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An Analysis on Finnish Wooden Bridge Practices

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Abstract: To date, the share of research, teaching materials, and practices related to the use of timber in bridge projects in Finland are quite limited compared to other materials, such as concrete. This article, which also includes a structural design example for dimensioning a girder bridge, focuses on the status, applications and prospects of wood use in bridge construction, reflecting the Finnish professionals' point of view. Key findings highlighted that: (1) the ideal use of wood would be in private road bridges and light traffic bridges; (2) while the use of wood in the bridge was assessed to be advantageous in terms of ecology, aesthetics, and environmental friendliness, it was reported to be disadvantageous in terms of long-term durability and connection details; (3) concrete and steel, whose prices fluctuate, could gradually be replaced by wood, a renewable material; (4) timber-concrete composite bridges were expected to become widespread in the future; (5) cross-laminated timber (CLT) could open up an opportunity for bridge decks; and (6) service limit state is often decisive for the dimensioning of wooden bridges. It is recommended to implement large-scale public projects for the wooden bridges by creating sustainable business models that will be supported both legitimately and economically by the local government. In this sense, close cooperation between authorities and other key market stakeholders is crucial.

Keywords: wood; timber; wooden bridges; girder bridge; structural design; experts; future outlook; Finland

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1. Introduction

Engineered wood products (EWPs) have increased their attractiveness as construction materials due to their superior ecological properties, increasingly competitive cost, mechanical features, and ease of handling [1–7]. Moreover, EWPs such as CLT are gradually being used in demanding implementations to meet sustainable building challenges, including high-rise structures, thanks to their many technical features (e.g., uniform strength and dimensional stability) and environmental aspects (e.g., low carbon) [8–12]. However, the use of EWPs in unsheltered bridge structures is very limited due to their exposure to harsh climatic conditions [13]. Structural engineers are most concerned with the service life of load-bearing structures, which is recommended as 100 years in Europe [14].

It is worth mentioning the main mechanical properties of wood (e.g., [15–19]). Wood can be defined as an orthotropic material, i.e., it has distinctive mechanical features in the directions of three mutually perpendicular axes. In addition, as far as the properties of wood are concerned, strength is the one which is the most frequently evaluated, and it is characterized by its mechanical properties. They consist of the modulus of elasticity, the modulus of rupture in bending, shear strength and stress in compression parallel to the grain, and compressive stress perpendicular to the grain. The mechanical properties mentioned above are significantly affected by the moisture content of the wood.

The Nordic Timber Bridge Program (NTBP) was launched in the late 1990s to promote wooden bridges [14], and comprehensive research was conducted at NTBP (1994–2002) [20]. NTBP was based on close cooperation between road agencies, wood industries, and research organizations in Scandinavian countries. NTBP had a major output determined by the number of publications, and hundreds of wooden bridges have been built in the northern regions since the program's inception [14]. However, the effects of this program in Finland were small compared to, for example, Sweden and Norway. Today, only 5% of bridges in Finland are made of wood [21].

Efforts to encourage wooden bridges continued after the NTBP ended. For example, the Wood Building Program between 2016 and 2021 was initiated in Finland. This program aimed to boost the usage of timber in urban growth, civic structures, bridges and halls [22]. However, the number of laminated timber bridges for vehicular traffic is still comparatively small in Finland. One such bridge that carries major vehicular traffic is a recently constructed highway crossing in Espoo's Tapiola district.

Different bridges of a wide variety of sizes can be constructed from timber, even for road transport. Prefabricated timber bridges can be built rapidly and the detrimental effects of construction on traffic flow can be reduced. The most important benefit of wood in bridge construction is its lightness and strength [23]. Thanks to the transition from massive timber to laminated timber, large beams can be made from wood.

It is worth mentioning here that fire can pose a serious threat to wooden bridges, especially wind and rain bridges [24]. Fires on bridges can cause considerable loss of life and property, as well as traffic congestion. Thus, the fire hazard in bridges is becoming an increasing concern throughout the entire life cycle of design, construction, use and maintenance [25]. Precautions to use fireproof paint, automatic fire extinguishing equipment, and skylights can make a great contribution to mitigating the risk of fire [26].

The wooden bridge concept in Finland is not seen in a positive light in terms of durability, longevity and maintenance [27]. Moreover, wooden bridges are often perceived as expensive because they are built as landmarks or works of art. Bridge construction in Finland is usually publicly tendered, and when bids are received, it is decided how the bridge will be built and what material will be used.

A total of 584 bridges were built in Finland between 2010 and 2014, but only 17 of them were wooden [20]. Wooden bridges represent about 5% of all road bridges. As a result, of Finland's total of 20,000 bridges, about 900 have wooden bridges. [28]. Compared to Finland, wooden bridges are much more popular in Sweden and Norway.

At the design stage, some features such as the vibration of the bridge should be taken into account compared to other materials in wooden bridges. The choice of construction material for bridges is the sum of many factors, the most important of which are intended use and cost-effectiveness. The choice of the wooden bridge can be justified by the good malleability of the wood, which provides aesthetic structural solutions. Wood, a renewable material, is also an ecological choice, and the wooden bridge is quick to assemble. For convenience, wooden bridges are best on private roads and light traffic lanes that are affected by lower stresses for the bridge.

A critical issue affecting the long-term durability of wooden bridges is the protection of structures, often made with impregnation [29]. The challenge in the near future is that the use of creosote as a preservative will be banned in the spring of 2023. Therefore, there is a need for new solutions that require research for the protection of wooden structures. The use of various innovations in Finnish conditions is limited. For example, it is worrying that salt-impregnated wood deck structures will experience copious rot problems in the early 2020s.

