School of Design and the Built Environment

Industry Foundation Classes (IFC)-based Method for Bridge Defect Information Representation and Analysis

Shuyuan Xu

This thesis is presented for the Degree of
Doctor of Philosophy
of
Curtin University

November 2021

Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Human Ethics. The research presented and reported in this thesis was conducted in accordance with the National Health and Medical Research Council National Statement on Ethical Conduct in Human Research (2007) – updated March 2014. The proposed research study received human research ethics approval from the Curtin University Human Research Ethics Committee (EC00262), Approval Number HRE2019-0673.

Signature:

Date: 2021.9.14

(left blank)

Acknowledgements

This project would not have been possible without the help of many people. I would like to express my gratitude to my main supervisor Professor Xiangyu Wang, who encouraged me to pursue my academic aspirations at the very beginning. In addition, he gave me opportunities to work with the best in both academia and industry, supported me financially, and trusted me all along the way. I would also extend my appreciation to my co-supervisor Dr. Jun Li, who gave me constructive advice especially in the development of the third objective. A great thank you goes to my associate supervisor Dr. Jun Wang, for his patient guidance, encouragement, and diligent efforts on the improvements of my academic papers. His solid knowledge in construction management provided me with insights on many scientific methods used in this project.

A great thank you goes to my Thesis Chairperson Professor Peng Wu, for his support and confidence in me and my work to introduce me to the Main Roads Western Australia (MRWA) for collaboration. I have also been extremely fortunate to work with a group of extraordinary colleagues in the Curtin BIM research centre: Professor Changzhi Wu, Dr. Wenchi Shou, Dr. Yongze Song, and Dr. Junxiang Zhu. Special thanks also to visiting scholars here: Professor Ioannis Brilakis, Professor Ian Smith, Dr. Marco Proverbio, and Professor Chimay J. Anumba, who have kindly offered invaluable insights on my research during their stay in Curtin. I am indebted to my colleagues and friends in the School of Design and the Built Environment, Curtin University, for their support, encouragement, and assistance.

This project reflects collaborations with industrial partners as well. I would like to thank Professor Keith Hampson, Ms. Lindsay Kyle, and Ms. Debbie Thackray at SBEnrc for providing me access to their projects throughout my research that contribute to this thesis. I would also thank Mr. Graham Jacob and Mr. Kamal Weeratunga at MRWA, for hosting me as an intern and trusting me throughout our collaboration. Special thanks go to Mr.Qindong Li, Mr. Tom Mchugh, Mr. Ammar Mohammed at MRWA, for ongoing encouragement, support, and trust during our collaboration. A special thank you to Sichuan Daotongda Engineering Co., Ltd, for providing me with the access to bridge inspection data used in this research and hosting me for focus groups study.

I would like to acknowledge financial support and recognition of my work by the Australian Research Council Linkage Program (Grant number LP170100341) and the Australian Research Council Discovery Project (Grant number DP170104613).

Finally, I would like to express my deepest gratitude to my family, for their love and support all along the way, and I dedicate this thesis to them all.

(left blank)

Abstract

Bridges constitute a critical part in modern infrastructure network. However, an increasing number of bridges have been displaying ageing issues in recent years. Road agencies and governmental authorities are responsible for ensuring the serviceability and reliability of their bridges. They conduct programmed inspections according to national or local manuals, evaluate their condition, and apply maintenance strategies to sustain their serviceability. Unlike structural health monitoring (SHM) technology, defect identification in bridge inspections generally relies on on-site visual examination and non-destructive testing. Experienced engineers determine the condition levels based on the detected defects and deterioration and in accordance with the specifications/manuals.

In the past decades, building information modelling (BIM) has been promoted to achieve the lifecycle management of civil assets. This is considering its capability to integrate information regarding the design, construction, operation, and maintenance phases. As an open, international, and vendor-neutral standard, Industry Foundation Classes (IFC) can digitally describe the built environment. IFC schemas have been used extensively, enriched, and extended to allow for the inclusive modelling of all types of information in civil projects. In this research, inspection-related information and analysis results are modelled and integrated into bridge BIM for more efficient management.

Among all types of bridge inspections, visual inspection is the most common approach applied by inspectors and/or engineers to obtain information regarding bridge conditions. However, the current practices and their integration into BIM involve three challenges: (1) On-site defect identification and defect information collection are time-consuming and laborious for experienced inspectors and engineers. In addition, standardisation of defects and their properties for data collection is required. (2) The current documentation of on-site inspection outcomes is not completely integrated into BIM platforms. This hinders seamless retrieval, exchange, and analysis of inspection-related information. (3) Analysis of defect information in the context of condition evaluation has not been embedded into the BIM environment. In addition, in the structural analysis domain, an efficient approach to evaluating detected defects is unavailable.

Accordingly, this thesis develops an IFC-based method for bridge defect information representation and analysis, including four subsequent parts. First, a defect model for concrete bridges is developed using mixed methods. It is aimed at supporting on-site defect identification. In the defect model, common defects of concrete highway bridges are categorised, defect relationships are mapped, and critical properties are listed to facilitate preliminary cause diagnosis. Second, an IFC-based method for defect representation in integrated bridge BIM is proposed. Here, defect geometry is modelled with a set of parameters, and an inclusive description of defect relationships is included. Third, the element-level condition assessment (as regulated in the European manual) is computerised and tested on the integrated bridge BIM. Finally, the defective bridge BIM in the second part is converted into a defect analysis model. Herein, a matrix-based bridge analytical model is first generated from the architectural model and then, the impacts of defects are quantified.

According to the case study results, the integrated bridge BIM (i.e., the case study in the second part) allows for model exchange between different vendors without information loss or misinterpretation. It also supports information retrieval and preliminary analysis tasks with efficiency and accuracy. In addition to the integrated BIM, case studies in the final two parts present reliable results of both condition evaluation and structural analysis. This demonstrates that the proposed IFC-based method for defect representation and analysis is a potential approach for supporting bridge managers with bridge inspections and subsequent maintenance decision-making. This research facilitates the automation of bridge inspection practices in terms of on-site condition data collection, defect information documentation, and analysis. Furthermore, the entire bridge inspection scheme can be completed within an interactive, efficient, and informative BIM environment. This would enable highly integrated lifecycle management of civil assets.

Contents

List of Figures

List of Tables

1 Background and motivation

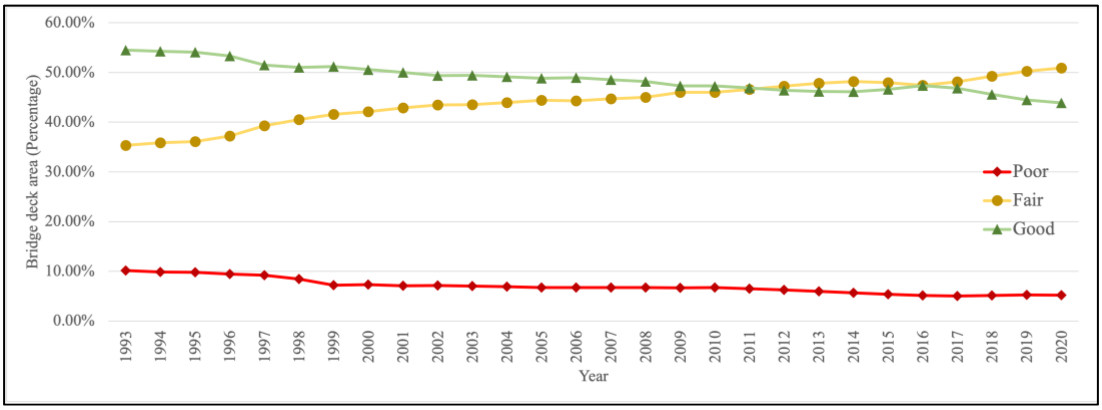
1.1 Chapter introduction

This chapter begins with an introduction to the overall background of this research, i.e., bridge management during the operation and maintenance (O&M) phases of the lifecycle. The review of the state of practice of bridge inspections clarifies the research problem, and the objectives of this research are proposed accordingly. Finally, the thesis structure is presented.

1.2 Background

Bridges constitute a critical part of contemporary infrastructure network. These enhance the capability to travel across various barriers such as intersecting roads, rivers, and valleys, and enables individuals to move from one region to another over shorter distances and with higher speeds. At present, an increasing number of bridges are displaying ageing problems, which adversely affect their safety and serviceability to a large extent. According to the National Bridge Inventory (NBI) data published by US Federal Highway Administration (FHWA) (see Figure 1.1), over the past three decades, there has been a dramatic and continuous increase in the total number of bridges, and the proportion of bridges in the ‘Fair’ condition has been increasing (Federal Highway Administration).

(a) Bridge count according to historical performance



(b) Bridge deck area (by percentage) according to historical performance

Figure 1.1 Bridge inventory data (Adapted from NBI published by US FWHA)

This phenomenon has been attracting increasing attention of road agencies and authorities worldwide and thereby, compelling them to develop management plans to efficiently maintain those important civil assets. To fulfil their responsibility, road agencies adopt a wide range of monitoring approaches to remain updated on the condition of bridge structures. The most prevalent approaches are programmed inspections and the use of structural health monitoring (SHM) systems. The former requires personnel to tour on bridge sites, manually assess entire bridge structures, and identify existing and potential defects. In addition to visual examination, supplementary non-destructive methods such as impact-echo testing, rebound, ultrasonic testing, and infrared thermography are required in certain cases. Furthermore, additional procedures such as underwater inspection can be conducted for complete examinations of structures (U.S. Department of Transportation 2012). The identified defects/deteriorations would be evaluated further by experienced engineers. Maintenance decisions can then be generated based on those diagnosis and assessment. The latter employs contact or non-contact sensors and installs these at strategic locations on the structures (Goyal et al. 2016; Tan et al. 2020). A wide range of responses can be monitored using those sensors: from strain, stress, and surface defects to dynamic characteristics. Structural analysis can be conducted based on those data to assess the safety and reliability of the structures. A combination of multiple monitoring approaches is generally used in actual projects. Meanwhile, in this research, the focus was on the inspection approach. Figure 1.2 presents photographs of on-site inspections.

Figure 1.2 Photographs of on-site inspections

Government and road authorities worldwide have published manuals for bridge inspection activities. These state the different levels of inspection that would be carried out throughout the lifecycle of constructed bridges. Table 1.1 lists a few inspection manuals with their country, administrative level, and corresponding publishing agency. Those inspection manuals were collected either using the Google search engine or from their official archived website. Keywords such as ‘bridge inspection’ and ‘structure inspection’ were used for the search. The documents were selected based mainly on their language (i.e., English and Chinese) and the scale of the country. The former basis was selected considering the limitations of the author’s language skills, whereas the latter was selected to ensure that the manual is based on sufficient practical experience.

Table 1.1 Inspection manuals exemplified in this research

Country	Administrative level	Agency/Publisher	Manuals
U.S.	National/ Federal	U.S. Department of Transportation (2012); American Association of State Highway and Transportation Officials (2018, 2019)	*Bridge Inspector's Reference Manual* *The Manual for Bridge Evaluation* *Manual for Bridge Element Inspection*
	State/ Provincial	New York state Department of Transportation (2017)	*Bridge inspection manual*
		Minnesota Department of Transportation (2019)	*Bridge and structure inspection program manual*
		Michigan transportation asset management council (2011)	*Asset management guide for local agency bridges in Michigan*
		Washington state Department of Transportation (2019)	*Washington state bridge inspection manual*
		Texas Department of Transportation (2018)	*Bridge inspection manual*
Canada	State/ Provincial	Alberta infrastructure and transportation (2008)	*Bridge inspection & maintenance system - inspection manual*
		Ontario and five other provinces, Ontario Ministry of Transportation (2008)	*Ontario Structure Inspection Manual*
UK	National/ Federal	Highways England (2017)	*Inspection of Highways Structures*
Germany	National/ Federal	Federal Ministry of Transport, Building, and Housing	*Bundesministerium für Verkehr, Bau und Wohnungswesen (BMVBW)*
Australia	State/ Provincial	Main Roads Western Australia (MRWA 2012, 2013, 2017)	*Inspection Guidelines (Level 1, 2, and 3)*
		NSW, RTA (2007)	*Bridge Inspection Procedure Manual*
		Department of Transport and Main Roads, State of Queensland (2016)	*Structures Inspection Manual*
		VicRoads (2018)	*Road structures inspection manual: Part 1 & 2*
New Zealand	National/ Federal	New Zealand Transport Agency (NZTA) (2001)	*Bridge inspection and maintenance manual*
China	National/ Federal	Ministry of Transport of the People's Republic of China (2015)	*Technical code for test and evaluation of city bridges*

Most of the aforementioned countries have stipulated bridge inspections as mandatory activities for their infrastructure assets, although a few of these (e.g., Germany) regulates only federal-level bridges. According to those documents, bridge inspections should be planned and carried out at a programmed frequency. Bridge inspections can be categorised into several types. Table 1.2 summarises the different types of inspections stipulated in different countries. Although a few states/countries have an equal number of inspection levels, these are listed separately because different specifications, frequencies, and requirements (e.g., personnel) are stipulated. It is noteworthy that notwithstanding the varied categorisation in those manuals, there is consistency in three major categories: routine visual inspections (also known as general inspection in the United Kingdom and New Zealand), in-depth inspections (namely, principal/detailed inspection), and engineering investigations. Routine inspection normally occurs every one–three years and identifies significant variations compared with the previous or initial state of a bridge. A detailed inspection is conducted over a longer interval (five–seven years) and requires close-proximity (within an arm’s distance) examinations of all inspectable parts of bridge structures. Based on specific issues observed or suspected in the above-mentioned activities, engineering investigations are conducted to clarify the cause, extent, and severity of deteriorations and defects. These investigations commonly employ a combination of various field tests and theoretical analysis.

Table 1.2 Different types of bridge inspections and required personnel

Country	Source	#	Inspection type	Required personnel
The United States	The Manual for Bridge Evaluation, US AASHTO	1	Initial/ inventory inspection	-
		2	Routine inspection	Team leader and assistant inspector
		3	In-depth inspection	Team leader required
		4	Fracture-critical member inspection	Team leader required
		5	Underwater inspection	Team leader required
		6	Special inspection	-
		7	Damage inspection	-
Canada	British Columbia	1	Routine condition inspection	Province inspectors
		2	Close-proximity inspection with equipment	Qualified and trained inspectors
	Alberta, Yukon, and Northwest Territories	1	General detailed visual inspection	At least a Class B inspector
		2	In-depth inspection (detailed measurements and close access)	Class A inspector
	Ontario, Saskatchewan, Manitoba,	1	Walk-around inspection	Not applicable
		2	Detailed visual inspection/ Regular inspections	By or under the direction of a

	New Brunswick, Prince Edward islands, and Nova Scotia			professional engineer (PE)
	Quebec	1	Element-level inspection	
The United Kingdom		1	Safety/ superficial inspection	Not applicable
		2	General inspection	
		3	Principal inspection	
		4	Special inspection	
		5	Inspection for assessment	
Germany		1	Cursory safety inspection	Road maintenance crews
		2	Routine (major) inspection	Bridge inspectors
		3	Routine (minor) inspection	Bridge inspectors
Australia	Western Australia	1	Routine visual inspections	Not applicable
		2	Detailed visual inspections	
		3	Special inspections and investigations	
	Victoria State	1	Routine maintenance inspection	Pre-qualified in the M2-BW category
		2	Inspection of structural condition	BI2 category
		3	Engineering investigation	Pre-qualified Proof Engineer
New Zealand		1	Superficial inspection	Bridge inspector
		2	General inspection	Bridge inspector. When necessary, a design engineer and other specialist staff
		3	Detailed inspection	A bridge inspector with specialist staff
		4	Special inspection	A bridge inspector with specialist staff
China		1	Frequent inspection (translated)	Not applicable
		2	Routine inspection (translated)	
		3	Special inspection(translated)	

With the advances in information technology, substantial efforts have been undertaken in recent years in architecture, engineering, construction, and facility management (AEC/FM) to achieve digitalised asset management. Since the end of the previous century, a variety of bridge management systems have been developed by authorities worldwide. The research on such cyber systems was extensive (American Association of State Highway and Transportation Officials ; Hawk et al. 1998; Khanzada 2012). Then, the industry strongly promoted building information modelling (BIM), which is aimed at facilitating the lifecycle management of civil assets. BIM proactively develops a digital environment to interactively organise all the information of a building/infrastructure. The information ranges from design specifications and construction details to the as-is condition during the O&M phases (Chong et al. 2016; J. Wang et al. 2015). With BIM technology, all relevant data throughout the lifecycle of a civil asset can be updated collaboratively, exchanged automatically, and accessed conveniently for analysis regardless of authority, platform, or software (Eastman et al. 2011). Subsequently, the concept of digital twin was proposed. It differs from BIM in terms of its capability to represent the physical reality with maximum precision. Technologies such as Internet of Things and Computer Vision (CV) are utilised extensively to collect as-is condition data and integrated into the dynamic digital twin.

This research focuses on the bridge inspections (visual inspections in particular) with the aim of determining how BIM technology can aid similar industrial activities.

1.3 Problem statement

As specified in several manuals, element-level inspection (AASHTO 2019; Alberta Infrastructure and Transportation 2008; Highways Agency CSS Bridges Group 2007) is a desired approach for collecting sufficient condition data for further assessment. Figure 1.3 illustrates the process of element-level inspection. With regard to the current inspection practices, this section identifies three significant challenges in this industrial field in terms of the data collection process, data documentation and representation, and analysis for future usage.

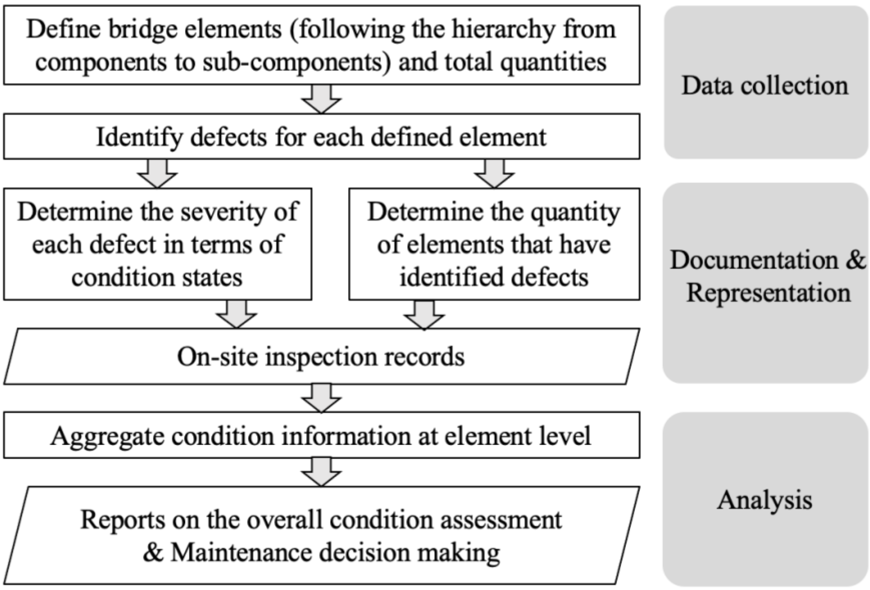


Figure 1.3 Element-level inspection procedure

- Challenges with regard to data collection

Current on-site inspections generally require personnel to tour on-site and manually identify deteriorations and defects on bridge structures. The drawbacks and challenges during the collection of as-is condition data are two-fold. First, the identification and preliminary assessment of defects are completed by on-site personnel through manual scanning and documentation, which are vulnerable to incomplete condition information and subjectivity (Phares et al. 2004). Several bridge authorities have specified the requirements for inspectors (Table 1.2) to improve the reliability of inspection results. Inspectors are chartered as specialists only after they complete a comprehensive bridge inspection-training course and/or satisfy several other requirements including years of experience, education, and possession of engineering licensure. However, personal assessments are subject to errors and biases. Second, inspectors, particularly professional engineers, encounter a large number of ageing bridges because their presence is required for each principal inspection activity. Alternatively, there is an increasing interest in the use of unmanned aerial systems (Highways England 2017), which are aimed at automating the data collection process and reducing practitioners' workload. CV techniques can then be used to automatically retrieve information (e.g., defect, their significance, and cause) from imagery, given the intensive study in the academia and wide applications in the industry (Xu et al. 2020). However, expert knowledge and experience of bridge inspection are required to facilitate this alternative solution.

- Challenges during the documentation of inspection data

The prevalent methods for documenting inspection data collected by specialists are generally unstructured. Specifically, inspectors note defect information on paper at sites and organise these into digital reports or excel sheets for presentation and long-term archiving. A typical inspection report contains information that can be divided into three categories: (a) background information of the inspection event, such as type of inspection, inspection date, and responsible personnel; (b) information on individual identified defects; and (c) condition ratings and/or maintenance decisions provided by experienced engineers. Images of critical defects are captured on-site and preferably attached to improve defect description and subsequent numerical measurements. Geometric information of defects including their shape features (e.g., length, width, or area) and spatial placement (e.g., position with regard to the bridge element on which it is located and orientation of development) are specified in the report.

Such data documentation approaches largely hinder the open BIM process in terms of multiple aspects. First, the retrieval and exchange of such information requires additional efforts. Unstructured data, particularly those documented in pdf reports, are heavy in text and hinder both engineers and computational software from identifying relevant information without ambiguities. Intensive information processing and analysis would be necessary to obtain informative engineering assessment. Second, inspection-based data (particularly, defect information) cannot be presented explicitly in the dynamic and integrated BIM platforms. These are generally in the form of textural descriptions or, in the best cases, images. Third, engineering assessment such as the logical relationship among several defects and potential root causes of certain defects cannot be included if these are documented in official excel-sheet formats.

- Challenges with regard to the usage of inspection data

It is highly challenging to use inspection-related data without additional information retrieval, interpretation, and processing if these are documented in unstructured forms. Even if appropriate documentation is achieved, the usage of inspection-related data is limited. In current practices, defect information is used extensively for condition assessment. First, the severity and extent of individual defects are assessed. Then, the condition information is aggregated at the element level. Finally, the overall condition assessment for the bridge is generated (Highways Agency CSS Bridges Group 2007). Weights are assigned to different elements according to their importance to the structure during the aggregation. Then, maintenance decisions can be made after a comprehensive analysis at the regional level, and detailed maintenance plans for single defects can be developed. Such condition evaluation based on defect information requires professional engineers to manually determine the condition score for each defect, calculate element-level condition indicator by selecting an appropriate aggregation approach (e.g., worst-case analysis), and categorise the bridge into the corresponding condition level. This process relies substantially on human efforts and expert assessment, which can be subjective and time-consuming.

Apart from this, further analysis in the structural domain is not applicable for inspection-related data. In practice, structural analysis is generally based on sensor data from SHM systems. However, SHM systems are installed only on socially, economically, and structurally important bridges. The direct usage of inspection-related data for structural analysis would be effective for managing most other bridges. The challenges involved in this approach originate from the fact that the root causes of defects are implicit. In addition, the fact that a defect can result from a combination of multiple underlying factors pose further difficulties for their analysis. Non-structural defects and structural defects co-exist in actual cases. This necessitates additional categorisation by professional engineers. An efficient approach to quantifying the impacts of defects on structures is absent and required urgently.

Overall, the challenges identified in this research are with regard to the entire procedure of bridge inspection, from data collection and data representation to their analysis. First, the identification, measurement, and on-site documentation of bridge defects are time-consuming and vulnerable to error. Second, current approaches to documenting and presenting such inspection-related information do not fit in any open BIM schemes. Finally, there is a deficiency of automated and effective usage of defect information in bridge BIM for condition evaluation or in the structural domain. The above three challenges identified at the early stage of this PhD program facilitates the conduction of this research and are presented in the following chapters.

1.4 Aim and objectives

Considering the challenges identified above, the aim of this study is to develop an Industry Foundation Classes (IFC)-based method for bridge defect information representation and analysis. The following four objectives are established to achieve this aim.

Objective 1: To develop a defect model for concrete bridges to assess defects in concrete highway bridges.

The novel defect model would illustrate in-depth three types of relationship of defects: (1) their relationship with physical elements, (2) inter-relationship among defects, and (3) their relationship with property and potential causes. A holistic research method, which includes a comprehensive literature review, focus groups, and case studies, is employed to develop and validate the proposed defect model. How this defect model could facilitate bridge inspection is also discussed.

Objective 2: To develop an IFC-based method to integrate inspection-related information into bridge BIM models.

An IFC-based method would be developed for defect documentation and representation. Specifically, inspection-related information including the background information of the inspection activity, defect information that are identified during inspections, and logical relationships among these (e.g., root cause) are modelled with existing IFC entities. This integrated bridge information model is exchanged across multiple BIM tools to evaluate its interoperability and tested for its efficiency of information retrieval.

Objective 3: To develop IFC-based approaches to analyse defect information based on the defective bridge BIM models.

The defect analysis scheme based on bridge BIM integrated with defect information constitutes two parts. First, an IFC-based approach to conducting bridge condition evaluation by aggregating condition information from the element level to the structure level would be developed. Second, defect analysis from the perspective of structural analysis would be achieved using a matrix stiffness method. The impacts of bridge defects (e.g., structural cracking) on an element's structural properties would be quantified and integrated into the analytical model. Both analysis approaches would be evaluated using case studies on actual bridges.

1.5 Contribution of the research

Current practices of bridge management in the industry, particularly bridge inspections without sensors for SHM, encounter various challenges. Such challenges are attracting increased attention from both industry and academia in the context of the continuously increasing number of ageing bridges worldwide. The IFC-based method proposed for defect representation and analysis would address the above challenges to a certain extent. Specifically, the contributions of this research are as follows:

First, the development of a defect model for concrete highway bridges is one of the most significant contributions of this research. The knowledge model is designed to facilitate standardisation during the collection of defect information on site, circumvent the need for inspectors and engineers to undertake tedious and potentially hazardous on-site operations, and ultimately contribute to the automation of bridge inspection. By retrieving rich experience and expert knowledge that have been collected and inherited over a long period in the industrial sector and formatting these into an accessible and user-friendly knowledge model, inexperienced practitioners and even machines would be enabled to conduct inspection tasks with the digitalised expert knowledge, in the near future. The inspection efficiency can be improved, and the inclusiveness and accuracy of the collected defect information can be ensured. Both false positives and false negatives can be identified for two-level examination.

Second, the proposed method to integrate inspection-related information into the bridge BIM models is also of significance. The contributions include the following: (1) Explicit representation of identified defects by using parameterised modelling methods for defect geometry is accomplished. Furthermore, a few representational approaches are available with regard to how the defects affect structural members. Unlike previous methods that attached photographs of defects to their corresponding locations or used external inference, this method allows for the exchange, retrieval, and analysis of such inspection information. (2) Defect entities are positioned parametrically and in relation to the alignment of corresponding bridge elements. This facilitates the retrieval of the affected cross-sectional entity during further analyses. (3) Observation of defect/degradation evolution over time is feasible through an assignment to time-stamped inspection events. (4) An inclusive and systematic description of various relationships of defects in bridge BIM models is provided. This is of practical significance for subsequent managerial operations including cause diagnosis, maintenance cost analysis, and decision making. Thus, the proposed method can effectively integrate diverse and quantitative information from inspection practices into bridge BIM models. This is a step closer to the ultimate objective of automated, efficient, and reliable bridge management.

Third, the approach to conducting condition assessment based on IFC-based integrated bridge BIM constitute another contribution of this research. Compared with previous bridge management systems, which support condition data calculations, the proposed approach utilises the IFC file of a defective bridge BIM model. This bridges the gap between BIM and traditional bridge management schemes. Such a link is of importance with regard to the ultimate goal of an integrated, interactive, and digitalised platform for infrastructure lifecycle management.

Finally, the proposed method for conducting structural analysis on a defective bridge BIM model is vital to the entire bridge management scheme. Current bridge inspection practices, particularly routine and detailed inspections, mostly concerns surface defects visible to inspectors. These are conducted mainly for the purpose of maintenance decision making, with additional actions for defect diagnosis when required. Meanwhile, structural safety and reliability are assessed through structural analyses. In this case, SHM systems, which use sensors to collect measurable structural responses to various loads and load cases, are generally employed. This final objective contributes to current industrial practices by significantly reducing the disparity between the aforementioned two practices for bridge management. Furthermore, the stiffness reduction coefficient, which quantifies the impact of structural cracking on load-bearing elements (e.g., beams), is tested. The recommendations regarding the determination of an appropriate coefficient are effective for future analysis of defective bridge elements in the structural domain.

1.6 Thesis structure

This thesis consists of 10 chapters in the following sequence (see Figure 1.4). Specifically,

Chapter 1 is an introductory chapter and provides the background of this research. The research problem is clarified by a review of the state of practice in the industry. In addition, the aim and objectives of this research as well as their contributions are presented.

Chapter 2 provides a review on several topics in the fields of bridge inspection and BIM. Concrete defects and relevant knowledge systems are first summarised. Structural analysis theories for (defective) highway bridges are then introduced.

Furthermore, advances of IFC/BIM, particularly for bridge inspections and defect analysis are reviewed.

Chapter 3 illustrates the research methodology and methods adopted in this research. The underlying research philosophy is first clarified, and specific research methods including documentary research, focus group study, and case study are illustrated accordingly.

Chapter 4 presents the development of a defect model for bridge inspections. The defect model representing the expert knowledge in industrial practices is established through documentary research and focus group study. A case study is adopted to validate the results. Common defect categories, a defect relationship map, and the relationship between defect properties and underlying causes are included in the defect model.

Chapter 5 presents the IFC-based approach for defect documentation and representation. Inspection-related information (e.g., defects) is targeted for modelling, and logical relationships of defects are included to further enrich defective bridge BIM. A case study based on the proposed approach is presented to demonstrate its interoperability across BIM tools and efficiency of information retrieval.

Chapter 6 presents the IFC-based defect analysis method for the purpose of condition assessment. The element-level condition assessment procedure is first computerised, and both stand-alone tools and plug-ins are developed. A case study of an actual bridge is conducted to validate the applicability of the proposed method.

Chapter 7 presents the IFC-based method to transfer an architectural bridge BIM model into an analytical model, with defect information converted as well. The defect analysis method in the structural domain is first tested using an illustrative simply-supported bridge, and the sensibility analysis of the stiffness reduction coefficient is presented. In addition, an actual bridge is used to practically validate the proposed method for defect analysis.

Chapter 8 presents in-depth discussions on each objective and their relationship with each other. The limitations and future work are also highlighted.

Chapter 9 concludes the thesis.

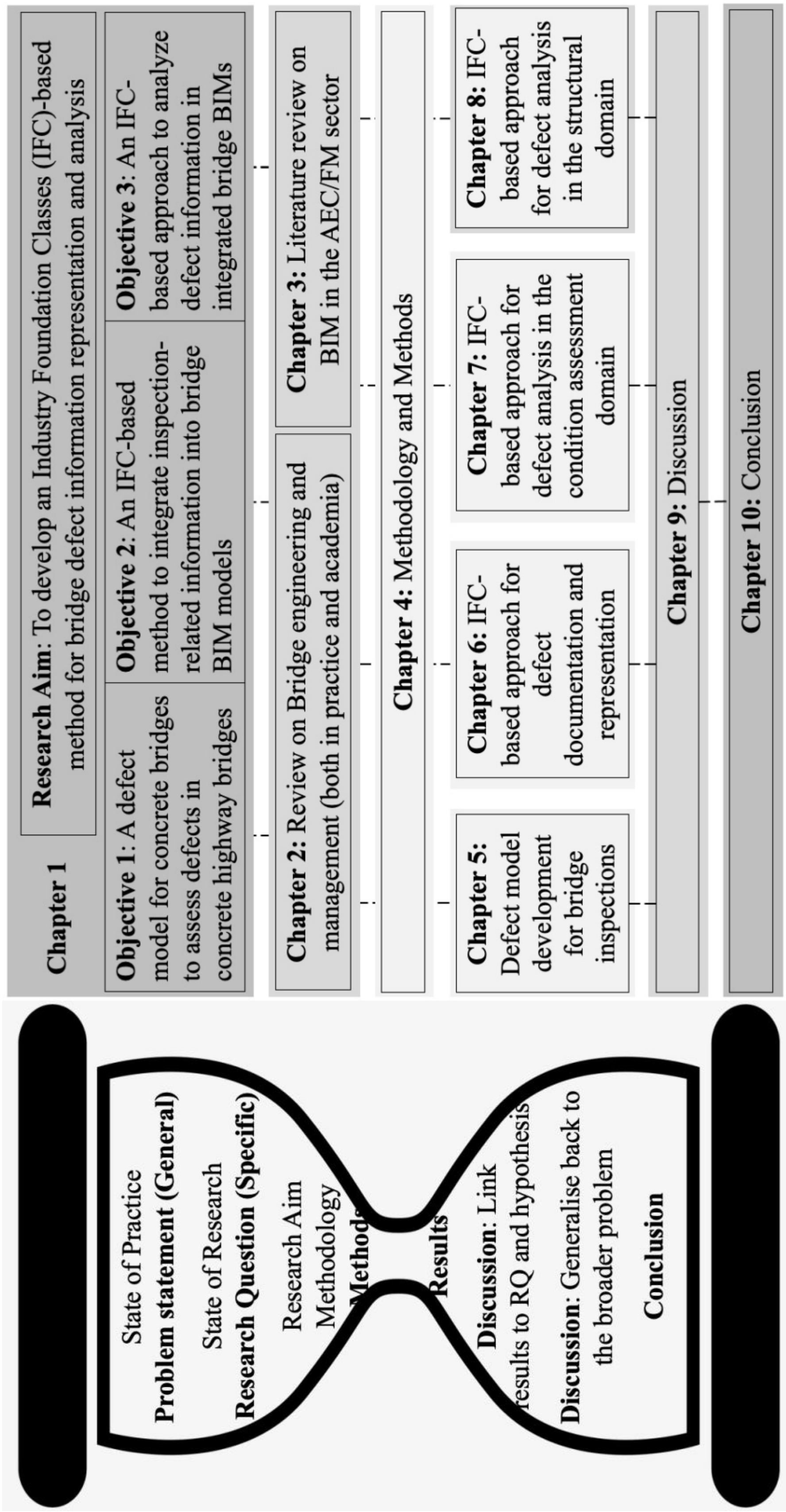


Figure 1.4 Thesis Structure

2 Literature review

2.1 Chapter introduction

This chapter presents an inclusive literature review of this field of study. Specifically, Section 2.2 addresses common topics in bridge engineering and management by enumerating defects/deterioration mechanisms of concrete (Section 2.2.1) and summarising structural analysis methods in the conventional bridge engineering domain (Section 2.2.2). Section 2.2.3 reviews current and potential methods to assess defects from the perspective of structural analysis. Section 2.3 provides a review on how IFC-based BIM technology has been used in the AEC/FM sector, with particular focus on bridges. Official updates and academic advances in the field of IFC-based infrastructure management, defect modelling, and defect analysis are reviewed and presented. Section 2.4 concludes this chapter.

2.2 Literature review of bridge defects

2.2.1 Common defects in concrete

Visual inspection methods are employed extensively during routine inspections and detailed inspections. Defects that are visible and/or straightforwardly identified with the aid of simple tools such as hammer are generally examined, measured, and documented. The categorisation of defects and deterioration mechanisms common to highway bridges has been studied for a long time. A rather mature system that categorises defects of different bridge materials and multiple bridge components (i.e., superstructure, substructure, and ancillary items) is available and documented in most inspection manuals. In addition, a few research studies, project reports, and government-issued technical notes (PCA 2002; VicRoads 2010; Zakić et al. 1991) also summarised typical distresses with reasonable classification of their causes. In this section, common defects and deterioration mechanisms of concrete structures (as documented in several inspection manuals and the literature) are clarified. Their definition, potential causes, and example images are provided below.

- Cracking

A crack is a linear fracture in concrete partly/completely through the member. They are generated in tension zones and spread along the force transmission path. In certain cases, these can be in the form of a map or block. A wide range of factors cause cracking during the various phases from construction to operation. For example, shrinkage cracking is induced by inadequate curing and the consequent low quality of material or workmanship during construction, whereas diagonal/vertical cracking can occur at highly stressed positions. Figure 2.1 presents common patterns of cracking including linear and map/block.

(a) Linear cracking on deck (b) Map cracking on pavement

Figure 2.1 Common patterns of cracking

- Scaling and disintegration

Scaling is a gradual and continuous flaking or loss of surface mortar and aggregate over irregular areas to a depth of approximately 5 mm. Disintegration is the physical deterioration/breaking down of concrete into small fragments or particles. In general, the concrete material first shows scaling, which develops into disintegration if not controlled effectively. Figure 2.2 presents an example of scaling and disintegration.

Figure 2.2 Example of scaling and disintegration (adapted from (PCA 2002)).

- Spalling

A spall is a fragment of concrete that is detached from the structure between fracture surfaces. It differs from scaling in that it extends to the reinforcement and deeper. The root causes are multiple: it can be a continuation of the corrosion process or caused by an external force, thermal action, or overloading of concrete under compression. Figure 2.3 presents photographs of spalling on concrete structures.

(a) Spalling with exposed reinforcement (b) Spalling on the soffit of concrete slab

Figure 2.3 Examples of spalling

- Delamination

Delamination is defined as a discontinuity in the surface concrete, which is substantially separated (but not completely detached) from the adjoining concrete. It gradually evolves from reinforcement corrosion and can be identified by the hammer tapping approach. Figure 2.4 shows an example of delamination on the deck of a concrete bridge.

Figure 2.4 Example of delamination

- Corrosion of reinforcement

Corrosion of reinforcement is self-explanatory. Its manifestation generally starts with rust stains on the concrete surface and evolves to surface concrete cracks, delaminates, and spalls. A group of studies in the literature focused on the simulation of the corrosion process with the aim of predicting its development in the elements over time. Severe corrosion may result in delamination and even spalling. Figure 2.5 presents images of exposed and corroded reinforcement in actual concrete bridges. Extensive rusting can also be observed in the image on the right side.

Figure 2.5 Exposed reinforcement with corrosion

- Leaching and deposit

Leaching is water seepage through cracks or voids in hardened concrete and can result in deposits. The manifestations of deposits include efflorescence, exudation, encrustation, and stalactite. Figure 2.6 presents examples of leakage and deposits on concrete bridges.

Figure 2.6 Leaching and deposits on concrete

- Surface defects

Multiple surface defects can occur on concrete. For example, honeycombing results in a rough porous concrete surface where the cement paste has inadequately filled the spaces between aggregates. Segregation is a differential concentration of the components of mixed concrete that results in non-uniform proportions in the structure. A cold joint is an incomplete bond at the joint owing to the partial setting of concrete in the first pour. Surface-deep cracking such as crazing can also be a surface defect.

- Alkali aggregate reactivity (AAR)/alkali silica reaction (ASR)

A highly expansive alkali–silica gel that is produced by the adverse reaction of certain aggregates with the alkalis in cement expands under moist conditions. Such activity requires specific environments for cultivation.

- Abrasion and erosion

Abrasion is a rough friable surface with grooving, pot holing, or spalling (particularly on edges) caused by rolling, rubbing, and friction. Meanwhile, erosion refers to water wash (specifically, abrasive materials carried in water, e.g., suspended sand and other debris). Erosion occurs when wet soil containing sulphates exists in a cold environment. Concrete made using limestone aggregates is affected by it.

- Scour

Scour is the removal of sediments from around bridge abutments and piers. Building/infrastructure foundations display substantial scour issue. Special underwater inspection would be necessary in such cases. Additional vulnerability assessment of the structure would also be required. Considering the need for special inspection tools to identify such issues, Figure 2.7 shows an example of exposed foundation of concrete bridge where scour tends to be present.

Figure 2.7 Images of exposed foundation

2.2.2 Knowledge systems on defects

Based on the above, previous studies on knowledge systems or expert systems that facilitate inspections and management are reviewed. The literature reveals the considerable efforts undertaken to develop knowledge/expert systems on defects. For example, Mbanjwa (2014) explored the relationship between major defects and environmental factors such as structure locations, type, age, and span length/width, and their contributory effects on the prevalence of defects. Other relationships with defects, i.e., those of diagnostic methods and repair techniques, were established as a part of a knowledge-based system BRIDGE-1 (Brito et al. 1994) to assist in-situ inspections. A group of researchers explored the feasibility of inferring structural performance criteria (e.g., state of damage) from visually observable defect manifestations (Ebrahimkhanlou et al. 2017; Farhidzadeh, Dehghan-Niri, Moustafa, et al. 2013; Farhidzadeh, Dehghan-Niri, and Salamone 2013), by retrieving and utilising previous knowledge (Ignat-Coman et al. 2008; Melchor-Lucero et al. 1995) and supplementing it with machine learning techniques (e.g., neural networks (Kawamura et al. 2003)). To further integrate defect information for damage analysis, Fröhlich (2020) proposed an approach for bridge defect categorisation with respect to their effect on the structural properties of bridges, i.e., dimensions, stiffness, or strength of a structural member. In terms of the inter-relationship mapping across distresses (known as failure modes in the field of mechanics and manufacturing), a few studies in these analogous disciplines developed different modelling methods including an analytical model for predicting interactive failures (i.e., failures that are mutually dependent) (Sun et al. 2006) and a diagnostic causality diagram with multiple hierarchical levels to represent the interrelationships among different failure modes and their relationships with the physical entity (Li et al. 2008).

However, few studies conducted bridge defect modelling to establish a cause-and-effect relationship across defects and investigate the likelihood of concurrence or exclusive presence, which can provide inspectors with reasonable insights into potential unhealthy areas with certain defects.

2.3 Literature review on theories of bridge structural analysis

In the history of bridge engineering, a few classical structural analysis models have been widely utilised in the industry, and several innovative methods have been proposed by academia. The following paragraphs summarise a few classical theories, matrix methods, and finite element methods for structural analysis. In the final section, defect analysis methods (in the non-structural and structural context) are presented.

2.3.1 Classical theories

Most classical methods of structural analysis were initially designed for manual calculations. Therefore, assumptions are made to reduce computational efforts. A few classical theories of bridge structures are presented below:

- Classical beam theories

The classical beam theories including the Euler–Bernoulli beam theory and Timoshenko beam theory are now standard in this field of study. Specifically, Equation 2.1 can be obtained according to the simple Euler-Bernoulli beam theory.

$$\frac{d^2}{dx^2}\left(D_{xx}\frac{d^2 w_0}{dx^2}\right) = q \; for \; 0 < x < L \qquad \text{Eq. 2.1}$$

, where w_0 represents the transverse deflection at the point $(x, 0)$ on the mid-plane of the beam. D_{xx} is the flexural rigidity of the beam and is equal to $E_x I_{yy} = E_x \int_A z^2 dA$. Either w_0 and $\frac{dw_0}{dx}$ or Q_x and M_{xx} are specified as the boundary conditions. The discontinuous region (D-region) is the region where the Bernoulli beam theory fails. This occurs because the section does not remain plane or normal to the neutral axis, and the beam thickness varies. With regard to the first-order shear deformation beam theory of Timoshenko, the underlying equilibrium equation can be expressed as Equation 2.2.

$$-\frac{d}{dx}\left(D_{xx}\frac{d\phi}{dx}\right) + K_s A_{xz}\left(\phi + \frac{dw_0}{dx}\right) = 0$$
$$-\frac{d}{dx}\left[K_s A_{xz}\left(\phi + \frac{dw_0}{dx}\right)\right] = q \qquad \text{Eq. 2.2}$$
$$for \; 0 < x < L$$

, where ϕ denotes the rotation of the cross-section and K_s is the shear correction factor to address the assumption that the transverse shear stress distribution through the beam depth is constant. In this theory, either w_0 and ϕ or $K_s A_{xz}\left(\phi + \frac{dw_0}{dx}\right)$ and $D_{xx}\frac{d\phi}{dx}$ need to be specified at the boundary. With regard to different boundary conditions such as simply supported, clamped, free, and elastically supported, the specifications of certain variables can be inferred.

In addition, a range of deviations based on the classical beam theories have been proposed and verified. For example, several third-order beam theories (Bickford 1982; Heyliger et al. 1988; Levinson 1981; Reddy 1984) have been developed to represent the quadratic variation in transverse shear stresses. In particular, the Reddy–Bickford beam theory can be expressed as Equation 2.3.

$$-\frac{d}{dx}\left(\bar{D}_{xx}\frac{d\phi}{dx} - \alpha\hat{F}_{xx}\frac{d^2 w_0}{dx^2}\right) + \bar{A}_{xz}\left(\phi + \frac{dw_0}{dx}\right) = 0$$
$$-\alpha\frac{d^2}{dx^2}\left(\hat{F}_{xx}\frac{d\phi}{dx} - \alpha H_{xx}\frac{d^2 w_0}{dx^2}\right) - \frac{d}{dx}\left[\bar{A}_{xz}\left(\phi + \frac{dw_0}{dx}\right)\right] = q$$
$$(A_{xx}, D_{xx}, F_{xx}, H_{xx}) = \int_A (1, z^2, z^4, z^6) E_x dA \qquad \text{Eq. 2.3}$$
$$(A_{xz}, D_{xz}, F_{xz}) = \int_A (1, z^2, z^4) G_{xz} dA$$
$$\hat{D}_{xx} = D_{xx} - \alpha F_{xx}, \hat{F}_{xx} = F_{xx} - \alpha H_{xx}, \hat{A}_{xz} = A_{xz} - \beta D_{xz}, \hat{D}_{xz} = D_{xz} - \beta F_{xz}$$
$$\bar{A}_{xz} = \hat{A}_{xz} - \beta\hat{D}_{xz}, \bar{D}_{xx} = \hat{D}_{xx} - \alpha\hat{F}_{xx}, \bar{F}_{xx} = \hat{F}_{xx} - \alpha\hat{H}_{xx}$$

A combination of w_0, $\frac{dw_0}{dx}$, and ϕ or of $\hat{V}_x$, αP_{xx}, and $\hat{M}_{xx}$ should be specified as the boundary conditions. Furthermore, a unified element stiffness matrix that can be specialised to the aforementioned three beam theories has been proposed by (Wang et al. 2000). It can be applied to beams with constant geometric and material properties. The above-mentioned classic beam theories are illustrated in Figure 2.8.

