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Project Report

FRP Bridges in the Flanders Region: Experiences from the C-Bridge Project

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Abstract: At the start of the C-Bridge project in 2018, the number of fibre-reinforced composite bridges in the Flanders region of Belgium was limited to a handful. These limited achievements were largely due to the poor knowledge of clients (public and private), project managers, design engineers, and contractors, which made the option of composites either unknown or still viewed with a certain degree of suspicion. In addition, there were no standards at the Belgian or European level for the design of such constructions. The C-Bridge project (roadmap into design, guidelines, and execution of composite bridges in Flanders) aimed to stimulate the design, the realization and the construction of composite bridges in Flanders by providing the necessary knowledge to the construction sector in the most suitable form. This knowledge consists of the current state of the art of composites in bridge construction, selection criteria for composite bridges, recommendations for specification texts, and in situ testing of composite bridges and structural and vibration analysis. This C-Bridge project should allow the awarding authorities and contractors to be able to make informed choices regarding fibre-reinforced polymer (fibre composite) bridges but also offer the possibility of making the necessary transformation to this new and promising material to various Flemish companies. The results of the project enable Flemish clients to draw up specifications for FRP bridges in the correct manner. Moreover, they can correctly interpret the calculation notes made available and make a correct assessment. The Flemish engineering firms, on the other hand, will be able to make their own designs of FRP bridges and bridge components. They can also build up a value chain within Flanders with Flemish contractors and producers. From the producers and suppliers' point of view, the results of the project will lead to a clearer profile of their products on the public and private market. Finally, the general contractors and constructors will be armed to withstand the challenges that FRP bridges entail to subcontractors in terms of execution, follow-up, delivery, and maintenance. The findings are helpful for the acceptance of fibre-reinforced composite bridges as an alternative to timber, steel, or concrete bridges and should generate a market expansion for FRP in the traditionally conservative bridge-building sector first in Flanders and later internationally.

Keywords: FRP bridge; selection criteria; specification texts; in-situ testing; structural design

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Citation: De Corte, W.; Uyttersprot, J. FRP Bridges in the Flanders Region: Experiences from the C-Bridge Project. *Appl. Sci.* **2022**, *12*, 10897. https://doi.org/10.3390/app122110897

Academic Editors: Antonella D'Alessandro, Tomasz Socha, Arkadiusz Denisiewicz, Mieczysław Kuczma and Krzysztof Kula

Received: 27 September 2022
Accepted: 25 October 2022
Published: 27 October 2022

1. Introduction and Background

Fibre-reinforced polymers (FRP), or fibre composites (FC), show important potential for the Flemish bridge-building sector. They are relatively stronger and lighter than traditional building materials, such as concrete and steel; they are more durable than timber; and they require less maintenance. Additionally, FRP bridges show fewer maintenance problems related to rheological behaviour during their service life than, for example, prestressed concrete, for which, e.g., carbonation phenomena, corrosion along steel rebar and tendons, significant cracking, and excessive deflections due to prestress losses, shrinkage, and creep of concrete can occur [1–3].

Especially when considering footbridges, the experience from foreign countries [4], such as the Netherlands, shows that this type of bridge offers an added value. In the context of the greening of mobility, these will become a much more important part of public infrastructure in the future [5–9]. The development of a functional bicycle network in Flanders is an example of this [10], but the material also offers important assets for road bridges for light and moderate road traffic and for bridge decks [11]. Additionally, many advantages are associated with the use of composites within replacement and extension projects for existing bridges [12,13], such as, for example, the reuse of existing foundations, piles and abutments, the limited installation time, cost and risks, the possibility for higher durability, and the lower total cost of ownership [14–17].

At the start of the C-Bridge project in 2018, only four small-scale FRP bridges existed in Flanders (Figure 1). These limited achievements in Flanders are largely due to the lack of knowledge among clients (public and private), project managers, design engineers, and contractors, as a result of which this option is either unknown or is still viewed with a certain degree of suspicion. The few bridges that were built in Flanders at the start of the project were also fully outsourced to Dutch companies that were both responsible for the design and construction of these bridges, so no experience was built up within the Flemish market. The few cases before 2018 in Flanders have therefore not led to a dissemination of knowledge in Flanders with regards to dimensioning, deformation and vibration behaviour, etc. A guarantee of durability that is given purely by the designer/manufacturer is indeed correct and permitted [18–21], but at the beginning of the C-Bridge project, there was still too little confidence for the (potential) owners.

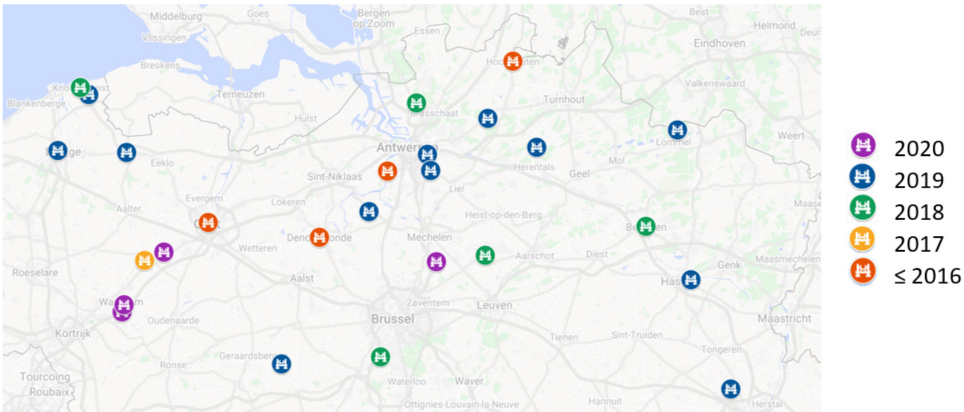


Figure 1. FRP bridges in Flanders from 2010 to 2020.

In addition, there were no standards at the Belgian [22] or European level [23–26], which poses a number of difficulties for the design. The necessary information is available but is very scattered (e.g., specification texts, standards, calculation methods), has limited access (e.g., calculation notes), is not yet binding (e.g., standards), or is very recent. At the end of the two-year project, the number of FRP bridges in Flanders had risen to around 27 (2020) and is still increasing.

2. Objectives of the C-Bridge Project

The global aim of the project was to stimulate the design, realisation, and construction of composite bridges in Flanders by making the necessary knowledge available in the most suitable form. This knowledge transfer should allow the clients to make well-considered choices but also offer the possibility of making the necessary transformation to this new and promising market to various Flemish companies.

