State of the Art in Damage Information Modeling for RC Bridges - A Literature Review*

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Abstract

In Germany, bridges have an average age of 40 years. A bridge consumes between 0.4% and 2% of its construction cost per year over its entire life cycle. This means that up to 80% of the construction cost are additionally needed for operation, inspection, maintenance, and destruction. Current practices rely either on paper-based inspections or on abstract specialist software. Every application in the inspection and maintenance sector uses its own data model for structures, inspections, defects, and maintenance. Due to this, data and properties have to be transferred manually, otherwise a converter is necessary for every data exchange between two applications. To overcome this issue, an adequate model standard for inspections, damage, and maintenance is necessary. Modern 3D models may serve as a single source of truth, which has been suggested in the Building Information Modeling (BIM) concept. Further, these models offer a clear visualization of the built infrastructure, and improve not only the planning and construction phases, but also the operation phase of construction projects. BIM is established mostly in the Architecture, Engineering, and Construction (AEC) sector to plan and construct new buildings. Currently, BIM does not cover the whole life cycle of a building, especially not inspection and maintenance. Creating damage models needs the building model first, because a defect is dependent on the building component, its properties and material. Hence, a building information model is necessary to obtain meaningful conclusions from damage information. This paper analyzes the requirements, which arise from practice, and the research that has been done in modeling damage and related information for bridges. With a look at damage categories and use cases related to inspection and maintenance, scientific literature is discussed and synthesized. Finally, research gaps and needs are identified and discussed.

Keywords: Building Information Modeling; Damage; Defects; Damage Information Modeling; Object-oriented Modeling; Life cycle; Bridges; Inspection; Maintenance

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1. Introduction

Bridges in Germany have an average age of 40 years [1] and 70% of the bridges are reinforced concrete bridges [2]. Over its entire life cycle, a bridge consumes between 0.4% and 2% of its construction cost per year. This means that between 16% and 80% of the construction cost are additionally needed for operation, inspection, maintenance, and destruction [3]. The condition state of the bridge is the central point for the operation phase. Is the bridge safe regarding its structure and traffic and is it durable? Recording the condition state means recording damages and defects of a bridge via an inspection performed by an engineer, respectively by an inspector.

Inspection and maintenance is conducted by different parties, which need to exchange information about construction, inspection planning, inspection results, maintenance suggestions, and execution. Major damage data acquisition on-site is paper-based. First improvements are done by using photos. Some companies already use Unmanned Aerial Systems (UAS) for visual inspections [4, 5]. After an inspection or an information exchange, an engineer must digitize the analog information [6] because all data is processed digitally, such as maintenance decisions and maintenance planning. Sacks et al. have stated that as result of the digitization process, an information loss happens [7]. To regain this data, engineers have to revise the information, which cost additional time and money. Future inspections could make use of digitally recorded damage data, like it is done in research already, e.g., to collect building data by UAS [8] and to process them automatically [9]. Both scenarios, manual and automated inspection, need an adequate way for data exchange. At the moment, the life cycle phases operation, maintenance, reconstruction and destruction gain little attention in literature [10]. For this reason, this paper focuses on inspection and maintenance. The topic of destruction is out of the scope of this paper.

Fanning et al. have shown the economic benefits of using Building Information Modeling (BIM) in civil engineering. Cost for construction can be lowered between 5% and 9% [11]. A standardization for damage information may help reduce the information loss and, hence, lower the cost. This standard needs to contain an Information Delivery Manual (IDM), a Model View Definition (MVD), and a data format comparable to the Industry Foundation Classes (IFC), among others. This paper aims to contribute two things: an overview about existing research in the field of Damage Information Modeling (DIM), and to reveal research gaps, which need to be filled to support adequate damage modeling in the context of BIM.

BIM contains geometric and semantic building information, which is necessary to model damages in a comprehensive way, e.g., for inspection planning, simulation, maintenance planning, and execution. Existing damage models, for example, structural damage models, would not satisfy all requirements for bridge operation. For this reason, this paper begins with descriptions of efforts done for BIM and BIM for bridges. Afterwards, it takes a look at the current state of practice. The first requirements and aspects for modeling damage can be drawn from national standards and guidelines. An analysis of data from practice delivers a categorization for damage. For a view on different use cases and object types, like defects, components, or component groups, several documents dealing with damages in different resources are analyzed. Finally, the conclusion describes the work conducted in the area of damage information modeling (DIM) and what has to be researched in future investigation.

2. BIM for infrastructure

As already mentioned, different actors contribute to the life cycle of buildings. According to [12], “Building Information Modeling is an information management method for construction projects based on the consequent use of digital models across the entire life cycle of a built facility.” OpenBIM has become an important concept in recent years because its aim is an open and independent model standard for BIM, so that all contributors can exchange and coordinate data without information loss and use the data for their work, at best, during all phases of the life cycle [12]. The 3D model of the building or structure is in the center of the modeling process. For 3D modeling, the IFC is utilized in the context of OpenBIM [13]. In addition to geometric information, building information models also contain semantic information, e.g., information about materials, processes, actors, functions, and relations. Based on this, Belsky et al. have presented work on how to enrich building models by inferring semantic information from these models automatically [14].

Figure 1 shows the complete life cycle of a building. Planning and visualization of the construction process can be realized based on the 3D model. Modeling the construction sequence upon the 3D model leads to 4D BIM [15]. Additionally, by modeling construction cost, BIM reaches the 5D level [7]. With these concepts, the design and construction process of buildings is well supported. Providing BIM functionality for the operation and maintenance phase is an emerging area. One problem related to a broad usage of BIM in operation and maintenance is an unsatisfactory interoperability [16]. A damage information model aims to improve the support of this interoperability by providing a concept for damage data exchange between multiple processes.

In case of new buildings, the architect hands over the BIM as-built model to the owner [7]. 78% of bridge square meters in Germany were built in the 1990s and earlier [1]. These bridges were not designed with the use of 3D CAD or BIM because the profound research in BIM first started at the end of the 1990s [12]. Hence, existing bridges, which were built without BIM, lack a digital model. To create as-built BIM models for existing buildings, a concept called “Scan-to-BIM” is utilized. Scan-to-BIM covers multiple things: techniques for data collection (i.e., photogrammetry, LIDAR, structure from motion, or similar) [17, 18, 19], monitoring the construction process [20, 21, 22], and inferring additional information from BIM models [23].

Further research deals with modeling civil infrastructure, called Civil Information Modeling (CIM). CIM covers multiple scopes: roads, bridges, tunnels, airports, rails, and related structures [10]. There are four extensions for IFC, which focus on different parts of civil engineering: IFC-Road for roads [24], IFC-Rail for rails [25], IFC-Tunnel for tunnels [26], and IFC-Bridge for bridges [13]. These four extensions use IFC-Alignment to design and plan alignments [27]. IFC-Alignment has been part of the IFC since version 4 [13]. IFC-Bridge has been integrated in version 4.2 [28]. The other extensions will follow during upcoming updates. Finally, IFC 5 will provide support for roads, bridges, tunnels and rails [29].

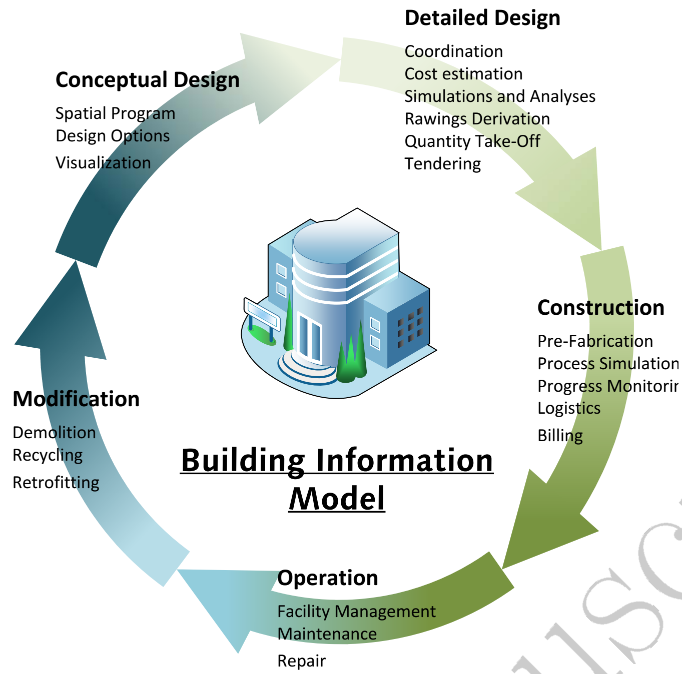

Figure 1: Building Information Model for the whole life cycle (acc. [12])

IFC-Bridge delivers topic related elements for the information modeling of bridges [30]. A Japanese [31] and French project have started in parallel to develop an IFC-Bridge extension. Through several stages in 2002, Yabuki et al. have published results from the later collaboration of both of them [32]. After further research [33, 34, 35], version 2 of IFC-Bridge has been presented in 2013 [30]. The most current version of IFC-Bridge has been presented in June 2019 [36] and is part of the IFC version 4x2 [24].