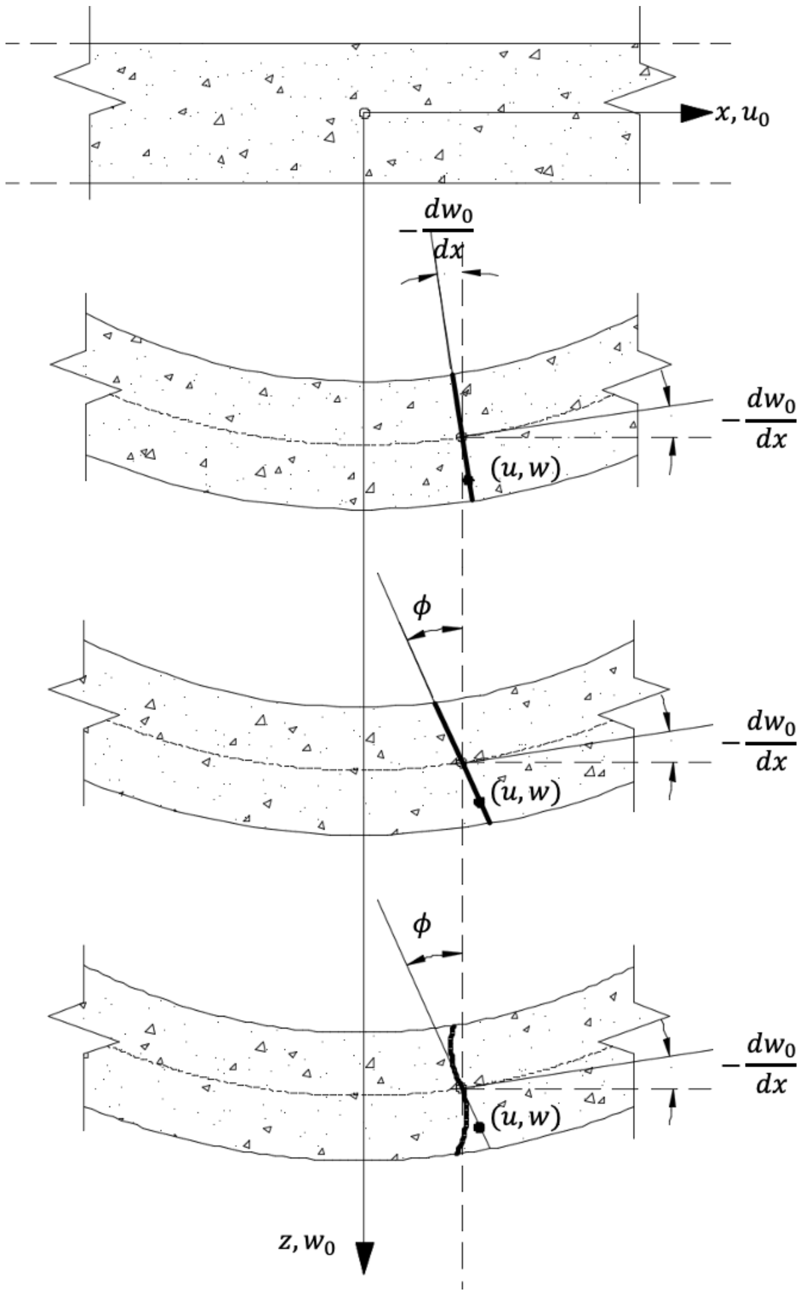
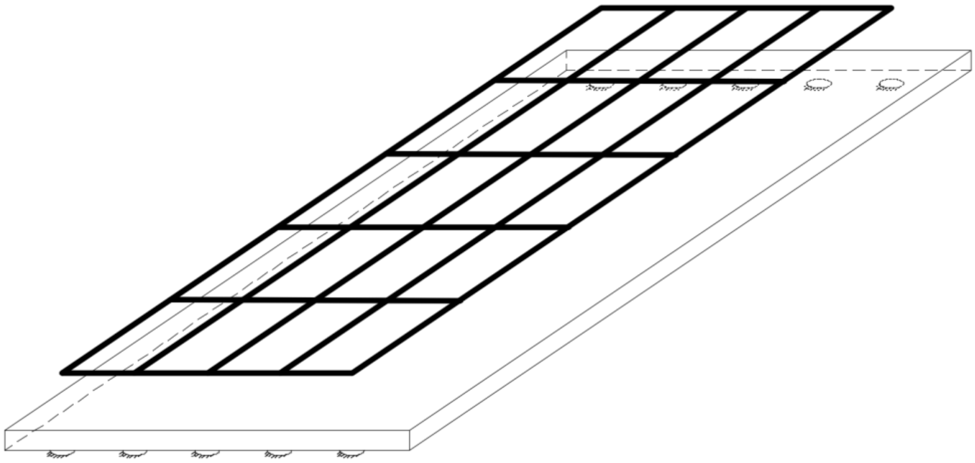


Figure 2.8 Illustrations of three classical beam theories (top to bottom: original beam, Euler–Bernoulli beam theory, Timoshenko beam theory, and Reddy–Bickford beam theory)

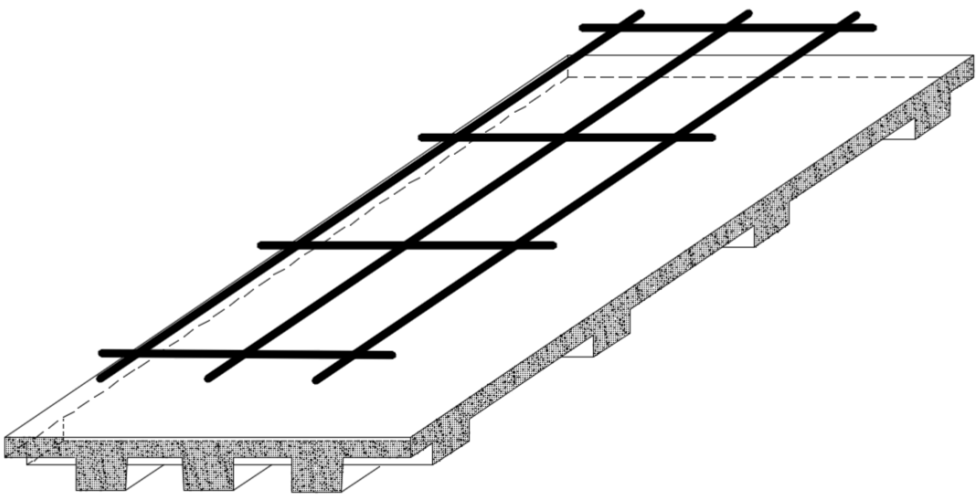
- Plane grillage model

The plane grillage model was first proposed in Edmund Hambly's publication 'Bridge Deck Behaviour' and has remained a popular resource for bridge engineers

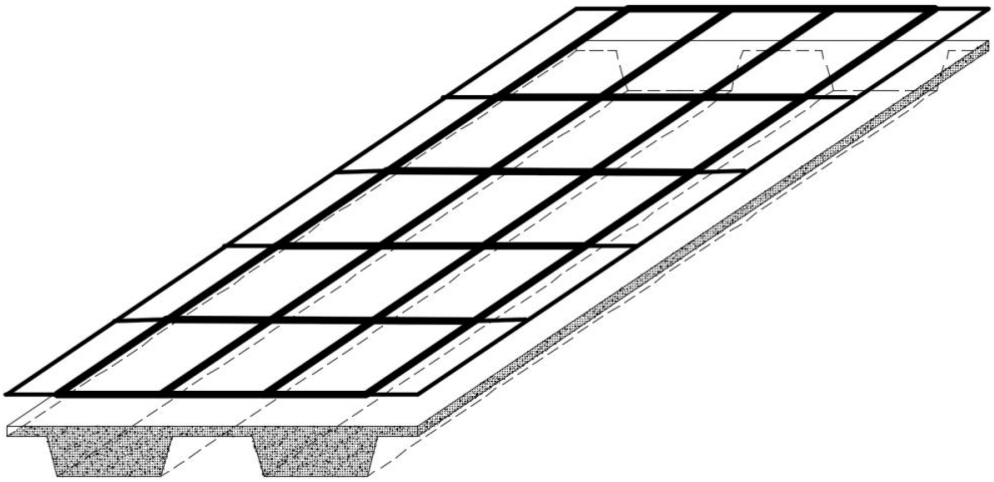
(Hambly 1991). The computer-aided grillage methods can significantly aid the analyses of a range of bridge structural forms including slab decks, beam-and-slab decks, and box-girder decks. Their grillage meshing methods are presented in Figure 2.9 (a)–(c), respectively. Essentially, the deck would be represented by an equivalent grillage of beams whose deflections and inner forces (i.e., moments, shear forces and torsions) are identical to those of the original structure. The fineness of the grillage mesh would affect the accuracy of the grillage model representing the structural responses to loads. Equation 2.4, Equation 2.5 and their variations are used to compute the properties of grillage members:



(a) Grillage meshing for slab decks



(b) Grillage meshing for beam-and-slab decks



(c) Grillage meshing for box girder beams

Figure 2.9 Grillage models for various structural forms

$$Bending\ inertia: I = \frac{bd^2}{12} \quad \text{Eq. 2.4}$$

$$Torsion\ constant: C = \frac{bd^3}{6} \quad \text{Eq. 2.5}$$

The downstand grillage model is an alternative to the plane grillage model. Here, beam elements are located in line with the centroids of the members they represent and downstand or upstand the connected member with rigid links. Figure 2.10 illustrates the concept of the downstand grillage model. A plate model with downstand beams was developed to consider the transverse interactions among beams. It is similar to the downstand grillage except for the fact that the transverse beam elements, which represent the deck slab, are replaced with plate elements.

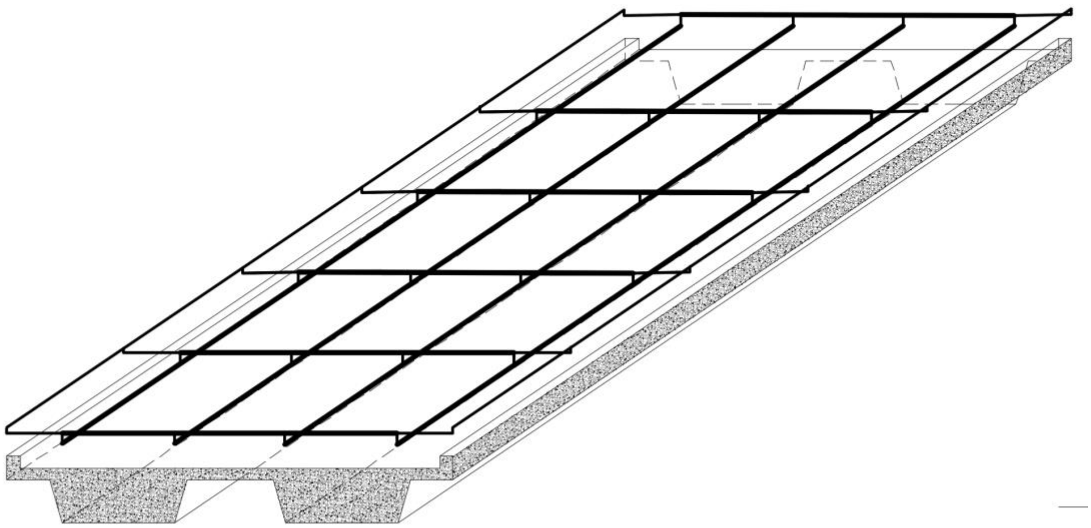


Figure 2.10 Illustration of downstand grillage model

- Strut and tie model

As stated previously, the Bernoulli beam theory is invalid in D-regions (e.g., cracked concrete) where nonlinear strain distribution occurs. Strut and tie modelling can be used as an alternative for analysing such D-regions. Figure 2.11 presents a typical strut and tie model. There are three key elements for most of these: strut, tie, and nodal zone. The central concept of a strut and tie model is to develop a truss-like structure and highlight the load transfer characteristics.

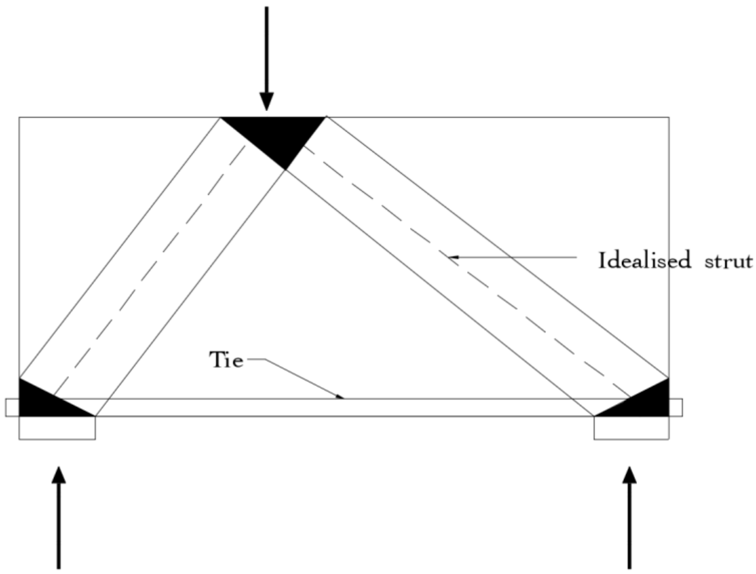


Figure 2.11 Theoretical strut and tie model

- Space frame lattice model

A three-dimensional space frame model better represents the three-dimensional behaviour of bridges than a two-dimensional grillage model. Furthermore, the space frame lattice model has been proposed and is suitable for stress analysis of an entire cross-section. It is currently documented in Chinese bridge design codes for wide application. In this model, all complex bridge structures can be separated into ‘plates’. These can be decomposed further into plate elements at a desired level of granularity. Figure 2.12 presents an example of modelling for a box girder.

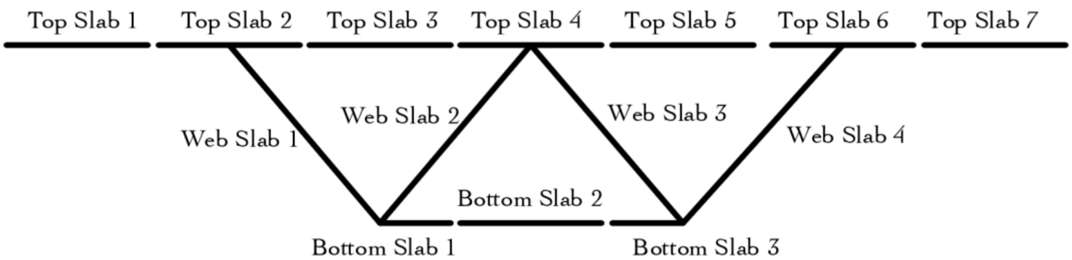


Figure 2.12 Illustration of space frame lattice model

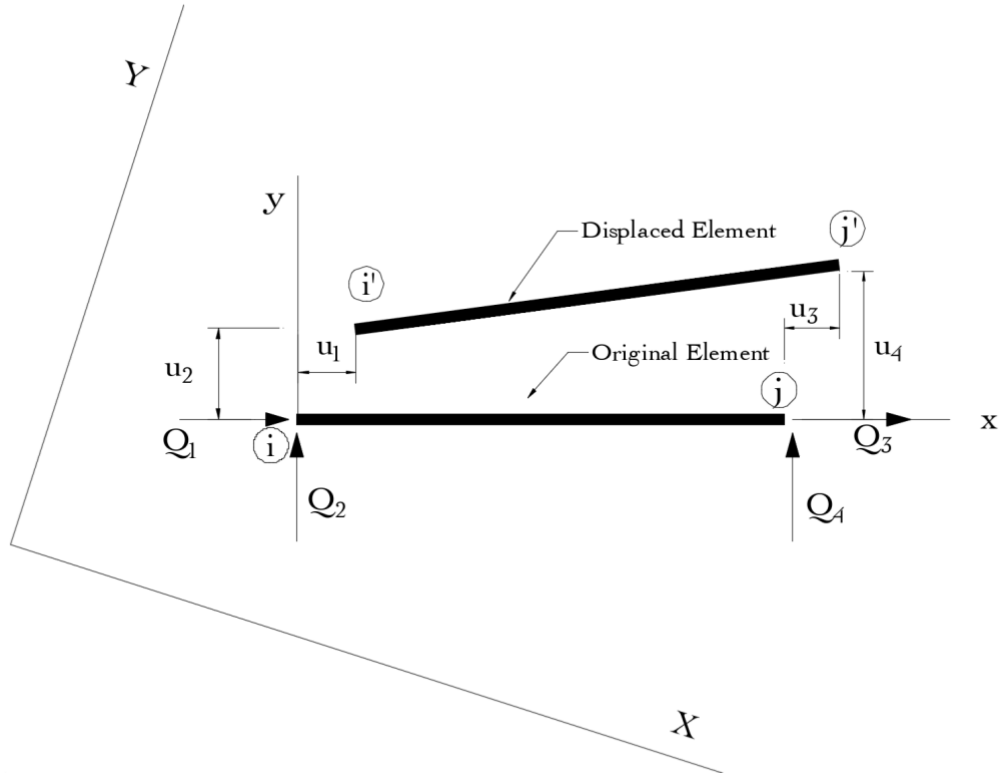
2.3.2 Matrix methods

Unlike the classical methods for structural analysis, matrix methods are designed for computer implementation and are more 'systematic and general', according to Kassimali (2011). Therefore, a computer program (i.e., the overall analytical procedure) developed for a certain type of structures can be applied to other types as well. Furthermore, computer programs can significantly reduce the human efforts required for numerical analysis. Three major types of relationships to be considered to establish the analytical model for structural analysis: equilibrium equations, continuity conditions, and stress–strain relationship. First, Equation 2.6 holds true for each member of a structure when it remains in equilibrium under loads and forces.

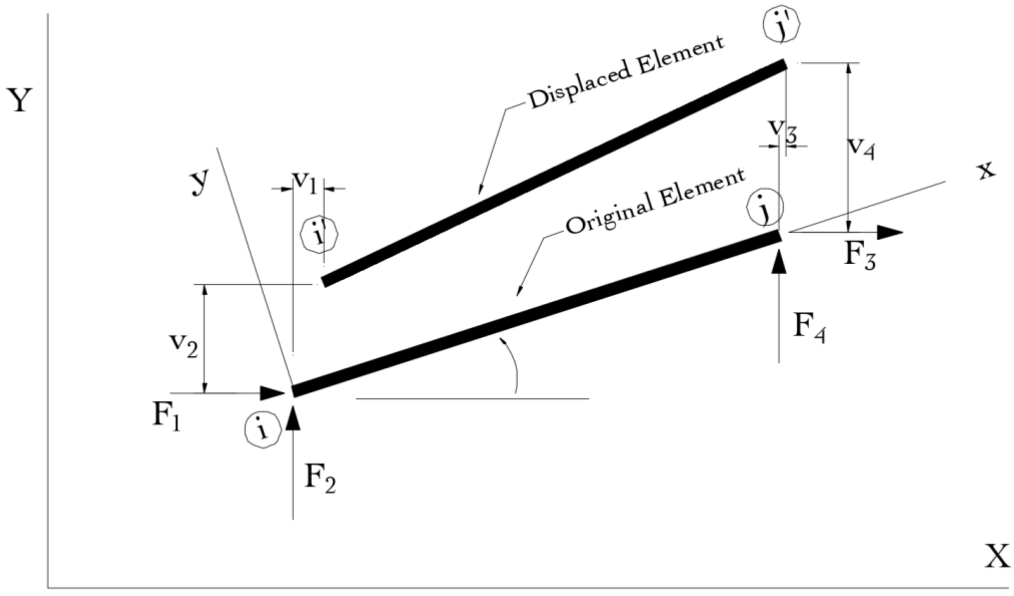
$$\sum F_X = 0, \sum F_Y = 0, \sum F_Z = 0$$
$$\sum M_X = 0, \sum M_Y = 0, \sum M_Z = 0 \quad \text{Eq. 2.6}$$

Second, it holds for all cases that the deformations of various parts of a structure are compatible with each other so that no gaps or overlaps exist in it. That is, the shapes of the structure remain continuous even when it deflected. Finally, the stress–strain relationship effectively connects the loads and structural deformation by stating that the stresses and strains of a structure are in line with the stress–strain properties of the structural material.

The key requirement of matrix methods is the effective formatting of stiffness matrices, including axial stiffness and flexural stiffness. Consider axial stiffness as an example. The process begins at the element-level, where the axial stiffness $\boldsymbol{k}$ is first calculated based on the local coordinate system, as illustrated in Figure 2.13 (a). The stiffness coefficient k_{ij} can be interpretated as the force required at the location and in the direction of the joint force P_i to cause a unit displacement d_j while the other joint displacements remain zero. Then, the transformation matrix from the local (element) coordinate system to the global (structure) coordinate system is obtained, as shown in Figure 2.13 (b). It is used to calculate the element global stiffness matrix $\boldsymbol{K}$. Facilitated by equilibrium equations and continuity conditions, the element global stiffness matrices can be integrated to form a structure stiffness matrix $\boldsymbol{S}$. It can then be used to solve unknown variables in the force–displacement relationship equation $\boldsymbol{P} = \boldsymbol{Sd}$. Here, $\boldsymbol{P}$ is the joint load vector, and $\boldsymbol{d}$ is the joint displacement vector. The analytical procedure for a framed structure (e.g., truss as the representative of framed structures) can be best understood from the flowchart in Figure 2.14.



(a) End displacements and end forces in an element's local coordinate system



(b) End displacements and end forces in the global coordinate system

Figure 2.13 Transformation from local to global coordinate system

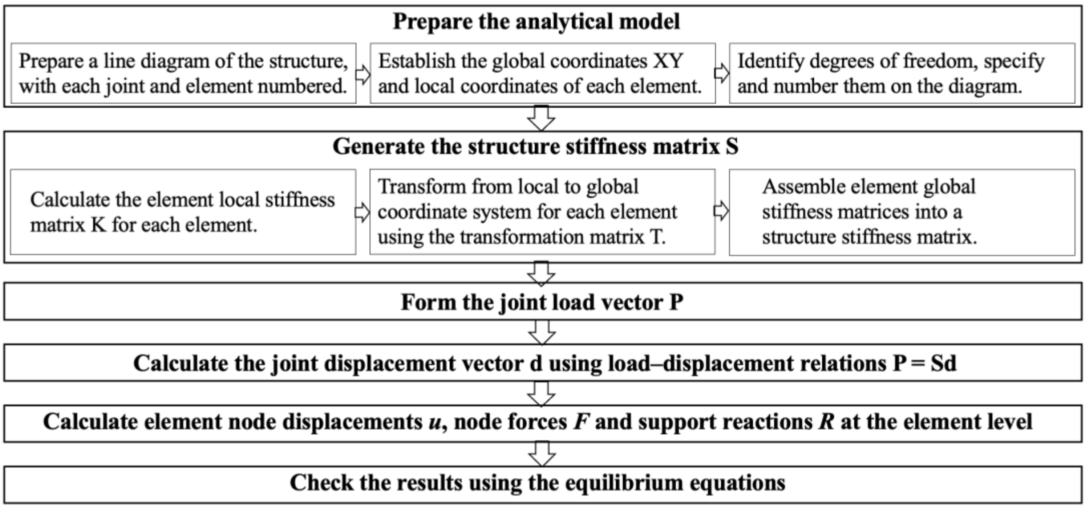


Figure 2.14 Flowchart of the analytical procedure

To computerise the above analytical process, structural data and load information are prepared accordingly as the input of the analysis program. Specifically, a joint coordinate matrix **COORD** is created to document the global coordinates of each joint. A support data matrix **MSUP** is then formatted to represent all the joints that are restrained to supports, in conjunction with their restraint conditions. The material properties (i.e., modulus of elasticity **E**) are included in an elastic modulus vector **EM,** whereas the properties of cross-section (i.e., cross-sectional area **A**) are stored in a cross-sectional property vector **CP**. In addition to the above data, the mapping from each element to its beginning and end joints, material, and cross-section type is specified using an integer member data matrix **MPRP**. The final category is with regard to load information, wherein a **JP** vector and **PJ** vector are used to document the joint numbers where forces are applied and the corresponding forces in the x- and y-directions, respectively. Once all the relevant data are input, the analysis module of the analysis program can be activated according to the above flowchart.

2.3.3 Finite element methods

As extensions to matrix analysis, finite element methods are capable of analysing a wider range of structural forms (e.g., surface structures) and free-form structures. In certain cases, finite element methods for structural analysis yield less accurate results compared with the matrix methods. This is because for matrix methods, the force–displacement relationships of structural members are obtained from the underlying differential equations, whereas for finite element methods, such relationships are calculated using work–energy principles. The meshing algorithm is vital to finite element analysis, and there have been attempts in the literature to automate the mesh generation process using extended IFC standards (Xu et al. 2019).

2.3.4 Defect analysis methods

As mentioned in the Background chapter, defects identified during inspections have not been used for analysis tasks in the structural context. This is mainly because it is difficult to quantify their impacts on the structures, and these normally do not severely undermine the load-bearing capability of structures. There are two major groups of applications in terms of defect analysis in practice: condition assessment and simulation of defect evolution. Condition ratings of defects are necessary for the overall condition assessment of bridge structures. An example is bridge element inspection, where the severity and extent of each defect are assessed and used to calculate the condition levels of the bridge component and bridge. Based on such inspection data (i.e., time-in-condition ratings), Li et al. (2020) proposed a Bayesian-based approach to establishing statistical distribution models for different types of bridges and components to predict their condition. Selected models are calibrated using both complete and incomplete condition data. Another key aspect of defect analysis is to simulate the propagation or evolution of damage. Potenza et al. (2020) proposed a defect analysis scheme based on colour-based image processing techniques, to quantitatively estimate the extension of defects on structural elements. Based on the analysis results, the defect severity level and evolution across time can be modelled subsequently. A few other studies developed deterioration models at the defect level, element level (Wellalage et al. 2015), and bridge system level (Ghodoosi et al. 2015; Ryall 2010b).

In addition to the above, there have been a few attempts both in industry and academia to consider defects from the perspective of structural analysis. McGuire et al. (2016) developed a custom software add-in for inspection data collection on site and a custom damage-evaluation tool for both structural analysis and maintenance recommendations. Specifically, damaged section properties, shear and flexural capacities, and load ratings were calculated by subtracting the damaged areas from the original cross-section. Fröhlich (2020) theoretically categorised the impacts of damage on the structural properties of bridge elements into three types: dimensions, stiffness, and strength. Potential modelling approaches for these three types of influences were recommended. In addition, a case study was conducted to assess the reliability of a T-beam concrete bridge, where the impacts of cracks and relaxation of unbounded rebar were analysed in the structural context.

Previous studies have modelled cracked concrete as a new material with unique stress–strain characteristics (Vecchio et al. 1986). Specifically, the stiffness and strength of concrete at cracked regions would be reduced, whereas compression and shear forces would be transmitted effectively. In addition, owing to the redistribution of internal forces and moments at the cracked sections, the highest stress and yielding of the reinforcement can be observed while the concrete between cracks is still reacting with significant tensile stresses. A few manuals have specified stiffness reduction factors for cracked components. For example, crack analysis with regard to load-induced anisotropy is performed using the effective stiffness and cracked stiffness in Eurocode. Furthermore, the dynamic behaviours of cracked structural components have been studied extensively. Caddemi and Caliò proposed the stability stiffness matrix and dynamic stiffness matrix method for analysing multi-cracked structures in their successive studies (Caddemi et al. 2013a, 2013b). Similarly, the adoption of dynamic stiffness matrix in vibration analysis of cracked beams has been presented in previous studies (Gounaris et al. 1988; Khiem et al. 2002). Nonetheless, as indicated by Artus et al. (2020) in their review, investigations of the data transfer from inspection to structural analysis environments are largely incomplete.

2.4 Literature review on IFC-based bridge inspection

Because the open BIM process has been promoted recently because of its capability to facilitate seamless information exchange across different software, platforms, end users, and authorities, IFC provides an international and platform-neutral solution for such open BIM processes. This exchange format, which is derived from the standard for the exchange of product model data (STEP), embeds richer semantics and allows for more systematic modelling approaches. A variety of BIM authoring tools including Autodesk Revit , FreeCAD (FreeCAD 2021), and Blender (Blender 2021) have been developed to support interaction with IFC-based models. In addition, the Python language and additional packages such as pythonOCC (Paviot 2017) and ifcopenshell (IfcOpenShell) can further facilitate various interactive 3D applications, particularly for generating, assessing, and analysing geometric data in IFC files.

2.4.1 IFC standards for infrastructure

Building SMART International launched an Infra room to develop IFC schema for infrastructure projects (Borrmann et al. 2017). In particular, an IFC-Bridge project was proposed in 2017 (Castaing et al. 2017) and was completed in 2019 (Borrmann et al. 2019). In this project, the IFC schema was extended to bridges considering the increasing demand in the infrastructure industry. The extended IFC schema can address bridge types ranging from slab bridge, girder bridge, slab–girder bridge, box-girder bridge, frame bridge, and rigid frame bridge to culvert. It is considered to be capable of representing truss bridge, arch bridge, cantilever bridge, cable-stayed bridge, and suspension bridge. In terms of construction materials, it addresses the following bridge types: reinforcing concrete (RC) bridge, prestressed concrete (PC) bridge, steel–concrete composite bridge, steel girder bridge, and steel bridge. Use cases predefined for the schema development consider most of the critical procedures during the design and construction phase of a bridge’s lifecycle, e.g., coordination detection, 4D construction sequence modelling, progress monitoring, as-built vs. as-designed comparison, and handovers. Meanwhile, these exclude intrinsically complex cases such as Design to Design (full model logic), structural analysis, code compliance assessment, drawing generation and exchange, and prefabrication and manufacturing.

New entities have been introduced with regard to four types of objects/concepts:

- Spatial elements, i.e., IfcFacility, IfcFacilityPart, IfcBridge, and IfcBridgePart;
- Physical elements that are specific to bridges, i.e., IfcBearing, IfcDeepFoundation, IfcCaissonFoundation, IfcVibrationDamper, and IfcTendonConduit;
- Systems (i.e., reinforcing and prestressing) modelled as new predefined types for existing entity IfcBuildingSystem; and
- Positioning description with a new relationship entity IfcRelPositions inherited from IfcRelConnects. It is noteworthy that this entity has the provision to allow for the propagation of placement/geometry information based on alignment dependencies.

In addition, an improvement that is related to this research is the addition of *defect* as a predefined type of surface feature element (i.e., IfcSurfaceFeature, a subtype of IfcFeatureElement). Although most BIM authoring tools cannot support IFC4.2, extensions in this research would be based on the most recent IFC standards.

2.4.2 IFC extensions for bridge engineering

IFC is essentially an ISO standard (2018) rather than being only data format or data models. The IFC standard specifies digital project information and their structure in the AEC community. Thereby, it allows for development and extensions in compliance with such specifications. Three feasible constructs provided to contain supplementary information are proxy elements, object entities, and property sets. In addition, contributions can be made to develop and further enrich the data dictionaries, Information Delivery Manual, and Model View Definition (MVD). There have been considerable attempts in the academia to contribute to the official IFC schemas.

To facilitate various operations during the design phase of bridge structures, a parametric IFC-Bridge concept was proposed by Ji et al. (2013) for the intelligent design process. Here, bridges with varying profiles can be modelled using a new entity IfcParametricSketch. Entity inheritance further yielded three novel entities: (1) IfcSketchGeometry, which represents shapes composed of ifcSketchLine, ifcSketchPoint, and ifcSketchArc; (2) IfcSketchGeometricConstraint, which models geometric constraints including parallel, perpendicular, coincident, fixed, horizontal, vertical, tangential, and equal length; and (3) IfcSketchDimensionalConstraint, which regulates the vertical dimension, horizontal dimension, parallel dimension, and angular dimension. Furthermore, a parameter entity IfcParametricValueSelect was added to collect data from an enumeration of constants (ifcParametricConstant) and formulas (ifcParametricFormula), so as to compute any arbitrary geometric parameters. The capability of such a parametric bridge model to be transferred between design software (i.e., Siemens NX and Autodesk Inventor) and structural analysis software (i.e., SOFiSTiK Structural Desktop) was also validated. Yabuki et al. (2006) developed a new IFC-BRIDGE data model on the basis of the J-IFC-BRIDGE product model and French IFC-BRIDGE product models. In addition, a multi-agent method was introduced for designing concrete bridges.

To support managerial operations during bridge construction (i.e., quality monitoring), a quality management model, IfcQualityManagement, was developed and linked to the conventional physical object model and construction schedule model (Ding et al. 2017). An IfcWorkScheduleInspection entity was introduced to include inspection results throughout the construction project, whereas an IfcAcceptance entity (linked to an external document (i.e., inspection reports)) was used for quality assurance.

With regard to the O&M phases of a bridge's lifecycle, previous studies extended current IFC schemas to include data collected by SHM systems or by inspection processes. For SHM system modelling, several studies modelled and visualised sensors on the Autodesk Revit platform (Davila Delgado et al. 2016; Valinjadshoubi et al. 2016). They achieved by creating shared parameters in the existing Revit family of sensors, including these in the Schedule interface, and updating their data via plug-ins (e.g., BIM ONE). To model additional sensor types (i.e., kinematic sensors such as vibrating wire strain gauge sensor) using IFC schemas, a generic custom property set, Pset_SensorTypeVibratingWireSensor, was developed in compliance with the existing entity IfcSensorType (Del Grosso et al. 2017). Three subsequent tests (i.e., syntactic assessment, semantic assessment, and unit test) were executed to validate the effectiveness of the novel IFC extension in information documentation and communication for SHM systems. Specifically, incorrect definitions of new entities (i.e., syntactic errors) and noncompliance between domain rules and the semantic model were identified and excluded. A meta-model (IFC Monitor) was developed to describe monitoring-related information including the semantic composition of an SHM system, network topology, and relationships between components in the SHM and bridge structure. Three new entities (i.e., IfcSensorNode, IfcSensorNetwork, and IfcSHMSystem) were developed, and domain rules were set up to regulate their definitions. For example, IfcSensorNetwork can be composed of only IfcSensorNode entities. In addition, IfcNetworkTopologyEnum, which collects all types of network topology, was defined to specify the attributes of IfcSHMSystem. J. Seongwoon et al. Jeong et al. (2017) proposed a framework to model information in bridge monitoring systems, by introducing new entities for bridge structures (i.e., FECoordinateSystem, FELineMesh, FELineSection, FELineRelease, FESurfaceMesh, FESurfaceSection, and FESurfaceConstaint), and load patterns and analysis conditions (i.e., FELoadPattern and FEAnalysisCase). Sensor information was imported directly from SensorML standards and stored in a new entity Sensor. Research on IFC-based bridge inspections is described in the next section.

The verification of the above-mentioned proposals for IFC extensions is closely associated with their capability to represent, update, and interoperate with satisfactory completeness and granularity of information. The capability to represent target information can be validated in a text editor (which requires manual reading, parsing, and interpretation), a model viewer, and modelling software, as conducted by Rio et al. (2013). Prominent open-source and cross-platform viewers for validating the capability of IFC schemas for visualisation and articulation include FreeCAD, Blender and IfcOpenShell, IfcConvert, IfcPlusPlus (with its equivalent in Windows, IfcQuery), and IfcOpenShell Python Viewer (Moult 2019a). FreeCAD displays the capability for generic parametric modelling, whereas Blender is more suitable for rapid prototyping and visualisation of not-too-massing projects. In addition, BIM visualisation software such as BIM Vision, Constructivity, DDS CAD Viewer, and Solibri Model Viewer were employed in (Zhang 2018) to help understand multiple geometric representation entities. Additional programming resources to analyse IFC data files recommended by Zhang (2018) include IFCToolboX, Java Toolbox IFC2x3/IFC4, Open IFC tools, and JSDAI.

2.4.3 IFC for bridge inspection

A review of the IFC-based modelling method for bridge inspection is presented considering the research aim of this work. As introduced in the Background chapter, manuals worldwide specify that bridge inspection tasks need to be conducted regularly at a programmed frequency. The modelling of inspection tasks is straightforward and has been achieved in a few previous studies (Hüthwohl et al. 2018). Relevant information like inspector’s name and title, weather condition and inspection level can be modelled. Defects and deteriorations in bridge structures are identified through visual scanning and/or non-destructive techniques. It is noteworthy that the capability of CV to replace visual inspection has been explored increasingly in recent years. Researchers have undertaken considerable efforts to integrate such defect information into bridge BIMs. J. Taraben et al. developed a documentation schema for bridge inspection practices with regard to the heterogeneous datasets that are generally considered and collected during inspections (Taraben 2019). A model container was deployed to include various acquired data (e.g., point clouds and image sets) and/or simulation models for bridge condition assessment (e.g., finite element model and traffic simulation model). Links across multiple data resources were also established to ensure a reasonable and well-informed evaluation of the overall bridge structure. Hamledari et al. (2018) introduced a method to update semantic information (i.e., types and properties of bridge elements) in IFC-based BIMs with regard to the discrepancy identified between as-is and as-designed object conditions. Inspection data were carried by a new IfcPropertySet instance, which was assigned to corresponding elements using IfcRelDefinesByProperties. The visualisation was achieved by colour-coding the defective elements. To support the inspection process, Tanaka et al. (2016) employed three novel entities (IfcMeasuredRegion, IfcDegradation, and IfcDegradationElement) to describe the inspection tasks and time-dependent deterioration information collected during inspections. In addition, a system that provides web content was added to facilitate remote observation of degradation data. For visualisation purposes and to further support condition assessment in bridge management, an extension (IfcDefect) was added as an inheritance of the IfcVoiding object to represent defects (Ghadiri Mohghaddam 2014). Their properties were recommended to be carried by Pset_DefectCommon, Pset_DefectLinear, Pset_DefectPlanar, and Pset_DefectVolumetric, and the location information by IfcObjectPlacement.

A few studies also included the relationship of defects in their proposed modelling methods. O'brien et al. (2015) used IfcElementPart to represent bridge defects. As a derivative of all the entities from IfcElement to IfcObject, the IfcElementPart entities can be assigned to IfcBridgeElement using IfcRelAssignsToProduct, related to repair actions using IfcRelAssignsToProcess, and described geometrically using IfcRepresentation. The evolution of defects over a sequence of inspection processes can be shown owing to the provision of IfcRepresentationContext.ContextType to permit IfcObject for multiple representations. Motamedi et al. (2017) first categorised degradations based on their relationship with the structural element's form, surface/material, and function. In addition, they modelled these with either novel entities as subtypes of IfcElement (e.g., IfcSurfaceDegradation for surface defects) or property sets accordingly. In addition, their physical relationship with the hosting element and logical relationship with root causes were described. However, the causal relationship between defects was established, thereby indicating the development path of degradations on structures rather than the actual underlying factor. To further model the underlying correlation among defects, Sacks et al. (2018) proposed an element defect-defect structure in the SeeBridge project. Here, element defect objects (modelled as IfcSurfaceTexture) were grouped into a defect object (modelled as IfcElementAssembly) according to the underlying links to causes. Element defects were also (optionally) aggregated to a bridge element object. Such aggregation/grouping relationships were modelled as IfcRelAggregates. External data resources (i.e., defect images) can be linked to model with IfcImageTexture for visualisation purposes. It is noteworthy that element defect refers to an individual defect identified in the inspection process. It ranges from surface distresses such as abrasion/wear, efflorescence, and scaling to defects that indicate structural/ durability issues such as crack, exposed reinforcement, rust staining, and spalling. Furthermore, the proposed MVD was validated in the XBIM Xplorer tool and examined for errors in terms of syntax, semantic structure, and content. A similar concept was introduced by Hüthwohl et al. (2018). Here, the representation of defects in bridge BIM was realised by attaching images of defects to the respective bridge components at a specified position rather than explicitly modelling their geometry with key properties.

To conclude, IFC schemas and extensions that are currently being proposed by the academia have the potential for further enhancement and enrichment in terms of an exhaustedly investigated taxonomy for defect types and their critical properties/parameters, description of relationships between defects, bridge and bridge components, and maintenance actions, and the clarification of the model's level of development. With regard to representation and visualisation, an effective method to integrate defect information into 3D bridge BIM models is unavailable.

2.4.4 IFC-based defect analysis

The IFC-based defect analysis essentially consists of two parts: the IFC-based structural analysis and IFC-based integration of defect information in the structural analysis. This section reviews these two parts separately.

- **Model transfer from BIM to structural analysis.**

The model transfer from an architectural model (i.e., BIM model) to a structural analysis model involves the seamless import and export of bridge information and an effective interpretation of structural information. The entire process of model transfer is also expressed as an information exchange in this work. The exchange can be divided into two subsequent steps: the exchange from the architectural design model to the structural model, and that from the structural model to the structural analysis model. Specifically, a structural model includes all the structural information for analysis including the detailed geometry, material properties, and reinforcement distribution. Furthermore, a structural analysis model includes the various loads and load cases and always corresponds to certain structural analysis software. Lehtinen and Hietanen proposed two subsequent MVDs (Lehtinen 2005; Lehtinen et al. 2007) to fulfil these two steps of model exchange, respectively. Building SMART documented the latter research (Lehtinen et al. 2007) as an official MVD: Structural Analysis view (BuildingSMART). However, it has not been maintained since its release and is inconsistent with the most recent version of IFC.

With regard to the exchange task from an architectural design model to a structural model, Hu et al. (2016) successfully converted geometric information of linear and planar structural elements (i.e., frame structures and shear wall structures) and performed interpretations using a rule-based method. Conversions from an architectural model to a structural model and those among structural analysis models are achieved via an IFC-based unified information model. Model modifications and augmentations such as clarification of structural connection are required on top of the exchange of geometric information. Ramaji et al. (2018) developed an interpreted information exchange mechanism to enable the basic interpretation of an analytical model from an architectural model in Coordination View. Because both input and output models are in the IFC format, the interpretation includes (1) a direct-exchange unit (dU) for project definition, unit information, and generic spatial information; and (2) four interpretation units (iUs) for linear building elements, planar elements, mechanical properties of materials, and coordinates of elements. This proposed framework is consistent with the model view defined for the conversion from an architectural model to a structural design/analysis model of modular buildings (J.Ramaji et al. 2014). Here, information exchange is divided into two types: simple/direct exchange and interpreted exchange. In addition to the efforts in the academia, a variety of commercial software programs can directly achieve the conversion from a building information model to an engineering analytical model in their interface. BIM authoring tools (e.g., Tekla software and Revit software), structural analysis tools (e.g., SAP2000), and third-party applications (e.g., add-ons developed by Scia Engineer) (Ramaji et al. 2018) can achieve this goal.

With regard to the transformation from a structural model to a structural analysis model, X. Wang et al. (2015) developed an IFC-based software specially for structural model transformation and to fill the gap between the IFC structural model (i.e., the IFC file that includes structural information) and the structural model in specialised structural analysis software (e.g., 3D3S). Sibenik et al. (2020) reviewed the state-of-the-art of data exchange between architectural design and structural analysis and proposed improvement strategies for this domain-specific data exchange. Shoieb et al. (2020) assessed the interoperability among structural analysis tools and accordingly, proposed a web-based structural analysis model converter to enable such processes.

- **Model transfer from defect design model to defect analysis model**

Few studies in the literature aimed to convert integrated BIM models with defect information from inspections, into defect analysis models. It is largely because of the unavailability of an efficient method for defect analysis in the structural context, as stated in Section 2.4. For earthquake damage assessment, Anil et al. (2016) developed a transformation mechanism from BIM to representations that are suitable for strength analysis and visual assessment, i.e., a strength analysis model and damaged model. A set of entities representing cracking, spalling, crushing, rebar damage, and residual displacement were included in the damaged model. However, observed damages were used to determine the damage severity of components with a rule-based method. McGuire et al. (2016) attempted to use BIM models with defects specified at certain locations in structural or finite element software and load-rating software (e.g., AASHTOW are bridge rating). Specifically, cross-sectional geometry information and defect locations were transferred from BIM software to structural evaluation platforms. Fröhlich (2020) attempted to achieve an automated derivation process for the semantic transfer from an architectural model to representations suitable for subsequent analysis tasks, by interpreting and transferring building elements and damage information in separate steps. A structural analysis model is derived from the bridge design model using design transfer view, whereas a damage information model is intrinsically related to the digital twin using bridge reference view and additionally linked to the design model for defect analysis.

2.5 Chapter summary

To summarise, this chapter first lists common defects of concrete material by providing their definition and images. Both classical and novel methods for structural analysis are presented, and a review of the defect analysis methods is provided. Then, this chapter reviews both officially released IFC standards and academic papers on the advances in IFC-based bridge management, including the representation of defect and defect analysis in a transferred IFC structural model.

The following are the conclusions:

(1) A standardised knowledge system for bridge defects, which is aimed at supporting current bridge inspection practices with expert knowledge, is available in the existing body of knowledge. This necessitates research efforts in this field of study.

(2) For defect representation and documentation, few studies have achieved parametric modelling of defect geometry, including shape representation and spatial placement. In addition, the description of underlying logical relationships of defects is incomplete. Identification of defect inter-relationships, cause diagnosis results and maintenance decision-making would aid the subsequent managerial operations.

(3) For defect analysis, neither an efficient method to quantify the impacts of various defects in bridge structures nor an IFC-based approach to converting a defective bridge BIM into a defect analysis model is available in the literature.

3 Methodology

This chapter presents the methodology adopted in this research work. As clarified by Saunders et al. (2009), a research 'onion' is used to include the hierarchical theories for research (see Figure 3.1). The research theories can be categorised into the following layers from general to specific: research philosophy, research approach, research strategy, methodological choice, time horizon, and techniques and procedures. The research philosophy (which indicates the researcher's perspectives of the relationship between knowledge items and how it is developed) would reflect on the selection of research strategy and specific methods. Considering this, the chapter is organised as follows: Section 3.1 first clarifies the research philosophy of this work and the corresponding approaches (Section 3.1.1). Then, an overall research design diagram is presented in Section 3.2. Specific techniques and procedures for these research methods are discussed based on this diagram in Section 3.3. The discussion mainly addresses why these are employed and how these can help solve the research question. Section 3.4 concludes this chapter.

