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Advancing Timber for the Future Built Environment

OPTIMISATION OF THE STRUCTURAL INSPECTION OF TIMBER BRIDGES USING DIGITAL MODELS

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ABSTRACT: The following paper presents investigations which combine non-destuctive testing (NDT) methods and integrate the data collected into digital structural models to improve maintenance management for timber bridges. In recent years, extensive research has addressed the development of advanced NDT techniques and digital structural models for the maintenance of bridges. The current focus is on Structural Health Monitoring (SHM) and Digital Twins (DT) for bridges made of concrete and steel. However, there is a large discrepancy between research and its practical applications in maintenance management especially for timber bridges. Reliable damage diagnostics using modern NDT methods are significantly more complex for wood as a highly anisotropic, inhomogeneous and porous material than for more homogeneous materials. The paper presents a new combination of microwave and ultrasound measurement methods, which aims to achieve a higher quality in the evaluation of load-bearing timber structures. Furthermore, investigations were conducted into how the inspection of timber bridges can be improved by utilising digital structural models. In order to use Building Information Modelling (BIM) in the inspection and maintenance of bridges, the provision of as-built models is necessary. On the one hand, efficient methods are needed to retrospectively generate these digital structural models to the required level of detail, as they generally do not exist for most bridges. On the other hand, the existing IFC standard lacks options for modelling damage patterns. Additionally, timber bridges have not yet been considered in the IfcBridge class. The article presents pilot applications for the manual and parametric generation of digital as-built models and shows possibilities for the implementation of results from structural inspections of timber bridges in particular. Therefore, a basic categorisation of the data structure for the modelling of timber-specific defects and measurement data from NDT is provided.

KEYWORDS: timber bridges, inspection, non-destructive testing, building information modeling, as-maintained-model

1 – INTRODUCTION

Bridges have to be regularly inspected in order to maintain stability, durability and traffic safety during their service life. While the BIM method is becoming increasingly important for the design and construction of new bridges, the use of digital methods for structural inspections has been limited to a few innovative pilot projects [1]. So far, the digital documentation of structural inspections, monitoring and diagnostics is not widespread in Germany.

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No implementations for timber bridges are known to date. In practice, measurement data and damage are mostly recorded manually on-site and subsequently digitised, despite extensive international and national research. The development of open BIM standards will drive forward digital transformation in the construction industry worldwide. The IFC data format will continue to be developed as the basis for an open source digital collaboration. The introduction of the IfcBridge class [2] was a major milestone for bridge construction. As a large number of bridge types is included in this new class, bridge components can now be digitally modelled more easily. However, explicit options for directly mapping timber bridges and their damages are still lacking. This paper discusses the increasing efficiency of structural inspection by using digital structural models to optimise the maintenance management of short and medium span timber bridges. To analyse the condition of the structure during an inspection, a new innovative combination of NDT methods will be presented, which will enable faster inspection of timber bridges with a higher level of quality in the future.

2 – REGULATION AND METHODS FOR INSPECTION OF TIMBER BRIDGES IN GERMANY

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. Incidents such as the collapse of a fungus-infested Bongossi bridge led to stricter regulations, so that wooden bridges over waters have been subject to annual inspection since 2013. The maintenance of wooden bridges is therefore five times more expensive than that of bridges made of other building materials. Research on protected timber bridges over waters shows that this represents an unjustified disadvantage for timber as an ecological building material [3]. The research results are expected to lead to a revision of the cycle for the main inspection of protected timber bridges.

Various methods of non-destructive, low-destructive and destructive testing are available for timber structures. An overview of established and practical NDT techniques can be found in [3] and [4]. In Germany, the recommended methods for timber bridge inspection are moisture measurement using the electrical resistant measurement method and ultrasonic wave-based tools in combination with drilling resistance measurement. Test methods for determining wood moisture content are of particular importance, as damage to timber structures mainly occurs due to excessive wood moisture. Ultrasonic waves and ground penetrating radar are successfully used for defect analysis and material characterisation of steel and concrete structures. As wood is a highly anisotropic, inhomogeneous and porous material, reliable structural analysis and damage diagnostics using these methods are considerably more complex. Sound velocity correlates with wood strength via the modulus of elasticity and density [5], [7]. In contrast, microwave methods are particularly sensitive to changes in wood moisture [6], but can also reportedly detect changes in density and fibre direction [7] as well as defects, metal fasteners and rot [8]. While microwave methods do not require direct coupling and can penetrate layers of air, ultrasonic waves are totally reflected at interfaces between solids and air. Several factors influence the measurement results, e.g. temperature, the frequency of the waves, the wood species, density, moisture content, the anisotropy and inhomogeneity and the size of the wooden component [4]. Suitable technical equipment and a high level of expertise are required to generate correct information on the performance of the wood using these methods. For this reason, however, neither method has yet been established in the inspection of timber bridges.

3 – THE RESEARCH PROJECT ULTRATIMB

3.1 OBJECTIVES

The hands-on assessment of all load-bearing components forms the basis of every structural inspection. For timber structures, the focus is on the detection of cracks relevant to load-bearing capacity and the reliable determination of material moisture, as wood moisture levels above 20 % can cause serious consequential damage due to rot. Decay occurs frequently, but is often only recognisable at an advanced stage, especially as internal rot. In addition, load-bearing members of protected timber bridges are often clad and not directly accessible, which makes them difficult to assess. The NDT methods available allow for a reliable assessment of the inside of the member either selectively or only with limited certainty.

