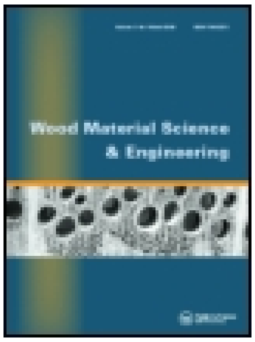

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REVIEW ARTICLE

Selected previous findings on the factors influencing the gluing quality of solid wood products in timber construction and possible developments: A review

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ABSTRACT

Various factors affect the bonding quality of elements used for timber construction. This review includes literature studies and personal experiences related to relevant technological variables defining glue bond performance in glue-laminated timber elements during their service life. The gluing of hardwood species receives special focus as it is considered by the industry to be the most challenging process for implementation. In particular, the effects of wood species, type of adhesive, glued-wood surface quality, physical and/or chemical modification of the wood, technological solutions for gluing, and varying climatic conditions during the use phase (relative humidity, temperature, air circulation, etc.) are considered. In addition, overlapping of individual influencing factors often leads to problems with bonding, thus requiring strongly integrating measurement methods (e.g. NIR spectroscopy). The causes of variations in the results when glued wood is tested using different standardized methods are discussed. A list of open research questions is provided, and problem solutions are recommended based on systematized cutting-edge knowledge. The aim of the work is to systematize the state of knowledge of wood gluing to create a basis for controlled and stable manufacturing processes. The progress of the work will be reported in further publications.

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Introduction

Timber construction has become increasingly important in the last 20 years because of the unique intrinsic properties of wood as a building material and its sustainable nature. Considerable growth in the industry can be observed, especially in the wide-span and multi-story timber construction sectors, where glued laminated timber (GLT) and cross-laminated timber (CLT) are frequently used as the main structural materials. The majority of GLT components are manufactured from softwood, even though a slight increase in hardwood-derived products was recently noticed. Beech (*Fagus* sp.), ash (*Fraxinus* sp.), or birch (*Betula* sp.) are used alone or in combination with softwood. In combination, hardwood addition leads to the local reinforcement of composite beams, particularly for loading perpendicular to the grain. Hardwood addition is also an effective solution for the local reinforcement of steel-wood composites, such as glued rods. In some cases, the addition of a thin (5–8 mm thick) surface layer of hardwood augments the visual appeal of timber structural elements. This may lead to the upgrade of buildings due to a prestigious "furniture-like" appearance instead of a "plain" softwood glulam look. It should also be mentioned that laminated veneer lumber (LVL), usually produced from softwood until now, was recently replaced by hardwood alternatives such as "Baubuche," which uses beech as the core raw resource.

All these products are considered to be wood-based composites that rely on the gluing of various timber elements in diverse configurations. The selection of an appropriate adhesive is, therefore, critical to assure the superior quality of timber products while minimizing production costs. The adhesive systems most frequently used for gluing GLT or CLT are based on melamine urea formaldehyde (MUF), melamine-formaldehyde (MF), phenol resorcinol formaldehyde (PRF), one-component polyurethane (1C-PUR), or emulsion polymer isocyanate (EPI) resins. Selection is based on cost, processed wood species, and the expected service class of the product as defined in Eurocode 5. Each adhesive used in load-bearing timber construction requires building authority approval, such as from the Institute for Building Technology in the case of the German market. The approved resin must withstand predefined elevated moisture and/or temperature conditions projected for the specific service life of the structure.

It is assumed that no major technical problems are related to the bonding of most softwood species, especially when applying PRF-based adhesives. However, the industrial gluing of hardwoods is significantly more challenging. MUF and MF adhesives are usually used and require longer closed assembly times compared to softwood element manufacturing (Schmidt *et al*. 2010, Knorz 2015, Ammann 2015, Ammann *et al*. 2016, Karami 2020). However, the gluing of beech and ash, as well as some softwoods (such as larch or southern yellow pine) with MUF, MF, or 1C- PUR, is still considered as problematic. The application of primers on the

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glued wood surface before adhesive application is the most common technique used to assure expected adhesion properties (Vick 1996, Zeppenfeld and Grunwald 2005, Kläusler 2014). Primers are also applied when gluing wood to other materials, such as metals.

The water-soluble polyol solution is used as a recommended pre-treatment in 1C-PUR systems offered by Henkel (Lüdke *et al*. 2015, Clerc *et al*. 2018). However, other primers can be customized for use with specific hard- and softwoods (Lüdke *et al*. 2015). An important technical limitation is the waiting time required after primer application. This time can be minimized depending on the reactivity of the selected resin. The waiting time can be omitted when using slow-curing 1C-PUR systems (Clerc *et al*. 2018). A simple surface treatment involving spraying water (e.g. 20 g m^{-2}) is often used in glulam production with 1C-PUR during winter to compensate for the very low relative humidity (RH) of the ambient air. Hydroxymethylated resorcinol formaldehyde (HMR) is recognized as an effective primer for diverse adhesive and timber configurations (Vick 1996, Christiansen 2005, Lopez-Sueves and Richter 2009). However, HMR has a relatively long primer activation time and possibly causes post-processing formaldehyde emissions. This severely limits its wide practical implementation in industry.

The detailed mechanism of the primer's interaction with the adhesion system has not yet been sufficiently researched or understood. It was experimentally demonstrated that the impact is very complex, despite the fact that only a small amount of primer is usually applied. The typical quantity sprayed on the wood surface before gluing with 1C-PUR is 20 g m^{-2}, assuming a 10% concentration of the active agent in the water solution. Such trace amounts of applied primers are difficult to detect because of the very large specific surface area of wood, which is considerably augmented by the high proportion of pores within the wood bulk (Plötze and Niemz 2011). Recent experimental trials revealed that primers, including surfactants, are very efficient in 1C-PUR systems, especially when gluing problematic softwoods (e.g. larch, southern yellow pine) and hardwoods (e.g. ash, oak, and beech).

