Fortschritt-Berichte VDI

Mathias Artus, M. Sc.
Erfurt

Modeling Damage Information for the Operation Phase of Bridges

Reihe 04
Bauingenieurwesen

Nr. 224

Bauhaus-Universität Weimar

Dissertation
zur Erlangung des akademischen Grades
Doktor-Ingenieur (Dr.-Ing.)
an der Fakultät Bauingenieurwesen
der Bauhaus-Universität Weimar

Modeling Damage Information for the Operation Phase of Bridges

vorgelegt von Mathias Artus
geboren am 05.05.1989 in Jena, Deutschland

Weimar, September 23, 2024

Referees Prof. Dr.-Ing. Christian Koch
Prof. Dr.-Ing. Volker Rodehorst
Prof. Dr.-Ing. Markus König

Publisher: Bauhaus-Universität, Geschwister-Scholl-Str. 8, 99423 Weimar, Germany
DOI: https://doi.org/10.25643/dbt.62532

Fortschritt-Berichte VDI

Mathias Artus, M. Sc.
Erfurt

Modeling Damage Information for the Operation Phase of Bridges

Reihe 04
Bauingenieurwesen

Nr. 224

Fortschritt-Berichte VDI

Artus, Mathias
Modeling Damage Information for the Operation Phase of Bridges
Fortschritt-Berichte VDI | Reihe 04 | Nr. 224
Düsseldorf: VDI Verlag 2024
164 Seiten, 57 Bilder, 16 Tabellen
ISBN 978-3-18-322404-3 | ISSN 0178-9511 | E-ISBN 978-3-18-622404-0
Preis: 68,20 EUR | Preis VDI-Mitglieder: 61,38 EUR

Für die Dokumentation: Building Information Modeling, BIM, Digital Twin, Brücken, Inspektion, Prüfung, Wartung, Instandhaltung, Schäden

Keywords: Building Information Modeling, Digital Twin, Bridge, Inspection, Maintenance, Operations, Damage, Assessment, BIM

Bridges are prone to a high level of deterioration because of their frequent and heavy load. To ensure traffic and structural safety as well as durability, bridges are inspected frequently. Registering condition states, performing assessment, and preparing data for maintenance tasks are time consuming and error prone because of primarily paper-based workflows and manual copy-pasting. An improvement in digitizing bridge condition data could decrease the demand of manual work and helps to lower financial efforts for these tasks; therefore, makes inspection, maintenance, and repair more attractive. This dissertation aims to provide a data model that extends the known principle of Building Information Modeling to the operations phase of bridges. Damage information, such as geometries or photos, may be included in existing building models with this approach. Based on that, engineers are enabled to assess bridges based on comprehensive building models instead of analog reports.

Bibliographische Information der Deutschen Bibliothek
Die Deutsche Bibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliographie; detaillierte bibliographische Daten sind im Internet unter www.dnb.de abrufbar.

Bibliographic information published by the Deutsche Bibliothek (German National Library)
The Deutsche Bibliothek lists this publication in the Deutsche Nationalbibliographie (German National Bibliography); detailed bibliographic data is available via Internet at www.dnb.de.

ISBN 978-3-18-322404-3 | ISSN 0178-9511 | E-ISBN 978-3-18-622404-0

Acknowledgments

A doctoral thesis is never the result of an individual person. Instead, the process of research and writing is accompanied by several conversations, discussions, feedback, reviews, and reflections. Hence, I would like to thank several people that have helped me in that manner. First, my supervisor Prof. Dr.-Ing. Christian Koch. His extensive feedback on my work and personal skills helped me to finish the present thesis. Similar to that, talks and discussions with my colleagues Judith, Fulya, and Christopher allowed me to have a broader view on the topic of Damage Information Modeling. Especially, the corporation with Mohamed for the article about the case study and the help of Christopher regarding structural analyses provided a huge value for me and the dissertation. Besides all talks and discussions, several proofreaders helped to improve the language and intelligibility: Niels Hordijk and Dimitri Legatiuk.

Furthermore, in my opinion, also the family is important for such a magnificent achievement. Therefore, I would like to thank my wife Uli, which supported me the entire time with listening to me, praying, and talking. Additionally, I thank my father for raising me up and introducing math, engineering, and computer science to me. I would like to thank several of our friends that prayed for me and listened my maybe a bit boring remarks on defects, bridges, and data models during the entire process of writing the journal articles and this thesis. Last, I thank God that I've been born in this time, location, and family, which allowed me to go to school, study, and finally write my dissertation.

Dedicated to my wife Ulrike.

