World Conference on
Timber Engineering
Oslo 2023

IMPROVEMENT OF THE DURABILITY OF TIMBER BRIDGES BY INTELLIGENT DESIGN AND RESPONSIBLE MAINTENANCE

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ABSTRACT: Timber bridges may contribute to climate protection due to their carbon sink capability and substitutional effect. One basic requirement for the increased application of timber as an ecological and sustainable construction material is long-term durability. This can only be achieved by consistently using structural protection measures in all stages of planning, construction and service life. The paper presents sample drawings for the design of structurally protected timber bridges and provides recommendations for useful maintenance measures. Using standardized drawings increases effectiveness and efficiency in engineering offices and reduces the danger of serious errors in planning. Regarding their ecological and sustainable advantages, a significant increase in the market share of timber bridges is to be expected in Germany. Aesthetic, well-protected and durable timber bridges of a high-quality standard will characterise the landscape in the future.

KEYWORDS: timber bridges, durability, design, sample drawings, details, maintenance

1 INTRODUCTION

Timber bridges have a centuries-old tradition. A few very old, well-protected bridges demonstrate the potential of timber as a natural structural material (Figure 1). However, the specifics of this orthotropic and hygroscopic material need to be considered in general timber construction and that of bridges in particular. Careful observance to the structural details is required. The material must be protected against moisture ingress. The strength and stiffness of wood decrease with increasing moisture content. Timber starts to swell and shrink with changing moisture, causing internal stress and cracks. Furthermore, a higher moisture content enables insects and fungi to attack and destroy the structure.

Figure 1: Old covered bridge in Aarberg (Switzerland), built in 1568 (photo: A. Simon)

If the specific requirements are ignored, there is high-risk potential for destruction, and the maintenance costs significantly increase. Inspections of several bridges in Germany have confirmed that most defects are caused by faulty design and a lack of protection and maintenance measures. The long-term durability of timber bridges can only be achieved by consistently using structural protection measures in all stages of planning, construction and service life. Therefore, the research project "Protected timber bridges (ProTimB)" was initiated to define a new standard for durable timber bridges. The results of the project have been published in a research report [1].

2 THE RESEARCH PROJECT PROTIMB

2.1 OVERVIEW

The outcome of the project is a set of technical guidelines for the design, construction and maintenance of protected timber bridges (Figure 2). Formally, it is inspired by the existing sets of rules for other materials established by the German Federal Highway Research Institute (BASt) to facilitate their application in practice.
The design rules [2] consist of references for planning, samples for structural analysis and 36 new sample drawings (MuZ-HolzBr). In addition, "Recommendations for technical contractual terms for timber bridges (ETV-HolzBr)" have been developed for construction [3].

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https://doi.org/10.52202/069179-0396

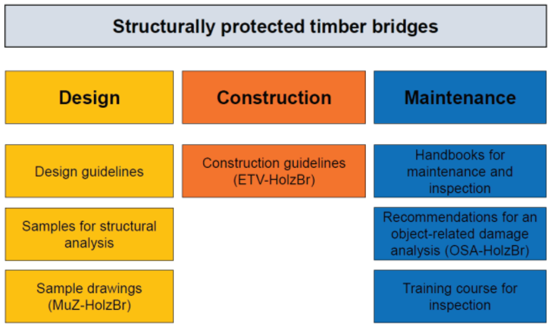

Figure 2: *Overview of the new guidelines and project results*

Sample handbooks have been written for the maintenance and inspection of timber bridges and recommendations for an object-related damage analysis (OSA-HolzBr) have been compiled. Furthermore, an advanced training course has been conceptualised for timber bridge inspectors. Additionally, nine protected timber bridges crossing rivers were comprehensively monitored [4]. The most important guidelines for design and maintenance will be presented in the following. For further details see [1].