The overall bond quality can vary due to the high variability of the wood as substrate, as well as numerous factors related to the gluing process itself. Consequently, it is very difficult to forecast glue joint performance and assure the expected resistance during the service life of the engineered timber product. Currently, no direct assessment method is available as an ultimate quality control tool for industrial gluing. However, near-infrared spectroscopy (NIRS) has been identified by the authors as a candidate technology potentially suitable for in-process applications. This technology has demonstrated its suitability for the straightforward determination of several wood properties considered relevant for the success of the gluing operation. However, a systematic study of diverse factors relevant to gluing is still lacking in the context of NIRS implementation (Gaspar *et al*. 2009). Therefore, the goal of the present work is to review all important factors that influence the glue bond quality and the interactions within the timber-adhesive system, with special focus on wood properties that can be assessed by employing NIRS. The work presented here is a state-of-the-art critical review. A literature analysis will help identify the known and unknown relationships to provide a basis for safer bonding of wood and its monitoring with new methods. It serves as an introduction to broader research that will be presented in follow-up reports.

Factors influencing glued timber performance during service

Glue bond formation and performance depend on numerous parameters. Marra (1992) and Knorz (2015) defined the strength and durability execution of glued products using the "Equation of Performance" (Equation 1):

$$GP = c \pm \sum AC \pm \sum WP \pm \sum SP \pm \sum AA \pm \sum WG \pm \sum PS, \qquad (1)$$

where *GP* is the glued product performance, *c* is a constant, *AC* is an adhesive composition factor, *WP* is a wood property factor, *SP* is a wood surface preparation factor, *AA* is an adhesive application factor, *WG* is a wood geometry factor, and *PS* is a product service factor.

An overview of the influence of the type of material and various technical/technological factors on the strength of bonded joints is presented in Figure 1. The specific effects of the most influential variables are discussed below.

Influence of the wood substrate

Wood is a natural, porous material with a very high specific surface area (Kollmann 1951, Kollmann and Coté 1968, Walker 2006, Plötze and Niemz 2011, Niemz and Sonderegger 2017). Hardwoods and softwoods are distinct species due to variations in microscopic structure, wood morphology, chemical composition, and extractive component content (Walker 2006). Furthermore, the orthotropy of natural wood leads to a profound influence of the grain orientation on the embedded mechanical properties. The combined effect of the intrinsic wood properties on glue bonds is particularly evident when assessing finger-joined connections by applying shear strength tests (DIN EN 302-1) or when determining the resistance to delamination according to the standardized procedure (EN 302-2). The influence of grain angle on the penetration wood by adhesives was investigated by Hass (2012), who revealed its great relevance. The grain angle influences the mechanical strength, which is reflected in the wood failure percentage of glued wood joints under excessive stress.

Substantial differences in density within annual rings or between early and late wood can be observed, especially in coniferous wood species (Lanvermann 2014). The bulk density can vary considerably between various species, as well as within a single tree. This can also influence the failure mechanisms of glued wood elements. The morphological structure of ring-porous hardwoods, such as ash or oak, differs significantly from that of diffuse-porous hardwood species, including beech and birch (Arnold *et al*. 2019). This results in differences in glue bond performance and the failure behavior of joints, not to mention difficulties in

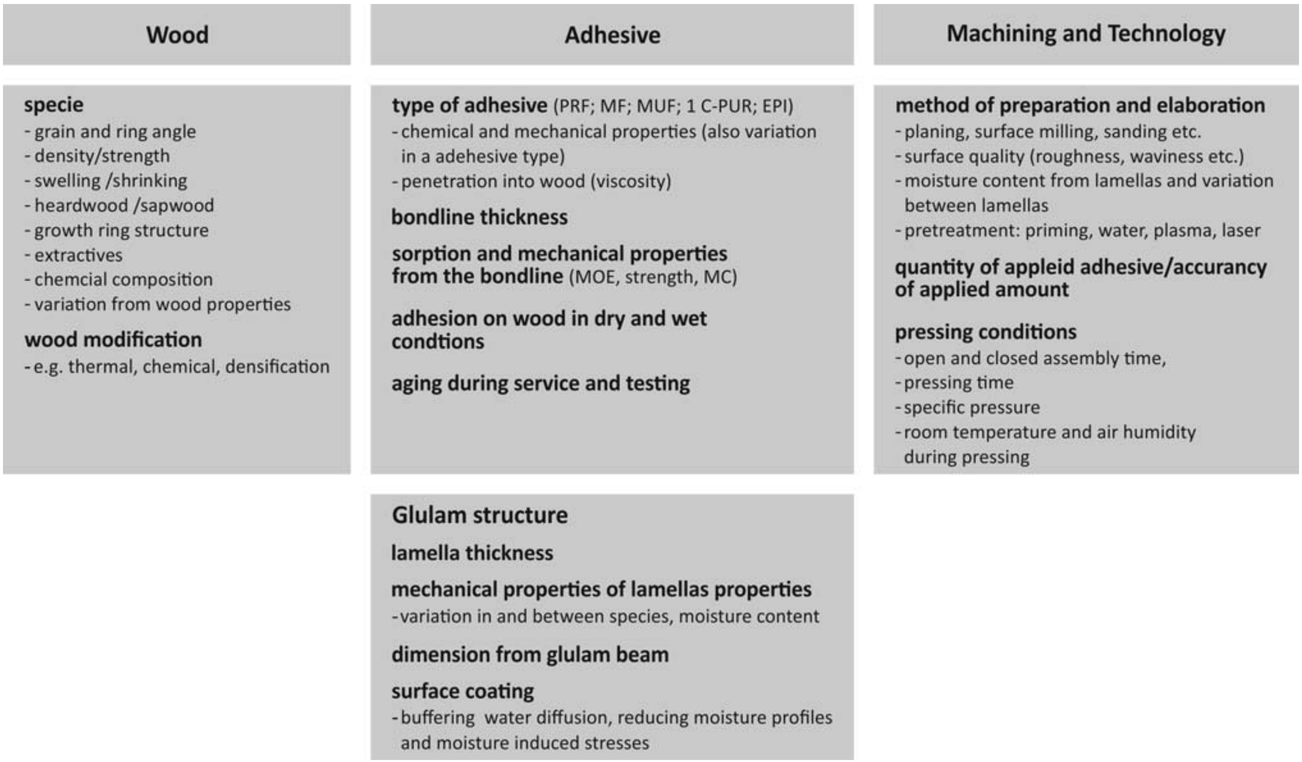

Figure 1. Overview of key factors influencing the strength of glue bonded joints.