3. Methodology

Figure 2 shows the methodology for identifying the research gap. Terms and definitions are explained in the background section. Next, standards and guidelines show the current practice and, hence, basic requirements regarding use cases and properties. A statistical data analysis reveals frequent and significant damage types. Finally, an analysis follows, which shows existing scientific literature under the consideration of use cases and damage types.

4. Background

A model represents only a single part of the real world, e.g., a geometric building model represents the shape of the building and another model may represents the construction process of the building. In case of defects, different models represent different aspects. In general, use cases can be grouped into structural, functional, and durability related use cases. Structural use cases consider the structural safety and behavior of the bridge. Functional use

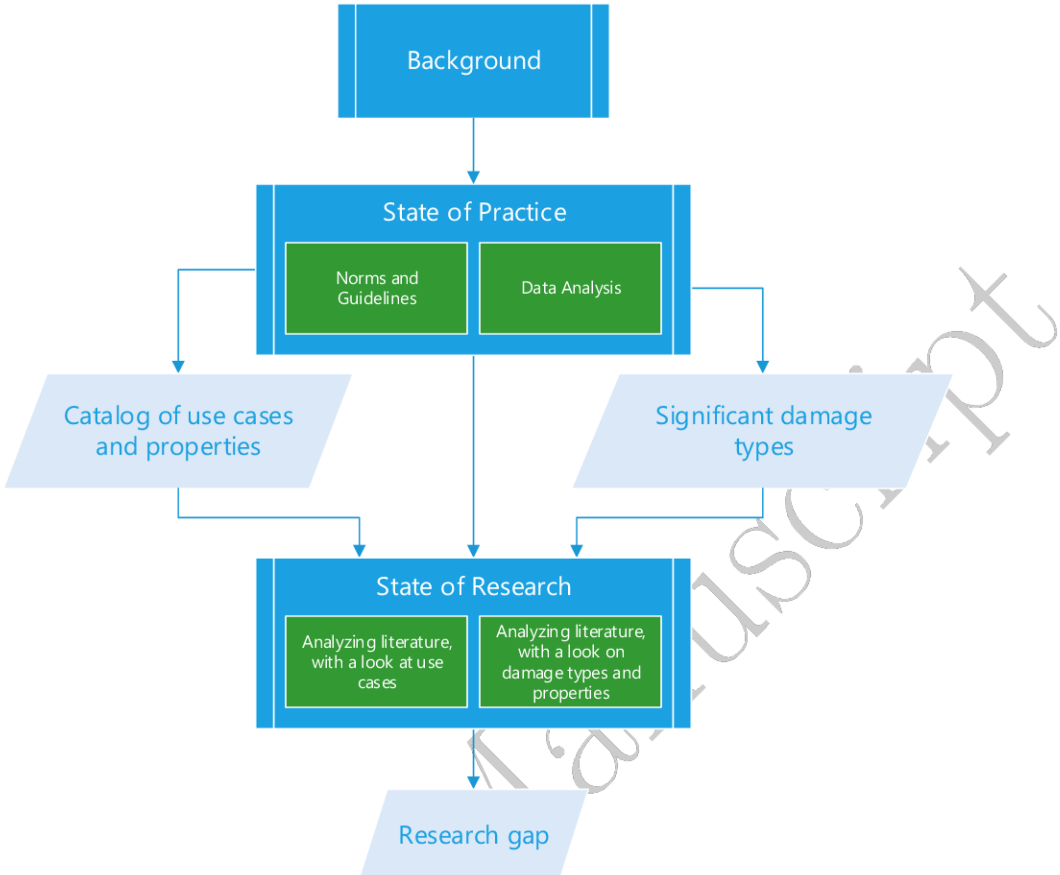

Figure 2: Methodology to analyze the state of research

cases handle issues, like traffic safety, inspection planning, and maintenance planning. Durability use cases care about the durability of the bridge. For every use case different models are applied. Figure 3 shows an overview of three existing damage model use cases. Figure 3 is not exhaustive, thus, other use cases may added.

First, there is the geometry model, which contains information about the shape of a defect or damage. This information can be more general, e.g., depth, width, length, and orientation of a crack. More detailed information is also possible, for example, representing a damage as an extrusion along a path. Other damages, such as carbonation or chloride migration, can have a geometrical representation, as well, even if they are not visible. Spheres or cones below the surface could be meaningful geometric representations of defects induced by chemical reactions.

Another model is the deterioration model that represents the process of deterioration. Tuutti explained it for the process of steel corrosion in concrete [37]. A crack at the surface of the concrete leads to depassivation, e.g., by chloride migration. After some time, the depassivation reaches the rebar of the structure and initiates the corrosion. This corrosion decreases the rebar's diameter and weakens the tensile strength of the rebar, which leads to increased distortion and, hence, to more cracks that are longer, wider, and deeper. At some point, the concrete spalls out

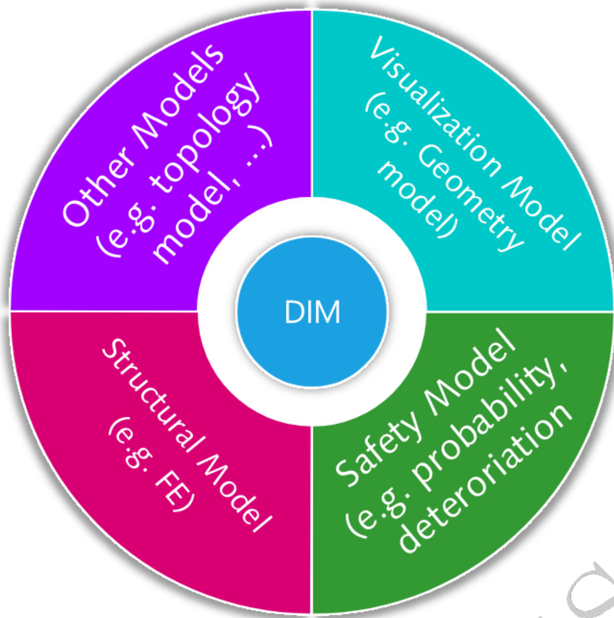

Figure 3: Exemplary damage model use cases

and reveals the reinforcement. Without maintenance actions, the structural safety is jeopardized. Similar models exist for further deterioration processes, e.g., carbonation [38]. In summary, a defect is a symptom or a consequence of deterioration and defects do not only impair structural safety , they also impact durability. These models need material parameters. More detailed models, which use detailed damage geometry, are also imaginable.

Third, if defects occur, it is necessary to analyze the impact of these defects on the structure. Part of the result of these analyses are occurring stresses within a damaged component and consequences of these stresses. This yields to a structural analysis model with additional damage information. Such models provide information about stresses in important areas of the structure [39]. Additionally, these models allow an analyses on crack growth, like shown by Moes et al. [40]. Depending on the method used, the information needs to be very detailed, e.g., a crack path, or the model can be more general, such as a bounding box of a crack. Furthermore, defects harm traffic safety, like, a corrosion of a railing at a bridge worsens the protection for pedestrians and cars from falling down.

Ongoing degradation processes lead to the necessity of maintenance. Probabilistic methods offer algorithms to estimate parameters of the life cycle of a structure, e.g., when will loads exceed a threshold or when is the best time for maintenance actions [41, 42]. These models operate on a much more abstract level and most times do not rely on detailed defect geometries.

A Damage Information Model should be able to store data, which is necessary for the aforementioned models. However, unnecessary data should be avoided during the exchange between actors. Hence, Model View Definitions (MVD) are crucial for the future use of damage information. Additionally, novel technologies, e.g., Virtual Reality (VR), point clouds, or machine learning offer new possibilities for inspection and maintenance. An adequate DIM also needs to support such up-to-date technologies.

Lastly, maintenance planning and execution as well as decisions on load restrictions are consequences to prevent further damages for structures and people. However, a DIM only includes information about the damage itself. An extension of the DIM in the sector of maintenance could be part of future research.

Several defects are severe but invisible, e.g., chloride migration, carbonation, alkali-silica reaction, or ripped tendons. A simple geometry under the surface might be invisible and, thus, useless. To visualize a projection of the damage on the surface could lead to misconceptions. However, the final model must be capable of storing data of invisible damages in a meaningful manner.

5. State of practice for bridge inspection and maintenance

A DIM needs to respect requirements from current practice and research. Hence, this section focuses on requirements for a DIM, arising from current practices of bridge inspection and maintenance.

