WG6: Review of certification procedures for bonded structures

Elements for a roadmap

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Abstract

An increasing interest in meeting unprecedented levels of eco-efficiency is observed nowadays. Consequently, many industries, including the aircraft, construction, automotive, naval, offshore, and wind energy sectors, aim to lighten structures by combining (or replacing) metals with composites.

Adhesive bonding is the most promising joining technology in terms of weight and performance. Nevertheless, in many industries, its application is still limited to secondary structures, whose failure is not detrimental to structural safety. The main reasons for this limited acceptance of adhesive bonding are our restricted knowledge of the associated key manufacturing parameters, non-destructive inspection techniques, damage tolerance methodologies, and tools for diagnosis and prognosis of structural integrity.

Certification of a product, service, or system is the provision, by an independent body, of a written assurance that the product, service, or system under consideration meets specific requirements. In the present report, we review the certification of adhesively bonded structures in four broad industrial sectors: civil aviation, building, automotive, and maritime.

After highlighting the goals of such a study, we will discuss several "elements" involved in the certification process: material compatibility, bonding process, component design, manufacturing, physical test, and simulation. We hope that our work on this topic will be used as a roadmap for developing certification schemes for primary adhesively bonded structures toward increasing the acceptance level of adhesive bonding in the industry.

1. Introduction

With the increasing pressure to meet unprecedented levels of eco-efficiency, the aircraft industry aims for superlight structures and towards this aim, composites are replacing the conventional aluminium. The same trend is being followed by civil, automotive, wind energy, naval, and offshore industry, in which the combination (or replacement) of steel with composites can increase the strength-to-weight ratio [1]. However, the design of joints does not follow this transition at the same pace. Composites, like the majority of other construction materials, are currently being assembled using fasteners. This represents a weight penalty for composites, since holes cut through the load-carrying fibres and destroy the load path.

Adhesive bonding is the most promising joining technology in terms of weight and performance. However, its lack of acceptance is limiting its application to secondary structures, components, and joints, whose failure is not detrimental to the structural safety. In primary (i.e., critical load bearing) structures, fasteners are always included along bondlines, as a "back-up" in case the bond fails. The main reasons for this lack of acceptance are the limited knowledge of their key manufacturing parameters, non-destructive inspection techniques, damage tolerance methodology, and reliable diagnosis and prognosis of their structural integrity.

What is the role of certification in this lack of acceptance? Would the development of certification schemes for primary bonded structures increase the acceptance of adhesive bonding in industry? Is the scientific and technological state-of-the-art sufficiently mature to provide a solid basis for certification schemes, or there are still significant knowledge gaps? The COST Action CERTBOND was initiated with the mission to boost the cooperation of different stakeholders from research organizations, industry, and certification bodies, and to produce a roadmap for certification schemes of adhesively bonded load-bearing structures.

1.1. Fundamentals of product certification

ISO introduced a general definition of certification as a process, that is independently of the specific nature of the product or service that is being certified [2]: "*The provision by an independent body of written assurance (a certificate) that the product, service or system in question meets specific requirements.*"

Several types of certification schemes can be developed consistently with the above definition (see [3] for a possible categorization). Figure 1 shows a generic model of certification processes based on the ISO definition, illustrating the interconnected roles and responsibilities of different stakeholders: manufacturer, product, certification body, third-party (required in some cases, for example Notified Bodies for the CE marking of some products to be sold on the European market) who is doing what and what are the responsibilities stipulated by the regulatory framework.

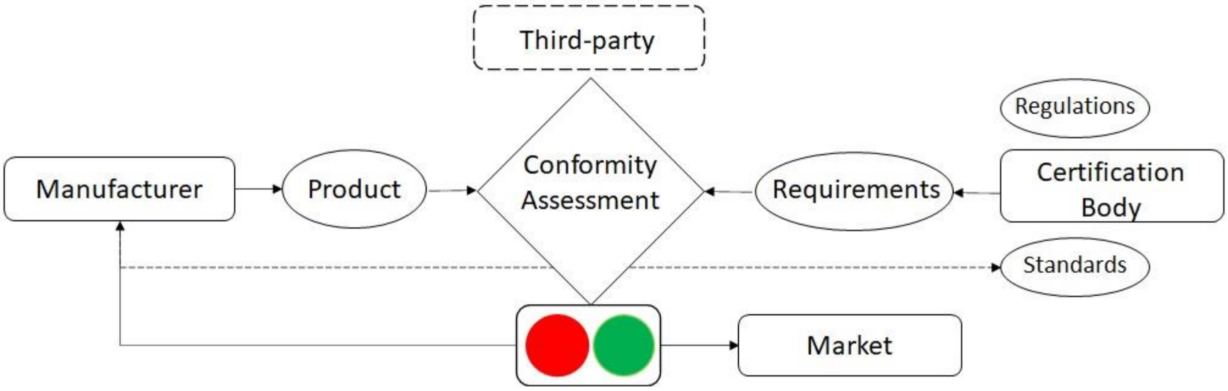

Figure 1. A generic process model for product certification schemes that should represent most of the cases found in different industrial sectors.

The attribution of responsibility among different parties (e.g., manufacturers, providers of testing services, certification bodies) is the other dimension to consider, besides the overall structure of the certification process and the type of evidence required. The presence of a third-party organization for the verification of conformity to stipulated requirements is not always mandatory. Requirements might be of different nature, for example, regulatory requirements might refer to standards or other technical documents that stipulate technical requirements to be considered in the Conformity Assessment process. Standards might be public or confidential: in the latter case, they are disclosed by the manufacturers only to the certification bodies.