predicting mechanical resistance. The presence of extractive components can enhance the natural resistance of wood to biotic agents. However, it usually negatively impacts industrial gluing processes. Most tropical wood species and some domestic wood species with high extractive contents are known to be difficult to glue (Zeppenfeld and Grunwald 2005, Frihart *et al*. 2021). Once again, the proportion and chemical structure of the extractive components vary between the heart and sapwood, resulting in different glue-abilities of elements manufactured from those materials. The suitability of the most frequently used industrial European hardwood species, such as oak (*Quercus* sp.), black locust (*Robinia* sp.), and ash (*Fraxinus* sp.), for gluing is known to vary due to their diverse extractive contents (Lüdke *et al*. 2015, Konnerth *et al*. 2016, Bockel *et al*. 2019, Bockel *et al*. 2020). In general, hardwoods have a higher density than softwoods and, consequently, higher mechanical strength and swelling/shrinkage. This leads to higher shear stresses in the bond line during the service life. This is clearly revealed when testing glue bonds in dry conditions (A1 test following DIN EN 302-1) or after immersion cycles in water (A4 delamination test following EN 302-2). Likewise, the elevated mechanical resistance of hardwoods leads to a lower rate of wood failure when gluing these higher density species.

The relationship between wood failure ratio and lap shear strength in beech wood LVL was investigated by Thole (2017). No direct correlation was found. Moreover, the extent of wood breakage did not provide any information regarding the expected strength of the glued composites. Standards specify the allowable wood failure ratio. It is evident that the performance requirements applicable to hardwood species are not easily transferred to softwood because of the higher native strength of hardwoods. Consequently, the latter (particularly beech wood) are usually selected for testing new adhesives (Figure 2).

Influence of adhesives

Adhesives used for gluing wood can be classified as water soluble or water insoluble. The first group contains MF, UF,

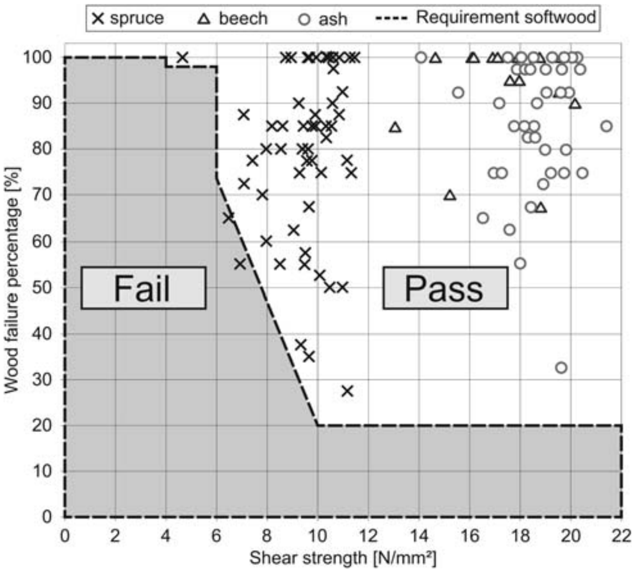

Figure 2. Shear strength and wood failure percentages of glue laminated timber made of beech and ash compared to spruce.

Note: an unacceptable performance limits for individual glue lines in softwood engineered products are marked as gray. (Arnold *et al*. 2019).

MUF, PRF, polyvinyl acetate, and EPI, and the adhesives may contain up to 50% water, depending on the formulation and application. An example of an adhesive that does not contain water is the group of 1C-PUR. The water present in adhesives causes the wood to swell, which leads to further changes in the pore structure and, thus, to alterations in the adhesive's penetration of the wood subsurface. The use of DMF (dimethylformamide) as a primer can cause even stronger swelling than that from water (Kläusler 2014, Ammann *et al*. 2016). However, a significant improvement in the shear strength of lap shear specimens after storage sequence A4 combined with a higher wood failure percentage can be achieved after applying DMF before gluing. This indicates the positive effect of the primer on surface wetting and the penetration of the wood by the adhesive.

Water migrates from the adhesive toward the wood when the glued joints dry. This leads to swelling of the wood and shrinkage of the adhesive film, particularly for UF, MUF, MF, and PRF (Sonderegger 2011). Consequently, cracks in the glued joint occur, ultimately resulting in advanced material damage (Hass 2012). Another effect of moisture uptake by the wood is the alteration of the surface roughness of the wood due to swelling. Such swelling/shrinking effects were not observed when gluing wood using 1C-PUR products.

The thickness of the glue line influences the strength of the joint (Kläusler 2014). Stiffer adhesives lead to a slightly increased wood failure rate (Kollmann 1955, Clauss 2011, Hass 2012, Kläusler *et al*. 2013, Knorz *et al*. 2016, Clerc *et al*. 2020b). The adhesion behavior of the glue towards the wood surface depends on the wood species and its chemical–physical compatibility with the adhesive. The glue resin must display sufficient adhesion to the wood in both wet and dry conditions to retain excellent cohesion characteristics. The stiffness of the adhesive in the glued joint determines the amount of stress transferred to the wood, and, thus, the wood failure rate (Hass *et al*. 2013). The elasticity of the glue line significantly affects the fatigue properties of the adhesive system components. The strain distribution in bonded joints can be measured using different techniques, such as digital image correlation (Knorz 2015).

Examples of delamination patterns observed in ash glulam joined using various commercially available adhesives are shown in Figure 3. Figure 3 also shows the effects of wood surface machining (planning vs. face milling), resin selection (EPI, MUF, and PUR), closed assembly time (10, 20, and 30 min), hardener addition (100%, 60%, and 35%), and the use of a DMF primer. A more detailed demonstration of the priming effect during 1C-PUR gluing is shown in Figures 4a and 4b. Even if the overall effect of the primer is highly positive, precise dosage control is critical as the presence of excess primer results in a deterioration of the glue bond delamination resistance. Priming with DMF technology is still unsuitable for industrially applied adhesive systems. Industrially used primers are based on hydrophilic emulsifier solutions, such as Loctite PR 3105 and HMR primer.