5.1. Use cases in the overall inspection and maintenance process

Figure 4 shows the entire process of inspection, rating and maintenance of bridges. The inspection process begins with the planning of the inspection. An inspector examines previous inspection reports to plan the inspection. The reports contain sketches, notes, photos, and maybe some calculations if an extensive investigation on defects has been performed. Inspection planning contains preparations on-site, staff and equipment planning, as well as traffic regulations. Inspectors record all defects with sketches, textual explanations, and photos on-site. Next, the condition rating follows. In special cases, additional calculations or simulations are necessary before the rating is performed. If a positive decision is reached for maintenance, the maintenance has to be planned and executed. At the end of the maintenance, all repair work must be approved by an engineer [43].

Inspection process

Literature about inspection and maintenance is exhausting. Hence, to limit the scope, this paper focuses on the inspection process, simulation, and condition rating. Table 1 lists the use cases characterized by the norms and guidelines of different countries.

Hearn has compared different national practices for bridge inspection [44], e.g., from the US, Denmark, Finland, Germany, and the UK. All nations in the report define multiple inspection types; simpler and superficial inspections are more frequent than in-depth inspections. Lastly, all collected data are stored digitally, however, differences exist in the time intervals, the process of data acquisition, and inspection intervals.

Inspection intervals range from less than twelve months up to 9 years for regular inspections. Next, the interval for inspection differs: some countries rely on visual inspection and others determine hands-on inspections, depending on inspection types. All countries mentioned above consider recording damage information using photos, audio, and other measurements.

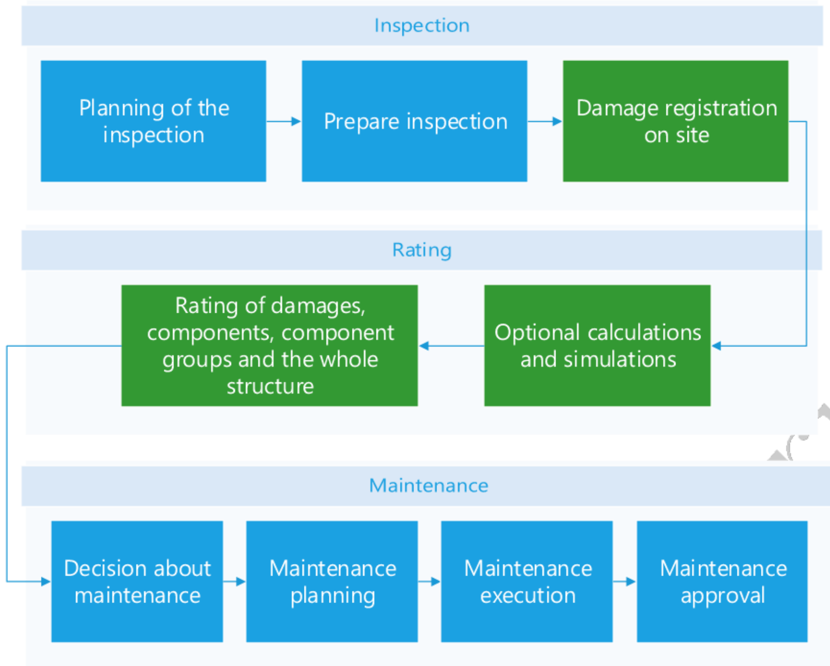

Figure 4: Overview about the processes for inspection, rating, and maintenance. This paper focuses on damage registration, simulation, and assessment (green boxes).

Some transportation agencies store summarized data about bridge components and the rating of these components, e.g., Denmark. Others register every damage and calculate condition ratings based on the collection of all damages, e.g. Norway, Germany, and South Africa [45]. A unique requirement of the Norwegian regulations is, for example, to rate the maintenance cost for every defect.

Rating process

The rating process and related tasks are in the focus of this paper because the evaluation of defects and their consequences is crucial to ensure proper performance of bridges. Table 2 summarizes the use cases in the context of the rating process. Hearn has compared inspection practices from multiple countries [44]. In general, there are two ways to define the condition state of a bridge. First, all defects are noted and rated. Based on these rating results, the rating of bridge components, component groups, and/or the entire bridge is calculated. For example, Finland, Norway, and Germany define their bridge rating in that sense. Contrary to this, other countries omit defect rating and, instead, rate bridge components, e.g., Sweden and Denmark. To rate defect severity objectively, Norway lists “150 types of deterioration and damage in bridge components” and their related condition rating [44]. Ten years after the report of Hearn, Germany has published its own catalog of defects and defect ratings [46]. Further, condition assessment can be based on relations between the maximum load of the damaged structure and the current load [47].

Simulations may help to determine the condition rating of bridges and, hence, are part of the assessment process.

Local defect	**Component**	**Component group**	**Bridge**
Record defect data	Record damage information, e.g. photos or measurements	Show overview of defects	Review on-site inspection
Recommend repair action	Take material samples		Save general data about the inspection
Independent visualization of the defect	Show defect at component		Show summary of defects
			Show condition state

Table 1: Use cases within the inspection process

At this point, some examples of simulations related to defects an structures follow. One point is the prediction of stochastic life time. Fagerlund investigated the impact of freeze-thaw processes on the service life time of concrete [48]. Šmodíkova et al. have taken into account the load bearing capacity of bridges [42]. A framework for inspection and forecast has been developed by Alsharqawi et al.[49].

Another goal of simulations are to calculate and infer damage propagation. Cracks occur as consequence of different reasons, e.g., as result of temperature differences within the concrete. Kwan et al. have analyzed the behavior of these cracks using the finite element method [50]. Additionally, the propagation of corrosion is within the scope of research. Xia et al. have published a numerical simulation model to predict corrosion propagation [51] and Ghauch et al. have used the finite element method to simulate moisture penetration in asphalt concrete [52]. These are only a few examples for damage propagation simulations out of numerous publications. Engineers can benefit from such simulations to objectively define and predict the condition state of bridges in the future.

Last, when a collapse could not be prevented, recorded defects are helpful to analyze the reason of the collapse. Lee et al. considered several defects, e.g., yielding and cracking to analyze a seismic-induced bridge collapse [53].

Maintenance process

After inspection and condition rating, the owner must decide whether restrictions are imposed, the bridge has to be repaired, or it needs to be closed and eventually be demolished or replaced. If the owner comes to the decision for repair, a decision about necessary repair actions has to follow. One repair action may affect multiple defects. One focus of the work within that area is the economical optimization of maintenance [54]. Additionally, there exists research, which simulates the repair results in a dynamic environment to test consequences of the realization of repair actions beforehand [55]. Table 3 contains some of the use cases regarding the maintenance process. There are further use cases in the field of maintenance. However, this paper focuses on inspection and condition rating of bridges.

Local defect	**Component**	**Component group**	**Bridge**
Simulate damage propagation	Simulate component behavior under load with defect(s)	Simulate component group behavior under load with defect(s)	Calculate load indices
Store defect condition state in different categories	Calculate/store condition state of the component	Calculate/store condition state of the component group	Calculate/store condition state of the bridge
			Forecast condition rating and service life time
			Post-collapse analysis

Table 2: Use cases within the rating process

Local damage	**Component**	**Component group**	**Bridge**
Process to repair the single defect	Overview of maintenance for the component (e.g. material, equipment and staff)	Overview of maintenance for the component group (e.g. material, equipment and staff)	Estimate maintenance cost
Estimate necessary staff, material and equipment needed to repair a single defect			Visualize repair process
Estimate cost to repair a single defect			

Table 3: Use cases within the maintenance process

5.2. Bridge management systems

Hurt and Schrock define Bridge Management Systems (BMS) as "[...] the activity of administrating resources to maintain operational bridges." [56]. Today, authorities are supported by software in this task and, hence, Bridge Management System has become a synonym for the software, which supports the task of bridge management, e.g., shown by Sung et al. [57]. In the present paper, BMS refers to the concept of storage and BMS software or application refers to the software.

Hearn mentions BMSs for many countries [44], all of which store the information in an abstract manner [58]. Many BMS lack 3D models of the structure and defects. Instead, the bridge and related defects are described with sketches, photos, explanations and parameters. For example, the German BMS predominantly stores photos, and textual descriptions of damages [59]. The United States store information in a similar way [45]. A report of the Federal Highway Administration regarding European inspection practices shows that "All countries visited practice standardization of inspection reports, forms, terms, and ratings." [60]. In Conclusion, the current practice of storing digital data in an abstract way in several countries is based on analog forms, which has been transferred into databases later. Database centered approaches lead to data dispersion and lack transparency [61, p. 704]. This data dispersion may avoided by using 3D BIM models.

BMSs are fundamental for developing future standards and software for the inspection-maintenance cycle. They offer information about bridges, bridge components, inspections, maintenance actions, and defects. A DIM has to include at least the information, which is stored nowadays within BMS. Further, it should support novel concepts for inspection, condition rating, and simulation with necessary data.