There are many different types of timber bridges in Finland, and the most common of these is the girder bridge. The bearing structure of girder bridges consists of at least two longitudinal main beams and transverse structures connecting them. Currently, they are the only wooden bridges that are type-approved by the Finnish Transport Infrastructure Agency (Väylävirasto) and use transverse tensioning technology in their construction. While wooden bridges are not often preferred in the world, especially in high-speed transportation, in Finland they are generally used as short and small spans for low-speed transportation due to the abundance of forest resources. In this sense, the purpose of using wooden bridges in Finland is mostly suspension (>50%) and waterway (>40%) bridges, followed by overpass bridges (~4%) [28].

As an industry, wooden bridges in Finland are currently quite small, making it difficult to find financing for innovations. In addition, the availability of employees who can carry out the development is also low. On the other hand, wood can provide engineers with the opportunity to build innovative bridges that are technically reliable, ecologically sustainable, and aesthetically suited to user needs. Considering the possibilities of wooden bridges, efforts should be made to expand their use in the most appropriate areas. With the increasing use of timber as a bridge construction material, steps will be taken toward a more ecological infrastructure that requires the cooperation of stakeholders. Discussing the potential and advantages offered by wooden bridges in Finland is one of the motivations of this study.

In the literature on wooden bridges, in 2000, Jutila and Salokangas [30] reviewed the results of important studies on wooden bridges and presented some practical applications. Lamar and Schafer [31] conducted structural analyses of two covered timber historic bridges, The Pine Grove Bridge and the Brown Bridge. Bigelow et al. [32] focused on the preservation process for timber bridge construction in the USA. Le Roy et al. [33] analyzed a novel timber structure technology where a high-performance fiber-reinforced concrete slab is fixed to glulam beams. Hammervold [34] provided a comparative environmental life cycle assessment of three Norwegian bridges with one steel box girder, one concrete box girder and one timber arch. Gustafsson et al. [27] performed a feasibility study to find opportunities for cooperation between information centers in Finland and Sweden in terms of the availability of technical knowledge. Franke et al. [35] investigated material behavior resulting from climate crises in relation to moisture content and dimensional changes in wooden bridges. Olorunnisola [36] introduced the use of wood in bridge construction, including different types of wooden bridges such as log bridges and truss bridges. O'Born [37] conducted a life cycle assessment to examine the comparative environmental effects of two design proposals for Mjøsa Bridge in Norway. Fojtík [38] evaluated the impact of moisture content conditions in timber bridges in Central Europe. Rashidi et al. [39] carried out a broad review of different deterioration mechanisms, preventive procedures, and feasible solutions for the preservation of wooden bridges. Srikanth and Arockiasamy [40] established non-parametric deterioration models for risk and reliability assessments of concrete and wooden bridges. Srikanth et al. [41] examined the performance of aging wooden bridges through field tests and deterioration models. Ostrycharczyk and Malo [42] studied the performance and instability of the arches depending on the wooden bridge form by using FEM models. Bergenudd [43] scrutinized a pedestrian wooden bridge at various construction stages by using dynamic testing and numerical modeling.

To date, the share of research, teaching materials, and practices related to the usage of wood in bridge projects in Finland are quite limited compared to other materials such as concrete. There is no comprehensive study of the status, applications, and future prospects of wood use in bridge construction, reflecting the Finnish professionals' point of view, emphasizing the unique properties of wood. This article, which also includes a structural design example for dimensioning a girder bridge, aims to fill this gap through expert interviews.

The main objectives of the research were (1) to map out the current situation of wooden bridges in Finland, (2) to identify the reasons for choosing the wooden bridge, (3) to reveal the challenges of wooden bridge projects in Finland, (4) to provide a future perspective to wooden bridge construction, and (5) to establish dimensions for girder bridges by structural design, as the most used type of wooden bridge in Finland. In order to understand the driving forces, potentials and obstacles for the planning and construction of Finnish wooden bridges, and accordingly to draw a promising future projection, the research questions were set as follows:

(1) What is the current status of wooden bridges in Finland?
(2) What are the main drivers and challenges of using wood in bridge construction?
(3) What is the future of wooden bridges in Finland?

(4) What are the main design parameters in the structural dimensioning of a wooden bridge?

It is believed that our research will support the widespread use of wood in bridges by contributing to the bridge structures to be developed in the construction market in Finland.

The remainder of the article is outlined as follows: First, wooden bridges in the Finnish context are explained. Then, the research materials and methods employed are given. Next, the results based on the professionals' interviews on Finnish wooden bridge construction and a structural design example for dimensioning a girder bridge are provided. This is followed by a discussion. Finally, conclusions with prospects, recommendations, and limitations of the research are presented.

2. Wooden Bridges in Finland

Before the 1960s, the main material used for bridge construction in Finland was wood, as in the Etelänkylä Great Bridge and the Old Haliko Bridge. The advantages of wood were its easy customization and availability as a domestic renewable material. The use of wood as a construction material in bridge construction has been limited in terms of durability. In many cases, it was considered more logical to use concrete or steel as the main building material, even in front of vehicle bridges. Especially after the Second World War, with the widespread use of concrete in bridge structures, wooden bridge construction in Finland has tended to decrease.

Most bridges in Finland are either state or municipalities owned and, in some cases, may be owned by companies or road councils. The Finnish Transport Infrastructure Agency acts as the owner of the bridges under it [28]. It is responsible for the development of the bridges in cooperation with the Finnish Railways Agency. Although not all bridges are state-owned and therefore under the control of the Finnish Railways Agency, many are designed and built according to the guidelines of the Norwegian Railways Authority. According to the skill structure record, a total of 22,118 bridges are used in Finland (8 November 2022), of which 18,001 are owned by the Norwegian Railways Authority [44]. However, the total number of bridges, private roads, and municipal bridges in Finland must also be taken into account, and not all are registered in the skill structure register. The number of private road bridges is estimated to be around 12,000. The distribution of bridges in Finland can be represented by bridge types, construction materials, and status levels. Figure 1 shows the different bridge percentages of the numbers at the end of 2021 [28]. According to the distribution below, it can be stated that concrete is a dominant building material in bridges.