Contents

Glossary

Application Programming Interface Communication interface for a computer program 73, X

as-built State of a model after the construction process 10, 85, 102, 115

as-damaged State of a model that includes damage information 2, 13, 37, 38, 45, 101, 102, 104, 114, 115

BIM Collaboration Format Data exchange format to communicate changes in model 28, X

Binary Large Object Is an entity of binary data as a single object, e.g., photos or videos. Depending on the storage type, i.e., database or file system, and the type of binary data, the kind on entity varies. 45, X

Boundary Representation Using the outer boundaries of a volume, a 3D shape is defined 42, X

Bridge Management System Formal definition of a bridge management system or guideline. Mostly, this systems are later implement via a software 96, X

Building Information Modeling A process and methodology to generate and exchange data about a building in the entire life-cycle 2, 24, VIII, X

buildingSMART Data Dictionary Online service of buildingSMART International for classifications, terms, nomenclature, and properties 10, X

buildingSMART International An open, neutral, and non-profit organization that aims to push on the digital transformation of the building asset industry 6, 8, 10, 85, VII, VIII

Constructive Solid Geometry Describing a solid geometry by combination of geometry primitives with subtraction, intersection, etc 98, X

Damage Information Modeling Modeling defects and deficiencies related to building elements with geometric and semantic information 2, X

Digital Imaging and Communication in Nondestructive Evaluation Standardized data exchange format for non-destructive evaluation and testing results 18, X

Digital Shadow One way connected digital model of a physical entity 10, 11

Digital Twin Two way connected digital model of a physical entity 5, 10, 11

EXPRESS Modeling language for product data 96, 101

Finite Element Analysis Calculation of equilibrium conditions in several finite elements of a component or structure 23, X

geo-semantic information Information that is a combination of geometric and semantic parts. Images, photos, and colored point clouds are examples for this information type because a photo consists of several points (geometry) that have a color (semantic) 27, 42, 43, 45, 86, 88–90, 95, 114

Heritage Building Information Modeling Application of the Building Information Modeling method to heritage buildings 24, X

Industry Foundation Classes Data structure defined by buildingSMART International and used for exchanging building information 9, VIII, X

Information Delivery Manual Documentation about processes, actors, and data during a selected process or task in order to describe a business process 6, X

Level of Development Means the combination of and 8, X

Level of Geometry Geometric detail of a given geometric information 8, X

Level of Information Detail level of semantic information 8, XI

Machine Learning Adaptive computer systems for analyzing data. 16, XI

Model View Definition Particular use of Industry Foundation Classes (IFC) for a workflow ore use case 8, XI

Non-Destructive Testing Group of analysis methods, which are used to evaluate material's parameters without causing damage 2, 18, XI

OmniClass Classification system for construction industry in the United States 10

photogrammetry Deduce information related to physical objects by taking and processing photos 16, 17

point cloud A collection of spatial points. Often retrieved from laser scans or 16, 17, 19, 21, 22, 25

Resource Description Framework Standardized model for linking data using triples 8, XI

Scan-to-BIM Generating BIM models from point clouds, which have been retrieved from photos or laser scans 10

SQLite File based SQL database system 8

Structural Health Monitoring Controlling bridge condition by continuously collecting sensor data with subsequent archiving, processing, and assessing 2, XI

Structure from Motion Generate point clouds of objects from a number of photos 102, XI

Structured Query Language Query language used to access numerous relational databases 39, XI

UniClass Classification system for the construction industry in the United Kingdom 10

Unified Modeling Language Set of diagrams to describe software design and behavior. 46, XI

Unmanned Aircraft System Autonomous flying vehicle or system 26, 37, XI

Acronyms

AEC Architecture Engineering and Construction 5, 6, 8, 10, 11, 31, 57, 72, 96, 97, 99, 100

API Application Programming Interface 73, 99, 100

BCF BIM Collaboration Format 28

BIM Building Information Modeling 2, 4–6, 10, 11, 13, 14, 18–20, 24, 29, 32, 37, 38, 42, 45, 46, 52, 57, 58, 69, 85, 86, 88, 90, 91, 96, 99, 100, 102, 112, 114–116

BLOB Binary Large Object 45

BMS Bridge Management System 96, 116

BRep Boundary Representation 42, 103

bsDD buildingSMART Data Dictionary 10, 18, 91

CSG Constructive Solid Geometry 50, 55, 63, 67, 72, 74, 78, 98

DICONDE Digital Imaging and Communication in Nondestructive Evaluation 18

DIM Damage Information Modeling 2, 4, 5, 17–19, 21, 24, 27–29, 31–33, 38, 39, 59, 61, 63, 77, 85, 86, 88, 89, 92, 95, 96, 99, 103, 111, 114–116

FEA Finite Element Analysis 23, 36, 93, 109, 111, 112, 115

HBIM Heritage Building Information Modeling 24, 87

IDM Information Delivery Manual 6, 8, 16, 18, 23, 85, 86

IFC Industry Foundation Classes 5, 8, 9, 18, 19, 27, 28, 46, 52, 57–66, 68, 69, 71–73, 76, 77, 79, 82, 88, 96–101, 103, 104, 108, 109, 115, 116, VIII, XIII, XIV