The objectives of the C-Bridge project cover the entire process that must be followed in the realization of a composite bridge, i.e., from the initial selection to the realization and even looking further into the exploitation phase of the bridge. The specific objectives of this project, listed below, are related to improved knowledge, and were defined after an intensive survey of the targeted group through one-on-one conversations with various actors in the Flemish construction sector. These specific objectives cover the entire process, from application to realisation, even through exploitation:

- A state of the art of composites in bridge construction;
- Selection criteria for composite bridges;
- Recommendations for specification texts for composite bridges;
- Recommendations for in situ testing;
- Structural and vibration analysis.

All findings are reported on the C-Bridge website [27], including various whitepapers devoted to the specific objectives described above. Apart from the state of the art [28], the main findings from the C-Bridge project related to the various specific objectives will be discussed in the following parts of this paper.

3. Selection Criteria for Composite Bridges

Table 1 provides a non-exhaustive overview of several composite bridges in Europe that will be used in the following sections to indicate the use of composite materials in bridge construction. The examples are indicative, and the choice of a particular type of material for the construction often depends on several factors that are not all covered in this section.

In general, five main selection criteria can be distinguished based on advantageous properties of FRP:

- Low self-weight;
- Low maintenance;
- Aesthetic design;
- Accelerated installation;
- Low electrical conductivity.

In what follows, specific examples for which these selection criteria have been applied in practice are presented.

3.1. Low Self-Weight

A first important advantage of FRPs compared to traditional building materials is the low self-weight in relation to the strength and stiffness of the material. This makes it possible to place this type of bridge on a poor load-bearing and swampy underground. Additionally, the dimensions of the foundations can be drastically reduced, and/or existing abutments, piles, or foundations can be reused.

An example is the bridge crossing the A27 Highway (bridge No. 1) [29], where it was not possible to use a standard pile foundation since the A27 Highway was constructed below the groundwater level and a foil barrier was installed to retain the groundwater. Drilling through this foil barrier would lead to major groundwater problems, and therefore, the bridge had to be founded on short jet grout columns. For this reason, the bridge had to be designed as light as possible, resulting in the choice of steel truss and an FRP deck with a weight reduction of 800 tons (compared to a full concrete bridge) or 72 tons (compared to a steel deck). Similarly, bridges No. 2 and No. 3 were installed on a swampy underground [30] which in the first case used to be part of a riverbed and in the second case is characterized by a high water table. In both cases, the substructure could be significantly reduced due to the low self-weight of the FRP superstructure. In the case of the Canada Bridge (bridge No. 4) [31], the abutments and the existing foundations of a deteriorated timber bridge originally located at the site could be reused due to the low self-weight of the FRP superstructure.

Table 1. Technical data of indicative examples of composite bridges in Europe.

No	Bridge	Location	Use	Length	Client	Producer	Contractor
1	Lightweight road bridge over the A27	Utrecht, The Netherlands	60 tons road traffic	142.0 m	ProRail	FiberCore Europe	Heijmans
2	Farys Beersel	Beersel, Belgium	Cyclists and pedestrians	7.0 m	Farys	Composite Structures	Janson Bridging Belgium
3	Maintenance-friendly bridge in wetland area	Herning en Snejbjerg, Denmark	Cyclists and pedestrians	Footbridge: 10.5 m Footpath: 30.0 m	Municipality Herning	Fiberline	-
4	Upstream and Downstream Canada Bridges	Bruges, Belgium	Cyclists and pedestrians: 5 kN/m^2 + 5 tons of service vehicle	41.0 m and 42.0 m	The Flemish Waterway	FiberCore Europe	Westconstruct (Besix)
5	Cyclist and Pedestrian Bridge Krilpad	Krimpen aan de Lek, The Netherlands	Cyclists and pedestrians: 5 kN/m^2 + 5 tons of service vehicle	10.5 m	Hoogheemraadschap Schieland & Krimpenerwaard	FiberCore Europe	Haasnoot
6	Pedestrian bridge Oude Vismijn	Ghent, Belgium	Cyclists and pedestrians: 5 kN/m^2 + 5 tons of service vehicle	20.0 m	Lofting Urbis Group	FiberCore Europe	Mevaco
7	Spiering Bridge, Movable Road Bridge	Muiden, The Netherlands	Heavy traffic, cyclists and pedestrians	12.2 m	Province of North Holland	FiberCore Europe	K Dekker BV
8	Bicycle path over the Leie	Deinze, Belgium	Cyclists and pedestrians + 5 tons of service vehicle	Ca. 235.0 m	Infrabel	FiberCore Europe	Westconstruct (Besix)
9	Pedestrian bridge Leieoever and Maaigemdijk	Deinze, Belgium	Cyclists and pedestrians + 5 tons of service vehicle	10.0 m	Municipality Deinze	Composite Structures	Persyn
10	Commune de Wiltz	Wiltz, Luxembourg	Cyclists and pedestrians + 25 tons of unintentional vehicle	10.5 m	Commune de Wiltz	Composite Structures	Janson Bridging Belgium
11	Access bridge offices Callens	Waregem, Belgium	Pedestrians: 5 kN/m^2	8.0 m	Callens nv	Composite Structures	Stadsbader
12	Flood resistant bridge	Chemnitz, Germany	Cyclists and pedestrians	73.0 m	Municipality Chemnitz	Fiberline	FIBER-TECH
13	Pedestrian bridge over the Exercitiesingel	Rotterdam, The Netherlands	Cyclists and pedestrians: 5 kN/m^2 + 5 tons of service vehicle	20.0 m	Municipality Rotterdam	FiberCore Europe	Wallaard Noordeloos
14	Hybrid Bridge Curling Hall	Zemst, Belgium	Cyclists and pedestrians: 5 kN/m^2 + 7 kN point load	6.5 m	Municipality Zemst	Composite Structures	Janson Bridging Belgium
15	Bicycle and pedestrian bridge Zwaluw	Bunschoten, The Netherlands	Cyclists and pedestrians + 5 tons of service vehicle	11.2 m	Municipality Bunschoten	FiberCore Europe	FiberCore Europe
16	Hybrid steel-GVVK cyclist and pedestrian bridge	Ikast-Brande, Denmark	Cyclists and pedestrians + unintentional vehicle	8.0 m	municipality Ikast-Brande	Fiberline	-
17	Pedestrian bridge Weverskade	Maassluis, The Netherlands	Cyclists and pedestrians + 5 tons of service vehicle	10.2 m	Municipality Maassluis/Lely Real estate	FiberCore Europe	Van Dijk Maasland
18	Translucent Cyclist and Pedestrian Bridge	Zumaia, Spain	Cyclists and pedestrians	28.5 m	Municipality Zumaia	Fiberline	-
19	Bicycle highway F11 Antwerp-Lier	Boechout, Belgium	Cyclists and pedestrians	30.0 m. 26.5 m free span	Province of Antwerp	Composite Structures	Franki Construct
20	Cyclist and pedestrian bridge over high-speed line	Lleida, Spain	Cyclists and pedestrians	38.0 m	Pedelta	Fiberline	-

