Integrating RC bridge defect information into BIM models

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ABSTRACT

Reinforced Concrete bridges are a vitally important part of our infrastructure. The status of this infrastructure needs to be monitored on a continuous basis in order to ensure its safety and functionality. This is currently being done by authorities worldwide via bridge inspection reports. The format and storage of these reports varies considerably across different authorities around the world and is sometimes comprised into a bridge management system (BMS). The lack of standardization severely hinders the use of inspection information for knowledge generation use cases of both practitioners and researchers. This paper presents an exploratory analysis and as a result an information model and a candidate binding to IFC to categorize inspection information of RC bridges and to standardize storage of this information in a format that is suitable for sharing and comparing it between different users and varying requirements. We were able to show in three steps, that IFC in its latest version IFC 4 provides sufficient functionality to serve as a basis for integrating relevant defect information and imagery. Firstly, we extracted types of defects and properties needed for bridge
assessment from existing bridge inspection manuals. Secondly, we modelled the defect entities, their properties and relations and thirdly, mapped them to appropriate IFC entities. A prototypical implementation serves as a proof of concept for automated sharing and comparing of information needed in RC bridge inspections and for establishing a knowledge base for bridge performance over time and across authorities.

INTRODUCTION

Bridge inspection data is collected through intense human effort. The resulting bridge condition information is kept in bridge inspection reports and is used for maintenance and preparation of subsequent inspections. These reports are stored in diverse and non-interoperable BMS systems or even on paper. This restricts their use to the intended workflows only (Johnson et al. 2016; The Highways Agency 2007), which has a threefold impact: First, for industry, having a closed and proprietary format precludes inspectors from exchanging bridge condition information easily for either educational use or for getting an expert opinion from someone not within the same authority. Secondly, this mode of record-keeping makes mining the data an extremely challenging task, which can hinder the development of new methods for designing, building and maintaining bridges in the future (Dekker 2006). Thirdly, it prevents using the information for structural and other analysis software for use in bridge repair and retrofit which forces further survey and wasting money through rework. This research explores how to overcome this.

The quality of inspection data, as it exists today, varies greatly with much being of poor quality (Phares et al. 2004). Maintenance decisions are made based on this data and more than £18 billion per year are spent for bridge maintenance in the US and United Kingdom alone (ASCE 2017; Department for Transport and Highways Agency 2014). Kong et al. (2003) claimed that preventive maintenance decisions can reduce the maintenance cost in infrastructure by up to 65 %, or £11.7 billion, but require precise knowledge about the bridge condition.

Inspectors typically list all defects identified during a bridge inspection in a bridge inspection report. They are required to describe affected elements, type of defects and their severities. For instance,
Table 1 shows relevant defects for reinforced concrete (RC) along with their appearance and interpretation criteria for selecting the most appropriate condition rating. Lines correspond to the different defect types, columns correspond to the respective condition ratings. Inspectors can also comment on specific aspects of a defect, such as how they inferred the condition rating of a defect, recommend a type of maintenance needed and estimate its cost.

A bridge inspection report is either printed on paper or stored as an electronic copy in a Bridge Management System (BMS). A BMS allows storage, manipulation and management of bridge data and supports engineering processes, asset management and resource planning. On-site data can be collected using electronic handheld devices. Electronic inspection forms consist of dropdown fields that enable inspectors to quickly input data and to reduce input errors. A bridge inspection report generally gives a holistic view of a bridge condition at a specific point in time, yet is laborious to create. An inspector spends more time on actually writing a bridge inspection report than on inspecting the bridge on site (Kouridi and Brilakis 2016).

Such reports also often lack in quality and completeness (Moore et al. 2001). As a result, inspectors and engineers have difficulty understanding the deterioration over time of a specific defect element or defect position; they have to read through all existing reports searching for comments on a specific element or position. This process is laborious and error-prone, especially when taking the number of biannual inspections into account over an average bridge lifetime of more than 40 years (The Highways Agency 2007; U.S. Department of Transportation 2012). Inspectors cannot filter and easily find previous comments and defect findings based on position, element type, time or severity. Recordings of a single defect identified in several bridge inspection reports are not logically linked such that an inspector can easily access old records.

There is still no established standard between different DoTs and companies (Johnson et al. 2016; The Highways Agency 2007), even though BMSs are developed to support an objective decision process based on inspection data. Non-compatible bespoke formats for storing bridge defect information exist. Inspection reports usually remain in a company’s BMS which makes sharing them with anyone outside the organization, for example bridge consultants or contractors, difficult and error prone. This
is a classic problem of information islands. Furthermore, BMSs are managed on the level of the whole structure and of nominal bridge elements; they do not store or represent bridge or defect geometry. This means information cannot be assigned to a specific part or location of an element, only to the element ID. The only way to record defect shape and location is through a freehand sketch or a photograph. Hence, understanding the extent of a defect or comparing the extent to a prior report entry is difficult.

Bridge inspection guidelines define the operational process of an inspection. They are used for inspector training and also serve as reference book during an inspection. Each authority publishes individual inspection guidelines adjusted to their particular needs. Differences originate from the geo-location and thereby conditioned properties such as weather, distance to an ocean or risk of earthquakes. Inspection guidelines describe what and how to generally document bridge defects. According to Highways Agency, an inspector has to collect “relevant data and describing defects in terms of their type, location, extent, severity and, if possible, cause” (The Highways Agency 2007). It also provides material-type specific tables for different defects and a description of how to determine a condition rating, as Table 1 is for reinforced concrete.