5.3. Damage properties data for a DIM

A Damage Information Model stores information about defects. However, in cases of inspections, condition ratings, and simulations, further data have to be included. The condition rating needs data of bridge components, component groups, and the entire bridge. Simulations, for example, Finite Element Analyses (FEA) for stress evaluation, need additional parameters about materials and loads. In this section, damage properties for the aforementioned use cases are derived. First, properties for a defect are listed. Properties for the bridge and its parts follow afterwards. Finally, data for processes follow.

Data for defect properties

Table 4 shows an overview of all properties for defects that are described in sources originating from state of practice guidelines or state of the art research papers. The data in the left column are created during inspections. The column in the middle shows data, which additionally are necessary for simulation purposes and the most right column contains data, which are related to the assessment. The current state of practice of inspections delivers images, tapping sounds, and text, which are directly related to a damage. Naturally, a defect afflicts a component, a component group, or the whole bridge. For damage propagation monitoring, a defect must be tracked over several

Inspection	Simulation	Condition Rating
Images/Video	Influences on material parameters	Damage condition rating in categories
2D geometry	Influences on component geometry	
3D geometry	Related damages	
Point cloud		
Mesh		
Audio recordings		
Text		
Damage Type		
Related inspections		
Linked components, component groups, and bridge		

Table 4: Local damage data

inspections. Hence, a defect has a relation to one or more inspections. Doycheva et al., for example, have used photogrammetry based on video data to detect potholes along streets [62]. Hence, an adequate DIM should be able to store a high amount of pictures through to videos in an adequate way. Beside this, laser scans are used for damage registration and detection [63]. Resulting point clouds, meshes from laser scans, and photogrammetry have to be part of a DIM as well. Additionally, non-destructive testing methods, e.g. with sonar for underwater inspections [64], ground penetrating radar [49], or ultrasonic pulse velocity [65] lead to a huge amount of measurements, which have to be included in a DIM.

Stolarska et al. have used FEA for crack propagation simulation [66]. Performing such simulation need at least a 2D damage geometry, respectively the influence of the defect on the geometry of the afflicted component. Future FEA may use 3D geometry data, as well. Material parameters, e.g. concrete thickness, water content, or cement type are relevant for simulations of defects, for instance, chloride migration [67]. Furthermore, deterioration models need relationships between defect entities. For more information, the reader is asked to refer to Section 4 and [37].

Lastly, a condition rating for the defect is necessary. Germany, as well as Norway, assess the severity of each single defect in multiple categories. Hence, damage condition rating should be supported by the DIM, too.

Data for bridge properties

Table 5 contains properties for components, component groups, and bridges. Aforementioned material parameters are important for damage propagation simulation. These material parameters are also important to run simulations on the component level. Further, if measurements are taken for a bridge component, e.g., thickness of coating, and these measurements do not indicate a defect, they still have to be stored. Hence, linking measurements to components is a necessity. Based on section 4, condition rating data for components, component groups, and the whole bridge are a minimum requirements. Load simulations or calculations are done in practice [44], for example, using FEA for load simulations. Deng et al. have used FEA to improve the bridge load rating of the United states

Component	Component group	Bridge
Material parameters	Rating	Rating
Measurement data		Traffic load data
Rating		

Table 5: Damage properties, which result from the use cases and are related to physical objects

Inspection	Condition Rating	Simulation
Date	Date	Date
Time	Time	Time
Inspectors	Responsible people	Simulation purpose
Bridge	Applied norm	Simulation type
Environment measurements (e.g. temperature, humidity, ...)	Comment	Simulation software
		Simulation results

Table 6: Parameters which are related to the inspection process

[68]. This method makes use of the traffic load data of bridges.

Data for process properties

Additionally, the processes of inspection, condition rating, and simulation have properties. Instead of being physical instances, they represent virtual objects. Table 6 shows the properties for these three processes. In short, properties about the date, time, responsible people and related bridges are necessary. Additionally, some environmental measurements are stored, e.g., temperature and humidity. Similar data is necessary for condition rating and simulations. The structure of simulation results are out of scope because of the exhausting number of simulation types and targets.

5.4. Analysis of inspection data from Thuringia in Germany

For an in depth analysis of data from practice, the Department of Construction and Transportation of Thuringia ("Thüringer Landesamt für Bau und Verkehr") supported this research with data from practice. All data have been extracted from the German BMS known as Road Information Database - Structure [1] [69] and reflects the state of October 2018. This data set includes 2,953 bridges and 25,610 defects.

For analyses, it is necessary to group all defects from data in categories. Based on the German damage catalog [46] the authors defined 22 damage types. Table 7 summarizes these damage types and their descriptions.

The first scope of the analysis is the frequency of defects categorized by their type. Figure 5 shows the result of the first analysis. The three most frequently occurring damage types are red. Results number four to ten are depicted in blue. *Cracks* have the highest frequency. Right after that come *divergence from specification/design*.

[1] German: "Straßeninformationsbank - Bauwerke" (short "SIB-Bauwerke")

#	Name	Description
1	Crack	Any visible crack at the surface, excluding cracks in coatings for wood or metal
2	Spalling	Spalling at the surface, excluding spalling at coatings for wood or metal
3	Joint damage	i.e. expansion joints or mortar joints
4	Loose, shear o, break, or cutting o of connection elements	e.g. cut of screws, broken rivets
5	Broken element	e.g. broken drainage
6	Material change without loss of substance	chemical changes in the material, e.g. namely corrosion, carbonation, alkali-silica reaction without loss of diameter or similar
7	Material change with loss of substance	chemical changes in the material, e.g. namely corrosion, carbonation, alkali-silica reaction with loss of diameter or similar
8	Moisture penetration, efflorescence, wash out	
9	Coarse grain/voids/foreign body encapsulation	several changes in the concrete
10	Divergence from specification/design	measured parameters, i.e. difference in height of a railing from specification
11	Missing of other parts	e.g, missing balustrade, traffic signs, etc.
12	Thickness of coating to thin or in bad quality the	meaning the coating of concrete over reinforcement
13	Waste, pollution and other foreign bodies	e.g. vegetation at the construction, bird excrement, pollution or waste
14	Degradation of the surrounding environment	e.g. scouring
15	Deformation	e.g. tilt, bulging, shifting of components
16	Change in position	e.g. settlement of the whole structure
17	Liquid leakage	e.g. leaking drainage
18	State and functionality of elements	e.g. fixed bearing, loose screw
19	Damaged coatings	e.g. spalling, cracks, bubbles at coatings for wood or metal
20	Other changes in surface	e.g. gloss loss, change in color
21	Divergence of material measurements or state	e.g. quality of concrete,
22	Other	Defects, which could not assigned to any other group, i.e. notch effect, damaged seal profile etc.

Table 7: Damage types for RC bridges, derived from the German damage catalog

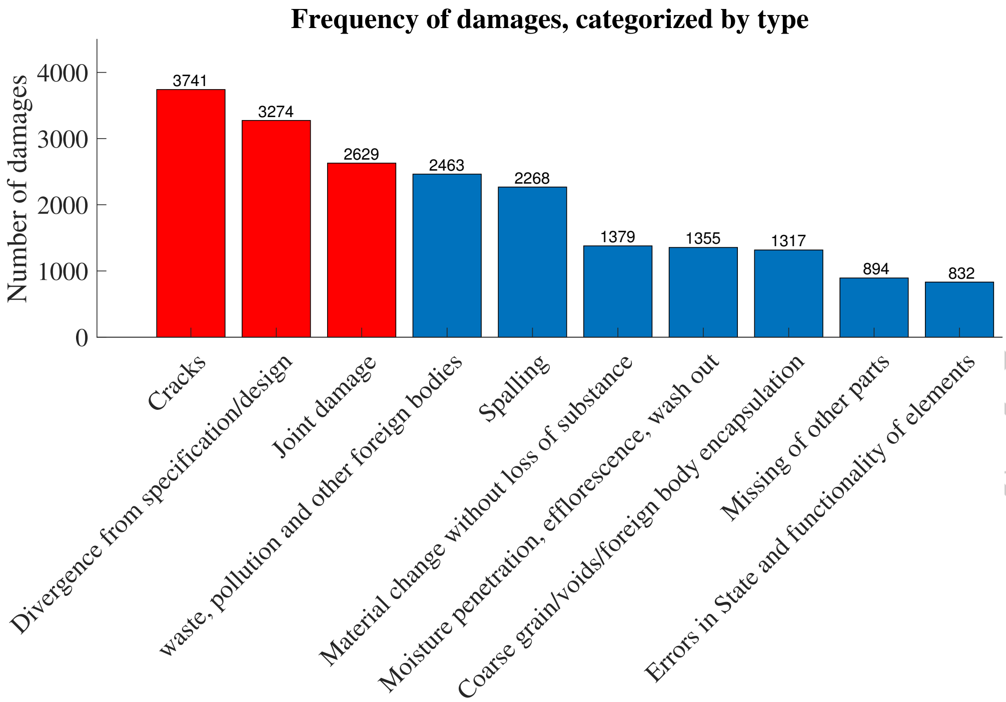

Figure 5: Amount of top ten damage types in Thuringia. Top three in red. (Best seen in color online)

Third are *joint damages*. On the tenth place are *errors in state or functionality*, for example, the functionality of bearings and bridge cables are limited. Those ten damage types are worth modeling because of their high frequency.