The low self-weight also has the advantage that the bridge can be easily transported in one or several pieces by road, water, or air and does not require heavy machinery during installation. The Krilpad bridge (bridge No. 5) [32] is situated in a nature reserve with a soft subsoil, making it impossible to transport any bridge, even FRP, over land to its destination due to the risk of environmental damage. Making use of the self-floating capacity of the sandwich-type FRP superstructure, it could be transported via the water without any additional aids. Then, the bridge was lifted into place onto a shallow foundation with minimal lifting equipment, again made possible by the low self-weight. The Oude Vismijn Bridge (bridge No. 6) [33] is located in the historic centre of Ghent, making the location inaccessible for heavy lifting machinery. In addition, the low self-weight also reduces the vertical action on the historic quays.

In addition, in the case of a movable bridge, the use of a counterweight can be avoided. For the Spiering Bridge (bridge No. 7), a transparent design without a bascule pit was desirable. To make this possible, lightweight leaves were necessary in order to reduce the mass inertia so that opening and closing could be performed by means of simple hydraulic cylinders. The use of a composite bridge deck resulted in a 50% weight saving compared to a steel deck. Using this concept, the total construction was also considerably less expensive than a traditionally built bascule bridge with a bascule pit.

Finally, FRP decks can easily be used for lateral extensions to existing bridge decks without major adaptation to the main superstructure. In order to realize a bicycle path across the Leie river without having to build a completely new bridge, railway bridge No. 8 was laterally extended by FRP decks mounted on steel cantilever brackets bolted to the main superstructure.

3.2. Low Maintenance

A second advantage of FRPs in bridge construction is the low maintenance requirements. This allows for a more flexible maintenance program over the lifetime of the bridge and should significantly reduce the costs associated with inspection and maintenance compared to traditional building materials [34]. Bridges No. 9, No. 10, and No. 11 had the requirement of low maintenance in the tender documents. Even in extreme situations, such as the flooding of bridge No. 12, the construction was deemed to be practically maintenance-free during its 100-year lifespan [35]. In addition, the material is also durable, as it is resistant to many environmental factors and physical agents. This durability will not be affected by moisture, rot, mould, or temperature. Bridge No. 3, located in a wetland, is an example of this; the inert FRP bridge deck requires fewer inspections and has consequently lower maintenance costs. For extra protection, the outside surface can be finished with a high-quality gelcoat or topcoat which is based on the same polymer as the bridge itself.

In addition, it is possible to incorporate sensors, such as BRAGG optical fibres, into the bridge deck during the manufacturing process to provide continuous monitoring of the bridge's condition [36]. For example, in the cross-section of the bridge deck of bridge No. 4, optical fibres were installed at regular distances in the top and bottom flanges and web plates to monitor the condition of the bridge, such as the deformation during the lifetime and to identify any damage in the bridge deck. These fibres were incorporated into the bridge deck during the production process and can therefore also provide an image of the internal strain and temperature distribution during in situ testing and throughout the lifespan of the bridge.

3.3. Aesthetic Design

When using vacuum infusion as the production process, a great amount of freedom in the design of the shape and the finishing is possible [37] due to the manual process of applying the mostly UD fibre fabrics. The client can opt for a very slender contemporary bridge with a handrailing resembling artwork, as is the case for bridge No. 13, or for a rural-looking bridge with a timber handrailing, as illustrated in bridges No. 14 and No. 15.

In addition, a minimalist design that blends in with the surroundings is also possible, as is the case with bridge No. 16. Here, a hybrid bridge was opted for, consisting of a steel superstructure, an FRP bridge deck, and a steel handrailing, with a uniform gravel surface matching the gravel used in the footpaths throughout the park the bridge is situated in. Moreover, bridge No. 17 has an S-shaped longitudinal profile, showing that non-prismatic or curved designs are easily manufactured using FRP.

If desired, even translucent FRP can be used in railings or bridge decks in which LED lighting can be incorporated. This concept was applied for bridge No. 18 [38], for which the sunlight shines right through the bridge and gives it a light-green-shaded appearance in the daytime, while at night, the bridge is transformed into a skylight using LED light tubes fitted on the inside.

3.4. Accelerated Installation

Since vacuum-infused FRP bridges are in many cases manufactured in one piece, a quick installation with minimal disturbance to the surrounding traffic will be possible, yielding significant gains within busy city centres. Bridges No. 19 and No. 20 were both installed in one piece with minimal disruption to the train schedule on the underlying railway connections. In the first case, the bridge was prefabricated and delivered to the site in one piece. In the second case, the various composite parts of the bridge were assembled next to the railway and hoisted into place in one piece using cranes in less than 3 h. In addition to the cases covered above, FRP bridges are also very suitable for projects for which temporary footbridges and road bridges for light and moderate traffic must be constructed as they can be easily transported and installed at a various number of sites.

3.5. Low Electrical Conductivity

GFRP (glass-fibre-reinforced polymer) material, most frequently used in bridges due to its low cost, has low electrical conductivity, which allows it to be installed closer to the high-voltage power lines of trains and trams without having to ground the bridge against eddy currents. As a result, for bridges No. 19 and No. 20, the approach ramps could be reduced in length, limiting material and land use for this purpose and resulting in easier access to the bridge for pedestrians and bicycles.