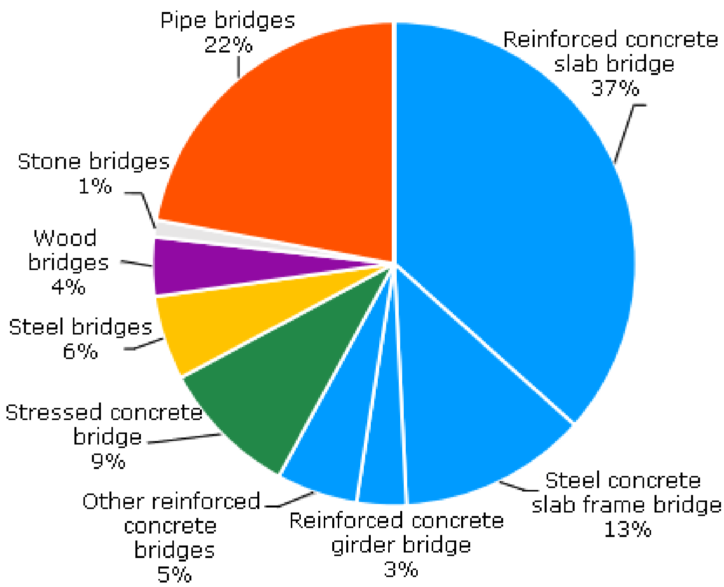

Figure 1. Percentage distribution of bridges by type [28].

The intended uses of wooden bridges in Finland are largely limited to suspension bridges, as in the cases of the Säpilä Bridge and Nahkiala bridge and waterway bridges as seen in Figure 2.

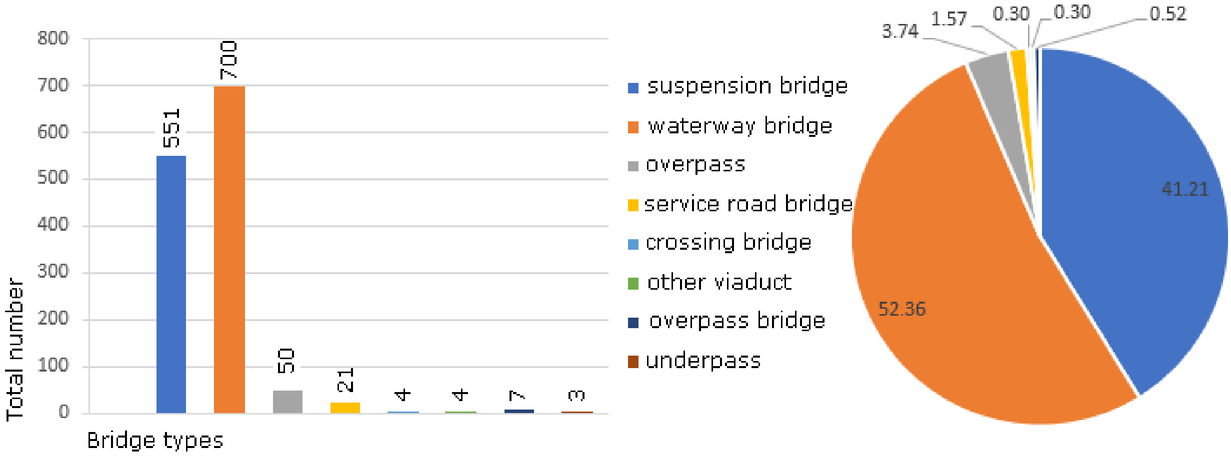

Figure 2. Distribution of intended use of wooden bridges in Finland [28].

There are several types of wooden bridges used in Finland, but the most common among them are beam or girder bridges (Figure 3). Compared to the total number of bridges, the number of wooden bridges is very small. In Finland, the Ministry of Transport and Communications instructed the increase in the use of wood in infrastructure in 2018 (10% by 2022, excluding railway bridges) [45]. The popularity of building wooden bridges is due to recent purchasing procedure practices and general attitudes toward timber construction over the past decade. The client's biases and lack of design expertise were reported as obstacles to the construction of the wooden bridge [46].

Figure 3. Example of a beam bridge from Finland (Photo courtesy of Puuinfo/Versowood Oy).

According to the Finnish Transport Infrastructure Agency [28], there are 1308 wooden bridges in Finland. Of this number, 638 are made of glulam. From a divisive point of view, it is between the position of vehicular traffic on the bus network and light traffic. It is also presented taking into account foreign wooden bridge standards in other Scandinavian countries and possible reasons for the differences compared to Finland. Table 1 shows the distribution of wooden bridge types in Finland.

Table 1. Distribution of bridge types in Finland [28].

Bridge Type	#
Beam	1218
Arc	22
Slab	27
Truss	34
Suspension	4
Beam frame	1
Pontoon	1
Cable-stayed	1
Total	1308

There are 1308 wooden bridges in Finland, of which 554 have primary positions on the waterway network (public road). As mentioned earlier, the girder bridge is the most common type of wooden bridge used in Finland.

Today, the most widely used main building material in girder bridges is glulam. The advantages of using glulam are that different section sizes can be used, and the main supports can also be curved. Other wood materials used in wooden bridges are sawn timber and LVL, but their use is minimal compared to glulam. In addition, before the popularity of glulam girder bridges, a large number of wooden log bridges were built in Finland.