The general process model sketched in Figure 1 may be tailored to the case of adhesively-bonded load-bearing structures (in the following, denoted shortly as “bonded structures”), and its actual implementation in different industrial sectors (that is, aviation, civil engineering, maritime, and automotive) is reviewed in Section 0. It is worth noting that certification and, more generally, quality assurance procedures, are devised for bonded joints in both structural and non-structural applications, that is even in cases where the loss of bond strength does not critically compromise the safety of the structure.

1.2. Quality management of adhesive joints

According to the definition introduced in Section 1.1, certification is all about independent verification that the product under examination fulfils a set of predetermined requirements. In the case of adhesively bonded structures, the requirements encompass both design and manufacturing aspects for the adherends as well as the adhesive material and how they are assembled to establish a reliable bond for the intended function of the structure.

The measure of fulfilment of stated requirements is essentially how the (multi-faceted and sometimes ambiguous) concept of quality is interpreted in the context of product certification, consistently with the general definition adopted by ISO 9001, the leading international standard for quality management systems [4] (which refers to [5] for the detailed definitions of "quality" and other relevant terms).

However, it should be observed that the notion of quality and systems for quality management are independent from any obligation for a product to be certified in order to access the market, for which the role of third-party attestation is crucial. Systems and processes to monitor and improve the quality of products are established essentially at any manufacturing company, even in absence of external requirements. Regarding adhesive joints, the automotive industry represents a striking example of this scenario, where quality management and quality control systems are firmly established since decades, especially for manufacturing, while there are no certification schemes that aim specifically at bonded parts. The development of quality management systems is often sufficiently motivated by business drivers such as efficiency and robustness of manufacturing processes and customer satisfaction.

Quality Management and Quality Assurance should not be confused with Quality Control, as pointed out in [6]. Quality Control is the process to assess the degree by which the product fulfils the requirement, including the technical means to perform the task (e.g., testing and inspection), which may be destructive or non-destructive. Quality Control focuses on the product, and it can be seen as a key part or function within the general framework of Quality Management, which according to the ISO definition, is intended as the process of monitoring and controlling all the activities within an organisation which determine the achievement of the quality objectives [5]. Quality management includes establishing quality policies and quality objectives, and processes to achieve these quality objectives through quality planning, quality assurance, quality control, and quality improvement [5].

Testing procedures and related standards used in Quality Control of adhesive joints are reviewed in several publications, for example [7]. In contrast to physical test methods, computational modelling techniques (such as those reviewed in [8]), are normally not part of Quality Control, in spite of being extensively used at the design stage to evaluate the expected load-bearing capacity of the joints. The current level of maturity of computational methods and capabilities suggests that the possibility to certify bonded structures by means of virtual methods (that is, the concept of "*simulation by analysis*" [9]) is quite remote, and it is likely to remain so, at least in the near future.

The definition of Quality Management systems for bonded structures has seen considerable interest from academic and industrial researchers for at least three decades, as evidenced by the early European project "QUality ASsurance In Adhesive Technology" (QUASIAT [10]). More recent contributions can be found in several publications, such as [11] [12] [13] [14].

Standardization efforts, particularly driven by the German Institute for Standardization (DIN), led to the development of two standards for Quality Management of adhesive bonding processes:

- Part 4 of DIN 6701, dealing with manufacturing control and quality assurance for bonded components in railway vehicles [15]. Part 2 and Part 3 of the same standards cover other aspects, namely qualification of suppliers of adhesive materials [16] and design and construction guidelines [15], respectively. Part 1 about basic terms and rules was published only in draft form and later withdrawn [17]. After being originally developed in Germany, DIN 6701 has become de facto an international standard for the railway vehicle manufacturing industry. Guidance about the certification process according to DIN 6701 can be found in [18].
- Part 1 of DIN 2304, which describes general quality requirements for adhesive bonding processes, regardless of the type of final product [19]. An introduction to this standard and its practical implementation can be found in several publications, for example [20] [21] [22].

2. Certification schemes of bonded structures

2.1. Civil aviation

Since 1944, the International Civil Aviation Organization (ICAO) has recommended all member states—over 193 countries currently [23]—the certification of any aircraft (or parts thereof) against standards of airworthiness established by national Civil Aviation Authorities (CAAs) [24]—such as EASA, FAA, TCCA, ANAC. This certification includes aspects of design, production, and maintenance [25]. First, CAAs issue design approvals (e.g., type certificate) for aviation products—aircraft, engines, and propellers—or articles—parts, and appliances (21.A.21 of [26]). Typically, an airworthiness certificate is, then, issued to an aircraft manufactured under a production certificate that conforms to its type certificate and is in condition for safe operation (21.A.174 of [26]). Such airworthiness certificate usually remains valid as long as a certified maintenance organization (e.g., a repair station or an airline) ensures the aircraft continued airworthiness [27]. Therefore, certification is typically mandatory in civil aviation.

Nonetheless, CAAs do not certify adhesives or bonded joints per se, but only as a part of an aviation product or article. For this certification, each joint is addressed as a bonding system [28]. As illustrated in Figure 2, bonding systems consist of four correlated elements: adhesive, substrate, surface preparation, and bonding process. Not only each element must be individually characterized, documented, and controlled but also the bonding system's performance (i.e., adhesion, strength, and durability) altogether [28] [29]. As a result, a bonding system is typically re-characterized whenever one (or more) of its elements is changed. Besides a qualified bonding system, design features (e.g., geometry and dimensions) are considered for substantiating structural bonding [30].