4. Specification Texts

In view of the need for information regarding the tendering of fibre-reinforced polymers (FRP) for bridge construction in Flanders, several national and international clients with extensive experience with this material were interviewed for the C-Bridge projects to gauge their experiences and recommendations for Flemish clients (government, municipalities) who are taking their first steps in the FRP world. The findings are bundled in the whitepaper "Specification Texts" [39], and the main recommendations are mentioned hereafter. Based on these recommendations, the Flemish Government (Department of Mobility and Public Works) is currently preparing standard specification texts for FRP bridges.

The main recommendations are related to:

- The tender phase;
- The design phase;
- The production and execution phase;
- The operational phase

4.1. Tender Phase

4.1.1. Form/Shape of the Bridge

If an FRP bridge is chosen, the specificity of composites as well as the production method should always be taken into account. Attention should be paid to:

- Avoid sharp corners, which can lead to fibre folds or breakage.
- Avoid a limited longitudinal slope; a certain tolerance on the finished product must be taken into account. This is mainly due to the curling of the bridge deck during

demoulding due to a difference in heat development in the section during curing. If this is not taken into account in the design, this can lead to drainage problems.

- Define the look of the bridge and not its exact dimensions. Here, the production process of an FRP as well as the subsequent realisation of connections (e.g., handrailing) must be taken into account.

4.1.2. Basic Requirements

In general, the Eurocode EN 1990:2002 [40] should be used as the basis for the design of FRP bridge structures. The following points, which are project-specific, must be clearly defined in the specification text:

- The intended use and service life of the structure with associated requirements for ultimate limit state (ULS) and serviceability limit state (SLS), i.e., deflection requirements and vibration requirements. In particular, the SLS requirements have a major impact on the material consumption and should be defined with care [41].
- Environmental influences (UV light, temperature, moisture, chemicals), time-dependent effects (creep, wear, fatigue), and accidental loads (fire, lighting strike, impact, vandalism) to which the bridge structure may be exposed during its intended life.
- The conditions for inspection, maintenance, and repair during the lifetime.

4.1.3. Basic Materials and Production Methods

The client as well as the contractor must fully understand and ascertain the base materials and production concepts available on the market. The following elements should be included in the specification text:

- A clear definition of the term composites as well as which parts fall under this definition.
- A list of the different types of resins, fibre types, and fibre architectures that could potentially be used for the production of the bridge.
- The production techniques and concepts that are allowed in the construction of the bridge.

4.2. Design Phase

4.2.1. Design of the Main Structure

A description of the design process and the influence of the design criteria is given in the paper [41]. Contrary to the process for for traditional materials, this is an iterative process in which adjustments to the basic material parameters can be made in consultation with the client in order to achieve an optimal design of the bridge structure.

4.2.2. Design of Connections and Joints

Parts of the construction at which stress concentrations can occur—for example, at adhesive connections, bolted connections, support points, and lifting points—require extra attention and detail in the design phase. In the event of brittle failure of a connection, a second bearing path must be provided if failure of the connection leads to the collapse of the construction.

4.2.3. Bridge Specifications, Drawings, and Calculation Notes

All steps taken in the design phase must be documented in the form of calculation notes and general as well as detailed technical drawings. Quality, production and assembly plans must be formulated for the production and assembly of the bridge, in such a way that the execution is considered to be in accordance with the design. The designer identifies which parts of the structure are sensitive to environmental influences as well as the parts exposed to friction/wear. Based on this identification, additional protective measures may need to be provided.

4.2.4. Management and Maintenance Plan

The designer must identify which failure mechanisms (i.e., impact, intra- and/or interlaminar damage, and debonding) may occur during the lifetime of the bridge structure. Based on this in-depth analysis, the designer should provide an appropriate inspection, maintenance, and repair plan for the bridge structure. Parts subject to degradation, mechanical wear, or fatigue must be designed in such a way that inspection, maintenance, and repair can be performed adequately. All components must be accessible for in-service inspection and maintenance. Where this is impractical, the design should provide appropriate protective measures so that the structural deterioration due to degradation is a low risk.

4.3. Production and Execution Phase

4.3.1. Production

Before the production of the bridge deck, a detailed manufacturing plan must be drawn up including production records of, among other things, the fibres (type, directions, construction), the resins (recipe, mixing ratio, preparation), and the production method (environmental conditions, manufacturer's instructions).

During the production of the composite bridge, stopping and/or inspection points should be inserted at critical moments where an independent or external party is required to perform an audit, such as a visual check of the arrangement and orientation of the fibre layers, before infusion and a check of a complete infusion of the bridge deck after demoulding. Then, the independent party can perform checks, and a discrepancy report can be created if necessary based on which the necessary adjustments can be made.

4.3.2. Materials Tests

Current guidelines [23] for the design of composite structures are based on a test-supported design in which at least the basic material properties should be determined through testing. These tests must be carried out on test specimens that have been produced from the same material as the bridge under identical production conditions. Depending on the details of the design, further material tests may be required, which must be identified in the quality plan prior to the production. The material properties can also be substantiated on the basis of the results of previous tests.

4.3.3. (Semi-)Full-Scale Tests

The specification text may also include tests on composite parts and/or full-scale tests [42] on the entire bridge or bridge deck. These tests can be performed either in the factory or on-site. In the design phase, a prediction must be made of the result of these tests, which are used as verification values.

4.3.4. Assembly and Installation of the Bridge

The bridge is assembled and installed according to the predetermined plan. In order to allow for the production tolerances of the bridge deck, it is recommended to accommodate connections with other elements only after the production and not during.

4.4. Operation Phase

A management, inspection, and maintenance plan must be provided based on the design study. This plan can be supplemented with bridge-management- or production-related aspects. During the life of the structure, various non-destructive techniques (NDT) are available for inspecting the FRP structures for both superficial and internal damage. The following NDTs can be found in the CIRIA document C779 [24] and NCHRP report 564 [43]: visual inspection, acoustic impact testing (including hammer tap test), thermography, shearography, ultrasonic inspection, radiography, acoustic emission, modal parameter method, and load testing.

5. In Situ Testing

Structural parameters such as the strength, stiffness and vibrational damping are challenging to determine for composite bridges from classical material tests. The basic data of strength and stiffness of the resin and fibres are known, but the infinite number of combinations of these two materials in terms of mass ratio and fibre directions allow only a prediction of the properties of the final composite. This implies a shift in quality control. Within the C-Bridge project, very relevant information has been gathered based on static load tests and dynamic vibration tests [44]. While the full results are available on the project website, in this paper, only the most important findings are reported.