The problem is that this procedure is vague and leaves room for manual interpretation, for example on how to measure a specific property. Inspectors are expected to distinguish crack severities by measuring crack width with a crack gauge. But what exactly has to be measured? The maximum or an average? Likewise, for thaumasite, distinction between different condition levels is even more vague; guidelines refer to minor, moderate and major thaumasite without defining minor, moderate and major. Inconsistent measurements lead to unreliable condition ratings and difficulty in clearly understanding if a defect dimension has increased over time. Phares et al. identified 56% of average condition ratings being incorrect with a 95% probability and inspection notes concerning important structural defects show significant variability and many times are completely omitted (Phares et al. 2004). Cracks, for example, could theoretically shrink in width if a different location is used for measurement. To the authors’ knowledge, no explicit and comprehensive measurement standards
exist for defect properties when conducting a condition assessment; both in terms of what to measure and how to measure.

This paper presents exploratory research meant to derive a useful information model for integrating bridge defect information into a BIM model in the end, rather than causal research meant to derive a new process. First, relevant information is identified by analysing established inspection guidelines from four authorities (Alberta Infrastructure and Transportation 2008; Johnson et al. 2016; Queensland Department of Main Roads 2004; The Highways Agency 2007) and the SeeBridge IDM (Sacks et al. 2016), which is based on the Israel bridge inspection guidelines and the European bridge inspection guidelines being developed. We compare defect types and extract their required properties for condition assessment. This list of relevant defect-type dependent properties is then further refined to a hierarchical structure of hierarchically modelled defect information objects, which is then matched to IFC entities for integrating defect information into the BIM model. Finally, a prototype implementation serves as a demonstration of utility and, as the presented results fully comply with IFC, an analysis shows how much of the applied IFC standard is supported by existing IFC viewers.

BACKGROUND

Two questions arise for integrating defect information: which information is relevant and how can it be modelled?

There is no comprehensive and justified definition of which defect properties are necessary for condition assessment and maintenance processes. However, there are related fields where these definitions exist: The Federal Highway Administration (FHWA) has released a detailed guide for pavement inspection on how to inspect and document defects depending on the pavement material type (Federal Highway Administration 2003). For example, seven different crack types are explained for asphalt concrete surfaces along with a sketch indicating location and pattern for each defect type and also condition state. In addition, measurements are defined for each condition state along with a description of how and where to take measurements. Similar definitions are published by other authorities (Minnesota Department of Transportation 2003; Wallis 2007). Defect types relevant for
bridge inspection are known. What is missing, however, is a complete definition of defect-type dependent and general properties which leave no room for interpretation to an inspector (incl. definition of measuring quantity, unit, location, tools), plus a condition rating standard that is solely based on these objective measurements.

The subsequent question is how to model relevant defect information. BMSs are most commonly used to manage bridge defect information as a part of the general bridge stock information. Each bridge is represented by a dataset where documents can be added, such as bridge inspection reports, or attachments, such as images taken during an inspection or design drawings. Detection methods for detecting defects, such as cracks, often use images to store defect maps (Adhikari et al. 2014; Zhu et al. 2011). These defect maps are equal in size as an input image. The difference is that each pixel colour value indicates an undamaged or damaged class assignment at a specific position as visualized in Figure 1. Besides a binary representation, it can also be used to represent a pixel-based classification result for multiple classes in one image, each class being represented by a pre-defined colour. This process of semantically segmenting is used in many different fields, for example for images taken with a car camera and segmenting them into classes such as roads, cars and signs (Badrinarayanan et al. 2015). Defect maps are designed for representing a segmented classification result to an input image on a pixel level, not a class level. Hence, clusters of pixels have to be separated based on their colour and location.

Lee et al. used the Drawing Exchange Format (DXF) file format commonly used in Computer Aided Design (CAD) to make defect information accessible for bridge management systems (Lee et al. 2008). This format was originally defined and used for storing and exchanging technical drawings during the design and construction phase of an industrial product. The advantage of DXF is that it is able to represent geometric information using vectors instead of locally separated pixels in images. Defects can actually be represented as a polygon instead of a number of pixels. This means that it is a machine-readable format that can be used directly for analysis. However, this schema for defect geometry is separate from the BMS itself, and defect data cannot be carried integrally with geometry in a DXF file. Both file formats were not intended for storing inspection data and crucial parts are
missing for the storage of bridge defect information, most notably the corresponding element, the
exact position and orientation on the element and the size of the surface patch covered by the
image/design file.

Building Information Modelling (BIM) is a process intended to electronically model the whole
lifecycle of a building in all its aspects, including its 3D geometry. Mainly used for planning and
construction, it was originally designed to also share data and knowledge resources to support
management, utilization, renovation, and demolition activities (Eastman et al. 2011). While BIM is a
data and process description, many companies have developed their own proprietary data
representations of BIM models. One of the main limitations is that they are not exchangeable between
different platforms and are proprietary, which means that they are not freely accessible and subject to
changes by their manufacturers.