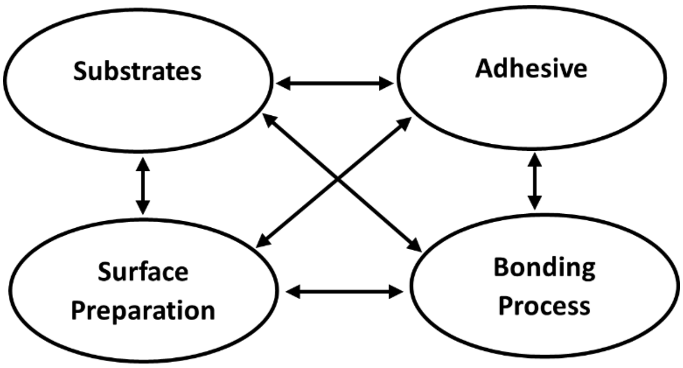

Figure 2 – Bonding system (adapted from [28])

Considering the importance of surface preparation for structural performance, structural bonding is defined as a joint created by the process of adhesive bonding, comprising one or more previously-cured composite or metal substrates [31] [32]. According to this definition, only co-curing and secondary bonding—as illustrated in Figure 3—are structural bonding.

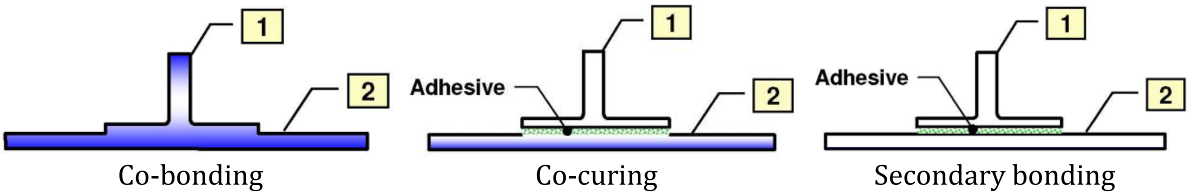

Figure 3 – Types of bonding (adapted from [31])

CAAs issue type-certificate to aviation products after finding compliance with specific airworthiness rules (e.g., CS-23 [33], CS-25 [34]). Airworthiness requirements are typically high-level—tending to be more and more performance-based. Currently, there is no airworthiness requirement specifically dedicated to structural bonding. Nonetheless, general airworthiness requirements—such as CS 23.2250, CS 23.2260, CS 25.601, CS 25.603, CS 25.605, and CS 25.613—establish that design details and materials and manufacturing processes (e.g., bonding) must be demonstrated – by means of physical testing – to be suitable for the intended purpose and durable throughout the product/article operational life, considering the environmental conditions expected in-service—such as temperature, fluids, and ultraviolet radiation.

Materials and manufacturing processes must be controlled and conform with specifications to ensure the consistent production of reliable structures and to guarantee that mechanical properties (e.g., strength) meet the values assumed in the design. Enough tests must support meeting these specifications to establish design values of those properties with statistical significance. Other general durability and damage tolerance requirements—such as CS 23.2240 and CS 25.571—establish that the necessary maintenance actions (e.g., inspections) must be put in place—supported mainly by tests—to ensure no catastrophic failure due to fatigue, manufacturing defects, accidental damage, and environmental damage occur throughout the aircraft operational life.

CAAs publish guidance on a means (but not the only ones) to comply with airworthiness regulations. Regarding structural bonding, EASA AMC 20-29 [32] (harmonized with FAA AC 20-107B [35]) establishes that string process control and durability substantiation are paramount to ensure the long-term safe operation of bonded structures. On top of that, for safety-critical structures, the applicant must (1) demonstrate limit load (defined as the maximum load expected in service) capability considering bond failure between arresting features; (2) test limit load capacity for each manufactured bonded joint; or (3) use non-destructive evaluation (NDE) to ensure bond's full strength. This concept applies also to bonded repairs [28] [29].

Option (1) is typically preferred, option (2) is occasionally used in selected applications, and option (3) is yet to be used in any certified aircraft. Alternatively, a fleet leader approach (including NDE and tear-down inspections) is used in specific structures, such as rotor blades [36]. FAA AC 21-26A [37] also provides guidance on structural bonding. This production-oriented guidance material sets forth essential features of quality systems—e.g., material specifications, process control, storage, and handling—to establish specifications based on approved data developed on proof-of-structures evaluations during type certification.

CAAs also published non-regulatory research reports about best industry practices in bonded structures and repairs [38] (see also [39] for an assessment of industrial practices and [40] for a survey of composites certification initiatives led by FAA). Industry publications (e.g., CMH17 [41], SAE CACRC [42], [43]) on such best practices supplement government policies as well.

Bonded joints are by and large used successfully in civil aircraft, despite several notable accidents/incidents that have bonded joint failure as a contributing factor [44]. The root causes underlying the failure of bonded joints in these events are often associated with production or maintenance issues. Lessons learned from such in-service experience typically corroborate current regulations, guidance, and best practices for certifying aeronautic bonded structures [45].

2.2. Civil engineering

In the last two decades, the design and manufacturing processes of adhesive bonding in civil engineering have been refined to ensure joint quality. However, past experience from industry indicates that bonding failures due to improper surface preparation and various manufacturing errors cannot be completely avoided [46]. Consequently, the development of reliability-based design and fabrication of structural bonding joints is primarily based on the development of reliable quality control and evaluation.

No specific certification scheme has been devised to address exclusively adhesive joints. Existing certification procedures are designed for specific types of construction products. Most of these certification schemes demand that the structural design of the products should be verified according to a codified set of rules (denoted as “*design codes*”) that establish the main guidelines for building engineering practice in different geographical areas (for example, Europe, USA, Canada, or Japan). As part of the certification of construction products, the design is usually verified to fulfil the requirements stipulated in the design code or other normative documents (for example, dedicated standards).

The following subsections focus primarily on certification schemes that entail the verification of structural design according to the European design code known as *Eurocode* [47]. Structural design for buildings and infrastructure in Europe is largely guided by this collection of technical standards, which was established as the common reference framework for structural design since the early 1990s (although its development started earlier), thus harmonizing key elements of construction industry practice, which was historically very diversified across different countries. The basic concepts underlying the certification of construction products in Europe are outlined in Section 2.2.1.