The research project “Quality assessment of wooden components using a novel NDT method by combining microwave and ultrasound methods and integrating them into digital building models (UltraTimB)” was conducted to improve the quality of structural analyses and damage diagnostics on timber components. The research was organised as a joint project with the Materials Research and Testing Institute at the Bauhaus-University Weimar (MFPA), the University of Applied Sciences Erfurt (FHE) and the Institute for Wood Technology Dresden (IHD). The project is based on the hypothesis that changes in moisture and density, which can reflect damage, cause measurable changes in the elastic and dielectric properties of the wood, which can be recorded in qualitative terms and quantified. Ultrasound and microwave methods were chosen because they enable fast and cost-effective linear, two- and three-dimensional scans in contrast to point measurement methods. Measurements should be possible both directly on the component surface and, for the first time, through cladding or air layers. The measurement results should be integrated into digital structural models in order to improve inspection and maintenance of timber bridges.

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3.2 METHODS

To detect structural defects and moisture damage on wooden members, multi-channel imaging microwave methods were used for the first time, both separately in transmission and in combination with multi-channel imaging ultrasonic methods in reflection (Figure 1).

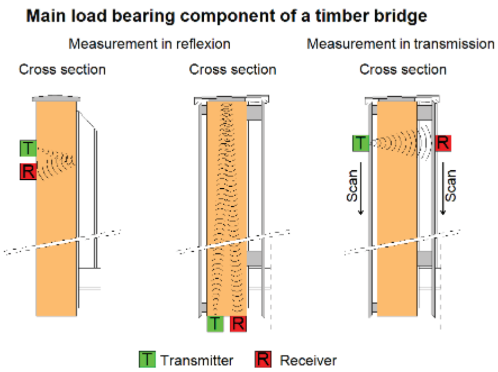

Figure 1. Intended measurement arrangement in situ

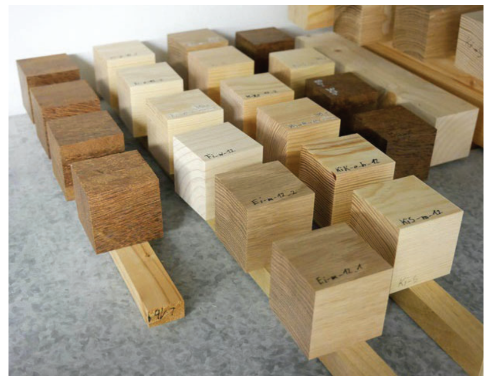

Figure 2. Reference cubes (photo: FHE, Thorben Niemann)

The experimental work was based on an iterative approach with increasing sample size and complexity. 27 reference cubes (Figure 2) were used as reference specimens to determine principal correlations between measured values and material parameters. The cubes consisted of various wood species relevant for timber bridges (spruce, pine, oak, bongossi) with four different groups of wood moisture contents (8, 12, 18, 30+ %) and three different degrees of decay. Particular attention was paid to the influence of anisotropy by considering the fibre direction in comparison to the measurement direction or wave propagation (Figure 3). For that reason, all cubes should be fabricated with growth rings parallel to the edges.

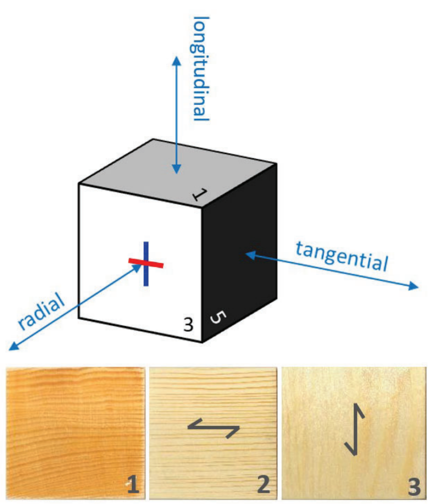

Figure 3. Definition of the fibre orientation and the growth rings of the reference cubes (photos: MFPA; Frank Bonitz)

Subsequently, 12 cuboid test specimens made of spruce with defined practice-relevant features and damages (cracks, holes, fasteners, adhesive joints) were analysed. Furthermore, seven assembled test specimens were designed to simulate defined levels of internal damage. Several wooden sticks representing either a different decay rate or a different moisture content were inserted into the interior of the modular spruce specimens. Defined decay rates (only discoloured - weakly decayed - heavily decayed) were achieved by incubating the sticks with white and brown rot fungi over different time periods (Figure 4).

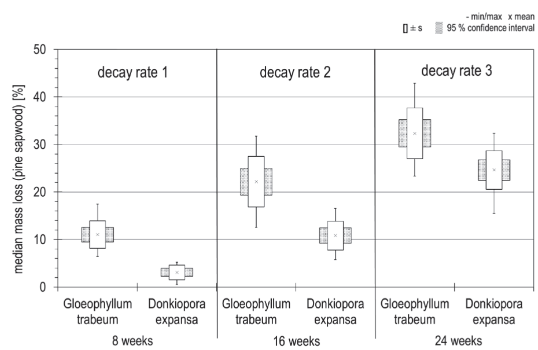

Figure 4. Decay rates and mass loss of sticks for assembled test specimens after different times of incubation, using Gloeophyllum trabeum as brown rot and Donkiopora expansa as white rot fungus

Finally, six practical samples with damage of unknown dimensions were removed from parts of dismantled bridges and analysed. These practical samples consisted of glulam, softwood and bongossi and showed cracks on the surface, fasteners and internal rot of unknown extent.