2.2 DESIGN

2.2.1 Overview

A set of new sample drawings [5] has been developed for the design of timber bridges. It is based on older drawing sets [6] and [7], which it updates and extends. The 36 new drawings illustrate durable and proven solutions for special structural details (Table 1).

Table 1: *Contents of the sample drawings for protected timber bridges*

Drawing	Contents
H-Belag 1-4	Variants of decks and their mounting (closed surfaces as asphalt sealings, concrete- and natural stone slabs and open surfaces using wooden planks)
H-Dicht 1-3	Design of sealings for the timber-superstructure
H-Gel 1-5	Variants of parapets and their fastening
H-Kap 1-2	Mounting of concrete caps on timber structures
H-Lag 1-3	Details for bearings
H-Schutz 1-8	Structural protection measures (covering, cladding, ventilation distances, protrusion)
H-Trog 1-2	Design of cross frames and bracing structures for trough bridges
H-Übe 1-4	Transition structures and expansion joints
H-Was 1-3	Details for drainage and dewatering
H-Zug 1	Accessibility of substructure

They are closely related to the familiar drawings of the German Federal Highway Research Institute (BASt) [8]. Annex D of the new version of the European Code for Timber Bridges EC5-2 [9] also shows sample drawings inspired by the results of the ProTimB project.

The drawings focus on the critical points of timber bridges such as decks, sealings, parapets, bearings and expansion joints. Special attention was paid to the structural protection measures including recommendations for covering, cladding, ventilation distances and protrusion. In Germany, structural protection takes precedence over chemical treatment. All load-bearing members must be structurally protected. Secondary structural members may remain unprotected but should then be regarded as "maintenance elements" with a lower service life of 10 to 20 years.

This strategy is also followed by the next edition of Eurocode [9].

According to this new code, timber bridges will be divided into four categories to define their design service life. For protected timber bridges in category 1, a design service life of 100 years is expected. To achieve this design service life analogously to bridges made of other materials, the main structural components shall be designed with structural protection. Category 2 includes timber bridges whose main structural members are protected for a 50-year design service life. Replaceable structural parts of protected bridges (category 3) should achieve a design service life of 25 years. For temporary structures (category 4), a maximum design service life of 10 years is expected. Unprotected timber bridges belong to category 4.

As a basis for planning protection measures, the use class (UC) has to be defined for every single timber member (Figure 3) according to [10].

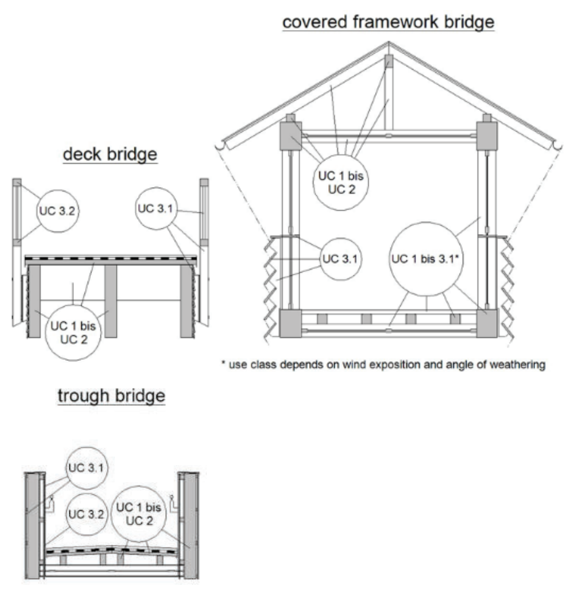

Figure 3: *Assignment of timber members to use classes (UC) in different exposure situations*

Appropriate structural protection measures and wood species, based on their durability class, should be derived from the use class. Analogously to the procedure according to [11], the main objective is to achieve use class 0 to avoid chemical treatment. For every single timber member, the classifications and protection measures should be summarised in a separate design plan as shown in Table D.1 of [9].