The requirements specifically given for the design of adhesive joints in Eurocode differ significantly depending on the material of the adherends. The majority of existing prescriptive rules or recommendations are given for connections between timber structures, whereas adhesive bonding of steel and aluminium parts is considerably less represented in the current standards. Guidance about requirements and experimental characterization of adhesives in structural applications can be found in the European standards EN 15274 (for general-purpose adhesives, with some limitations in material combinations and loading conditions) [48] and EN 15275 (specific for co-axial metallic assemblies) [49]. For information on pre-normative research targeting adhesive bonding for metallic structures in the framework of Eurocode, see [50].

2.2.1. Certification of construction products in Europe

Certification of construction products benefits manufacturers, architects, contractors, and developers, assuring them that products meet safety and performance requirements [51] [52]. Design Codes might formally be designed as or refer to national or international standards to establish minimum requirements for regulatory compliance.

The standards are typically developed through consensus processes coordinated by Standards Development Organizations. Standardization work is carried out by dedicated committees that are open to all stakeholders, such as manufacturers, researchers, service providers, suppliers, etc. In some cases, manufacturers are allowed to self-declare that the performance of their products fulfil the relevant regulatory requirements [51]. In other cases, the conformity must be attested by an independent organisation, that is the product must undergo a formal certification process as intended in the ISO definition reviewed in Section 1.1.

2.2.1.1. Design verification – general framework and requirements

Design verification is an important part of the certification process for most construction products. The methodology for design verification is based on the partial factors method described in Eurocode [53]. The capacity of structures to fulfil structural safety and serviceability requirements is assessed within a probabilistic framework where the design loads E_d (and combinations thereof) and the design resistance R_d are characterized separately and then compared, which can be formally expressed as

$$E_d \leq R_d. \quad (1)$$

Uncertainty in loads and resistance, which typically arise from natural variability of natural phenomena and manufacturing processes, as well as imperfect knowledge of the actual service conditions for the structure are managed through the introduction of suitable safety factors, which amplify the magnitude of the loads and decrease that of resistance to make conservative estimates about the safe performance of the designed product. Specification of requirements, loads, material properties, and safety factors that should be considered in the evaluation of E_d and R_d are detailed in individual chapters of Eurocode, depending on the type of materials and structures included in the design under verification. Regarding adhesive bonding, requirements and design guidelines are spread over various parts of Eurocode.

For example, a partial safety factor higher than 3 is recommended for adhesively bonded aluminium parts, that is $\gamma_{M3} \geq 3$ [54], in order to provide adequate safety margin against the possible consequences of uncertainty from manufacturing and unknown behaviour during the building lifetime, which is often 50 years or more. The prescribed safety factor for bonded aluminium parts is larger than that recommended for mechanical fasteners, denoting a particularly conservative attitude towards adhesive bonding as joining technique for aluminium components.

In contrast to metallic structures, more detailed guidance is available regarding the use of adhesive in timber constructions. A list of the most representative examples of timber products used in civil engineering with their respective standards for requirements, classification, and characterization, is reported in Table 1.

Bonding is an integral part of the majority of novel timber products both in structural and non-structural applications. Substantial improvement in quality and reliability are expected to result from more standardization in the bonding process, particularly for the formation of the bond line. Enhancements of structural strength and durability of timber products rely significantly on the in-depth understanding of adhesive properties and their susceptibility to the interaction with timber species, and other characteristics of the product.

The selection of adhesive in each application is driven by several factors: the end use of the product, compatibility with the wood type, and bonding conditions [55]. Wood adhesives can be categorised by their application (e.g., structural, semi-structural, non-structural), by the strength and durability that they provide to the bond, or the type of polymers they are made of. Linear polymers such as polyethylene and polypropylene develop linear links that resemble strings of beads. The other type of polymer develops branches of linear chains and the properties of formed polymers change significantly as the branches change. As the density and length of polymers changes the melting point, other properties such as flexibility and strength of the adhesive bond are affected [56].

Table 1. List of adhesively bonded timber construction products and respective design standards.