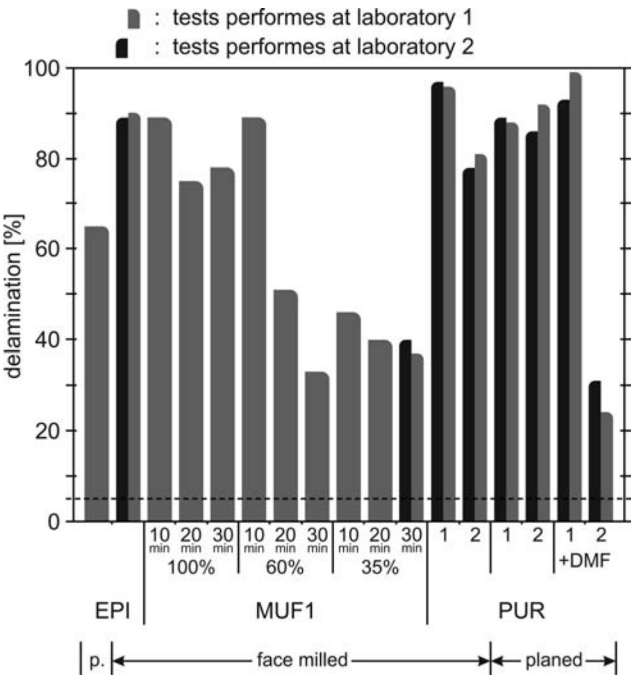

Figure 3. Delamination of ash wood according to DIN EN 302-2 when glued with different adhesives (Ammann *et al*. 2016).

Effect of wood modification

Thermo-hydro-mechanical and chemical modifications change the native wood properties and, thus, its glue-ability. An extensive overview of glue bonding processes applied to modified wood was presented by Lüdtkemeier (2017) as a part of his PhD thesis. The thermal modification of wood results in substantial changes to some of the mechanical properties of wood, as well as the wood's hygroscopicity. Consequently, the swelling and shrinkage of the treated wood reduces. Experimental research has shown that the lap shear strength of glued, thermally modified wood samples is lower than that of unmodified wood when tested under normal climatic conditions. However, the gap between the strengths of untreated and treated wood samples reduces under more severe climatic conditions, such as during storage sequences A4 and A5 according to DIN EN-204 (Altunok *et al*. 2012).

Acetylation is one of the most common forms of chemical wood modification (e.g. the "ACCOYA®" process). The modification involves the replacement of highly hygroscopic hydroxyl groups present in the cell walls of the constitutive wood polymers with hydrophilic acetic groups. This results in wood that is permanently swollen. Numerous studies have been conducted to assess the effect of wood acetylation on the performance of adhesive joints. Bongers *et al*. (2016) stated that better results can be achieved by gluing acetylated wood using various PUR adhesives compared to gluing untreated wood. The good adhesive strength of acetylated wood when using resorcinol formaldehyde adhesives is shown in Figure 5, as reported by Frihart *et al*. (2017). Similar results were obtained by Olaniran *et al*. (2021) in tests performed on

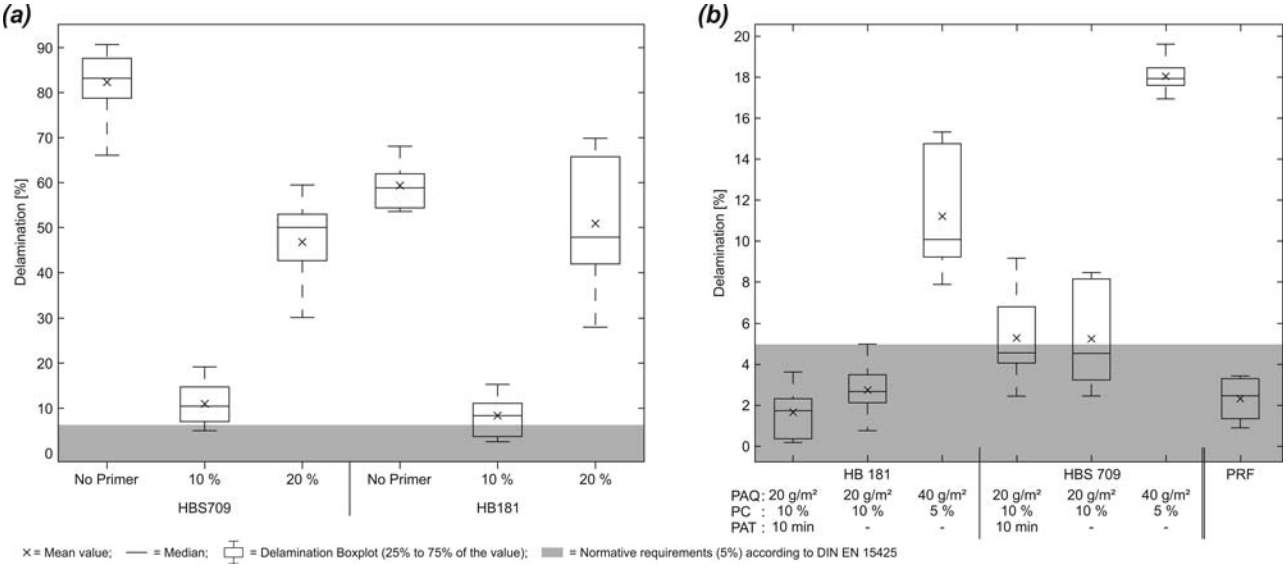

Figure 4. Delamination of ash wood industrially glued using different 1C-PUR (series 1, primer LOCTITE PR 3105) (a), and with variable primer applied quantity (PAQ), primer concentration (PC), and primer activation time (PAT) (series 2, primer LOCTITE PR 3105 for HBS 709, HB 181 and PRF) (b) (Clerc *et al.* 2018).

rubberwood. An increase in shear strength was observed in the acetylated wood after treatment A2 (4 days storage in water at 20 ±5 °C) according to DIN EN 302-1.