One special feature of the sample drawings is the definition of maintenance elements. If non-load-bearing or easily replaceable timber components are exposed to weathering (e.g. railings, cladding and planks), a significantly shorter service life is to be assumed for these components compared to the service life of the protected main load-bearing structure. Weathered timber components must be regularly maintained and replaced if their stability, traffic safety or durability is impaired. Therefore, these components are explicitly marked as maintenance elements.

The following will offer important design advice and present and explain examples of the drawings.

2.2.2 Bridge deck surfaces and sealings

In principle, a closed deck is preferable to an open deck, as the main girders located under the deck are structurally well protected by a dense layer. Bridges over roads and railway lines should generally be provided with a closed deck.

For a closed deck, an under-ventilated construction is recommended. In contrast to the direct arrangement of the sealing on the main supporting structure, an under-ventilated structure enables direct checking for leaks, creates a second sealing level and reduces blistering during asphalt paving. An under-ventilated construction can also be more easily repaired. The following setup should be used (H-Belag 1 (Figure 4) in connection with H-Dicht 1):

- Top layer: mastic asphalt, 25 – 45 mm thickness,
- Protection layer: mastic asphalt, 25 mm thickness, mounting temperature 180 – 200°C,
- Sealing: polymer-bitumen water-proofing membrane fixed to timber deck,
- Epoxy resin-based primer,
- Wood-based panel on squared timber as spacer for under-ventilation, minimum surface inclination 2.5 %,
- Protective layer, diffusion-open,
- Timber deck, minimum surface inclination 2.5 %.

In the case of open decks, the planks must be fastened to a separate decking beam placed next to the main beam (H-Belag 3 and H-Belag 4). Direct fastening of the planks to the main girder is not permissible, as the fasteners penetrate the sealing arranged above the main girder and thus impair structural timber protection. The decking planks and the decking beam are maintenance elements with a shorter service life, as they are exposed to direct weathering and dirt through use. A sheet metal cover on the top side and a nail sealing strip (H-Belag 3) or a plastic membrane extend the service life of the separate decking beam. In the case of open decks, the joint between the end of the superstructure and the chamber wall must be closed to prevent dirt, grit, leaves or similar from falling through and remaining on the support bench (H-Belag 3 and H-Übe 4).

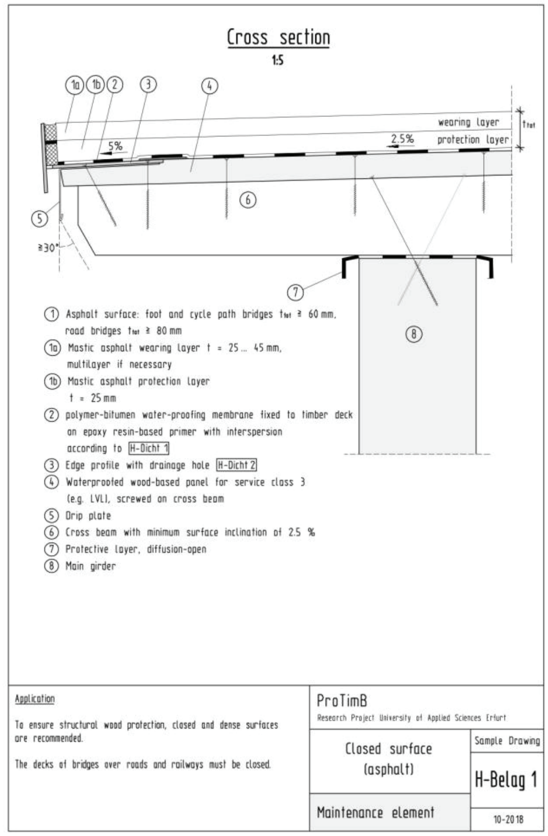

Figure 4: *Sample drawing H-Belag 1 showing the surface layers and the sealing*

2.2.3 Railings

Weathered wooden railings are maintenance elements with a shorter service life. They need to be replaced after 10 to 20 years.