Furthermore, the influence of specific damage types to the final rating, respectively the severity, of a bridge is essential. To understand the data and provide transparency, the German algorithm for rating a bridge is outlined here and depicted in Figure 6. This algorithm has been developed by Haardt [70].

1. Every defects gets a rating in three categories: safety (S), traffic safety (V), and durability (D).
2. Taking these three partial ratings, the algorithm calculates a general defect rating Z for a damage. Special matrices define these calculations.
3. All defects are sorted by their component group and a rating for this component group is calculated by using the highest Z value.
4. Finally, the bridge rating is based on the highest rating over all component groups.

Figure 6 shows this process with the help of an example. Depending on the severity of a defect, the number of defects at a component group, the type of the component group, and the afflicted component groups a value of 0.1 can be added or subtracted in step 2, 3, and 4. Summarizing, the bridge rating is based on the worst defect rating $\mp$ 0.3.

Only defects, which have at least a Z-rating of 2, have been taken into account for the statistical analysis on severity. This approach was chosen because lower Z-ratings are not considered for repair actions in Germany. The sample for the statistical analysis consists of 14,557 registered defects. Moreover, this sample contains 2,355 bridges out of the overall amount of 2,953. Figure 7 shows the frequency of defect occurrences, which influences the final

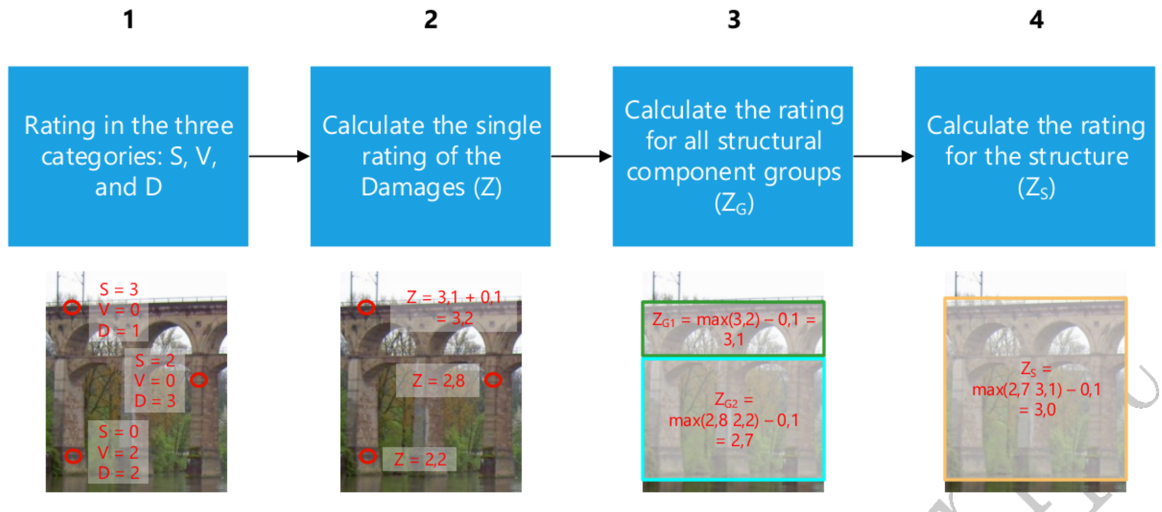

Figure 6: Bridge-assessment process in Germany: (1) rate each defect in safety (S), traffic safety (V), and durability (D). (2) calculate the single rating (Z) for each defect. (3) calculate the rating for the structural components. (4) calculate the rating for the structure. Bridge photo taken from `https://commons.wikimedia.org/wiki/Bridge#/media/File:Bietigheim-Bissingen_Viadukt_02.jpg`

rating of the afflicted bridge. Additionally, the figure shows how many defects have a Z-rating below 1.5 (blue), between 1.5 and 2 (green), between 2 and 2.5 (yellow), between 2.5 and 3 (orange), between 3 and 3.5 (red), and 3.5 and 4 (dark red). Cracks are, again, dominant within this comparison. *Divergences from specification/design* are far behind on the fifth place, in contrast to the second place, which they have in figure 5. However, the *thickness and dimensions of concrete coatings* appear in the top ten, as well as *material change with loss of substance*. For the other damage types the position within the top ten list differs.

Material change with loss of substance is an important group, because it has a high amount of ratings between 2.5-3 as well as a rating between 3-3.5. Figure 8 shows a more detailed view of defects with a rating worse than 2. A further investigation shows that 127 occurrences of *material changes with loss of substance* are the sole reason for the final rating. That are approximately 50 % of the cases where *material changes with loss of substance* occur. In case of cracks, only 18 % of the *cracks* are the sole reason for the final rating. This analysis leads to the fact, that material changes are crucial for damage modeling, because they have a high impact on the final rating in case they occur.

5.5. State of practice summary

Inspections, on the one hand, rely on manual and paper-based recordings. On the other hand, first attempts have been made to automate damage registration. A digital model for defects could improve the inspection and maintenance process, e.g., omit manual information transfers, enable computer-based querying and data analysis, improve data management, and boost automation of inspection and condition rating processes. A first improvement has been achieved by the usage of BMS and UAS. However, BMS can be raised to the next level by using 3D models, data from automatized inspections, and improved semantics, like, relationships, processes, responsibilities, materials or material changes.

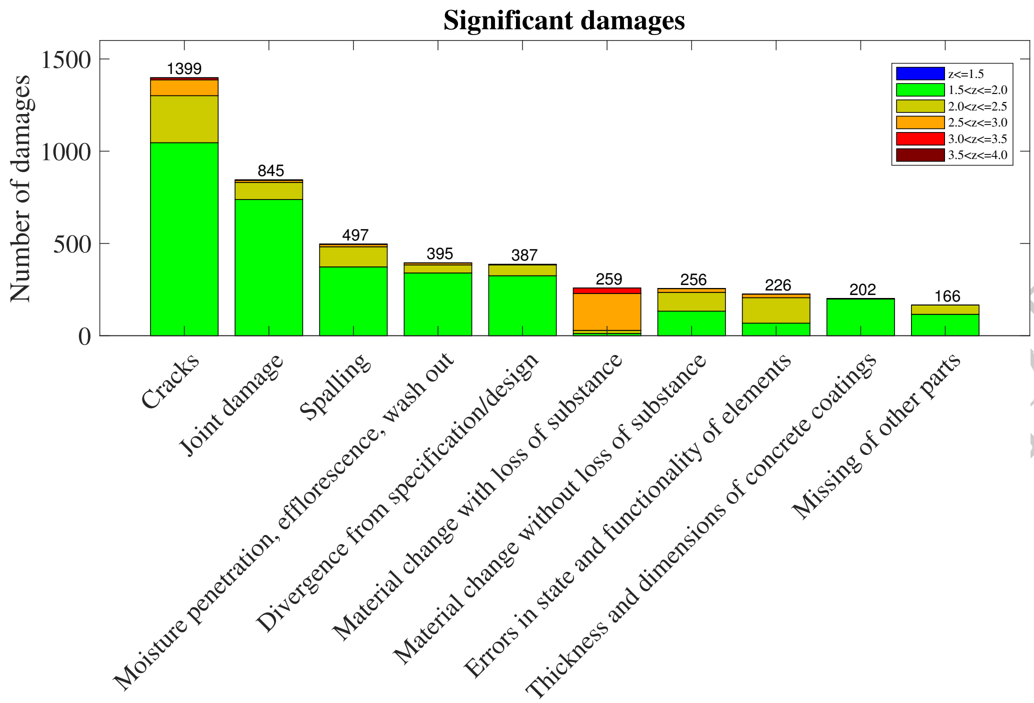

Figure 7: Amount of the top ten damages at bridges in Thuringia, Germany, considering the severity. The colors display the Z-rating between one and four. (Best seen in color online)