The dielectric measurements were performed on the cubes with a surface probe (PNA) in reflection (Figure 5) and on all samples with newly developed ultra-wideband antennas (UWB) in transmission (Figure 6).

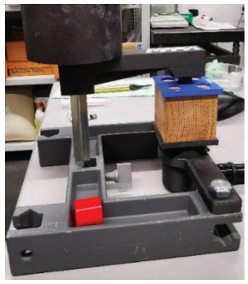

Figure 5. Test configuration for reference cubes with a surface probe (PNA) (photo: MFPA, Frank Bonitz)

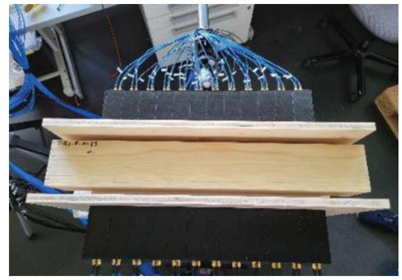

Figure 6. Test configuration for cuboid test specimens with ultra-wideband antennas (UWB) measuring without direct contact through cladding and air layers (photo: MFPA, Frank Bonitz)

The ultrasonic measurements of the reference cubes used longitudinal and transverse waves in a transmission arrangement (Figure 7). The cuboid test specimens and practical samples were analysed in reflection using ultrasonic devices and ultrasonic arrays (Figure 8).

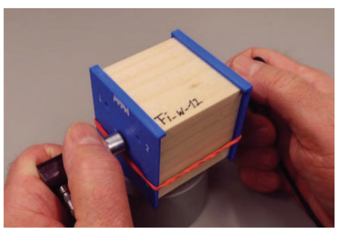

Figure 7. Test configuration for reference cubes with ultrasonic device (photo: MFPA, Martin Schickert)

Figure 8. Newly developed ultrasonic array for cuboid test specimens (photo: MFPA, Martin Schickert)

The results were evaluated using comparative X-ray analyses of the cuboid samples and conventional diagnostics including the determination of strength, modulus of elasticity, raw density and wood moisture content. A commercially available georadar measuring device was also used for comparison purposes. For the first time, a contact-free analyses through cladding and air layers was tested using the microwave method in transmission. The test specimens and the entire measurement programme are shown in Figure 9.

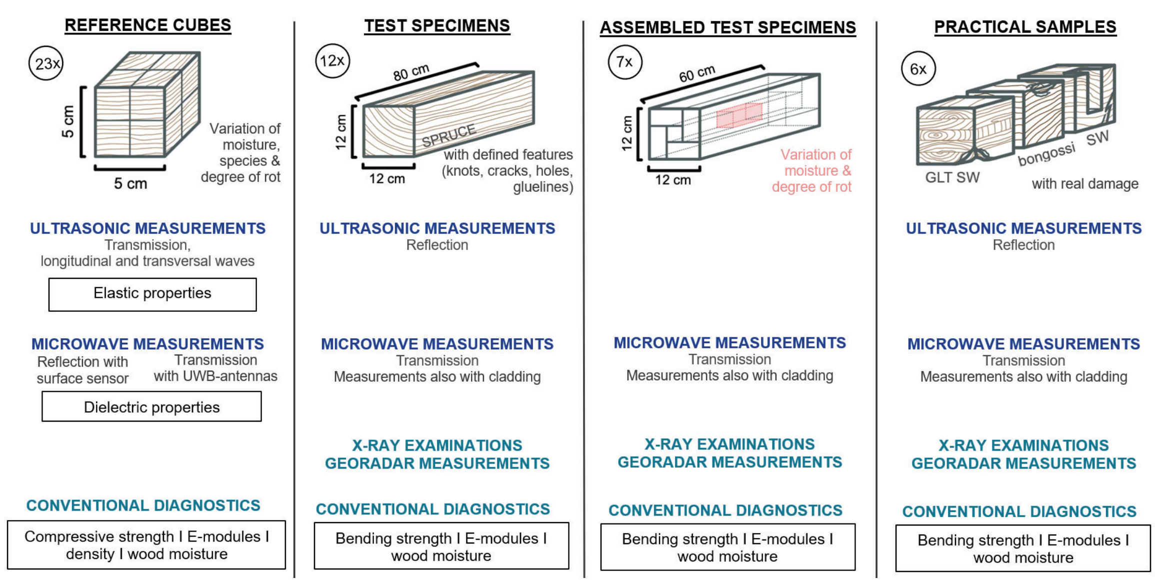

Figure 9. Overview of the test specimens and the respective diagnostic methods

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3.3 FIRST RESULTS

Preliminary results obtained from the reference cubes are presented below. The complete evaluation of all measurement series on all test specimens will be documented in the final research report in June 2025 and presented in [9].

The results from the reference cubes confirm the correlations known from other research literature [6] [7]. By increasing moisture content, sound velocity decreases while permittivity significantly rises (Figure 10). Permittivity is very sensitive to changes in wood moisture. The evaluation of the integral measurement with UWB shows a smaller influence of anisotropy (fibre direction) and inhomogeneity (growth ring pattern) at higher levels of wood moisture content. For all levels of wood moisture content, the influences of density, growth ring pattern and fibre direction overlap significantly (Figure 11).

In contrast, the sound velocity of the ultrasonic waves showed a good correlation with the mechanical properties (strength and modulus of elasticity) on the reference cubes of the same wood species. The anisotropy of the wood has a decisive influence on the measurement results using both methods. Sound velocity is for instance up to 3.7 times greater in the longitudinal direction than that of the radial direction (Figure 11). This ratio corresponds to the value range of 3 to 4 specified in [7].