5.1. Static Load Tests

Static load tests have been carried out on two composite footbridges in Bruges and one composite footbridge in Puurs. They provide deflection values and, if internal sensors (e.g., BRAGG optical sensors) are present in the bridge deck, internal stresses or strains. The following experiences are relevant:

- When comparing the theoretically calculated deflection values, care must be taken to exclude the conversion factors that account for the environmental influences and the aging effects. Such values might not be directly available from the calculation notes.
- When performing static load tests, the effects of temperature and solar radiation are relatively large compared to the load effects. A relevant example relates to the static measurements on the Canada Bridges in Bruges (bridge No. 4 in Table 1) where, during the reference measurement (without load), the temperature in the upper flange's temperature had already risen to 46 °C due to direct solar radiation. The variable load was generated by water containers placed on the bridge surface. The containers, and the resulting shade they provided, decreased the temperature in the upper flange to 34 °C. During the execution of the static load test, i.e., the gradual filling of the containers, the temperature in the upper flange decreased further and finally reached the temperature of the bottom flange (25 °C). As such, during the test, a differential temperature between the upper and lower flanges of about 20 °C was measured without more exact information due to the changing temperature and solar conditions, including local shade, at every measurement. An estimate of the influence of a temperature gradient of 40 °C, viewed as an upper bound for in service conditions, between the upper and lower decks was simulated with engineering software and resulted in a maximum vertical upward deflection at midspan of 7.5 mm. It should therefore be noted that the temperature and solar radiation on a composite bridge deck have a non-negligible effect on the accuracy of the deflection measurements during an in situ test.
- When preforming an on-site creep test, two problems arise. Firstly, the duration of such a test is limited in time (e.g., one week) and is essentially too short to draw accurate extrapolations for creep effects. Secondly, the recorded strains or deflections caused by temperature and solar radiation are much larger than those resulting from creep-controlled climate circumstances (indoor) prior to installation on-site.

5.2. Dynamic Vibration Tests

As demonstrated in [44], due to the low self-weight compared to a concrete bridge and the limited stiffness compared to a steel bridge, human-induced vertical vibrations are a typical design criterion for GFRP footbridges. It is therefore important to accurately assess the vibration response. The dynamic behaviour, including the first natural bending frequency and the structural damping ratio, can be determined in situ by means of vibration tests, which can be performed with a large amount of highly accurate tri-axial acceleration sensors or by using the smartphone's internal acceleration sensors. Both testing methods have been used during the C-Bridge project.

- A previously reported [27] vibration study used tri-axial acceleration sensors (GeoSIG GMS-18-63) arranged in a dedicated measurement grid with three reference sensors (which remain in all setups) and twelve roving sensors (which are relocated for the different setups) on the Canada footbridges. In this study, an evaluation was made of the comfort level of one of both composite bridges based on the measured vertical accelerations using the comfort limits defined in the design guides. The results from these tests are very accurate, but the measurements are costly and time-consuming.

- Another vibration study used the internal acceleration sensors of a smartphone and the VibSensor application [45] to assess the dynamic behaviour on ten composite bridges in Flanders. The elaboration and results of this study can be found in [44]. Herein, experimental data for the dynamic properties (i.e., first fundamental flexural frequency, damping ratio, comfort class) of ten web-core sandwich panel FRP composite footbridges are presented. The paper shows that data based on smartphone accelerometers enables easy, quick, affordable, and abundant measurements while at the same time yielding reliable experimental values. Given the relatively short spans, the heel and excitation test methods were used rather than the ambient vibration method. The tests indicated damping ratios of one to three percent, which are strongly dependent on the number of people on the bridge during the measurement. Additionally, comfort analysis tests indicated that the current design guidelines for pedestrian comfort analysis [46–48] are overconservative and do not reflect the effect of pedestrian-induced damping, which is especially apparent for this bridge type given its very low modal mass and relatively low damping ratio.

6. Structural Analysis

The structural analysis of a composite bridge is quite analogous to the analysis of a reinforced concrete or steel bridge [49,50]. However, there are a number of important differences.

- The material is strongly anisotropic.
- Typical beam or plate elements exhibit significant shear deformation, which should not be disregarded in the calculation
- Certain failure modes (e.g., delaminations on the material level because of interlaminaire stresses, shear failure at structural level) are totally unknown or unexpected for a structural engineer.

As a result of the C-Bridge project, the papers [41,44] describe a concise analytical method for designing a web-core sandwich panel FRP footbridge, including a parametric study. In this paper, it is concluded that the design of a composite footbridge is almost exclusively based on serviceability limits, such as the maximum deflection and the natural frequency under a pedestrian flow. In what follows, two extensions to the aforementioned paper are presented: a comparison of the derived results for two relevant bridges (Puurs and Mortsel) to the effective calculation notes and a comparison of the design example in [51] to results from structural engineering software.

6.1. Comparison with Representative Calculation Notes

In addition to the calculation example presented in [51], a comparison is presented here between the calculation tool developed in the C-Bridge project and existing calculation notes from the design phase of two composite bridges in Flanders (Puurs and Mortsel). Based on this, conclusions can be drawn regarding the extent to which the calculation tool is representative of the design unity checks and which elements may cause differences. The composite footbridges in Puurs and Mortsel were chosen because they have, respectively, simply supported and double-sided clamped boundary conditions.

6.1.1. Simply Supported Footbridge Puurs

The most important results of the calculation are given in Table 2. In the first column, the relevant parameter is addressed; in the second column is its value as given in the calculation note; in the third column is its value as derived using the calculation tool; and in the last column is its value derived using the calculation tool after modification, explained hereafter.

Table 2. Comparison between the calculation note and the (modified) calculation tool for the simply supported FRP footbridge in Puurs.

