Integration of Wave-Based Non-Destructive Survey Results into BIM Models

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Abstract. Aging bridges and rising load indices induce increases in bridge deterioration. Several nationalities conduct non-destructive testing (NDT) methods to analyze current bridge conditions. Traditional practice relies on exchanging plans and reports. However, sufficient planning and interpretation of NDT surveys require comprehensive building information. Building Information Modeling (BIM) has become an established concept for design, planning, and construction of buildings and structures. Combining the concept of BIM and NDT promises benefits in case of planning and performing surveys and interpret resultant data. This paper describes a framework that incorporates building information, inspection data, and data of wave-based surveys, for instance ultrasonic and Ground Penetrating Radar (GPR), to allow in-depth building assessment.

1. Introduction

The European Commission asserted an increase of road freight transport in recent years that led to a higher load on road bridges (Directorate-General for Mobility and Transport, 2021). Hence, bridge load capacities have to be checked to enhance bridges' life-time (Bundesministerium für Verkehr und digitale Infrastruktur, 2020). In Germany, heuristic load capacity analyses are based on historical information about materials and construction processes (Bundesministerium für Verkehr, Bau und Stadtentwicklung, 2011). Additional surveys, for example Non-Destructive Testing (NDT), provide detailed and up to date information about the structural quality of the bridge. Results from NDT surveys may prove or disprove assumptions made earlier, and hence, allow precise statements about bridge load capacities. This information may be utilized when supporting decisions about required maintenance actions or repair. Subsequently, financial properties may be invested in a more targeted manner.

German guidelines for inspections define visual inspections as basic processes examining bridge conditions. Some defects, for example, extensive moisture penetration or cracks exceeding defined thresholds reason an in-depth investigation, such as structural or material analyses (Deutsches Institut für Normung, 1999; Bundesministerium für Verkehr, Bau und Stadtentwicklung, 2017). The inspector assumes defects and decides about further investigations, such as a radar survey analyzing moisture penetration or localize tension ducts (Taffe, Stoppel and Wiggenhauser, 2010). The test engineer receives the order of the NDT method in conjunction with plans and inspection reports, which are the basis for testing engineers who perform personal on-site inspections and arrange the surveys. During a third visit on-site, the engineer performs the survey, and finally, all survey results are interpreted and send back as a report. This workflow is error prone and time consuming because its paper-based data exchange.

Interpretation of the data requires the relation between survey results and building information, for example, a correct interpretation of radar images requires knowledge about component dimensions and as-designed positions of reinforcement and tendon ducts. BIM models include all required geometric and semantic information (Borrmann, König, Koch and Beetz, 2018). Based on the conceptual definitions of BIM, the open standard of the Industry Foundation

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Classes (IFC) has been defined (International Organization for Standardization, 2018). Since the planning of Inspections and NDT needs not be based on the actual structural situation, the as-built model is required as a starting point, as opposed to the as-planned model. Results of NDT surveys may reveal defects, that have to be incorporated in the BIM model, hence, a data model for defects is required as well.

Although novel developments define a standardized data exchange for the NDT sector, e.g., the Standard Practice for Digital Imaging and Communication in Nondestructive Evaluation DICONDE (ASTM, 2016), exchanging data in practice is performed via reports and 2D CAD files. Niederleithinger and Vrana (2021) emphasized the necessity for combining BIM and NDT to provide quality assurance data to engineers and inspectors. Contradictory to that, Braml, Wimmer, Maack, Küttenbaum, Kuhn, Reingruber, Gordt and Hamm (2021) used an ontological approach to link building and sensor data. They remarked in their paper that BIM for bridges is too coarse, and hence, they used a different method to include building data. A detailed explanation about required building information is missing, as well as a detailed description on how they store and transfer building and sensor data. Schickert, Koch, Kremp and Bonitz (2020) improved the perception and ease interpretation of NDT results by using Augmented Reality (AR) for visualization. However, the underlying building model consisted only of a CAD model of the test specimen. Based on prior work, a workflow to establish the combination of building information in the form of BIM and NDT data was proposed by (Schickert, Artus, Lai and Kremp, 2021). However, definitions of required data for planning and interpretation tasks are missing up to now. In summary, a comprehensive method combining BIM and NDT is desirable. This study aims to develop a framework that provides building information to the testing engineer for planning surveys, integrating and interpreting results. To limit the scope, this paper focuses on wave-based NDT surveys, such as Ultrasonic and Ground Penetrating Radar (GPR) because they are often used to analyze bridges.

This study focuses on the following research questions.