Knots on the surfaces of wooden planks and handrails can lead to break-outs and increase rotting. Therefore, the components of wooden railings should contain as few knots as possible.

Architecturally interesting alternatives to wooden railings are steel railings with wooden handrails. For the handrail, the use of acetylated or other modified wood is recommended due to its higher durability and low tendency to crack and deform.

When fixing the railing to the main beam, it is important to make sure that the structural wood protection of the main beam is maintained. Water must not be led to the main girder via the fastening elements (pos. 5 of H-Gel 5, see Figure 5).

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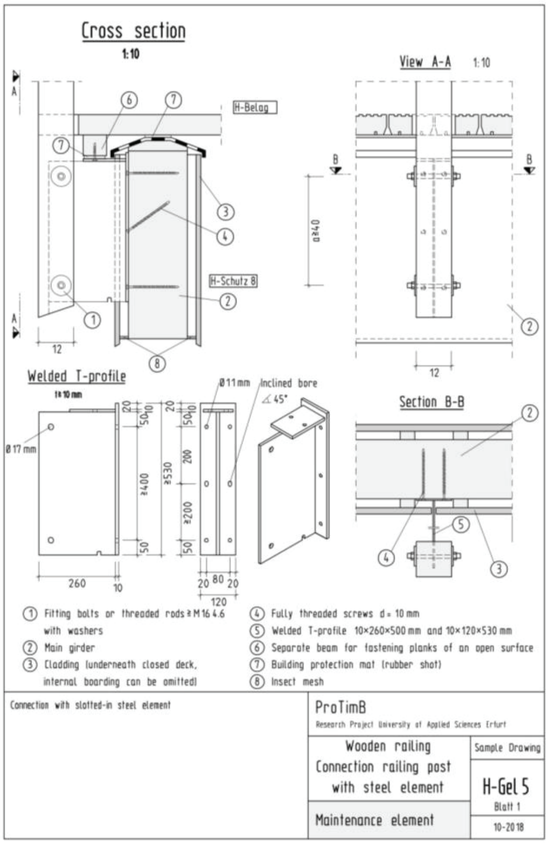

Figure 5: Sample drawing H-Gel 5 explaining the connection of a railing post by a steel element

For pedestrian bridges, the minimum height of the railings is 1.00 m. If bridges are used by cyclists, the railings must be at least 1.30 m high.

2.2.4 Structural protection measures

The sample drawings in H-Schutz regulate details of structural timber protection as the most important basis for durability.

Structural timber protection can be attained by using a closed surface or a sufficient roof overhang and/or by cladding. Any covering must protrude at least far enough to prevent rain falling at an angle of 30° from the vertical from reaching the load-bearing timber structure (H-Schutz 1, see Figure 6). At wind-exposed locations, a significantly larger angle of rain incidence can occur. In this case, the protective measures must be extended. Lower chords of trusses are particularly at risk, as water can penetrate the connecting details, nodes and horizontal cracks and cannot run off. If wind exposure is unknown, it is recommended to plan load reserves in the static calculation for the subsequent installation of additional cladding. Alternatively, it is possible to calculate the main structure with reduced strength in service class 3 (as necessary for unprotected members) instead of service class 2 (as permitted for protected members).