Timber product	Description	Standard requirements
Glue-laminated timber	Glulam is made of dimensional timber; trued, finished, and glued on the faces, with the grain laying parallel to layers above and below. Species used for the laminates are: spruce, pine, fir, larch, and poplar, although recently hardwood is also used such as beech. Before gluing, the wood is dried to a moisture content of 12 to 15%, and the surface of each laminate is accurately machined to ensure that the glue layer is of even thickness throughout. The development of resin glues contributed to the wide use of glued laminated timber construction.	EN 14080: Timber structures - Glued laminated timber and glued solid timber – Requirements [57]
Glued finger joints	The use of finger joints with glulam allowed for the production of glulam beams and columns on large scale. Glulam finger joints were developed to provide a broad surface area for gluing. Automatic finger-jointing machines help cut the finger joints, connect and glue them together under pressure, allowing for a strong, durable joint, capable of carrying high loads comparable to natural wood with the same cross-section. Finger joints are subject to continuous testing in the production (internal) and external control phases. Formaldehyde emission is also regulated by EN 14080 [57], Annex 2, 2.1.2.2.	EN 14080: Timber structures - Glued laminated timber and glued solid timber – Requirements [57]
Cross-laminated timber (CLT)	The manufacturing of CLT is generally divided into nine steps: primary timber selection, timber grouping, timber planing, timber cutting, adhesive application, panel lay-up, assembly pressing, quality control, and marking and shipping. Application of the adhesive occurs shortly after planning to avoid any issues affecting the surface of the timber. Applying the adhesive is most often done in one of two ways: a through-feed process or side-by-side nozzles. In the through-feed process, extruder heads distribute parallel threads of adhesive along the piece of timber in an airtight system to avoid air gaps in the glue that could affect bonding strength. This is typically used for Phenol Resorcinol Formaldehyde (PRF) or Polyurethane Reactive (PUR) adhesives. For PUR adhesives, the layers of timber may be misted to help with curing. The side-by-side nozzle option is commonly reserved for CLT layers that are formed in advance and work by installing the nozzles along a beam that will travel along the length of the timber and apply the adhesive. To avoid additional manufacturing costs, the adhesive is typically only applied to the top and bottom faces of the lumber, but edge-gluing can be done if necessary.	EN 16351 CLT-Timber structures - Cross laminated timber – Requirements [58]
Laminated veneer lumber (LVL)	LVL laminated veneer lumber products are used in all types of construction projects, from new buildings to renovation and repair. LVL is incredibly strong and dimensionally stable. LVL derives its high strength from its homogeneous bonded structure. The wood raw material for LVL originates from sustainable forests. LVL structures in construction act as long-term carbon storage. The service life of the LVL is considered to be as long as the lifetime of the building, provided the LVL product is installed according to instructions. For a numerical service life value, 100 years can be used. LVL is made of 3 mm thick rotary peeled and strength-graded softwood veneers. The veneers are bonded with weather and boil-resistant phenol formaldehyde adhesive. In S-beam and T-stud all the veneers are oriented in the same direction. In the Q-panel, Qp-beam, and L-panel, parts of the veneers are oriented in a crosswise direction to enhance the transverse strength and stiffness of the products. LVL is made as a continuous billet which is cut to length and sawn into LVL beams, planks, or panels according to the customer's requirements. LVL products are CE marked according to the EN 14374 standard.	EN 14374:2004 - Timber structures. Structural laminated veneer lumber. Requirements [59].
Oriented Strand Boards (OSB)	OSB plate which is manufactured in wide mats from cross-oriented layers of thin, rectangular wooden strips compressed and bonded together with wax and synthetic resin adhesives. The adhesive resins types used include: urea-formaldehyde (OSB type 1, nonstructural, nonwaterproof); isocyanate-based glue (or PMDI poly-methylene diphenyl diisocyanate based) in inner regions with melamine-urea-formaldehyde or phenol formaldehyde resin glues at the surface (OSB type 2, structural, water resistant on face); phenol formaldehyde resin throughout (OSB types 3 and 4, structural, for use in damp and outside environments) [60].	EN 300 Oriented Strand Boards (OSB) – Definitions, classification, and specifications [61].

The requirements and experimental characterization of adhesives found in timber constructions are extensively covered in several European standards. A list of the most common types of adhesives used in timber constructions and related standards is reported in Table 2.

Table 2. List of most common types of adhesives used in timber constructions.

Adhesive	Description	Standards
Formaldehyde	Formaldehyde adhesives (resorcinol formaldehyde (RF), phenol resorcinol formaldehyde (PRF, urea-formaldehyde (UF), and Mixed Urea Formaldehyde (MFincluding melamine urea formaldehyde MUF) are usually waterborne resins and the curing procedure involves polymerisation and loss of water. The loss of water in the bond line delays the reaction of adhesives with wood due to the reduction in wettability and movement of resin. This will limit the collision required for the polymerisation process and heat transfer. Thermosetting phenol-formaldehyde (PF) or UF are the polymers used more commonly in structural veneer-based wood product applications. For exterior veneer-based wood product applications usually PFs are used and UFs are mainly used for interior applications. Formaldehyde adhesives develop a rigid bond and do not creep due to the combined development of polymeric chains and cross-linking groups.	**Classification and performance requirements** PUR: EN 15425:2017 [62] Casein: EN 12436:2005 [63] EPI: EN 16254:2013+A1:2016 [64] **Test methods** Creep deformation EN 15416-3:2017+A1:2019 [65] Open assembly time EN 15416-4:2017+A1:2019 [66] Minimum pressing time EN 15416-5:2017+A1:2019 [67] Tensile strength at high temperature: EN 14257:2019 [68] Static strength at rising temperature EN 14292:2005 [69] Pot life: EN ISO 10364:2018 [70] Emissions of volatile compounds after application EN 13999-1:2014 [71] EN 13999-2:2014 [72] EN 13999-3:2007+A1:2009 [73] EN 13999-4:2007+A1:2009 [74] Longitudinal tensile shear strength EN 302-1:2013 [75] Resistance to delamination EN 302-2:2017 [76] Acid damage on transverse tensile strength: EN 302-3:2017 [77] Wood shrinkage on tensile strength EN 302-4:2013 [78] Maximum assembly time EN 302-5:2013 [79] Working life: EN 302-7:2013 [80] Static load test in compression shear EN 302-8:2017 [81]
Isocyanates	Isocyanates in wood (Polymeric Diphenylmethane Diisocyanate, Emulsion Polymer Isocyanates, Polyurethane Adhesives). Isocyanates are used in wood adhesion due to their reactive characteristics to compounds with reactive hydrogen. These adhesives however can react very fast with wood moisture which will compete against the required reaction with the hydroxyl group in wood's cellulose and hemicellulose and phenol and hydroxyl groups in lignin sections. The other drawback of these adhesives is their high reactivity level with the human body which could cause safety concerns during the gluing process. The most used type of isocyanates is polymeric diphenylmethane diisocyanate (pMDI) in manufacturing oriented strand board (OSB). PUR adhesives are also now widely in use for a wide range of applications in timber products including glulam and cross-laminated timber (CLT).	
Epoxy resins	Epoxy resins are compounded with ketimines that assist with releasing the curing agent when the adhesive is exposed to moisture. Similar technology is already used in coating products. Epoxies are produced with a range of curing times which can influence the degree of cure and mechanical strength of the adhesive layer [57].	
Phenol Resorcinol	This type of adhesive is mainly used in the manufacture of load-bearing timber structures, i.e., to fulfill EN 14080 [57]. They may as well be used for boatbuilding and products exposed to high humidity, such as windows, outdoor garden furniture, playground equipment	
Polyvinyl and ethylene acetate (PVA) and dispersions	These are waterborne adhesives that are cost-effective and do not require a heat-curing operation and they are mainly used in furniture construction. These adhesives commonly exhibit good flow into the cell lumens that are exposed to glue however due to the high molecular weight they do not usually penetrate wood cell walls. Polyvinyl acetate (PVA) is commonly used for wood gluing in nonstructural and furniture making however it lacks water resistance and has low load-bearing properties.	
Bio-based adhesives (protein glues, tannin adhesives, lignin adhesives)	The protein driven from wheat grain (gluten) can react with aldehydes in a similar way to urea. Gluten has a high level of amine groups (lysine and arginine) which react similarly to the ones in melamine and phenols. The availability of gluten from grain is an advantage for its application in wood adhesion. However, the powder form of the gluten limits its applicability to be used in current industrial manufacturing operations. Lignin has a phenolic structure which makes it a potential replacement for phenol in phenolic resins used for wood adhesion. Lignin-based adhesives can be considered in two major categories including phenol formaldehyde and formaldehyde-free adhesives. Initial investigations into using unmodified lignin in phenolic adhesives showed a reduction in glue strength and an increase in press time, so chemical modification of lignin has been suggested as a solution. The use of Kraft lignin and polyethyleneimine (PEI) for the development of a formaldehyde-free adhesive showed very high shear strength and water resistance in the glue developed.	
Miscellaneous composites	In this group of adhesives depending on the role of timber in the composite there are three different product types known: wood-fiber cement boards, wood-plastic composites, and wood filler for plastics. Wood-fiber cement products use plant fiber to reinforce the panels and reduce the possibility of fracture development, this field is still under further studies. Wood-plastic combinations are used to reduce product weight for industries such as the automotive industry. These products require good polymer-fiber interaction otherwise exposure of fiber to moisture and under stress, the interface can fail.	