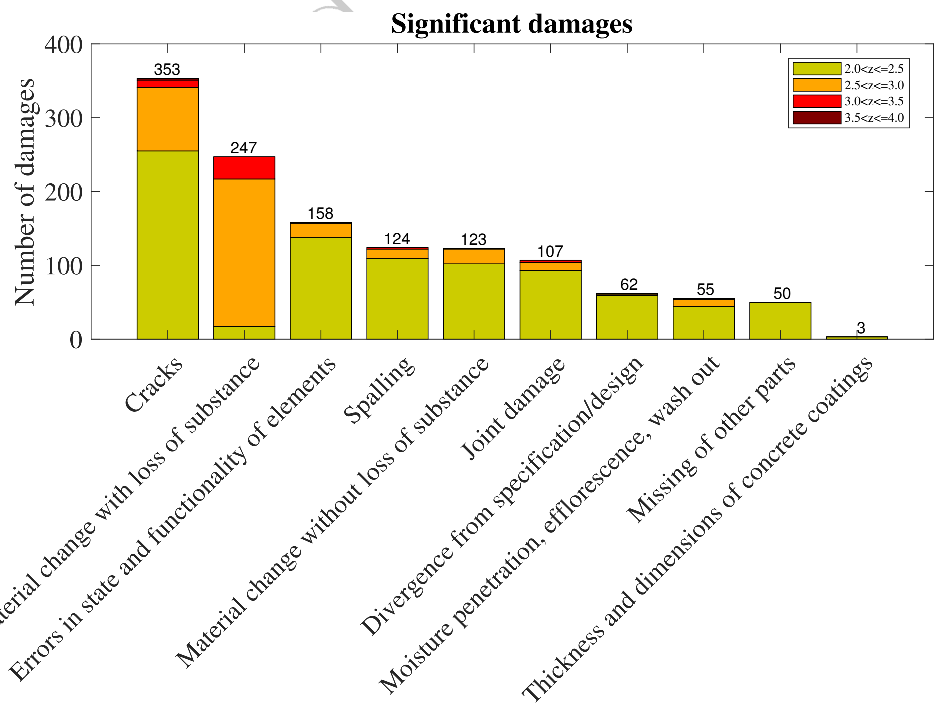

Figure 8: Significant damages with a rating > 2.0

Different nationalities have different damage assessment strategies, containing the damage types and properties, which are registered [71]. A future data model should be flexible enough to handle these different requirements. For statistical in-depth analyses, data from Thuringia has been used. Analyses about most frequent damages reveal the top ten damage types, which are important and significant for damage information modeling. Another analysis about damage severity leads to the 11$^{\text{th}}$and 12$^{\text{th}}$ type. The final 12 damage types for RC bridges, which are considered in this paper, are

1. Cracks
2. Divergence from specification/design
3. Joint damage
4. Waste, pollution, foreign, bodies
5. Spallings
6. Material change without loss of substance
7. Moisture penetration, efflorescence, wash out
8. Coarse grain/voids/foreign body encapsulation
9. Missing of other parts
10. Errors in state and functionality of elements
11. Material change with loss of substance
12. Thickness and dimensions of concrete coatings

This data may not represent world wide statistics, however, it can be used in addition to the qualitative data from Hüthwohl et al. [71]

6. State of research in damage information modeling

After the analyses on inspection practice, an investigation on scientific research follows. This section groups and discusses several papers, which are dealing with inspection, simulation, and condition rating.

6.1. Statistical information

Overall, 50 references have been analyzed; 33 articles are from journals and 13 articles are published in conference proceedings. Additionally, the review considered one book, one dissertation, one technical report, and one master thesis. Figure 9 shows a growing interest in the last 8 years. The present article is written in 2020, hence not all literature from 2020 has been published yet.

The articles from journals are spread over 17 journals. Most of the articles have been published in Automation in Construction and in the Journal of Computing in Civil Engineering as shown in Figure 10 left. Most of the conference papers have been presented at the International Conference on Computing in Civil and Building Engineering. All in all, the papers have been published throughout 7 different conferences.

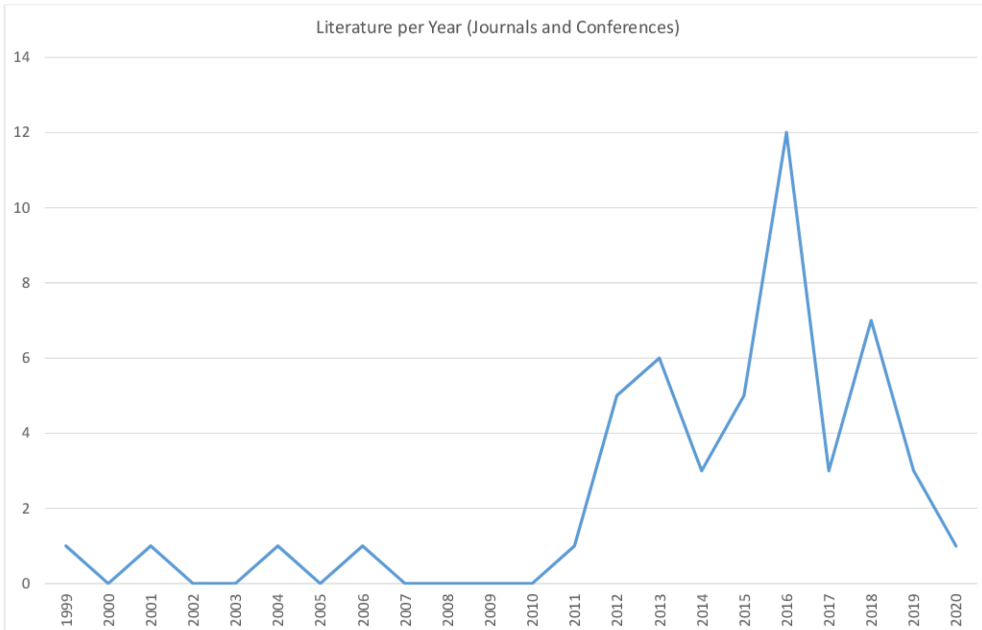

Figure 9: Year of publication of all literature

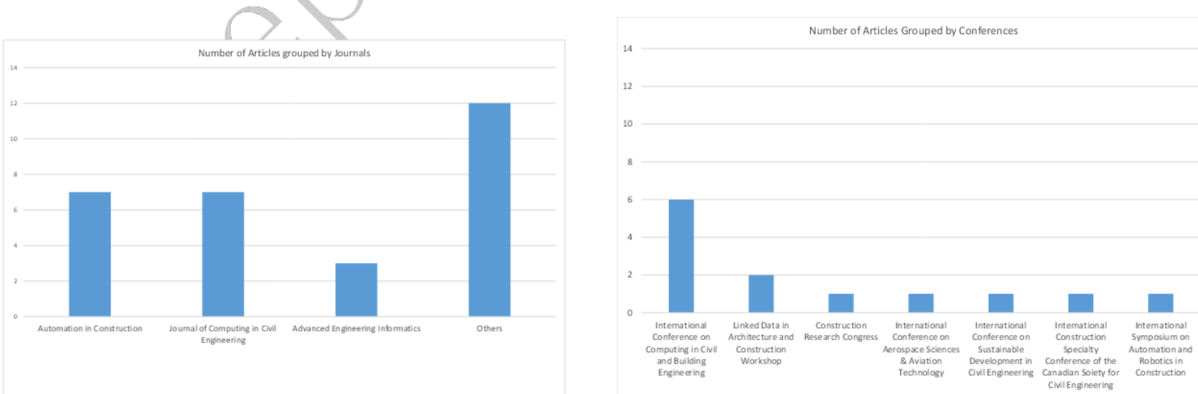

Figure 10: Articles grouped by journals (left) and conferences (right)

6.2. Scope of use cases and properties

This section analyzes the literature under consideration of use cases and damage properties. All publications are analyzed regarding the covered processes of inspection, simulation and condition rating and with a view to the covered damage properties.

6.2.1. Literature evaluation regarding properties of single defects

Inspection

The first task in the inspection process, is the data acquisition. Conventional data acquisition is performed by an engineer on-site. Currently, on-site inspection is paper-based. Inspection reports can be processed and interpreted automatically to lower time consumption [72]. Even if inspections in civil engineering will be fully automated in the future, reports will remain important for data exchange.

Instead of doing inspections paper-based, the process would benefit from digital data acquisition, e.g., using a tablet or smart phone. If multiple bridges shall be inspected on a route, the device can select automatically the bridge data for inspection [6]. Further, a digital inspection could be performed based on the drawings of the building [73]. An engineer can add annotations to the digital 2D plan and does not have to digitize the data later in the office. However, this approach lacks the third dimension. Hence, annotated damages need additional information about the third component of their position, which can lead to misunderstandings. Using some component IDs would make the localization of defects easier [74]. For improved localization, a defect is linked directly to the afflicted bridge components and the defect position is defined in 3D space [75, 76]. Last point to support current inspection practice is to store photos, which are related to the defect [77, 78].