- Which building and damage information is required to plan and interpret radar surveys?
- How can this information be incorporated into existing BIM models?
- How can the required information be visualized to ease planning and interpretation?

2. Parameter Definition for Wave-Based Surveys

Wave-based surveys are used to measure internal parameters of concrete components or structures, e.g., localize internal objects of concrete components, measure layer thicknesses, or to do qualitative checks of moisture penetration. Wave-based surveys use, for example, radar or ultrasonic waves. Independently from the wave type, a transmitter sends one or multiple waves into the survey object and a receiver receives the waves reflected at material transitions. Raw measurement data consists of amplitudes over time and is called a single track. Within this single track, reflections can be identified, and hence, the transit time for the signal and its reflections are calculated. Based on the transit times and the propagation velocity of the signal, positions of medium transitions are calculated. Several measurements alongside a line on the surface of a component may be combined to measure the profile or cross section of a component. To retrieve 3-dimensional data, a grid of measurements on the component's surface is combined. The visualization of a line and a grid is called B-Scan and C-Scan respectively. Furthermore, grid data may be visualized as 3-dimensional geometry as shown by Figure 1 right.

Later interpretation of this data, such as the localization of tendon ducts, requires knowledge about the as-built building or structure. This leads to a chicken-and-egg problem because the radar survey aims to measure the positions of reinforcement and layers, but, on the other hand, needs the as-planned positions of these parts in order to evaluate their measurements. Hence, some information, which can be delivered by BIM, are positions of tendon ducts, reinforcement, and information about layers in components. This data is already part of BIM (Borrmann, König, Koch and Beetz, 2018).

Furthermore, surveys based on waves are influenced by surface defects such as cracks, spalling, or delamination. These data is not included in conventional BIM models. Artus and Koch (2020) developed BIM extensions to incorporate damage information, which is called Damage Information Modeling (DIM). These DIM models contain geometric information about defects that enables engineers to inspect a bridge in the office in order to prepare on-site surveys. Further data is necessary to properly combine survey results, damage, and building models.

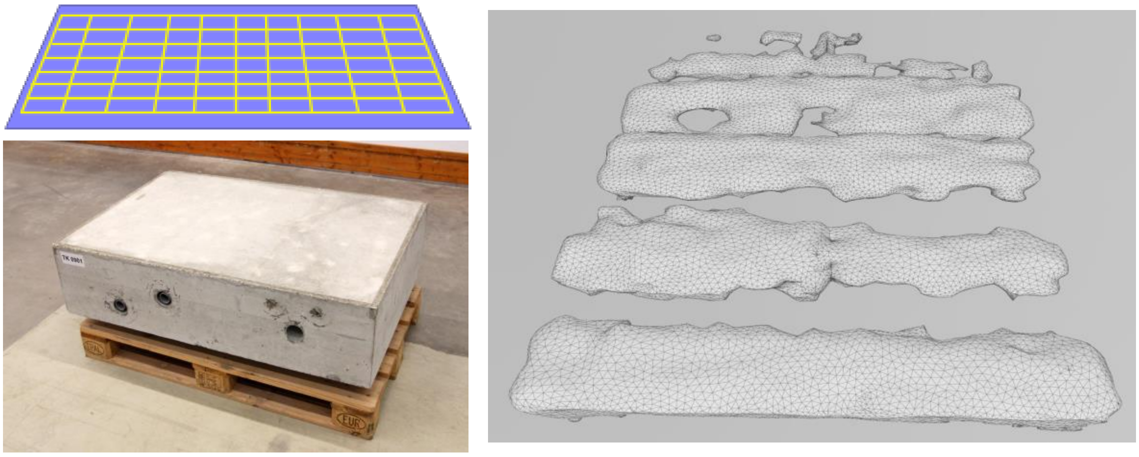

Figure 1: Scan grid (top left) of a surface of a test specimen (bottom left) and resultant 3D reconstruction of measurement results of back wall (right). The holes occur because of shadowing effects.

Table 1 shows an overview of the proposed parameters required for survey planning. Based on the test objective and the post-processing of the signal, different test results and visualizations may be generated, for example, measuring the radar reflection on a single line or in a grid using a B- or C-Scan, respectively. The component and structure ID are necessary to identify the structure and component of the survey. The test objective defines the aim of the survey that could be measurement of thickness of components, layers, or shells, localization of reinforcement, tension-ducts, or anchors, registration of voids or imperfections, or analysis of moisture, salt content, or homogeneity of the component. Additional descriptions, such as special setups or processes, are stored in the survey description. Survey start and end contain the timestamps of the survey, which includes planning, performing, and data analyses. Furthermore, the test result time specifies the time stamp when the data has been collected. A position based on Global Positioning System (GPS) data or other geographic information and the orientation of the measurement results are stored in the survey location. Textual descriptions of the component and test objective are optional. Finally, the inspection area and possible defects are required.