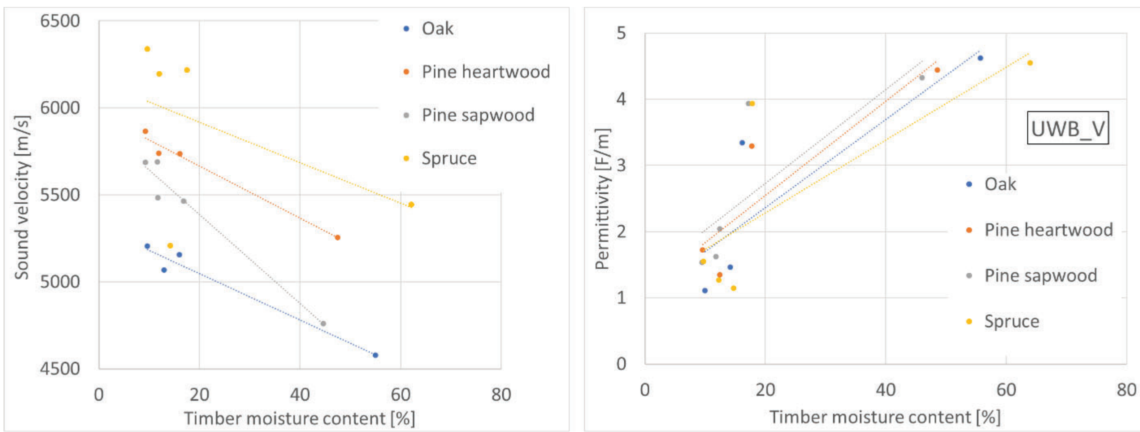

Figure 10. Correlation between the sound velocity (left) and the permittivity (right) and the timber moisture content of the reference cubes

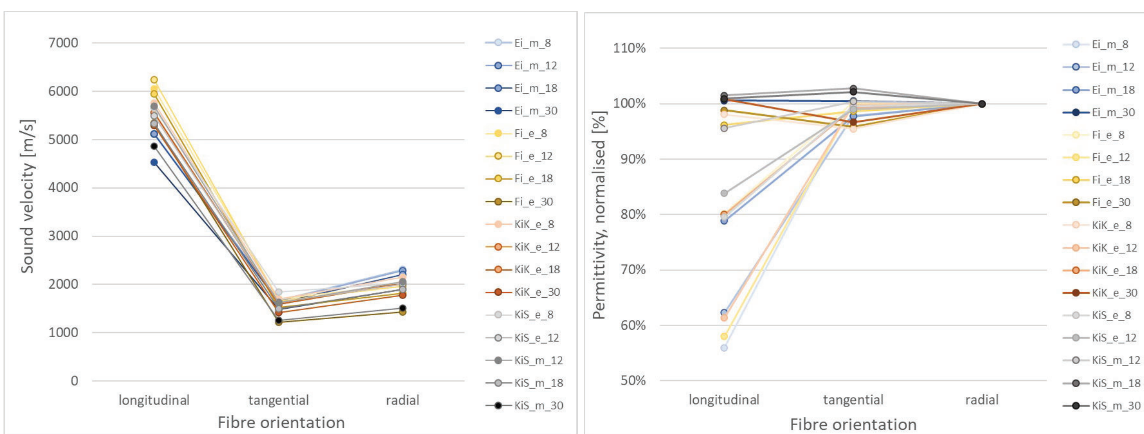

Figure 11. Correlation between the sound velocity (left) and the permittivity (right, normalised in relation to the radial direction) and the fibre orientation of the reference cubes

The investigations on the cuboid test specimens showed that cracks and local areas of decay can be detected at different levels using the two methods. The ultrasound method is limited at interfaces such as cracks or gluelines and requires an adequate coupling of the sensors. In contrast, the microwave method facilitates the detection of hidden areas behind cladding and in particular the interior of the structure, as boundary areas and air layers can be penetrated. The results obtained so far are promising. A planned classification approach combining ultrasonic and microwave techniques has the potential to significantly improve the evaluation and robustness of NDT results. Further evaluation of the entire test series will show which synergies arise from the combination of the two measurement methods offering extended diagnostic potential for bridge inspection in the future.

4 – DIGITAL MODELS FOR STRUCTURAL INSPECTION

4.1 DEFINITION OF THE SCOPE OF APPLICATION

Digitalisation, in particular the concept of DT, provides decisive support for responsible bridge maintenance. The documentation, linking and evaluation of all data from operation and maintenance enable a continuous assessment of the current condition of the bridge. Extensive research has been done on the use of DT for SHM. A systematic, comprehensive literature review is given in [10]. While the BIM method is becoming increasingly important for the construction of new bridges in Germany [11], the use of digital methods in structural inspection has been limited to a few large and innovative pilot projects so far [12][13][14]. The intention of the pilot projects is to create DTs that contain the results from the current structural inspection as well as continuously recorded condition data from SHM. Data aggregation should enable a condition and structural safety assessment as a basis for the digital maintenance management system to optimise the maintenance of infrastructure. For large bridges whose availability is of great importance in the critical infrastructure sector, such as large highway or federal road bridges with high traffic loads, the development and updating of DTs is a declared objective for the future. For small and medium span timber bridges, which are generally owned by local authorities, the effort of producing DTs is disproportionate to the benefit. In many cases there is no longer enough personnel available for structural inspection and maintenance, especially in the municipal road network,. For these bridges, the aim is to increase the efficiency of on-site structural inspections and to transfer the data automatically into a digital model as a basis for cost-efficient maintenance. To achieve this objective, the UltraTimB research project analysed options for generating digital models, defining the required level of detail, categorising significant timber bridge-specific damage and developing methods for their integration. A basis for this was provided by [3] with the data structure for the characterisation of timber bridges in the national database ASB-ING.