A complete automation of damage registration is a further improvements. Photos are a common basis in practice for damage registration and will remain important for future damage recording. Hence, it is necessary to respect such photos in the information model. One way to include photos in the damage information model would be to relate the photos to the bridge component [79]. Another possibility is to relate photos to the defect itself [77, 80]. During manual inspection, only photos of defects are acquired. Automated inspections, which are performed by drones, take photos of the entire structure for further processing. Hence, numerous photos are related to bridge components and not to a defect. On the one side, those photos could be deleted for saving memory. On the other side, for documentation and transparency, it can be worth to keep those photos. All work considered have related the photos either to a bridge component or to a damage. If a DIM shall support current and future inspection practices, photos should be related to both, bridge components and defects because photos taken by drones do not necessarily indicate defects. This circumstance has not been taken into account by any research until now.

A similar problem comes into account with point clouds. Point clouds are the input for damage registration algorithms. The question arises how to store point clouds and how to store the relationship between the detected defects and point cloud areas. One possibility is to manually annotate defects using an overlay of a point cloud and a BIM model [81]. Beneficial for this process is to highlight differences directly in the point cloud using colors [82]. Independent from the method of generating the information about defects, a point cloud or a section of a point cloud can be part of future damage information. The question, how to integrate point clouds and involved relationships into damage information models, has not been answered until now.

Zeibak-Shini et al. [83] have proposed a method to generate BIM models of earthquake-damaged buildings from laser scans. Point clouds from laser scans are analyzed and matched with the BIM model. Further investigations have improved the mapping of damaged components and the related components from the as-built BIM model [84]. This research shows also the difference between defects from deterioration and disasters. Disasters lead to extensive damages, e.g., completely broken elements up to the complete breakdown of the structure, which further leads to problems in mapping components from the collapse place to the original building components. In case of deterioration, a mapping of remaining components to the BIM model is unnecessary.

Dependent on the damage type and the country, where the bridge is located, it is necessary to store different damage properties. A photo or texture is an important visual property for inspections and assessments in numerous countries [71]. Defects can be characterized by attributes, a process, i.e., inspection or maintenance, and a cause, as well [85]. Comparing these works with identified damage properties from table 4, reveals the absence of defect geometries and the absence of influences on the material parameters, which are necessary for material changes, for example, carbonation or alkali-silica reaction. Even more generic approaches lack consideration of influences on material parameters [86].

Damage information is important for different use cases, as shown in Section 5.1. Hence, an information model benefits from multiple levels of modeling. Three levels can be defined: building elements, damage areas, and individual defects [87, 86]. Storing information about every level separately is one possibility. Another concept is to deduce abstract information from more detailed information, which leads to less memory consumption but needs algorithms to infer abstract information from detailed information. Storing information separately for every level, needs additional memory and less computation, respectively fewer algorithms.

Further, a damage model can be defined as part of the building model [71] or the damage data are defined in an external model with links to the building model [88, 89], known as linked data models. On the one hand, storing damage information together with the building model has the advantage that all data is together and a single file has to be transferred. Additionally, by using existing standards, e.g., IFC, already developed software can be used for visualization and editing. On the other hand, existing standards and files could be inflated by this information.

A different concept of storing information is the use of linked data models. Linked data models separate information in multiple models and define interfaces, for example, an ID, to connect the individual entities from the different models. Semantic web and ontology are terms related to linked data models. The semantic web approach makes usage of the Web Ontology Language (OWL) from the W3C [90]. In general, ontology in the internet means a concept to model semantic relationships between information entities [91]. Two or more entities have a named relationship, for instance, a defect has a defect cause. These relationships can be defined for every use. The concept of ontology does not define relationships and properties for specific domains. Specialists, such as, civil engineers, have to define these necessary relationships and properties. Because of the high flexibility, multiple researchers have used linked data models and ontologies to handle data of inspection, simulation, and assessment [88, 72, 92]. Some ontology models mainly consider meta information, such as, causes, impacts, and related processes [89, 92].

In case of disasters, broken elements have to be modeled. This can happen through deterioration, as well. Extensions of the IFC offer the possibility to model components, which have been broken down into multiple parts [93]. During an earthquake, interior components of a building are afflicted. For search and rescue purposes Bloch et al. have developed a simulation, which calculates the building geometry after an earthquake. Resulting outputs can be used to estimate the interior constitution after a real earthquake [94], i.e., this methodology helps to calculate invisible parts of defects. Invisible parts of defects occur also at bridges, like, carbonation or chloride migration. However, this work does not show a way to structure the information for such invisible damages. Additionally, less severe defects arise from earthquakes. Torok et al. have developed an inspection system to acquire photos on-site, reconstruct the mesh of the building, and detect cracks [9]. Relationships between damage information and point clouds can be stored as state of a single point, for example, a point is damaged or part of a specified defect. A similar approach has been proposed for landslides [95]. These models lack semantic information, such as relationships between damages and a distinction between component geometry and defect geometry.

Multiple instance of the same damage type are grouped in practice, for example multiple cracks of a crack map. However, structural analyses would benefit from recording every single damage, as shown by Anil et al [96]. Hence, the structure suggested by Anil et al. allows both ways of storing damage information., storing single defects and summarize them.

Special bridge inspections, for example, by radar or ultrasonic, deliver additional data for bridge inspection [97]. Most of this data is handled as photos, besides point clouds [98]. This is suitable for human interpretation. Another representation, such as, a matrix with real numbers, may be a better basis for automated analysis.

In conclusion, achievements are the collection, storage and processing of photos. However, a structure of storing photos, point clouds, measurements, and relationships is missing. Approaches to detect and register defect geometries, have been researched. Still, the manner to store geometries, for example, as extrusions, boundary representation, independent from building components, or as part of the components remains vague. Additional data, such as, videos, data from sonar, radar or ultrasonic, are stored as images until now. Other methods, for instance, storing sonar responses as matrices, may promote automated analyses of such data and allow to relate single measurements to an explicit point in the BIM model. A last question is: should the DIM be part of the BIM, i.e., extending the IFC, or should it be independent from the building information, which means to realize it with linked data approaches.

Simulation

Simulations process defect information, which have been recorded through out the inspection, for the later assessment. As shown in section 4, there are multiple fields of simulation, like, deterioration and structural analysis. Integrating damage information into the model types is discussed in this section.

Much work deals with damage propagation, for example, the prediction of crack growth [40]. Numerous research exists in this field by using FE methods [66] or probabilistic methods [99]. A definition for data exchange between inspection data and FE methods remains uncertain. A similar issue exists for material changes. Several research deals with probabilistic approaches [100], with thermodynamics [101], or with FE methods [102]. Besides all this research, missing is the integration of inspection data into the simulation.

FE methods are also used for bridge assessment. Current practice is to transfer data manually from inspection to simulation environments, like it is conducted by Anil et al [96]. They have defined their own data structure to consider defects within FE analyses. This data model respects mainly crack paths and patterns, which is sufficient for earthquake defects and for some deterioration simulations.

Another approach to support FE analyses for structural bridge analysis is to hand over cross sections and defect positions to analysis software [103], which leads to adjusted element properties. This method is usable to address material changes, as well. However, adjusting every volumetric element in a BIM or DIM model would lead to a immense growth of data and would mix damage and building information. Another possibility is the utilization of bounding boxes of the defect instead of the detailed geometry. Hence, the load bearing cross section is changed [104]. Additionally, discrete [105] and smeared FE models [106] exist for cracks. Other FE analyses on corroded rebar are based on detailed damage geometries [107]. Despite all achievements in this sector, automation in data transfer is less investigated.

On the one side exists much work regarding damage registration, data acquisition and simulation. on the other side, numerous research lacks data transformation from acquisition to simulation. The question, how to retrieve simulation properties from the damage information, remains unanswered. Currently, engineers are responsible for transferring damage data from the building model to the simulation. This gap can be bridged by a DIM.

Condition rating

Based on national standards, engineers decide about the final condition rating, see section 5.1. Simple texts come in handy to support decision making for maintenance [108]. However, text blocks lacks visualization. The next level is to provide photos and additional data for the condition assessment and link them with components of a BIM [109, 61], i.e., extending a BMS with a 3D building model. Definitions of necessary relationships for condition ratings remain uncertain. As illustrated in Section 5.1, some nations rate defects and others rate components or component groups. Therefore, multiple relationships and levels of condition assessment are necessary. However, none of the considered literature has taken this problem into account. Either, condition rating is related to a bridge element [110], or to the single damage [111]. Furthermore, damage reasons are important, for example, a crack in concrete is a result of normal loads or a result of reinforcement corrosion, which influences the condition rating. This has been considered by Hamdan, et al. [86, 88]. Similar relationships have been respected for construction supervision [89, 92].