Influence of surface alteration

The surface of the wood is subjected to diverse alterations after initial processing. These include surface aging and moisture-induced variations. Ageing is a complex process of chemical–physical property changes, such as surface oxidation, which occur after the creation of fresh surfaces during cutting. This results in changes in surface wettability and surface free energy. Hence, best practices recommend performing gluing immediately after surface machining, especially when the manufactured structural elements are made of hardwood.

Moisture variations are related to cyclic sorption and desorption associated with variations in the RH of the air. A very low RH during the winter results in rapid drying of the wood subsurface. The wood moisture at the surface adapts to the surrounding climate within minutes, whereas the moisture transported from the bulk interior takes place via diffusion which is very slow (Niemz and Gereke 2009). This frequently leads to technical problems in wood gluing with 1C-PUR resins. It is known that this adhesive family requires water for hardening, which is in deficit when the wood is dry. The glue only penetrates the wood superficially to a depth of 0.1–0.3 mm. Extra water is usually sprayed onto the glued wood surface (20 g m^{-2}) to compensate for the very low RH of the air during winter production.

Other moisture-induced features are related to the deformation of wooden boards due to internal stresses in the wood caused by moisture gradients. This is exhibited as warping of the boards, requiring additional pressure to compensate for the curvature. The higher the modulus of elasticity and/or the thickness of the glued boards, the more pressure is required to compensate for the shape deviation. This is often problematic, especially when glulam lamellae are bonded to cross-sections with larger dimensions. Stresses preserved after gluing warped elements may remain and slowly release over time. This can damage the engineered timber elements during their service life.

Riegel (1997) described how subsurface layers are deformed and broken when cutting wood substrates. The

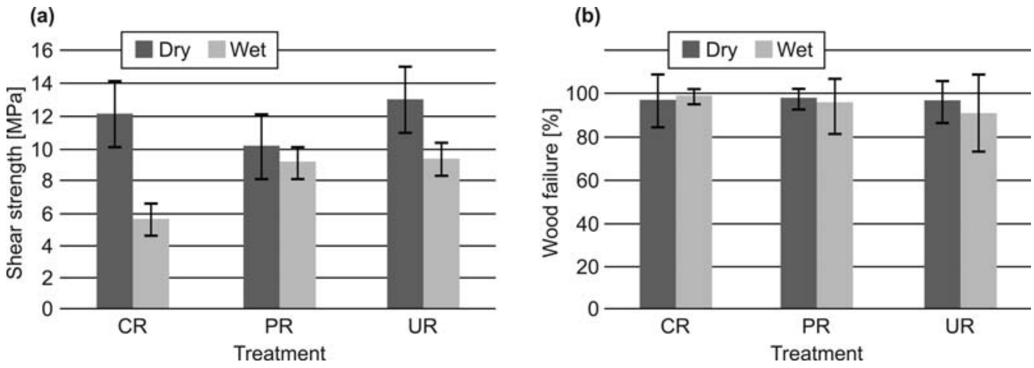

Figure 5. The shear strength (a) and percentage wood failure (b) for resorcinol-formaldehyde bonding of unmodified (CR), planed acetylated (PR) an unplanned acetylated (UR) wood (Frihart *et al.* 2017).

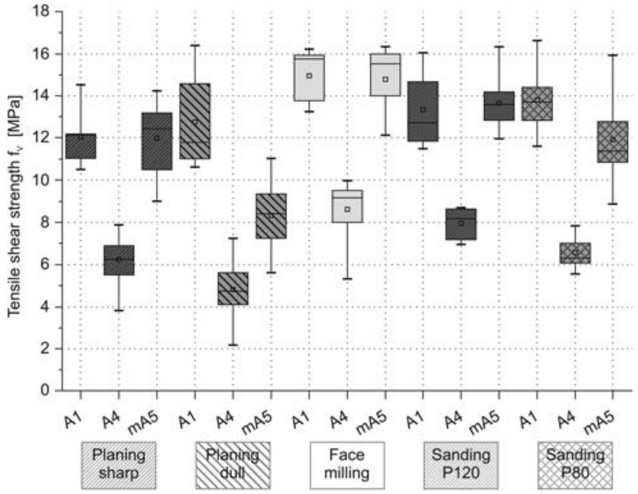

Figure 6. Influence of the surface roughness on the lap shear strength of copper-beech wood composite bonded with 1C-PUR (Kläusler 2014)

Note: A1, A4 and mA5 correspond to the testing sequence according to DIN EN 302-1.

deformation depends on the type of machining and the process conditions. The damage caused by machining decreases in the order of milling, sanding, and finishing, and influences the quality of the bond. The glued surface topography, including flatness, waviness, and roughness, is an important factor influencing glue bond performance. The type and extent of surface irregularities, such as cutter marks, fuzzy/torn grains, scratches, or surface burns should be carefully controlled. Moreover the surface topography should be regularly assessed. The use of sharp tools with optimal geometry, combined with suitable process conditions, is crucial to ensure the expected bond quality. Figure 6 presents a comparison of the mechanical resistances of glue bonds when joining wood pieces machined using diverse cutting configurations.

Influence of gluing technology

Various technological factors have a considerable influence on wood bond quality. The most influential factors are the proper application of the adhesive and the assurance of optimal pressing conditions. The quantity of adhesive should strictly comply with the technical recommendations of the glue manufacturer. As a rule of thumb, the resin must be distributed homogeneously over the entire glued surface. The same requirement applies to the spraying of the primer(s), which is assumed to be part of the complete gluing system. Glue application must be completed for all elements of the glued lamellae batch before commencing the open assembly time. The specific pressure and the accuracy of pressure distribution are key to ensuring high glue bond quality. A slightly elevated pressure compared to that used for softwood gluing is required when the processed wood has a higher density, such as hardwoods. This is due to the higher stiffness of the boards, as well as the need to compensate for cutting marks or any other surface topography irregularities.

The indoor climate variations during gluing, particularly air temperature and RH, can significantly affect the reaction kinetics. In particular, a low air RH negatively influences the reaction kinetics of 1C-PUR systems. An elevated air temperature combined with a low RH results in a high evaporation rate of water when curing products glued using water-based systems.