Composite bridges, such as the Vihantasalmi bridge (Figure 4), are extremely rare in Finland. These can be found in different forms, the most traditional being a concrete layer attached to a wooden support structure. One advantage is that it increases the span without increasing the weight of the structure too much. This is a result of the wood's lightness and good tensile strength. In addition, concrete has good compressive strength and adds stability to the composite structure with its mass. The concrete cladding board also provides weather protection for the wooden beam supports, which can have a positive effect on the preservation of the structure. The advantage of composite bridges over normal wooden bridges is that there is no need to use strong chemical preservation methods. Among the Scandinavian countries, Finland was the only country where timber-concrete composite (TCC) was used in bridge construction. The first TCC bridge was opened to traffic in Finland in 1993 [29].

Figure 4. Vihantasalmi bridge, Mäntyharju, Finland, 1999 (Photo courtesy of Puuinfo/Versowood Oy).

3. Materials and Methods

The paper was carried out via a literature review and specialist interviews [47] to consolidate the research (e.g., [48–52]) (Table 2). Finnish professionals from various areas, e.g., the industry sector and university, were broadly selected for the interviews to bring together as many diverse perspectives as possible and to shed light on the current state, development, and future outlook of wood bridges in the Finnish context.

Table 2. Interviewees by their position/title, and organization type.

	Interviewee 1	Interviewee 2	Interviewee 3	Interviewee 4	Interviewee 5	Interviewee 6
Position/title	Specialist in wooden bridges	Sales manager	Bridge expert	Bridge branch manager	Chief technology officer (bridges)	Professor
Organization type	Organization of indirect state administration	Timber producer & refiner	Finnish government agency	Structural design office	Structural design office	University
Characteristics of interviewees	Long-term experience in forestry expert positions	Long-term experience in the selling of wooden products and bridges	Long-term experience in bridges, especially steel structures	Long-term experience in bridge design including wooden bridges	Long-term experience in bridge design and many development projects	Long-term experience as a wooden bridge expert and ten years in academia

In the paper, in-depth interviews were performed with different professionals to collect qualitative data about Finnish wooden bridges. This approach is a qualitative research method that includes intensive personal interviews with a small group of people to explore their perspectives on a specific idea, course, or circumstance. The main benefit of in-depth interviews is that they give much more complete information than other data-gathering techniques. In-depth interviews can also provide a more relaxing atmosphere for gathering information [53].

Moreover, semi-structured interviews were applied as the ideal technique in this study; here, the procedure allowed communication between the questioner and the contributor, and thematically prepared questions developed a basis for dialog. In addition, in these interviews, the different perspectives inspire the development of new topics beyond those originally surveyed [54–57]. The development of the interview depends on the occurrence of the key themes.

Since there are no interviews or surveys similar to this study on wooden bridges in the literature, interview questions were generated through further research on wooden bridges, expert guidance and discussions by authors familiar with the current timber industry and timber research field.

In the interviews performed for this paper, the questions were prepared individually for each expert and the particular view of each expert was highlighted. Also, as opposed to full ranking, a discussion for all interviews became partly open as it was intended to collect as much as possible based on the understanding of pre-organized questions and responses, new inquiries, and a broad understanding of the experts.

Each interview lasted approximately one hour. Interviews were formed through e-mail and administered via an online video conferencing program. The program used made it possible to record the interviews, which enabled the analysis of the results. After the interviews, the video recordings were meticulously re-examined, and the results of the interviews were sent through e-mail to the interviewees for more assessment and completion.

The expert selection was made by goal-directed sampling. The two main considerations for the selection were: the experts had adequate knowledge of wooden bridges and the experts had first-hand experience in wooden bridge projects or had closely followed the progress of the wooden bridge construction. They were selected among the experts who stand out with their knowledge and experience in wooden bridge projects and construction in Finland. This offered a complete image of how experts see the current state of the wooden bridge market.

The thematic assessment approach was chosen as it is the most prevalent form of analysis in qualitative research [58–60]. It is a technique of categorizing, examining and re-recording themes within data. Themes are patterns among datasets that are required to define a phenomenon and are associated with a particular research problem, and these themes become categorizations for more assessment. This assessment consists of writing field comments, revising transcripts, and encoding interviews [61–63].

All notions, focus, themes and categorizations are examined over a context based on thematic patterns. Tendencies in literature reviews also play a role in generating themes. This structure allows for simpler pattern fitting and comparisons among contributors. These themes and theme-related questions are given in Table 3 and Supplementary Materials Section S1. In addition, interview questions were prepared by taking into account the knowledge and experience of the experts interviewed on issues associated with wooden bridge structures.

Table 3. The main themes, addressee and main purpose of the interview questions (Supplementary Materials Section S1).

Main Themes		Corresponding Sub-Sections	Addressee	Main Purpose
Topics	**Sub-Topics**			
The choice of a wooden bridge and the current situation in Finland	Reasons to choose a wooden bridge and the current situation in Finland comparison with other Nordic countries	Section 4.1.1	Experts with long-term experience in wooden bridges	Identifying wooden bridge experts' views
The challenges of wooden bridge construction	Protecting wooden bridges	Section 4.1.2		
	Key slowdowns			
Future outlook of wooden bridge construction	The possibilities of wooden bridges	Section 4.1.3		
	The best aptitudes for wooden bridges			
	using CLT as a deck structure concrete-timber composite bridges			

Since all the participants were Finnish, the interviews were performed in Finnish. The audio was recorded and transcribed in a software program. Great care was taken to verify the translation from Finnish to English. To avoid any bias, meticulous comparisons were made between the translated form and the original form for precision and consistency. To avoid a directive interview and potential bias, the authors focused on what the interviewed experts meant and their explanations. The time the authors spent on active listening far exceeded their speaking time.

In the article, the data were analyzed by the authors. As the number of interviewees was at a manageable level, analyses were conducted manually, without employing any numbering system for the answers, by going over the answers, highlighting, and classifying the points emphasized by the interviewed experts. Classification of the data acquired is a major part of the analysis [64]. When assessing the reliability of the findings, it should also be noted that the perspectives are geared towards demonstrating a comprehensive picture of the future over a fact-based forecast.