Load factors as basis for condition assessment have to be considered in the whole DIM [47]. These load factors result from bridge properties and defects. None of the work included in this review, has considered these relationships. Maintenance actions and cost would be another source for condition rating and decision making. From past maintenance actions and related cost, future cost for the same structure or damage types may estimated [112].

Borrmann et al. have published a framework for life cycle management of bridges [113]. They have defined a framework with modules for data acquisition, damage prognosis and estimations for repair times and have shown the benefit of data exchange between all of these steps. A similar approach based on ontologies [114] shows how condition rating can be automated. Ren et al. hand over to administrators the decision about necessary parameter.

Summary

Table 8 shows an overview over all examined literature. Researchers focused heavily on acquiring and digitizing inspection data. The aim is to visualize all data for the engineer for condition rating and provide novel algorithms and concepts to access this data. Although there are many ways of simulating damage propagation, traffic load, and deterioration to estimate future condition rating and necessary maintenance, the data transfer between inspection and simulation and between simulation and condition rating has to be done manually to the present day. Due to the growth of data, the necessity grows to automatize data transfer.

Local damage	**Inspection**	**Simulation**	**Condition Rating**
Text	[47, 115, 74, 75, 85, 108, 109, 80, 72, 86]		[47, 115, 89, 116, 109]
Images/Video	[113, 73, 89, 116, 74, 61, 57, 117, 109, 79, 86, 71, 118]		[113, 109]
Audio recordings	[74]		
2D-damage geometry	[73, 81, 96, 86]	[96]	[96]
3D damage geometry	[83, 9, 93, 81, 94, 119, 103, 43, 120, 121, 76, 71, 118, 86]	[103, 104]	[122, 110, 103, 43, 87, 118]
Point cloud	[83, 9, 119, 84, 123, 80]		
Mesh	[9, 95]		[109]
Measurements	[124, 35, 61, 120, 121, 71, 118, 109, 86]		[113, 35, 61, 118]
Other damage data	[97, 98]		
Damage type	[6, 113, 35, 103, 43, 71, 78, 118]		[6, 113, 35, 103, 43, 71, 118]
Rating(s)			[111, 35, 61, 57, 71]
Related inspections	[35, 77, 80]		[35]
Influence on material parameters	[109]	[103]	[109]
Influence on component geometry	[119]	[103, 104]	
Related damages	[35, 92, 85, 71]		[35]
Linked component(s)	[113, 47, 83, 115, 122, 75, 112, 110, 93, 96, 94, 61, 92, 119, 103, 43, 57, 77, 84, 117, 71, 118, 78]		[122, 112, 96, 61, 103]
Other semantics	[74, 92, 23]		

Table 8: Literature for damage properties

6.2.2. Literature evaluation regarding rroperties of components

Building data is covered by the BIM methodology. Material parameters and measurement data can be stored as object parameters [12] within a building information model. Further, the building smart Data Dictionary (bsDD) defines property sets for condition rating [71]. This sector has gotten much attention until now because its tight relation to the design and construction phase.

Component	Literature
Material parameters	[12]
Measurement data	[12]
Rating	[71]

Table 9: Literature related to additional Component parameters

6.2.3. Literature evaluation regarding properties of component groups and the entire bridge

In general, the rating of bridge components and the whole bridge are part of existing BMSs. Simulations of the dynamic behavior need load data for calculations. As seen in table 10, mostly BMS's offer the possibility to attach a rating to a bridge. Detailed information about BMSs can be found in Section 5.2. OBrien et al. have worked on different distributions to predict the traffic load on a bridge [41]. This approach shows that few parameters for a distribution are necessary to represent the load data for simulations.

Component group	Literature	Bridge	Literature
Rating	[125, 57]	Rating	[125, 57]
Load data for simulation	[41]	Load data for simulation	[41]

Table 10: Damage properties, which result from the use cases and relate to physical objects

6.3. Scope of damage categories

Numerous research in damage detection deals with cracks or spalling [126] and less investigation in other damages like corrosion, carbonation, and alcali-silica reaction is performed. [127]. Sacks et al have addressed corrosion, efflorescence, scaling and abrasion, as well and have developed an information model, which respect these damages [118].

Different defects may have different properties. Because of that, analyzing the literature with the focus on the damage types, is important. Sacks et al. have proposed SeeBridge in 2018. SeeBridge describes an overall system for bridge information modeling with inspection data [43, 118]. A detailed model for damage data is not explained within the paper.

Torok et al. have focused on defects caused by earthquakes. Defects after earthquakes are most frequently cracks and spalling [9]. Also McGuire et al. have focused on cracks, delamination and spalling [103].

Material changes have been considered by Kubota et al. [35]. The paper shows some of the identified damage categories from chapter 5.4. Ma et al. have shown how to model broken elements [93]. In the scope of deterioration, broken elements are seldom. A similar damage mode is covered by Bloch et al. [94]. They have modeled a collapsed

Damage type	Literature
Cracks	[9, 103]
Divergences from specification/Design	
Joint damages	
waste, pollution and other foreign bodies	
Spalling	[9, 103]
Material change without loss of substance	[35]
Moisture penetration, efflorescence, wash out	
Coarse grain/voids/foreign body encapsulation	
Missing of other parts	
State and functionality of elements	
Material change with loss of substance	
Divergence of material measurements or state	
Lower rated damages	[93, 94, 119]
Damages in general	[43, 118]

Table 11: State of the art, with a view on the modeled damages

building for search and rescue operations. However, complete collapses are not favored in the field of inspection and maintenance. Finally, Ling Ma et al. have modeled buildings, which are damaged by earthquakes, these buildings have, for example burst outs [119].

Table 11 shows the damage types covered by literature considered. The damage types on the left side are the most important types from chapter 5.4. The table shows much investigation have been done regarding cracks and spalling. The main reason for this is that cracks and spalling are in the scope of automated damage detection, as well. Defects, which are under the surface, like material changes, have gain less attention.

7. Research gaps and discussion

In conclusion, there are few investigations within the sector of damage information modeling. For a comprehensive damage information model a structure for all related data is necessary. The examination of the different use cases shows that the 3D model is central for the DIM for visualization and defect localization. The first question to be answered would be, which geometry modeling method should be taken. Possibilities are cuboid bounding boxes, extrusions or Boundary Representations (BREP). Problematic is the visualization of material changes because these are under the surface. These questions have not been addressed by research so far.

A small sample of the sector simulation has been presented to explain general concepts and requirements. Less investigation has been done related to a concept of data exchange between inspection and simulation as well as data exchange between simulation and assessment. Condition rating benefits from such data integration in that manner that the automation of the process of assessment can be improved.

Depending on the damage type, different properties are necessary for the rating, for example, freeze-thaw defects require the chloride and water containment or the assessment of cracks requires their orientation. Semantic information on defects supports the assessment, e.g., connecting cracks with a corresponding corrosion, having a registered defect propagation over time or the related deterioration phase. Those questions have not been addressed by the current research.

Material changes relate to material parameters of components. This information is necessary to simulate damage propagation and component stresses. The problem with simulation input parameters is that the parameters differ very much, depending on scope and type of the model. The question, how to model these material changes adequately in a damage information model, is another gap in knowledge.

Two options for the model design have been illustrated. One way is to integrate damage information directly into the BIM model, which leads to fewer data sources. However, current standards, such as, IFC, are very complex and a further extension adds further complexity. The other way is to store damage data in another model with information about related structure(s) and components. Such definition would be independent from existing standards and prevent their bloating. Disadvantageous is that splitting building model data and damage data can lead to data dispersion.

The literature review shows a growing interest in damage information modeling. Multiple papers have been published in the last years, which deal, for example, with automated damage recognition and bridge assessment. However, modeling the damage data is only a byproduct of most current research. Some research has focused on the geometry of damages for simulation as well as search and rescue. Another group focuses on supporting inspections of bridges via inspection automation. That leads to the current patchwork rug of several approaches and scopes in the field of DIM.

The different use cases, need different views and properties of bridges, their state, and defects. Within that context, data and relationships need to be addressed to cover the requirements of inspection, visualization, assessment, simulation, repair, and maintenance. Future investigation will address the concept of a comprehensive DIM.

8. Summary

This paper has presented a review of the state of research and state of practice of damage information modeling. Examining standards and guide lines for bridge inspection, lead to the resulting damage categories and several use cases for a DIM. Statistical analyses have been performed with the data from the Department of Construction and Transportation of Thuringia in Germany. These analyses have shown 12 important damage types for a DIM. Based on this information, all literature has been grouped by use cases and damage types. The review has resulted in several gaps in knowledge. Most often, investigations on single damage types or use cases have been conducted, without respecting data transfer between workflows. In addition, the review has revealed a huge focus on cracks and spalling. Other damage types have gotten less attention in the current research. Finally, the paper comes to the conclusion, that a comprehensive damage information model would be the next step in the development of BIM, in particular, as-damaged BIM.

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