For visualization and assessment, data from Table 1 shall be exchanged via IFC files. An *IfcTask* represents a survey with related time information and responsibilities. Structure and component identifiers are the Global Unique Identifiers (GUID) of the entire structure and component respectively. The survey location, weather condition, test object condition, and test objective description are stored within an *IfcPropertySet*. Surface defects are covered by the aforementioned concept of DIM, and hence, are stored as *IfcVoidingFeature*. Last open point is the inspection area. In general, BIM and IFC offer possibilities to include geometries. However, the problem is which entity is used in conjunction with the geometry. Inspection areas may be understood as spatial zones, which is similar to a lighting or thermal zone using *IfcSpatialZone*. GPR tests a component from the surface, hence, the inspection area can be understood as a 2D plane or, if the depth of the scan is considered, as a cuboid.

Table 1: Overview of planning parameters.

Parameter name	**Data type**
Structure ID	String
Component ID	String
Test objective	Enumeration
Testing engineers	Actor [1:n]
Survey description	String
Survey start	Date time
Survey end	Date time
Survey location	String
Weather condition	String
Test object condition	String
Test objective description	String
Inspection area	Plane or spatial geometry
Surface defects	Subtraction or solid geometry

Furthermore, inspection results have to be integrated into the BIM model. Table 2 shows an overview of mandatory test result data for a wave-based survey. Information about the device, such as manufacturer and model, are required to consider device specific parameters. The test result summary is a textual summary of from the engineer and the coordinate system provides information about the local coordinate system of the test results depending on the coordinate system of the building. A comprehensive description of result parameters for ground penetrating radar may be found in Deutsche Gesellschaft für Zerstörungsfreie Prüfung e.V. (2008).

3. Modeling in IFC and Visualization

All result data has to be integrated into the BIM model and linked to related components. Both could be directly integrated into the BIM model but the result data may include multiple components. This leads to two possible solutions, either splitting up the geometry into several geometries or simply include the result as external reference. If the geometry is split and directly included, external references are omitted but some information could be misleading because of missing parts of the results, and hence, significance is compromised. Furthermore, it is preferred to include the results as external references. 2D and 3D result data may be included as external references and the results are kept in the CAD format provided and are integrated via document references. In case of later inquiries or verification of the test data, the raw data is important, which consists of vectors and matrices. Storing matrices and vectors in IFC is possible but impractical, so a reference to the location of the raw data is included in the IFC file.

Table 2: Overview of result data of wave-based surveys.

Parameter name	Data type
Device manufacturer	String
Device model	String
Device serial number	String
Test result time	Date time
2D test results	Image (as reference)
3D test results	Solid geometry (as reference)
Test result coordinate system	6-dimensional vector (position and orientation)
Test result summary	String

Except the 2D and 3D test results, the data may be stored as *IfcPropertySet* in relation to the survey. One approach to include 2D test results into IFC files would be to use textures. However, B- and C-scans represent material or layer information from below the surface, hence, using these result images as textures on the component surface would be misleading. The resulting images may be added as a document to the inspection area. Correct positioning of 3D result data from grid scans is mandatory for subsequent interpretation. Traditionally, engineers use a visible point at the structure or component to describe the measurement location, for example, 2 meters from the upper left corner of the pier to the right and 1 meter downwards. This positioning has to be transformed and included into the BIM model as shown in Table 1 by the attribute test result coordinate system.

Figure 3 shows an excerpt of the IFC file created with the test result as proxy #39115 and the survey result as document reference #39128. The label "Survey result" as object type for the proxy helps to identify elements that are results. Another possibility is to use a type object, which has the advantage to carry more information. Using the document association #39131 the STL file is linked to the tested component, which is not part of the excerpt, and related properties. STL files are CAD files without dimensioning; hence, this dimensioning has to be delivered additionally. Last, the property 'Image type' indicates that the related document contains 3-dimensional geometric information. Figure 3 shows the second excerpt of the IFC file with the testing engineer (#39137) and the weather condition during the survey (#39140).