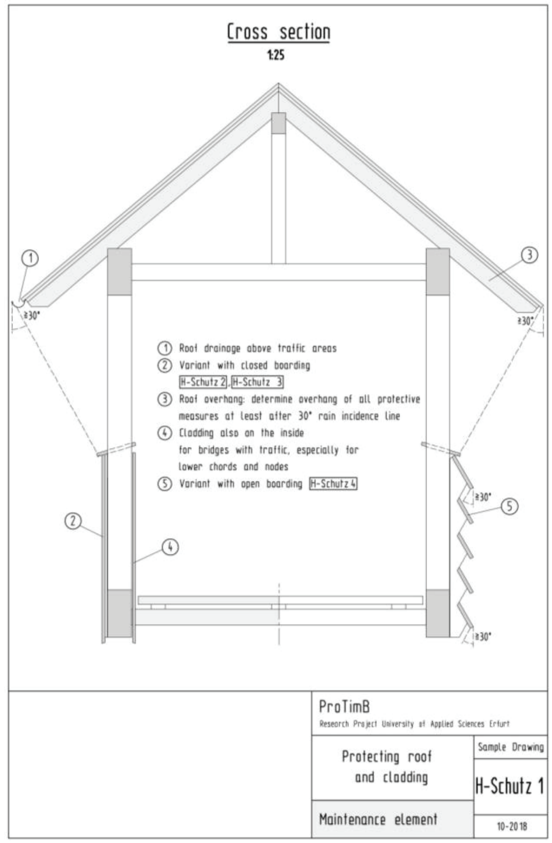

Figure 6: Sample drawing H-Schutz 1 explaining general structural protection measures

Construction with a sufficient lateral overhang is preferable to cladding, as hands-on inspection of the main structure is easier. Open claddings (H-Schutz 4) facilitate hands-on inspection (Figure 7).

Figure 7: Swiss timber bridge structurally protected by a roof and an open cladding (photo: A. Simon)

Closed cladding should be easily removable or hinged to improve the inspection of the construction behind (H-

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Schutz 6, see Figure 8). Due to better water drainage, vertical cladding is preferred to horizontal cladding (H-Schutz 2). Inside trough bridges, horizontal boards can be advantageous, as individual horizontal lamellas could be more easily replaced in the splash water area.

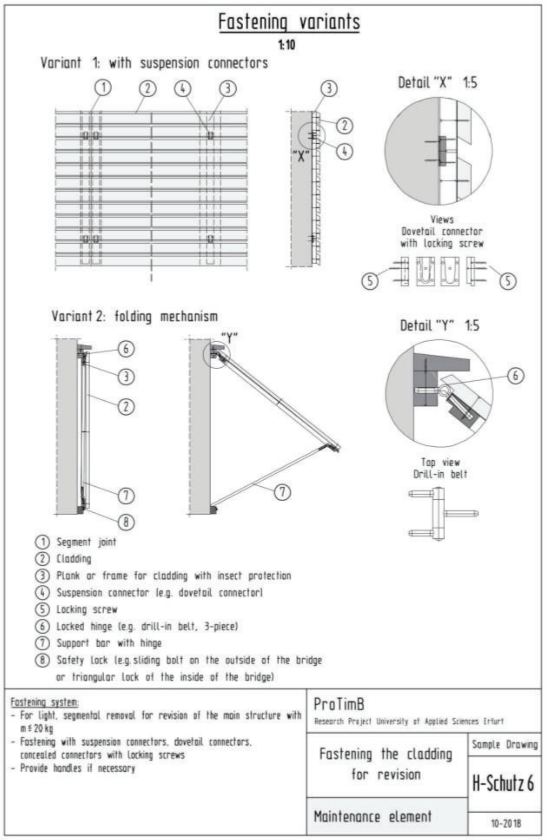

Figure 8: *Sample drawing H-Schutz 6 showing a removable cladding for inspection*

The following basic and special measures for structural timber protection should be observed in timber bridge construction:

- Wooden bridges should be designed for low-maintenance (e.g. by integral structures, watertight expansion joints, closed surfaces) or in a maintenance-friendly manner (facilitation of cleaning and inspection by sufficiently large distances between the components).
- During assembly, the moisture content of the wood should correspond to the expected moisture content on site (approx. 16 to 18 M%).
- Wooden components and their connections must always be designed in such a way that precipitation is deflected by weather protection. Alternatively, it has to be drained away so fast that no increase in wood moisture can occur and no moisture accumulation takes place. Timber components shall be installed with air circulation at an appropriate distance from other building components and from the terrain to avoid moisture transfer or moisture accumulation and to allow rapid drying. Direct weathering must be effectively prevented during transport, storage and the construction phase (e.g. by covering with foil).
- Insect infestation must be precluded (e.g. by using kiln-dried timber, insect-impermeable covers, coloured heartwood with sapwood content ≤ 10 % or open arrangement of timber members with regular inspection).