Responses from the interviews were grouped under the identified recurring themes: (i) the choice of a wooden bridge and the current situation in Finland; (ii) the challenges of wooden bridge construction; and (iii) the future outlook of wooden bridge construction. The participant identities and the findings of the interviews were kept anonymous and confidential.

Along with the literature survey and interviews, in this paper, the design of a girder bridge was conducted as a research method that is commonly used in the solution of research and design concerns in the structural field, as in the cases of architectural research studies [65–73]. This method allows structural engineers to consider, write, discuss and publicize as a bridge from concept to practice as in architectural design practices [74–77]. Characteristics of the main business applications used in existing architectural design practice, complicated mass modeling techniques (e.g., Revit, SAP 2000), parametric modeling, and information modeling approach of buildings are considered in the papers (e.g., [78–80]). In this sense, the dimensioning of a girder bridge was carried out, which will be detailed in Section 4.2.

After discussing Finnish wooden bridge applications and future prospects from experts' point of view in Section 4.1, it is worth noting that in order to contribute to the promotion of wooden bridges in Finland, it is important to show in Section 4.2 that their structural design is not complicated.

4. Results

The results were primarily divided into findings from interviews and the dimensioning of a girder bridge, detailed below.

4.1. Interviews

As noted in the previous section, the outcomes of the interviews are divided into themes that offer insight into wooden bridge construction and future outlook in Finland. Regardless of whether the question referred to a specific theme or who the interviewee was, the themes arose in more than one context in the interviews. Interview results were given according to the following categories: (i) the choice of a wooden bridge and the current situation in Finland; (ii) the challenges of wooden bridge construction; and (iii) future outlook of wooden bridge construction, as given in Table 3.

4.1.1. The Choice of a Wooden Bridge and the Current Situation in Finland

The ideal way to justify the choice of wooden bridges, according to experts, was their use as private road bridges and light traffic bridges. In addition, the factors supporting the selection of wooden bridges, especially the concepts of ecology and renewability, came to the fore. The locality of ecologically used products should also be taken into account, as long transport distances begin to damage the environmental value of wood. Structures can be produced locally, especially in areas with trees of suitable size.

From an economic point of view, the competitiveness of wooden bridges seems contradictory, as in many cases the wooden bridge will be cheaper than the concrete alternative, but cost-effectiveness over the whole life cycle of the bridge must also be considered. In this case, concrete bridges, which have two times longer life than wooden bridges, can be preferred.

The aesthetics created by wooden bridges came to the fore among the selection criteria, especially for those which served as landmarks in the interviews. It was emphasized that there may be more wooden bridges in Finland, but the financial difficulties of wood, which is not cost-competitive, should be resolved for challenging solutions compared to other construction materials. In addition, the importance of the location of the bridge was mentioned in the selection of materials in conditions where the use of concrete may be limited due to transportation opportunities.

When asked about the current status of wooden bridges in Finland, the interviewees stated that more bridges could be built, and underlined that the intended use should also be taken into account. The situation in Finland was also compared with the situation in Sweden and Norway. The most obvious difference between Sweden was that the wooden bridges there were unsaturated, but the shorter service life and a faster bridge were considered to need refurbishment as well. It was emphasized that Norway started to build long bridges with a much more courageous attitude. On the other hand, it was stated that the wealth of Norway was an effective factor in this regard and enabled the production of more expensive solutions.

According to interviews, bridge positions can be difficult, for example, for reinforced concrete construction, besides private roads, loads are not at the level of public roads, so lower-bearing wooden bridges are ideal for serving the purpose. In addition, winding roads arranged on private roads are usually more problematic, that is, they are built quickly, and wooden bridges offer the opportunity to take short breaks on the road section.

4.1.2. The Challenges of Wooden Bridge Construction

Concerning the difficulties of wooden bridge construction, the current situation was brought up in the discussions where uncertainty about the future prevailed. It was stated that the use of creosote as a filler in bridge structures will be banned in April 2023 and this will create a big problem in Finland, for example, in terms of climatic conditions, because wooden structures outside must be impregnated with something such as creosote. It was emphasized that the creosote ban is only valid for bridge structures and its use in other wooden structures such as columns will make the situation even more difficult.

Interviewees noted that other challenges for wooden bridge construction are long-term durability and uncertain attitudes towards wooden bridges. It was underlined that since the long-term durability of wood is weaker than other materials, the cost level in terms of life cycle increases considerably due to the need for renewal. Weight-bearing structures are relatively difficult to repair because, in the case of wood, it is not easy to assign load-bearing capacity to an existing structure.

It was also noted that the above-mentioned saturation problem is due to the uncertainty of the long-term durability of the substitutes due to the lack of any data on user experience. It was pointed out that the negative attitude towards wooden bridge construction is directly reflected in many factors that reduce the production, competition, and development efforts of the structures.

In the interviews, it was claimed that mostly metal or wooden parts were used for the structural protection of load-bearing structures in Sweden. In terms of the functionality of the protection, attention was drawn to the use of the right type of wind openings for the ventilation of the buildings to be protected. It was exemplified that some bridges were closed to protect the deck structure.

It was stated that difficult connection details, which in principle always have to be measured separately, also complicate the design of wooden bridges. In the case of steel, for example, the design of the connections is largely successful according to the instructions. During the discussion of balustrades on wooden bridges, a connection issue came up. This situation negatively affected both the newly built bridges and the design of the bridges that needed to be repaired. In terms of life cycle sustainability, integrating a repairable guardrail into the old structure was identified as a critical challenge.