Influence of mechanical loads and the surrounding climate

Timber structural components in service are exposed to mechanical stresses induced by diverse external factors, such as the dead load of a building, the weight of snow on the roof in the winter, and the action of the wind. Some mechanical stresses are induced by cyclic changes in the wood moisture content, resulting in moisture gradients along the wood cross-section. This phenomenon is analogous to that observed when drying wood in a kiln. The physical effects of drying wood are well known and have been researched over a long period (Kollmann and Coté 1968). The specific microclimate is associated with the geographical location of the exposed timber structure (Ross 2010, Niemz and Sonderegger 2017, Gereke 2009). Cyclic moisture variations of wood occur seasonally inside heated buildings, especially during the winter when the RH is very low (<30% RH) (Wilcox *et al.* 1991). Consequently, the subsurface of the wood dries more than in the bulk interior, leading to excessive tensile stresses resulting from inhomogeneity in wood shrinkage. In extreme cases, these stresses may cause crack formation within the bulk wood or even result in delamination of the adhesive joints. Conversely, compressive stresses due to swelling of the wood during the moist summer conditions occur on the wood surface. These may lead to permanent plastic deformation due to the relatively low compressive strength of wood perpendicular to the fiber direction.

Forced air circulation considerably accelerates wood drying (Kollmann, 1955). This distinctive effect is observed in timber buildings with large flat facades or with multiple windows facilitating the flow of the ambient air. Other timber elements highly affected by excessive drying are objects in the proximity of elevated air circulation zones, such as stairways, doors, or terraces. Moisture-induced problems in timber elements become noticeable after several sorption cycles, usually coinciding with several years of service. Evidently, the extent of the alteration of the glue bonds is case dependent and is influenced by several factors, including the material's climatic environment, the design of the structure, architectural detailing, adhesive type, and intrinsic wood properties. While thinner structural elements tend to deform by the warping of the constitutive lamellae, very large cross-sections, such as glue-laminated timber beams, suffer from surface cracks or glue line delamination. This is usually associated with elevated transverse tensile stress, especially in curved glulam beams. It should be mentioned, however, that certain cracks in glued wood composites are considered normal and are tolerated. The formation of cracks is a natural feature of wood that is frequently observed in solid wood beams and is present in most historical timber buildings.

Extensive research on delamination and crack formation in dry climates was conducted by Angst and Malo (2010, 2013), followed by Hassani *et al*. (2016). They developed a model for the calculation of stress in glued wood, considering the material properties, glued joint characteristics, and the configuration of the glued beam structure. A protocol for the preparation of relevant calculations was reported by Hering (2011). Although it is important to properly understand the aging mechanism, the long-term performance of glue-laminated timber products has not been sufficiently researched (Hering 2011, Niemz 2016, Clerc *et al*. 2017, Clerc *et al*. 2020a, 2020b, Huč *et al*. 2020). The numerous laboratory tests conducted provided adequate reference data corresponding to reasonable exposure times covering multiple years of service. In summary, the problem of aging biomaterials is very complex, implying great research potential. Simultaneously, the results of such research may have a major impact on the evolution of the timber construction industry.

Several methods are suitable for controlling moisture content variations in wooden elements in service to avoid crack formation and/or delamination. Chemical wood modification is a well-accepted solution, even at the expense of high raw material costs. An alternative approach is surface treatment, where protective coatings/films reduce moisture uptake and slightly increase the resistance of the wood to moisture diffusion (Sonderegger *et al*. 2015, Volkmer *et al*. 2015).

Quality control of glue bonds

Testing of glue bond performance

Standard wood-bond quality monitoring, as implemented in the modern timber construction industry, relies on manual reporting by producers, usually in the form of a written declaration that approves adhesive systems that were fabricated following the DIN EN 14080 standard for wood construction. The production process itself may also be monitored in-house, frequently with the assistance of external audits. Two standardized methods are considered most relevant for ensuring the proper performance of glued engineered timber elements during their prospective service life (Aicher *et al*. 2018, Arnold *et al*. 2019). The first is a delamination test following DIN EN 302-2, while the second is a block shear strength test following DIN EN 392.

The test specimens in the delamination test are exposed to cycles of harsh conditions and high moisture loads. Each cycle includes soaking in an autoclave at 10–25 °C, followed by drying at 27.5 °C ±2.5 °C and a RH 30 ±5%. The drying process can be performed at even higher temperatures of 65 ±3 °C and a lower RH of 12.5 ±2.5% when following certain variations of the standardized tests. The test results are the ratio of the delamination length to the total length of the glue bond line. In contrast, block shear strength tests are usually performed at normal climatic conditions corresponding to 20 °C and a 60% RH. The result of the tests are glue bond resistances expressed in MPa.

There are specific requirements for the minimum block shear strength and the maximum allowable delamination, defined by universal product quality descriptors. However, in real production environments, a limited number of randomly selected elements are tested during manufacturing. The pre-defined sample length is relatively short and corresponds to 75 mm in the case of delamination testing. Consequently, only limited wood/adhesive composite volumes are reflected in the assessment results. This leads to the poor reliability of such testing methodologies and limited quality assurance, since tests are performed on a very small fraction of the overall volume of the engineered wood products. No automatic at-line or online monitoring solutions are currently integrated with glue-laminated timber production. Such systems are common, however, in the manufacturing of other wood-derived composites, such as particle/fiber boards and plywood. Stress wave velocity measurements are usually applied for board quality assurance. Similar technologies based on ultrasound propagation were tested in the laboratory to determine their suitability for delamination detection in glue-laminated timber products (Sanabria *et al*. 2011, Sanabria 2012). Hasenstab (2006) presented an extensive overview of non-destructive testing applications for solid wood and GLT products. The focus was the impulse-echo method, which is rarely used for testing wood. Unfortunately, the industrial applications of such solutions are currently limited as further adaptations are required for feasibility.

Determination of wood moisture content

The correct moisture content of glued elements is critical for the assurance of optimal resin setting, as well as the future performance of the glued products. The measurement of the electrical resistance or the impedance of wet wood is the most popular technique applied for quality assurance of glue-laminated timber products. The measurement results are used to sort and remove lamellae that are too wet or too dry according to the production process specifications. However, electrical resistance measurements have important limitations, such as limited accuracy and uncertainty, which are affected by moisture gradients and the volume of the sample tested, especially in the subsurface layers of wood. This results in uncertainty in the moisture level measurements. The achievement of accurate moisture levels is indispensable for the proper setting of some resins, including 1C-PUR.