Parameter	Calculation Note	Calculation Tool	Calculation Tool (Modified)
General features			
Total mass, Mbridge, tot [kg]	8210	8221	8221
Bending stiffness, EIX [MNm^2]	135	137	137
Shear stiffness, GAXY [MN]	250	249	249
Checks SLS			
Natural frequency, unloaded, f0, unload, lt [Hz]	3.4	2.83	3.3
Natural frequency, loaded, f0, load, lt [Hz]	2.9	2.44	2.9
Deflection distributed load, wLC3, lt [mm]	158	159	159
Deflection service vehicle, wLC4, lt [mm]	38	39	39
Checks ULS			
Compression upper flange, σx, uf, M [MPa]	122	81	119
Tension lower flange, σx, lf, M [MPa]	122	80	117
Shear stress web, τxy, w, V [MPa]	34	33	37
Compression web, σy, w, LC5 [MPa]	33	40	34

- The values of mass, bending stiffness, and shear stiffness are almost identical and cannot be the origin of discrepancies.
- A clear deviation of both unloaded and loaded natural frequencies is noticeable. This is due to a correction factor of 1.18 used in the calculation note based on the manufacturer’s practical experience.
- Differences occur in the maximum tensile and compressive stresses in the flanges. These are due to different values used for the load factors in the ULS in the calculation note among other factors taking into account local interruptions in the fibres, which should normally have been used on the resistance side of the equation.
- The vertical compressive stress in the webs caused by concentrated loads (load case 5: accidental impacts [41]) is significantly influenced by the lower value of this concentrated load used in the calculation note in comparison to the recommended value in Eurocode 1991 [52].

After correction for the causes mentioned above, which are essentially not related to the design method, a modified calculation is performed with the calculation tool. The results indicate that in all cases, the differences can be eliminated by this modification. As such, the method from [41] is in accordance with the calculation note.

6.1.2. Double-Sided Clamped Footbridge Mortsel

The most important results of the calculation are given in Table 3. In the first column, the relevant parameter is addressed; in the second column is its value as given in the calculation note; in the third column is its value as derived using the calculation tool (based on [41]); and in the last column is its value derived using the calculation tool after modification, explained hereafter.

Table 3. Comparison between the calculation note and the (modified) calculation tool for the double-sided clamped FRP footbridge in Mortsel.

Description	Calculation Note	Calculation Tool	Calculation Tool (Modified)
Laminate properties			
Longitudinal stiffness flanges, Ex [GPa]	30.74	29.55	27.93
Transverse stiffness flanges, Ey [GPa]	14.08	13.23	14.16
Shear modulus flanges, Gxy [GPa]	4.39	4.38	4.63
Longitudinal stiffness webs, Ex [GPa]	15.74	17.86	15.24
Transverse stiffness webs, Ey [GPa]	15.74	17.86	15.24
Shear modulus webs, Gxy [GPa]	5.69	6.67	5.69
Checks SLS			
Natural frequency unloaded, f0, unload, lt [Hz]	2.61	3.37	3.28
Deflection self-weight, wSW, lt [mm]	39.00	43.00	39.50
Deflection distributed load, wLC3, lt [mm]	21.10	51.94	19.45
Deflection service vehicle, wLC4, lt [mm]	17.70	10.89	11.65

- The values of bending stiffness and shear stiffness are not identical. In the calculation note, the structure of each of the laminates is specified in detail, from which the laminate properties are determined in the calculation tool based on the CLT. Since all checks are significantly influenced by the laminate structure, its effects should be analysed. The calculation tool initially provides a reasonable approximation of the reported values. However, the laminate structures reported in the calculation note are highly detailed, with different fibre volume fractions in different plies of the same laminate, while only one fibre volume fraction for the entire bridge can be entered into the calculation tool. When the underlying calculation of the tool is adjusted to provide stiffness values based on the specified detailed laminates, better matching values are obtained. The small differences that are still present are likely due to slightly different starting values for the properties of the E-glass fibres and the polyester resin.
- In the calculation note, the natural frequency in unloaded condition is determined from finite element software and deviates considerably from the calculated values from the calculation tool. This is most likely due to the simplified clamped boundary conditions, based on the beam theory, that are used in the calculation tool.
- The values for the deflection as a result of the self-weight are fairly close.
- The deflection due to the uniformly distributed load deviates significantly due to a difference in the applied load. In the calculation tool, a combination value of one is used on the live load, whereas in the calculation note, this is 0.35.

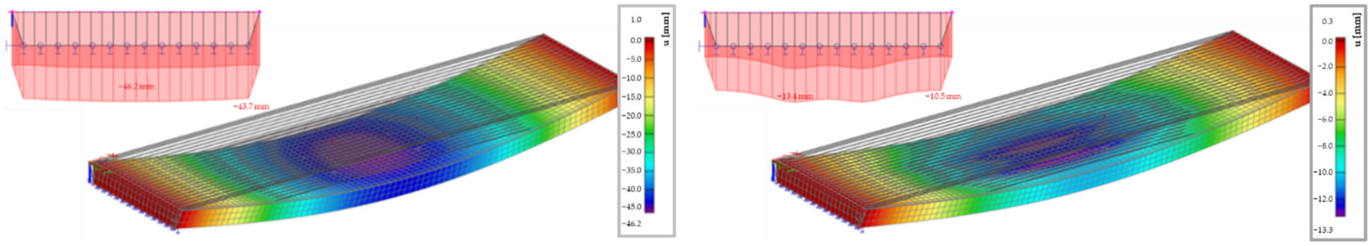
After correction for the causes mentioned above, which are essentially not related to the design method, a modified calculation is performed with the calculation tool. The results indicate that in all cases, the differences can mostly be eliminated by this modification, although the results remain influenced by the laminate stiffness values. As such, the method from [41] is in accordance with the calculation note except for the first natural frequency as a result of the simplification of the boundary conditions.

6.2. Comparison with Structural Engineering Calculation Software

In general, it can be said that the analytical calculation tool for the global analysis of an FRP bridge deck provides a good approximation of the deflection, the first natural frequency, and the stresses in the top and bottom flanges and webs. However, if local phenomena have a significant influence on the design, it may be necessary to switch to structural engineering software, which can be used to calculate the effects of the structural and material orthotropy on the deflection, especially in the transverse direction of the bridge deck. In what follows, the 2D calculation example from [41] is extended to a 3D analysis using a structural engineering software to assess the 3D effect, which is omitted in the analytical 2D method described in [41].

6.2.1. Deflection in LC3 (Distributed Load SLS) and LC4 (Service Vehicle SLS)

Figure 2 shows the deflection under a uniformly distributed load and a service vehicle for the example of a GFRP footbridge with a 16 m span and a width of 4 m, as elaborated in [41]. Firstly, the analytically calculated deflection under the distributed load is 46.23 mm without taking into account the conversion factors for environmental factors and aging. As can be seen from Figure 2, derived from the calculation software, the deflection of the centreline of the bridge at midspan is 46.2 mm, while it is only 43.7 mm at the edges of the bridge deck. This difference can be attributed to the orthotropic nature of both the material and the structure. Nevertheless, it can be concluded that the analytically predicted deflection corresponds to the 3D predictions with sufficient accuracy, and no 3D calculation is needed.