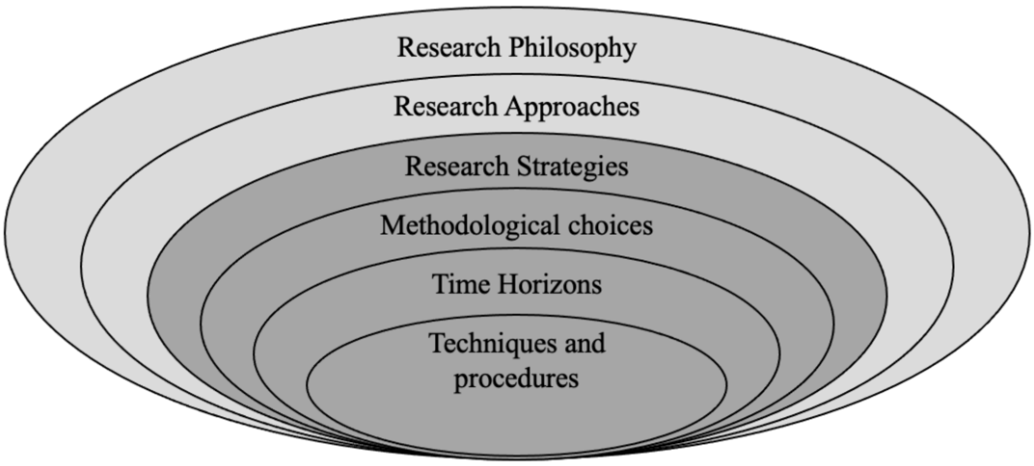


Figure 3.1 Theoretical architecture of the research 'onion' (adapted from (Saunders et al. 2009))

3.1 Question of paradigm

3.1.1 Research philosophy

As mentioned above, the research philosophy is influenced substantially by the researcher's perspective of what is acceptable knowledge and the process by which this is developed. In abstract terms, a research philosophy can be considered as a multi-dimensional set of continua, and the determination of the philosophy can be regarded as the positioning on each of the continua. There are three dimensions (i.e., questions) to consider: (1) What is the characteristic of reality? (2) What is considered acceptable knowledge? (3) What is the role of values? Table 3.1 presents the continua under these three dimensions.

Table 3.1 Research philosophy represented in a set of continua

What is the characteristic of reality?	External	Socially constructed
	Objective	Subjective
What is considered acceptable knowledge?	Observable phenomena	Subjective meanings
	Law-like generalisations	Details of specifics
What is the role of values?	Value free	Value bound

To further clarify the terminology in philosophy, these dimensions are mapped, and their converse aspects are discussed accordingly. The term ontology best describes the study of the characteristics of reality. There are two aspects of ontology: **subjectivism** and **objectivism**. With reference to the continua, objectivism asserts that 'social entities exist in reality external to and independent of social actors', whereas subjectivism considers that 'social phenomena are constructed from the perceptions and consequent actions of social actors'. With regard to the second question (What is considered acceptable knowledge?), epistemology is defined. Three aspects of epistemology are **positivism**, **realism**, and **interpretivism**. Positivism indicates that researchers prefer to collect observable data and are more likely to develop law-like generalisations. Realism considers that objects have an existence independent of the human mind. Meanwhile, interpretivism emphases on 'social actors' and prefers to interpret the social roles in line with the significances we accord to these/us. Finally, axiology highlights the role of values. When an effective position in the continua table is not applicable, **pragmatism** can be adopted. It asserts that multiple ways of interpreting the world exist and that no individual perspective is effective for visualising reality comprehensively.

Therefore, this research work reflects on the philosophy of positivism. In line with the definitions by Remenyi et al. (1998), a positivist approach to research has the following characteristics: (a) it works with observable social reality, i.e., facts, and the researcher is completely independent of the data collection process; (b) based on the gathered facts, hypotheses are tested, verified, and developed further; (c) it tends to generate law-like generalisations, assembling those produced by physical and natural scientists. It is commonly considered that a highly structured methodology would be adopted in a positivist research to facilitate replication (Gill et al. 2002).

3.1.2 Research approaches

As determined by the positivist research philosophy, the next step is to attach appropriate research approaches. According to the definitions in Key Concepts in Ethnography (O'Reilly 2009), in inductive research, the researcher begins with an open mind and minimum preconceptions, where theory is gradually developed from the data. Meanwhile, a deductive approach to research is to first obtain a hypothesis from existing theory and test the truth or falsity of the hypothesis by referring to the empirical world and collected data. Thus, deduction as the dominant research approach in the field of natural sciences generally consists of the following four stages: (1) deduce a hypothesis out of the theory; (2) operationalise the hypothesis by establishing an operational relationship between variables; (3) test the hypothesis; (4) use the outcomes to verify or modify the hypothesis. Inductive approaches are concerned more with the context and humans' interpretations of their social world, rather than developing a rigid methodology and research objects in operational forms. In certain cases, a combination of both approaches is feasible and effective.

With regard to the complete independence of the researcher from the research subject, the use of quantitative data, and the research path from theory to data, a deductive research approach is adopted in this research.

3.2 Question of methods

To develop a clear and constructive research design, the purpose of the research is first clarified. This research exemplifies an exploratory study from out of the three categories (i.e., exploratory, descriptive, and explanatory). An exploratory research enables one to determine 'what is happening, to seek new insights, to ask questions, and to assess phenomena from a fresh perspective' (Gill et al. 2002). Explanatory studies normally involve the establishment of relationships between certain variables to explain a phenomenon. Descriptive research, which is embedded in the above two types of studies in most cases, is adopted to accurately describe individuals, events, or scenarios. The following three layers are determined to complete the research design (which transforms a research question and objectives into a feasible project): research strategies, options, and time horizons.

3.2.1 Research strategies

Effective research strategies should be determined considering the philosophical commitments, their capability to answer the research question, and available resources. A few commonly used research strategies include experiment, case study, survey, and archival research. Specifically, experimental studies are designed mainly to identify causal relationships between variables. Thus, these are commonly used in exploratory and explanatory research. In general, an experiment involves an experimental group and a control group to allow for manipulation of the dependent variable. Such a strategy can be adopted in either a laboratory or the field. Unlike an experiment, which requires a highly controlled context, the case study strategy can be used to explore a phenomenon of interest within its real context (Yin 2009). Either an individual case or multiple cases can be included in the strategy. Triangulation would be necessary when multiple sources of data are involved. Survey is a strategy suitable for exploratory and descriptive research given its capability to obtain considerably more data than a case study. It can be implemented in the form of questionnaire, interview, or observation. In archival research, the main data that are collected and analysed are in the forms of archived documents and administrative records. Table 3.2 lists the above strategies and their correspondence with the various research purposes.

Table 3.2 Strategies matching research purposes

Research strategy	**Research purpose**
Experiment	Exploratory, explanatory
Case study	Exploratory, explanatory
Survey	Exploratory, descriptive
Archival research	Exploratory, explanatory, descriptive

In this study, a combination of archival research, survey, and case study is adopted. Detailed data collection techniques and data analysis procedures are presented in Section 3.3 and corresponding chapters.

3.2.2 Methodological choices

The two terms, qualitative and quantitative, are extensively used to differentiate the data collection techniques and data analysis techniques in research activities. The data collection techniques or data analysis procedures in quantitative research involve numerical data, whereas qualitative research mainly involves non-numerical data. The approach to combining qualitative and quantitative techniques and procedures is defined as methodological choices. Figure 3.2 illustrates the categorisation of methodological choices.

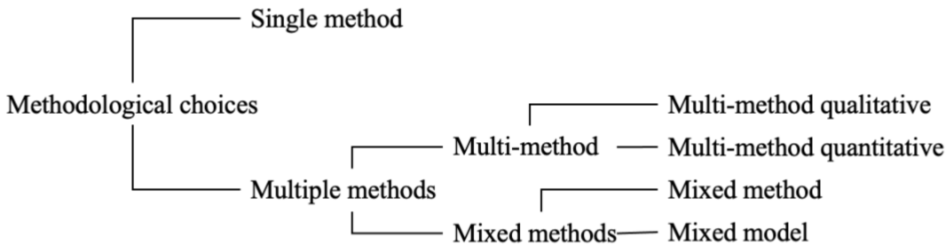


Figure 3.2 Categorisation of methodological choices

Given the short history of the mixed methods approach in social sciences research, a uniform definition of this term is unavailable in the literature. Nonetheless, an increasing number of researchers have started to regard mixed methods research as the 'third research paradigm' (Johnson et al. 2004). With regard to the intense debate and criticism concerning its terminology, a clear definition is provided by Saunders et al. (2009) by first categorising research into single method and multiple method in terms of the research choices. *Multiple method* indicates that more than one data collection technique and analysis procedure is adopted in the research. Multiple method research can be categorised further into multi-method approach and mixed-method approach. An approach to distinguishing between the two is to determine whether the collection and analysis techniques adopted belong to the same scheme of quantitative or qualitative research or not. Thus, multi-method approaches are categorised further into multi-method qualitative and multi-method quantitative. In a mixed-method study, both quantitative and qualitative data collection techniques and data analysis procedures are applied to answer the research question(s). If there is no combination of qualitative and quantitative techniques for data collection and analysis, the study is a mixed-method study. The term mixed model would be used if conversion between quantitative and qualitative data occurs.

In this research, a mixed-model approach is adopted. Here, qualitative data (e.g., inspection reports for case study) are quantified for statistical analysis.

3.2.3 Research time-horizons

To determine the time horizon of research design, it needs to be clarified whether the research concerns a phenomenon that occurs at a particular time or one that occurs over a given period. Based on this categorisation, the study can be either cross-sectional or longitudinal. Even when the research project involves a time constraint, a means to add longitudinal elements into it is to utilise open data published by various institutions, platforms, or research teams over time. This research is essentially cross-sectional because methods for IFC-based defect representation and analysis are proposed and validated using a few cases collected during the research program. A longitudinal element is incorporated in the first objective, where knowledge from inspections over the long history of bridge management is involved and collected for analysis.

Figure 3.3 presents an overview of the proposed method for this research, i.e., the research design.

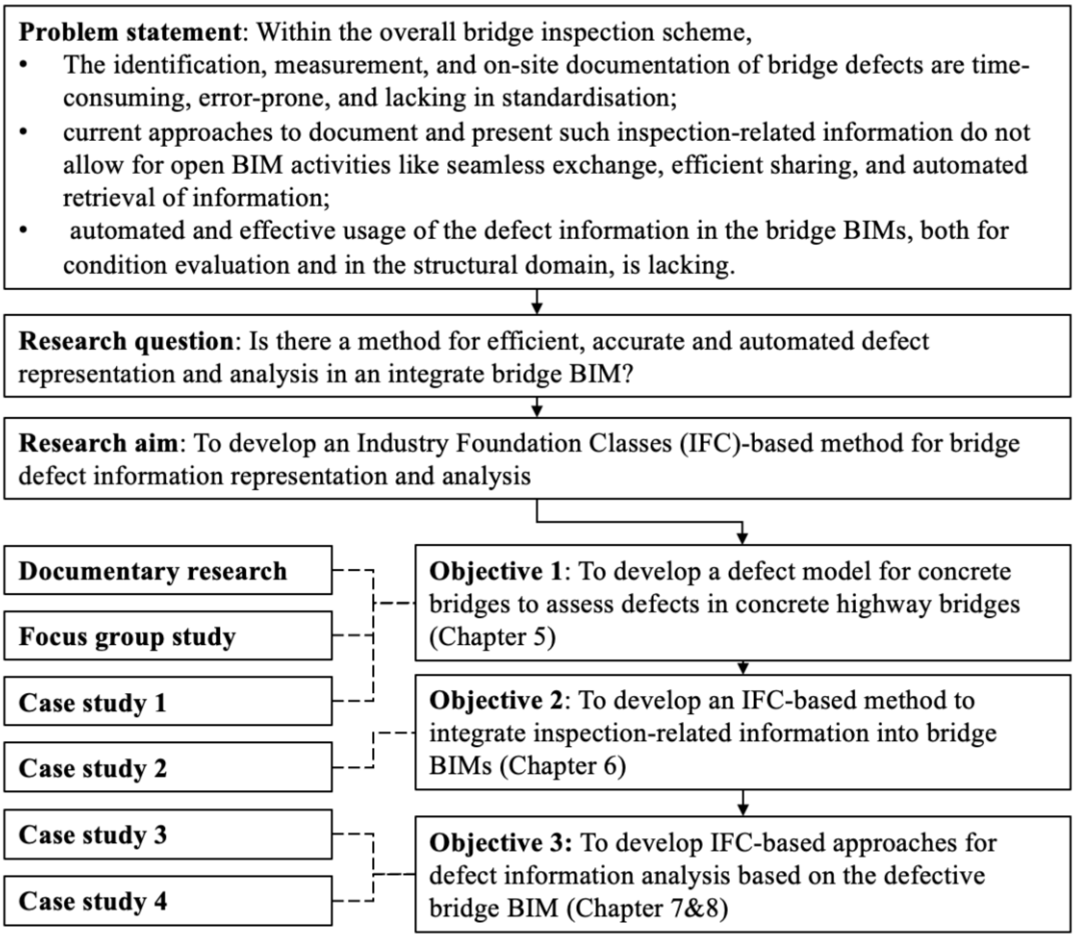


Figure 3.3 The research design

3.3 Techniques and procedures

Because this is an exploratory research with a deductive approach, the following research strategies would be employed: documentary research, focus group, and case study. These research strategies are selected mainly because of their capability to facilitate the answering of research questions and achievement of research objectives.

3.3.1 Documentary research

As indicated by Tight (2019), documentary research is the performance of a systematic review or evaluation of documents. It represents the qualitative world view. The advantages of such a research method originate from the fact that such documents exist and are conveniently accessible to researchers worldwide at a low or zero cost. In addition, rich knowledge and experience can be accumulatively recorded by previous researchers or practitioners in the field of study, which is particularly effective for early researchers. Analysis of both academic and policy literature are performed, and these are known as literature review and policy research, respectively. A variety of forms of documents can be collected and evaluated. These range from advertisements, newspapers, program proposals, and summaries to institutional reports according to the categorisation by Bowen (2009). In this research, documentary research is aimed at the initial development of the defect model in the first objective.

Data collection techniques: The following academic databases were employed: ScienceDirect, Science Citation Index, Social Sciences Citation Index, American Society of Civil Engineers (ASCE), and Scopus. Then, Google Scholar was deployed as a supplementary search tool. Keywords such as 'defect', 'relationship', 'model', 'bridge', and 'structure/civil infrastructure' for the first objective were combined to form the search string. Both academic publications (e.g., journal articles, conference proceedings, and book chapters) and documents published and/or archived in administrative organisations in the field of bridge management were included. Specifically, bridge inspection manuals and relevant guidelines issued and followed by road agencies worldwide were collected. Manuals published at a federal/national level provide generalised specifications, whereas those issued by local agencies (albeit derived from the former) provide more detailed information. Other documents include standards that are generally compiled for various civil structures (Department of Transport and Main Roads 2016; NZTA 2017) and government reports on bridge management.

Data analysis procedures: Three subsequent procedures are typically performed to analyse the collected documentary data: skimming, which is a superficial examination; reading, which refers to thorough examination; and interpretation (Bowen 2009). As a classic qualitative research method, content analysis is designed to obtain valid inferences from the text based on a set of specialised rules (Krippendorff 2018) and/or organise these into categories according to the central research question (Bowen 2009).

3.3.2 Focus group study

There are two principal means for qualitative data collection: participant observations and open-ended interviews. A focus group exhibits unique strengths and weaknesses compared with these important means (Morgan 1997). Specifically, focus groups enable the researcher to observe a considerable amount of interaction on a topic in a limited period as he/she 'controls' the focus group sessions. Through group discussions, similarities and differences in the participants' opinions and experiences can be obtained directly during the event without post analysis. Accordingly, the weaknesses of focus groups with regard to participant observations originate from the fact that the naturalism of interactions is undermined by the control. The weakness compared with individual interviews is that it is challenging to obtain an in-depth understanding of the opinions and experiences of any specific participant.

In this research, focus group study is aimed at enriching the primary defect model in the first objective. This qualitative research strategy can be effective in terms of three aspects. First, because discussions between participants on bridge inspection are adequate and no other social actions are targeted, its intrinsic weakness of a lower degree of naturalism can be overlooked. Second, the depth deficiency can be compensated for by effectively controlling the sessions. Thereby, concentrated amounts of data that are highly relevant to the researchers' interests can be obtained. In addition, a pre-interview is conducted prior to the focus groups to prepare the researcher for the intensive group discussions. Understanding of bridge inspection practices from the perspective of practitioners is obtained in advance. It is not conveniently available in the literature.

Participants: The candidate participants of this focus group are inspectors and engineers who have been involved in bridge inspection activities or analogous industrial sectors (e.g., maintenance and SHM). Two criteria are followed to select a suitable group of participants and increase the validity of the survey: (1) they have at least five years of experience in bridge inspection and longer in civil engineering; and (2) they work in different types of organisations involved in bridge management, e.g., design and research institute, department of transportation, and construction unit. Thereby, both the diversity and total number of participants can be maximised. Although opinions differ on the optimal size of a focus group, a relatively small (i.e., between five to twelve) size seems to be beneficial for in-depth conversion and effective discussions (Krueger 2014; Lazar et al. 2017; Robson 2002). In this research, a focus group of 10 experts was held and Table 3.3 lists information on these 10 interviewees. Their personal identities are omitted for confidentiality purposes. It is worth noting that all interviewees work in China, thus the results obtained through the focus group inform one context only and require further enrichment if applied to projects in other regions of the world.

Table 3.3 List of interviewees

NO.	Position/ Title	Years of experience in civil engineering	Years of experience in current position
1	Chief engineer	10	5
2	Chief engineer	19	10
3	Senior engineer	15	10
4	Senior engineer	10	5
5	Senior engineer	12	12
6	Senior bridge inspector	10	8
7	Bridge inspector	5	5
8	Bridge inspector	19	5
9	Bridge inspector	12	12
10	Bridge inspector	6	6

Data collection techniques: The event was structured in three subsequent steps. At the beginning, considering ethical issues, the authors requested consent from participants to obtain information on their position and experience. The research topic was introduced by the main researcher. The second step was to discuss the initial defect model. A questionnaire was designed and handed out to facilitate the discussions. The final step was an open question-and-answer session, which explored recommendations for further improvement. Participants were encouraged to express their perspectives on the defect model from a practical or professional perspective. The data collected at the end included (a) an audio recording of the entire event and (b) questionnaires filled out by the participants.

Data analysis procedures: On the one hand, the audio-recording was translated into text using NVivo 12 Pro software after the event. Content analysis was conducted to retrieve knowledge from the interview script, which was then combined with the initial defect model (developed in Phase 1) using a direct method. On the other hand, questionnaires collected at the end of the event were analysed quantitatively and combined to enrich the primary defect model. The outcome at this stage was an enriched version of the initial defect model, with an emphasis on the mapping of defect relationships. It is presented in Chapter 5.

3.3.3 Case studies

Case study is commonly defined as an in-depth investigation into a specific subject or bounded phenomenon in its real-life context. Its focus could be a person, a group, and an event, or an organisation. As indicated by Mills et al. (2010), the selection of cases depend largely on whether the research question is exploratory, explanatory, or descriptive, and on empirical or theoretical considerations. In this study, the case study method was used intensively as both qualitative research method and quantitative research method.

3.3.3.1 Case study 1

Under the qualitative context, the first case study was used mainly to accomplish the first objective and validate the defect model developed in previous phases. A multi-case study design was adopted because it allowed for a comparison between the cases and thereby, better served the purpose of validation. Specifically, 272 inspection reports were collected from a bridge management agency in Yunnan Province, China. All the concrete bridges under study are located on a national highway. These were inspected periodically between 2013 and 2016. The inspection reports were manually developed and documented on a network-based infrastructure management system.

NVivo is a popular software program given its capability to organise and analyse various data sources. Essentially, different types of nodes can be created upon data sources or data if these are conceptually similar. The process can be carried out manually or automatically. The software then provides several data searching and retrieval tools (i.e., queries) and data display tools including models, charts, and coding stripes. In this study, all the inspection documents were imported into NVivo 12 Pro, and only a relevant part of reports (i.e., recording of identified defects) were included in the NVivo project for analysis.

3.3.3.2 Case study 2-4

To accomplish the second and third objectives of this study, case study bridges were selected as representatives of highway bridges worldwide and used to verify the proposed IFC-based method for representation and analysis. In terms of structure types, simply-supported girder bridge, continuous girder bridge, and rigid frame bridge were included to represent the large majority of concrete highway bridges. Prestressed and reinforced concrete bridges are also addressed. Detailed information on the case study bridges, mostly in the form of constructed drawings, were collected from municipal institutions and management authorities.

Such case study bridges were modelled, and the proposed method for defect representation and analysis were tested for validation.

3.3.4 Combination of multiple information resources

It is established that deficiencies and biases can be overcome or counterbalanced to a certain extent by combining methods and/or resources of information. Accordingly, triangulation has been applied extensively. It can yield potentially more valid interpretations supported by convergence of evidence and enable a deeper understanding of the specific research question (Mills et al. 2010). The following six types of triangulations have been identified by previous researchers (Denzin 2017; Kimchi et al. 1991; Miles et al. 1994): data source triangulation, data type triangulation, investigator triangulation, theory triangulation, methodological triangulation, and analysis triangulation. In this research, given the multiple research methods employed, methodological triangulation was used. Furthermore, because method triangulation was being used, data type triangulation was also included. Considering the various analytical techniques used, analysis triangulation was included. Thus, all the above-mentioned research strategies and methods specifically proposed for each objective were combined to achieve the research aim. This is illustrated in detail in the following chapters.

3.4 Chapter summary

To summarise, this chapter illustrates various aspects from the high-level philosophical commitments to the low-level techniques and procedures of this research. Questions of paradigms are first clarified by explaining the research philosophy and research approaches adopted. Then, the question of methods is specified with regard to strategies, methodological choices, and time horizons. Furthermore, the data collection techniques and analysis procedures of each research strategy are presented. How these facilitate the development of corresponding objectives is also illustrated. An overall research design is presented in Figure 3.3.

4 Defect model for bridge inspection

4.1 Chapter introduction

This chapter presents the the evolution of the defect model from Phase 1 to 3, according to the research framework proposed in Section 3.3. The chapter is structured as follows. From Section 4.2 to Section 4.4, the evolution in terms of defect categories, defect relationships and defect patterns will be presented respectively. Section 4.5 concludes the chapter with a summary.

4.2 Framework for the defect model development

The research framework to develop the novel defect model can be best understood as a flowchart in Figure 4.1. There are three major phases, namely (1) initial defect model development, (2) defect model modification and enrichment, and (3) defect model validation and improvement. Three research methods, i.e., literature review, focus groups and case studies, are employed to retrieve knowledge and experiences. The defect model will include three major parts and accordingly, research methods were mapped to those three sub-topics, as shown in Figure 4.1. Noted that each part of the defect model, i.e., sub-model, is investigated using multiple research methods, the contributions of different sources of information to each sub-model are specified in the Results and analysis section.

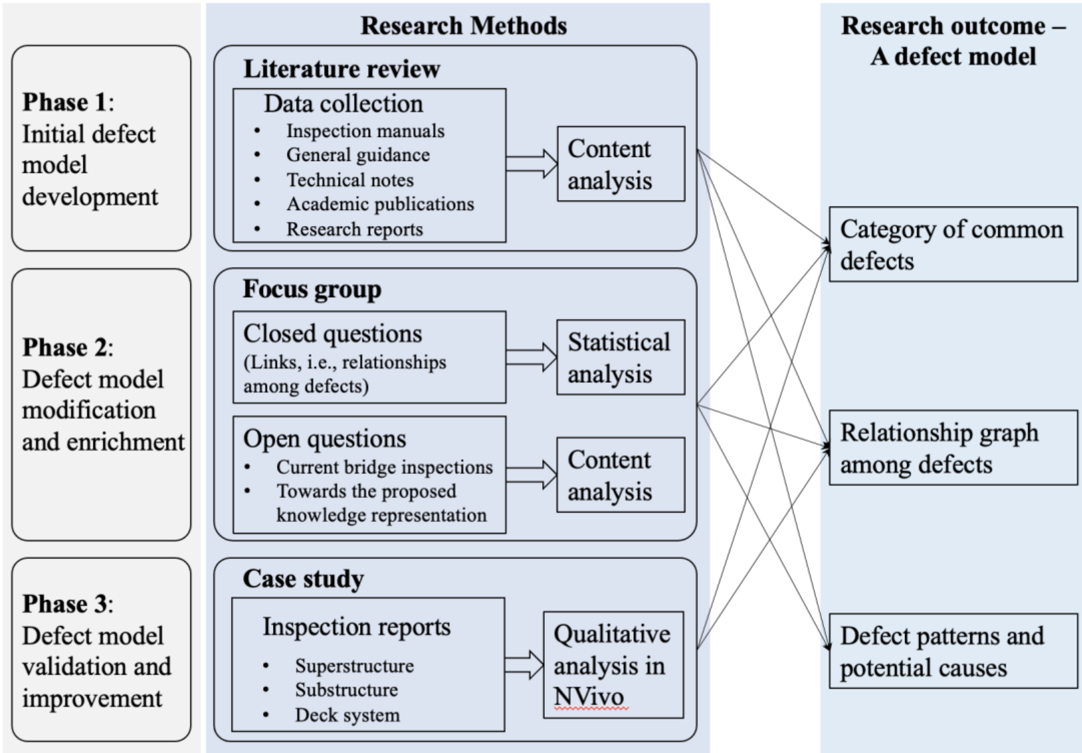


Figure 4.1 Research framework for Objective 1

4.2.1 Phase 1 - Initial defect model development

The aim of this phase is to develop an initial defect model, by first identifying common defects in concrete bridges, uncovering internal relationships among defects, and exploring their patterns. The comprehensive documentary research identified academic publications and documents published and/or archived in administrative organisations related to bridge inspection. Table 1.1 in Chapter 1 lists the manuals that were reviewed, indicating the country and agency where they were published and carried out. Knowledge was then extracted and summarised using a content analysis approach. To illustrate, for manuals and guidelines that cover not only onsite inspection but also subsequent condition ratings and maintenance decision-makings, the following two types of filters were applied to retrieve the relevant content, including:

- Level 1 and/or level 2 inspections (to exclude information on maintenance strategies) and
- Concrete bridges (to exclude information on structural steel, timber, etc.).

For the initial defect model development, a number of indicators (as shown in Table 4.1) were identified to extract relevant content which was coded accordingly.

For example, phrases such as “manifest as” are normally followed by descriptions of defect patterns. The location preference of certain defects is represented by expressions like “vulnerable at/ near/ in/ ...”, “check (defect) at (position on bridge elements)”, or simply prepositions of place. Terms like “lead to”, “result in/from”, “cause”, “due to”, etc. suggest causal relationships across various defects. The co-existence relationship is indicated by words/phrases like “accompany”, “together (with)” and “associated with (another type of defect) closely”. Since the wording in a single document tends to be uniform, once the expression pattern was identified, the text query approach was used to extract relevant knowledge. The full content was reviewed afterwards, in case any information was overlooked.

Table 4.1 Indicators related to targeted information in manuals

Key information	Indicators
Location to occur	“(most commonly) occur in/ at/ …” “has been detected in ...” “the most common example of … is found in …” “often seen at…”
Manifestation pattern	“take the form of…” “.. be an indicator that …” “appear as” “…evidenced by …” “visual signs”
Causal relationship	“… render the concrete more vulnerable to …” “… provide an environment for .. to occur” “accelerate…” “the severity of … increases until …” “cause” “result in…”
Co-presence relationship	“associated with” “accompanied by”

After the within-study literature analysis illustrated above, knowledge extracted from different documents was synthesized and presented collectively in the form of a defect model. All reviewed documents were weighted equally during the integration, given the fact that only mainstream inspection manuals were reviewed and analysed. Two major ways to enhance the representation and legitimation of the integration results include between-source triangulation and between-source initiation (Onwuegbuzie et al. 2012). The former one was used to seek convergence and corroboration of information from different documents while the latter one to discover paradoxes and contradictions, respectively. Specifically, for the categorisation of common defects, the differences between the individual documents represents an indicator of uncertainty associated with defects, which therefore were eliminated from the model. Take location-dependent defects (e.g., ASR) as an example, there are cases when one document emphasizes them as critical defects on concrete bridges while the other document skips them. To maintain the generality of defect model during phase 1, those defects were excluded. For defect relationship mapping, any divergence identified led to a re-framing of the graph, by adding or removing links between defects. As for the identification of defect properties that are critical in inspections, between-source complementarity was conducted to ensure the completeness of condition information to be collected. In this way, the preliminary defect model was established with inter-subjective comprehensiveness and reliability.

4.2.2 Phase 2 - Defect model modification and enrichment

The aim of this phase is to modify and enrich the initial defect model developed through the literature review in phase 1. To this end, focus group study in the form of semi-structured group interviews were carried out, as illustrated in Chapter 3 Section 3.3.2. To be specific, the questionnaire used as an instrument of group discussion was divided into two sections to better explore the relationship among common defects: (1) relationships among defects for a particular bridge element; and (2) inter-element relationships. For the first section, defects on major concrete elements and miscellaneous elements made from other materials (e.g., expansion joints and bearings) were studied, respectively. A n×n dimension table was designed for each part, where n represents the number of defect types. Participants were invited to rate each link (i.e., relationship between defect A and defect B) in terms of 0, 0.25, 0.5, 0.75, and 1, where 0 means there exists no direct relationship and the other scores show different levels of strength of a particular link. The entire instrument was attached in Appendix 1. In the last part of the focus group study when open questions were raised and discussed, the questions were as follows: “Do you believe this defect model can improve current inspection practices?”, “If yes, in what way it can help?” and “If not, how to modify it?”

When integrating the expert knowledge into the primary defect model, the combination of multiple complementary sources of information was achieved by conducting between-source triangulation, supplementary and initiation. Specifically, common defect categories and defect relationships in the initial defect model were reinforced when similar contents appeared. Defect categories that were not included in the initial model were either merged into existing ones with or without modifications to the original one or eliminated if there are issues of regional constraint. New links between defects in the relationship graph were only established when more than 80% participants assigned non-zero ratings to that link. When conflicts occur, further research into manuals and relevant documents was conducted to figure out the reason for contradictory information, being errors during data collection or other possibilities. If inconsistency remained, the corresponding link was removed. On top of that, all the rating results collected from the questionnaires were analysed to further enrich the relationship graph. The ratings were first filtered to leave out those of invalid links and then calculated to obtain the final score of corresponding links. Since the ratings were given based on personal judgement, a trimmed mean was computed where the maximum and minimum in a set of data were eliminated and the rest were averaged. The score of each link can be interpreted as the possibility of concurrence or casual effects between the nodes, i.e., defects.

4.2.3 Phase 3 - Defect model validation and improvement

This phase aims to validate the enriched defect model developed in Phase 1 and 2 using case studies. A total of 272 inspection reports were collected from a bridge management agency in Yunnan Province, China. All studied concrete bridges are located on a national highway. They were inspected periodically between 2013 and 2016. Inspection reports were manually created and documented on a network-based infrastructure management system.

The structure of the inspection reports is in line with the logic underlying bridge condition assessment in practice. They include two major parts: a record of on-site inspection outcomes, and a table assessing the bridge's overall health condition. In the first part, there is basic information on the targeted bridge, including the route it belongs to, SLK (Straight Linear Kilometre) number, and the total number of primary elements that are inspected, i.e., girders or/and slabs, pier columns and pier caps. Defects are then recorded according to their location of occurrence, namely superstructure, substructure and deck. For every identified defect, their critical features, such as width, length and location of cracks, are indicated. Pictures were captured and attached for major defects. The second part illustrates the hierarchical condition rating system, from the element level to the entire structure. Table 4.2 lists elements for the three major groups in bridges.

Table 4.2 Bridge elements and element groups

Superstructure	Principal bearing elements	Deck	Decks
	Secondary bearing elements		Wearing surfaces
	Bearings		Expansion joints
Substructure	Foundations		Kerbs and sidewalks
	Abutments and wing walls		Approach, approach slabs and ramps
	Piers		Drainage and deck drains
	Retaining walls		Railing systems
	Embankment and slope protection systems		Signs and other attachments
	Streams and waterway		

During this phase, the collected inspection reports were quantitatively analysed and the results were compared to the enriched defect model (from phase 2). Such comparison can validate the ability of the developed model to support current inspection practices and further improvements can be achieved. Specifically, all documents were imported into NVivo 12 Pro, and only the first inspection reports (i.e., recording of identified defects) were included in the NVivo project. First, individual defects were counted for their frequency of occurrence in the observed 272 cases, to validate the list of common defects on concrete highway bridges. Specifically, each report was coded as a “case” while each defect type was coded as a “node” in the project. Links between them were established, by coding descriptions on the type of defect in each report at the corresponding node. By counting the number of these coded references, dominant defects were identified and illustrated as hierarchical charts. And after comparing to the previous findings (from Phase 2), common defects were corroborated and further sort out based on their frequency of appearance in the studied region. Secondly, the defect relationship graph (from Phase 2) was targeted for validation. Since inspection reports record the condition of bridge components at a certain time, causal relationships can’t be observed. However, by counting the frequency of concurrence of defect pairs, their association relationships were investigated. In NVivo, cluster analysis was deployed to explore correlations between defects, in terms of the similarity of their references. For each pair of defects, the Pearson correlation coefficient was calculated to estimate the possibility of their concurrence. The calculation results were integrated to the link scores (from Phase 2) using a weighted average method. The ratio was set at 1:10, given the limited number of inspection cases studied. The result did not necessarily cover all the relationships identified in previous phases, yet a considerable number were verified and improved where applicable. Finally, by looking at the descriptions of identified defects more closely, critical patterns that should be recorded during inspection practices were further confirmed.

Collectively, an improved version of the defect model was created, including three major parts, categorisation of common defects, relationships among the identified defects, and mapping between property, cause and defect.

4.3 Results and analysis

The results of the defect model development will be presented in this section. Defect categories with regard to bridge elements, inter-relationships among defects, and mapping from defects to their property and causes are developed based on the aforementioned three phases.

4.3.1 Defect categories

The identification of bridge defects, especially dominant ones, is instrumental to the entire defect modelling process. The final defect categorisation results are presented in Table 4.3, and the contributions of phases 1-3 are marked accordingly.

The first phase identifies the majority of defect types (defect in black in Table 4.3) and confirms the categorisation criteria of these defects. As suggested in Ontario Structure Inspection Manual (Ontario Ministry of Transportation 2008), bridge defects are categorised into two groups: material defects and performance deficiencies, which are further divided based on bridge elements. Concrete defect contains generic deteriorations that can occur in concrete components. The scope includes major load-carrying elements in both the superstructure and substructure. Other elements listed in Table 4.2 consist of various materials such as asphalt pavement, sliding plate in bearings, sealant in expansion joints, and so on. Performance deficiency refers to the failure of a particular bridge element to fulfil its designed function. For example, superstructure is evaluated according to its capability to carry and transmit loads to the substructure without excessive deformations and/or vibrations. Under this group, malfunction of expansion joints/bearings is defined as a restriction of their designed movement or insufficient reserve for anticipated movement. Joints are especially subjected to the accumulation of debris in the gap, which imposes constraints to potential future movement.

Table 4.3 Common defects on RC Highway bridges

Material defect		**Performance deficiency**
Concrete defect	**Other material defect**	
Structural cracking*	*Wearing surfaces*	*Bearing*
Non-structural cracking*	Pothole	Missing
Corrosion of rebar	Cracking	Non-uniform contact
Exposed reinforcement*	Spalling	Misalignment/ movement
Spalling	Delamination	*Expansion joint*
Delamination	Surface defects[2]	Leakage
Scaling	*Expansion joint*	Misalignment
Disintegration	Material damage*	Malfunction
Leakage	De-bonding	*Superstructure*
Deposits, e.g., Efflorescence	*Bearing*	Excessive vibration
Other surface defects[1]	Corrosion of steel components	Deformation
Honeycombing	Material damage*	Movement
Pop-outs	Rotation/ deformation	*Substructure*
Leakage	*Drainage*	Settlement
Patch/ repair	Material damage	*Drainage*
Abrasion/ wear	*Waterway*	Blockage
Fire damage	Scour	Improperly positioned discharge
Impact damage		*Approach slab*
		Misalignment
		Settlement

[1] Other surface defects on concrete elements include discolouration, stratification and cold joints.

[2] Surface defects of wearing surfaces (i.e., pavement) include flushing, slippery surface, rutting and distortions like heaving.

*Changes in phase 2 are marked with an asterisk.

A few modifications were added according to the group interviews conducted in phase 2 (marked with an asterisk). In particular, concrete cracks are further categorised into structural and non-structural, where the former requires investigations on causes and can be associated with other defects. The latter affect bridge durability but not necessarily structural safety. Another notable change is to include exposed reinforcement since it can either visually present the extent of reinforcement corrosion or indicate other damages. Material defects of expansion joints and bearings are simplified. These elements consist of several materials and their composition varies across different types. Thus, material damage includes corrosion of steel components, if any, and integrity of other materials (e.g., sealants in joints, elastomeric pads and plates in bearings). Other materials can suffer from cracks/splits/tears, abrasion/wear, loss of resilience (for seal/sealant of joints) and missing parts.

A strong emphasis was placed on the inspection of bearings and joints. Bearings play a vital role in transmitting loads from the superstructure to substructure. Thus, their distresses can function as a cause leading to explicit/implicit performance issues. For example, bearing deformation is caused by shear force or eccentric compression, and in some cases, evolves into excessive rotation. Abnormal contacts between bearing surfaces and adjacent components (i.e., girder/slab it supports or bearing seat) can introduce detrimental stresses and thereby result in damage.

During phase 3, defects are further sorted out according to their frequency of occurrence in real-life cases. The analysis results show that cracking, corrosion of reinforcement and exposed rebar are dominant in reinforced concrete components. As for other materials, pavement, as wearing surfaces, and expansion joints carry intensive vehicular loads and are thereby vulnerable to cracking and other surface distresses. Performance deficiencies of bearings and joints are prevalent, followed by insufficient drainage, while functional failures of primary load-bearing components are less common. Figure 4.2 lists the pictures of a few common defects on non-concrete elements.

(a) Deformation of bearings

(b) Misalignment of bearings

(c) Missing bearings

(b) Non-uniform contact in bearings

(e) Defects on the pavement

(f) malfunction of expansion joint

(g) Misalignment between superstructure and substructure

Figure 4.2 Defects on non-concrete elements

4.3.2 Defect relationships

Defect relationships are developed on the basis of identified common defects, which are presented as a knowledge graph in Figure 4.3. It can be observed that the entire graph is divided into seven parts according to the physical hierarchy of bridge structures. It can be viewed from top to bottom, and includes approach slab and pavement, superstructure and expansion joints, bearings and drainage, substructure and waterway. Relationships modelled in the graph include cause-and-effect relationship (i.e., links with arrows) and concurrence relationship (i.e., links without arrows). A causal relationship means the defect at one end will develop into/give rise to the other defect, while concurrence relationship means the linked defects are closely associated. Links are quantified in terms of their strength of relationship, where applicable. The scores of links can be interpreted as follows: (a) A score of zero means that two defects exclude each other on a bridge or one defect won't encourage the formation of the other; (b) A link scored at 1 indicates that one defect must accompany the other to occur, or one defect must lead to the formation and development of the other; (c) Scores between (0, 1) represent the possibility that a certain relationship exists in real-life cases.

Phase 1-3 all contribute to the formation of this relationship graph. To be specific, links marked as double solid lines are created in phase 1, which are mostly inter-element relationships for concrete components. While links marked as a single solid line are created in phase 2. The rating results obtained through the focus group and statistically analysed afterwards are assigned to those links. All scores are rescaled to [0, 1]. Phase 3 validates this relationship graph (association relationships in particular) with real-life cases. It is worth noting that manuals and other literature pay considerable attention to deterioration mechanisms and causes, such as carbonization and chloride ingress that led to the corrosion of reinforcement, Alkali-Aggregate Reaction (AAR), and so on, and map them to visible defects. In contrast, studies on real-life inspection reports concern defects that can be measured and evaluated with less causal analysis. Regarding such discrepancy, only measurable defects are included and mapped at this stage.

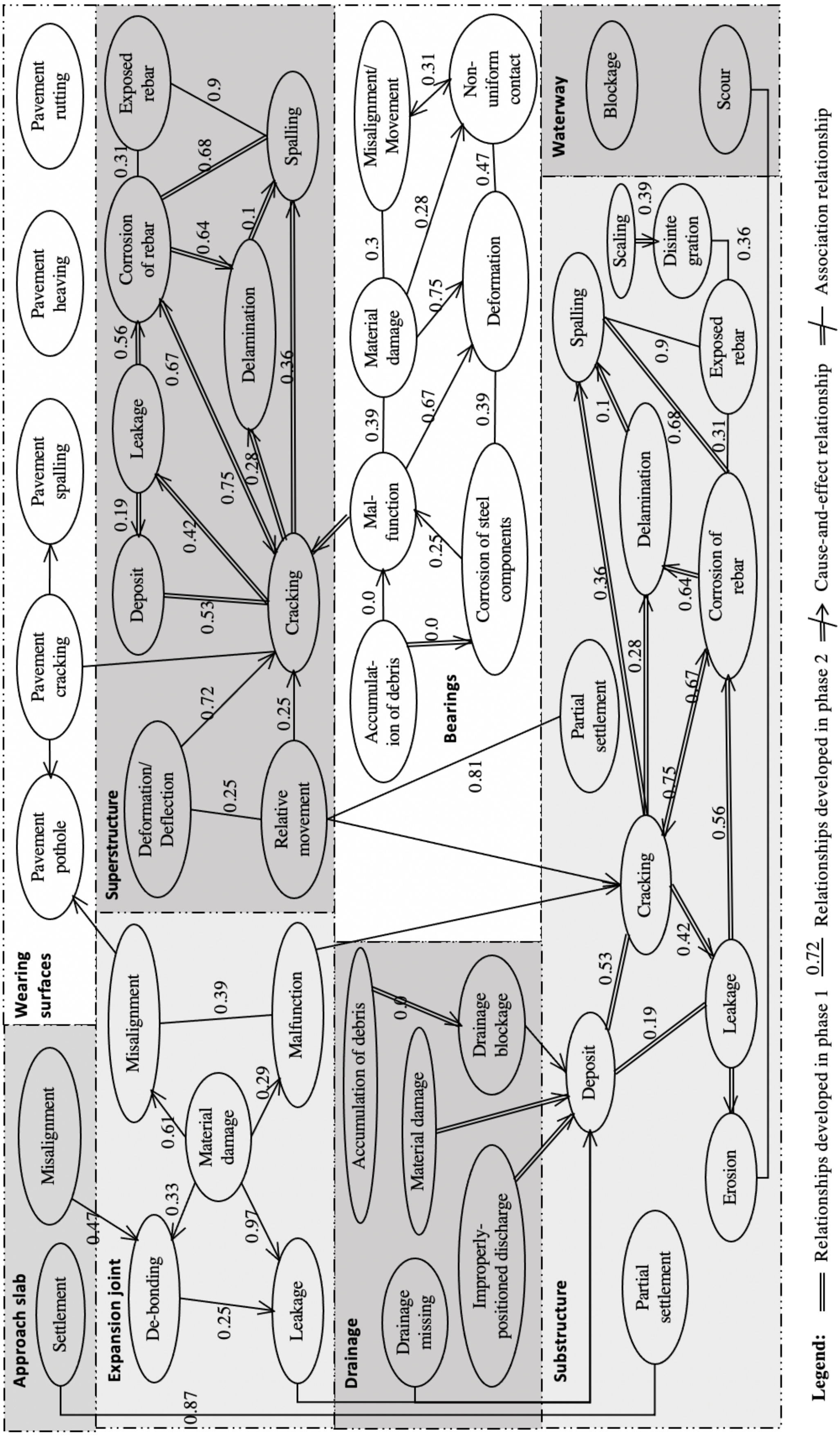


Figure 4.3 Defect relationship graph

The intra-element relationships of concrete components are clear. There are a few paths of defect development. For example, scaling, if allowed to grow, evolves into disintegration. Corrosion of reinforcement, due to the increase of its volume, results in cracking, delamination and/or spalling. For this reason, spalling is always accompanied by exposed reinforcement which is likely to be corroded. Cracking leads to concrete leakage, and such an environment with moisture greatly promotes the corrosion of rebar and the formation of deposits. Other surface defects, such as honeycombing, pop-outs, etc., have little impact on bridge safety and are in inertia in most cases. Deflections exceeding serviceability limits always result in cracks at the section with maximum stress.

For other bridge components, similar defect evolutions can be observed. On expansion joints, material damage sometimes accounts for the loss of bonding between the seal and its adjacent pavement, which further affects its watertightness. Alternatively, defects such as cracks, splits, tears or holes in the sealant will also allow for the leakage of road drainage. A leaching joint can lead to a series of deteriorations on the substructure. Other material issues on anchorage devices and welded connections tend to evolve into misaligned joint components, negatively impacting the safety and comfort of road users. The worst condition for joints is malfunction, regarding their ability to absorb the relative movement of their adjacent materials. Accumulation of debris is mostly responsible for this behaviour in real cases. When it comes to bearings, either the corrosion of steel components or damage to other materials can lead to their deformation. A uniform contacting surface between bearing and superstructure/substructure is vital to an even stress distribution. Excessive eccentric compression or shear force gives rise to deformation, movement and even failure. Failure of bearings can also result from damages on materials that are responsible for movement adjustment.

The inter-element relationships are always in line with the transmission of forces throughout the entire bridge structure. For example, the lack of reserve for potential movement (e.g., temperature-induced expansion) at expansion joints can lead to several distresses. On one hand, it can evolve into movement of the entire beam and/or bearings. Such lateral movement of the superstructure accounts for numerous cases where blocks for seismic protection suffer from spalling and even reinforcement exposure. On the other hand, additional forces transferred to the substructure (ballast walls, in particular) can lead to cracking. Another example revolves around the malfunction of bearings. In the early stages, there is abrasion at the bearing surfaces of the superstructure/substructure, which reduces cover to reinforcement. In worse cases, additional restraints to movement might lead to deformation and/or distortions of the girder it supports. Essentially, any alterations to the structure, in terms of support conditions, external loads and constraints, can bring about safety issues. They will manifest as non-surface defects such as structural cracks. Also, since superstructure and substructure work closely together to carry loads and function, changes in any one part (e.g., partial settlement of substructure due to scour in stream bed and embankment) propagate to the other.