LoD Level of Development 8, 45–47

LOG Level of Geometry 8

LOI Level of Information 8

ML Machine Learning 16, 20, 102

MVD Model View Definition 8, 18, 85

NDT Non-Destructive Testing 2, 12, 17, 18, 24, 37, 46, 47, 88, 116

RDF Resource Description Framework 8

SfM Structure from Motion 102, 108

SHM Structural Health Monitoring 2, 18, 19

SQL Structured Query Language 39

UAS Unmanned Aircraft System 37, 115

UML Unified Modeling Language 46, 47, 49, 51, 54–56, 83

VR Virtual Reality 115

Abstract

Bridges are prone to a high level of deterioration because of their frequent and heavy load. To ensure traffic and structural safety as well as durability, bridges are inspected frequently. Often, it is more efficient to demolish and repair a bridge because their maintenance and repair of them are expensive primarily due to high staff efforts. Furthermore, registering condition states, performing assessment, and preparing data for maintenance tasks are time consuming and error prone because of primarily paper-based workflows and manual copy-pasting. An improvement in digitizing bridge condition data would decrease the demand of manual work, helps to lower financial efforts for these tasks; therefore, makes inspection, maintenance, and repair more attractive. In the long term, this results in lower costs, building material demand, and also CO_2 emissions.

BIM aims to support the entire building life-cycle using geometric-semantic models of the building. Currently, acquiring, exchanging, and processing of building data during design, planning, and construction of buildings have been investigated. Studies about the efforts and effects of BIM show a big potential saving time and money as well as reducing construction errors. However, BIM lacks support of the longest phase of a building or structure: the operating phase. Using BIM during the operating phase has gotten less attention and a systematic and comprehensible methodical approach is missing to model data from the operating phase. In particular, this information is relevant for civil engineering structures, for example, bridges, because it helps to ensure traffic and structural safety as well as durability. During frequent inspections, deficiencies and defects are registered on paper and later manually transferred into table-based systems in the office. As BIM helped to reduce plans and reports during the design, planning, and construction phase, it is assumed that this reduction can also be achieved during operating phase.

In order to use BIM during the operating phase of bridges, two geometric-semantic models need to be developed: one model for bridges themselves and one model of deficiencies and defects affecting these bridges. Numerous bridges are older than the concept of BIM, which means that there are no geometric-semantic models of these bridges. Some concepts, for instance Scan-to-BIM aim to generate geometric semantic models of existing buildings. As for the second requirement, a digital model for defects and deficiencies, a huge gap is evident. In situations where geometric-semantic models of damage and defects exist, they are incomplete and designed for specific applications. For this reason, this dissertation describes concepts and models to acquire, exchange and process geometric and semantic data of defects and deficiencies considering multiple use cases.

In the first step, an analysis of the as-is-state is performed; this contains reviewing current norms and guidelines and statistical analyses of bridge condition data from Thuringia. For the statistical analysis, damage types are defined and the frequency and severity are rated. The most frequent and severe damage types are selected for subsequent modeling and implementation.

Second, based on the selected damage types and use cases, the requirements for the data model are defined. To guarantee immediate and prospective usability, current norms as well as up-to-date methods from research need to be considered. The final data model is built to fulfill the defined requirements. This is achieved by synthesizing the existing approaches and extending the model where it is required. The result is an open-source data model for acquiring, exchanging, and processing bridge condition data. Additionally, by keeping the model flexible and open, further integration of information artifacts are possible later on, e.g., additional damage types can be integrated without changing the model structure.

Third and last, the resulting model is tested with an example scenario. The bridge inspection is the central point for the assessment and, therefore, has been selected for testing purposes. Considering current research results, a framework was designed that uses photos from bridge defects as input and processes them to generate defect geometries. These geometries are included in and aligned with the building model of the bridge before this model is enhanced with semantic information.

The final data model is an open interface to acquire, exchange, and process bridge condition data; furthermore, semantic, geometric-semantic, and semantic data are considered. Using established data formats from the AEC sector, the model is implemented via the IFC and verified by visualizing generated models in different IFC viewers. This approach allows easy integration of the given information model into existing software. Although the model is implemented using an open and established standard, numerous software applications show errors and problems during importing, visualizing, and processing the data. Future implementations of IFC software have to respect the IFC standard in its entirety.

By extending BIM with the provided Damage Information Model, it is possible to address the operating phase of bridges. This helps to extend bridges' life time, reduce material demands, and CO_2 emissions. Due to the availability of 3D building and damage models, the provided approach may improve transparency and communication of repair and maintenance actions. Improving the automated generation of structural models, development of durability analyses, and new methods for communicating bridges' states and maintenance are three examples for future research.