4.2 SUBSEQUENT CREATION OF DIGITAL STRUCTURAL MODELS

Over the last decade, Bridge Information Modelling (BrIM) has established itself as a specific form of BIM in infrastructure construction [10]. The use of 'as-planned' BrIM models for bridge construction is increasingly becoming the standard. Changes during the construction phase are documented in further developed 'as-built' models. In future, maintenance management will be based on updating these models in the form of 'as-maintained' models. Almost 80 % of bridges in Germany are more than 35 years old. Therefore, they were planned and built without 3D CAD or BIM, as the main research into BIM began at the end of the second millennium. As BrIM models are often not yet available for maintenance, they have to be created retrospectively. The basis for subsequent modelling can be 2D plans, the building record and later on-site structural inspection using digital structural survey methods, e.g. photogrammetry and laser scanning (see e.g. [15]). The use of digital structural survey methods becomes economical when 3D objects are generated semi-automatically (parametrically or knowledge-based) or fully automatically from the recorded 3D point cloud and are semantically annotated [1]. Although automatic generation has been successfully implemented for individual pilot bridges, a general solution is still needed for all bridge types [1]. Furthermore, manual remodelling of the entire bridge infrastructure in Germany with a total bridge area of 57 million m² (as of 2022) would be too time-consuming and unnecessary [14]. Due to the high modelling effort, it seems more advisable to specify a lower level of detail for subsequently created models for the purposes of maintenance management than for new construction. The aim is to only record the geometry and information in as much detail as is necessary for the use cases to be implemented.

Within UltraTimB, established methods of subsequent modelling (manual and parametric modelling) were used to create 'as-built' models and to compares them in terms of their applicability and effectiveness (Figure 12). The models created were based on 2D plans and an on-site inspection. Drone technology (UAV) was also used to assist in capturing components that could not be reached from the ground. While precise subsequent modelling of the entire structure is very time-consuming, the automatic generation of a simplified framework model is very fast, but its model accuracy is significantly lower. Based on the project objectives, the required accuracy should be determined specifically for each individual project.

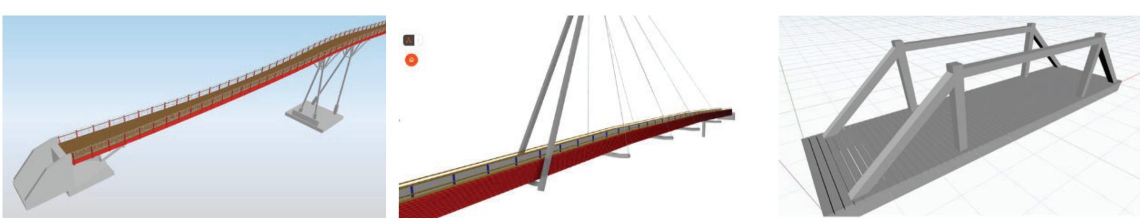

Figure 12. Examples for subsequently created 'as-built' models of timber bridges with different LoD using 2D plans and information from bridge inspection (left and middle) and simple parametric modelling (right) (images: FHE/Florian Planert, Thorben Niemann)

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4.3 REQUIREMENTS FOR AS-MAINTAINED MODELS

As-maintained models usually require geometric, semantic and material data, time-variable and safety-relevant information as well as supplementary documents (images, reports, logs, plans, GIS data). A Level of Development (LoD) must be defined for the creation of the model, which includes the definition of the Levels of Geometric (LoG) and alphanumeric information (Level of Information (LoI)). A distinction is made between levels of detail from LoD100 to LoD500 with increasing accuracy and depth of information. While a LoD100 is sufficient in the early design phases, execution planning is usually based on LoD300-400 (Figure 13). With regard to the required accuracy and depth of detail, there are no specifications for the maintenance phase to date. The model should be as detailed as necessary for the tasks planned, but not as detailed as possible, as a greater depth of detail is always accompanied by an increase in model complexity and data management effort. As a basis for maintenance management, the subsequently created model should be sufficiently accurate as to be able to localise damage and other maintenance information. The LoD for the description of damage also depends on the accuracy of the measurement methods and therefore cannot be specified uniformly for the entire structure.

[15] distinguishes between damage elements that depict damage with a high level of detail (e.g., precise depiction of a single crack) and damage areas that contain a rather coarse depiction of damage with a lower level of detail. Several damage elements can be combined into damage areas (e.g., several cracks are combined into one area that is described as cracked).

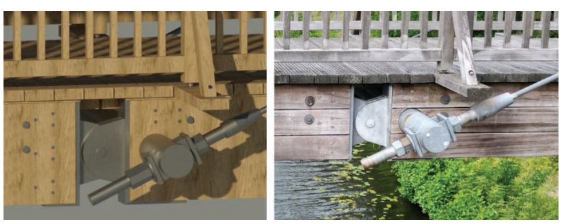

Figure 13. Suspension connection of a timber bridge, as-built model with LoG 400 (left), photo (right) (Images: FHE, Leonard Jordan)

The effort for creating an as-maintained model must be considered in relation to its utilisation. If a model needs to be generated retrospectively, an abstracted LoD200-300 seems to be sufficient to implement the relevant structural damage and monitoring data with localised accuracy. The high effort involved in generating an LoD500 is inefficient for timber bridges with small and medium spans.