The wood moisture content, as well as the glue curing kinetics, are indirectly controlled by the precise conditioning of the production facility climate. Both air temperature and RH are monitored during the process at all locations where gluing procedures are implemented. The process conditions are precisely controlled, with a set of relevant parameters recorded for certification according to DIN EN 14080.

Application of the primer and adhesive

The quantity of applied primer and adhesive is key to ensuring optimal glue bond quality. These quantities are typically experimentally optimized in preliminary tests (Künniger *et al*. 2006).

Monitoring of wood surface smoothness

The wood surface roughness of the glued elements is another critical factor that influences glue bond quality. The direct measurement of surface roughness and the determination of surface topography are rarely performed in a systematic manner, even if suitable technological solutions are available (Sandak *et al*. 2020). Instead of continuous surface roughness monitoring, manufacturers rely on the frequent scheduling of tool changes, adjustments to the feed speed, and the superior quality of the cutting tools. Consequently, information regarding the quality of glued surfaces, which is valuable for statistical process control, is very limited, especially in small production plants.

Selection of wood suitable for glue laminated timber products

All lamellae used in the production of elements with a strength class higher than GL24 are required to be strength graded. Additional visual pre-sorting by experienced graders is frequently performed when gluing hardwood products to minimize future delamination problems in engineered timber products. The gluing of hardwood has been reported to be much more demanding than that of softwoods (Ohnesorge *et al*. 2010, Lüdke *et al*. 2015, Ammann, *et al*. 2016, Konnerth *et al*. 2016, Aicher *et al*. 2018, Clerc *et al*. 2018). Hardwood processing requires producers with significant practical experience, as well as an extensive knowledge base. This results in the design of custom hardwood glulam configurations, the adoption of innovative gluing technologies, and the knowledgeable application of optimized adhesives. Lap shear tests according to treatments A1, A4, and A5 defined in DIN EN 302-1 are performed on beech wood to ensure proper glue joint strength. This reflects the fact that beech has a significantly higher shear strength than softwoods, resulting in higher stresses on the glued joint than on the wood. Failure when lap testing spruce wood in the dry state usually occurs in the wood itself, preventing the quantification of the proper adhesive strength. The three standardized test configurations, A1, A4, and A5, can yield significantly different stress distributions for the same adhesive joint. Reported mechanical stresses are also influenced by the sample size due to the "volume effect," as well as possible relaxation after the gluing of large samples. Diverse intrinsic wood properties can also alter the test results. These properties include physical features, such as density, strength and anatomical structure (Hunt *et al*. 2018), as well as hygroscopic and chemical characteristics. Regarding the latter, the effect of extractive components on glue bond performance is still not fully understood (Konnerth *et al*. 2016, Aicher *et al*. 2018, Liska *et al*. 2020).

Industrial machine grading systems usually rely on bending stiffness measurements or the assessment of the modulus of elasticity from the natural vibration frequency measurements. Strength classes are typically assigned according to the DIN EN 338 standard. It should be mentioned that modern scanning systems provide a large amount of additional machine-readable data resulting from wood grading procedures. Density, grain angle, growth ring pattern, wood color/texture characteristics, and the presence of material deficiencies are normally determined in addition to mechanical strength. These data may be of great value for statistical process control, as well as for the glue bond quality assurance system. The same set of information can also be used for wood cutting process optimization, particularly for elements requiring a specific visual appeal, such as exterior coated surfaces or parquet lamellae.

Non-standardized methods for glue bond analysis

Diverse alternative methods to the standardized solutions described above are applied to determine timber glueability. Some of these techniques involve the measurement of a variety of material characteristics with a very high spatial resolution and/or the assessment of unique traits that determine the cohesion and adhesion processes. For example, digital image correlation was used to measure crack initiation and crack propagation in adhesive joints under load (Knorz *et al*. 2016). Atomic force microscopy (AFM), scanning electron microscopy, and related nanoindentation (NI) techniques enable the determination of the mechanical properties of the wood cell wall at the nanometer scale (Sonderegger *et al*. 2015, Casdorff *et al*. 2018, Bockel *et al*. 2020). A similar level of observation can be achieved by analyzing the materials in situ when performing tests in a synchrotron. Such tests can be combined with other analyses, such as acoustic emissions induced by the micro-tensile testing of glue bond joints (Baensch 2015). Even if the level of detail provided by these analytic techniques is excellent, the useability of such highly detailed information for the interpretation of the behavior of real adhesion systems is limited, since only a very small volume/section of the glued sample can be analyzed using these high-resolution techniques. Therefore, the results are unlikely to be representative of the macro-sample configuration. Figure 7 illustrates the

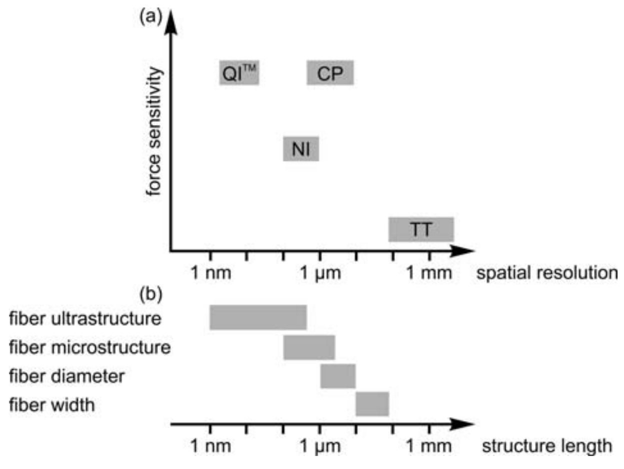

Figure 7. Force sensitivity of diverse high-resolution test methods assisting analysis of wood integration with a primer as studied by Cassdorff (2018) (a), corresponding wood structure dimensions listed as a reference scale (b).