Mirzaei et al. examined, if Autodesk Revit can be used for bridge inspection information (Mirzaei et
al. 2012). They identified limited support for inspection specific features such as attaching images to a
specific element. McGuire et al. compared common BIM platforms (LEAP Bridge, Tekla Structures,
Revit) for modelling defects followed by structural performance testing. Their work focuses on the
structural assessment and the corresponding defect modelling requirements (McGuire et al. 2016).
Integrating or modelling defect information in conformity with existing inspection and condition
assessment guidelines was not part of their scope. As a result, the integrated defect properties (based
on damage cubes only for representing the damaged area) differ from the ones that are required by the
inspection manuals (e.g. width of cracks, exposed reinforcement for spalls). Hence, using this method
for bridge inspection in general will fail validation because essential inspection guideline
requirements are missing. For this reason, an information model for bridge inspection needs to start
with analysing existing inspection guidelines. Borrman et al. presented a system for building
condition rating based on 3D bridge models. It allows marking defects at surfaces of individual bridge
components. For importing geometry information, the proprietary ACIS file format SAT has been
employed (Borrmann et al. 2012).
Industry Foundation Classes (IFC) define an interchangeable open data model for BIM that is supported by most commercial software systems and can overcome restrictions between proprietary platforms. IFC version 2x3 was released in February 2006 and is the most commonly used IFC standard. It can facilitate maintenance information and as-is performance data, such as current condition or damage states for facility management (William East et al. 2013). Anil et al. used IFC to model damage information for post-earthquake assessment of reinforced concrete frames (Anil et al. 2013; Ma et al. 2015). More specifically, defect maps were added using IfcGeometricRepresentationSubContext. Extracted crack properties were linked as external text files using IfcRelAssociatedDocument, and IfcSurfaceStyleWithTextures was proposed to link corresponding external crack images. This work shows, how to use the abstract data model of IFC to model defect data. The presented work, however, is not sufficient for defect documentation in a bridge inspection, as it was designed solely for cracks during an earthquake inspection and therefore does not define which defect class dependent property sets for bridge inspection exist and how to map defect texture onto a specific element surface.

BIM and IFC were developed with a focus on buildings. Horizontal infrastructure projects have unique requirements such as alignment. To address this, the responsible instance for enhancing the IFC standard, buildingSMART International Ltd., started a new committee, the Infrastructure Room. This committee is working on infrastructure-specific standardization projects for rail, road, bridge and tunnel (buildingSMART International Ltd. 2017a). Bridge information modelling (BrIM) was given the highest priority because they are relatively close to buildings, considerable work has been done in France and most existing bridge infrastructure is close to reaching its designed life span. Committee work to date has not yet taken bridge inspection requirements into account (Hartmann and Director 2016).

Tanaka et al. proposed an IFC extension based on a more recent version of the IFC standard (IFC4) and the Bridge Information Modelling (BrIM) standard. They introduced new IFC entities for documenting inspected regions (IfcMeasuredRegion) and defect findings (IfcDegredation, IfcDegredationElements) along with new connection types to connect instances of the new entities.
with bridge elements (IfcRelConnectsToMeasuredRegion) and to connect defect findings at different timestamps (IfcRelConnectsToTimeVariations) (Tanaka et al. 2016). Crucial parts for holistically modelling defect information are missing from Tanaka et al.’s extension: First, it did not investigate what data is relevant for condition assessment. Secondly, it did not explain why the existing IFC standard, already an extensive standard, does not provide sufficient entities and connections to meet the requirements for bridge defect information. To date, no-one has assessed whether IFC4 can be used for adding bridge defect information without extending the standard.

Existing work for the stated problem can be summarized as follows: Bridge inspection guidelines define the way an inspection is performed, the relevant defect types and a documentation schema. Each authority publishes its own inspection guidelines, which vary considerably, and maintains its own BMS.

In conclusion, based on the state of research, although methods for managing bridge defect information exist, essential gaps in knowledge remain: (1) There is no comprehensive and justified definition of what defect (classes/types/properties or mix of them) is scientifically necessary for bridge condition assessment and maintenance processes. (2) There is no IFC compliant schema or data extension model that is able to store the defect (classes/types/properties) effectively for condition assessment and maintenance purposes. (3) It is unknown whether the existing IFC schema richness is sufficient to hold defect (class/type/property) data as explained above.

The objective of this work is to address the gaps in knowledge by answering the following research questions:

• What are the transnational bridge inspection guideline requirements regarding documentation of inspections in general and of the relevant defect types and defect-type dependent properties?

• What building information modelling data structures are appropriate for representation of the consolidated documentation requirements?

• How can the proposed information modelling structures be bound into an existing BIM schema definition?
The research was exploratory in nature, and followed the methodology framework depicted in Figure 2. We analysed multiple transnational and transcontinental bridge inspection guidelines regarding their general inspection information and regarding relevant RC defect types, to comprehensively cover global inspection requirements instead of focusing on one guideline only. For the defect types, we then extracted the raw properties usually accessible using the condition rating tables. This is the information which later on lets an engineer interpret and assess the findings. We consolidated the properties by identifying and removing / splitting overlap to avoid redundancy. We compiled both the general information and the defect information in a hierarchical structure. Separate data fields only represent raw data; a hierarchical structure converts it to meaningful information. We then matched this structure to an existing BIM standard schema to make it applicable for the existing bridge inspection process.