4.4 MODELLING AND LOCALIZATION OF INSPECTION RESULTS

So far, the modelling and localisation of inspection results has not been regulated in the IFC schema. Only prototype concepts exist. In addition, the regulations only cover reinforced and prestressed concrete, steel and composite bridges. The exclusion of timber bridges represents a considerable competitive disadvantage for this sustainable and ecological construction method in infrastructure. During the operational phase, data are collected from the

1. structural inspection,
2. structural monitoring and
3. structural diagnostics.

Due to the structures' small size, the creation of a joint model that addresses all three use cases (1, 2 and 3) is proposed as a simplified basis for recording their results.

Two different methods were adapted in the research project for the documentation of inspection results (Figure 14, Figure 15): the annotation of damage information using the BIM Collaboration Format (BCF) and the localisation of features as damage objects directly on the structural member with annotation of the semantic information as attributes [16].

A simple form of damage modelling uses the BCF format. For communication purposes, annotations can be linked to documents or model elements and thus be precisely integrated into the model. This functionality of the BCF format is used for damage modelling [14]. Damage data, localisation, versioning and image representation (photo) should be recorded in the model to document the damage. This method can be implemented quickly and easily by structural inspection personnel.

A more precise variant uses diagnostic objects that are localised in the diagnostic model and represent the results of the bridge inspection, monitoring and diagnostics. So far, IFC is primarily designed as a data schema for the digital descriptions of the built asset industry. It does not yet offer an explicit domain for the structural conditions of existing bridges. Therefore, specific entities to describe defects do not exist in the IFC standard. However, the IFC offers several alternatives: IfcProxy or IfcBuildingElementProxy, IfcAnnotation, IfcSurfaceFeature and IfcVoidingFeature. The advantages and disadvantages of these IFC entities are discussed in [17]. As part of UltraTimB, the use of IFC default geometry (element proxy) and data storage via separate property sets was investigated to determine the potential for integrating different data and data structures from bridge inspection, monitoring and building diagnostics into BrIM. This approach was also adopted by [18]. With the IfcProxy and the IfcBuildingElementProxy entities, IFC has very flexible elements that map different types of damage and can be used for the data exchange of BIM models in bridge construction. User-defined timber bridge-specific attributes can be specified via the IfcPropertySetTemplate. Two different diagnostic objects were used for the precise localisation of features, damage and measurement data on timber bridges: damage objects and measurement data objects. Damage and features can be defined via diagnostic objects in the form of solids, linear and point elements. Besides the geometrical information, a defect needs material parameters and other predefined properties (Table 1). With this categorisation of timber bridge-specific characteristics a standardised procedure is now available for the first time for recording damage to timber bridges.

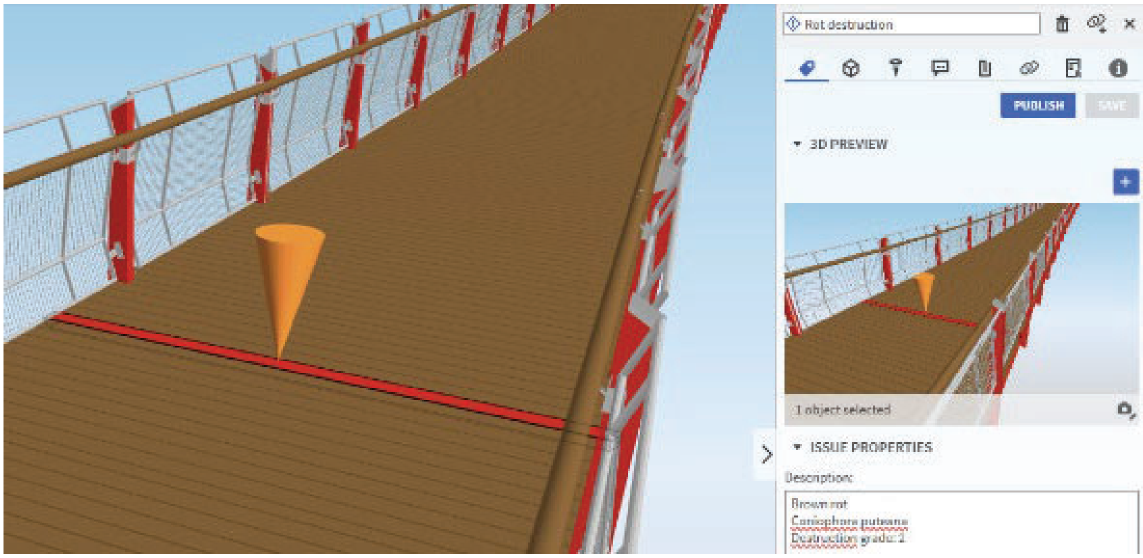

Figure 14. Annotation of a defect using BCF- functionality – a pointer localises the defect as an issue (Image: FHE, Florian Planert)