Another group of inter-element relationship concerns non-structural factors. Defects on wearing surfaces are not regarded as structural damage themselves, but they can function as insightful indicators to problems in the structure. The transverse cracks running through the bridge deck, located near an expansion joint and in parallel with it are caused by excessive tensile stresses at this section. Accordingly, it is reasonable to infer that cracks on the beam underneath are extensive. Vertical misalignment of expansion joints and approach slabs cause vehicle bumping at bridge head, which applies increased impacts on road pavement and might lead to distresses such as potholes and pattern cracks in the long run. When it comes to durability, a major concern is moisture. It creates a favoured environment for the development of multiple deteriorations. The improper-positioned discharge of drains can cause deposits and erosion locally, and the same applies to leaks at expansion joints. Blockages in drainage due to debris and insufficient drains cause standing water on roadway, in voids of girders/slabs (e.g., box girder) and at bearings, posing safety issues to road users and accelerating the deteriorations of construction materials.

4.3.3 Defect patterns and potential causes

Bridge inspection practices take two factors into account to facilitate subsequent decision making, namely defect properties and preliminary diagnosis results. Comprehensive descriptions can not only support condition assessment but provide engineers with solid ground to infer hidden causes. Also, defects of the same type require different maintenance actions given their properties. For example, cracks whose width exceeds 0.15mm require grouting method while hairline cracks only need closing treatment on the surface. Table 4.4 lists defect properties that are critical for condition assessment and thus are targeted during inspections for common concrete defects. It is mainly based on the study in phase 1, with additions from phase 2 highlighted in bold. Without a doubt, numerical measurement of defects, e.g., width, length, depth and area, are critical, since they indicate the severity of the defect (Ryall 2010a) and can be potentially used to quantify their impacts on structural stiffness/strength (Fröhlich 2020). Aside from this, the position information of identified defects is instructive (The Concrete Society 1982). Cracks located at a highly stressed section of bridge, aided by other details of its appearance, can be categorised as structural. While supplemented with orientation information, given that cracks initiate at the wide end and evolve towards the narrow end, more patterns can be obtained. For example, longitudinal cracks occur frequently in primary load-carrying elements such as the main girder and slabs, while abutments (especially ballast walls and wing walls) and piers (pier caps, in particular) suffer from vertical cracks. In addition, the evolving direction of cracks in the vicinity of reinforcement can further indicate clues to its root cause. The presence of repairs should also be noted, since they cover the development of previous defects which are subjected to further deteriorations. Examples are radial cracks surrounding a patch, deposits or other signs of leakage near a sealed crack.

Table 4.4 Critical properties of defects for bridge inspection

Defect	**Critical property**
Cracking	Width, length, depth, spacing, orientation; **Position** Structural or non-structural
Delamination	**Position**, area
Spalling	**Position**, area, depth
Exposed reinforcement (corroded)	Loss of section
Leakage	Area, presence of sealed cracks
Scaling	Position, area, depth
Disintegration	Position, area, loss of section
Deposits	Position, area
Honeycombing	Area, depth
Pop-outs	Area, depth
Abrasion	Area, depth
Deflection	Maximum deflection

The root cause of defects, in some cases, determine the maintenance strategy. For example, spalling caused by reinforcement corrosion require the rust cleaning and concrete re-pouring. While for spalling due to insufficient structural bearing capacity, structural strengthening should be properly done. Nevertheless, the diagnosis of bridge defects in real-life cases is not straightforward. There always exist multiple contributing factors and additional investigations are needed to uncover hidden ones when necessary. Figure 4.4 categorises potential causes into five classes, from the bridge design stage, to construction and operation phases. It is generated based on the literature (phase 1) and interview of the focus group (phase 2). Adverse factors during their service life further include physical effects, chemical actions and structural issues. The figure also presents a few examples. For instance, the formation of cracks can be traced back to construction phase, when plastic cracks and thermal contraction cracks develop due to inadequate curing and the poor quality of the material. Their location and pattern follow some trackable rules, though with a certain level of variations. An in-depth study of non-structural cracks in concrete can be found in (The Concrete Society 1982). Structural cracks are normally linear, progressive and detrimental to both durability and safety. They do not necessarily follow patterns, since the structure type, load type and environmental factors will combine to cause cracking. Some common locations in a simply supported RC bridge that is vulnerable to cracking are listed in Figure 4.4.

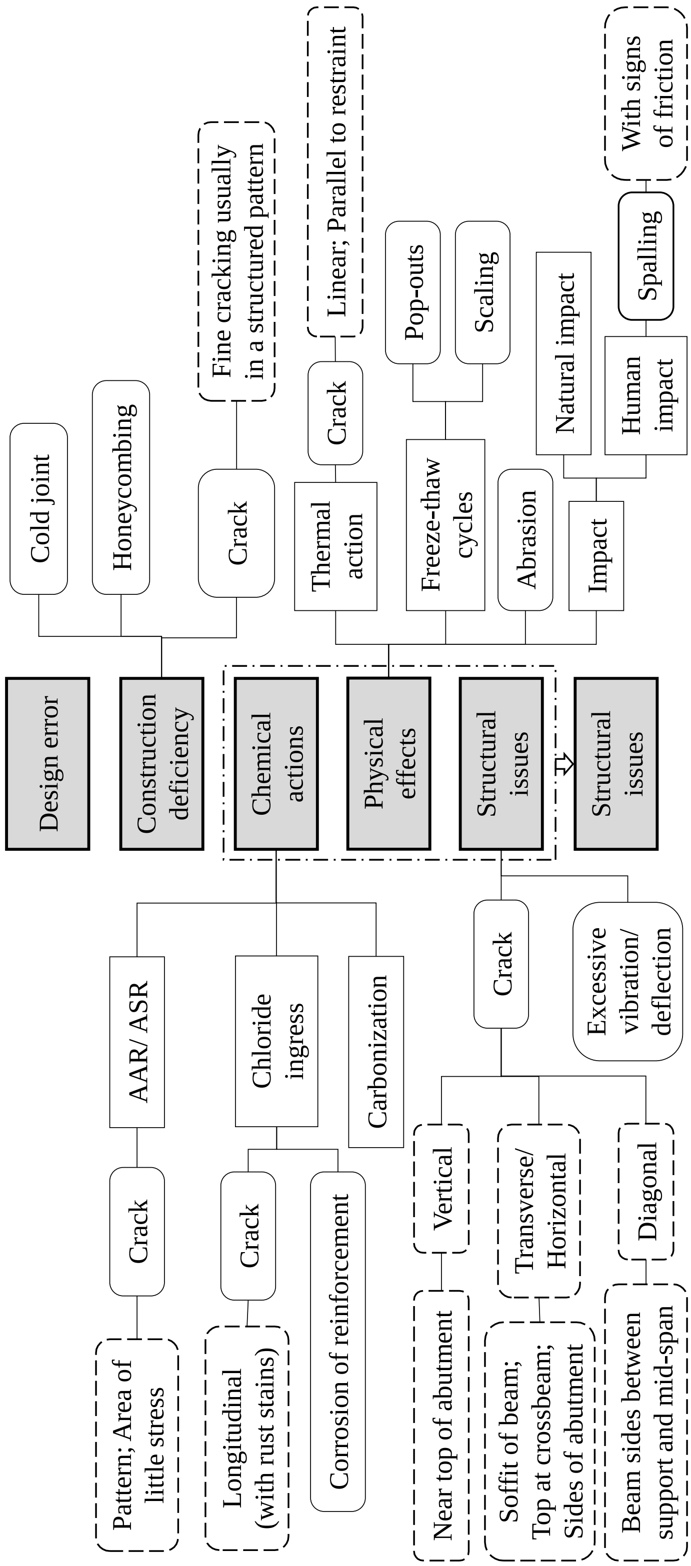


Figure 4.4 Potential causes of defects with examples

4.4 Chapter summary

To summarise, this chapter illustrates the research framework to develop the novel defect model for bridge inspections. The outcome regarding the first objective is then presented, by first categorising common defect with regard to physical entities (i.e., bridge element), establishing internal relationships among those defects, and relating defects to their properties and potential causes. Contributions of three phases in the research framework to the outcome were specified as well.

5 IFC-based method for defect documentation and representation

5.1 Chapter introduction

This chapter presents the development of a documentation and representation method for inspection-related information using IFC and its validation on a case study bridge. The structure of this chapter is as follows: Section 5.2 presents the framework for the proposed method to integrate inspection-related information in bridge BIMs. Section 5.3 presents the case study, whose results are included in Section 5.4. The last section concludes.

5.2 Proposed methods based on IFC

This section illustrates the methods used to achieve the second objective proposed in Chapter 1, which is to develop an IFC-based method for defect documentation and representation inspection data for bridge assets, with special focus on the parametric modelling of defect information. Figure 5.1 illustrates the framework of the proposed method which includes three main modules: (1) Data modelling of inspection tasks; (2) Data modelling of individual defect; and (3) Data modelling of defect relationships. Each of them is explained in detail in the following sections. To note, the entire modelling scheme was developed based on the latest release of IFC Standard, i.e., IFC 4x3 (buildingSMART International 2020).

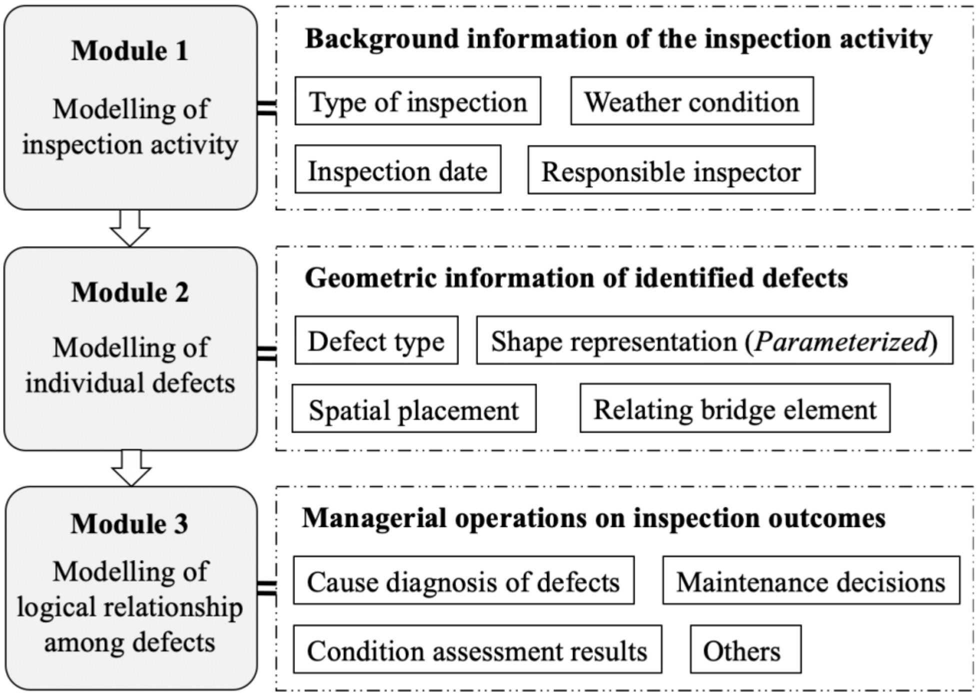


Figure 5.1 Framework of the proposed IFC-based modelling scheme

5.2.1 Module 1 - Data modelling of inspection tasks

This module aims to model different types of inspections and their associated background information through IFC schema (see Figure 5.2). To represent the inspection activity itself, an existing IFC entity, IfcTask is used which is a subtype of IfcProcess. IfcTask was originally designed to describe an activity scheduled in a construction project and has been generalised to cover a range of design and operation-related activities as well. Various inspections, e.g., general inspection, detailed visual inspection and special inspection, can be nested by an overall "Inspection" task entity and specified with IfcTask.Name accordingly. Time information (e.g., schedule start, schedule finish and duration) can be defined using IfcTaskTime and then link to IfcTask directly. Routine inspections normally have a fixed frequency, thus can be defined through IfcTaskTimeRecurring alternatively. Special investigations that are requested upon notable deficiencies discovered during regular inspections can be defined as successive process of regular inspections. The sequential relationship is defined using IfcRelSequence. All the other necessary information such as the weather condition on inspection date can be recorded in IfcTask.LongDescription.

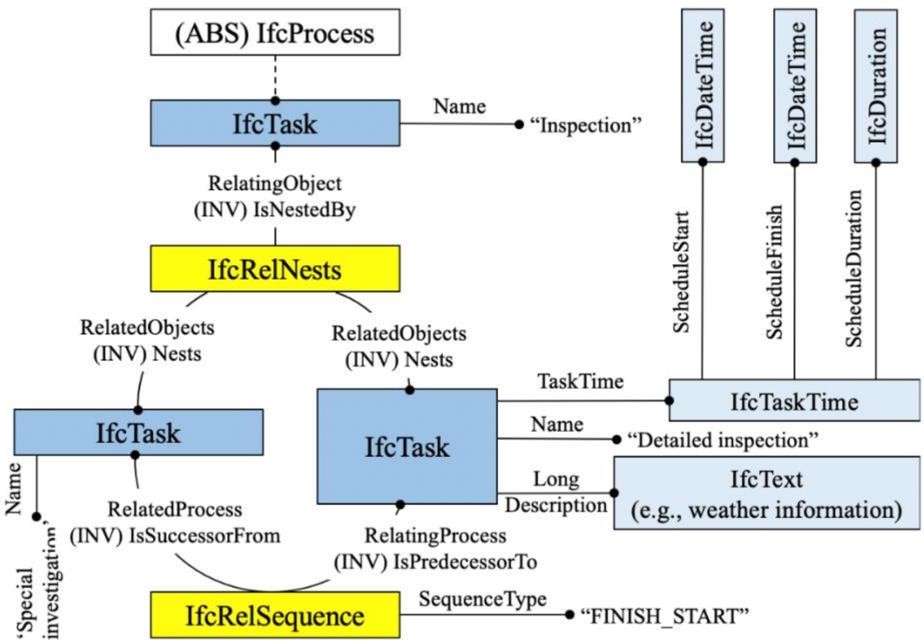


Figure 5.2 Data Modelling of inspection tasks

According to the definition of an IfcProcess, the inspection task takes bridge elements that are checked for physical integrity and functional satisfaction as input and outputs identified defects. For programmed inspections (i.e., general inspection and detailed inspection), the entire bridge is normally inspected, while for special investigations (e.g., underwater inspections), certain bridge parts like foundation are targeted. The input - output relationships are established using IfcRelAssignsToProcess, which assigns bridge elements to inspection task, and IfcRelAssignsToProduct, which assigns inspection task to identified defects, correspondingly. The diagram of these relationships is embedded in Figure 5.6 - 3.1.

5.2.2 Module 2 - Data modelling of individual defects

The second module aims to model individual defects parametrically, in particular their geometry. An added enumeration type, DEFECT, for IfcSurfaceFeature is now available since IFC4x2 to describe distresses that are identified on the surface of bridge element. Given its inheritance from IfcElement, it is capable of modelling concurrence cases where multiple defects are present and locating close to each other, e.g., spalling and radial cracking around it, using aggregation relationship. As for the connection between defects and the respective bridge element it locates on, a whole/part relationship, rather than a spatial containment relationship, is used. The following paragraph describes the geometric modelling of defect objects with a parametric approach, including shape representation and spatial placement.

5.2.2.1 Shape representation

A simple way to document the shape features of defects in IFC is to use the concept 'property sets for objects' (i.e., IfcObject o-- IfcRelDefinesByProperties --o IfcPropertySet). The properties can be stored in the form of single value, bounded value, enumerated value, list value or table value. Yet this method couldn't visualise the defect directly on the bridge element. To meet the requirements for representation and future usage, defects are first categorized based on their impacts on structural elements, as inspired by (Fröhlich 2020) and modified. One major group of defects affects the dimension of corresponding bridge elements, such as spalling that manifest as a loss of mass, corroded reinforcement that reduces the effective tensile are and cracking that clips the member's cross section to certain extent. The other type of influence from defects regards the stiffness or strength of bridge element, which can be quantified in terms of material properties, e.g., effective and cracked stiffness proposed in Eurocode (EN 1992-2 2005). A parameter study to calibrate the deterioration model might be necessary. In this work, the former group of defects is targeted. Defect geometry is not only presented explicitly but generated from a full set of parameters. An IfcShapeRepresentation entity is used and assigned to the defect object (i.e., IfcSurfaceFeature) through IfcProductDefinitionShape, following which a variety of geometric representation items are used to define its shape. Figure 5.3 is the illustration of defect's shape modelling.

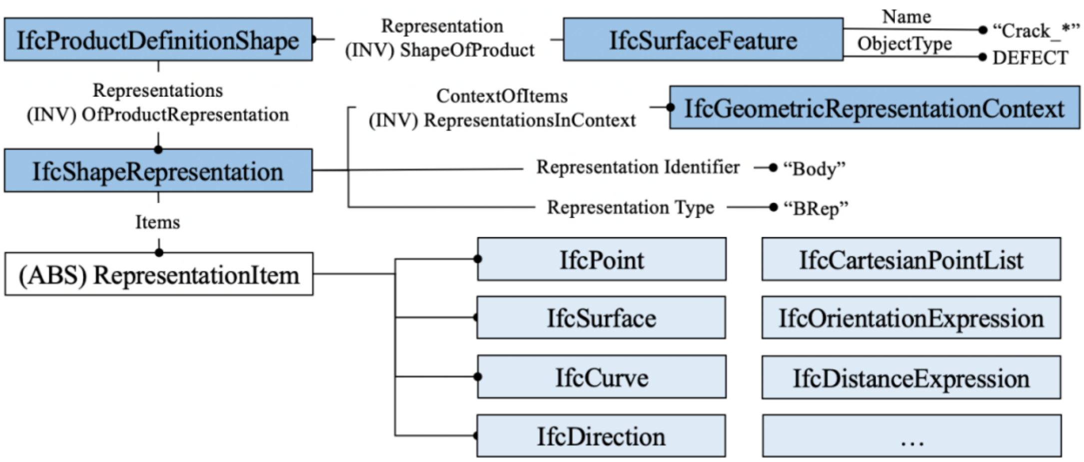
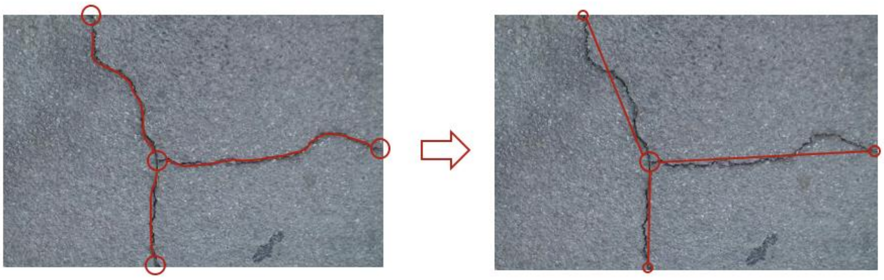
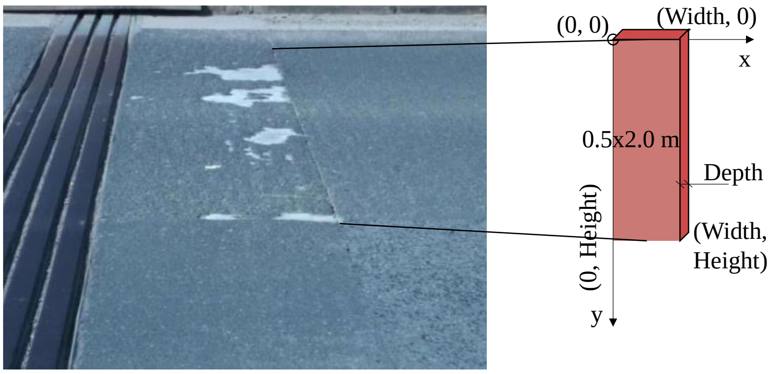


Figure 5.3 Modelling of defect's shape representation

According to the critical properties of bridge defects that are normally collected during inspections, as listed in Table 4.4, the most applicable geometric model is determined to be “Body”. Suitable representation types that can be predefined range from solid models (e.g., Brep and CSG) to Surface model. For defects whose depth are measured during inspection and documented as critical properties, solid models are adopted. Take crack (load-independent cracks, in particular) as an example of linear defects, its geometry can be generated from a few key nodes (e.g., end points and turning points) and links between them with a given thickness (i.e., width of cracking). For complex cracks like map cracking and crazing, critical nodes to be captured and used for modelling will additionally include intersections and bifurcations. The twisting curves can be simplified into straight line segments as illustrated in Figure 5.4 (a). Two different modelling methods (i.e., WireFrame and Surface) for cracks were tested. In the first approach, as shown in Figure 5.5 (a), key nodes of cracking (i.e., end points for linear cracks, end points and intersecting points for map cracks) were first determined to define crack segments (represented using IfcCompositeCurveSegment). Those curve segments then constituted the shape of this crack object, i.e., IfcCompositeCurve. As for the second method (as illustrated in Figure 5.5 (b)), a crack surface was generated by sweeping its width (using IfcArbitraryOpenProfileDef) along the length direction. This method can be used to model complex geometry as well, as long as key points on its skeleton are identified.



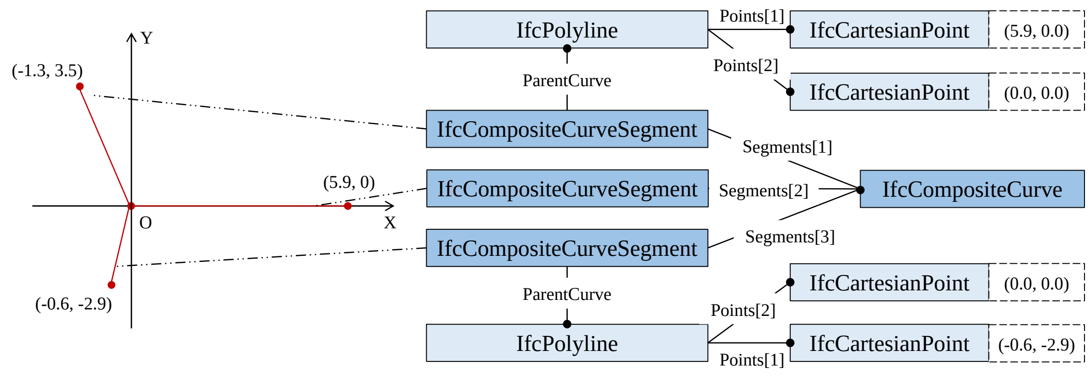
(a) Illustrations of crack shape representation



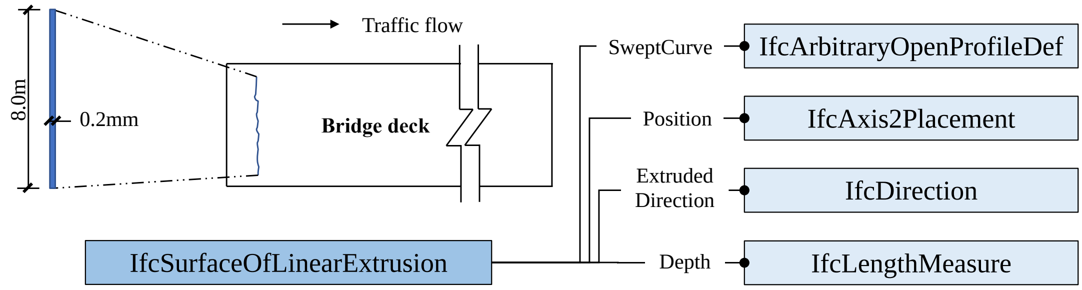
(b) Illustrations of pavement patch representation

Figure 5.4 Illustrations of different types of defects and modelling methods

When it comes to faceted defects like spalling, scaling, etc., delineation of the outer-bound curve in the form of polygon is vital and can be described with IfcPolyline. According to a survey to 272 inspection reports by authors, the width and height of faceted defects are recorded in addition to their areas. For this reason, the defect surface can be defined in the local coordinate system by four vertexes, as indicated in Figure 5.4 (b). Together with depth information, an IfcExtrudedAreaSolid is used to represent. Table 5.1 lists the shape representation for different defect types. In both cases, either surface or solid model can be defined as the representation type, considering whether depth information is vital for later analysis. It is worth noting that although the depth of these defects is neither necessarily collected during inspections nor easily measurable in practice, the completeness of such information is beneficial for later usage, e.g., to quantify the reduction of effective cross section for load-bearing (Fröhlich 2020). For surface defects like leakage and deposit, Surface model is employed and similar approaches to parametrize the defect geometry can be applied.



(a) Crack modelling as Wireframe using IfcCompositeCurve



(b) Crack modelling as Surface using IfcSurfaceOfLinearExtrusion

Figure 5.5 Two modelling methods for surface cracking.

Table 5.1 Defect types and shape representations

Defect types / Representation type	Linear defects Surface cracks	Faceted defects Spalling and scaling
Surface	IfcSurfaceOfLinearExtrusion	IfcCurveBoundedSurface
Solid model	IfcExtrudedAreaSolid	IfcExtrudedAreaSolid

5.2.2.2 Spatial placement

Another vital property for almost all types of defects is spatial placement, including position and orientation (for linear defects in particular). Descriptions of these features in inspection reports, for example, can be expressed as “a certain distance away from a reference position, e.g., the end of the main girder” and “developing vertically from the top of abutment”. For this reason, an efficient approach to position an individual defect is by referring to the bridge element it locates on. Essentially, the local placement of an IfcSurfaceFeature entity is defined by IfcLocalPlacement, which creates a local coordinate system by relating to another local coordinate system (i.e., the respective bridge element’s coordination system). The relative positioning of these two local coordinate systems is then defined with an

IfcAxis2Placement entity and related to IfcLocalPlacement through the RelativePlacement attribute. The oriental transformation from the reference coordinate system to the local one can be specified in IfcAxis2Placement.RefDirection. Figure 5.6 indicates the modelling of certain defect's spatial information based on parameters for the transformation of coordinate systems and local positioning. In addition to the spatial relationship, defect objects are directly associated to the respective bridge element through a whole-part relationship, which is defined using IfcRelAggregates.

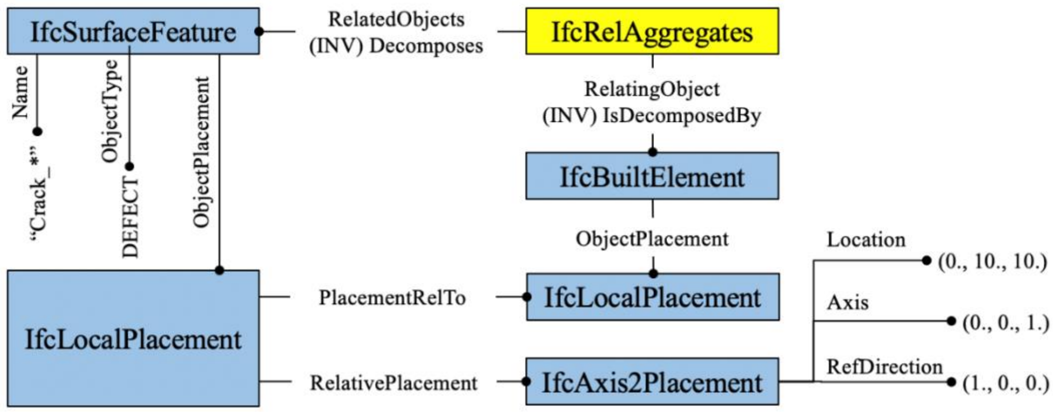


Figure 5.6 Modelling of defect's spatial placement

5.2.3 Modelling of inter-relationship across defects

The last but not least important module is to represent the logical relationship among identified defects, with the aim to support a range of managerial operations such as cause diagnosis and maintenance decision makings. The inter relationship across defects is manifold. For example, since a majority of road agencies and authorities worldwide conduct element-level inspections on their responsible bridges, defects can be grouped for the purpose of condition rating and assessment (AASHTO 2019). Specifically, defects that are present on the same bridge element will be combined for evaluation, so as to determine the condition of this structural member. Thus, the logical relationship for the purpose of condition evaluation is their spatial relationship at the same time. Figure 5.7 represents the modelling of another two logical relationships across defects. (a) Defects can be inter-related based on their root causes. Several defects that locate on different bridge components can be derived from the same underlying issue. For example, cracking and/or a heaving pavement near the end of bridge might be caused by the performance failure of expansion joint. The insufficient ability of expansion joint to accommodate the movements of the superstructure will manifest as an abnormal joint gap. And the same underlying cause can also lead to horizontal cracks on the inner face of abutment due to the additional bending stress transmitted from the upper structure. (b) Another type of logical relationship between defects is related to maintenance actions. For surface distresses such as honeycombing and spalling with exposed rebar, similar rehabilitation methods can be applied to this group of defects. Such a logical collection of defects that have non-geometric and topological relationship will be represented by an IfcGroup entity, and relevant defects will be linked to the group with IfcRelAssignsToGroup. According to different grouping principles, this defect group can be further related to maintenance work orders (described using IfcProjectOrder). The reason to use an IfcTask object to connect the maintenance request and defect group is to facilitate the monitoring of repair work's status. Figure 5.7 illustrates various relationships around defects, where three types of defect relationships indicated in Section 5.2.1 and 5.2.3 are clarified in the grey boxes.

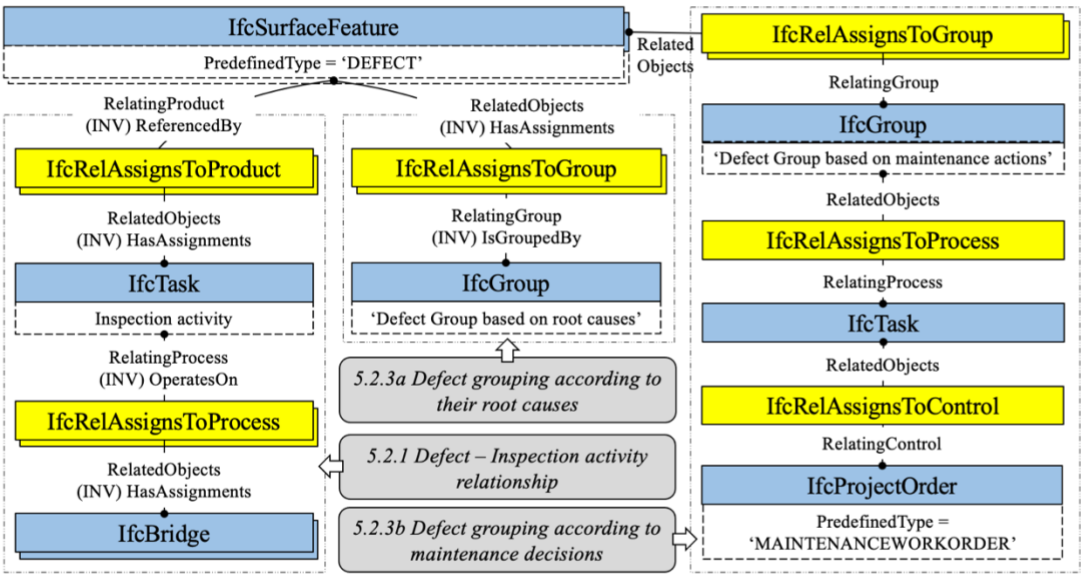


Figure 5.7 Modelling of logical relationship across defects

5.3 Experiment

To evaluate the applicability of the parametric-driven method for IFC-based documentation and representation of inspection data, an experiment was carried out by following the flowchart presented in Figure 5.8. First, design data and inspection-related data of a selected bridge were collected. A basic Bridge BIM model was created based on design data. With two modelling scenarios defined according to inspection reports, the parametric-driven modelling method of inspection-related data, proposed in Section 5.2, was then implemented. The integrated Bridge BIM model, exported as an IFC file, was lastly tested to validate its interoperability across BIM tools.

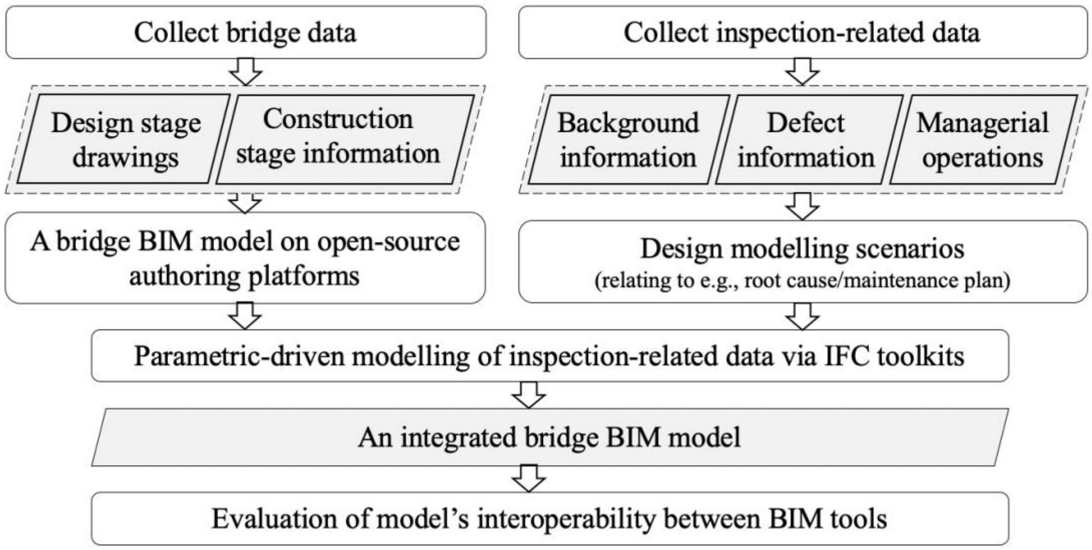


Figure 5.8 Flowchart of experiment on the proposed method

5.3.1 Data collection

Honghe bridge on G85 highway, locating in Yuanjiang county, Yunnan Province, China, was selected for experiment. The reason for selecting this bridge is twofold. For one, the chosen bridge is representative of large-span highway bridges, regarding its structural type and construction material. For another, data archived of the chosen bridge is relatively complete, ranging from inspection reports over the past five years to monitoring data that can be potentially used in the subsequent objectives. Table 5.2 lists basic design information of this bridge. As the largest bridge on G85 highway, the bridge was built in the form of a continuous rigid-frame highway bridge. It has five spans with the middle span crossing over the Red River, and Figure 5.9 (a) presents a picture of its elevation view. Design data of the experiment bridge, e.g., design drawings, are well documented as pdf files and collected for this research.

(a) Bridge overview (b) On-site inspections

Figure 5.9 Photos of the experiment bridge

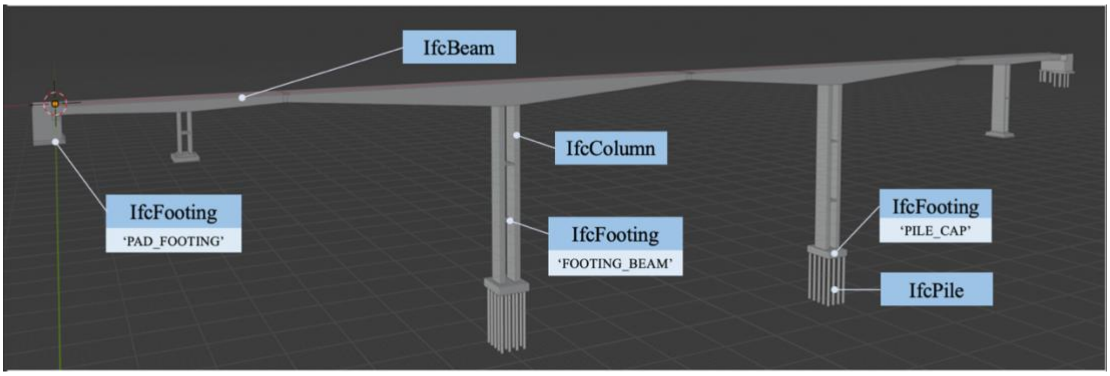
Table 5.2 Design information of the experiment bridge

Basic information	Highway number	*G85*	Bridge location	*K209+499.6*
Dimensions	Overall span (m)	*801* (58-182-265-194-70)	Total width (m)	*11*
Superstructure	Form	*Continuous rigid frame*	Material	*Prestressed concrete*
Substructure (Abutments)	Form	*Gravity abutment*	Material	*Grouted rubble*
Substructure (Piers)	Form	*Rectangular two-column pier*	Material	*Reinforced concrete*
Foundation	Form (0#, 5#)	*Spread footing*	Form (1#~4#)	*Pile foundation*
Miscellaneous	Expansion joints	*FD-80*	Bearings	*Pot bearing*

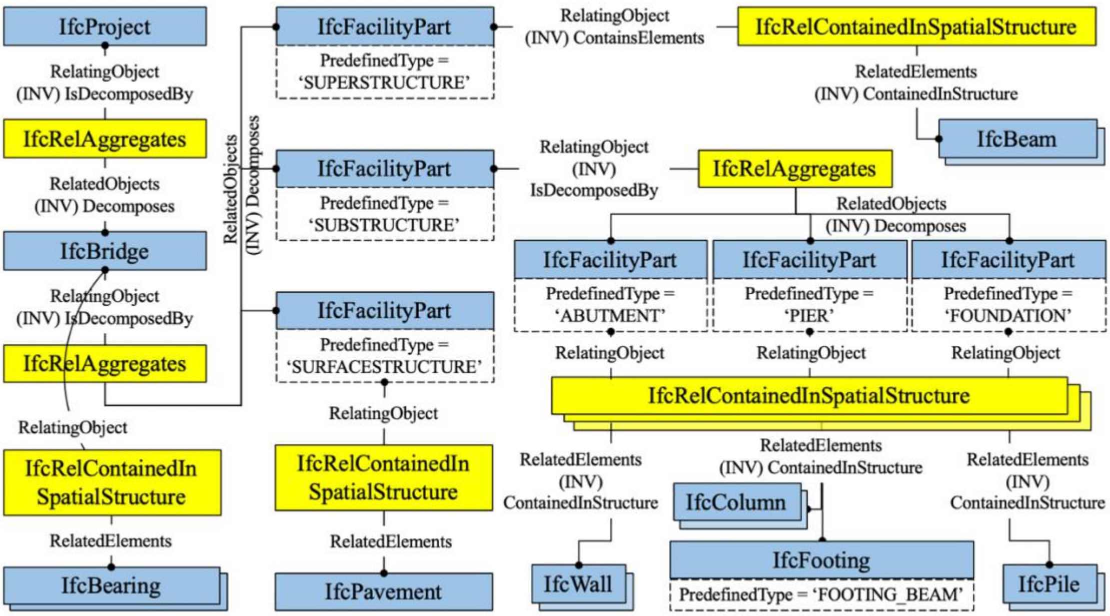
Due to increasingly explicit aging problems on bridge itself and a growing emphasis on infrastructure management in recent years, routine visual inspections have been carried out by its responsible authority at a yearly basis since 2013. Figure 5.9 (b) shows a picture of on-site inspection activities. Inspection results have been documented (in the form of excel sheets) since then, recording information about identified defects on superstructure, substructure and deck system, respectively. A few of the defects were attached with up-close pictures captured on site. Additionally, condition ratings at the bridge element level were calculated and included in a separate table aside. On top of annually archived excel sheets, a detailed inspection report in 2018 was collected as well. In this document, structured descriptions of existing defects and suggestions on maintenance actions were provided.

5.3.2 Creation of the basic bridge BIM model

The modelling of the experiment bridge was achieved using an open-source 3D authoring tool, Blender ("The Blender Project") together with the BlenderBIM Plugin ("BlenderBIM Add-on"). Blender is capable of parametric modelling, which can benefit the creation of variable cross section girder in this project. It is also suitable for rapid prototyping and visualisation of not-too-massing projects. BlenderBIM is an add-on built on IfcOpenShell to support open BIM with Blender. Figure 5.10 (a) is the overall elevation view of the experiment bridge modelled in Blender. Though IFC4x2 (buildingSMART International 2019) was the first released standard that specifically extended for the modelling of bridge assets, it has been deprecated by IFC4x3 earlier in 2020. Thus, the hierarchical architecture of the Bridge BIM model created in this research utilised the latest IFC Standard release (buildingSMART International 2020) (as shown in Figure 5.10 (b)). The spatial composition, from IfcProject, IfcSite (optional), IfcBridge, to IfcFacilityPart, is in line with the structural breakdown process of bridges. Each bridge part, e.g., superstructure, abutment and foundation, contains several bridge elements which can be defined using IfcBuiltElement objects. Yet expansion joints still can’t be modelled using the current IFC standard. In Blender, geometries were first created and then assigned to suitable IFC entities, e.g., IfcBeam for the main girder. The Bridge BIM model was lastly exported into an IFC file (with a suffix of .ifc) using the IfcBlender plug-in developed based on IfcOpenShell.



(a) An overview of the basic bridge BIM model



(b) Hierarchical structure of the bridge BIM project

Figure 5.10 The Bridge BIM in Blender

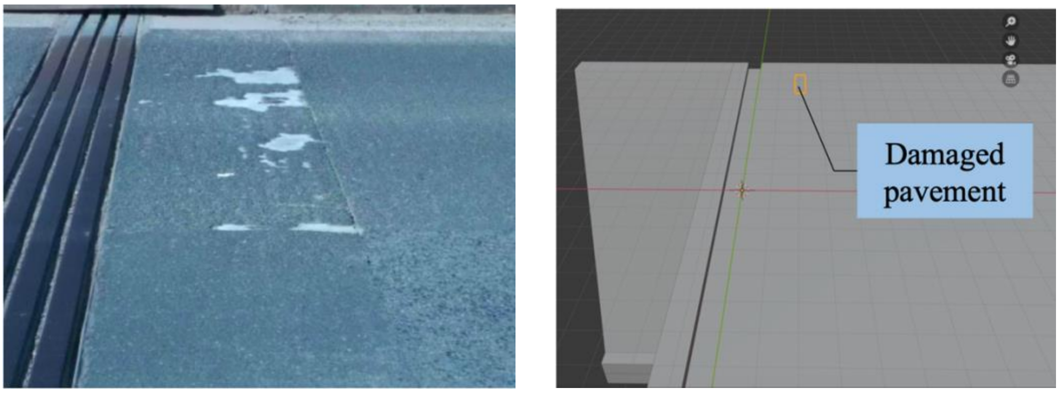
5.3.3 Parametric modelling of inspection-related data

A python environment embedded with IfcOpenShell (IfcOpenShell) and pythonOCC (Paviot 2017) packages was established to interact with the original Bridge IFC file. These packages have been widely used to parse IFC files (Moult 2019b) and write updated information. To evaluate the ability of the proposed method to represent various types of defects and facilitate multiple managerial operations as demanded in practice, two modelling scenarios were designed according to the inspection report. These two scenarios cover a range of defect types and aim to support cause diagnosis of defects and maintenance requests, separately.

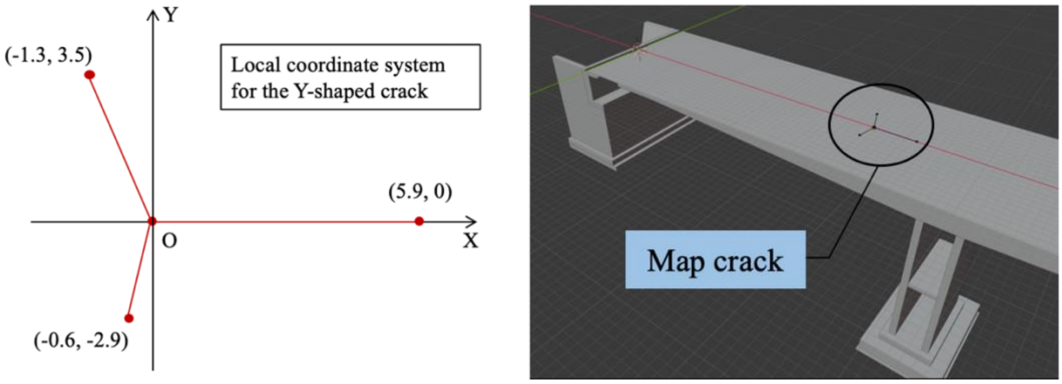
5.3.3.1 Scenario 1

The first scenario was designed to model defects with regard to their root cause (as indicated in Figure 5.7 – 5.2.3a). Firstly, as proposed in Section 5.2.1, an IfcTask entity was created to model the inspection practice itself and relevant background information and was named as ‘Detailed_Visual_Inspection’. Duration, start time and end time of this inspection were represented by IfcDuration and IfcDateTime respectively, all of which were referred to in the definition of IfcTask.

Defects on bridge deck, i.e., pavement damage and map cracking, were targeted. Both defects were caused by excessive traffic load and vehicular friction. According to the report, the damaged pavement patch, as shown in Figure 5.11 (a), was located 1.8m away from the expansion joint on #0 abutment and 1m away from the right side of deck. The area was measured as 2.0m (transverse) * 0.5m (longitudinal). As for the map cracking, it was simplified in this experiment, for illustration purpose, into a Y-shaped crack. Its dimensions in its local coordinate system were indicated in Figure 5.11 (b). The maximum width was measured as 2mm and was used for modelling the entire map crack. It was positioned at ¼ span of the first beam segment and its distance to the left side of deck was 2.5m.