Inspection guidelines have common practices, but, as mentioned before, authorities adapt them to their specific needs. For example, if the geolocation of an authority’s area has no cold weather, it will not list defects induced by freeze thaw cycles. We have compared multiple inspection guidelines in order to extract representative properties for this work. We chose inspection guidelines in a way to cover a variety of continents, climate zones and tectonic regions. We were limited to the ones that were available in English. A list of the peer reviewed documents can be found in Table 2. In general, many US inspection guidelines, including the one from California, are based on a reference inspection guideline published by American Association of State Highway and Transportation Officials (AASHTO) and therefore are related (AASHTO 2013). Inspection guidelines were compared regarding their general information, the reinforced concrete defects, severities and severity distinction features. Other documentation blocks, such as maintenance requirements, were not considered.

An inspector provides general information about a conducted inspection that are essential for the correct assessment of a bridge and hence can be considered as background information to the bridge
damage information. This general information typically consists of three blocks. A first block is
information that helps assigning a bridge inspection report to a specific bridge and gives background
information about the structure type. It consists of a structure ID, bridge name, street name,
construction type, bridge age and material. A second block documents additional information
regarding the inspection itself. This is the date, time, duration and type of inspection, weather
condition and if additional tools were used during the inspection. A final block lists responsible
people such as the chief inspector or assistant. All the inspection guidelines reviewed require such
information. The UK guideline has the most detailed general information block with additional fields
for completeness and photographs taken.

Inspection guidelines define multiple defect types and their relevant properties. An inspector is
expected to generally collect all relevant information describing defects in terms of their type,
location, extent, severity and, if possible, cause. Inspectors should give a clear and accurate
description of the condition of a structure. We compared five inspection guidelines regarding the
listed defect types for reinforced concrete and how condition states are distinguished. Defects on pre-
stressed reinforced concrete and construction defects were not considered for simplicity. It should also
be noted, that we did not try to validate the correctness or completeness of the defect description, but
rather more to identify and extract a representative list of defects and their measurable defect
properties. The resulting summary is vague and possibly not sufficiently precise for a structural
engineer since the existing inspection documents are already vaguely formulated. It is not part of this
work to formulate better guidelines, but to extract defect properties from existing inspection
guidelines. These properties were either taken from the guidelines defect description or from the
corresponding condition ratings. We compared descriptions for condition ratings and extracted
properties of the most specific ones. For example, quantitative descriptions with definite
measurements such as width, length and height were preferred to general qualitative descriptions such
as slight, minor and major. Resulting defects and their type dependent properties are listed in Table 3.
Defects, that were only present in one inspection guideline, are not further investigated but are listed
in the column “other defects”.

• **Cracks** - All inspection guidelines list cracks as a defect class. Only the Israel bridge inspection guideline differentiates crack types based on their likeliness of affecting the stability of an element or structure, which already requires an assessment. It also gives distinct minimal and maximal width values for corresponding condition ratings. The UK guideline explains different crack causes: flexural cracks, shear cracks and torsion cracks, but they are all documented as a single crack type with different severity. One needs to know if the crack occurs in an area of high flexural behaviour, if it is located close to the supports, and how it is oriented relative to the supports in order to distinguish them. Hence, the properties that have to be extracted are width of a crack, the flexural behaviour in this area, if it is close to a midspan or support and the orientation relative to a support. A definition of high flexural behaviour or how to interpret distance to a support is missing.

• **Delamination** - Delamination conditions are distinguished by early signs of delamination (cracks along with rust staining in the UK, crack width in Israel) and by low or high flexural and/or shear action in an occurring area. A severe delamination state also takes exposed reinforcement into account. Delamination is a defect that can be visible in multiple ways, it might even be not visible at all. Assessing delamination requires to detect basic defects cracks and rust staining. In addition, it requires knowledge about the location and the flexural and shear behaviour in this area.

• **Spalling / Exposed Rebar / Corrosion** - Spalling, exposed rebar and corrosion is grouped as they cannot occur separately. Exposed rebar is accompanied by spalling, and corrosion refers to the corrosion of its reinforcement steel bars. The UK inspection guideline requires an inspector to identify if a spall is minor or major, if and what type of reinforcement bars are exposed (shear links / main bars) and to what state the exposed rebar is corroded (general/pitting). There is no additional information given on how to distinguish between minor and major spalls. The guideline of California and Alberta provide a better understanding by taking the defect diameter and/or depth into account. The relevant properties are diameter, depth, exposed rebar and corrosion state.

• **Efflorescence** - Efflorescence is visible as white deposits on a concrete surface. This defect is listed in Alberta, Israel and California. No additional definition of which properties are relevant for this
type of defect is given. More important is to recognize which other defect types come along with
this defect, for example, if cracking or spalling occurs. The Israeli inspection guideline points out,
that these other defects have to be assessed separately. Hence, the properties that are required for
Efflorescence are if accompanied by other damages and if this other damage is structurally
relevant.

- **Freeze-thaw** – This defect is listed by the UK and Israel inspection guideline. However, both fall
short of giving a distinct definition on how to identify and distinguish condition states of freeze-
thaw. Both state slight, minor, major freeze-thaw as condition state without giving additional
explanation. Only the Israel guideline lists an additional feature based on a peeling surface or
exposed reinforcement. Hence, required properties are peeling surface and exposed reinforcement.