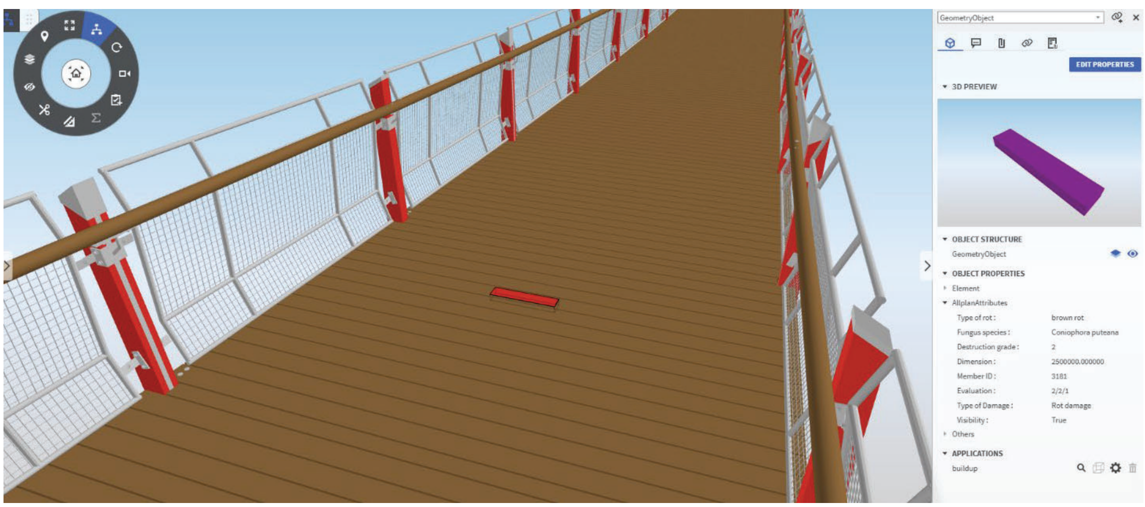

Figure 15. Localisation of a defect as a damage object in the damage model of a timber bridge (Image: FHE, Florian Planert)

To assist the bridge inspector in implementing the diagnostic data in the diagnostic model, some processing steps have been digitised. A mobile application for a tablet or smartphone was initially developed as a recording tool. With this app, the bridge inspector can digitally record the damage and measurement data on-site during the inspection in a location-precise and component-related manner. For improved localisation, a defect is linked directly to the affected bridge component and the defect position is defined in 3D space. Every damage entered should be assessed directly with regard to its influence on stability (S), traffic safety (V) and durability (D) according to the standardised assessment system in Germany. Afterwards the results are automatically transferred to the digital model. Photos of the damage, ideally taken directly via the tablet on which the app is running, or measurement results can be linked directly via the database.

A Python script automatically reads the database and generates and locates the diagnostic objects in the diagnostic model. The IFC export of the model is required for OpenBIM utilisation. The generated model can be regarded as a preliminary stage of a digital shadow.

This approach may facilitate the bridge inspection considerably. The use of the app during inspection and the automated transfer of diagnostic data to the digital model increase the efficiency of the on-site inspection and reduce the amount of post-processing. Another benefit results from the elimination of any media discontinuities. Furthermore, the defects can be precisely localised and the potential for subjective errors is significantly reduced. The proposed method enables damage trends to be mapped and changes in condition to be analysed over time. Further advantages arise from the

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improvement of collaborative co-operation between clients, planners and bridge inspectors.

Table 1: Predefined properties for damage objects and measurement data objects for timber bridges

Damage/ Measurement	Predefined properties	Geometrical representation
Rot destruction	Type of rot, Fungus species, Destruction grade, Visibility, Dimension, Member ID, Evaluation S/V/D[1]	Volume, point
Insect damage	Insect species, Destruction grade, Active infection, Dimension, Member ID, Evaluation S/V/D[1]	Volume, point
Crack	Length, Depth, Width, Delamination, Member ID, Evaluation S/V/D[1]	Line
Defect	Specification, Member ID, Evaluation S/V/D[1]	Volume, point
Other feature	Description, Member ID, Evaluation S/V/D[1]	Volume, line, point
Measurement	Measurement type, Measurement principle, Temperature, Wood species, Measured value, Member ID	Point

[1]S/V/D = Stability / Traffic safety / Durability

5 – SUMMARY

This article is dedicated to the improvement of structural testing of timber bridges through a novel combination of two NDT methods and the implementation of the test results in digital structural models. It presents the research results of the UltraTimB project. The UltraTimB research project investigated the combination of NDT with ultrasonic and microwave methods to improve the quality assessment of timber bridges.

Initial analyses on reference cubes showed that microwave measurements can be used to qualitatively assess the moisture content of wooden components. In addition, ultrasonic wave analysis can provide qualitative information on mechanical properties (strength and modulus of elasticity) and map density changes so that e.g. decay can be detected. Both methods are significantly influenced by the anisotropy and inhomogeneity of the wood. Using microwaves, it was possible to assess main structural members behind covers or cladding for the first time. The combination of test procedures enables rapid scanning and can provide continuous subsurface information about the structure without the need for direct contact. So far, this is only a prototype development. In the future, it should be possible to test protected timber bridges with improved damage detection and increased efficiency using the newly developed combination of methods. Further extensive measurement series using the combination of measurement methods and reference methods on test specimens with defined characteristics and on practical samples are currently being analysed and will be documented in the final report of the research project.

Furthermore, investigations were also conducted into how digital models can be used to increase the efficiency of the structural inspection of timber bridges. Using several timber bridges as examples, methods for the subsequent generation of as-built models were tested and compared. Two different methods were adapted for the implementation of damage and measurement data in digital bridge models. A recording tool supports on-site inspection via a database and automates the localisation of recorded damage objects in the as-maintained model. The automatic implementation of the damage data in the digital model enables fast and error-free localisation and thus seamless logging of damage over the life cycle of a timber bridge. Digital models can successfully change the inspection and maintenance of timber bridges and reduce the time and cost-intensive effort required for the main inspection.