2.2.1.2. Design verification – conformity assessment

Eurocode rules and design specifications for bonded structural joints are quite simplified and they are often inappropriate for practical design tasks. Furthermore, the analytical calculations normally done to dimension components are based on assumptions and idealizations of loads, geometry, and material properties whose effects as potential source of errors in the predicted performance can be hardly quantified.

Reliable design rules and appropriate requirements for bonded structural joints require an extensive amount of information that is challenging to provide in all circumstances. Examples of important factors that might be costly to characterize, especially for adhesive joints, are the statistical distribution of the resistance and its consequences for durability [82]. Furthermore, the application of a full probabilistic approach might result unfamiliar and impractical to designers and practicing engineers. Therefore, there is a significant risk that design verification procedures based exclusively on prescriptive rules and calculations lead to a poorly reliable assessment of the structural performance of bonded structures.

The alternative approach proposed in the framework of Eurocode is the possibility for design verification to be conducted with a combination of tests and calculations, which is often denoted as "design assisted by testing". Annex D of EN 1990 [47], gives guidance on the planning and evaluation of tests to be carried out in connection with structural design, where the number of tests is sufficient for a meaningful statistical interpretation of their results. Basic statistical techniques for estimating fractiles are briefly described in Appendix C of [83].

Design assisted by testing relies on physical testing of the construction product for establishing design values. Depending on the maturity of the design, the test object might be the finished product or a prototype, a part of a full construction or a model representation, and the testing procedure might be carried out in laboratory environment or in situ.

The "*design assisted by testing*" approach is particularly useful in those cases where the calculation rules or material properties given in Eurocode are inadequate, or when the design to be tested might demand lower economic resources compared to alternative building solutions, provided that safety is not compromised. Tests should be set up and evaluated in such a way that the structure has the required level of reliability concerning all possible limit states and design situations, as would be achieved by just following the stipulations from Eurocode.

Therefore, all relevant sources of uncertainty related to the measurement procedure (e.g., calibration of equipment, environmental factors, operators) as well as to intrinsic limitations in sample size and selection should be evaluated and kept within an acceptable range. Furthermore, the conditions during testing should so far as possible be representative of those which can be expected to arise in practice.

In any case, a reduction in design reliability using Eurocode is not permitted. Therefore, partial factors for loads and material strength comparable to those used in Eurocode should be used.

As clearly stipulated in [47], design assisted by testing should not be intended as an option for designers to significantly reduce the partial safety factors.

2.2.1.3. Production control

Certification in civil engineering applications regards not only how the construction products are designed, but often also how they are manufactured. For example, structural components made of steel and aluminium must be CE-marked to be authorized for circulation within the European market for building materials and components. The prerequisite for companies to be qualified to assign CE marking to their products is that the company itself is certified to fulfil the requirements of the EN 1090-1 standard [84]. The certification according to EN 1090-1 must be issued by a Notified Body (see [2] for guidance on specific terminology regarding product certification).

To meet the requirements of EN 1090-1, manufacturers must implement the Factory Production Control (FPC) management system that controls that steel and aluminium products comply with the requirements specification and the prerequisites in the dimensioning basis. The FPC management system must include procedures, regular inspections, tests, and assessments as well as the application of the results to the management of materials included in your design. FPC can be based on an ISO 3834 [85] system or ISO 9001 [4] system, however, it must be specifically adapted to the requirements of EN 1090-1.

If the products entail the use of adhesive bonding, the implemented FPC should include a specific section dedicated to procedures for quality assurance of the bonded components or systems. No specific guidance is given just for adhesive bonding in the governing standards for the certification of production systems.