- **Scaling** - Scaling is a loss of surface mortar. It is listed in the inspection guidelines of Israel and
Alberta. Condition rating is determined based on depth, type of exposed aggregate and if
reinforcement steel is visible. No clear distinguishing feature is given between scaling and freeze-
thaw.

- **Abrasion / Wear** - This defect is listed in Californian and Israeli guidelines. Both distinguish the
condition states based on the kind of exposed aggregate. Israel also takes the reinforcement into
account. Hence, the required properties are if coarse aggregate is visible and/or if reinforcement
steel is exposed

**INTEGRATING INSPECTION INFORMATION INTO IFC**

Existing inspection guidelines are intended for being used by human inspectors. Little consideration is
given on how the output of an inspection can be embedded into a structured, electronic model.
Guidelines only specify paper-based report templates as a documentation format. Sketches are to be
made on separate paper. The advantage of this approach is its flexibility which at the same time poses
the main research challenge: Transferring this to a well-structured model automatically reduces the
flexibility. For example, an inspector can always make freehand notes or sketches on a paper form to
document details beyond the predefined form structure. A well-structured electronic model, instead,
only allows using it in a predefined manner. Hence, it is important to analyse and identify
documentation requirements so that the predefined model can fully represent these guideline
requirements.

We use IFC for several reasons to demonstrate this integration process. IFC is a neutral and open
exchange format that is widely spread in the industry and supported by most of the relevant software
packages. It is well documented and supports 3D building models. IFC requires a hierarchical data
structure and defines three basic components for modelling buildings: objects, relationships and
properties. Objects are abstract entities, structured in an ordered hierarchy. Instances of these entities
are used to represent a real life element or object. Relationships relate different objects to each other
and properties add context information to an object. Before starting to select the appropriate entities,
we need to restructure the inspection and defect information.

STRUCTURING THE DATA

Three data blocks are modelled: general information about the bridge, responsible people for the
inspection and background information to the inspection. The first block is meant for linking a report
to a specific bridge. It can be ignored as we are integrating the defect information directly into one
holistic model. The second block is general information about the inspection, more precisely:
inspection type, weather condition and time duration. And the third block is the inspecting person.
Additional people, such as an advisor, could be added likewise. Database forms could be used to
provide condition summaries automatically once the data is available in order to present an inspector a
familiar report format. More sophisticated ways of presenting the defect data could be developed,
such as filtering methods or deterioration over time, but this is out of scope of this paper. Figure 3
visualizes the general information objects and their relation.

Next, different defect levels have to be considered. Even though an inspector on site does not
distinguish between directly visible defects and their interpretation, this distinction is essential when
integrating the data. The reason for this can be explained by analysing Table 1: The problem of
identifying and assessing a defect can be illustrated by looking at cracks: A crack can be a defect on
its own, but it is also present within three other defect classes (Damaged pre-stress, delamination, thaumasite / freeze-thaw). Hence, we are using two separate defect levels to accommodate this separation between identification and assessment, element defects and defects. An element defect is solely determined by its visible and geometrical appearance and has no condition assessment itself. It affects only one element and is not a combination of multiple defect types. This kind of defects is referred to as an element defect. As this defect represents a unique defect appearance at a specific time, a distinct instance is added for each visual element defect during each inspection. It is explicitly related to one specific inspection. This way, by representing a defect appearance separately for each inspection, the expansion of an element defect over time is documented.

To group these multiple element defect instances, a defect is introduced which can group element defects timewise and type-wise. To give an example: corrosion can induce cracks, spalling, bleeding or even invisible element defects such as delamination. All these element defects should be tied together as they originate from the same source. Additionally, the deterioration over time should be represented. Hence, each time an element defect is identified, it is modelled as a separate instance of element defect, as explained earlier, and tied together as one defect. This second kind of defect generally combines element defects with the same cause over time. A defect has no visual representation itself as it is a combination of visual element defects. It is referred to as defect.

Contrary to element defects, these defects can propagate over several elements and contain different element defect types and multiple element defect instances. The condition assessment is done on the level of a defect, not an element defect. The reason is, that a condition assessment stands for the impact on a structure, this structural impact can only be assessed based on taking all contributing facts into account, which are the element defects along with structural considerations. As they are independent from a specific inspection, they are not directly tied to one. They are only related to the inspections through the element defects. Figure 4 presents the defect hierarchy in a diagram. With the outline of the objects, we can now determine how to structure the properties. Table 3 serves as basis but further structuring helps to simplify the property sets. It is the aim to have small and simple, well-
defined property sets for each element defect type without redundancy regarding the defect types or properties.

The properties can be separated into two groups, one that directly describes a defect feature and is unique to a defect type and a second, more general one that depends on the location and orientation of a defect. Location and orientation dependent properties are relevant for multiple defects and are structured in a separate property set. Another repetitive property set is the one describing exposed reinforcement along with corrosion. This is also separated in an own property set. All resulting property sets are listed in Table 4. Defect imagery taken during an inspection mostly shows a tiny part of a bridge in a high resolution, such that the defect is properly represented in an image.