2.2.5 Accessibility

In order to facilitate the bridge-inspection, minimum distances should be maintained between the superstructure and the substructure as well as the surrounding terrain (H-Zug 1, see Figure 9). Sufficient distances also guarantee air ventilation and prevent the influence of spray water and vegetation.

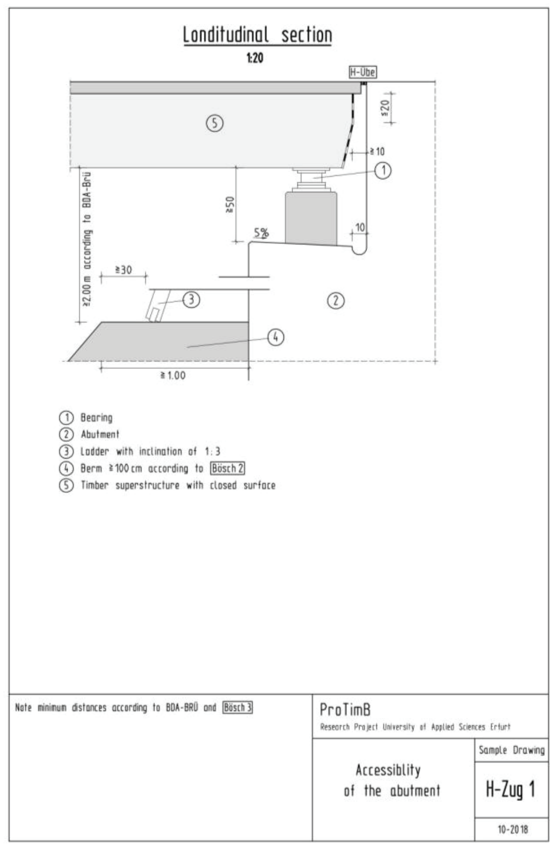

Figure 9: *Sample drawing H-Zug 1 showing minimum distances for good ventilation and easy inspection*

Special protection of the end-grain surfaces is necessary, e.g. by arranging waterproof transition joints, arranging rear-ventilated sheets or boards or by means of diffusion-open paint or membrane. Ventilation and accessibility of the end-grain surfaces can be ensured by chamfering the beam's ends and maintaining a distance to the chamber wall of at least 0.10 m.

https://doi.org/10.52202/069179-0396

A clear distance between the superstructure and the support bench of at least 0.50 m enables the bearings to be easily checked. In addition, the wooden main beams are prevented from being affected by water and dirt on the support bench. Manual cleaning of the support bench is also facilitated. A sufficiently wide and plane area in front of the abutment and a clear height of at least 2 m enable the inspection of the superstructure's underside (Figure 10).

Figure 10: *Bottom view of a timber-concrete composite bridge (Birkbergbridge, Germany) showing a sufficient distance between superstructure, support bench and ground for good ventilation and easy inspection (photo: A. Simon)*

2.3 CONSTRUCTION

"Recommendations for technical contractual terms for timber bridges (ETV-HolzBr)" have been developed for construction [3]. This document defines basic material requirements for the timber, engineered wood products, thermally and chemically modified wood, adhesives and steel components. Specifications are given for minimum dimensions, surface qualities and limits for deformation due to shrinkage and swelling. The production, storage, delivery, quality control and assembly of structural timber elements are regulated. For the purposes of quality control, the document defines limits for dimensional and moisture tolerances, cracks and surface qualities at the factory and at the construction site. Furthermore, it contains necessary measures to be taken for structural timber protection and the corrosion protection of steel components in timber bridges. Suggestions for the design of timber-concrete composite bridges and of wildlife bridges complete these guidelines. With the extension of the Eurocode for timber structures [11], execution rules will also be normatively regulated in the future.