2.3. Automotive

Vehicle manufacturers have responded to the increase in prices of raw materials and legislative restrictions on CO_2 emissions for vehicle fleets by concentrating on designing lighter vehicles. An obstacle to this effort is the increase in weight resulting from steadily growing safety requirements, such as supplemental airbags or structures to absorb crash energy. Furthermore, the use of electronic systems is growing due to increasing customer demands in terms of comfort, which also add extra weight to the vehicle. Given the fact that the mass of the car body constitutes a large part of the total mass of the vehicle, it is reasonable to pay special attention to lightweight car body construction.
The adhesive bonding technology has been increasingly applied in the automotive sector for the last 40 years. In more recent years, in particular, multi-material combinations are increasingly used in car bodies, because of their potential to reduce the vehicle weight by optimizing materials use depending on their intended function at different locations in the structure. At the design stage, it is important to consider the different types of stress the materials will be subjected to. For example, in addition to crash resistance, stiffness, and

resistance to fuel and oil, galvanic corrosion due to different electrochemical potentials must be avoided, particularly in material combinations.

Multi-material combinations call for suitable adhesive joining technologies. To ensure the performance of the entire vehicle, especially concerning crash safety, rigidity, and corrosion, quality assurance methods are required to ensure the efficiency of adhesive bonds in applicability and costs. Nevertheless, no specific standards for the qualification and certification of the adhesive bonding process are publicly known.

ISO 9001 [4] considers adhesive bonding as a special process, and, therefore, there is a need for qualification and certification of the involved procedures and operators. In contrast, the publicly accessible literature on the certification adhesive bonds in automotive industry is scarce. Among the few available sources on research that address this subject, there is the very short description of the joint project supported by the European Union in 1997, where several large automotive companies were involved (Ford, Volkswagen, Toyota, Renault) [86].

The project aimed at defining methodologies for the qualification and certification of adhesive bonding procedures and operators applied to the joining of automotive components. In the frame of that project, adhesive bonding specifications and qualification variables were defined accordingly to the product to be manufactured. The project intended also to facilitate mutual understanding of design specifications within the automotive industry, introducing standardized definitions for the main parameters involved in the qualification of adhesive joints.

More recent work highlighted the role played by physical testing in early stage of vehicle development as a key enabler of *preventive* quality management systems. Present-day conventional destructive test methods must be supplemented by non-destructive methods. A preventive quality management already used in the early stages of development by simulation methods can help reduce inspection costs and expensive reworking in the prototype phase. and its potential to facilitate a wider adoption of adhesive bonding as joining technique in automotive manufacturing [87].

2.4. Maritime

A comprehensive overview of the applications of adhesive bonding as joining techniques in maritime engineering is given in the book edited by Weitzenböck [88]. The opening of Chapter 5 outlines the regulatory framework for the certification of adhesive joints in maritime structures [89]:

"*Merchant ships in international trade must satisfy the international regulations of the International Maritime Organization. Conventional merchant ships, typically of welded steel construction, must satisfy the international convention for the Safety of Life at Sea (SOLAS)* [90]*. Classification societies issue ship design rules that are accepted under SOLAS. None of* *these provide provisions for adhesive bonded joints. Therefore acceptance of adhesive bonded joints in major load-bearing parts of steel merchant ships would require interaction with the relevant classification society and may require consultation with the relevant flag state administration. An efficient lightweight structure is of particular importance for high speed craft. Hence the High Speed Craft (HSC) Code of the IMO* [91] *allows for the use of composite materials in the major load-bearing structure. Classification societies issue design rules for HSC that are accepted under the IMO HSC Code. DNV Rules for Classification of High Speed, Light Craft and Naval Surface Craft provide specific provisions for bonded joints and require qualification tests carried out on realistic samples that have received realistic ageing in the specified service environment.*"

Certification of maritime structures (e.g., ships, offshore constructions) is carried out by specialized organizations denoted as "Classification Societies". The different Classification Societies develop their own technical standards, including requirements and conformity assessment methods, which are typically publicly available. The main standards and reference documents concerning adhesive bonding in maritime structures issued by the leading Classification Societies in the maritime industry are listed in Table 3.

The assessment tasks in the certification of maritime structures are performed by representative of the Classification Societies, who act more as surveyors rather than inspectors. Their goal is to check if the structural design proposed by the manufacturers is safe, without excluding the possibility to fulfil the requirements in several ways. The Societies are even allowed to advise the manufacturers about possible technical solutions to fulfil safety requirements. That is quite in contrast with the design and certification practice in construction industry, which is generally more prescriptive.

Regular controls are performed on ships to evaluate, for example, fatigue damages, or damages from incorrect loading/use (some checks are made every year, then every 5 years the ships are docked and inspected). Classification societies perform these checks themselves (exclusive surveyance), whereas in aviation manufacturers are delegated by certification bodies to perform that (possibly, with the help of subcontractors for some parts).

Table 3. Standards and reference documents for adhesive bonding in maritime structures.

Classification Society	Standard/Guidelines for adhesive joints	Description
Bureau Veritas	Guidance Note NI613: Adhesive joints and Patch repair	This guideline is currently being updated into a much more detailed version for adhesive bonding, for structural application, and a separate guidance note on patch repairs [92].
	Guidelines from project QUALIFY (Enabling Qualification of Hybrid Structures for Lightweight and Safe Maritime Transport)	The project QUALIFY aimed to provide certification guidelines for hybrid metal-

		composite adhesive joints for the maritime industry [93].
Lloyd's Register	Rules for the Manufacture, Testing and Certification of Materials – Chapter 14.	These guidelines regard materials used for the construction, conversion, modification or repair of ships, other marine structures and associated machinery which are classed or are intended for classification by Lloyd's Register. They are to be manufactured, tested and inspected in accordance with these Rules [94].
American Bureau of Shipping (ABS)	Requirements for Bonded and Composite Repairs of Steel Structures and Piping	This standard provides classification requirements for marine vessels and offshore units where bonded and composite repair methods provide a suitable repair solution for deteriorated steel structures or piping at construction, conversion, or renewal [95].
Det Norske Veritas	Classification Rules: DNV-RU-SHIPS, July 2023 – Part 2 Materials and welding – Chapter 3 Non-metallic materials, Section 10	General requirements for structural adhesive in ship building [96].
	Recommended Practice: DNVGL-RP-C301: Design, fabrication, operation and qualification of bonded repair of steel structures	This RP provides an assessment and decision-making process on whether to proceed with a bonded patch repair and a design and qualification process to design and fabricate bonded patches. The scope of this RP covers design, materials, structural analysis, fabrication, testing, in-service inspection, and maintenance of bonded repairs. Aspects relating to documentation, verification and quality control are also addressed [96].
	DNVGL-CP-0086: Adhesive systems	This Class Programme describes the procedures and requirements related to documentation, design and type testing applicable for Type Approval of adhesive systems [96].