The prototype for a BIM viewer has been developed using Unity in combination with IfcOpenShell (IfcOpenShell, 2015) and xBIM (Lockley, Benghi and Černý, 2017). Figure 4 shows an overview of the implementation and data processing pipeline. After selecting the IFC file, IfcOpenShell generates an OBJ file that can be loaded by the Unity application at runtime. In parallel, xBim.Essentials are used to read the IFC file into the memory and provide access to available semantic information.

```
#39115=IFCPROXY('3o0qbRQDP5MRKKu45U1K_6',#39116,
    'GPR test result','3D Test result of GPR survey',
    'Survey result',#39126,$,.PRODUCT.,$);
#39128=IFCDOCUMENTREFERENCE('da1s1d1_ascii_Linsen.stl',
    '1fI_EeNvCEO_1iYeKFZsVA','sd','sd',$);
#39129=IFCPROPERTYSET('3MfYz00HfAwucWalt6hbd2',#39116,
    'File Parameter',$,(#39130,#39132));
#39130=IFCPROPERTYSINGLEVALUE('Model Scaling',$,
    IFCIDENTIFIER('Meter'),$);
#39132=IFCPROPERTYSINGLEVALUE('Image Type',$,
    IFCIDENTIFIER('Image_3D'),$);
#39131=IFCRELASSOCIATESDOCUMENT('1RS$3mF1XEjh9wwMItwRWB',
    #39116,'Related Parameters','Connect related parameters.',
    (#39115,#39129),#39128);
```

Figure 2: Excerpt of an example IFC file with the test result as proxy (#39115) and the related STL file as reference (#39128).

```
#39133=IFCTASK('1g7QA_8LmkahfwvLcbanAQ',#39116,
    'Radar survey',$,'Non-destructive Testing','2022-US-42',
    $,'finished','Radar survey on-site',.F.,0,
    #39134,.USERDEFINED.);
#39134=IFCTASKTIME('Radar survey time',.MEASURED.,$,
    .ELAPSEDTIME.,$,$,$,$,$,$,$,$,$,.F.,$,'5d',
    '2022-02-22T08:15:00','2022-02-28T09:00:00',$,
    IFCREAL(100));
#39135=IFCRELASSIGNSTOPROCESS('1-yeVHSLz0WlYPLEYCJQfA',#39116,$,
    $,(#39115),.PRODUCT.,#39133,$);
#39136=IFCACTOR('0TBDQzdFeEunoqbfunjIYw',#39116,$,$,
    'Testing Engineer',#39137);
#39137=IFCPERSON('42/3141','Gropius','Walter',$,$,$,#39138,
    $);
#39138=IFCACTORROLE(.ENGINEER.,$,'Testing Engineer');
#39139=IFCPROPERTYSET('01_HQ7Oz10iNua2bPmAtQA',#39116,
    'Survey information',$,(#39140));
#39140=IFCPROPERTYSINGLEVALUE('Weather Condition',$,
    IFCLABEL('Cloudy, slight rain'),$);
```

Figure 3: Excerpt of an example IFC file with the testing engineer (#39137) and the weather condition (#39140).

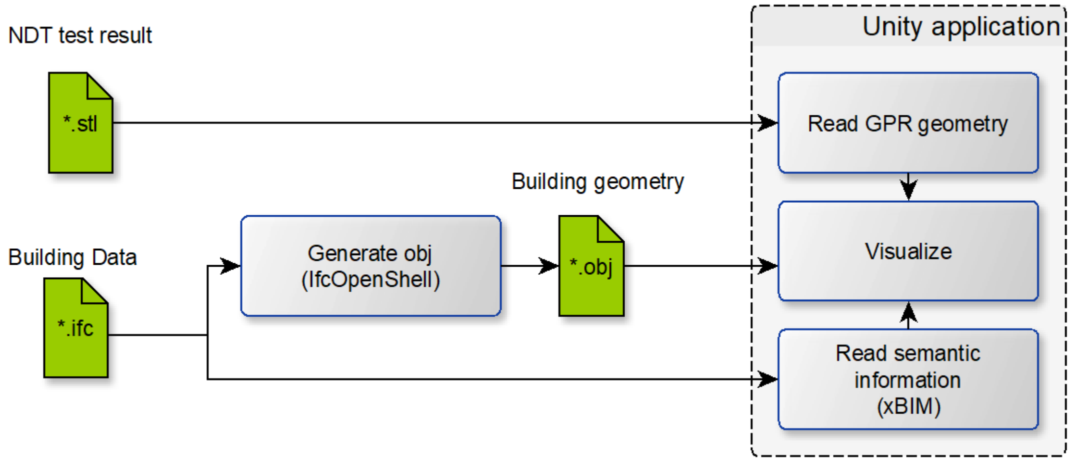

Figure 4: Implementation and data processing in the application.