Unfortunately, these images might show severe distortions and, because mostly taken as close-up, it is difficult for an inspector to fully understand the exact position and orientation of a defect based on an image and prone to any kind of optical illusion. It is preferable to relatively register a camera position to an element with the correct location and orientation. This way, understanding the defect relative to the element is simple and by back-projecting the image onto the surface, distortions are removed. This process is illustrated in Figure 5.

SELECTING IFC ENTITIES

Having the data structures and relations in place, we can now start the modelling process. We assume to have an as-is IFC model of at least Level of Detail 300 (LoD 300) as input model which can be used to integrate inspection and defect information. In general, IFC has a large variety of rather abstract, universal entities, such as IfcObject for any kind of object and quite specific ones, such as IfcBoiler, for a closed, pressure-rated vessel in which water or other fluid is heated. Each entity comes with a semantic definition of what it is meant for.

The difficulty is to make the right choice in picking an IFC entity. It would be formally correct to just always use a universal entity such as IfcProxy. However, it is good practice to be as specific as possible in order to have a semantically meaningful model representation. This means to decide on the deepest entity in the hierarchy that complies with the given semantic description. The problem is that
some of the entities might not completely fit or appear to be too abstract. The typical answer to this question is to propose an extension to IFC. This, however, has key limitations: first, an extension has to pass the verification process and then has to be embedded into existing software. This process is very time-consuming and might fail as an extension might never be accepted. Secondly, IFC already is an extensive and complex standard that was developed over many years, involving many parties. Constantly extending this standard bears the risk that it becomes unmanageable at some point. Hence, we contend that the existing standard should be preferred where possible.

An Information Delivery Manual (IDM) to specify the technical components, activities and information exchanges and a Model View Definition (MVD) to specify the data exchange schema to serve the IDM can be used for defining and, even more importantly, checking the conformity of any given data exchange structure. This allows to specify the way the properties are represented in an IFC file and which IFC entities are allowed to be used. Developing this is beyond the scope of this work, but was done based on this work by Ma et al. (Ma et al. 2017).

RESULTS

SELECTED IFC ENTITIES

For general information, the IFC standard contains an entity named IfcTask, which is defined to be used to “describe an activity” such as “operation related activities” (buildingSMART International Ltd. 2017b). It inherits from IfcProcess and does not have a geometrical representation. Name, title and company of an inspector is put into IfcTask.Name. Any comments, including the weather condition, is stored as IfcTask.Description. The inspection level or type of inspection (e.g. safety, general or principal) is stored in IfcTask.WorkMethod as it matches the IFC attribute definition of describing the method of work used in carrying out a task. The time and duration is linked to a related IfcTaskTime. Besides the actual date, time and duration of an inspection, this entity also allows to be used for scheduling an inspection and to compare planned and required inspection time. The IfcTask describing the context information is assigned to each element defect, but not the defect itself, using IfcRelAssignsToProcess. This way complies with the optimal structure described in Section 4.1.
except that a person is not modelled as an own entity but an existing attribute is used. Figure 6 illustrates how to use IfcTask to model inspection context information. For defects and their properties, IfcElementAssembly is defined as representation of “complex element assemblies aggregated from several elements, such as discrete elements, building elements, or other elements” and “it does not need to have an explicit geometric representation” (buildingSMART International Ltd. 2017b). Hence, it is appropriate for modelling a defect.

Besides grouping associated element defects, a defect also includes a condition rating, the actual engineer’s assessment. In IFC 2x4 a property set for condition rating was introduced: Pset_Condition. This property set has three separate properties to describe a condition, namely AssessmentDate, AssessmentCondition for an overall condition expressed in a short authority-dependent numerical (1,2,3,… or good, fair, poor,…) unit and AssessmentDescription for a qualitative, text-based description of the condition. The defect is assigned to an IFC element using the aggregation relationship IfcRelAggregates. This way, a defect can be assigned to one or even multiple elements in case a defect is propagating over several elements. Figure 7 demonstrates how to use the presented IFC structure for modelling a defect.

IfcSurfaceFeature is used for modelling element defects. This entity is derived from IfcElement and thus has an own geometrical representation. It is defined as “a modification at (onto, or into) … the surface of an element” and may minor increase, remain or decrease the mass of an element (buildingSMART International Ltd. 2017b). A tessellated shape representation is modelled using IfcShapeRepresentation. This gives flexibility about form and position of a defect in 3D. It consists of a list of 3D points, defined in IFC as IfcCartesianPointList3D, and based on this, corresponding triangles defined by IfcTriangulatedFaceSet. Any other valid IFC shape representation would be feasible. This one has the advantage of simplifying the subsequent texture mapping. Element defect properties are added similarly as for defects using IfcPropertySets with the difference, that this time there is no standard property set definition that can be referred to. The property sets are individually created per defect class based on the individual properties from Table 4. The last column indicates the most suitable data type. In general, IFC allows to assign property sets to multiple IfcElements.
However, in this case a property set describes individual defect measurements taken at a specific point in time and thus must be assigned to the corresponding IfcSurfaceFeature exclusively which represents the specific element defect from which measurements were taken. Figure 8 presents an example crack modelled as element defect.