4.1.3. Future Outlook of Wooden Bridge Construction

With a forward-looking perspective, it was emphasized that there could be a further increase in the construction of wooden bridges due to the problems caused by the climate crisis. Although wood is at a disadvantage compared to other materials in terms of lifetime efficiency, its use can be justified by a monetary carbon value. Real-life cycle costs add the value of the carbon footprint translated into a cost where the tree can be seen better. In addition, it was foreseen that wood, a renewable material, will replace steel and concrete, which fluctuate in price, and no significant increase in prices is expected.

In the 1990s and early 2000s, it was noted that some degree of wood-concrete composite structures was built in the Scandinavian Timber Bridge Program (NTBP). Based on this, the reason why their construction was stopped was included on the agenda. The interview focused on potentially thought-level compound bridges as they could offer solutions to some problems. These are, for example, protecting wooden structures and increasing the opening under its weight with a smaller structure. At the same time, the carbon footprint is better because the need for concrete is quantitatively reduced. On the other hand, in this regard, the fact is that concrete can be used in all situations and has emerged as a material that provides convenience and cost advantage.

In addition, the difficulty of design studies was included in the agenda. Several of these structures were designed, but the designers lacked the knowledge to raise the junction structure at a low threshold as a solution option. The interviewees especially emphasized the difficulty of linkages that provide common solutions. However, it was clear that re-raising the composite wood-concrete bridge as a reflection product could be a solution. The idealness of the composite option is emphasized for using wood in bridges with more traffic, which is a small step towards reducing the carbon footprint.

Another structural issue discussed during the interviews was the use of CLT in bridge structures. Although CLT has gained some ground in building construction, it has limited use in Finnish bridge construction. In Central Europe, it was used as a deck structure, as on several bridges in Sweden. The possibility of using CLT in Finland has been voiced, as problems arise from rotting fungi on side decks. However, poor user experience was also recorded when using CLT in Finland. On the other hand, it has been reported that the transportation of the products will adversely affect the ecological advantage of using wood since CLT production is mostly directed to central Europe. It was emphasized that the use of CLT in bridge structures will require development work, where exiting the market situation for wooden bridges can be difficult. However, if a good preservation method and long-term durability can be provided for this, it is foreseen that there will be opportunities in bridge decks with CLT.

It was also underlined that the need for bridge renewal and relocation will increase significantly in the next 10 years, with special road bridges initiated based on inspections. These wooden bridges have a market niche and the marketing of wooden bridges for road owners should also be promoted. Smaller avenues were also found for municipalities where wooden bridges would be a neatly functional and ecological solution. However, as a strong alternative, the development of a new impregnation solution and the use of salt impregnation supported by waterproofing came to the fore. When it comes to roads, the fact that they are smaller than other materials and that they are built quickly has also been seen as a factor in the preference for wooden bridges.

4.2. A Structural Design Example for Dimensioning a Girder Bridge

An example is presented where a glulam girder bridge was dimensioned for vehicular traffic. Bridge loads are defined by national Eurocodes (SFS-EN 1990/A1, SFS-EN 1991-2, and SFS-EN 1991-1-1 ... 7) according to the annexes and the implementing instructions of the Finnish Railways Authority (NCCI1). The dimensioning of the wooden bridge was carried out according to the Eurocodes (SFS-EN 1995-1-1 and SFS-EN 1995-2) and their national annexes and the implementing guidelines of the Finnish Railways Authority (NCCI 5). It is worth noting that NCCI 5 (strength) is based on SFS-EN 1995-1-1 and SFS-EN 1995-2, and NCCI 1 (loads) is based on SFS-EN 1990 and SFS-EN 1991.

In the example presented, the focus was on the superstructure; in this case, the purpose of the dimensioning was the glued main beams and deck structure. A structural model of the bridge structure SOFiSTiK program [81] was created to determine the most critical stresses (Figure 5).

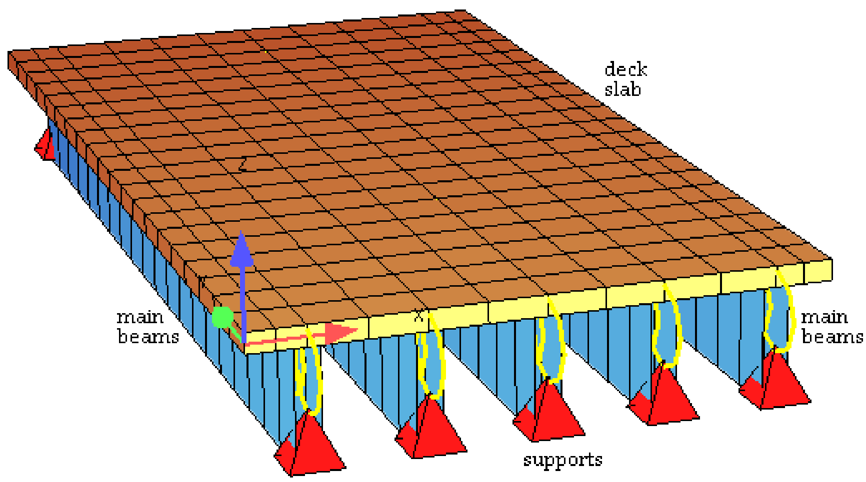

Figure 5. Structural model used to determine stresses.

The structural model was produced based on actual measurements. The width of the deck was chosen as 5.4 m and the length of the bridge was 10 m. The effective width of the deck is 5 m. A side plank cladding was chosen as the deck floor, in this case, the cover was modeled as an orthotropic tile element, thus transferring loads only in the transverse direction of the bridge. The glulam beams, which act as the main supports, were hinged to the foundation structure, so when looking only at the superstructure, the supports were modeled as structural joints in points. Glulam beams were modeled as rod elements.