(a) Damaged pavement patch in real-life photo (left) and Blender (right)



(b) Simplified map cracking in illustrations (left) and Blender (right)

Figure 5.11 Pavement defects with the same root cause

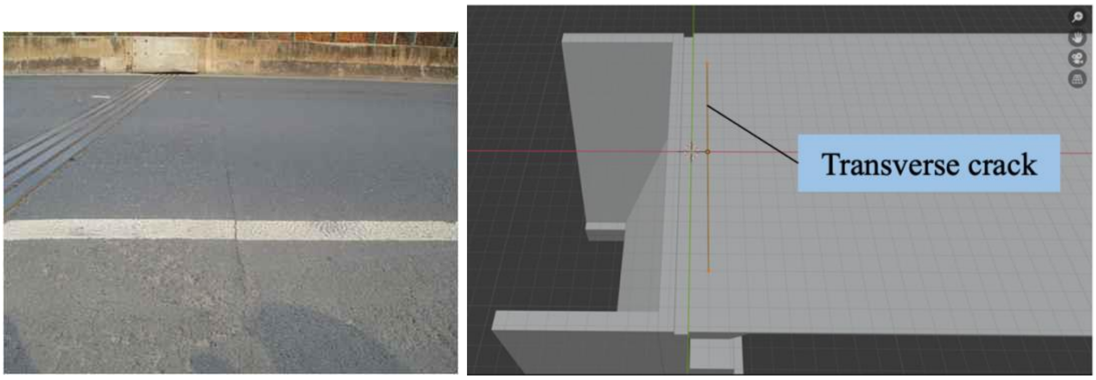
IfcSurfaceFeature, with its predefined type defined as 'DEFECT', was created for individual defects. IfcRelAssginsToProduct was used to relate defects to the inspection task while IfcRelAggregates was used to relate defects to the corresponding bridge element. To locate these defects, a local coordinate system for individual defect was first defined using IfcLocalPlacement, with relative to that of the corresponding bridge element, i.e., the main girder represented by IfcBeam. To be specific, the girder object was first selected using by_type method in IfcOpenShell. The IfcLocalPlacement entity of the girder element can be retrieved through the ObjectPlacement attribute and available for reference. Then, the transformation from the related coordinate system into the relating one, defined using IfcAxis2Placement, can be achieved.

As for the shape representation of cracking, as indicated in Section 3.2.1, the use of IfcSurfaceOfLinearExtrusion (i.e., Figure 5.5 (b)) was used due to its capability in proper visualization in Blender and inclusiveness of information representation (i.e., width of cracking). For the geometric modelling of worn pavement patch, the surface was created by defining key points on the outer bound and combining them into a polyline. Such a modelling method, both for spatial placement and shape representation, allows for flexible modification and interaction, since the feature points are determined by respective parameters (e.g., Cartesian coordinates), which can be input by inspectors or computer vision analysis outcomes.

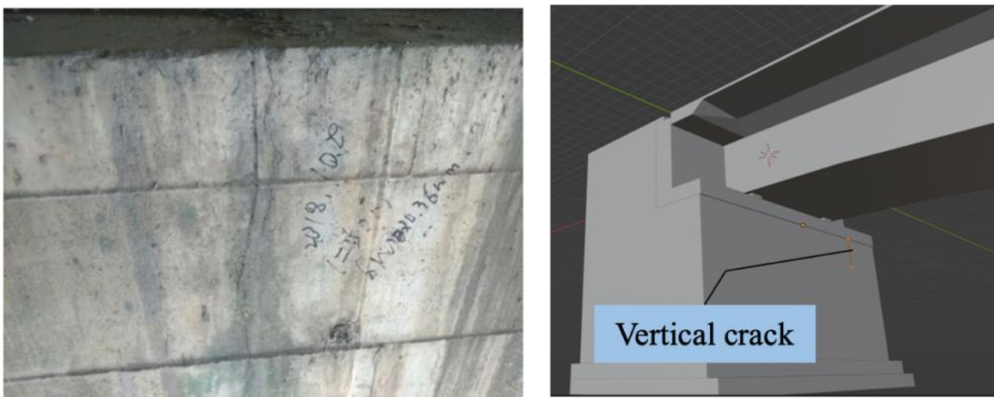
Lastly, the logical relationship between these two defects lies in the same root cause, i.e., excessive vehicle loads on bridge deck. For this reason, an IfcGroup object was created and a relationship entity, IfcRelAssignsToGroup, was used to assign relevant defects to it. Defects in this group will share an attribute that states the underlying cause. A wider range of potential causes can be modelled using this approach. For example, the performance failure of bearings and/or expansion joints can lead to structural cracks and spalling on both super- and sub- structures. The blockage of drainage system might contribute to accumulation of water in the box of main girder and efflorescence on concrete surface. Such a relationship allows for the grouping of defects regardless their spatial location and it would be practically meaningful in the sense that major maintenance decisions can be made based on diagnosis.

5.3.3.2 Scenario 2

Alternatively, the second scenario modelled the inter-relationship among defects regarding their maintenance requests, as suggested in Figure 5.7 – 5.2.3b. The modelling of inspection task and individual defects followed the suits in 6.3.3.1. Specifically, a transverse crack on bridge pavement (as shown in Figure 5.12 (a)) and a vertical crack on the front face of #0 abutment (Figure 5.12 (b)) was selected for modelling. The maintenance decision for both cracks was closing treatment, which would be further supplemented with pressure grouting if the width of cracking exceeded 0.15mm. Their dimensions were documented as 16m length * 0.14 width and 5.05 length * 0.36 width, respectively.



(a) Transverse crack on pavement in real-life photo (left) and Blender (right)



(b) Vertical crack on abutment in real-life photo (left) and Blender (right)

Figure 5.12 Defects with the same maintenance decision.

In addition, there was honeycombing identified on the web plate of the 1st-span girder, locating 7m away from the #0 abutment and 3m above the girder bottom. The dimensions were 1.0m*0.5m. Spalling with exposed rebar was recorded to be on the flange of the same girder segment. It had an area of 0.3*0.3m2. The maintenance suggestion for these two types of defects and other concrete surface damages was to first clear loose concrete around the damage, rust cleaning if applicable, and patch with epoxy mortar.

Both cases were modelled similarly to the first scenario. IfcGroup entities were created to logically relate multiple defects. Their corresponding maintenance requests were represented by IfcProjectOrder, with its predefined type defined as ‘Maintenance Work Order’. Assignment relationships were used to direct the defect group to its maintenance request and/or maintenance task.

5.4 Experiment results

After the modelling, this part presents the experiment and evaluation results of the proposed method. The inspection-related information added to the bridge BIM model is documented according to STEP standards. Figure 5.13 (a) ~ (c) presents the sections in BIM IFC file which record information about inspection task, defects and defect inter-relationships, respectively.

```
#48857=IFCTASKTIME('Time information',$,$,.WORKTIME.,$,$,$,$,$,$,$,$,$,$,
$,'P0Y0M0DT5H30M0S','2015-04-19T09:00:00','2015-04-19T14:30:00',$,$);
#48858=IFCTASK('30X6FuqWuHwgMbWZKMuM01',#5,'Detailed_Visual_Inspection','inspection-2015',$,$,'detailed
visual inspection executed in 2015','Completed',$,.T.,$,#48857,$);
```

(a) IFC schema for the inspection task

```
#48859=IFCCARTESIANPOINT((1.,0.,0.));
#48860=IFCDIRECTION((0.,0.,1.));
#48861=IFCDIRECTION((1.,0.,0.));
#48862=IFCAXIS2PLACEMENT3D(#48859,#48860,#48861);
#48863=IFCLOCALPLACEMENT(#47652,#48862);
#48864=IFCCARTESIANPOINT((7.E-05,0.,0.));
#48865=IFCCARTESIANPOINT((-7.E-05,0.,0.));
#48866=IFCPOLYLINE((#48864,#48865));
#48867=IFCARBITRARYOPENPROFILEDEF(.CURVE.,'section_1',#48866);
#48868=IFCCARTESIANPOINT((0.,-8.,0.));
#48869=IFCDIRECTION((0.,0.,1.));
#48870=IFCDIRECTION((1.,0.,0.));
#48871=IFCAXIS2PLACEMENT3D(#48868,#48869,#48870);
#48872=IFCDIRECTION((0.,1.,0.));
#48873=IFCSURFACEOFLINEAREXTRUSION(#48867,#48871,#48872,16.);
#48874=IFCSHAPEREPRESENTATION(#24,'Body','Surface',(#48873));
#48875=IFCPRODUCTDEFINITIONSHAPE($,$,(#48874));
#48876=IFCSURFACEFEATURE('30X9BsqWuHwgMbWZKMuM01',#5,'crack_1','Transverse_Crack_on_Deck',
$,#48863,#48875,'DEFECT',$);
```

(b) IFC schema for defect modelling (i.e., two cracks)

```
#48895=IFCRELAGGREGATES('30XBLCqWuHwgMbWZKMuM01',#5,'crack_1_to_beam',$,#47661,(#48876));
#48896=IFCRELAGGREGATES('30XBbmqWuHwgMbWZKMuM01',#5,'crack_2_to_abutment_0',$,#48845,
(#48894));
#48897=IFCGROUP('30XBriqWuHwgMbWZKMuM01',#5,'defect_group_1','Having maintenance decision_1',$);
#48898=IFCRELASSIGNSTOGROUP('30XC5yqWuHwgMbWZKMuM01',#5,'defect_relationship_1',$,
(#48876,#48894),.GROUP.,#48897);
#48899=IFCRELASSIGNSTOPROCESS('30XCUoqWuHwgMbWZKMuM01',#5,'Defect_To_Task',$,(#48876,#48894),
$,#48858,$);
```

(c) IFC schema for defect grouping

Figure 5.13 Screenshots of IFC file for the integrated bridge BIM

As proposed, the IFCTASK entity (#48858) represents the inspection activity. The IFCSURFACEFEATIRE entity (#48876) represents an individual defect, whose shape is defined by #48874 and location by ##48863. Multiple defects having the same maintenance decision are associated using IFCGROUP (#48897), which are further assigned to managerial elements.

5.4.1 Interoperability of the integrated bridge BIM

On top of that, the interoperability of IFC-based integrated bridge BIM was evaluated, by following the flowchart in Figure 5.14. On one hand, an export-import cyclical test was conducted in the same software, Blender, by first exporting the original bridge BIM model, updating the BIM IFC with inspection-related information, and importing the enriched IFC file back to visualise. On the other hand, similar test was conducted across BIM viewers and authoring tools, by importing the integrated BrIM IFC to other software such as Solibri and FreeCAD. To note, the bridge BIM IFC was customised to previous IFC standard so as to be compatible with specific software. We could see that in either case, defect information (a linear crack in this case) has been successfully delivered between those BIM tools. The ability to keep the completeness of information, inspection-related information in particular, during exchange fits in the open BIM process. In this way, various authorities involved in the operation and maintenance phases of civil assets, e.g., road agencies, inspection/maintenance contractors, might access the bridge BIM project from different software and platforms without missing or ambiguous information.

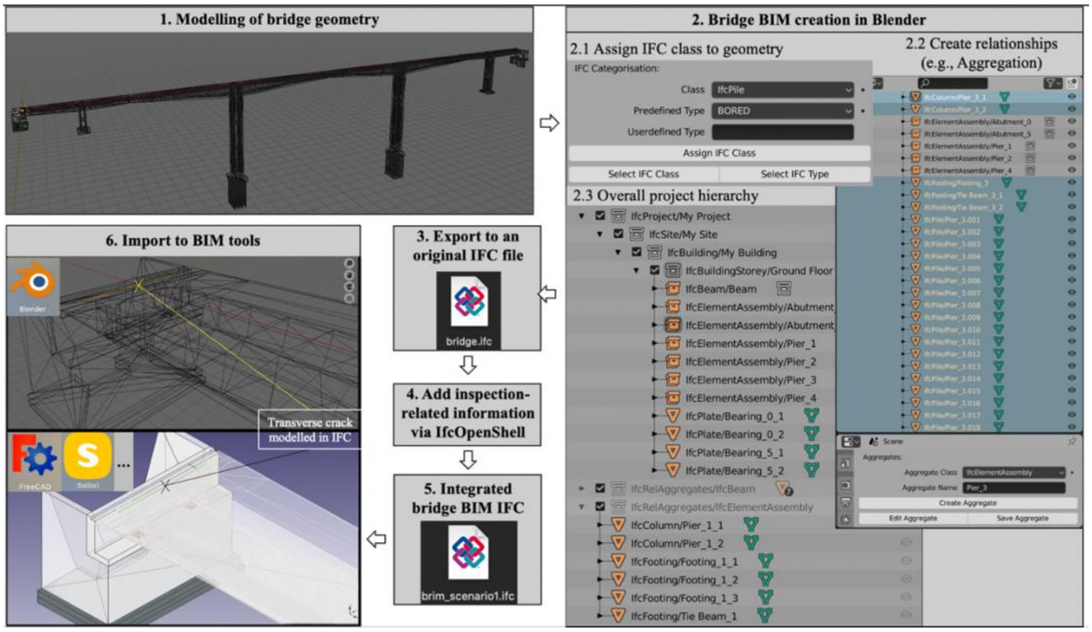


Figure 5.14 Flowchart of interoperability check

5.4.2 Validation on information retrieval

An additional test was set up to illustrate the benefit this modelling method could possibly bring. Various managerial operations in practice are based on the efficient and accurate retrieval of defect information. On the experiment bridge, a total of 120 cracks were identified during inspections and the width information of three of them is missing in the report. Thus, 117 cracks were modelled using the proposed method (described in Section 5.3.2) and integrated in the bridge model. The information retrieval tasks tested in this study include two parts. One is to count the total number of cracks whose maximum width is greater or less than 0.15mm, respectively (referred as Task "Number counting" hereafter). The other is to calculate the total length of cracks based on the same categorisation criteria (referred as Task "Total length calculation"). Three different methods were tested on these two retrieval tasks, including (1) manual searching in the inspection report; (2) manual searching in the BIM authoring tool (i.e., Blender); and (3) automatic searching in the IFC-based model file. Results of the first method, L_0, were cross-checked by several people to make sure their accuracy and used as the ground truth of these two tasks. Results of the latter two methods, denoted as L_1 and L_2, were compared to the ground truth and error was calculated using Equation 5.1.

$$Error = \frac{L_i - L_0}{L_0}, i = 1, 2 \quad \text{Eq. 5.1}$$

Table 5.2 presents the performance of each method when executing the required information retrieval and preliminary analysis. It shows that automatic information searching in IFC-based model, without using the BIM authoring tools' interface, largely improves its efficiency and ensures accuracy at the same time.

Table 5.3 Efficiency of three methods on information retrieval tasks

Method / Task	Manual searching in inspection report	Manual searching in BIM authoring tool	Automatic searching in IFC-based model
Number counting	5.5 min	14 min	0.16 s
Total length calculation	6 min	16min	0.16 s
Error	(Ground truth)	0.04	0

5.5 Chapter summary

An IFC-based method for defect documentation and representation in bridge BIM have been proposed in this chapter and validated through an experiment on a real-life bridge. The method has been proven to be capable of modelling three levels of inspection-based information: (1) bridge inspection activity; (2) identified defects through inspections and (3) logical relationship around defects. Specifically, modelling of defect geometry, i.e., shape and spatial placement, is achieved parametrically, which aims to benefit subsequent managerial operations like information update, retrieval, and exchange. Moreover, a variety of spatiotemporal and logical relationships around defects are modelled systematically, ranging from defect-cause relationship to defect-maintenance action relationship.

6 IFC-based condition evaluation

6.1 Chapter introduction

Based on the integrated bridge BIM models developed in Chapter 6, this chapter develops an IFC-based method for defect analysis under the condition rating scheme. Section 6.2 first introduces the condition calculation procedure from individual defects to the entire bridge structure. The proposed method using the most recent IFC standards is illustrated in Section 6.3. It is validated through a case study and presented in Section 6.4. Section 6.4 also provides an in-chapter analysis of the results. Section 6.5 concludes this chapter with a summary.

6.2 Condition evaluation procedure

Condition assessment is necessary in practice to evaluate the infrastructure condition and thereby, facilitate the decision making regarding whether to rehabilitate or replace assets. As stated in (Moradi et al. 2019), 'Infrastructure condition information can be considered the most valuable tool for conducting asset management planning strategies because this information describes current scenarios and is required to predict future asset performance'. However, approaches to condition assessment vary across countries with respect to whether element-level inspection is conducted and whether the assessment is based on individual defect. Condition state is defined in (Hajdin 2018) as 'an ambiguous measure of the deviation of the inspected bridge from the 'as new' condition'. However, specifications of condition states/levels vary across manuals worldwide. Table 6.1 summaries the bridge condition levels in bridge management systems worldwide.

Table 6.1 Condition levels for bridges according to manuals worldwide

Country	# Condition levels	Target
Australia (WA)	4	Bridge components
	5	Bridge using Bridge Condition Indicator (ranging from 0 to 100+)
The United Kingdom	5	Severity of individual defect
	5	Extent of individual defect
	5	Bridge using Average/ critical Condition performance indicator (PI) (ranging from 0 to 100)
The United States	4	Bridge elements
	10	Bridge components (e.g., deck, superstructure, and substructure)
	10	Structural evaluation of an entire bridge
New Zealand	5	Bridge
Canada	5 (British Columbia)	Bridge components
	10 (Alberta, Yukon, and Northwest Territories)	Bridge components
	4 (Ontario, etc.)	Bridge elements
	4 (Quebec)	Element-level
Germany	5	Element-level damage with regard to their impacts on structural stability, traffic safety, and durability
China	5	Bridge

In this research, the condition assessment procedure regulated in (Highways Agency CSS Bridges Group 2007) and in line with the bridge element inspection approach (as illustrated in Figure 1.3) is presented and used as the theoretical basis for subsequent modelling. The breakdown of a typical bridge is shown in Figure 5.10 (b). In a typical bridge element inspection, bridge elements would be reported at a detailed level. This implies that defects in sub-elements are identified, and the severity and extent for each sub-element are assessed accordingly. A list of sub-elements with respect to elements is presented in Table 6.2. The table is adapted from a CSS report (Highways Agency CSS Bridges Group 2002) and the Chinese standards for highway bridge inspections (Ministry of Transport of the People's Republic of China 2011). Bridge elements are categorised into four sets: superstructure, substructure, deck, and ancillary elements. The elements and sub-elements that are commonly observed or included in concrete highway bridges are in bold. In addition, because girder bridges are dominant in concrete highway bridges, (sub-)elements that belong to other bridge types (e.g., arch bridges, cantilever bridges, and truss bridges) are marked in grey.

Table 6.2. List of bridge elements and sub-elements.

	Bridge elements	Sub-elements	Importance	Weight
Superstructure	**Primary deck element**	**Main Beams**	Very High	0.70
		Truss members		
		Culvert		
		Arch		
		Arch Ring		
		Vousoirs/Arch Face		
		Arch Barrel/Soffit		
		Encased Beams		
		Subway		
		Box beam interiors		
		Armco/Concrete pipe		
		Portal/Tunnel portals		
		Prestressing		
		Sleeper bridge		
		Tunnel Linings		
	Transverse beams	**Concrete deck slab**	Very High	0.18
	Secondary deck element	Timber deck	Very High	N/A
		steel deck plates		
		Jack Arch		
		Troughing		
		Stone slab (or primary member)		
		Troughing Infill		
		Buckle plates		
	Bearings		High	0.12
	Bearing plinth/shelf		Medium	N/A
	Half joints		Very High	N/A
	Tie beam/rod		Very High	N/A
	Parapet beam or cantilever	Edge Beams	Very High	N/A
	Deck bracing	**Diaphragms**	High	N/A
	Spandrel wall/head wall	Stringcourse	High	N/A
		Coping		
Substructure	Wing walls	Newel	High	0.02
	Retaining walls	Counterfort/Buttresses	Medium	
		Gabions		
		Wall		
	Embankments	Approach Embankments	Low	0.01
		Side slopes		
	Abutments (incl. arch springing)	Arch Springing	High	0.30
		Abutment slope		
		Bank seat		
		Counterfort/Buttresses		
	Pier/column		Very High	0.30
	Cross head/capping beam		Very High	
	Foundations	**Piles**	High	0.28
	Invert/riverbed	Channel bedstones	Medium	0.07
	Fenders/cutwaters/collision protection	Flood Barrier	Medium	0.02
	River training works		Medium	
	Revetment/batter paving		Medium	
	Aprons		Medium	N/A

Deck	Carriageway surfacing	Ramp Surface	Medium	0.40
		Approaches		
	Movement/expansion joints	Sealants	High	0.25
	Footway/verge/footbridge surfacing		Low	0.10
	Handrail/parapets/safety fences	Balustrade	High	0.10
	Superstructure drainage		Medium	0.10
	Substructure drainage	Subway drainage	Medium	
		Retaining wall drainage	Medium	
	Signs		N/A	0.05
	Lighting	Subway Lighting	N/A	
		Primary Lighting		
		Secondary Lighting		
Ancillary	**Water proofing**		Medium	N/A
	Painting: deck elements	Sealants	Medium	N/A
		Decorative Appearance		
	Painting: substructure elements	Sealants	Medium	
		Decorative Appearance		
	Painting: parapets/safety fences	Sealants	Medium	
		Decorative Appearance		
	Access/walkways/gantries	Steps	Medium	N/A
		Barrier		
	Machinery		Medium	N/A
	Approach rails/barriers/walls	Posts	N/A	N/A
		Remote approach walls		
	Services	Manholes	N/A	N/A
		Pipes		
		Mast		

The definitions with regard to 'importance' are adapted from a CSS report (Highways Agency CSS Bridges Group 2002), and the weights are adapted from the Chinese standards for highway bridge inspections (Ministry of Transport of the People's Republic of China 2011).

When the condition data of sub-elements are combined at the element level, the weight of each sub-element can be determined according to their dimensions (e.g., length, width, height, or deck area served). Specifically, the weight of the i-th sub-element, W_{SEi}, is calculated using Equation 6.1.

$$W_{SEi} = \frac{Dimension\ of\ subelement\ i}{Maximum\ dimension\ of\ subelements} \quad \text{Eq. 6.1}$$

The aggregation of severity score uses the worst-case approach, assuming that the worst sub-element severity indicates the element severity. With regard to extent ratings, ratings from A to E are first converted into numerical values using Table 6.3. The worst-case approach is also used. The element condition score (ECS) is then calculated based on the severity and extent using either Equation 6.2 or the official calculation table archived in the HA SMIS inspection system (Manuals).

$$ECS = Severity + Extent \quad \text{Eq. 6.2}$$

Table 6.3 Conversion from extent ratings to numerical values

Extent ratings	Numerical values
A	0.0
B	0.0
C	0.1
D	0.3
E	0.7

When element condition scores are integrated into a higher level, the importance of the element is first evaluated as a weight (as specified in Table 6.2). Examples of elements that are of 'Very High' importance are primary deck element, transverse element, secondary deck element, pier, capping beam, and parapet beam. Elements of 'High' importance include deck bracings, abutment, bearings, expansion joints, and wing walls. Drainage and retaining walls are elements of 'Medium' importance. The remaining elements such as revertment and embankments are of 'Low' importance. Element importance factors (EIFs) are assigned to those elements in accordance with their level of importance, i.e., elements of 'Very High', 'High', 'Medium', and 'Low' importance are assigned factors of 2.0, 1.5, 1.2, and 1.0, respectively. Simultaneously, the ECS in conjunction with the element importance is first converted into an element condition factor (ECF) using Equation 6.3 and then, into an element condition index (ECI) using Equation 6.4. The equations are adapted from Section 4.3 of the guidance document issued by Highways Agency CSS Bridges Group (2007).

$$\begin{aligned} &ECF = 0.0 \ \ for\ elements\ of\ \text{Very High}\ importance; \\ &ECF = 0.3 - [(ECS - 1) \times 0.3/4] \ \ for\ elements\ of\ \text{High}\ importance; \\ &ECF = 0.6 - [(ECS - 1) \times 0.6/4] \ \ for\ elements\ of\ \text{Medium}\ importance; \\ &ECF = 1.2 - [(ECS - 1) \times 1.2/4] \ \ for\ elements\ of\ \text{Low}\ importance \end{aligned} \qquad \text{Eq. 6.3}$$

$$ECI = ECS - ECF \qquad \text{Eq. 6.4}$$

In addition to the above parameters, an average structure condition score SCS_{AV} is computed based on the ECIs and EIFs of the elements included, as indicated in Section 4.6 of the corresponding guidance document (Highways Agency CSS Bridges Group 2007), i.e., Equation 6.5.

$$SCS_{AV} = \frac{\sum_{i=1}^{N}(ECI_i \times EIF_i)}{\sum_{i=1}^{N} EIF_i} \qquad \text{Eq. 6.5}$$

Alternatively, the maximum ECI of elements of 'Very High' importance is adopted to represent the critical structure condition score SCS_{cr}. Furthermore, at the bridge level, the condition performance indicator (PI) is obtained. It ranges from 0 (indicating the worst possible condition) to 100 (indicating the best possible condition). Similar to the structure condition score, the average and critical values can be calculated for various managerial purposes by using Equation 6.6 and Equation 6.7, respectively. The equations are adapted from Section 4.7 of the same document (Highways Agency CSS Bridges Group 2007).

$$Condition\ PI_{AV} = 100 - 2[(SCS_{AV})^2 + (6.5 \times SCS_{AV}) - 7.5] \quad \text{Eq. 6.6}$$

$$Condition\ PI_{cr} = 100 - 2[(SCS_{cr})^2 + (6.5 \times SCS_{cr}) - 7.5] \quad \text{Eq. 6.7}$$

Condition PI is officially defined in the document as the ‘percentage service potential’ of a structure. Moreover, with regard to its scale from 0 to 100, bridges are categorised into five condition levels: ‘Very Good’, ‘Good’, ‘Fair’, ‘Poor’, and ‘Very Poor’. Table 6.4 presents the categorisation of condition levels. Based on such condition assessment results, authorities and asset managers monitor the variations in the condition of structures over time and accordingly, determine the maintenance plans to sustain the current condition, improve the condition, or permit it to deteriorate. It is observed that the distribution of condition PIs into condition stages is non-uniform. This is mainly because the improvement from 5 to 4 (41% in terms the condition PI scale) and that from 2 to 1 (11% in terms the condition PI scale) require different amounts of funding and efforts.

Table 6.4 Categorisation of condition stages with regard to condition PI

Condition PI_{Av}	Condition stage
$90 \leqslant x \leqslant 100$	No significant defect likely in any element. Structure is in a ‘Very Good’ condition overall.
$80 \leqslant x < 90$	Mostly minor defects/damage, but may also have a few moderate defects. Structure is in a ‘Good’ condition overall.
$65 \leqslant x < 80$	Minor-to-Moderate defects/damage. Structure is in a ‘Fair’ condition overall.
$40 \leqslant x < 65$	Moderate-to-Severe defects/damage. Structure is in a ‘Poor’ condition overall.
$0 \leqslant x < 40$	Severe defects/damage in a number of elements. One or more elements may have failed. Structure is in a ‘Very Poor’ condition overall. It may be unserviceable.

To further facilitate managers with their maintenance decision-making at a regional level, the condition of a structure type group or multi-span bridges can be assessed by aggregating the condition PIs of multiple bridges. The weight of each bridge is assigned according to its deck areas.

6.3 Sub-method development

The IFC-based method for defect analysis under the condition assessment scheme is developed based on the theoretical foundation presented in Section 6.2. The overall development is illustrated using the flowchart in Figure 6.1. The applicable procedure for condition evaluation that is particularly suitable for element-level inspections has been illustrated in detail above.

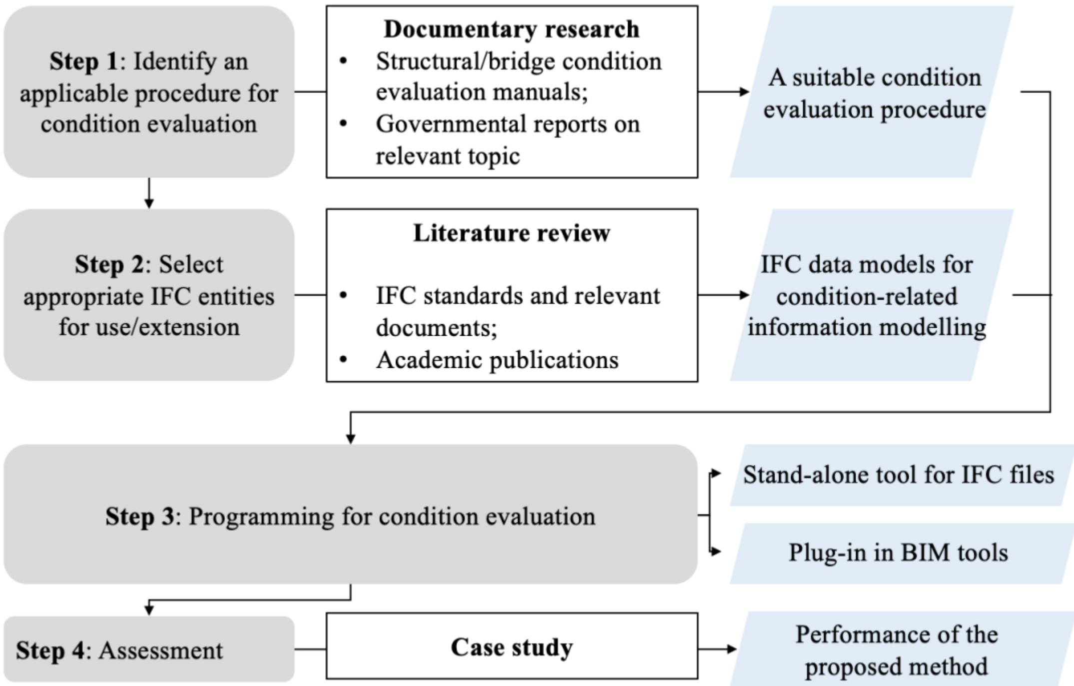


Figure 6.1 Flowchart for the development of IFC-based condition evaluation

6.3.1 Selection of IFC data models

As proposed in Chapter 6, bridge defects identified through inspections are modelled using the IfcSurfaceFeature entity. A property set, Pset_Condition, is available in IFC 4.3 to document the condition assessment results. Assessment date, assessment condition, and additional descriptions can be included. It is noteworthy that the Pset_Condition object is designed to describe IfcElement entities in various hierarchical levels. Defects and sub-elements ranging from beams, pavement, bearings, and columns to footings are included. However, the connection between Pset_Condition and elements (such as abutment; pier; and higher-level ones such as superstructure, substructure, and deck system) is not included in the official IFC standard. Considering this, an extension to the Pset_Condition object is proposed. The extended Pset_Condition can describe IfcElement entities as well as IfcSpatialElement entities. This allows for condition assessment at the element level. In this manner, condition ratings of high-level bridge elements and an entire bridge can be assigned accordingly, thereby ensuring the inclusiveness of the condition assessment scheme. The mapping from the 'condition' property to the corresponding elements is illustrated in Figure 6.2, where the entities in red constitute the extension proposed in this study.

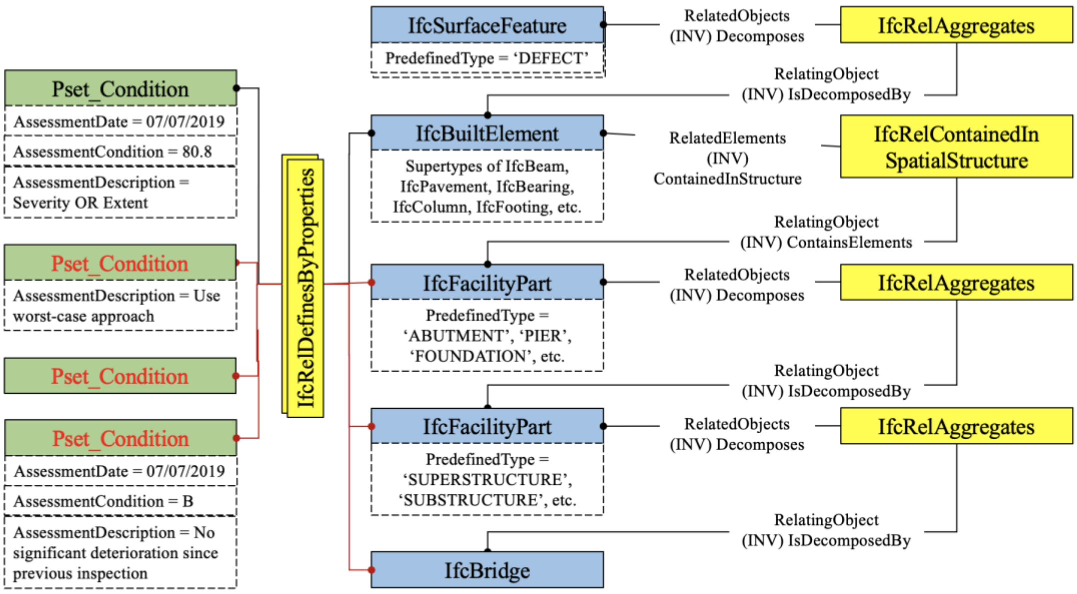


Figure 6.2 Mapping condition assessment results to IFC entities (Extended Pset_Condition is marked in red)

Specifically, the severity and extent information of individual sub-elements (i.e., IfcBuiltElement entities) can be assigned simultaneously and specified using the AssessmentDescription property. The condition assessment results (i.e., the AssessmentCondition property) can be presented either in values on a scale from 0 to 100 or predefined levels such as A–E, according to different manuals.

6.3.2 Programming for condition evaluation

Inspectors only collect defect information and generate preliminary estimates of their severity and/or extent through on-site inspection activities. Based on such field data, senior engineers with richer experience perform condition rating at the sub-element level. The determination of the condition score of defects and elements is subjective, and this subjectivity cannot be diminished as long as a professional engineer's assessment is required in this process. This method develops an automatic condition evaluation scheme to calculate the overall bridge condition by referring to the low-level condition data collected by engineers. The underlying concept of the scheme is shown explicitly in Table 6.5.

Table 6.5 Pseudo code of the condition evaluation procedure

Pseudo code
For all Elements i (1–N) in Bridge A,
For all Sub-elements j (1–Mi) in Element i,
Determine its severity Sj and extent Ej;
Calculate its weighting in Element i, Wj;
Calculate the severity of Element i using the specified approach (e.g., worst-case approach);
Calculate the extent of Element i using the specified approach, and convert it into numerical values;
Calculate the *element condition score* (ECS);
Determine its importance and corresponding element importance factors (EIFs);
Calculate the *element condition factor* (ECF) using Equation 6.3.
$ECF = 0, if$ importance = "Very High" $ECF = 0.3 - \left[(ECS - 1) \times \frac{0.3}{4}\right], if$ importance = "High" $ECF = 0.6 - \left[(ECS - 1) \times \frac{0.6}{4}\right], if\ if$ importance = "Medium" $ECF = 1.2 - \left[(ECS - 1) \times \frac{1.2}{4}\right], else$ Eq. 6.3
Calculate the *element condition index* (ECI);
Calculate the average structure condition score SCS_{AV} and critical structure condition score SCS_{cr} on a scale of 0–100;
Categorise the bridge condition into five levels: A, B, C, D, and E.

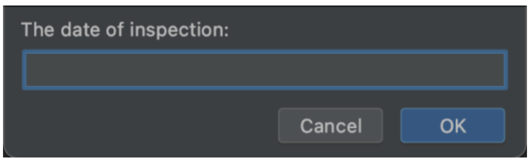
The condition evaluation scheme developed based on the above programming logic can be either a plug-in in BIM software or a stand-alone tool for IFC file processing. Specifically, it allows for the manual input of condition data at the sub-element level by engineers and then, automatically combines these to generate the overall condition level of the bridge. In between, the aggregation approach for severity and extent can be specified by managers beforehand, so as to fit in different bridge management schemes.

6.3.3 Case study and assessment

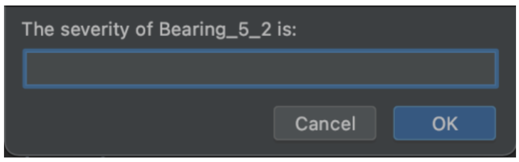
Two types of experiments were conducted to test the practicality of the proposed condition evaluation scheme. On the one hand, a Jupyter Notebook that permits interactive inputs from engineers was developed. This stand-alone tool processes IFC files of integrated bridge BIM models and automatically completes the overall condition evaluation. On the other hand, an open-source BIM authoring tool, Blender, was used to develop the embedded tool because it provides a scripting platform for user-specific commands. A case study bridge was modelled and tested to ensure the applicability of the developed tools. The condition evaluation results generated by the developed tool were compared with the ground truth, i.e., condition levels determined by traditional assessment methods.

6.3.3.1 Stand-alone tool for IFC files

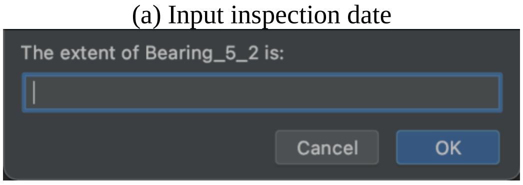
The tool developed to process IFC files was based on Python and a Jupyter notebook. The Python code is presented in Appendix 2. Specifically, at the sub-element level, the tool allows for manual inputs by engineers and/or inspectors. The inspection date is documented as one of the properties of the condition entity, which facilitates the research on the deterioration over time. The severity and extent of each sub-element are provided based on engineers' assessment. Additional descriptions can also be added. The interface for manual inputs is shown in Figure 6.3. Alternatively, the tool can directly read condition score tables prepared by engineers, if applicable. Another solution would be to employ deep learning techniques to automatically assign a condition score to the corresponding element. Images of damaged bridge elements need to be collected, processed, and integrated into a database, and extensive training should be carried out.



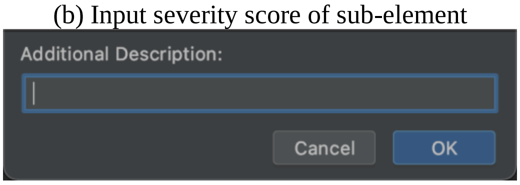
(a) Input inspection date



(b) Input severity score of sub-element



(c) Input extent score of sub-element



(d) Input descriptive condition information

Figure 6.3 Interface for manual inputs

During the condition aggregation from the sub-element level to the structure level, all the relevant information such as the element dimensions (e.g., length and volume) used to determine sub-element weights can be retrieved from the IFC-based BIM model. At each level, the aggregated condition score/indicator would be assigned to the corresponding element via the property set Pset_Condition. The final output of the developed tool is an updated IFC file with the condition information calculated and integrated.

6.3.3.2 Plug-in in BIM tools

Several BIM tools allow for scripting and an interactive update of the model. In this study, the open-source BIM authoring tool Blender was adopted for illustration. A Python interpreter is straightforwardly embedded in Blender and remains active while Blender is running (Blender). A BlenderBIM addon (developed on top of Ifcopenshell) was installed in advance. The development of the plug-in is similar to that of the stand-alone tool for IFC file processing.

6.4 Case study and discussion

Concrete girder bridges vary in terms of their cross-sectional types, substructure forms, etc. Simply-supported girder bridge and continuous girder bridge are two of the most dominant structural types for highway bridges worldwide. Their shear amount and significant level of similarity provides a significant opportunity for a standardised BIM-based management system. However, girder bridges generally follow identical breakdown architecture. The three key components (i.e., superstructure, substructure, and deck system) are divided further into a variety of elements. In this case study, a rigid frame highway bridge (the one used while considering Objective 2) was employed as an example to verify the applicability of the proposed condition evaluation scheme. Basic information on the bridge is provided in Section 5.3. The condition information (i.e., severity score and extent level) at the sub-element level was estimated based on the inspection report and is listed in Table 6.6.

Table 6.6 Condition information at sub-element level

	IFC entities	Severity	Extent		IFC entities	Severity	Extent
Main beam	IfcBeam/ A	2	D	Pier_2	IfcColumn/ Pier_2_1	2	C
	IfcBeam/ BC	2	C		IfcColumn/ Pier_2_2	1	A
	IfcBeam/ CD	3	B		IfcFooting/Tie Beam_2_1	1	A
	IfcBeam/ E	3	C		IfcFooting/Tie Beam_2_2	1	A
Diaphragm	IfcBeam/ Joint_AB	1	B	Pier_3	IfcColumn/ Pier_3_1	1	A
	IfcBeam/ Joint_C	2	C		IfcColumn/ Pier_3_2	1	A
	IfcBeam/ Joint_DE	3	D		IfcFooting/Tie Beam_3_1	1	A
Bearings	IfcPlate/ Bearing_0_1	1	A		IfcFooting/Tie Beam_3_2	1	A
	IfcPlate/ Bearing_0_2	1	A	Pier_4	IfcColumn/ Pier_4_1	1	A
	IfcPlate/ Bearing_5_1	1	A		IfcColumn/ Pier_4_2	1	A
	IfcPlate/ Bearing_5_2	1	A		IfcFooting/Tie Beam_4	1	A
Abutment_0	IfcWall/ Backwall_0	3	C	Foundation	IfcFooting/ Footing_1_1	1	A
	IfcWall/ Wingwall_0	1	A		IfcFooting/ Footing_1_2	1	A
	IfcFooting/ Footing_0_1	1	A		IfcFooting/ Footing_1_3	1	A
	IfcFooting/ Footing_0_2	1	A		IfcFooting/ Footing_2	1	A
Abutment_5	IfcWall/ Backwall_5	2	B		IfcFooting/ Footing_3	1	A
	IfcWall/ Wingwall_5	1	A		IfcFooting/ Footing_4_1	1	A
	IfcFooting/ pile cap_5	1	A		IfcFooting/ Footing_4_2	1	A
	IfcPile/Pier_5_1… IfcPile/Pier_5_10	1	A		IfcFooting/ Footing_4_3	1	A
Pier_1	IfcColumn/ Pier_1_1	2	B		IfcPile/Pier_2_1… IfcPile/Pier_2_25	1	A
	IfcColumn/ Pier_1_2	2	C		IfcPile/Pier_3_1… IfcPile/Pier_3_20	1	A
	IfcFooting/Tie Beam_1	1	A				

By interacting with the bridge BIM IFC file, the developed stand-alone tool concluded that the case study bridge was in ‘Good’ condition. The condition PI was calculated to be 83.70. According to the inspection report, the overall condition score is 81.69, and the bridge is categorised as belonging to the second level out of a total of five levels. The deviation in condition PIs could be a result of the fact that the modelling of the case study bridge is incomplete. Elements such as expansion joints, drainage, and safety fences (which were not of ‘very high’ importance) were not modelled in the bridge BIM, although these were damaged. Their aggregate condition scores would have worsened the condition PI. Furthermore, visual inspection may not necessarily include the underwater foundations (e.g., Piles). Few defects or deteriorations were documented for foundations, whereas a few cracking and leakage was identified in piers and abutment. This indicates inconsistency to a certain extent.

6.5 Chapter summary

To summarise, this chapter develops Python-based tools to update bridge BIM IFC files with condition evaluation results. The tool, either in the form of a plug-in in the BIM platform or a stand-alone executive file, is demonstrated to be capable of accomplishing the condition evaluation procedure and generating reliable condition ratings. It is noteworthy that the level of detail (LOD) of the bridge BIM model is a contributing factor to the accuracy of the condition score at the structure level.

7 IFC-based model transfer from defective BIM model to defect analysis model

7.1 Chapter introduction

This chapter proposes a model transfer method from architectural bridge models integrated with defect information to defect analysis models in terms of structural analysis. The proposed method adopts a matrix analysis approach to semi-automatically convert bridge BIM models to analytical models and uses a stiffness reduction coefficient to describe the impacts of defects on bridge structures. This chapter is structured as follows. Section 7.2 presents the matrix-based method for model transfer and analysis. Section 7.3 presents case studies on both illustrative beam structures and real-life bridges. Results and in-chapter discussions are provided in Section 7.4. Section 7.5 concludes the chapter.

7.2 Sub-method development

This study is aimed at developing a method for seamless exchange from a defect design model to a defect analysis model. Specifically, defect design model refers to a bridge BIM model wherein defect information is integrated using the method developed in Chapter 6. Meanwhile, defect analysis model refers to an analytical model that considers the adverse impact of defects on the structure. Several BIM authoring tools such as Autodesk Revit support the modelling of an analytical model in conjunction with an architectural model. However, the export of information in the structural analysis domain is not necessarily available. Thus, the proposed method for model transfer from a defective BIM model to a defect analysis model starts with the model exchange from the architectural bridge model to an analytical model based on IFC standards. The overall procedure is illustrated in Figure 7.1.

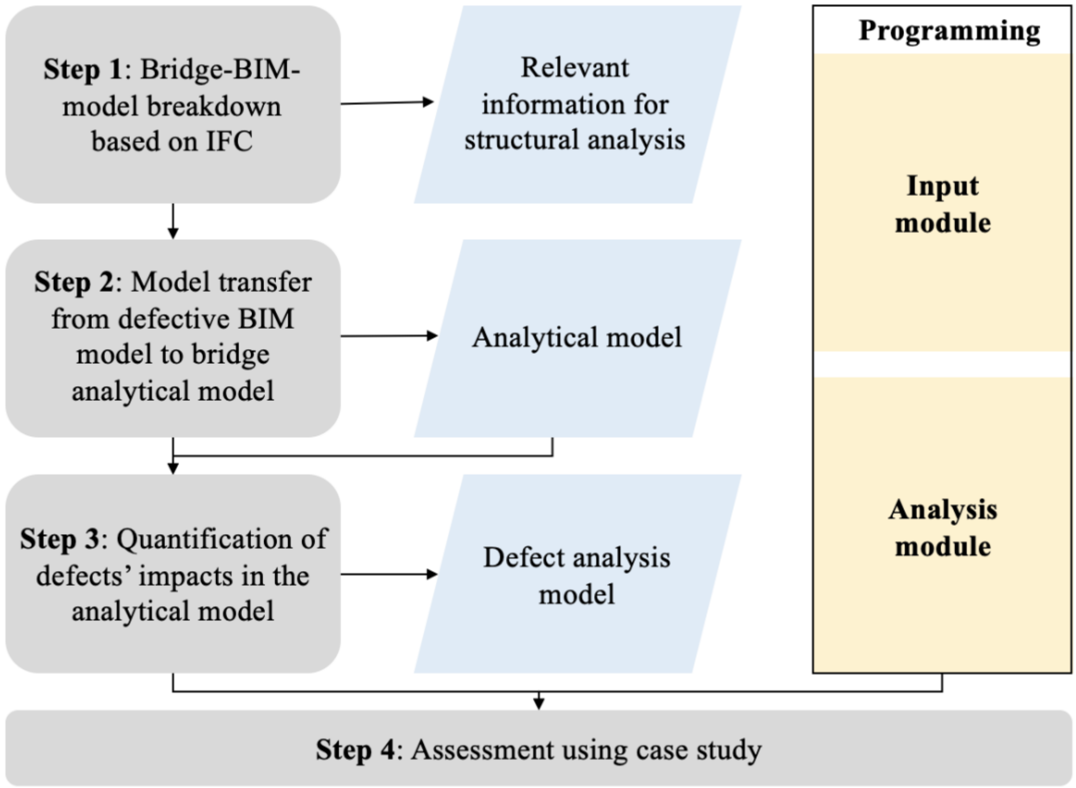


Figure 7.1 Flowchart of proposed method for model transfer

7.2.1 Breakdown of Bridge BIM

The data collection process first targets the bridge structure. The geometry, material properties, and information on the internal structural system (i.e., reinforcement) are collected. To further facilitate the model transfer and interpretation, it is assumed that the structural idealisation (i.e., the model preparation for FEA or the interpretation step in a transfer process) has been completed by structural engineers. As stated in (Fröhlich 2020), reasons for omitting this process include its subjectivity to research and standards, flexibility for the assessment of load bearing behaviours, and complexity given the need for nonlinear material modelling/analysis of reinforced concrete. Specifically, finite element formulations have been determined as beam, based on which a structural analysis model can be developed alongside the central axes of bridge elements or specific cross-sections. Furthermore, FE models can be generated with effective meshing algorithms.