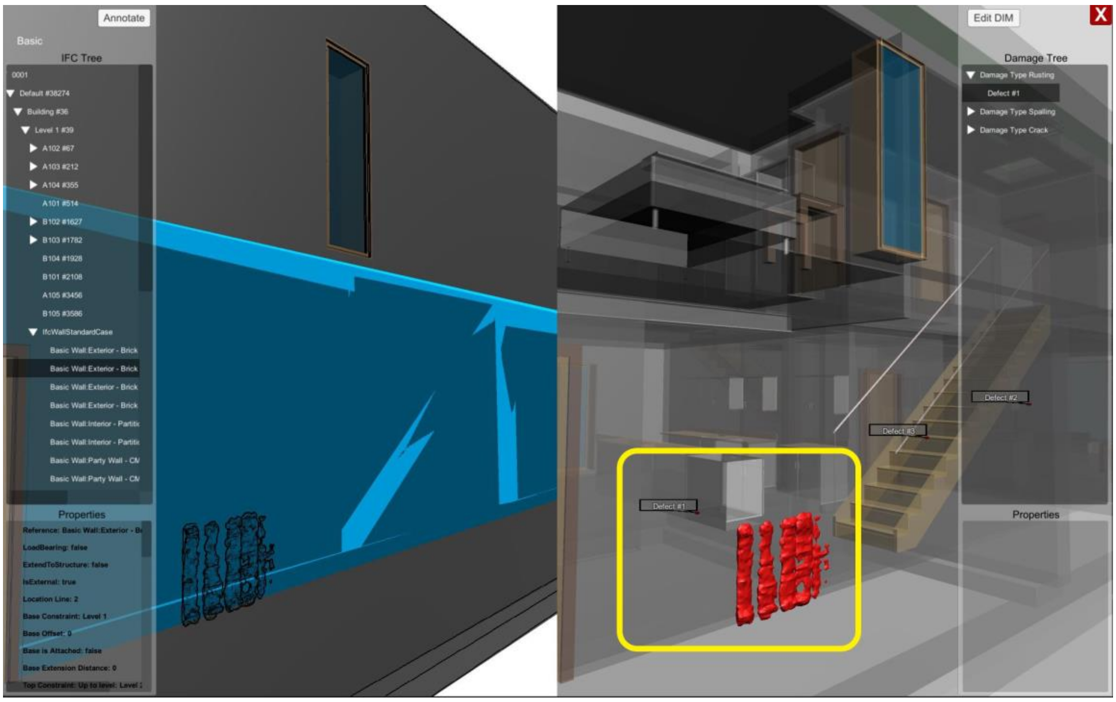

Figure 5: Screenshot of the developed prototype for visualizing material defects.

Based on the naming conventions and the document reference, the file is interpreted and visualized as shown in Figure 5. The red body is the same geometry as shown in Figure 5, right. Since wave-base surveys provide information about the interior of components the visualization requires transparency to represent this. However, transparency worsens the perception of localization. This has led to a split screen solution visualizing the building without transparency on the left and with transparency on the right. Looking on the left, the user can identify what is in the foreground and what in the background and on the right, survey results are visible colored in red. Also, a tree view of the building is to be seen on the far left and the far right list shows registered defects within the model.

4. Conclusion

On the one hand, appropriate evaluation of GPR test results requires information about the tested structure or building and BIM provides this information. On the other hand, instead of utilizing existing building information, engineers go on-site to plan NDT surveys. Subsequently, the visualization of test results is limited to images and CAD files lacking interconnection to the tested building or component. A proper visualization that combines both, building information and test results, promises better perception and eases interpretation.

This study aimed to develop a data model that links wave-based survey information and test results with existing building information. In addition to process, building, and damage information, test results are stored as 2D images or 3D geometries. Instead of including this result data directly into the BIM model, they are linked via document references. The implementation of this model has been done by using the open IFC standard for data exchange and Unity for visualization. Finally, the visualization of the test data in relation to the building data reveals the reason of observed reflections, and hence, eases the interpretation.

This study aimed to develop a data model to link NDT and building data. However, according to (Borrmann, König, Koch and Beetz, 2018) a standardized terminology is required as well. Furthermore, instead of using paper based reports, CAD files, and images for data exchange, the building's NDT sector requires a standardized data exchange definition, such as the IFC format for BIM, to keep up with digitization. A more general problem is the discussion about the data that should be included in IFC and data that should be referenced only. NDT survey acquire dynamic data of structures and buildings similar to sensors used for structural health monitoring. Future work has to identify criteria that help to decide if supplemental data is included into IFC files directly or referenced only.

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