The research results provide a contribution to the necessary standardisation of the data structure for the recording and evaluation of results from inspection, monitoring and structural diagnostics of timber bridges. In order to meet the requirement for a single source of truth, the development of an interface to the SIB programme, which is mandatory for national authorities to record the results of bridge inspections, is essential.

6 – ACKNOWLEDGMENT

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7 – REFERENCES

[1] Federal Highway Research Institute (publisher): Seitner, M.; Probst, R.; Bormann, A.; Vilgertshofer, S. (2022) *Building Information Modeling (BIM) im Brückenbau*. Reports of the Federal Highway Research Institute - Bridge and Civil Engineering Volume B 182.

[2] IFC-Bridge Project Team (2019) *IFC-Bridge – Project status overview.* BuildingSMART International home of openBIM. https://ifcinfra.de/wp-content/uploads/2019/05/2019-03-26_IFC-Bridge_Overview_.pdf

[3] Simon, A.; Arndt, R.; Jahreis, M.; Koch, J. (2019) *Entwicklung einheitlicher Richtlinien für den Entwurf, den Bau, die Überwachung und Prüfung geschützter Holzbrücken – Protected Timber Bridges (ProTimB)*. Final research report. University of Applied Sciences Erfurt, Germany.

[4] Abdoli, F.; Rashidi, M.; Wang, J.; Siddique R.; Nasir, V. (2024) *Structural health monitoring of timber bridges – A review.* Elsevier B.V. https://doi.org/10.1016/j.rineng.2024.103084

[5] Hasenstab, A. (2006) *Integritätsprüfung von Holz mit dem zerstörungsfreien Ultraschallechoverfahren*, Dissertation. Technische Universität Berlin.

[6] Kupfer, K. (2005) *Electromagnetic aquametry. Electromagnetic wave interaction with water and moist substances.* Springer Berlin, New York.

[7] Niemz, P.; Mannes, D. (2012) *Non-destructive testing of wood and wood-based materials.* Journal of Cultural Heritage 13,3 (2012), pp. S26 S34.

[8] Senalik, C. A.; Wacker, J. P.; Wang, X. (2022) *Evaluating the Efficacy of Ground-Penetrating Radar as an Inspection Tool for Timber Bridges.* Conference Proceedings 4th International Confrence on Timber Bridges Biel/Bienne, Switzerland, 9-12 May 2022. https://doi.org/10.24451/6j5j-qw13

[9] Bonitz, F.; Niemann, T.; Schickert, M.; Arndt, R.; Simon, A.; Scheiding, W. (2025) *Non-destructive testing of timber structures using combined microwave and ultrasonic techniques: A novel approach to quality assessment.* International Symposium on Non-destructive Testing in Civil Engineering NDT-CE 2025, September 24-26, 2025, Izmir, Türkiye (accepted paper for an oral presentation).

[10] Mousavi, V.; Rashidi, M.; Mohammadi, M.; Samli, B. (2024) *Evolation of Ditgital Twin Frameworks in Bridge Management: Review and Future Directions.* Remote Sens. 2024, 16, 1887. https://doi.org/10.3390/rs16111887

[11] Federal Ministry for Digtial and Transport (publisher): Meister, A.; Scholz, F.; Banemann, S. (2022) *Federal Trunk Roads BIM Masterplan – Digitalization of planning, construction, maintenance and operation in Federal trunk road construction using Building Information Modelling (BIM).* https://bmdv.bund.de/SharedDocs/EN/Documents/StB/bim-masterplan-englisch.pdf?__blob=publicationFile

[12] Ullerich, C.; Grabe, M.; Wenner, M.; Herbrand, M. (2020) *smartBridge Hamburg – prototypical piloting a digital twin.* Bautechnik 97, 2020. https://doi.org/10.1002/bate.201900108

[13] Kang. C.; Voigt, C.; Eisermann, C.; Kerkeni, N.; Hegger, J.; Hermann, W.; Jackmuth, A.; Marzahn, G.; Marx, S. (2024) *The Nibelungen bridge as a pilot project for digitally assisted structural maintenance.* Bautechnik 101, 2024. https://doi.org/10.1002/bate.202300089

[14] Federal Highway Research Institute (publisher): Hill et. al. (2022) *Bauwerksprüfung mittels 3D-Bauwerksmodellen und erweiterter/virtueller Realität.* Reports of the Federal Highway Research Institute - Bridge and Civil Engineering Volume B 185.

[15] Hamdan, A. (2023) *Ein ontologiebasiertes Verfahren zur automatisierten Bewertung von Bauwerksschäden in einer digitalen Datenumgebung.* Dissertation. Schriftenreihe des Instituts für Bauinformatik, TU Dresden 2023.

[16] Astour, H.; Niemann, T. (2024) *Development of an approach for digital diagnosis and monitoring of engineering structures using BIM as-built models*. Internationals Conference on Computing in Civila and Building Engineering (ICCCBE), August 25-28, 2024, ETS Montréal, Québec, Canada.

[17] Artus, M.; Koch, C. (2023) *Object-oriented damage information modelingconcepts and implementation for bridge inspection.* American Society of Civil Engineers, 2023. https://doi.org/10.1061/(ASCE)CP.1943-5487.0001030

[18] Fritsch, C.; Voigt, C.; Burkhardt, J.; Arndt, R.; Marx, S. (2024) *Digital building diagnostics – a digital transformation project.* Bautechnik 101, 2024. https://doi.org/10.1002/bate.202300057

 https://doi.org/10.52202/080513-0341