The IFC standard supports the exchange from an architectural model to a structural analysis model via MVD, Structural Analysis View (BuildingSMART). IFC entities for structural analysis enhance the capability to represent key elements in a structural analysis model, ranging from IfcStructuralMember for structural member modelling and IfcStructuralAction for load description, to IfcStructuralReaction for analysis result presentation. An IfcStructuralAnalysisModel entity is then used to assemble all the above-mentioned information as an inheritance from IfcSystem. The IFC entity mapping from an architectural model to a structural analysis model is illustrated in Figure 7.2. Specifically, Region ‘A’ represents the composition of a (partial) structural analysis model. It includes two types of structural items: structural members and support conditions. Region ‘B’ illustrates the definition of load combinations/cases applied to the structure. Individual loads/actions are first grouped into IfcStructuralLoadGroup or in most cases, IfcStructuralLoadCase. It is then assigned to the analysis model via IfcStructuralAnalysisModel.Loadedby. Similarly, the structural responses (presented via IfcStructuralResultGroup) cannot use the aggregation relationship to connect to the analysis model. Rather, the HasResults attribute is used. The grouping from all the relevant responses/reactions of the structure to the result group is achieved again using the IfcRelAssignsToGroup entity. In Region ‘D’, the relationship between several partial structural analysis models and an overall analysis model is described using the aggregation concept. Among these partial analysis models, there are cases wherein the reaction of one partial model acts as the action of another partial model. Such a relationship is described in Region ‘E’, where an IfcRelAssignsToProduct entity is employed. Finally, Region ‘F’ presents the mapping from a structural analysis model to spatial elements (e.g., superstructure, substructure, and surface structure) via an IfcRelReferencedInSpatialStructue entity. This completes the structural analysis sector for bridge management.

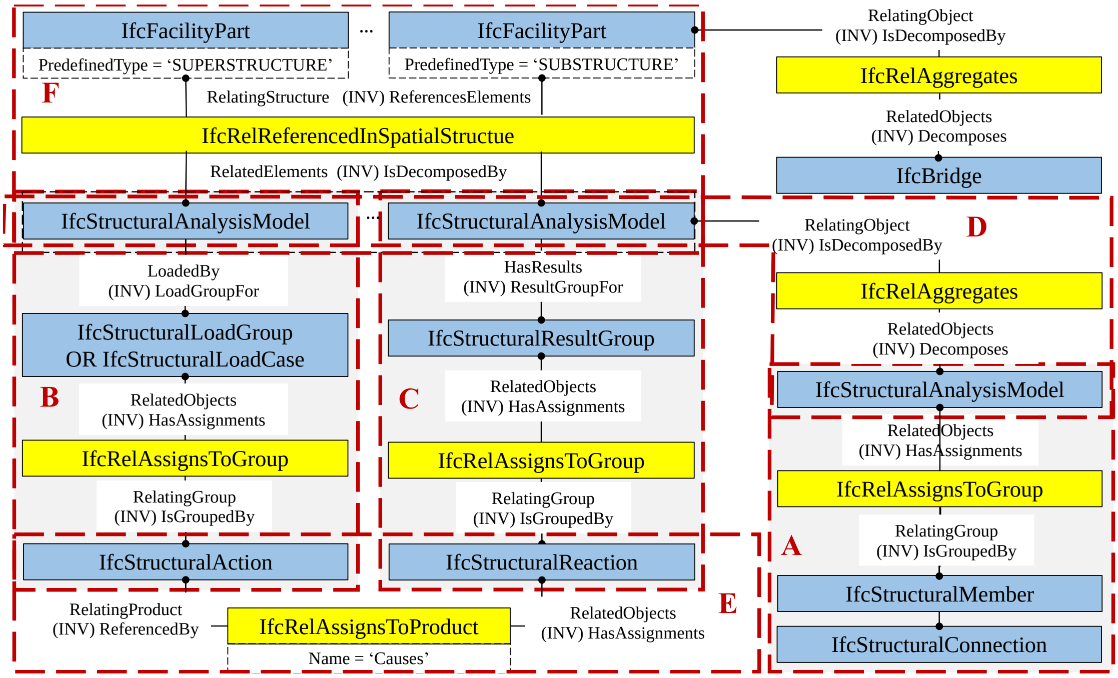
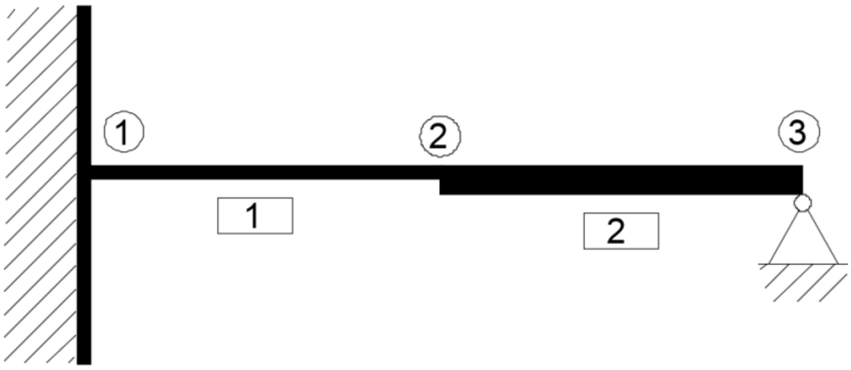


Figure 7.2 IFC entities for structural analysis

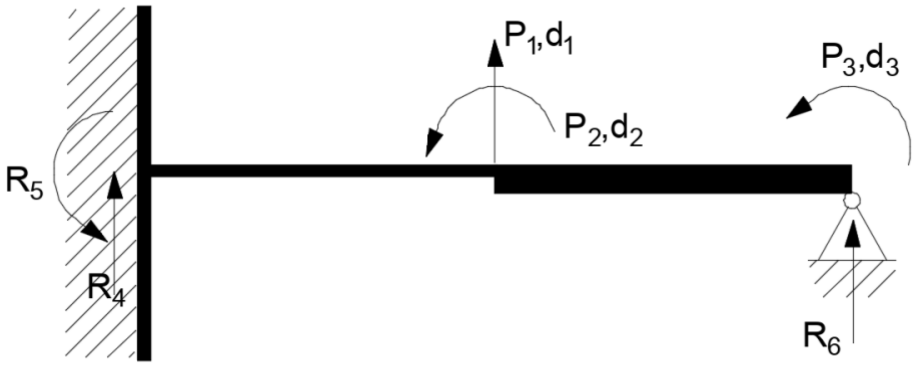
The IFC structural analysis scheme currently neither supports numerical analysis (unless it relies on commercial software developed particularly for structural analysis, such as Autodesk Robot Structural Analysis Professional and SAP2000) nor allows for the direct export and presentation of analysis results. Matrix methods are adopted to effectively reduce the disparity between the IFC structural analysis view and the actual numerical analysis of structures. Although structural analysis models ranging from Bernoulli beams and strut-and-tie models (Schlaich et al. 1987) to grillage methods have matured and have been implemented extensively in practice, matrix methods are selected for structural analysis given their capability for efficient computerisation and suitability for beam bridges. To facilitate these, further processing is necessary to prepare the model for computerised analysis in addition to the entity exchange from the architectural domain to the structural analysis domain. The information necessary for structural analysis would be retrieved using the ifcopenshell Python package. Such information includes structural data such as material properties, cross-sectional properties, and boundary conditions, and load information such as forces and load cases.

7.2.2 Programming of matrix methods for structural analysis

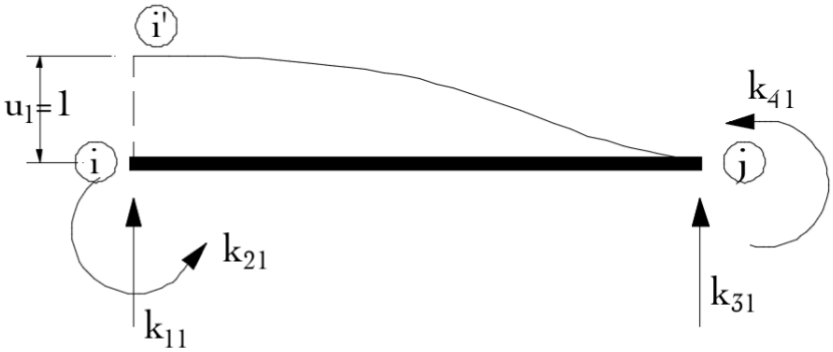
According to the general analytical procedure for programming in Section 2.3.2, the preparation of analytical models of beam begins with the identification of the number of degrees of freedom (NDOF). A two-dimensional simply-supported beam with variable cross-section is used for illustration, as shown in Figure 7.3.



(a) Simply-supported beam with variable cross-sections



(b) Degrees of freedom and restraint numbering



(c) Description of element stiffness matrix

Figure 7.3 Example beam for matrix structural analysis

Specifically, owing to the linear characteristic of beams, only one coordinate (i.e., x-direction) requires transformation from the global to the local coordinate systems. A beam joint has a maximum of two degrees of freedom: a translation in the direction perpendicular to the beam's centroid axis and a rotation in the XY plane. Thus, the calculation of the NDOF can be expressed as Equation 7.1.

$$NDOF = 2 \times NJ - NR \qquad \text{Eq. 7.1}$$

, where NJ represents the number of joints in the analytical model and NR the number of restraints.

In this case, the NDOF equals four, which results in a joint displacement vector ***d***:

$$\boldsymbol{d} = \begin{bmatrix} d_1 \\ d_2 \\ d_3 \\ d_4 \end{bmatrix}$$

Accordingly, the NDOF × 1 joint load vector ***P*** and the number of restraints (NR) × 1 reaction vector ***R*** can be expressed as the following equations, respectively:

$$\boldsymbol{P} = \begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \end{bmatrix}$$

$$\boldsymbol{R} = \begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ R_4 \end{bmatrix}$$

Then, the stiffness matrices for each element are generated. These indicate the relationships between the forces (including the moments) at the end of each element and the displacements (including rotations) of its ends when external loads are applied to the structure. Each item in the stiffness matrix k_{ij} represents the force required at the location and in the direction of Q_j to generate a unit value of displacement u_i. Consider the computation of k_{11} as an example. As shown in Figure 7.3, the moment of the cross-section at an arbitrary location $(x, 0)$ can be expressed as Equation 7.2.

$$M = -k_{21} + k_{11} \cdot x \qquad \text{Eq. 7.2}$$

According to the inherent mechanics of beam bending, the marginal in-plane deflection follows the differential equation, i.e., Equation 7.3.

$$\frac{d^2 \bar{u}_y}{dx^2} = \frac{M}{EI} \qquad \text{Eq. 7.3}$$

, where $\bar{u}_y$ represents the deflection of the beam's centroid axis in the y-direction and EI is the element's flexural rigidity. Combining the above two equations, we obtain Equation 7.4.

$$\frac{d^2\bar{u}_y}{dx^2} = \frac{1}{EI}(-k_{21} + k_{11} \cdot x) \qquad \text{Eq. 7.4}$$

The slope θ and deflection of the element can be expressed in Equation 7.5 and Equation 7.6, separately, by integrating the above differential equation.

$$\theta = \frac{d\bar{u}_y}{dx} = \frac{1}{EI}\left(-k_{21} \cdot x + k_{11} \cdot \frac{x^2}{2}\right) + C_1 \qquad \text{Eq. 7.5}$$

$$\bar{u}_y = \frac{1}{EI}\left(-k_{21} \cdot \frac{x^2}{2} + k_{11} \cdot \frac{x^3}{6}\right) + C_1 x + C_2 \qquad \text{Eq. 7.6}$$

The unknown stiffness can be obtained by applying the four boundary conditions at both the ends. The element stiffness matrix can be generated as follows using a similar approach:

$$\boldsymbol{k} = EI \begin{bmatrix} \frac{12}{L^3} & \frac{6}{L^2} & -\frac{12}{L^3} & \frac{6}{L^2} \\ \frac{6}{L^2} & \frac{4}{L} & -\frac{6}{L^2} & \frac{2}{L} \\ -\frac{12}{L^3} & -\frac{6}{L^2} & \frac{12}{L^3} & -\frac{6}{L^2} \\ \frac{6}{L^2} & \frac{2}{L} & -\frac{6}{L^2} & \frac{4}{L} \end{bmatrix}$$

Similarly, the fixed-end force vector Q_f of each element, which is the reaction forces/moments developed in the direction of certain DOFs under external forces when all the joints are fixed in the structure, can be derived as follows:

$$\boldsymbol{Q_f} = \begin{bmatrix} Q_{f1} \\ Q_{f2} \\ Q_{f3} \\ Q_{f4} \end{bmatrix} = \begin{bmatrix} FS_b \\ FM_b \\ FS_c \\ FM_c \end{bmatrix}$$

Then, the element stiffness matrix and element force vector would be integrated into a structure stiffness matrix $\boldsymbol{S}$ and structure fixed-joint force vector $\boldsymbol{P_f}$ by referring to the element code numbers. In conjunction with $\boldsymbol{P}$, the force–displacement relationship equation of the structure, i.e., Equation 7.7, would be satisfied in all cases.

$$\boldsymbol{P} - \boldsymbol{P_f} = \boldsymbol{Sd} \qquad \text{Eq. 7.7}$$

After all the unknown variables at the structure level are solved at this stage, the element-level displacements, end forces, and support reactions can be computed. The final step of the program would examine the calculation results according to the equilibrium equations for errors. The flowchart of the analysis program is presented in Figure 7.4.

Programming	Procedures
Input module	• Obtain joint data vector; • Obtain support data vector; • Obtain material properties vector; • Obtain cross-sectional properties vector; • Obtain element data vector; • Obtain joint loads vectors; • Obtain element loads vectors.
Analysis module	• Determine the number of degrees of freedom (NDOF) of the model & the structure coordinate number vector NSC; • Integrate stiffness matrices and load vectors at the element level into the structure level, resulting S and P; • Calculate joint displacements using Gauss–Jordan elimination P = Sd; • Determine internal forces at the element level.

Figure 7.4 Flowchart of the analysis program

7.2.3 Defect analysis method

Unlike previous studies, which obtained structural parameters (e.g., deformations and modal parameters such as mode shapes and eigenfrequencies) through SHM systems and directly used these as input in the as-is structural analysis model, this chapter aims to assess the bridge's structural status using defect information, particularly structural damage. Inspired by (Fröhlich 2020), deterioration variables are proposed to model the structural responses to damages. The parametrisation of both physical elements and defect elements is effective for defects that affect the dimensions of structural members. Thereby, the cross-sectional properties of the defected element at the location can be calculated efficiently. For defects that impact the strength or stiffness of concrete, a coefficient is added to the relevant material properties. Structural cracking (which is generally manifested as a linear fracture at a location in concrete where stress is concentrated) is considered as an example type of defects in bridges. A critical mechanical assumption of the classical beam approach is that of a linear strain distribution. However, at discontinuity regions (e.g., cracked concrete) where nonlinear strain distribution occurs, the cracked reinforcement concrete is considered as a new material model. Stress redistribution occur at the cracked sections, which results in a concentration of tension forces in the reinforcement and concentrated compression stresses in non-cracked parts.

The determination of beam stiffness at a crack can be influenced by various factors ranging from the cross-sectional property, external loading, and restraint, to different cracking development stages. A few design manuals for concrete structures provide recommendations on stiffness reduction at cracking. Table 7.1 lists the manuals and their recommendations regarding this topic. As regulated by Table 6.6.3.1.1 of the US code ACI 318-14, the modified moment of inertia of cracked beams can be either $0.35I_g$ or calculated using the following Equation 7.8.

$$I = \left(0.80 + 25\frac{A_{st}}{A_g}\right)\left(1 - \frac{M_u}{P_u h} - 0.5\frac{P_u}{P_0}\right) \quad \text{Eq. 7.8}$$

where A_{st} is the total area of the non-prestressed longitudinal reinforcement. A_g is the gross area of the concrete section. h is the overall height of the element. M_u is the factored moment at the section. P_u is the factored axial force, whereas P_0 is the nominal axial strength at zero eccentricity. The factored moment of inertia should also be within the range $0.35I_g$ – $0.875I_g$. The reduction coefficient for the stiffness of cracked non-PC beams according to various standards worldwide varies from 0.30 to 0.70.

Table 7.1 Recommendation values for stiffness reduction in standards

Element	ACI 318-14 (American Concrete Institute 2014)	ASCE 41-13 (American Society of Civil Engineers (ASCE) 2014)	Eurocode (Standardization 2005)	CSA A23.3-14 (Computers & Structures 2015)	NZS 3101* (New Zealand Standards Association 2006)
Beams (non-prestressed)	$0.35I_g$	$0.30I_g$	$0.50I_g$	$0.35I_g$	$0.70I_g$ $for\ rectangular$ $0.60I_g$ $for\ T, L\ beams$
Beams (prestressed)	N/A	I_g	$0.50I_g$	$0.35I_g$	N/A
Columns	$0.70I_g$	$0.7I_g\ if\ P_u \geq 0.5A_g f_c'$ $0.3I_g\ if\ P_u \leq 0.1A_g f_c'$	$0.50I_g$	$0.70I_g$	$I_g\ (if\ P_u \geq 0.5A_g f_c') \sim 0.70I_g\ (if \leq 0.1A_g f_c')$
Flat plates Flat slabs	$0.25I_g$	$\frac{1}{3}I_g$	$0.50I_g$	$0.25I_g$	N/A
Walls	$0.35I_g$	$0.50I_g$	$0.50I_g$	$0.35I_g$	$0.50I_g \sim 0.70I_g$

Note: I_g represents the moment of inertia of the gross concrete section about the centroid axis. Reinforcement is omitted.

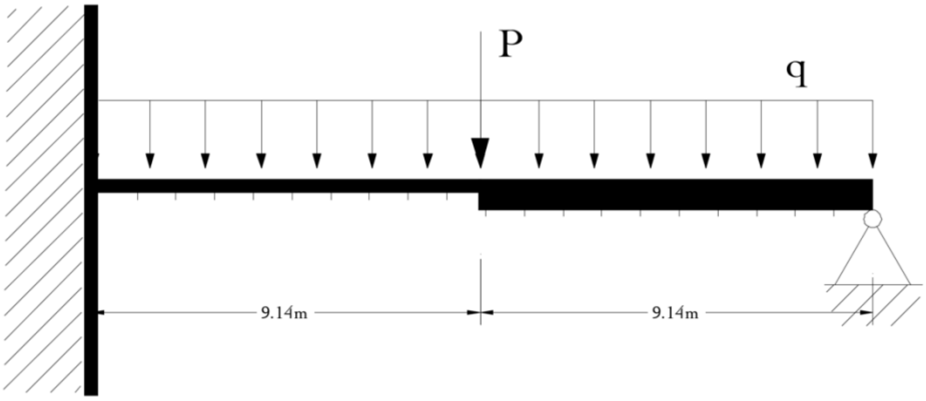
* The factored stiffness considers the serviceability limit state. Another set of factors for ultimate limit state is available in the NSZ3101 standard.

Li et al. (2010) developed a program specifically for calculating factored mean stiffness at a crack. The program follows six steps to retrieve effective stiffness values that are more accurate than the recommended values in standards: (a) calculate the cracking force and/or moment, (b) obtain the stiffness at a crack, (c) define the position of the shifted centroidal axis, (d) quantify the tension stiffening effect owing to the removal of the centroidal axis at the cracking location, and (e) determine the mean stiffness of the element. In this study, the stiffness reduction coefficient recommended in ACI 318-14 (American Concrete Institute 2014) is adopted for defect analysis.

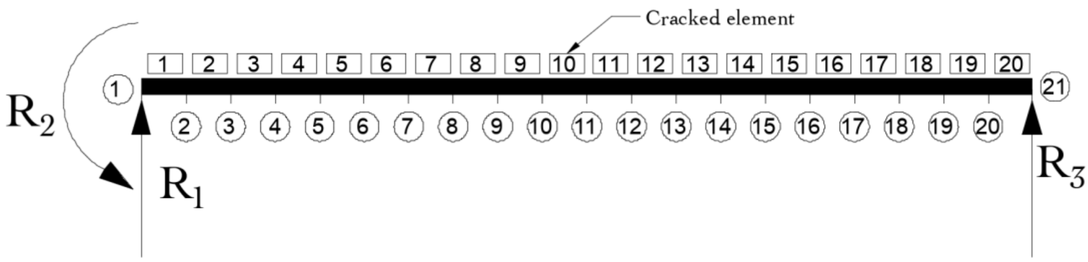
7.3 Case study and analysis

7.3.1 Illustrative simply-supported bridge

A simply-supported beam composed of two elements (see Figure 7.5) is used as the first case for illustration. A Python program is developed to computerise the matrix methods for the structural analysis introduced above. The script (see Appendix 2) can automatically construct the analytical model using appropriate input data and conduct structural analysis accordingly. This case mainly aims to validate the developed program for matrix structural analysis and present a sensibility analysis of the stiffness reduction coefficient for cracked concrete.



(a) Beam structure under lane loads according to the Chinese standards (Ministry of Transport 2018)



(b) Numbering of analytical model

Figure 7.5 Illustrative beam structure for primary case study

In this program, clockwise moments and upward forces are assumed to be positive. However, according to the sign convention in engineering, shear forces that spin an element clockwise and moments that bend a beam concave upward are defined to be positive. Note that under positive moments, the materials in the top and bottom parts of the beam undergo compression and tension, respectively. In addition, in professional engineering drawings, positive and shear forces are drawn above and below the x-axis, respectively. Cross-sectional moments are drawn adjacent to tension, which implies that positive and negative moments are drawn below and above the x-axis, respectively. Table 7.2 summarises the sign convention and corresponding drawing rules.

Table 7.2 Sign convention and engineering drawing.

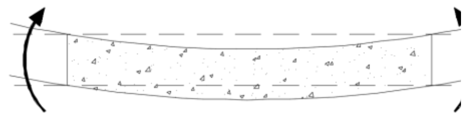
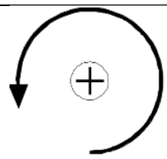
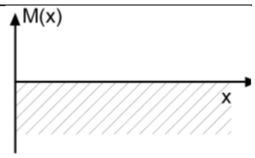
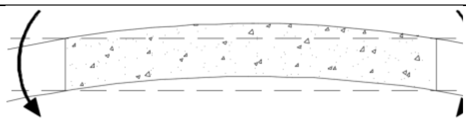
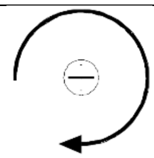
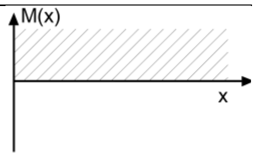
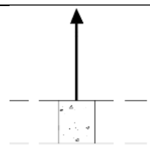
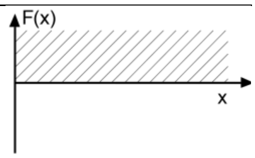
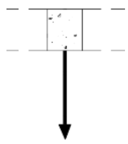
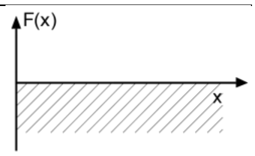
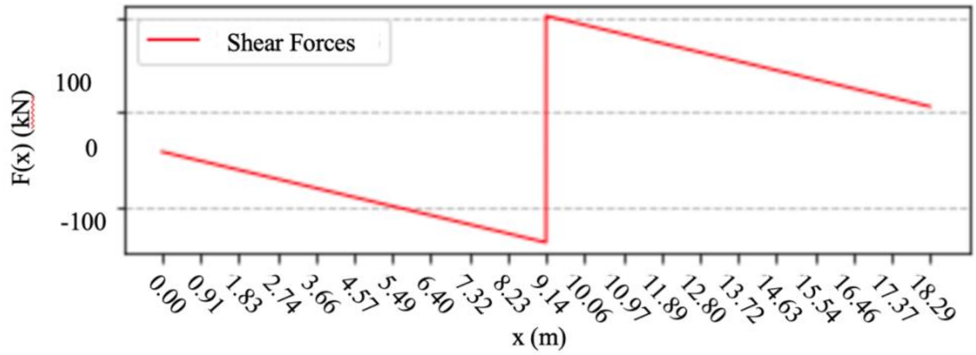
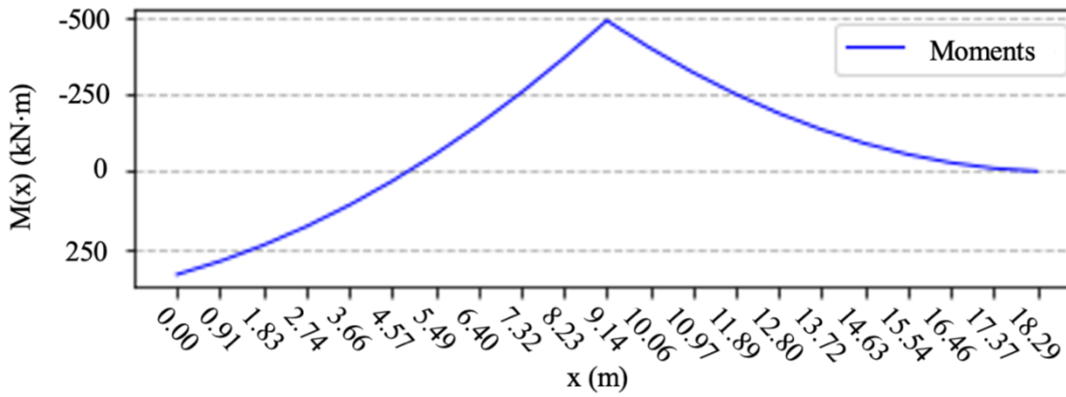
Types of forces	Sign	Sign convention	Sign regulation in the program	Professional drawing
Moments	+			
	-			
Shear forces	+			
	-			

Figure 7.6 presents the structural analysis of an intact beam structure using the program, including shear forces (a) and moments (b). It can be concluded that the analysis results are theoretically reliable.



(a) Shear forces

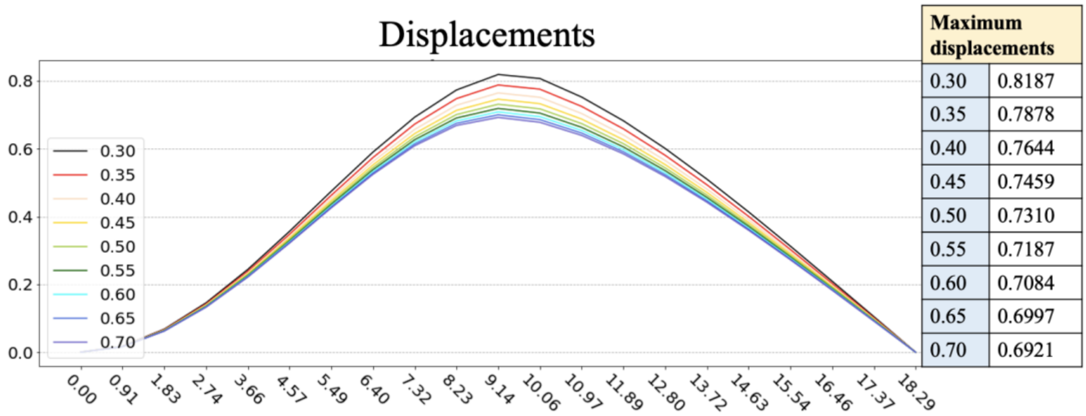


(b) Moments

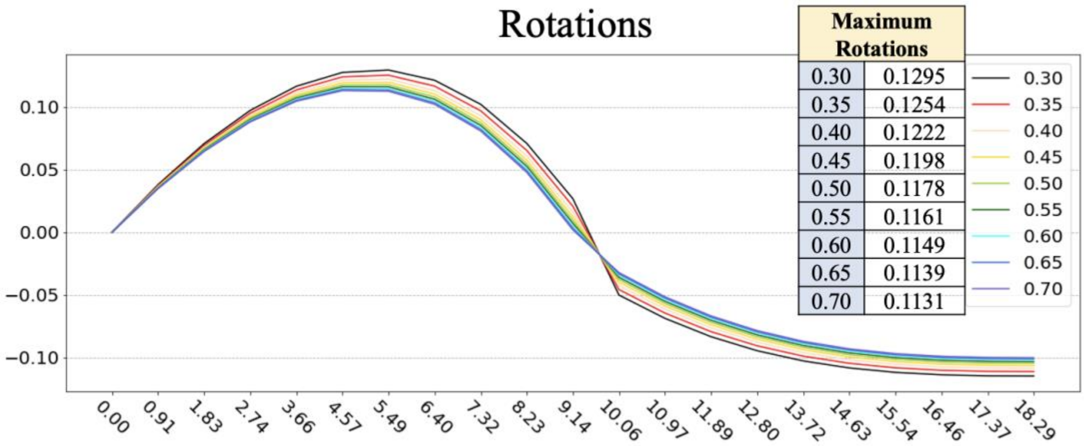
Figure 7.6 Matrix-based structural analysis of an intact beam structure

To specify the location of cracking more accurately, the two-element beam was divided further into 20 segments, thereby resulting in 21 joints as shown in Figure 7.5(b). The cracking occurs on the soffit of the tenth element, i.e., the middle of the span, where the largest tensile stress occurs. Thus, the stiffness matrix of the tenth element requires modification. In this sensibility analysis, the stiffness reduction coefficient of cracked element varied from 0.30 to 0.70 at intervals of 0.05. The stiffness-based structural analysis results are presented in Figure 7.7. Displacements (including rotations) and internal forces (including moments) at the degrees of freedom along the beam's longitudinal direction are presented. It is observed that cracking at the second element causes an increase in both structural deflections and internal forces, thereby posing safety issues for the entire structure. A decrease in the stiffness reduction coefficient of cracked concrete implies that the defective condition is becoming severe and that impacts of cracking on structural deflections are increasing. The growth rate of the maximum displacements at the middle span increases from 1.09%

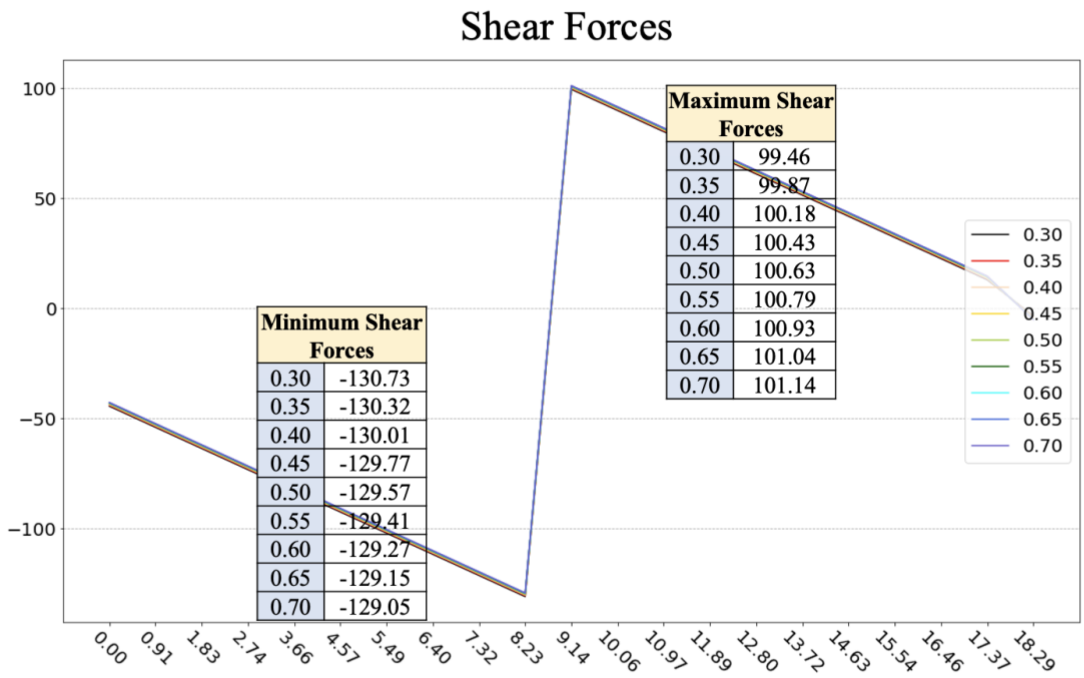
(with the reduction coefficient decreasing from 0.70 to 0.65) to 3.92% (with the coefficient decreasing from 0.35 to 0.30). Similarly, the growth rate of maximum rotations increases from 0.77% (with the reduction coefficient decreasing from 0.70 to 0.65) to 3.29% (with the reduction coefficient decreasing from 0.35 to 0.30).



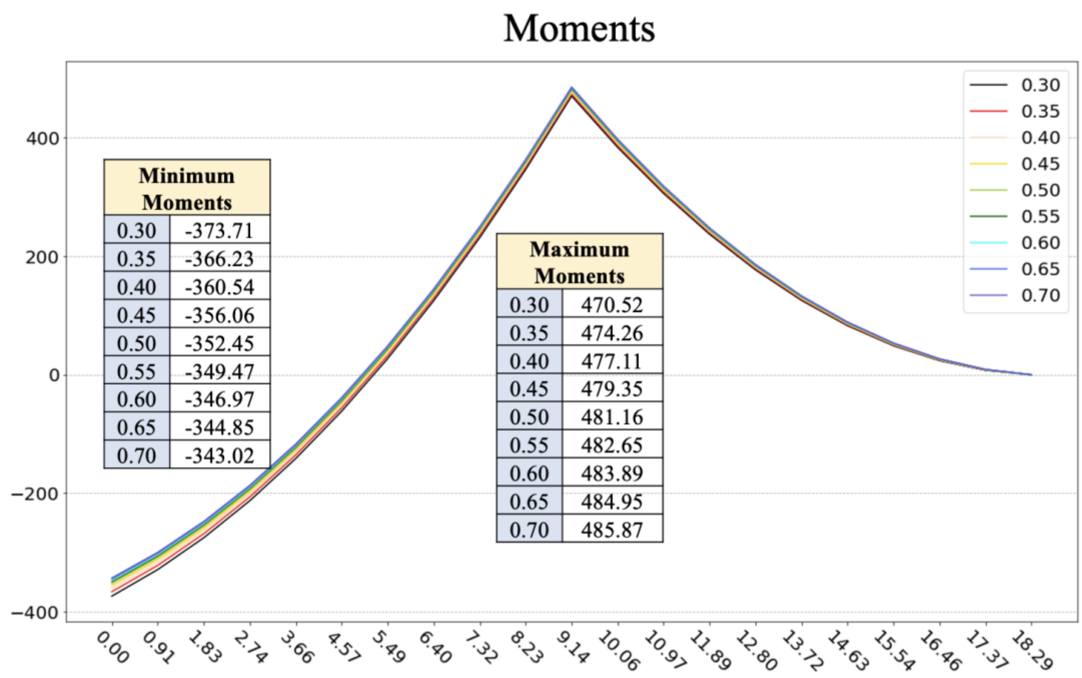
(a) Displacement with respect to stiffness reduction coefficient



(b) Rotation with respect to stiffness reduction coefficient



(c) Shear force with respect to stiffness reduction coefficient



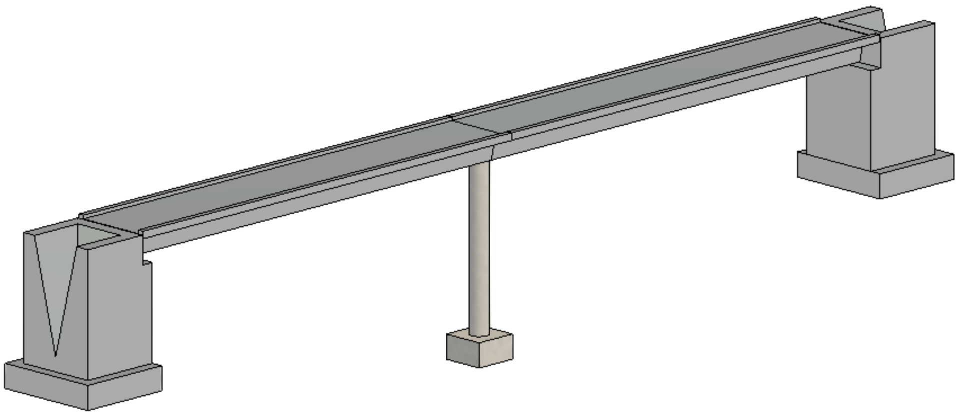
(d) Cross-sectional moment with respect to stiffness reduction coefficient

Figure 7.7 Sensibility analysis results

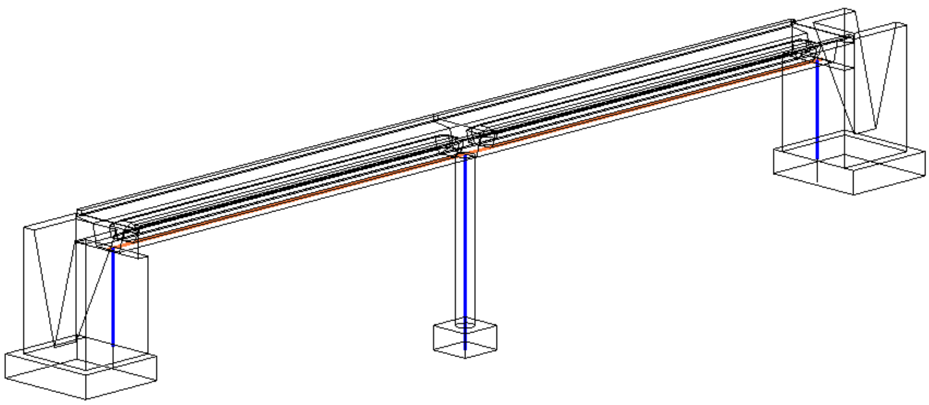
With regard to internal forces (see Figure 7.7 (c) and (d)), the negative forces (including moments) increase as the cracking deteriorates, whereas the positive forces decrease. The main reason is that the capability of structural materials to sustain loads decreases because of cracking at the middle span where the maximum positive moments occur. As a result, the internal forces at the fixed end of the beam (i.e., the first joint) increase and the growth rate varies from 0.53% to 2.04% as the stiffness reduction coefficient decreases from 0.70 to 0.30.

7.3.2 An actual RC continuous bridge

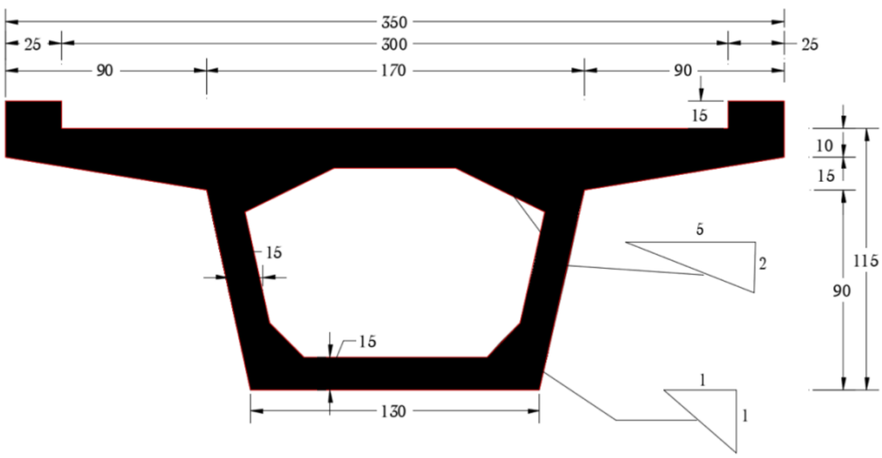
After the development of the effective program for matrix-based defect analysis, a real-life reinforced concrete bridge is used to evaluate the proposed defect analysis method. The case study bridge is first modelled in a BIM authoring tool (Autodesk Revit 2021), as shown in Figure 7.8. All the relevant information for structural analysis is modelled, including geometry, material properties, and supporting conditions. Specifically, the case study bridge has two spans of 20 m each. The main girder is in the form of a single box, and the cross-section with detail dimensions is shown in Figure 7.8 (c). The pier is composed of a single column, and the gravity abutment is used at both ends of the bridge. An IFC file is then exported based on IFC 4 standards in the Revit. It is noteworthy that no structural analysis view is currently available in Revit for exporting an analytical model to platform-neutral tools.