Having the triangles of the already modelled element defect, we can directly use IfcTextureVertexList and IfcIndexedTriangleTextureMap to define a mapping of the 3D triangles to a 2D image. This technique originates from Computer Graphics and is known as UV mapping (Murdock 2008). It is illustrated in Figure 5. To each corner of a triangle in 3D, a corresponding set of 2D coordinates is defined, whose coordinates are referred to as U and V (In the scope of IFC, these coordinates are named S and T). Texture coordinates U and V are specified in the range of [0,1] and are scaled automatically during runtime to the image size. It has to be mentioned that the use of the texture mapping feature is not yet very well supported as, so far, IFC is mainly used during the design process, where the benefit of having textured surfaces is significantly smaller. The texture image itself is referenced as a uniform resource identifier (URI) by using IfcImageTexture. A URI can either be a locally stored file or a resource located in a private or public network. The advantage of externally referencing the texture file is that the IFC file is kept small and readable whilst binary code is outside. A problem exists when an image texture file location changes or a resource in the network is no longer available. This results in a corrupted IFC file. IfcBlobTexture offers a solution by embedding the image binary data into an IFC file. This ensures the availability of the image data to the cost of a significantly increased file size and complicates readability. Common image compression formats, such as jpeg or png, are supported for both entities. This way, a surface texture can be assigned explicitly to an element and it can even be precisely located on an element. Having this transformation, we can directly take measurements in pixels from the image and convert them into physical measurements in our 3D model space. The corresponding example IFC code is given in Figure 9.

CASE STUDY
In order to prove the feasibility of the presented concept, we defined a set of example defects, modelled and augmented with potential real life data. We evaluated, which of the bridge inspection requirements is supported by existing documentation formats (paper-based, image-based, dxf, existing work based on IFC2x3, presented method). In addition, we implemented a prototype viewer and evaluated it along with other most commonly used IFC viewers, to see, how much of the presented scheme can be visualized and is supported by each viewer.

The fictitious exemplary inspection and defect situation for illustrating the concept was set as follows: A simple example structure consists of two orthogonally oriented beams. They were inspected two times, once in 2012 and once in 2014. During the inspection in 2012, a simple crack was detected affecting beam one. It was oriented upwards starting at the bottom of one side of the element. In the second inspection in 2014 this crack has increased in length and width and an inspector assumed that it also structurally propagates to the other beam. In addition, a corrosion defect appeared on beam one which was identified to be due to a spalling on two surface sides of the element including exposed and corroding reinforcement. Pictures were taken from both defects. This situation was modelled using the presented concept. A sketch of the defect location is presented in Figure 10.

We measured the performance by analysing which of the requirements is fulfilled by existing documentation formats. Table 5 presents the results. The last column presents a performance score. We tested the following attributes:

- General inspection information: Is there a way to model general inspection information as defined in Figure 3?
- Defect type: Is there a way to model defect types presented in Table 4 in a self-explanatory way?
- Defect location: Is there a way to exactly determine the location of the defect on the structure?
- Defect extent: Is it possible to extract the extent, absolutely and relatively to the structure?
- Defect severity: Is it possible to store a condition rating?
Defect cause: Can the cause of a defect be stored and explained, including an inspector’s reasoning and conclusion?

Additional defect properties: Is there a way to add properties to an element defect, depending on the defect type and the properties listed in Table 4.

3D geometry: Is there a way to model arbitrary defect geometries in 3D?

Group different defect types: If having a group of different element defect types, can they be linked such that their causal relationship is described?

Group defects affecting multiple elements: If having a defect that propagates over multiple elements, is there a way to group them such that their causal relationship is described?

Image registration / defect texturing: Can defect imagery be registered properly and placed on top of the element’s geometry so that it is identically located and identically looking as it is on site?

Machine readability: Can a computer extract, transform and process the stored data on a bridge inspection relevant level? As an example, this could mean to extract all cracks on beams from multiple models where crack width is greater than a given threshold.

Easily shareable: Is there a way to send defect documentation electronically without taking much time or causing excessive costs?

Fully integrated data type: Is the model and corresponding and referred documentation in one package or is it split in many chunks?

To compile the inspection building model files for the case study, we used a text editor and manually added and manipulated the IFC files. This required several hours. It is obviously not the intended way for eventual implementation, but in the absence of BIM tools that can model and export IFC files with the proposed schema, it is necessary for the case study. In the authors’ opinion, implementation in existing BIM software can reduce the time required for integrating defect information into a BIM
model at least to the time required to document inspection findings with existing methods, and likely much more.

VIEWER IMPLEMENTATION

A prototypical viewer was implemented based on the Gygax research platform (Huethwohl et al. 2017). This platform is written in C# and C++ and enables the use of typical data formats for AEC industry (images, videos, point clouds, BIM models) and their preferred processing libraries in a uniform way. Main supported data formats are images, videos, point clouds and BIM models. In the scope of this work, the BIM functionality was particularly used. Gygax supports IFC files and utilizes the IFC Engine DLL published by RDF (RDF ltd. 2017). This library supports reading and writing of IFC files and also has a built-in geometry kernel which translates text-based IFC geometry description into a triangle mesh that can be processed by 3D engines. Gygax uses the Helix Toolkit for visualization of supported data types in one 3D space. More specifically, Helix Toolkit (Holance et al. 2016) is used in combination with SharpDX, which is a .NET wrapper of the DirectX API, to allow high performance GPU processing even with large input datasets.