The dimensioning of the main beams was carried out with the help of loads from SOFiSTik. In the structural model, the structures' weights were used as loads, and in addition, the deck floors and railings were permanent loads. Variable loads included traffic load and wind load. The traffic loads related to the LM1 and LM3 load diagrams were examined. The wind load was adjusted both longitudinally and transversely. Load combinations were performed in SOFiSTiK according to NCCI 1 Annex 1A. The load combinations examined according to the load combinations used were 1, 3, 6, and 7 combinations, according to the attached tables.

The dimensioning of the side floor cladding was carried out manually by calculation because with SOFiSTik it is easier than stated to make these stresses act on a plank by giving greater stress in the impact area. When dimensioning the deck, traffic load diagrams containing bogie loads LM1 and LM2 were considered. Of these, the condition that gave the determining strain was examined.

Regarding the strength of main beams, compression/tension, shear, bending, buckling, torsion and torsional and bending + tension, bending + compression, bending + buckling, and torsion + buckling as combined stresses. In addition, the deflection of the beam and the vibration of the entire superstructure in the operating limit condition were investigated. Deck floor planks were examined for shear and bending resistance. The dimensioning example has been simplified, so it does not include all the details the designer needs to make it look like a plan or dimension.

As a result of the examinations, 5 glulam beam numbers of 240 × 1080 mm were determined. The beams were spaced 1080 mm apart and the strength class is GL30c. The dimensions and strength of the beams turned out to be such that separate roll support for the structure was not needed. Cover dimensions were chosen as 50 × 200 mm. The strength class of sawn edge plank flooring was C24. Figure 6 shows the principal diagram from the dimensioned section.

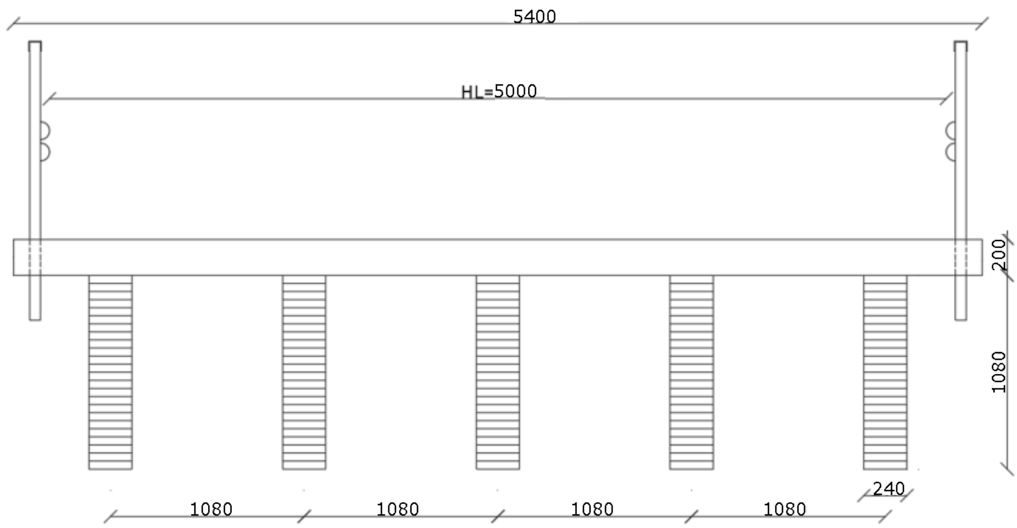

Figure 6. Dimensioned cross-section (all dimensions are in mm).

Tables 4 and 5 below show the most critical stresses, corresponding strengths, and utilization rates on main beams.

Table 4. Stresses, strength, and utilization rates of main beams [81].

		Load (kN)	Stress (MPa)	Strength (MPa)	Usage Rate (%)
Shear	V.y	29.2	0.169	3.208	5.2
Shear	V.z	376	2.176	3.208	68.2
Compression	F.c	86	0.332	22.917	1.5
Tensile	F.t	64	0.247	18.333	1.4
		Load (kNm)			
Bending	M.y	871	19.458	27.5	71.2
Bending	M.z	11.7	14.196	27.5	52.0
Torsion	T	3.9	0.254	5.374	4.0

Table 5. Buckling and combined stresses of main beams [81].

	Usage Rate (%)
Deflection y-direction	1.5
Deflection x-direction	7.4
Rotation	74.5
Bending + pulling	72.6
Bending + compression	71.2
Bending + buckling	72.7
Twisting + buckling	62.9

The utilization rates of the above-mentioned break-in limit state inspections were not very high, since in this case, the deflection of the beam was the most decisive factor. Following the rules given in NCCI 5, the allowable deflection value with the traffic design loads is L/400, which means 25 mm deflection with the 10 m beam span. Gains comparable to this value can be obtained directly from SOFiSTiK from the vertical displacement of the element points. At this point, the cross-section of the beams had to be increased, because otherwise the limit value of deflection would have been exceeded. As a result, with the selected section, the magnitude of the deflection was 23.3 mm, which gives the utilization rating of 93.2%.

The requirement for vibration sizing of the superstructure in the case of service limit was also examined. In this context, the lowest natural frequency of the structure was calculated according to NCCI 5. If the value is greater than 5 Hz, a more accurate vibration analysis is not required. In the calculation of the characteristic frequency, the cover plate was only considered as a permanent load on the beams, and the vibration was considered only for the main beams. With this solution, you can be on the safe side in terms of the calculation. The lowest value of the characteristic frequency was 29.497 Hz, and it can be said that there was no need for vibration sizing with this value. In the case of the vehicle bridge, the vibration usually does not become critical.

The side plank deck was dimensioned for shear and bending. The stresses were determined separately in the area between the beams, and on the load-bearing projection of the deck slab. Table 6 shows the most critical stresses and utilization rates.

Deck tile usage rates remained very low. However, the calculation was checked in a case where the plank and hence the deck height would be 150 mm, but in this case, the shear resistance would not be sufficient. The calculation of structural model loads is presented in more detail in Supplementary Materials Section S2.