3. Discussion

As illustrated in Section 0, adhesive bonding finds applications in various industry sectors, both for structural and non-structural components. In many cases, the products that include adhesively bonded parts must be certified before being allowed on the market. These certification schemes present common characteristics, and they have to meet similar challenges. Similarities and differences in certification schemes for bonded structures across different industrial sectors are briefly reviewed in this section.

It is worth noticing that the mandatory character of product certification is common to various industrial sectors. Different levels of certification are required to allow bonded structures to access specific markets. These levels typically encompass aspects of design and production at a minimum.

The certification of adhesively bonded structures requires design values of critical mechanical properties. These design values are typically established based mainly on tests. These tests are expected to consider environmental effects likely to occur throughout the bonded structure's operational life. Enough test evidence is typically required to ensure a certain level of statistical significance to these design values.

A general observation made in [89], that outlines a scenario common to several industrial sectors, regardless of the differences in the type of connections and regulatory frameworks: "*In practice, bonded assemblies representing the real joint design would have to be tested, unless documentation is provided showing that the model used for predicting failure is reliable*".

Besides the design, the production of bonded structures is also typically certified. This production certification typically requires an established quality system. This quality system typically comprises stringent processes control supported by engineering-data-based specifications. Among these processes, surface preparation is typically closely controlled. Process control is acknowledged as particularly relevant for bonded structures considering structural bonding's strong process dependence.

In-service experience of certified bonded structures is mainly positive across the industry. Nonetheless, in-service events having bond failure as a contributing factor have been reported in different industry sectors. These failures are often associated with poor process control.

Despite all the similarities in structural certification among different industry sectors, it is also possible to identify significant differences. In some sectors (e.g., the building industry), the design of bonded structures mainly relies on prescriptive requirements (e.g., Eurocode rules and design specifications). These requirements prescribe design methods for specific applications and are publicly available. On the other hand, in other sectors (such as civil aviation) only high-level requirements are typically established. Authorities typically publish general guidance materials to support applicants. These guidance materials set forth one means (but not the only one) to show compliance with these requirements. The applicants are responsible for establishing means and methods of compliance considered acceptable to the authorities. These means and methods are typically proprietary data.

There are also certification differences related to the structure's lifecycle. Besides the commonly required design and production certification of the bonded structures, maintenance activities are also certified in some industry sectors (e.g., civil aviation). The differences in the intended function of the designed structures in different industrial sectors, as well as in design and manufacturing methodologies have important consequences on the attitude towards risk and quality management, as observed in the following extract from [89]:

"*Marine engineering structures are usually designed as a one-off. This limits the scope for very comprehensive procedure for documenting structural reliability such as are available for bonded joints, for example, in aircraft where large series of identical structures are manufactured. Furthermore, heavy duty steel structures tend to transmit very large loads, putting higher demands on the capacity of bonded load-bearing joints than in other applications. For these reasons, the methods of aircraft engineering cannot be directly transferred and it would be better to aim for a design procedure based more strongly on modelling and failure prediction.*"

A common challenge to the certification of bonded structures in all industrial applications is the assessment of durability [82]. The quality of the structural performance of adhesive joints is hard to assess over the whole interval of time during which the structure is expected to fulfil its intended function. All existing experimental (destructive and non-destructive) and theoretical methods to reliably predict the strength of the bonds and their degradation over time present drawbacks that make it difficult to identify a single procedure that would adequately perform for all products under all in-service circumstances.

4. Conclusions

Structural bonding has been applied for decades to join composite materials in a myriad of applications from several industrial sectors, such as building, civil aviation, maritime, and automotive). Experience has shown that the success of these applications (measured in terms of indicators such as reliability and structural performance) typically depends on demonstrating that the bonded joints meet specific (e.g., design and production) requirements. Different certification schemes have been devised to provide a formal framework that could establish trust in the demonstration of bonded joints properties among all the parties affected by the applications of bonded structures, that is manufacturers (including suppliers), regulatory bodies, customers, and society as a whole.

Certification processes across different industrial sectors share some core similarities (demonstration of material compatibility, bonding process, component/connection design, manufacturing, the use of physical test and numerical simulation as conformity assessment means) — despite industry-specific particularities — and common challenges. There is a need to tackle these challenges to further expand adhesive bonding in safety-critical applications. A major challenge relates to bonding-specific requirements. These requirements are often proprietary data, only too generic, or even non-existent in many industries. Therefore, collective efforts to establish publicly available bonding-specific standards, specifications, and guidelines would be mutually beneficial.

These efforts should explore bonding-related best practices and lessons learned from accumulated in-service experience across different industries. Moreover, research on bonding could also aid in closing these requirement gaps. These gaps include, for instance, universally accepted standards on tests to warrant the durability of composite bonded joints, to accelerate bond environmental ageing artificially, and to establish cost-effective means to interrogate bond quality reliably after the fact.

Different industries could also benefit (in different ways) from guidelines on the certification of structural bonding developed considering all its process-dependent, systemic, and multidisciplinary characteristics.

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