When opening an IFC file with embedded defect information, a two-columned window is presented. One column is to visualize the 3D geometry of the model including the overlaid defect textures. On zooming in to a specific defect, the defect gets clearly visible. Even small details, like cracks, can be inspected. Defects that propagate over multiple surfaces of an element, are visualized on each corresponding surface. Examples are given in Figure 11.

A second column is a tree view that maps the logical tree structure of the IFC model. When clicking on a specific model element in the 3D view, the corresponding node in the tree gets highlighted. Additional information, such as property sets, is presented as children nodes. Figure 12 shows this tree. The first node represents the beam itself, followed by the defect crack, which has two children: the element defect representation and a condition rating. The condition rating relates to the latest available information, hence it states the last inspection date as assessment date. Within the element defect, one can find the inspection information in the IfcProcess node, followed by the defect type
dependent properties and the defect location properties. Each node lists the corresponding property
details.

As a final evaluation step, we tested the IFC viewer along with most commonly used IFC viewers to
see how much of the presented concept is supported by each viewer. The IFC viewers were chosen
from a review paper (Abanda et al. 2015) and additional commonly known viewers were added. The
performance of each viewer was examined by answering the following questions. Results are listed in
Table 6.

• Open file: Is it possible to open the file at all?

• Show 3D geometry: Are the two example beams correctly presented?

• Show element defect geometry: Is the geometry of each element defect visualized accurately?

• Show element defect texture: Is the texture of the element defect correctly shown? Is the
  registration correct?

• Zoom in to see high resolution defect details: Is it possible to zoom in closely to see the details of
  the crack and recognize the exposed reinforcement of the spalling?

• Show defect properties: Is a list shown with the defect condition properties?

• List nested element defects to defect: Is the relation between a defect and its corresponding element
  defects evident?

• List element defect properties: Are element defect properties listed including type dependent
  properties and location properties?

• General inspection information accessible: Is the corresponding general inspection information
  accessible along with the element defects?

CONCLUSION AND FUTURE WORK

We have presented results of a bridge inspection guideline analysis and a novel concept for
integrating RC defect information into an open and well-defined BIM model using the latest IFC
standard (IFC 4 Add 2). In order to have a meaningful and significant basis on what information to include into a BMS for the purposes stated, existing bridge inspection guidelines were examined and requirements for defects and their properties were extracted, analysed and listed. We presented a method on how to convert this information into an object-oriented hierarchy and how to assign corresponding IFC 4 entities, both structurally and content-wise. The resulting IFC entities were presented. A typical inspection situation was defined and findings were documented in an example file in order to illustrate the feasibility of the concept. We developed a prototypical viewer which is able to open and visualize the resulting model. The presented scheme was finally evaluated by comparing it to common defect formats. It was shown that the existing IFC 4 standard is capable of modelling bridge defects and general bridge inspection information in compliance with existing bridge inspection guidelines. Limitations to this method exist in the extraction of defect properties, the modelling approach in general and the IFC entity selection:

Presented defect properties are vaguely formulated as they have been extracted from existing inspection guidelines, a clarification and consolidation of these guidelines is desirable. Using a geometrical modelling approach require geometrical as-is IFC models for every bridge. These models do not exist for a majority of bridges. Both research and authorities have identified this problem. Research has started to develop methods to automatically model as-is bridges based on point cloud data or images and authorities have started to require geometrical models for every newly built bridge. Finally, the selection of an IFC entity to an object type, such as IfcSurfaceFeature for an element defect, could be argued. There is no clear definition of which entity is correct, it is more a question of interpreting the entities’ description. Most important is the consistent use of entities to avoid confusion in what the entities represent. We pointed out that an IDM/MVD is a possible solution to this. Another limitation is the use of existing, most appropriate IFC entities which might not perfectly fit. This directly raises the question of why not adding more distinct IFC entities, and using existing ones. Our opinion is that the existing IFC standard should be used where possible as it already offers a variety of different entities and excessive standard extensions lead to a confusingly complex standard. Beyond that, proposing standard extensions is time consuming and they might not pass the validation
process. It is expected, however, that the current IfcBridge standardization project will provide a minimal set of extensions required to better capture the semantics of bridge elements. The project will also develop MVDs for a number of use cases, including inspection, which will formally specify what properties are required and how they must be represented in an IFC file. The MVD technology will also allow to check instance models for compliance with these specifications.

Yet, inspectors can integrate their findings directly into a geometrical representation of a bridge with the presented data format. Writing table-based reports is no longer required and reports can be automatically extracted based on the model information. Resulting bridge models can easily be exchanged across authorities or countries. Researchers can use this format to build bridge damage datasets, which allow to assess and evaluate new inspection and maintenance methods. This will help to improve the inspection and maintenance process and increase value for money for tax payers.

Integrating maintenance requirements and cost estimates is interesting for future work. This information is usually given by an inspector during an inspection. Furthermore, although the presented concept is able to cover and report the history of inspections and the corresponding defect information thoroughly, it does not yet cover maintenance and repair work that was actually conducted. Adding this information would help an inspector to fully understand a structure, its degradation, conducted maintenance work and future serviceability.

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