Table 6. Stresses, strength, and usage rates of the deck slab [81].

		Load (kN)	Stress (MPa)	Strength (MPa)	Usage Rate (%)
Shear	V.y	29.2	0.169	3.208	5.2
Shear	V.z	376	2.176	3.208	68.2
Compression	F.c	86	0.332	22.917	1.5
Tensile	F.t	64	0.247	18.333	1.4
		Load (kNm)			
Bending	M.y	871	19.458	27.5	71.2
Bending	M.z	11.7	14.196	27.5	52.0
Torsion	T	3.9	0.254	5.374	4.0

5. Discussion

There is no comprehensive study of the status, applications and future prospects of wood use in bridge construction, reflecting the Finnish professionals' point of view, which emphasizes the unique properties of wood. This article, which also includes a structural design example for dimensioning a girder bridge, aims to fill this gap through expert interviews. Interview results were given according to the following categories: (i) the choice of a wooden bridge and the current situation in Finland; (ii) the challenges of wooden bridge construction; and (iii) future outlook of wooden bridge construction as seen in Table 7. It is believed that this research will support the widespread usage of wood in bridges by contributing to the bridge projects to be developed in the Finnish market.

Table 7. Corresponding sub-sections and highlights.

Corresponding Sub-Sections	Highlights
Section 4.1.1 The Choice of a Wooden Bridge and the Current Situation in Finland	(a) The most ideal use of wood is in private road bridges and light traffic bridges. (b) Wood is an ecological and aesthetic material is the most important reason why it is preferred in bridge construction.
Section 4.1.2 The Challenges of Wooden Bridge Construction	(c) The disadvantage of wooden bridges was reported as their lack of long-term durability. (d) Banning the use of creosote as a filler in bridge structures in April 2023 will pose a major problem for wooden bridges in terms of impregnation. (e) There are difficulties in the connection details of wooden bridges. (f) There may be a further increase in the construction of wooden bridges due to the problems caused by the climate crisis.
Section 4.1.3 Future Outlook of Wooden Bridge Construction	(g) Concrete and steel, whose prices fluctuate, could gradually be replaced by wood, a renewable material. (h) Timber-concrete composite bridges, which are expected to become widespread in the future, have many advantages such as a carbon footprint compared to fully concrete bridges. (i) If a good method of protection and long-term durability can be achieved, CLT could open up an opportunity for bridge decks. (j) The need for bridge renovation and relocation will increase significantly in the next 10 years.
Section 4.2. A Structural Design Example for Dimensioning a Girder Bridge	(k) Service limit state is often decisive for the dimensioning of wooden bridges. (l) When dimensioning a bridge, it is important to consider what loads affect each structure. (m) Finite Element Method (FEM) is a useful method for making stress calculations, but it is more convenient to calculate local stresses by hand, for example when calculating deck slab.

Even though the experts in the survey came from different fields of wooden bridge projects, their viewpoints stated in the interviews were coherent, supportive and complementary. The highlights of Finnish wooden bridge practices are summarized in Table 7.

6. Conclusions

According to the findings, it can be said that Finland as an industry currently has a very small market for wooden bridges, and has low worker availability, making it difficult to find financing for innovations. However, considering the possibilities of wooden bridges, efforts should be made to expand their use in the most appropriate areas. In addition, with the increasing use of wood as a bridge material, steps will be taken toward a more ecological infrastructure that requires the cooperation of stakeholders. In this sense, it is thought that the perspectives and expectations obtained from the expert interviews will provide insight into the critical players and policymakers in the construction sector.

It is believed that the results of this research will contribute to the improvement of specifications in Finland. For example, difficulties in connection details such as the balustrades of wooden bridges raised in the study will lead relevant stakeholders such as designers, manufacturers, and regulators to develop joint solutions. Solutions to these and similar challenges will have a direct impact on the relevant specification. Similarly, it can be thought that a positive professional attitude towards promising timber-concrete composite bridges will be reflected in government incentives or building specifications.

The use of wood, which is a carbon store, in bridges can have a significant environmental impact on the Finnish construction industry, contributing to the Finnish Ministry of Transport and Communications and the Finnish Ministry of Environment's target to be carbon neutral by 2035. As well as its continued reputation as an environmentally friendly material, its use in prestigious projects and the increase in good practices will greatly contribute to the positive perception of the public. While cost competitiveness, connection details, and longevity are among the issues that require improvement in wooden bridges, hybrid solutions can help overcome these challenges.

It is recommended to implement large-scale public projects for wooden bridge construction by creating sustainable business models that will be supported both legitimately and economically by local authorities. In this sense, close cooperation between local governments such as municipalities, and builders, manufacturers and other key stakeholders is crucial. Furthermore, it is also crucial to provide the required theoretical and practical training in wooden bridge projects and construction, both in educational institutions and in the construction sector. In addition, legislators have critical duties in the official and regulatory procedures of issues that will affect the future of the wooden bridge market.

Potential areas for future research could include the use of CLT in bridge structures, the possibilities and combination alternatives of wood composite/hybrid structures, and the use of preservation methods. In addition, comparative studies can be made between Finland and Scandinavian countries, and other countries where wooden bridges are common. According to studies and practices in other countries, timber bridges are very competitive in terms of both construction and life cycle costs. It should also be noted that wood is a renewable resource and is a homegrown material in Finland.

This research has limitations. A larger interview sample might be administrated to collect data to provide a richer dimension to the research. Thus, findings that are more applicable for generalization can be achieved. In this context, findings that are particularly useful for the wooden bridge market should be seen as information worthy of further research in order to verify it on a larger population scale. Furthermore, this article is geographically limited to Finland. In different regions where wooden bridges are common, different perspectives may have been established.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app13074325/s1, Section S1: Interview Questions; Section S2: A Structural Design Example for Dimensioning a Girder Bridge.

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