2.4 MAINTENANCE

Respecting the principles of structural protection is mandatory but not sufficient for durable timber bridges. Their intended service life of 60 to 100 years can only be achieved in combination with regular maintenance and inspection. Manuals for maintenance and inspection have been developed within the ProTimB project [1].

The maintenance manual explains useful service measures, their necessary intervals, the required technical equipment and means of access to facilitate economical maintenance. Service measures include:

- the cleaning of the superstructure, benching, road surface, bridge drains and drainage channels,
- the removal of vegetation all around the bridge in a radius of at least 2 m,
- the renewal of coatings, sealants, joints,
- the repair of planks, asphalt layer, cladding, cover plates and parapet members.

An interval is recommended for every measure, taking the structural element's service life and seasonal weathering and pollution into account. In addition, a continuous monitoring of the timber moisture content is advised.

2.5 BRIDGE INSPECTION

Independently of maintenance, bridges must be regularly inspected in Germany. Every bridge has to be visited twice a year and checked once a year. Additionally, the basic inspection and main inspection have to be performed alternately every three years. The main inspection requires a hands-on check of every structural component and is therefore the most complex and expensive. For special types of timber bridges such as framework bridges, cable-stayed bridges or bridges for wildlife, an inspection manual supplements the maintenance manual. The inspection manual explains the tasks for continuous observation (usually twice a year) and the annual survey as well as for the basic and the main inspection in detail.

It is recommended to use the checklists for continuous observation and survey, which are part of the inspection manual, in parallel to the maintenance manual. The following aspects have to be checked during the annual observation:

- All structural protection measures have to be checked for functionality (covering, sealings, cladding).
- All accessible members have to be checked for sufficient protection from moisture and dirt (marks of running water, timber with earth contact, growth of moss and algae).
- The timber moisture content has to be measured in damp and vulnerable areas.
- All accessible members have to be checked for wood-destroying fungi, incipient rot and wood-destroying insects.
- Protruding connectors have to be observed (screws in planks, dowels in knot areas).

It is recommended to record damage and compare it with the condition of the previous observation. On this basis, necessary conservation measures can be derived to ensure economical bridge maintenance and to achieve long durability.
The inspection manual contains the recommended measuring methods and provides special hints for organisation, accessibility, documentation and traffic security during the inspection. Regarding individual structural characteristics, the regular inspection of every timber bridge can be optimised and performed economically. If a regular inspection reveals complex damage of unclear cause or unclear dimension of defects, further recommendations are given for the implementation of an object-related damage analysis.

3 CONCLUSIONS

Technical guidelines guarantee professional state of the art design and construction standards.
The sample drawings for timber bridges describe recommended structural details for the planning, calculation and execution of timber bridges. They represent proven and durable solutions for recurring technical tasks and reflect the respective state of the art.
Intelligent design and responsible regular maintenance improve the durability of timber structures, enabling bridges made of timber to achieve the service lives of concrete and steel bridges.
Aesthetic, well-protected and durable timber bridges of a high-quality standard will characterise our landscape in the future.

ACKNOWLEDGEMENT

The new guidelines for protected timber bridges were developed within the research project "Protected Timber Bridges (ProTimB)". The research has been supported and funded by the Federal Ministry of Education and Research of Germany, the companies of the Qualitätsgemeinschaft Holzbrückenbau e. V. (Schaffitzel Holzindustrie GmbH + Co. KG, Schmees & Lühn Holz- und Stahlingenieurbau GmbH, Grossmann Bau GmbH) and Setzpfandt Beratende Ingenieure GmbH & Co. KG. The authors thank all partners and supporters for their technical and financial support.

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