(**a**) (**b**)

Figure 2. Longitudinal and transverse deflection under (**a**) a uniformly distributed load (LC3) and (**b**) a service vehicle (LC4).

Secondly, the analytically calculated deflection under the service vehicle load is 11.99 mm without taking into account the conversion factors for environmental factors and aging. As can be seen from Figure 2b, derived from the calculation software, the deflection of the centreline of the bridge at midspan is 12.6 mm, while it is only 10.5 mm at the edges of the bridge deck and 13.4 mm directly under the wheel prints. This much larger difference can once again be attributed to the orthotropic nature of both the material and the structure as well as a much more pronounced 3D effect due to load localisation. Here, it can be concluded that the analytically predicted deflection corresponds less to the 3D predictions, and a 3D calculation might be needed, although the 2D analytical prediction is sufficiently accurate as it does not determine the design.

6.2.2. Natural Frequency (Un-)Loaded

The first natural bending frequencies in unloaded and loaded conditions, calculated with structural engineering software, are 4.37 Hz and 3.93 Hz, respectively. For comparison, the natural frequencies according to the analytical approach are 4.38 Hz and 3.93 Hz, respectively (all values without considering conversion factors). It can be concluded that there is a very good match between the analytically calculated values and the results from the structural engineering software. The simplified 2D analytical also seems appropriate here. Obviously, this will no longer be the case for more complicated bridge geometries.

7. Dynamic Human–Structure Interaction

The benefits of the low self-weight weight also come with a downside, which is the increased sensitivity to dynamic excitation by walking or jogging pedestrians. This can lead to vibrations, of which the acceleration may cause discomfort to (standing) pedestrians on the bridge. Therefore, there is a need for calculation models that accurately predict vertical acceleration, which is to be expected under a given pedestrian stream. Currently, such models exist, but may be over-conservative for web-core sandwich-type composite footbridges [53–58]. As a result of the C-Bridge project, the actual accelerations measured on site are found to be lower, and the damping is found to be higher [59–64] than predicted. The reason for this discrepancy is presumably the effect of human–structure interaction

(HSI). Humans are mechanical systems of their own, which interact with the bridge. In particular, this leads to a human-induced damping in addition to the structural damping of the bridge. Its effect is, however, difficult to estimate and therefore forms the subject of ongoing research. Here, we present results from a 3D engineering software model that attempts to take into account the influence of human–structure interaction to estimate the vertical accelerations and, consequently, the comfort of the composite bridge.

The model (Figure 3) is based on the web core sandwich panel FRP bridge in Puurs (See Section 6.1.1 and [44]). The structural damping of the bridge is modelled using Rayleigh damping, and a free vibration is induced on the bridge by means of a triangular impact load of short duration.

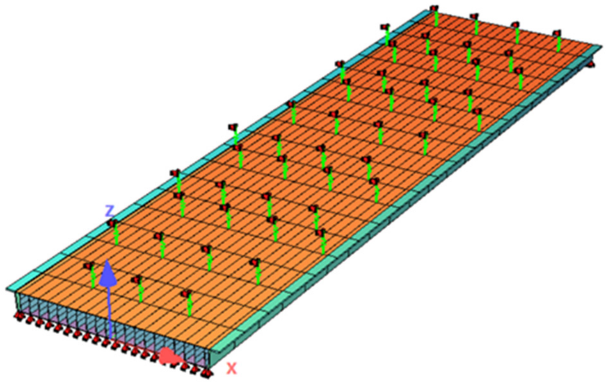


Figure 3. Numerical model of web-core sandwich panel FRP bridge in Puurs with SDOF pedestrians.

Pedestrians are modelled on the bridge as single degree of freedom (SDOF) systems consisting of a nodal mass connected to its support by a damper and a spring. The SDOF system is characterized by a mass, spring constant, and damping ratio. It is assumed that 95% of a person's mass is sprung. With an average mass of 70 kg for one person, this results in a mass of 66.5 kg assigned to the nodal mass. A natural frequency of a person with one or two legs slightly bent, as is the case during walking, is equal to 3.25 Hz on average. The damping ratio of the SDOF system is equal to 30% based on [59,65]. From the mass, the natural frequency, and the damping ratio, the damping spring constant and damping coefficient can be calculated using dynamic equations describing a SDOF system, which are then assigned to the spring-damper element in the numerical model.

In the simulations, a varying number of pedestrians is used in such a way that the pedestrian density ranges from 0 to 1.5 pedestrians per square meter. Additionally, the structural damping ratio of the bridge itself is varied, ranging from 0% to 5%. The resulting observed damping ratio in the free vibration as a function of pedestrian density for a pedestrian natural frequency of 3.25 Hz (walking pedestrian with bended knees) is shown in Figure 4.

Figure 4 shows that the damping ratio is initially equal to the structural damping ratio, as expected, and subsequently increases steeply with increasing pedestrian density. Around 0.2 P/m^2, a peak is reached, after which the damping ratio declines gradually. Despite this decline, the observed damping ratio remains much higher than the structural damping ratio across the entire range of pedestrian densities. The maximum observed damping ratio can be a multiple of the basic structural damping ratio, especially if the latter value is low to begin with.

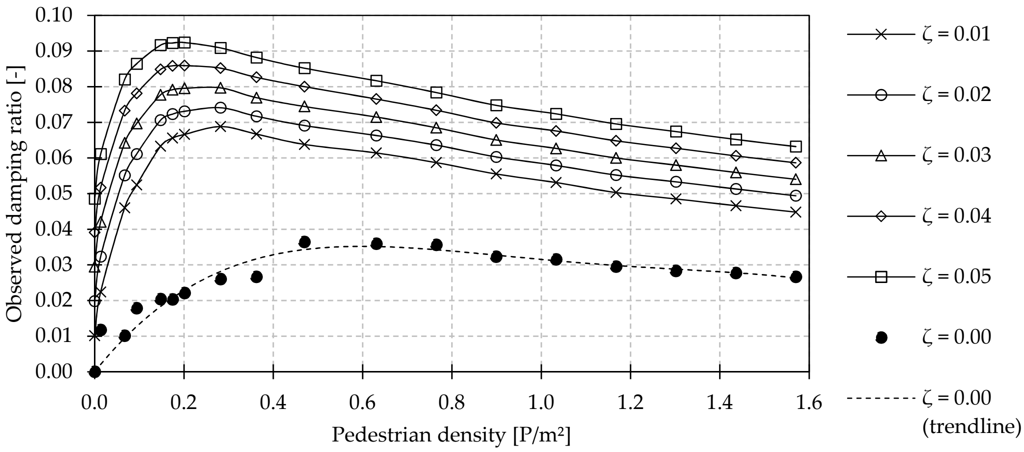


Figure 4. Calculated damping ratio as a function of pedestrian density.