(a) 3D model of the case study bridge in Revit 2021



(b) Analytical model of the case study bridge (The red line represents the analytical beam while blue lines are analytical models of substructure)



(c) Box cross-section of the main girder (Units: cm)

Figure 7.8 The two-span continuous RC bridge for case study

Unlike the illustrative case in the above section, the bridge BIM IFC file is first processed to prepare an analytical model. The input module of the proposed method (its core functions are presented in Appendix 2) is used to form input data vectors/matrices necessary for the analysis module. Conversion from architectural model to analytical model is achieved by obtaining the beam elements and their longitudinal placements (via the attribute .ObjectPlacement), as presented in Figure 7.9 (a). This includes an appropriate segmentation and the numbering of analytical joints and elements. In this case, all the cross-sectional representations of beam elements are retrieved, and the OpenCV library ("OpenCV: Open source computer vision") is employed to calculate cross-sectional properties (e.g., area and moment of inertia I_g) using coordinates of points that form an arbitrary polygon. Figure 7.9 (b) presents the IFC schemas relevant to a beam's cross-sectional properties. The attribution of reinforced bars is added manually because the modelling of reinforced steel in BIM authoring tools is not necessarily included in actual projects. Then, the material information and its mapping to beam elements are obtained by identifying IfcRelAssociatesMaterial entities and their relating/related objects, as shown in Figure 7.9 (c). The supporting conditions are inferred by retrieving substructure elements including piers and abutments. An interactive coding environment (Jupyter Notebook) is used to retrieve and interpret relevant information from the hierarchy of IFC data models. Otherwise, an inclusive collection of the hierarchical breakdown of IFC projects in terms of various types of bridge structures, different cross-sections, and corresponding representations is required. The defect information is also read, and the structural impacts of cracking are quantified using a stiffness reduction coefficient of 0.50.

```
#6= IFCCARTESIANPOINT((0.,0.,0.));
…
#32= IFCAXIS2PLACEMENT3D(#6,$,$);
#33= IFCLOCALPLACEMENT(#160,#32);
#148= IFCAXIS2PLACEMENT3D(#6,$,$);
#149= IFCLOCALPLACEMENT(#33,#148);
#159= IFCAXIS2PLACEMENT3D(#6,$,$);
#160= IFCLOCALPLACEMENT($,#159);
#1894= IFCAXIS2PLACEMENT3D(#6,$,$);
#1895= IFCLOCALPLACEMENT(#149,#1894);
#1896= IFCBUILDINGELEMENTPROXY('3D7GwLrnfEHOxtiCOrOYoK',#42,'box_girder:box_girder:264256',$,
'box_girder:box_girder',#1895,#1891,'264256',.NOTDEFINED.);
…
#1993= IFCCARTESIANPOINT((20000.,-1729.67601217002,0.));
#1995= IFCAXIS2PLACEMENT3D(#1993,$,$);
#1996= IFCLOCALPLACEMENT(#149,#1995);
#1997= IFCBUILDINGELEMENTPROXY('3D7GwLrnfEHOxtiCOrOYtq',#42,'box_girder1:box_girder:264480',$,
'box_girder1:box_girder',#1996,#1990,'264480',.NOTDEFINED.);
```

(a) Global placement of beams

Outer Bounded Polygon

```
#1706= IFCCARTESIANPOINT((-1745.73837469983,135.278619441694));
#1708= IFCCARTESIANPOINT((-1778.86783252228,-162.886500960392));
#1710= IFCCARTESIANPOINT((-1530.39689885393,-190.494382479099));
#1712= IFCCARTESIANPOINT((-1513.8321699427,-41.4118222780763));
#1714= IFCCARTESIANPOINT((1467.81903407815,-372.706400502624));
#1716= IFCCARTESIANPOINT((1451.25430516693,-521.788960703647));
#1718= IFCCARTESIANPOINT((1699.72523883532,-549.396842222359));
#1720= IFCCARTESIANPOINT((1732.85469665778,-251.231721820287));
#1722= IFCCARTESIANPOINT((849.402488059,-52.454974885554));
#1724= IFCCARTESIANPOINT((750.014114591646,864.126691535676));
#1726= IFCCARTESIANPOINT((-542.034740483997,1007.68767543297));
#1728= IFCCARTESIANPOINT((-840.199860886081,135.278619441694));
#1730= IFCPOLYLINE((#1706,#1708,#1710,#1712,#1714,#1716,#1718,#1720,#1722,#1724,#1726,#1728,#1706));
```

Inner Bounded Polygon

```
#1732= IFCCARTESIANPOINT((-274.238289752484,22.0863052150027));
#1734= IFCCARTESIANPOINT((-642.665468619688,260.480362129083));
#1736= IFCCARTESIANPOINT((-494.11534613365,695.127016810458));
#1738= IFCCARTESIANPOINT((-322.552082410234,832.37762778919));
#1740= IFCCARTESIANPOINT((497.401998695442,741.271618777446));
#1742= IFCCARTESIANPOINT((634.652609674173,569.708355054029));
#1744= IFCCARTESIANPOINT((684.169317169516,113.054274819171));
#1746= IFCCARTESIANPOINT((272.397764317921,-38.651034126155));
#1748= IFCPOLYLINE((#1732,#1734,#1736,#1738,#1740,#1742,#1744,#1746,#1732));
#1750= IFCARBITRARYPROFILEDEFWITHVOIDS(.AREA.,'box_girder',#1730,(#1748));
#1757= IFCEXTRUDEDAREASOLID(#1750,#1756,#22,20000.);
…
#1767= IFCSHAPEREPRESENTATION(#120,'Body','SweptSolid',(#1757));
#1769= IFCAXIS2PLACEMENT3D(#6,$,$);
#1770= IFCREPRESENTATIONMAP(#1769,#1767);
…
#1887= IFCMAPPEDITEM(#1770,#350);
#1889= IFCSHAPEREPRESENTATION(#120,'Body','MappedRepresentation',(#1887));
#1891= IFCPRODUCTDEFINITIONSHAPE($,$,(#1889));
#1896= IFCBUILDINGELEMENTPROXY('3D7GwLrnfEHOxtiCOrOYoK',#42,'box_girder:box_girder:264256',$,
'box_girder:box_girder',#1895,#1891,'264256',.NOTDEFINED.);
```

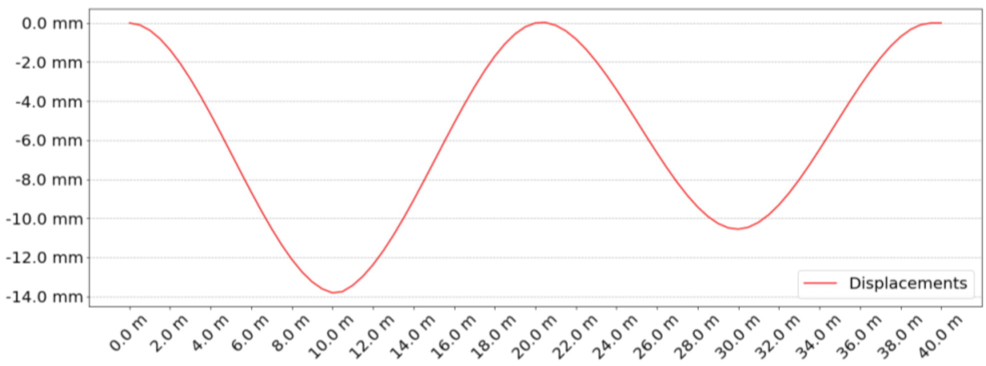
(b) Retrieval of beam's cross-sectional properties

```
#390= IFCBUILDINGELEMENTPROXYTYPE('16D2xXnJz3ZfQoWQAEX9g8',#42,'Box Girder:Box
Girder',$,$,(#455,#457),(#386),'246576',$,.NOTDEFINED.);
#394= IFCMATERIAL('Concrete - Precast - 35 MPa',$,'Concrete');
#421= IFCBUILDINGELEMENTPROXY('16D2xXnJz3ZfQoWQAEX9gA',#42,'Box Girder:Box
Girder:246578',$,'Box Girder:Box Girder',#419,#413,'246578',.NOTDEFINED.);
…
#659= IFCBUILDINGELEMENTPROXYTYPE('16D2xXnJz3ZfQoWQAEX9CT',#42,'Box Girder1:Box
Girder',$,$,(#687,#689),(#657),'248485',$,.NOTDEFINED.);
#672= IFCBUILDINGELEMENTPROXY('16D2xXnJz3ZfQoWQAEX9CV',#42,'Box Girder1:Box
Girder:248487',$,'Box Girder1:Box Girder',#671,#665,'248487',.NOTDEFINED.);
…
#1384=
IFCRELASSOCIATESMATERIAL('1bL33HyMv3J86OEwrPchCs',#42,$,$,(#390,#421,#659,#672),#394);
…
```

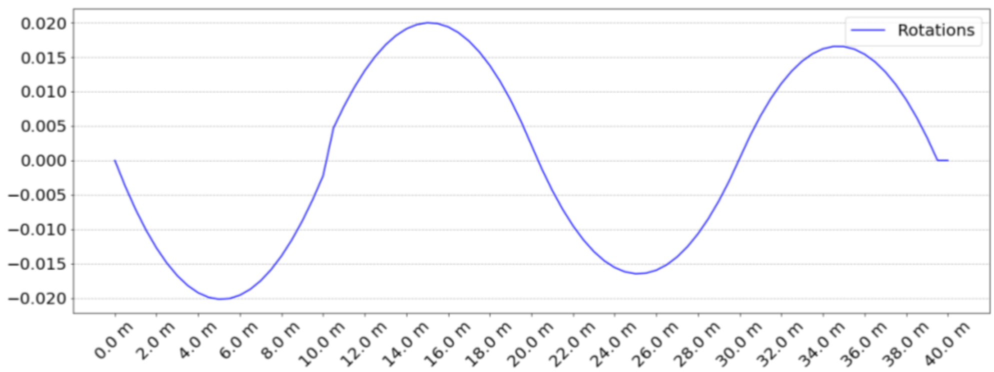
(c) Material mapping to bridge elements

Figure 7.9 IFC schema relevant to the model transfer process

The beam bridge is subjected to a combination of dead load and vehicular lane loads. The defect analysis results, including deflections and internal forces, are presented in Figure 7.10. It is noteworthy that although the calculation results for the joints are precise compared with those of other analysis methods such as finite element analysis, the LOD of the element division is significantly related to the accuracy of analysis results. It would be effective to specify the regions affected by defects rather than assume that the entire beam's bending stiffness has been reduced by a linear crack in the middle. The figure presents the analysis results of the case bridge.



(a) Displacements of case bridge (with a crack in the middle of the first span)



(b) Rotations of case bridge (with a crack in the middle of the first span)

Figure 7.10 Analysis results of case bridge

It can be observed that the displacements of the first span are larger than those of the second span owing to the cracking at the middle of the first span. Nonetheless, these are within the reasonable range of deflections. In addition, there is a discrepancy at the cracked region with regard to rotations, wherein a higher gradient is caused by the material discontinuity.

7.4 Chapter summary

This chapter presents a method to convert IFC-based defective bridge BIM models into analytical models for defect analysis. The impacts of defects on bridge structures can be quantified and integrated into the analytical model using stiffness matrix methods. Two example bridges were selected for the case study to verify the capability of the proposed method in analysing defects from the perspective of structural reliability.

8 Discussion

8.1 Chapter introduction

Section 8.2 presents discussions on the results for each of the aforementioned three objectives, the link among these objectives, and their facilitation of the current bridge management practices. Next, limitations and insights are presented in Section 8.3. Section 8.4 concludes this chapter with a summary.

8.2 Significance, novelty, and potential implementations

8.2.1 Practical implementations of the defect model

The first objective is to develop a novel defect model for bridge inspection activities. The results present the defect model in three interrelated parts: (1) Common defects are categorised into material defects (including concrete and other materials) and performance deficiencies and assigned to bridge elements where these are likely to occur. (2) The intra- and inter-element relationships among defects are illustrated separately and integrated in an overall defect graph. (3) Critical properties and potential causes are mapped to defects to further support on-site inspectors with their work. The practical significance and potential implementations of the research output are illustrated below:

- **Standardisation of bridge defects.** Actual bridge inspections encounter considerable diversity in terms of the identified defects, their properties, and their condition. The subjectivity in the above decision-making processes is long-standing owing to the constant need for the involvement and assessment by engineers (Chase et al. 2016). Although photographs and supplementary notes are attached to inspection reports, managers responsible for determining appropriate maintenance strategies continue to generate different interpretations of a structure's status. From this perspective, as part of the advancement towards automation in the construction industry, improvements can be achieved by reducing human interpretation at the data collection stage. A standardised bridge defect scheme can achieve this goal. The list of common defects aims to define and categorise these in a standardised manner and thereby, facilitate automated defect identification with reduced ambiguity during on-site inspections. In addition, the identification of defect properties that are critical to condition assessment ensures the completeness of inspection data. Thus, robotised collection of defect information can generate a comprehensive and unbiased description of the target structure.

- **Supporting on-site defect identification.** A relationship graph that maps the defects in various bridge components into an overall system is proposed to facilitate an efficient and (if trained exhaustedly) automated search for defects on site. Inexperienced practitioners and machines without a background in structural engineering can use this to infer the presence of other defects based on their observations during the inspection. The identification of a certain defect evolution path can further facilitate the determination of concealed major causes of visible deficiencies/deteriorations. The improvements required to fully utilise the defect relationship graph are two-fold: verify existing links and introduce missing ones and reinforce the scoring system that measures the strength of relationships between defects. In particular, a few inter-element links have not been rated. Because of the absence of rules or formulas, intensive learning from actual cases would be an alternative solution for quantifying such relationships. It is to be noted that certain defects are confined to certain regions because their development relies significantly on special environments or environmental factors. An example is concrete cracking caused by AAR/ASR. It is preferable to exclude such location-dependent defects during the reinforcement learning process. In this manner, the final results can be robust to various application scenarios (e.g., bridge location) and thereby, have a maximised generality.
- **Supporting on-site preliminary defect diagnosis.** The analysis of the underlying causes of defects is fundamental to scientific maintenance decision-making. However, owing to the limited information that can be obtained through visual inspection, few engineers can make final decisions based only on inspection reports. In practice, information from design and construction stages, historical records of the structure in terms of its repair or retrofit actions, and supplementary investigations are utilised to finalise the diagnostic process. Another challenge encountered

by the industry is that bridge defects are generally attributed to a combined action of multiple adverse factors. Therefore, the cause–defect graph is implemented considering its capability to offer users (particularly inexperienced practitioners) with reliable recommendations on their cause analysis. Engineering assessment is required at this stage. In the future, it may be significant to sort the relationships among various causes by exploring the potential for their combination and exclusion.

8.2.2 Novelty of the IFC-based method for defect representation

The second objective of this research is to develop an IFC-based method to document and represent inspection-related information in bridge BIM models. The modelling process consists of three subsequent steps: (1) modelling of inspection activity, (2) geometric modelling of individual defects with a set of parameters, and (3) modelling of relationships around defects. The proposed method has been demonstrated to be efficient in terms of information retrieval and preliminary analysis and to be interoperable among BIM tools, through an experiment.

To further highlight the novelty of this part of the study, the method proposed in this study is compared with previous endeavour in the field of defect management using IFC data models (see Table 8.1). The table summarises the modelling capability of previously developed methods and the proposed method with respect to inspection activity, defects, and their relationships with certain parameters. It is observed that the novelty of the proposed method mainly lies in its capability of defect modelling and defect relationship modelling. For defect representation, the methods have evolved from a simple property assigned to the affected element (Hamledari et al. 2018), to a separate entity. The description of its geometric features has been becoming increasingly explicit: from attached external document or images to properties assigned to the defect entity. Following this path, this study represented each defect using the IfcSurfaceFeature entity (in line with the most recent IFC standard) and modelled their geometry with predefined parameters. Similarly, defect positioning on a bridge has been becoming increasingly specific. It has narrowed down from an entire element (Hamledari et al. 2018) to the affected region of the element (Tanaka et al. 2016), zoom-in images (Hüthwohl et al. 2018), and a parametrised exact position with reference to the affected element in this work. In both cases, this study was inspired by the above-mentioned research and achieved the parameterisation of defect modelling in bridge BIM. The advantages of parameterisation originate from the fact that structured documentation, convenient update, seamless exchange, and better visualisation can be achieved across platforms, software, and end users. Moreover, the proposed parametric approach largely enhances the adaptability of these defect models to a wide range of bridge defects beyond the examples illustrated in the experiment. Specifically, cracking is used to exemplify the modelling process of a linear defect, for which the parametric definition of its skeleton is critical. Meanwhile, spalling, damage on bridge pavement, and honeycombing are examples of faceted defects, whose surface are parametrically defined through the outer-bounding polyline. Arbitrarily shaped profiles can be developed when necessary inputs of key points on the polyline are provided.

Table 8.1 Comparison of previous studies on IFC-based modelling of inspection-related data

	Capability to model								
References	Inspection activity	Defect			Defect relationship				
		Defect entity	Geometry of defect	Positioning of defect	With inspection activity	With bridge elements	Among each other	With potential causes	With maintenance actions
Hamledari et al. (2018)	√	X	x	X	x	√	x	x	x
Tanaka et al. (2016)	√	√	x	√	x	√	x	x	x
Hu et al. (2019)	√	√	x	X	√	√	x	√	√
Motamedi et al. (2017)	x	√	√	√	x	√	√	x	x
Hüthwohl et al. (2018)	√	√	x	√	√	√	√	x	x
Proposed method in this paper	√	√	√	√	√	√	√	√	√

Note: The symbol ‘x’ indicates that the corresponding objective was not included in that method. The symbol ‘√’ represents that the method modelled the corresponding data.

Another novelty of the method proposed in this work relates to its capability to model a variety of spatiotemporal and logical relationships of defects. This has practical significance for managerial operations. As summarised in Table 8.1, previous methods for IFC-based relationship mapping were neither inclusive nor systematic. For example, with regard to the construction stage, information on subcontractors responsible for the defective elements is effective for on-site quality control. These are described in (Hamledari et al. 2018). During the O&M phases, the relationship between defects and the corresponding inspection event can be used to monitor the evolution of defects across time (Hüthwohl et al. 2018; Tanaka et al. 2016). However, other relationships around defects can be complex. For example, defect diagnosis, i.e., the relationship between defects and potential causes, requires dedicated research effort. As indicated and attempted in (Hu et al. 2019), a Resource Description Framework graph was developed to detect root causes of common defects in tunnels. The detection was accomplished mainly based on domain rules and expert knowledge and facilitated with additional information from monitoring systems. Yet, only an object property *ResultFrom* was used to assign potential causes to defects. The modelling of such defect relationship was proposed and validated by Sacks et al. (2018), where multiple defects were linked logically into an IfcElementAssembly regarding the same underlying cause. Another example is the inter-relationships among defects, including causal and concurrence relationships. Several grouping schemes of bridge defects have been developed (Hüthwohl et al. 2018). However, none of the previous studies modelled all types of defect relationships or modelled these in a structured and systematic manner. The experiment has shown that the proposed method achieves a higher level of information inclusiveness (ranging from related events, preliminary diagnosis results, and maintenance recommendations to correlation among defects) and presents these systematically. In this manner, those information can be retrieved, exchanged, and reused efficiently by different stakeholders and authorities.

It is noteworthy that according to the interoperability evaluation results, IFC 4×2 and IFC 4×3 are not currently available for deployment. Most of the BIM tools do not update their support for IFC files to the most recent IFC standard. This is particularly so when considerable variations are introduced in IFC 4×2 by the IFC-Bridge project. The robustness of interacting free-form geometry across BIM tools is inadequate, particularly the geometry that is developed parametrically. The reason is rooted in the differences in geometric modelling approaches across platforms. The unavailability of certain modelling method in a software program is closely related to its incapability to read the corresponding IFC schemas and thereby, its failure to represent the geometry. Therefore, it is safe to adopt commonly used geometric models (e.g., body) and representation types (e.g., BRep) than infrequently used ones when both are applicable.

In addition, a few relationships are not readable by different BIM vendors, e.g., aggregation to Blender. More real-life case studies should be carried out to fully investigate the performance of interactive cooperation between various BIM vendors.

8.2.3 Significance of the defect analysis approaches

The third objective is to develop a method to directly analyse defect information in the integrated bridge BIM. The analysis consists of two major parts: one is under the scheme of condition assessment of bridge assets and the other is in the structural context. In both cases, IFC is used to represent relevant information and facilitate information interpretation so as to achieve the model transfer from an architectural design model (with defect information) into representations that are suitable for defect analysis. The significance of this part of the research and how it fits in the practical applications are illustrated below:

The computerisation of the element-level condition evaluation procedure demonstrates its practical applicability in the existing management procedures. The developed approach allows for integration into existing bridge management platforms or systems as a plug-in tool and into open-source BIM authoring tools. In both the cases, the information documented in IFC-based BIM can be seamlessly utilised and presented simultaneously. Additional manual work such as importing of the condition data into a pre-formulated work sheet can be eliminated.

The significance of the proposed method for structural analysis of the defective bridge is two-fold. First, the developed program achieves automatic conversion from an architectural bridge BIM to a matrix-based analytical model based on IFC standards. The development of the analytical model and the analysis process can be fully computerised using matrix-based structural analysis methods. This would eliminate the need for competitive modelling for different managerial purposes (e.g., architectural design, structural analysis, and safety assurance). The retrieval of structural information out of IFC-based BIM, including geometry, cross-sectional and material properties, and supporting conditions, is demonstrated to be efficient and accurate. Second, the impacts of visual defects, particularly structural defects, can be quantified and integrated into the analytical model with efficiency and reliability to a certain extent. The analysis results of a defective bridge in the structural domain provide informative understandings on the safety and reliability of the entire structure. This can compensate for the maintenance decision-making based only on condition rating results. In this manner, the disparity between the two important schemes in bridge management (i.e., condition assessment and structural safety/reliability analysis) can be reduced significantly.

Overall, the three objectives are linked with each other and are combined to facilitate the vital scheme in bridge management, i.e., bridge inspections. In accordance with a typical bridge inspection project, the proposed three objectives address challenges in the three stages, i.e., data collection, data representation, and data analysis, respectively. By combining these, the aim of this research (to improve efficiency, better support decision makings for maintenance, and ultimately automate the process within an integrated open BIM environment) can be accomplished. Nevertheless, these three objectives are mutually independent and therefore, can be investigated separately and in parallel. Overall, this research provides a comprehensive framework for future studies in this sector.

8.3 Limitations and insights

The limitations of this study are indicated sequentially with regard to the four major results (Chapters 4–7).

First, the limitation of the first objective necessitates future work to address the needs and challenges so as to apply the defect model in real-life inspection projects. On the one hand, the defect model requires intensive training with experience and further improvement, particularly for the scoring system in the defect relationship graph. On the other hand, the proposed defect model should be tested in actual cases. It would be effective to understand its adaptability and robustness to variations in real projects (such as in the construction quality, environmental impacts, and highly diversified load combinations on the bridge), and its applicability in practice can be better evaluated. To further increase the practicability of the proposed defect model, work would be undertaken to integrate it with decision-based models for maintenance actions (e.g., rehabilitation, repair, or replacement). By mapping inspection results to actual maintenance strategies, this defect model can potentially support maintenance decision-making. In turn, monitoring and analysis of the bridge’s responses to maintenance actions can help improve the integrated model and determine the value of information to be included.

The limitations with regard to the second objective are two-fold. First, the precision of defect information in the integrated bridge BIM can be improved further. Given that a seamless integration of CV systems and BIM is not available, a feasible approach (as applied in this experiment) is to replace the precise dimensions with the maximum ones recorded in the inspection report (e.g., maximum width of cracking and area of spalling). This alternative method is reasonable from the perspective of practical applications because the maximum dimensions directly determine the condition ratings of corresponding defects. In addition, the calculation results obtained when the maximum dimensions of defects are used for structural assessment are more conservative than those for the as-is condition. There are also cases where defect information is partially missing from on-site inspections. Either experience-based inference or supplementary data (e.g., defect images) are required. Nonetheless, more accurate geometric modelling would be aimed at in the future work so as to facilitate accurate structural assessment. A potential alternative is to deploy CV technology. By using registered cameras on sites, defect images can be collected and directly located in the global coordinates of bridge BIM. Geometric information (e.g., the skeleton of linear defects or the bounding curve for area defects) can also be extracted from the visual data efficiently. The image processing method can achieve higher accuracy in terms of the identification of feature points and higher level of automation for simultaneous information exchange and storage.

Another limitation of the proposed method for defect representation originates from the fact that the IfcSurfaceFeature entity only addresses defects that are on the surface of bridge elements and mostly visible to inspectors. It largely matches the requirement of routine and detailed visual inspections. However, a few more types of degradations are excluded. Among these, a major group includes deflections and other forms of distortions of structural elements, relative movements between the superstructure and substructure, etc. These defects can be indicators of severe structural safety issues and therefore, are critical particularly for the subsequent structural analysis. Another group of excluded defects either are invisible (such as inadequate reinforcement cover and cavity under the surface) or do not have geometry for visualisation (e.g., accumulation of water in box girder, presence of debris at bearings or expansion joints, and the decrease in material stiffness and strength). These generally are inconvenient to identify. Therefore, surface tests such as rebound hammer test, intrusive tests such as concrete breakout, and material sampling for laboratory test are necessary during special inspections. At this stage, to ensure the inclusion of defect information in bridge BIM, an external document such as an inspection report is preferably attached for reference until efficient modelling methods for the explicit representation of the aforementioned defect types are developed.

With regard to the results in Chapter 6, the aggregation process of condition data from individual defect to the entire structure is essentially clear and explicit. Thus, the limitation of the developed condition assessment tool based on an IFC-based defective bridge BIM is mainly related to the subjectivity involved in low-level condition ratings. Current practices require trained and experienced personnel for the evaluation task. Otherwise, descriptions and example images of defects/elements in different condition levels are used to support the rating. A potential solution to this issue would be a deep learning-based tool to automate the condition rating at the element level. However, a considerable number of defect images as well as their condition scores should be collected and organised to form the dataset for training. These are generally archived by the governmental department in charge of bridge management. Owing to the deficiency of sufficient data, this work did not include the development of this tool. It would be considered as a future work.

Finally, the matrix method used for structural analysis can be improved in the following two aspects given its capability to integrate defects in the analytical model: First, the three-dimensional beam is projected into a two-dimensional plane, and the transverse torsional stress distribution is omitted. A finite element model would be capable of considering deflections in the cross-sections. Furthermore, research on the automatic meshing methods based on IFC are available in the literature (Xu et al. 2019). In this case, the means for quantifying the impacts of defects on relevant finite elements, particularly those that adversely affect the stiffness/strength of structural members, need further exploration. Second, although the development of an analytical model based on the IFC file of bridge BIM can be achieved without human intervention, certain structural information (e.g., reinforced and prestressed bars) and definition of loads and load cases still require manual input. Such information is either unavailable in the BIM model in the authoring tools or lost during the export of IFC files. Therefore, the means to ensure the completeness and semantic clarity during information exchange, retrieval, and sharing remains a topic of significant interest in BIM-related studies.

Overall, an integrated software application that can be used in the inspection site needs to be researched. The capability of the proposed method to support inspection practices and applicability in real-life projects require additional efforts to verify, which consist of the future work.

8.4 Chapter summary

This chapter discusses the research outputs for the three proposed objectives. Their significance, novelty, and potential implementations in practice are also discussed. In addition, the limitations of each topic are presented, and future work and insights are proposed accordingly.

9 Conclusion

This chapter concludes the entire research work. This research identifies issues and challenges in the industry with regard to the current practices of bridge inspections. Accordingly, this research aims to develop an IFC-based method for bridge defect information representation and analysis by achieving three subordinate objectives. The conclusions on each topic are illustrated in detail below:

First, a three-phase investigation was conducted to develop a defect model for concrete highway bridges. The three phases of the investigation were initial development, modification and enrichment, and validation and improvement. Three research methods, i.e., literature review, focus group, and case study, were adopted in the three phases, respectively, to achieve this goal. The defect model first categorises common defects related to bridge elements and materials. The second part of the model identifies relationships among these, i.e., causal relationship and concurrence relationship, with a score that rates the strength of the link. The relationship graph indicates that there are several paths of defect evolution, both at intra-element and inter-element levels. It also shows that bearings (as the joint between superstructure and substructure) are essential to identify such paths. The final part of the defect model maps the critical property and potential causes of defects to support management decision-making, e.g., diagnosis of defects and condition assessment. The proposed defect model exhibits scope for enhancement and constant enrichment using data from real-world inspection projects. This would be vital for the extensive use of this knowledge system to enable standardised, automated, and efficient bridge inspections.

The second part of this research was aimed at expanding the applicability of bridge BIM models, particularly for visual inspection activities. An IFC-based method for defect documentation and representation was proposed. Inspection-related information including the background information of the inspection activity, defect information identified during inspections, and logical relationships among these (e.g., root cause) were modelled with existing IFC entities according to the IFC 4×3 standard. Because ‘defect’ has been introduced as a predefined type of IfcSurfaceFeature since the release of IFC 4×2, this research adopted this data model and focused on the parametric modelling of defect geometry. Both shape representation and spatial placement could be achieved for different defect types within the existing IFC standard. In addition, logical connections across defects that have practical significance for multiple managerial operations were modelled. A case study was conducted on a five-span rigid-frame bridge by integrating inspection-related data into the original bridge BIM IFC file via IfcOpenShell. This integrated bridge information model was exchanged across multiple BIM tools to evaluate its interoperability. It was demonstrated that the proposed method can effectively integrate diversified and quantitative information from inspection practices into bridge BIM models and facilitate automated, efficient, and reliable bridge management.

IC-based bridge BIM integrated with defect information from inspections (i.e., the defective bridge BIM developed in the above topic) were analysed to complete the bridge inspection procedure. The analysis was first conducted as a condition assessment, where the typical element-level inspection procedure was fully computerised. Then, the defective bridge BIM in the architectural domain was converted into an analytical model in the structural domain using matrix methods. The model transfer included (a) the transfer from the architectural bridge BIM into the analytical model and (b) the transfer of defect information. The impacts of defects on bridge structures were quantified using a stiffness reduction coefficient. Both deflections (i.e., displacements and rotations) and internal forces (i.e., shear forces and moments) were calculated and plotted along the superstructure of a bridge. Case studies were conducted to verify the proposed methods for both condition assessment and structural analysis. It was demonstrated that the proposed method, particularly the latter part, largely reduces the disparity between experience-based bridge management schemes for bridge serviceability and numerical analysis scheme for bridge safety and reliability.

Reference

AASHTO (American Association of State Highway and Transportation Officials). 2018. The manual for bridge evaluation. Washington, DC: AASHTO.

AASHTO (American Association of State Highway and Transportation Officials). 2019. Manual for bridge element inspection (2rd Edition). Washington, DC: AASHTO.

Alberta Infrastructure and Transportation 2008. Bridge inspection & maintenance system - inspection manual.

American Association of State Highway and Transportation Officials. 2021. AASHTOWare Bridge Management 7.0. http://aashtowarebridge.com/

American Concrete Institute 2014. Building code requirements for structural concrete (ACI 318-14) and commentary (ACI 318R-14).

American Society of Civil Engineers (ASCE) 2014. Seismic evaluation and retrofit of existing buildings.

Anil, E. B., Akinci, B., Kurc, O., and Garrett, J. H. 2016. Building-information-modeling–based earthquake damage assessment for reinforced concrete walls. *Journal of Computing in Civil Engineering, 30*(4), 4015076. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000551

Artus, M., and Koch, C. 2020. State of the art in damage information modeling for RC bridges – A literature review. *Advanced engineering informatics, 46*. https://doi.org/10.1016/j.aei.2020.101171

Autodesk Inc. 2021. Autodesk Revit. Accessed Aug 17, 2021. https://www.autodesk.com/products/revit/overview

Bickford, W. B. 1982. A consistent higher order beam theory. In Southeastern conference on theoretical and applied mechanics. 137-150. Huntsville AL, USA.

Blender. Python API Overview. Accessed 26/07/2021. https://docs.blender.org/api/current/info_overview.html

Blender. 2021. Blender. Accessed Aug 17, 2021. https://www.blender.org/

The Blender Project. Accessed July 17, 2020. https://www.blender.org/

BlenderBIM Add-on. Accessed Aug 17, 2021. https://blenderbim.org/

Borrmann, A., Amann, J., Chipman, T., Hyvärinen, J., Liebich, T., Muhič, S., Mol, L., Plume, J., and Scarponcini, P. 2017. IFC infra overall architecture project: Documentation and guidelines. Accessed Aug 17, 2021. https://www.buildingsmart.org/wp-content/uploads/2017/07/08_bSI_OverallArchitecure_Guidelines_final.pdf

Borrmann, A., Muhič, S., Hyvärinen, J., Chipman, T., Jaud, S., Castaing, C., Dumoulin, C., Liebich, T., and Mol, L. 2019. "The IFC-Bridge project–Extending the IFC standard to enable high-quality exchange of bridge information models." In Vol. 1 of Proceedings of the 2019 European Conference for Computing in Construction, 377-386. https://ec-3.org/conf2019/wp-content/uploads/sites/2/2019/08/Contribution_193_final.pdf

Bowen, G. A. 2009. Document analysis as a qualitative research method. *Qualitative research journal*. https://doi.org/10.3316/QRJ0902027

Brito, J., Branco, F., and Ibañez, M. 1994. A knowledge-based system for concrete bridge inspection. *Concrete International, ACI, Detroit, MI.*

BuildingSMART. MVD - Structural Analysis View. https://standards.buildingsmart.org/MVD/RELEASE/IFC2x3/TC1/Structural/StructuralAnalysisView.zip

buildingSMART International. 2019. Industry Foundation Classes 4.2 bSI Draft Standard: IFC Bridge proposed extension. https://standards.buildingsmart.org/IFC/DEV/IFC4_2/FINAL/HTML/

buildingSMART International. 2020. Industry Foundation Classes 4.3 RC1. https://standards.buildingsmart.org/IFC/DEV/IFC4_3/RC1/HTML/

Caddemi, S., and Caliò, I. 2013a. The exact explicit dynamic stiffness matrix of multi-cracked Euler–Bernoulli beam and applications to damaged frame structures. *Journal of Sound and Vibration, 332*(12), 3049-3063. https://doi.org/https://doi.org/10.1016/j.jsv.2013.01.003

Caddemi, S., and Caliò, I. 2013b. The exact stability stiffness matrix for the analysis of multi-cracked frame structures. *Computers & Structures, 125*, 137-144. https://doi.org/https://doi.org/10.1016/j.compstruc.2013.05.003

Castaing, C., Dumoulin, C., Grant, R., Chipman, T., Kim, H., Liebich, T., and Borrmann, A. 2017. IFC Bridge project plan. BuildingSMART Infra Room.

Chase, S. B., Adu-Gyamfi, Y., Aktan, A., and Minaie, E. 2016. Synthesis of national and international methodologies used for bridge health indices. *Technical Report FHWA-HRT-15-081*.

Chong, H. Y., Lopez, R., Wang, J., Wang, X., and Zhao, Z. 2016. Comparative analysis on the adoption and use of bim in road infrastructure projects. *Journal of Management in Engineering, 32*(6), 05016021. https://doi.org/doi:10.1061/(ASCE)ME.1943-5479.0000460

Computers & Structures, I. 2015. Concrete frame design manual (CSA A23.3-14).

Davila Delgado, J. M., Butler, L. J., Gibbons, N., Brilakis, I., Elshafie, M. Z., and Middleton, C. R. 2016. Management of structural monitoring data of bridges using BIM. In Proceedings of the Institution of Civil Engineers-Bridge Engineering. 170(3), 204-218. Thomas Telford Ltd.

Del Grosso, A., Basso, P., Ruffini, L., Figini, F., and Cademartori, M. 2017. Infrastructure management integrating SHM and BIM procedures. In 4th Conference on Smart Monitoring Assessment and Rehabilitation of Civil Structures (SMAR 2017). Istanbul, Turkey: Istanbul Technical Univ. https://data.smar-conferences.org/SMAR_2017_Proceedings/papers/293.pdf

Denzin, N. K. 2017. The research act: A theoretical introduction to sociological methods. Transaction publishers.

Department of Transport and Main Roads 2016. Structures inspection manual. State of Queensland: Department of Transport and Main Roads.

Ding, L., Li, K., Zhou, Y., and Love, P. E. D. 2017. An IFC-inspection process model for infrastructure projects: Enabling real-time quality monitoring and control. *Automation in Construction, 84*, 96-110. https://doi.org/https://doi.org/10.1016/j.autcon.2017.08.029

Eastman, C., Teicholz, P., Sacks, R., and Liston, K. 2011. BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors. John Wiley & Sons. https://books.google.com.au/books?hl=en&lr=&id=aCi7Ozwkoj0C&oi=fnd&pg=PP7&dq=a+model+for+building+information+management+of+structural+inspection&ots=ZbFbHTD0Ev&sig=7_1ku0-PRggD8w9pW1H16hI1oEw&redir_esc=y#v=onepage&q&f=false

Ebrahimkhanlou, A., and Salamone, S. 2017. A probabilistic model for visual inspection of concrete shear walls. In Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2017. 10168, 101680Y. International Society for Optics and Photonics.

EN 1992-2 2005. Eurocode 2: Design of concrete structures - Part 2: Concrete bridges - Design and detailing rules. The European Union.

Farhidzadeh, A., Dehghan-Niri, E., Moustafa, A., Salamone, S., and Whittaker, A. 2013. Damage assessment of reinforced concrete structures using fractal analysis of residual crack patterns. *Experimental Mechanics, 53*(9), 1607-1619. https://doi.org/10.1007/s11340-013-9769-7

Farhidzadeh, A., Dehghan-Niri, E., and Salamone, S. 2013. Crack pattern quantification for advanced visual inspection of concrete structures. In Structural Health Monitoring 2013. 2, 2523-2530.

Federal Highway Administration, U. S. National Bridge Inventory (NBI) https://infobridge.fhwa.dot.gov/

FreeCAD. 2021. FreeCAD. Accessed Aug 17, 2021. https://www.freecadweb.org/

Fröhlich, J. 2020. On systematic approaches for interpreted information transfer of inspection data from bridge models to structural analysis

Ghadiri Mohghaddam, D. 2014. Framework for integrating bridge inspection data with bridge information model Doctoral dissertation, Concordia University. https://spectrum.library.concordia.ca/id/eprint/978607/1/Ghadiri_Moghaddam_MASc_F2014.pdf

Ghodoosi, F., Bagchi, A., and Zayed, T. 2015. System-level deterioration model for reinforced concrete bridge decks. *Journal of Bridge Engineering, 20*(5), 4014081. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000670

Gill, J., and Johnson, P. 2002. Research methods for managers. Sage.

Gounaris, G., and Dimarogonas, A. 1988. A finite element of a cracked prismatic beam for structural analysis. *Computers & Structures, 28*(3), 309-313. https://doi.org/https://doi.org/10.1016/0045-7949(88)90070-3

Goyal, D., and Pabla, B. S. 2016. The vibration monitoring methods and signal processing techniques for structural health monitoring: A review. *Archives of Computational Methods in Engineering, 23*(4), 585-594. https://doi.org/http://dx.doi.org/10.1007/s11831-015-9145-0

Hajdin, R. 2018. Managing existing bridges–on the brink of an exciting future. In Maintenance, Safety, Risk, Management and Life-Cycle Performance of Bridges: Proceedings of the Ninth International Conference on Bridge Maintenance, Safety and Management (IABMAS 2018). 70. Melbourne, Australia. CRC Press. https://books.google.com.au/books?hl=en&lr=&id=HFt0DwAAQBAJ&oi=fnd&pg=PA70&dq=Managing+existing+bridges+-+on+the+brink+of+an+exciting+future&ots=-FtXIggB66&sig=1LFiCmWw_dwkdyvlElRIXQ65JDc&redir_esc=y#v=onepage&q&f=false

Hambly, E. C. 1991. Bridge deck behaviour. CRC Press.

Hamledari, H., Azar, E. R., and McCabe, B. 2018. IFC-based development of as-built and as-is BIMs using construction and facility inspection data: Site-to-BIM data transfer automation. *Journal of Computing in Civil Engineering, 32*(2), 04017075. https://doi.org/doi:10.1061/(ASCE)CP.1943-5487.0000727

Hawk, H., and Small, E. P. 1998. The BRIDGIT bridge management system. *Structural Engineering International: Journal of the International Association for Bridge and Structural Engineering (IABSE), 8*(4), 309-314. https://doi.org/10.2749/101686698780488712

Heyliger, P. R., and Reddy, J. N. 1988. A higher order beam finite element for bending and vibration problems. *Journal of Sound and Vibration, 126*(2), 309-326. https://doi.org/https://doi.org/10.1016/0022-460X(88)90244-1

Highways Agency CSS Bridges Group 2002. Bridge condition indicators Volume 1: Commission report.

Highways Agency CSS Bridges Group 2007. Guidance document for performance measurement of highway structures. Part B1: Condition performance indicator.

Highways England 2017. Part 4: Inspection of highway structures (BD 63/17). Section 1: Inspection, Vol.3: Highway Structures: Inspection and Maintenance, Design Manual for Roads and Bridges. The Stationery Office.

Hu, M., Liu, Y., Sugumaran, V., Liu, B., and Du, J. 2019. Automated structural defects diagnosis in underground transportation tunnels using semantic technologies. *Automation in Construction, 107*, Article 102929. https://doi.org/10.1016/j.autcon.2019.102929

Hu, Z.-Z., Zhang, X.-Y., Wang, H.-W., and Kassem, M. 2016. Improving interoperability between architectural and structural design models: An industry foundation classes-based approach with web-based tools. *Automation in construction, 66*, 29-42. https://doi.org/10.1016/j.autcon.2016.02.001

Hüthwohl, P., Brilakis, I., Borrmann, A., and Sacks, R. 2018. Integrating RC bridge defect information into BIM models. *Journal of Computing in Civil Engineering, 32*(3), 04018013. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000744

IfcOpenShell. IfcOpenShell: the open source ifc toolkit and geometry engine. Accessed Aug 17, 2021. http://www.ifcopenshell.org/

Ignat-Coman, A., Isoc, D., Joldis, A., and Gaziuc, I. 2008. A case-based reasoning approach for fault detection state in bridges assessment. In 2008 IEEE International Conference on Automation, Quality and Testing, Robotics. 1, 178-183. https://doi.org/10.1109/AQTR.2008.4588730.

J.Ramaji, I., and M.Memar, A. (2014). Multi-story modular buildings -- From architectural model to structural design/analysis model ver1.0 http://www.blis-project.org/IAI-MVD/

Jeong, S., Hou, R., Lynch, J. P., Sohn, H., and Law, K. H. 2017. An information modeling framework for bridge monitoring. *Advances in Engineering Software, 114*, 11-31. https://doi.org/10.1016/j.advengsoft.2017.05.009

Ji, Y., Borrmann, A., Beetz, J., and Obergrießer, M. 2013. Exchange of parametric bridge models using a neutral data format. *Journal of Computing in Civil Engineering, 27*(6), 593-606. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000286

Johnson, R., and Onwuegbuzie, A. 2004. Mixed methods research: Paradigm whose time has come.

Kassimali, A. 2011. Matrix analysis of structures. Cengage Learning. https://books.google.com/books?id=nPZhzgEACAAJ

Kawamura, K., and Miyamoto, A. 2003. Condition state evaluation of existing reinforced concrete bridges using neuro-fuzzy hybrid system. *Computers & Structures, 81*(18), 1931-1940. https://doi.org/10.1016/S0045-7949(03)00213-X

Khanzada, K. M. 2012. State of bridge management in canada Doctoral dissertation, North Dakota State University.

Khiem, N. T., and Lien, T. V. 2002. The dynamic stiffness matrix method in forced vibration analysis of multiple-cracked beam *Journal of Sound and Vibration, 254*(3), 541-555. https://doi.org/10.1006/jsvi.2001.4109

Kimchi, J., Polivka, B., and Stevenson, J. S. 1991. Triangulation: operational definitions. *Nursing research, 40*(6), 364-366.

Krippendorff, K. 2018. Content analysis: An introduction to its methodology. Sage publications.

Krueger, R. A. 2014. Focus groups: A practical guide for applied research. Sage publications.

Lazar, J., Feng, J. H., and Hochheiser, H. 2017. Chapter 8 - Interviews and focus groups. In J. Lazar, J. H. Feng, & H. Hochheiser (Eds.), *Research Methods in Human Computer Interaction (Second Edition)* (pp. 187-228). Morgan Kaufmann. https://doi.org/https://doi.org/10.1016/B978-0-12-805390-4.00008-X

Lehtinen, S. (2005). Generic AEC/FM View Description - Architectural design to structural design Ver3.0 http://www.blis-project.org/IAI-MVD/

Lehtinen, S., and Hietanen, J. 2007. Generic AEC/FM View Description - Structural design to Structural Analysis Ver1.0. Virtual Building Laboratory, Tampere University of Technology. Accessed Mar 2021. http://www.blis-project.org/IAI-MVD/

Levinson, M. 1981. A new rectangular beam theory. *Journal of Sound and Vibration, 74*(1), 81-87. https://doi.org/10.1016/0022-460X(81)90493-4

Li, G., Gao, J., and Chen, F. 2008. Construction of causality diagram model for diagnostics. In Proceedings - Annual Reliability and Maintainability Symposium. https://doi.org/10.1109/RAMS.2008.4925777.

Li, M., and Jia, G. 2020. Bayesian updating of bridge condition deterioration models using complete and incomplete inspection data. *Journal of Bridge Engineering, 25*(3), 04020007. https://doi.org/10.1061/(ASCE)BE.1943-5592.0001530

Li, Y., Walraven, J., Han, N., Braam, C., Hoogenboom, P., and Houben, I. 2010. Predicting of the Stiffness of Cracked Reinforced Concrete Structures. Predicting of the Stiffness of Cracked Reinforced Concrete Structures.]

Manuals, H. S. A guide for structure inspectors and a guide for structure engineers.

Mbanjwa, T. 2014. An investigation of the relationships between inventory and inspection data of RC bridges and RC culverts in the Western Cape Province University of Cape Town.

McGuire, B., Atadero, R., Clevenger, C., and Ozbek, M. 2016. Bridge information modeling for inspection and evaluation. *Journal of Bridge Engineering, 21*(4), 04015076. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000850

Melchor-Lucero, O., and Ferregut, C. 1995. Toward an expert system for damage assessment of structural concrete elements. *Artificial Intelligence for Engineering, Design, Analysis and Manufacturing, 9*(5), 401-418. https://doi.org/10.1017/S0890060400002729

Miles, M. B., and Huberman, A. M. 1994. Qualitative data analysis: An expanded sourcebook. sage.

Mills, A. J., Durepos, a., and Wiebe, E. (2010). Encyclopedia of case study research. In. https://doi.org/10.4135/9781412957397

Ministry of Housing and Urban-Rural Development of the People's Republic of China 2015. Technical code for test and evaluation of city bridges.

Ministry of Transport of the People's Republic of China 2011. Standards for technical condition evaluation of highway bridges.

Ministry of Transport, t. P. s. R. o. C. 2018. Specifications for design of highway reinforced concrete and prestressed concrete bridges and culverts.

MnDOT (Minnesota Department of Transportation). 2019. Bridge and structure inspection program manual.

Moradi, S., Zayed, T., and Golkhoo, F. 2019. Review on computer aided sewer pipeline defect detection and condition assessment. *Infrastructures, 4*(1), 10. https://www.mdpi.com/2412-3811/4/1/10

Morgan, D. L. 1997. Focus groups as qualitative research. SAGE Publications, Inc. https://doi.org/10.4135/9781412984287

Motamedi, A., Yabuki, N., and Fukuda, T. 2017. Extending BIM to include defects and degradations of buildings and infrastructure facilities.

Moult, D. 2019a. How to view BIM IFC files on Linux. https://thinkmoult.com/how-to-view-bim-ifc-files-linux.html

Moult, D. 2019b. Using IfcOpenShell to parse IFC files with Python. https://thinkmoult.com/using-ifcopenshell-parse-ifc-files-python.html

MRWA (Main Roads Western Australia). 2012. Detailed non-destructive bridge inspection guidelines - Concrete and steel bridges (Level 3 inspections). Perth, WA: MRWA.
MRWA (Main Roads Western Australia). 2013. Routine Visual Bridge Inspection Guidelines (Level 1 Inspections) for Bridges. Perth, WA: MRWA.
MRWA (Main Roads Western Australia). 2017. Detailed visual bridge inspection guidelines for concrete and steel bridges (Level 2 insptections). Perth, WA: MRWA.
New Zealand Standards Association 2006. New Zealand Standard NZS 3101 Part 2. Code of practice for the design of concrete structures.
NYSDOT (New York State Department of Transportation). 2017. Bridge inspection manual.
NZTA (New Zealand Transport Agency). 2017. Bridges and other significant highway structures inspection policy.
O'Reilly, K. 2009. Key concepts in ethnography. In. SAGE Publications Ltd. https://doi.org/10.4135/9781446268308
O'brien, W. J., and Ponticelli, S. 2015. Towards the integration of inspection data with bridge information models to support visual condition assessment. Towards the integration of inspection data with bridge information models to support visual condition assessment.] Reston, VA.
Ontario Ministry of Transportation 2008. Ontario structure inspection manual. Ontario: Ministry of Transportation.
Onwuegbuzie, A. J., Leech, N. L., and Collins, K. M. T. 2012. Qualitative Analysis Techniques for the Review of the Literature. *The Qualitative Report, 17*, 1-28.
OpenCV: Open source computer vision. https://docs.opencv.org/4.5.2/d6/d00/tutorial_py_root.html
Paviot, T. 2017. pythonOCC - 3D CAD for python. Accessed July 8, 2021. http://www.pythonocc.org/
PCA (Portland Cement Association). 2002. Types and causes of concrete deterioration.
Phares, B. M., Washer, G. A., Rolander, D. D., Graybeal, B. A., and Moore, M. 2004. Routine highway bridge inspection condition documentation accuracy and reliability. *Journal of Bridge Engineering, 9*(4), 403-413. https://doi.org/10.1061/(ASCE)1084-0702(2004)9:4(403)
Potenza, F., Rinaldi, C., Ottaviano, E., and Gattulli, V. 2020. A robotics and computer-aided procedure for defect evaluation in bridge inspection. *Journal of Civil Structural Health Monitoring, 10*(3), 471-484. https://doi.org/10.1007/s13349-020-00395-3
Ramaji, I. J., and Memari, A. M. 2018. Interpretation of structural analytical models from the coordination view in building information models. *Automation in construction, 90*, 117-133. https://doi.org/10.1016/j.autcon.2018.02.025
Reddy, J. N. 1984. A simple higher-order theory for laminated composite plates.
Remenyi, D., Williams, B., Money, A., and Swartz, E. 1998. Doing research in business and management: an introduction to process and method. Sage.
Rio, J., Ferreira, B., and Martins, J. P. P. 2013. Expansión del modelo IFC con sensores estructurales [Expansion of IFC model with structural sensors]. Informes de la Construcción, 65(530), 219-228.
Robson, C. 2002. Real world research: A resource for social scientists and practitioner-researchers. Wiley-Blackwell.
RTA (Roads and Traffic Authority). 2007. Bridge inspection procedure manual. Paramatta, NSW: RTA.
Ryall, M. J. 2010a. Chapter 2 - Inspection and condition rating. In *Bridge Management (Second Edition)* (pp. 43-102). Butterworth-Heinemann. https://doi.org/https://doi.org/10.1016/B978-0-7506-8511-5.10002-0
Ryall, M. J. 2010b. Chapter 13 - Deterioration modelling. In M. J. Ryall (Ed.), *Bridge Management (Second Edition)* (pp. 525-541). Butterworth-Heinemann. https://doi.org/https://doi.org/10.1016/B978-0-7506-8511-5.10013-5
Sacks, R., Kedar, A., Borrmann, A., Ma, L., Brilakis, I., Hüthwohl, P., Daum, S., Kattel, U., Yosef, R., Liebich, T., Barutcu, B. E., and Muhic, S. 2018. SeeBridge as next generation bridge inspection: Overview, Information Delivery Manual and Model View Definition. *Automation in Construction, 90*, 134-145. https://doi.org/https://doi.org/10.1016/j.autcon.2018.02.033

Saunders, M. N. K., Lewis, P., and Thornhill, A. 2009. Research Methods for Business Students. *Dongbei University of Fi*.
Schlaich, J., Shafer, K., Jennewein, M., and Kotsovost, M. 1987. Toward a consistent design of structural concrete. *Pci Journal, 32*(3).

