of wood	**Beech**	**Oak**	**Oak**	**Sweet chestnut**
Approval	Z-9.1-821	Z-9.1-679	ETA-13/0642	ETA-13/0646
Approval holder	Studiengemeinschaft Holzleimbau e.V.	Holz Schiller GmbH	Elaborados y Fabricados Gámiz. S.A.	SIERO LAM S.A.
Origin of wood	-	Germany, Czech Republic	France	
Visual classification				
DIN 4074-1. DIN 4074-5 [20]	LS 10. LS13	LS 13	LS 10. LS13	LS 13
HRN EN 338 [21]	D 35	D 30	D 30	D 24
Laminations				
Thickness [mm]	≤30/≤42*	19-23	20 ± 2	-
Width [mm]	≤160	50-70	≤160	-
Length [m]	-	≥300	300-1200	-
GLT				
Height [mm]	≤600/≤900*	76-280	80-400	80-400
Width [mm]	≤160	50-70	50-160	70-220
Length [m]	-	≤12/≤4**	≤12	≤13.5
Strengt [N/mm²]				
Bending $f_{m.k}$	28.0-48.0	31.5/59.0**	33.0	30.0
Tensile ‖ $f_{t.0.k}$	21.0	28.5/29.4**	23.0	20.0
Tensile ⊥ $f_{t.90.k}$	0.5	0.6	0.6	0.7
Compressive ‖ $f_{c.0.k}$	25.0	48.0	45.0	45.0
Compressive ⊥ $f_{c.90.k}$	8.4	9.0	8.0	5.5
Shear $f_{v.k}$	3.4/2.5*	5.5	4.0	4.2
Application class	1	1.2	1.2	1.2

*concerns hybrid girders; **concerns Premium girders bending strength of beech-made GLT is presented, in [68] through parametric analysis. An increase in length of finger joint, reduction in finger spacing and taking into account thickness of finger tip, have proven to be favourable for bending strength of GLT members.

Commercial program packages that are successfully used for numerical modelling of GLT made of deciduous hardwood are ABAQUS [71] and ANSYS [72]. Although a fairly good correspondence between experimental and numerical results has so far been observed, due to short time of application, additional parametric analyses will still have to be made so as to properly determine advantages and limitations of each particular model. It should also be mentioned that experimental studies have been made for GLT made of oak [73], beech, ash, black locust [74] and ash [40]. The results obtained during these studies constitute a valuable contribution to further calibration of numerical models. In addition to the testing of entire beams, it should be noted that a good quality GLT model also requires experimental results relating to the properties of laminations and finger joints, as well as relating to the behaviour of wood at the occurrence and subsequent propagation of cracks [75].

5. Current regulations on deciduous hardwood GLT in Europe

No requirements for deciduous hardwood GLT are given in current European standards. Conifer wood properties can be determined via standardized laminations, cross-sectional properties, or by testing full size girders [6]. In order to make use of advantages of deciduous hardwood species and to increase timber resources, some countries have issued technical approvals for deciduous hardwood GLT. Thus German Institute for Construction (DIBt) issued approvals for GLT made of dark red meranti, beech, and oak. Dark red meranti is a tropical tree and its approval is in force since 2004. It comprises GLT ranging between 55 and 145 mm in width, up to 320 mm in height, and up to 6 m in length [76]. With regard to deciduous hardwood species typical for Europe, Germany has proven to be the pioneer in the testing and approval of this hardwood. Such GLT approval for beech, issued in 2009 by DIBt, covers homogeneous and hybrid girders in combination with spruce, fir, or pine [77]. The approval for oak GLT has been in force since 2013 [78]. Although the GLT made of deciduous hardwood has not been regulated on the European level, the European Organisation for Technical Approvals (EOTA) has issued approval for oak GLT [79] and sweet chestnut GLT [80]. Principal properties of deciduous hardwood GLT species for which approval has been granted by DIBt and ETA are presented in Table 5. It should be noted that, once a construction product is approved by ETA, its manufacturer can prepare a declaration of properties and put the CE mark on the product. This CE mark enables its use and sale in the entire European economic area.

A more detailed overview of all technical approvals for GLT members made of deciduous hardwood species is given in [47, 81, 82]. These approvals, issued in the context of individual products only, also point to the need to develop a uniform and integrated European standard for GLT members made of deciduous hardwood species.

6. Conclusion

Current environmental factors favour long-term development of deciduous hardwood species, as their proportion in European forests is continuously on the rise, compared to conifers. In the context of timber, this shifts the focus from the traditional use of conifers toward a highly intensive research that is expected to close current technological gaps in the use of deciduous hardwood for the production of GLT members. Although a huge leap forward has been made over the past two decades, designers and manufactures are still faced with a number of unknowns. Due to inexistence of standardised girders and computation models, manufacturers are forced to use an experimental approach when determining product properties and, in this respect, every product is tested as a ready for production member, and then a technical approval is requested for such product.

Studies completed so far show that GLT made of deciduous hardwood species boasts a much higher mechanical resistance compared to conifer-based GLT members. Despite that, the absence of legal framework, higher manufacturing price, and insufficiently developed manufacturing technology, are the main reasons why designers and manufacturers still prefer GLT products based on conifer wood. However, recent appearance on the market of commercial adhesives for deciduous hardwood species has greatly fostered development and production of GLT based on deciduous hardwood species. This primarily concerns beech wood for which some companies already have a well-developed manufacturing technology. Other than for beech wood, commercial adhesives have also been developed for oak, sweet chestnut, and birch wood. As to ash wood, despite some promising results related to GLT properties, this wood has not as yet met resistance to delamination requirements in GLT, and so intense research is currently underway. Selection of deciduous hardwood for use as GLT offers a greater area of application, and creation of more elegant structures but, compared to conifer based GLT members, more development still needs to be done to improve the profitability and manufacturing process for deciduous hardwood. It is only in this way that deciduous hardwood will gain an opportunity to take up a much greater share on the GLT production market. In this respect, a possibility for making savings is the combined use of hardwood and conifer wood in the form of hybrid girders.

From the strategic standpoint, it is necessary to invest in further research of deciduous hardwood in order to permit its optimum use and to enable proper long-term management of this resource. The authors of this paper hope that this article will encourage GLT manufacturers to make use of the deciduous hardwood potential that is currently available in forests. Standardised tests leading to GLT members with CE mark will certainly assist in the creation of a European standard, which will in turn enable engineers to make full use of advantages offered by deciduous hardwood, while also ensuring proper use of a good-quality construction product.

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