The human-induced damping effect was also observed during in situ vibration tests on different composite footbridges in Flanders [66,67]. When applying the above-mentioned pedestrian density dependent damping ratio in the calculation method from [44], the measured vertical vibrations on the Puurs bridge coincide well with the analytical predictions. The implication of these findings is that damping for bridges of this type is much higher than what would be expected if the HSI were neglected. Consequently, vertical accelerations are lower, and the comfort level is higher due to this effect. Further study is needed to confirm this procedure for a wide range of composite footbridges.

8. Project Results

The C-Bridge project results have been published on the C-Bridge website [27] in Dutch, as required by the funding agency. On this website, the main conclusions of the seven work packages are given based on various white papers. These deal with a listing of the current state of the art in composite materials for bridge building applications, specification texts, normative documents and structural analysis, execution, delivery and maintenance, long term perspectives (bio-based materials [68,69] and life cycle analysis), and a roadmap to familiarize potential builders with the use of composite materials in civil engineering structures and the potential concerns that these create compared to traditional building materials (such as steel and reinforced concrete).

In addition to this, a calculation tool is provided, which provides an estimate of the material consumption and cost for a web-core FRP sandwich panel footbridge with simply supported or clamped boundary conditions. In addition to this, the tool also allows for an optimization of the bridge cross section for a given slenderness ratio. Based on this tool, a research paper [41] has demonstrated the determining influence of serviceability limit state (SLS) design requirements on the material consumption of this bridge type, and has pointed out the influence of human structure interaction (HIS) on material consumption, a mechanism currently not included in FRP footbridge design. This effect was also assessed during the project using vibration measurements, and a subsequent research paper [44] has confirmed the effect of HSI on these very lightweight bridges.

The project team has successfully disseminated the current state of the art to the various actors in Flanders, providing the necessary knowledge to make informed choices regarding FRP bridges. In addition, from a design point of view, the effect of SLS requirements and HSI have been demonstrated. The C-Bridge project was finalized during a workshop attended by more than 150 people from the field including from the government, design firms, contractors, producers, suppliers, etc.

9. Conclusions

By removing the most important barriers to the application of FRP materials in bridge construction, the C-Bridge project allowed for an important increase in knowledge in the Flemish bridge construction sector. This increase in knowledge was situated in the following areas:

- The state of the art regarding composites in bridge construction;
- Selection criteria regarding the choice for a composite bridge;
- Foreign experiences and recommendations for the preparation of Flemish type specification texts for composite bridges;
- Recommendations regarding the implementation and follow-up of the construction phase via in situ testing;
- Recommendations on structural analysis of FRP footbridges, including the effects of model simplifications;
- The relevance of human–structure interaction in the vibrational response of composite footbridges.

The results of the project enable Flemish clients to draw up specifications for FRP bridges in the correct manner. Moreover, they can correctly interpret the calculation notes made available and perform a proper assessment. The Flemish engineering firms will be able to make their own calculations on FRP bridges and bridge components. They can also build up a value chain within Flanders with Flemish contractors and producers. From the producers and suppliers' point of view, the results of the project will lead to a clearer profile of their products on the public and private markets. Finally, the general contractors and constructors will be armed to withstand the challenges that FRP bridges entail to subcontractors in terms of execution, follow-up, delivery, and maintenance. In general, the project should generate a market expansion for FRP in the traditionally conservative bridge building sector.

However, this C-Bridge project has not yet eliminated all uncertainties concerning composite bridges, and extensive additional research will be necessary. At the moment, for example, little information is available regarding the vibration behaviour and the human–structure interaction of GFRP bridges. Secondly, combination with other (environmentally friendly) alternatives, such as flax and jute fibres is currently unknown and seen with a certain degree of suspicion by many partners in the procedure of tendering bridge projects. However, these environmentally friendly alternatives display great added value, especially when considering the production of the fibres compared to the currently used materials. Furthermore, the connection of composite bridge segments for the assembly of larger spans by, for example, bolted and/or adhesive connections, is currently rarely applied due to the challenges that still exist. Lastly, the long-term perspectives, especially the end of life of this type of bridge, are still uncertain.

Apart from these current uncertainties at the time of publication, the C-Bridge has nevertheless led to a broadening and dissemination of important knowledge in the Flemish construction community regarding composite bridges and has significantly lowered the bar for the use of composite materials in bridge projects, as can be seen in the increasing number of composite bridges built in Flanders in recent years.

Author Contributions: Conceptualization, W.D.C. and J.U.; methodology, W.D.C. and J.U.; software, W.D.C. and J.U.; validation, W.D.C. and J.U.; formal analysis, W.D.C. and J.U.; investigation, W.D.C. and J.U.; resources, W.D.C. and J.U.; data curation, W.D.C. and J.U.; writing—original draft preparation, W.D.C. and J.U.; writing—review and editing, W.D.C. and J.U.; visualization, W.D.C. and J.U.; supervision, W.D.C.; project administration, J.U.; funding acquisition, W.D.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Agency for Innovation and Entrepreneurship (VLAIO) of the Flemish government grant number 18001.

Data Availability Statement: Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request. This concerns, among other things, the acquired data in connection with the structural analysis of an FRP footbridge using the C-Bridge Excel calculation tool and engineering calculation software and the vibration data obtained from the performed human-induced vibration tests.

Acknowledgments: This project was realised due to the financial support of the Agency for Innovation and Entrepreneurship (VLAIO) of the Flemish government. The Ghent University and WTCB project team would also like to thank all participants (governments, clients, contractors, consultancy firms, and manufactures) of the different board groups for their active participation during the two-year C-Bridge research project and to provide the necessary documents and footbridge cases for the analysis and implementation of the necessary research studies.

Conflicts of Interest: The authors declare no conflict of interest.

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