Note: CP - compact sample, AFM – atomic force microscopy, NI - nanoidentation, QITM - quantitative imaging, TT - micro-tensile test.

problem related to the scale of observation when applying high-resolution procedures such as micro-tensile tests (TT), AFM, or NI (Cassdorff 2018). The results of ultra-high resolution methods for glue bond analysis appear to be as inconclusive for solving specific problems as very low resolution techniques. Conversely, the best model for predicting glued wood performance is realized when integrating a large number of parameters representing different aspects of the substrate material, the adhesive, the gluing process, and degrading factors occurring during the service life (Lobenhoffer 1990, Schweitzer 1992, Hasener 2004). The multivariate data analysis approach combined with data fusion algorithms is an example of an efficient solution that can be applied for this purpose (Sandak *et al*. 2021).

The detection limits of instruments used for glue bond analysis are key in determining their suitability for delivering valuable reference data and for their successful integration with industrial monitoring systems. The presence of a primer on the wood surface before gluing can be detected by analytical instruments only when applied in sufficiently high concentrations (Casdorff *et al*. 2018, Bockel *et al*. 2020, Figure 7). Nevertheless, it was identified that a 10% water solution of the primer applied at a rate of no more than 20 g m^{-2} was optimal when gluing ash wood using 1C-PUR. This resulted in a delamination rate of only 2.8% for HB 181 (Henkel) without primer action time. The delamination rate was even lower (2.3%) when the Aerodux (PRF) primer from Dynea was applied, as presented in Figure 4 (Clerc *et al*. 2018). The corresponding delamination rate for wood without primer exceeded 80%, while a 20% water solution of the primer resulted in a delamination rate of 50%. Moreover, doubling the amount of the applied primer at a rate of 40 g m^{-2} did not result in reduced delamination.

Open questions and proposed approach for innovation

The majority of methods recently used to evaluate glue bond quality allow the assessment of a single aspect of the studied system at a time. However, the complex interactions between the glued material, the surface treatment, the adhesive applied, and the gluing process conditions, among others, necessitates a broad characterization method portfolio. Moreover, deficient bonding performance may be associated with numerous other factors, such as the anisotropic distribution of the wood moisture content over the bonded lamella surface, annual ring variations, the specific gravity of the wood in neighboring lamellae, the grain angle, and the annual ring orientation. Glued wood surface properties after processing, such as roughness, waviness, and cell walls destroyed by cutting with dull knives, as well as local variations in the extractive component content, can also affect glue bond resistance during the service life of the element. Finally, complex chemical and electrochemical interactions between the wood and the adhesive, combined with specific reaction kinetics, are not properly understood and are not integrated with production process monitoring.

Modern wood industries, especially those following the data-driven paradigm of Industry 4.0, allow access to the diverse information acquired by scanners combined with production lines. This offers a unique opportunity to re-define quality assurance protocols and increase the credibility of engineered timber products for long-lasting service in different structures. Although a broad spectrum of relevant properties is accessible, several physicochemical aspects are not covered by existing scanning technologies. Therefore, the authors have identified that NIRS has great potential to fill the gaps in missing material/process characteristics. Several studies have demonstrated that NIRS can be successfully used to predict the chemical composition and various physical properties of wood (Sandak *et al*. 2010, Sandak *et al*. 2011, Sandak *et al*. 2016, Tsuchikava and Schwanninger 2013). Figure 8 shows an example of the capability of NIRS to predict mechanical strength. Near infrared spectrometers can be easily integrated with production lines as demonstrated in other industries, such as the pharmaceutical, agriculture, and food sectors. Novel developments in the field of NIRS allow the implementation of hyperspectral imaging systems capable of space-resolved spectral analysis. The potential uses of NIRS in the systems monitoring of gluing processes include the mapping of the wood moisture content, the determination of the presence of extractive components, the estimation of wood density, and the assessment of surface roughness. When combined with other available characteristics via data fusion, multivariate data analysis is considered a highly promising, innovative methodology for the modern wood gluing industry (Schubert and Kläusler 2020). The overall aim is to develop approaches for improved process control under industrial conditions. This is also the focus of the review.

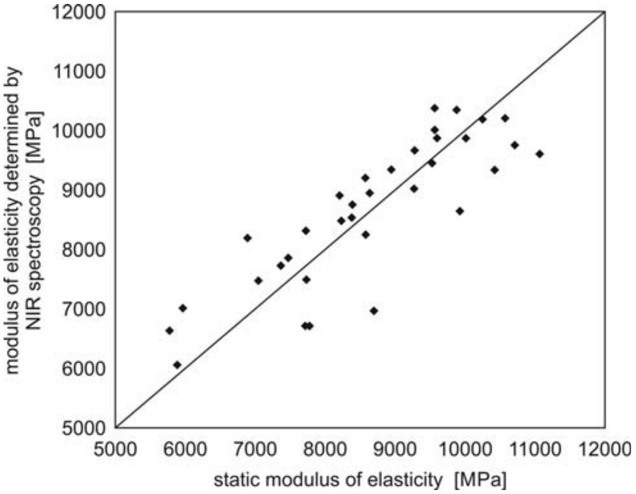

Figure 8. Correlation between measured and from the results of the NIR spectroscopy estimated modulus of elasticity of wood according to (Thumm and Meder 2001).

Summary and conclusions

The gluing of wood is a valuable technology that allows the preparation of innovative engineered timber products. However, this process is highly complex considering the complex interactions between the wood surface, adhesives, and the gluing process. High-value timber products are required have a long service life and a continuous high load-bearing capacity. Quality assurance solutions for the production process are therefore indispensable to guarantee the expected performance of engineered timber products and the full satisfaction of users. This can be achieved by a good understanding the factors affecting the strength of the glue bond and its resistance to delamination. Diverse sensing techniques integrated with state-of-the-art production lines are able to supply an extensive amount of data that can be correlated with the predicted glue bond performance. It is proposed, however, to include NIRS in the measurement system portfolio, thereby allowing the prediction of several traits missed by other available scanning technologies. An original solution for extensive data modeling combined with multisensor fusion is necessary to achieve this goal. This is an objective of the ongoing work that will be reported as a follow-up to this review.

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