Shoieb, K., Serror, M. H., and Marzouk, M. 2020. Web-based tool for interoperability among structural analysis applications. *Journal of construction engineering and management, 146*(6), 4020058. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001840
Sibenik, G., and Kovacic, I. 2020. Assessment of model-based data exchange between architectural design and structural analysis. *Journal of Building Engineering, 32*, 101589. https://doi.org/10.1016/j.jobe.2020.101589
Standardization, E. C. F. 2005. Eurocode 8: Design of structures for earthquake resistance - Part 3: Assessment and retrofitting of buildings.
Standardization, I. O. f. 2018. ISO 16739-1: 2018–Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries.
Sun, Y., Ma, L., Mathew, J., and Zhang, S. 2006. An analytical model for interactive failures. *Reliability Engineering & System Safety, 91*(5), 495-504. https://doi.org/https://doi.org/10.1016/j.ress.2005.03.014
TAMC (Michigan Transportation Asset Management Council). 2011. Asset management guide for local agency bridges in Michigan. Lansing MI: MDOT.
Tan, Y., and Zhang, L. 2020. Computational methodologies for optimal sensor placement in structural health monitoring: A review. *Structural Health Monitoring, 19*(4), 1287-1308. https://doi.org/10.1177/1475921719877579
Tanaka, F., Hori, M., Onosato, M., Date, H., and Kanai, S. 2016. Bridge information model based on IFC standards and web content providing system for supporting an inspection process. In 16th International Conference on Computing in Civil and Building Engineering (ICCCBE 2016). 1140-1147.
Taraben, J. 2019. A model for building information management of structural inspections. In Forum Bauinformatik: 11.–13. September 2019 in Berlin. Proceedings. Universitätsverlag der TU Berlin. https://books.google.com.au/books?hl=en&lr=&id=nwawDwAAQBAJ&oi=fnd&pg=PA307&dq=IFC+bridge+inspection&ots=6aTr9jTvDE&sig=rAwl3-4q4WDypz-9dWpqIQR7PoM&redir_esc=y#v=onepage&q&f=false
The Concrete Society 1982. Non-structural cracks in concrete : report of a Concrete Society Working Party. London: Concrete Society.
Tight, M. (2019). Documentary research in the social sciences. In. SAGE Publications Ltd. https://doi.org/10.4135/9781529716559
Transit New Zealand 2001. Bridge inspection and maintenance manual. Wellington, NZ.
TxDOT (Texas Department of Transportation). 2018. Bridge inspection manual.
U.S. Department of Transportation, FHWA (Federal Highway Administration). 2012. Bridge inspector's reference manual. Arlington, Virginia: FHWA.
Valinjadshoubi, M., Bagchi, A., and Moselhi, O. 2016. Managing structural health monitoring data using building information modeling. In Proceedings of the 2nd World Congress and Exhibition on Construction and Steel Structure, Las Vegas, NV, USA. 22-24.
Vecchio, F. J., and Collins, M. P. 1986. The modified compression-field theory for reinforced concrete elements subjected to shear. *Aci Journal, 83*(2), 219-231.
VicRoads 2010. Technical note 38: Cracks in concrete.
VicRoads 2018. Part two: Road structure inspection proceduresRoad structures inspection manual. Road structures inspection manual. Kew VIC: VicRoads.
Wang, C. M., Reddy, J. N., and Lee, K. H. 2000. Chapter 3 - Shear-flexural stiffness matrix. In C. M. Wang, J. N. Reddy, & K. H. Lee (Eds.), *Shear Deformable Beams and Plates* (pp. 39-54). Elsevier Science Ltd. https://doi.org/https://doi.org/10.1016/B978-008043784-2/50003-4
Wang, J., Sun, W., Shou, W., Wang, X., Wu, C., Chong, H.-Y., Liu, Y., and Sun, C. 2015. Integrating BIM and LiDAR for real-time construction quality control. *Journal of Intelligent & Robotic Systems, 79*(3), 417-432. https://doi.org/10.1007/s10846-014-0116-8
Wang, X., Wang, X., Yang, H., Yang, H., Zhang, Q., and Zhang, Q. 2015. Research of the IFC-based Transformation Methods of Geometry Information for Structural Elements. *Journal of intelligent & robotic systems, 79*(3), 465-473. https://doi.org/10.1007/s10846-014-0111-0
Wellalage, N. K. W., Zhang, T., and Dwight, R. 2015. Calibrating markov chain–based deterioration models for predicting future conditions of railway bridge elements. *Journal of Bridge Engineering, 20*(2), 4014060. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000640
WSDOT (Washington State Department of Transportation). 2019. Washington State bridge inspection manual. Olympia, WA: WSDOT.

Xu, S., Wang, J., Shou, W., Ngo, T., Sadick, A. M., and Wang, X. 2020. Computer vision techniques in construction: A critical review. *Archives of Computational Methods in Engineering*, 1-15. https://doi.org/10.1007/s11831-020-09504-3

Xu, Z., Rao, Z., Gan, V. J. L., Ding, Y., Wan, C., and Liu, X. 2019. Developing an extended ifc data schema and mesh generation framework for finite element modeling. *Advances in Civil Engineering, 2019*, 19, Article 1434093. https://doi.org/10.1155/2019/1434093

Yabuki, N., and Li, Z. 2006. Development of new IFC-BRIDGE data model and a concrete bridge design system using multi-agents. In, 1259-1266. Berlin, Heidelberg. Springer Berlin Heidelberg.

Yin, R. K. 2009. Case study research: Design and methods (Vol. 5). sage.

Zakić, B. D., Ryzynski, A., Guo-Hong, C., and Jokela, J. 1991. Classification of damage in concrete bridges. *Materials and Structures, 24*(4), 268-275. https://doi.org/10.1007/bf02472082

Zhang, J. 2018. Towards systematic understanding of geometric representations in bim standard: An empirical data-driven approach. In *Construction Research Congress 2018*. https://doi.org/10.1061/9780784481264.010

Appendix (additional materials related to the study)

Appendix 1 – Questionnaire

This appendix includes the questionnaire used in the focus groups, with a special focus on the investigation of relationship around defects. The original design of this questionnaire was in English, as presented in this appendix, and it was the version submitted for ethical application before the conduction of focus groups. However, the questionnaire provided during the event was translated in Chinese, since all participates are native in Chinese rather than English. The questionnaire is presented as below.

Dear Sir/Madam,

Thanks for attending today's workshop. Through this workshop, we aim to explore as much experience and knowledge in the field of bridge inspection as possible, regarding the identification of bridge defects, defect diagnosis and potentially their assessment. Given your rich experience in bridge engineering, inspection, and maintenance decision-makings, we sincerely invite you to take part in today's group interview and fill this questionnaire as well. Your comments would be of great help to my research and I, representing our research team, would truly appreciate it.

If you have any concerns, please contact me.

Personal information (Relevant to this research)

1. Your position is __________________.
2. You have been working in this field (i.e., civil engineering) for ___ years.
3. You have been in your current position for________years.
4. Your professional background：
5. □ Bridge engineering □ Management □ Construction □ Other disciplines in civil engineering (e.g., road engineering)

Defect model developing

In this module, we will use this questionnaire as a clue and conduct group interview, investigating and developing a defect model for bridge inspections. At this stage, a few assumptions are as follows.

- We would like to discuss all types of deterioration mechanisms on bridge structures, not just visible defects.
- Only concrete highway bridges are considered in this discussion. Steel bridges, composite bridges, and other complex structural forms like suspension bridge are beyond the research scope.
- We focus on bridge inspections, concerning frequent and notable scenarios that can be observed during inspections.

If you have any concerns or comments to make, please feel free to raise it during the discussion.

Part 1. Common defect identification

In this part, we would like to invite you all to identify common defects on bridge structures which are paid special attention during inspections. The following list of defects are obtained through documentary research.

Material defects - Concrete

Cracking

Reinforcement corrosion

Spalling

Delamination

Scaling

Disintegration

Deformation

Stain/ Dampness

Deposit e.g., Efflorescence

Honeycombing

Pop-outs

Abrasion/ Wear

Patch/ Repair

Material defects – other materials

Pavement

Pothole

Cracking

Delamination between pavement and the main girder

Rutting, heaving, wear…

Expansion joint

Material damage

Bearings

Material damage

Corrosion of steel components

Deformation or fracture

Drainage

Cracking

Missing of drainage components

Waterway

Erosion or scour

Performance deficiency

Superstructure

Movement

Substructure

Settlement

Partial settlement

Expansion joint

Leaking joint

Misalignment

Debonding

Improper gap

Malfunction

Approach slab

Misalignment to the main bridge

Settlement

Bearings

Loose bearings

Misalignment

Uneven contact

Malfunction

Drainage

Blockage of inlets

Improperly positioned outlets

Insufficient outlets

Waterway

Blockage of waterway

Re-alignment change

Part 2. Defect relationship mapping

In this part, we invite you to identify relationships among common defects on bridge. There are several types of relationship. Regarding whether the defects affect the same bridge element, there are inter-element and intra-element relationships. Considering whether one defect support the progressing of another defect, there are causal relationship and concurrence relationship, respectively. Under such categorization scheme, there are four tables we would like your ratings on the strength of relationships.

Part one：Intra-element relationship of defects (Concrete elements)

Note：1. In this part, you are invited to assess **causal relationships** between defects which locate on the **same** element.

2. In each blank space, please fill in a score which represents the extent about how defect A impacts defect B.

3. The score will be an integer between 0 and 4. Specifically,

0 means that Defect A will not lead to defect B;

1 means that Defect A is a minor contributor to defect B;

2 means that Defect A, together with one/several other factor, leads to defect B;

3 means that Defect A is the primary contributor to defect B;

4 means that Defect A leads to defect B.

A \ B	Cracking	Rebar corrosion	Spalling	Delamination	Scaling	Disintegration	Excessive deformation	Stain/ dampness	Deposit	Honeycombing	Pothole	Abrasion/ wear	Patch/ repair	Movement	Settlement
Cracking															
Rebar corrosion															
Spalling															

Delamination															
Scaling															
Disintegration															
Excessive deformation															
Stain/ dampness															
Deposit															
Honeycombing															
Pothole															
Abrasion/ wear															
Patch/ repair															
Movement															
Settlement															

Part two：Intra-element relationship of defects (Concrete elements)

Note：1. In this part, you are invited to assess **concurrence relationships** between defects which locate on the **same** element.

2. In each blank space, please fill in a score which represents the possibility of defect A and defect B occurring at the same time.

3. The score will be an integer between 0 and 4. Specifically,

0 means that Defect A and defect B will not occur at the same time.

1 means that Defect A and defect B seldom accompanies each other (25% possibility of concurrence).

2 means that Defect A and defect B concur in 50% cases.

3 means that Defect A always accompanies defect B to occur (75% possibility of concurrence).

4 means that Defect A and defect B occur at the same time in all cases.

B / A	Cracking	Rebar corrosion	Spalling	Delamination	Scaling	Disintegration	Excessive deformation	Stain/ dampness	Deposit	Honeycombing	Pothole	Abrasion / wear	Patch/ repair	Movement	Settlement
Cracking															
Rebar corrosion															
Spalling															
Delamination															
Scaling															
Disintegration															
Excessive deformation															
Stain/ dampness															
Deposit															
Honeycombing															
Pothole															
Abrasion/ wear															
Patch/ repair															
Movement															
Settlement															

Part three：Intra-element relationship of defects (Other elements)

Note：1. In this part, you are invited to assess **concurrence relationships** between material defects and performance deficiencies which locate on the **same** element. Concrete elements are out of the scope in this part.

2. In each blank space, please fill in a score which represents the possibility of defect A and defect B occurring at the same time.

3. The score will be an integer between 0 and 4. Specifically,

0 means that Defect A and defect B will not occur at the same time.

1 means that Defect A and defect B seldom accompanies each other (25% possibility of concurrence).

2 means that Defect A and defect B concur in 50% cases.

3 means that Defect A always accompanies defect B to occur (75% possibility of concurrence).

4 means that Defect A and defect B occur at the same time in all cases.

Expansion joints

B / A	Material damage	Leaking joint	Misalignment	Debonding	Improper gap	Malfunction
Material damage						
Leaking joint						
Misalignment						
Debonding						
Improper gap						
Malfunction						

Drainage

	Cracking	Blockage of inlets	Improperly positioned outlets	Insufficient outlets

Cracking				
Blockage of inlets				
Improperly-positioned outlets				
Insufficient outlets				

Bearings

	Material damage	Corrosion of steel components	Deformation or fracture	Loose bearings	Misalignment	Uneven contact	Malfunction
Material damage							
Corrosion of steel components							
Deformation or fracture							
Loose bearings							
Misalignment							
Uneven contact							
Malfunction							

Waterway

	Erosion or scour	Blockage of waterway	Re-alignment change
Erosion or scour			
Blockage of waterway			

Re-alignment change	

Part four：Inter-element relationship of defects									
Note：1. In this part, you are invited to assess **relationships** between defects (including material defects and performance deficiencies which locate on different elements. 2. Please rate the relationships between 0 and 4 according to the criteria above.									
Defect relationship between superstructure and auxiliary elements									
A \ B		Cracking	Reinforcement corrosion	Spalling	Delamination	Excessive deformation	Stain/ dampness	Deposit	Movement
Expansion joint	Leaking joint								
	Misalignment								
	Debonding								
	Improper gap								
	Malfunction								
Approach slab	Misalignment								
	Settlement								
Bearing	Loose bearings								
	Misalignment								
	Uneven contact								

	Malfunction								
Drainage	Blockage of inlets								
	Improperly positioned outlets								
	Insufficient outlets								
Waterway	Blockage of waterway								
	Erosion								
	Re-alignment change								
Defect relationship between substructure and auxiliary elements									
A \ B		Cracking	Reinforcement corrosion	Spalling	Delamination	Excessive deformation	Stain/ dampness	Deposit	Settlement
Expansion joint	Leaking joint								
	Misalignment								
	Debonding								
	Improper gap								
	Malfunction								
Approach slab	Misalignment								
	Settlement								

Bearing	Loose bearings								
	Misalignment								
	Uneven contact								
	Malfunction								
Drainage	Blockage of inlets								
	Improperly positioned outlets								
	Insufficient outlets								
Waterway	Blockage of waterway								
	Erosion								
	Re-alignment change								

Defect relationship among auxiliary elements

A \ B		Expansion joint					Approach slab		Bearing			Drainage			Waterway		
		Leaking joint	Misalignment	Debonding	Improper gap	Malfunction	Misalignment	Settlement	Loose bearings	Misalignment	Uneven contact	Malfunction	Blockage of inlets	Improperly positioned outlets	Insufficient outlets	Blockage of waterway	Erosion
Expansion joint	Leaking joint																

	Misalignment																
	Debonding																
	Improper gap																
	Malfunction																
Approach slab	Misalignment																
	Settlement																
Bearing	Loose bearings																
	Misalignment																
	Uneven contact																
	Malfunction																
Drainage	Blockage of inlets																

	Improperly positioned outlets																
	Insufficient outlets																
Waterw ay	Blockage of waterway																
	Erosion																
	Re-alignment change																

Appendix 2 – Core python code

This appendix documents the core python codes used in this work. The first part presents the code for defect representation and documentation. The second part presents the code for the condition evaluation scheme.

Code for defect representation

```
import uuid
import ifcopenshell

O = 0., 0., 0.
X = 1., 0., 0.
Y = 0., 1., 0.
Z = 0., 0., 1.


# Utility functions
# Creates an IfcAxis2Placement3D from Location, Axis and
RefDirection specified as Python tuples
def create_ifcAxis2placement(ifcfile, point=O, dir1=Z, dir2=X):
    pt = ifcfile.createIfcCartesianPoint(point)
    direction1 = ifcfile.createIfcDirection(dir1)
    direction2 = ifcfile.createIfcDirection(dir2)
    axis2placement = ifcfile.createIfcAxis2Placement3D(pt,
direction1, direction2)
    return axis2placement


# create an IfcLocalPlacement from location, axis and refDirection
specified as python tuples, and relative placement
def create_ifcLocalPlacement(ifcfile, point=O, dir1=Z, dir2=X,
relative_to=None):
    axis2placement = create_ifcAxis2placement(ifcfile, point, dir1,
dir2)
    ifclocalplacement = ifcfile.createIfcLocalPlacement(relative_to,
axis2placement)
    return ifclocalplacement
```

```
# create an IfcPolyline from a list of points, specified as python
tuples
def create_ifcPolyline(ifcfile, point_list):
    ifcpts = []
    for point in point_list:
        pt = ifcfile.createIfcCartesianPoint(point)
        ifcpts.append(pt)
    polyline = ifcfile.createIfcPolyline(ifcpts)
    return polyline


create_guid = lambda: ifcopenshell.guid.compress(uuid.uuid1().hex)

ifcfile = ifcopenshell.open('BrIM.ifc')
# obtain references from file
owner_history = ifcfile.by_type('IfcOwnerHistory')[0]
context = ifcfile.by_type('IfcGeometricRepresentationContext')[0]

# model the inspection acitivity
inspection_duration = 'P0Y0M0DT5H30M0S'  # 5.5 hours
inspection_start = '2015-04-19T09:00:00'
inspection_end = '2015-04-19T14:30:00'
inspection_time = ifcfile.createIfcTaskTime('Time information',
None, None, 'WORKTIME', None, None, None, None, None, None, None,
None, None, None, None, inspection_duration, inspection_start,
inspection_end, None, None)
inspection_task = ifcfile.createIfcTask(create_guid(),
owner_history, 'Detailed_Visual_Inspection', 'inspection-2015',
None, None, 'detailed visual inspection executed in 2015',
'Completed', None, True, None, inspection_time, None)
```

Scenario 1 illustration

In this scenario, two defects are caused by the same reason, i.e., excessive vehicular wear and tear and thus grouped.

```
## model the first defect, i.e., pavement damage
# model spatial placement
beams = ifcfile.by_type('IfcBeam')[:2]
beam_a = beams[0]
beam_a_placement = beam_a.ObjectPlacement
```

```
damage_placement_1 = create_ifcLocalPlacement(ifcfile, (1.0, 7.25,
0.0), (0.0, 0.0, 1.0), (1.0, 0.0, 0.0),
relative_to=beam_a_placement)

# model shape representation
outerbound_point_list_1 = [(0.0, 3.0, 0.0), (0.5, 3.0, 0.0), (0.5,
0.0, 0.0), (0.0, 0.0, 0.0), (0.0, 3.0, 0.0)]  # 3.0*0.5m2
outerbound_curve = create_ifcPolyline(ifcfile,
outerbound_point_list_1)
# (ABS) IfcBoundedSurface: IfcCurveBoundedPlane
position_of_basis_plane = create_ifcAxis2placement(ifcfile)
basis_plane = ifcfile.createIfcPlane(position_of_basis_plane)
damage_surface = ifcfile.createIfcCurveBoundedPlane(basis_plane,
outerbound_curve)

# create DEFECT entity
damage_representation_1 =
ifcfile.createIfcShapeRepresentation(context, 'Body', 'Surface',
[damage_surface])
damage_shape_1 = ifcfile.createIfcProductDefinitionShape(None, None,
[damage_representation_1])
damage_1 = ifcfile.createIfcSurfaceFeature(create_guid(),
owner_history, 'damage_1', 'Pavement damage',
                                            None, damage_placement_1,
damage_shape_1, 'DEFECT')

## model the second defect, i.e., crack
# spatial placement
defect_placement_2 = create_ifcLocalPlacement(ifcfile, (45.5, 0.0,
0.0), (0.0, 0.0, 1.0), (1.0, 0.0, 0.0),

relative_to=beam_a_placement)

# shape representation
swept_section_point_list_2_1 = [(0.0015, 0.0, 0.0), (-0.0015, 0.0,
0.0)]  # 3mm
swept_curve_2_1 = create_ifcPolyline(ifcfile,
swept_section_point_list_2_1)
swept_profile_2_1 =
ifcfile.createIfcArbitraryOpenProfileDef('CURVE', 'Section_2_1',
swept_curve_2_1)
```

```
swept_position_2_1 = create_ifcAxis2placement(ifcfile, (0.0, 0.0,
0.0), (0.0, 0.0, 1.0), (1.0, 0.0, 0.0))
swept_direction_2_1 = ifcfile.createIfcDirection((1.0, 0.0, 0.0))
swept_length_2_1 = 5.9
crack_part_2_1 =
ifcfile.createIfcSurfaceOfLinearExtrusion(swept_profile_2_1,
swept_position_2_1, swept_direction_2_1, swept_length_2_1)

swept_section_point_list_2_2 = [(0.00075, 0.0, 0.0), (-0.00075, 0.0,
0.0)]  # 1.5mm
swept_curve_2_2 = create_ifcPolyline(ifcfile,
swept_section_point_list_2_2)
swept_profile_2_2 =
ifcfile.createIfcArbitraryOpenProfileDef('CURVE', 'Section_2_2',
swept_curve_2_2)
swept_position_2_2 = create_ifcAxis2placement(ifcfile, (0.0, 0.0,
0.0), (0.0, 0.0, 1.0), (1.0, 0.0, 0.0))
swept_direction_2_2 = ifcfile.createIfcDirection((-0.348, 0.937,
0.0))
swept_length_2_2 = 3.734
crack_part_2_2 =
ifcfile.createIfcSurfaceOfLinearExtrusion(swept_profile_2_2,
swept_position_2_2,

swept_direction_2_2, swept_length_2_2)

swept_section_point_list_2_3 = [(0.001, 0.0, 0.0), (-0.001, 0.0,
0.0)]  # 2mm
swept_curve_2_3 = create_ifcPolyline(ifcfile,
swept_section_point_list_2_3)
swept_profile_2_3 =
ifcfile.createIfcArbitraryOpenProfileDef('CURVE', 'Section_2_3',
swept_curve_2_3)
swept_position_2_3 = create_ifcAxis2placement(ifcfile, (0.0, 0.0,
0.0), (0.0, 0.0, 1.0), (1.0, 0.0, 0.0))
swept_direction_2_3 = ifcfile.createIfcDirection((-0.203, -0.979,
0.0))
swept_length_2_3 = 2.96
crack_part_2_3 =
ifcfile.createIfcSurfaceOfLinearExtrusion(swept_profile_2_3,
swept_position_2_3, swept_direction_2_3, swept_length_2_3)
```

```
crack_representation_2 =
ifcfile.createIfcShapeRepresentation(context, 'Body', 'Surface',

[crack_part_2_1, crack_part_2_2, crack_part_2_3])
crack_shape_2 = ifcfile.createIfcProductDefinitionShape(None, None,
[crack_representation_2])
crack_2 = ifcfile.createIfcSurfaceFeature(create_guid(),
owner_history, 'crack_2', 'Y_Shaped_Crack_on_Deck', None,
defect_placement_2, crack_shape_2, 'DEFECT')

# assign the defects to respective bridge element
ifcfile.createIfcRelAggregates(create_guid(), owner_history,
'crack_to_beam', None, beam_a, [damage_1, crack_2])

# model the logical relationship, i.e., grouping according to cause
diagnosis results
defect_group = ifcfile.createIfcGroup(create_guid(), owner_history,
'defect_group_1', 'excessive_traffic_load', None)

ifcfile.createIfcRelAssignsToGroup(create_guid(), owner_history,
'defect_relationship_1', None, [damage_1, crack_2], 'GROUP',
defect_group)
ifcfile.createIfcRelAssignsToProcess(create_guid(), owner_history,
'Defect_To_Task', None, [damage_1, crack_2], None, inspection_task,
None)

ifcfile.write('brim_scenario_1.ifc')
```

Scenario 2 illustration

In this scenario, two concrete defects require the same maintenance action, i.e., clear loose concrete around the damage; rust cleaning if necessary; patch with epoxy mortar, and thus grouped.

```
# model the first defect, i.e., honeycomb on the web plate of beam_a
# spatial placement
honeycomb_placement = create_ifcLocalPlacement(ifcfile, (7.0, -5.75,
-2.0), (0.0, -1.0, 0.0), (1.0, 0.0, 0.0),
relative_to=beam_a_placement)

# shape representation
```

```
outerbound_point_list_honeycomb = [(0.0, 0.0, 0.0), (1.0, 0.0, 0.0),
(1.0, -0.5, 0.0), (0.0, -0.5, 0.0), (0.0, 0.0, 0.0)]  # 1.0*0.5m2
outerbound_curve_honeycomb = create_ifcPolyline(ifcfile,
outerbound_point_list_honeycomb)
position_of_basis_plane_honeycomb =
create_ifcAxis2placement(ifcfile)
basis_plane_honeycomb =
ifcfile.createIfcPlane(position_of_basis_plane_honeycomb)
damage_surface =
ifcfile.createIfcCurveBoundedPlane(basis_plane_honeycomb,
outerbound_curve_honeycomb)

# create DEFECT entity
honeycomb_representation =
ifcfile.createIfcShapeRepresentation(context, 'Body', 'Surface',
[damage_surface])
honeycomb_shape = ifcfile.createIfcProductDefinitionShape(None,
None, [honeycomb_representation])
honeycomb = ifcfile.createIfcSurfaceFeature(create_guid(),
owner_history, 'honeycomb', 'honeycomb on beam web plate', None,
honeycomb_placement, honeycomb_shape, 'DEFECT')

# model the second defect, i.e., spalling on the flange
spalling_placement = create_ifcLocalPlacement(ifcfile, (7.0, 0.0,
0.0), (0.0, 0.25, -3.5), (0.0, 3.5, 0.25),

relative_to=beam_a_placement)
# shape
outerbound_point_list_spalling = [(0.15, 0.0, 0.0), (0.15, -0.3,
0.0), (-0.15, -0.3, 0.0), (-0.15, 0.0, 0.0), 0.15, 0.0, 0.0)]  #
0.3*0.3m2
outerbound_curve_spalling = create_ifcPolyline(ifcfile,
outerbound_point_list_spalling)
position_of_basis_plane_spalling = create_ifcAxis2placement(ifcfile)
basis_plane_spalling =
ifcfile.createIfcPlane(position_of_basis_plane_spalling)
spalling_surface =
ifcfile.createIfcCurveBoundedPlane(basis_plane_spalling,
outerbound_curve_spalling)

# create DEFECT entity
```

```
spalling_representation =
ifcfile.createIfcShapeRepresentation(context, 'Body', 'Surface',
[spalling_surface])
spalling_shape = ifcfile.createIfcProductDefinitionShape(None, None,
[spalling_representation])
spalling = ifcfile.createIfcSurfaceFeature(create_guid(),
owner_history, 'spalling', 'spalling on beam flange', None,
spalling_placement, spalling_shape, 'DEFECT')

# assign the defects to respective bridge element
ifcfile.createIfcRelAggregates(create_guid(), owner_history,
'honeycomb_to_beam', None, beam_a, [honeycomb])
ifcfile.createIfcRelAggregates(create_guid(), owner_history,
'spalling_to_beam', None, beam_a, [spalling])

# model the logical relationship according to maintenance actions
defect_group_2 = ifcfile.createIfcGroup(create_guid(),
owner_history, 'defect_group_2', 'Having maintenance decision_2',
None)

ifcfile.createIfcRelAssignsToGroup(create_guid(), owner_history,
'defect_relationship_2', None, [honeycomb, spalling], 'GROUP',
defect_group_2)
ifcfile.createIfcRelAssignsToProcess(create_guid(), owner_history,
'Defect_To_Task', None, [honeycomb, spalling], None,
inspection_task, None)

ifcfile.write('brim_scenario_2.ifc')
```

Code for condition evaluation

```
import uuid
import ifcopenshell
import ifcopenshell.util.pset
from ifcopenshell import util

create_guid = lambda: ifcopenshell.guid.compress(uuid.uuid1().hex)
ifcfile=ifcopenshell.open('BrIM.ifc')
owner_history = ifcfile.by_type("IfcOwnerHistory")[0]
```

```
elements = ifcfile.by_type('IfcElement')
n = len(elements)
component_list = []
for i in range(n):
    if elements[i].is_a() != 'IfcSurfaceFeature':
        component_list.append(elements[i])

#document condition scores at the sub-element level
component_n = len(component_list)

dtdate = input('The date of inspection:')

for com in range(component_n):
    component = component_list[com]
    name = component.Name
    property_values_severity = [
        ifcfile.createIfcPropertySingleValue('AssessmentDate',
'AssessmentDate', ifcfile.create_entity('IfcDate',dtdate), None),
        ifcfile.createIfcPropertySingleValue('AssessmentCondition',
'AssessmentCondition', ifcfile.create_entity('IfcLabel', input("The
severity of "+name+" is:")), None),
       ifcfile.createIfcPropertySingleValue('AssessmentDescription'
, 'AssessmentDescription', ifcfile.create_entity('IfcText',
input("Additional Description:")), None)
    ]
    severity_property =
ifcfile.createIfcPropertySet(create_guid(),owner_history,
'Pset_Condition', 'Severity', property_values_severity)

    property_values_extent = [
        ifcfile.createIfcPropertySingleValue('AssessmentDate',
'AssessmentDate', ifcfile.create_entity('IfcDate',dtdate), None),
        ifcfile.createIfcPropertySingleValue('AssessmentCondition',
'AssessmentCondition', ifcfile.create_entity('IfcLabel', input("The
extent of "+name+" is:")), None),
       ifcfile.createIfcPropertySingleValue('AssessmentDescription',
'AssessmentDescription', ifcfile.create_entity('IfcText',
input("Additional Description:")), None)
    ]
    extent_property =
ifcfile.createIfcPropertySet(create_guid(),owner_history,
```

```
'Pset_Condition', 'Extent', property_values_extent)

    ifcfile.createIfcRelDefinesByProperties(create_guid(),
owner_history,None, None, [component], severity_property)
    ifcfile.createIfcRelDefinesByProperties(create_guid(),
owner_history,None, None, [component], extent_property)

ifcfile.write('BrIM_03.ifc')
```

Code for defect analysis in the structural domain

```
import ifcopenshell
ifcfile=ifcopenshell.open('case_2.ifc')
import cv2
import numpy as np
import re
```

Input module

This part of script represents the core functions in the input module for defect structural analysis, where structural data and defect information are retrieved from ifc file of an integrated bridge BIM and formatted as input vectors.

```
#utility function to calculate cross-sectional properties of certain
polygon
def profile_property(poly_entity):  # poly_entity is the IfcPolyline
entity
    contour = []
    points = poly_entity.Points
    for point in points:
        coord = point.Coordinates
        contour.append([[round(coord[0]), round(coord[1])]])
    poly = np.array(contour)

    profile_area = cv2.contourArea(poly)
    profile_moment = cv2.moments(poly)
    # use opencv package requires the coordinates to be integer,
since they refer to pixels.

    return profile_area, profile_moment

#utility function to adjust units
```

```
def unit_change(list, factor):
    n = len(list)
    for i in range(n):
        list[i] = list[i]*factor
    return list


# main function to generate material property vector EM
def EM_formation(material_list, concrete_dict):
    n_material = len(material_list)
    EM = []

    for i in range(n_material):
        material = material_list[i]
        if material.Category == 'Concrete':
            stren = re.findall('(\d+)', material.Name)
            iE = concrete_dict[stren[0]]  # Elastic modulus of the
ith material type
            EM.append(iE)
    return EM

#main function to create joint data vector COORD,
def beam_vector_formation(beams, material_rels):
    COORD_beam = []  # documents all joint coordinates at the beam
level
    CP = []
    mat_beam = []  # map cross sectional property Ix and material
type to end coordinates

    for i in range(len(beams)):
        beam = beams[i]
        # deterimine coordinates (x) of beginning and end
        placement = beam.ObjectPlacement  # IfcLocalPlacement
        rel = placement.PlacementRelTo
        relative = placement.RelativePlacement
        point = relative.Location
        coord_i = point[0][0]

        # calculate cross sectional properties for each beam
        product_rep = beam.Representation
        reps = product_rep.Representations
```

```
        for rep in reps:
            items = rep.Items
            for item in items:
                source = item.MappingSource
                target = item.MappingTarget
                # print(source, target)

                origin = source.MappingOrigin
                mappedrep = source.MappedRepresentation
                mappeditems = mappedrep.Items
                for mappeditem in mappeditems:
                    # IfcExtrudedAreaSolid
                    profile = mappeditem.SweptArea
                    # calculate area and moment of the outerbounded
                    outer = profile.OuterCurve
                    area_out, moments_out = profile_property(outer)
                    area = area_out
                    I_x = moments_out['mu20']
                    I_y = moments_out['mu02']

                    inners = profile.InnerCurves
                    for inner in inners:
                        area_in, moments_in =
profile_property(inner)
                        area -= area_in
                        I_x -= moments_in['mu20']
                        I_y -= moments_in['mu02']
                    # print(area, I_x, I_y) #mm, mm4
                    if I_x not in CP:
                        CP.append(I_x)

                    post = mappeditem.Position
                    coord_b = post.Location[0][0] + coord_i
                    dir = mappeditem.ExtrudedDirection[0][2]
                    coord_e = coord_b - dir * mappeditem.Depth
                    if coord_b not in COORD_beam:
                        COORD_beam.append(coord_b)
                    if coord_e not in COORD_beam:
                        COORD_beam.append(coord_e)

                    mat_beam.append([beam, min(coord_b, coord_e),
```

```
max((coord_b, coord_e)), area, I_x])

        # retrieve material entities for each beam
        for rel in material_rels:
            # retrieve the linked material entity
            material_type = rel.RelatingMaterial
            if material_type in materials:
                material_type_no = materials.index(material_type) +
1
                # retrieve the linked element end coordinates
                eles = rel.RelatedObjects
                for i in range(len(mat_beam)):
                    info = mat_beam[i]
                    if info[0] in eles:
                        mat_beam[i].insert(-2, material_type_no)

    COORD_beam.sort()  # ensure coordinates are in ascending order
    return COORD_beam, mat_beam, CP

#main function to obtain multiple input vectors at the decomposed
element level
def element_vector_formation(COORD_beam, l0, mat_beam, CP):
    #decomposite beams into elements and obtain the joint data
vector COORD
    L = []
    COORD = []  # initialize the joint data vector

    for i in range(len(COORD_beam) - 1):
        L.append(COORD_beam[i + 1] - COORD_beam[i])
    for j in range(len(L)):
        n = int(L[j] / l0)
        COORD.extend([COORD_beam[j] + k * l0 for k in range(n)])
    COORD.append(COORD_beam[-1])

    # form the element data vector EPRP
    EPRP = []
    for cp in mat_beam:
        coordb = cp[1]
        coorde = cp[2]
        material_no = cp[3]
        ix = cp[-1]
```

```
        CP_type_no = CP.index(ix) + 1
        for k in range(len(COORD) - 1):
            if (COORD[k] >= coordb) & (COORD[k + 1] <= coorde):
                EPRP.append([k + 1, k + 2, material_no, CP_type_no])

    return COORD, L, EPRP

#main function to create support data vector MSUP
def support_vector_formation(COORD, piers):
    MSUP = [[1, 1, 1]]
    for pier in piers:
        place = pier.ObjectPlacement
        ref = place.PlacementRelTo
        relative = place.RelativePlacement.Location
        pier_loc = relative[0][0]

        # find the corresponding support joint
        diff = lambda coord: abs(coord - pier_loc)
        closest_loc = min(COORD, key=diff)
        support_no = COORD.index(closest_loc) + 1
        MSUP.append([support_no, 1, 0])
    MSUP.append([len(COORD), 1, 0])

    return MSUP

#main function to obtain joint&element load vectors
def load_vectors_formation(L, COORD_beam, COORD, EPRP, mat_beam):
    JP = []
    PJ = []
    MP = []
    PM = []
    # apply self-weight and vehicular loads
    for i in range(len(beams)):
        L0 = L[i]
        load_coord = COORD_beam[i] + L0 / 2
        Vehicular_P = (L0 - 5) * 180 / 40 + 180  # kN
        if load_coord in COORD:
            JP.append(COORD.index(load_coord) + 1)
            PJ.append([-Vehicular_P, 0])
        else:
            diff_2 = lambda coord: abs(coord - load_coord)
```

```
            loc = min(COORD, key=diff_2)
            if loc < load_coord:
                MP.append([COORD[loc] + 1, 1])
            else:
                MP.append([COORD[loc], 1])
            PM.append([Vehicular_P, 0, abs(load_coord - loc), 0])

    # evenly distributed loads
    vehicular_q = 10.5  # kN/mm4
    Ecs = 2500  # kg/m3
    for i in range(len(EPRP)):
        MP.append([i + 1, 3])
        PM.append([10.5, 0, 0, 0])
    for cp in mat_beam:
        coordb = cp[1]
        coorde = cp[2]
        area = cp[-2] * 10e-6  # m2
        self_q = area * Ecs
        for k in range(len(COORD) - 1):
            if (coordb >= COORD[k]) & (COORD[k + 1] <= coorde):
                MP.append([k + 1, 3])
                PM.append([self_q, 0, 0, 0])

    return JP, PJ, MP, PM

concrete_dict = {'15':2.2e4,
                 '20':2.55e4,
                 '25':2.80e4,
                 '30':3.00e4,
                 '35':3.15e4,
                 '40':3.25e4,
                 '45':3.35e4,
                 '50':3.45e4,
                 '55':3.55e4,
                 '60':3.60e4,
                 '65':3.65e4,
                 '70':3.70e4,
                 } #MPA
materials = ifcfile.by_type('IfcMaterial')
material_rels = ifcfile.by_type('IfcRelAssociatesMaterial')
elements = ifcfile.by_type('IfcElement')
```

```
# retrieve beams and substructure elements
beams = []
abutments = []
piers = []
for ele in elements:
    if 'girder' in ele.Name:
        beams.append(ele)
    elif 'Abutment' in ele.Name:
        abutments.append(ele)
    elif 'Pier' in ele.Name:
        piers.append(ele)

EM = EM_formation(materials, concrete_dict)
COORD_beam, mat_beam, CP = beam_vector_formation(beams,
material_rels)
l0 = 500  # length of (minimal) sub-element= 0.5m
COORD, L, EPRP = element_vector_formation(COORD_beam, l0, mat_beam,
CP)
MSUP = support_vector_formation(COORD, piers)
JP, PJ, MP, PM = load_vectors_formation(L, COORD_beam, COORD, EPRP,
mat_beam)

#adjust units
COORD = unit_change(COORD,10e-3)
CP = unit_change(CP, 10e-12)
EM = unit_change(EM,10e-3)

#get variables of the model
NJ = len(COORD) #number of joints
NE = NJ-1 #number of elements
NCJT = 2
NMP = len(EM) #number of material types
NCP = len(CP) #number of cross sectional property tpyes
NJL = len(JP) #number of joint loads
NEL = len(MP) #number of element loads
#number of supports
NS = len(MSUP)
#number of restraints
NR = 0
for sup in MSUP:
    if sup[1] == 1:
```

```
        NR += 1
    if sup[2] == 1:
        NR += 1
#number of degress of freedom
NDOF = NE*NCJT - NR
```

Analysis module

This part of script represents the core functions in the analysis module for defect structural analysis. Specifically, the following steps are included: (a) the analytical model is first pre-processed; (b) calculate the stiffness matrix and end loads at the element level and integrate them to form the structure matrix; (c) calculate the unknown variables in the joint placement vector by solving the P=Sd equation; (d) obtain displacements and forces at the element level.

```
# step 1 - determine NDOF and NSC
def NSC_formation(NCJT, NJ, NDOF, NS, MSUP):
    NSC = np.zeros((NCJT * NJ))
    i = 0
    j = 0
    k = NDOF
    while i < NJ:
        icount = 0
        i1 = 0
        while i1 < NS:
            if MSUP[i1][0] == i + 1:
                icount = 1
                i2 = 0
                while i2 < NCJT:
                    i3 = i * NCJT + i2
                    if MSUP[i1][i2 + 1] == 1:
                        k += 1
                        NSC[i3] = k
                    else:
                        j += 1
                        NSC[i3] = j
                        print(type(j))
                    i2 += 1
            i1 += 1
        if icount == 0:
            i2 = 0
```

```
            while i2 < NCJT:
                i3 = i * NCJT + i2
                j += 1
                NSC[i3] = j
                i2 += 1
        i += 1
    NSC = NSC.astype(np.int_)
    return NSC

#step 2 -integrate element matrix (stiffness and end load) to the
structure
# map forces&restraints number to joint number
NSC = [4, 5, 1, 2, 6, 3]

# utility function to caluclate element stiffness matrix
def ESTIFF(E, ZI, BL):  # BK is the element stiffness vector
    BK = np.zeros((4, 4))
    Z = E * ZI / (BL * BL * BL)
    BK[0][0] = 12 * Z
    BK[1][0] = 6 * BL * Z
    BK[2][0] = -12 * Z
    BK[3][0] = 6 * BL * Z
    BK[0][1] = 6 * BL * Z
    BK[1][1] = 4 * (BL * BL) * Z
    BK[2][1] = -6 * BL * Z
    BK[3][1] = 2 * (BL * BL) * Z
    BK[0][2] = -12 * Z
    BK[1][2] = -6 * BL * Z
    BK[2][2] = 12 * Z
    BK[3][2] = -6 * BL * Z
    BK[0][3] = 6 * BL * Z
    BK[1][3] = 2 * (BL * BL) * Z
    BK[2][3] = -6 * BL * Z
    BK[3][3] = 4 * (BL * BL) * Z
    return BK


# utility function to store element stiffness matrix into structure
stiffness matrix
def STORES(JB, JE, NCJT, NDOF, BK, S):
    i = 0
```

```
    while i < 2 * NCJT:
        if i < NCJT:
            i1 = (JB - 1) * NCJT + i
        else:
            i1 = (JE - 1) * NCJT + (i - NCJT)
        N1 = NSC[i1]
        if N1 <= NDOF:
            j = 0
            while j < 2 * NCJT:
                if j < NCJT:
                    j1 = (JB - 1) * NCJT + j
                else:
                    j1 = (JE - 1) * NCJT + (j - NCJT)
                N2 = NSC[j1]
                if N2 <= NDOF:
                    S[N1 - 1][N2 - 1] += BK[i, j]
                j += 1
        i += 1
    return S


# utility function to obtain fixed-end force vector of an element
def EFEFLL(ieL, BL, MP, PM, QF):
    # QF is the fixed-end force vector of ith element
    LoadType = MP[ieL][1]
    if LoadType == 1:
        BW = PM[ieL][0]
        BL1 = PM[ieL][2]
        BL2 = BL - BL1
        FSB = BW * (BL2 ** 2) * (3 * BL1 + BL2) / (BL ** 3)
        FMB = BW * BL1 * (BL2 ** 2) / (BL ** 2)
        FSE = BW * (BL1 ** 2) * (BL1 + 3 * BL2) / (BL ** 3)
        FME = -BW * (BL1 ** 2) * BL2 / (BL ** 2)
    elif LoadType == 2:
        BM = PM[ieL][0]
        BL1 = PM[ieL][2]
        BL2 = BL - BL1
        FSB = -6 * BM * BL1 * BL2 / (BL ** 3)
        FMB = BM * BL2 * (BL2 - 2 * BL1) / (BL ** 2)
        FSE = 6 * BM * BL1 * BL2 / (BL ** 3)
        FME = BM * BL1 * (BL1 - 2 * BL2) / (BL ** 2)
```

```
    elif LoadType == 3:
        W = PM[ieL][0]
        BL1 = PM[ieL][2]
        BL2 = PM[ieL][3]
        FSB = W * BL * (1 - BL1 * (2 * (BL ** 3) - 2 * (BL1 ** 2) *
BL + BL1 ** 3) / (BL ** 4) - (BL2 ** 3) * (2 * BL - BL2) / (BL **
4)) / 2
        FMB = W * (BL ** 2) * (1 - (BL1 ** 2) * (6 * (BL ** 2) - 8 *
BL1 * BL + 3 * (BL1 ** 2)) / (BL ** 4) - (BL2 ** 3) * (4 * BL - 3 *
BL2) / (BL ** 4)) / 12
        FSE = W * BL * (1 - BL2 * (2 * (BL ** 3) - 2 * (BL2 ** 2) *
BL + BL2 ** 3) / (BL ** 4) - (BL1 ** 3) * (2 * BL - BL1) / (BL **
4)) / 2
        FME = -W * (BL ** 2) * (1 - (BL2 ** 2) * (6 * (BL ** 2) - 8
* BL2 * BL + 3 * (BL2 ** 2)) / (BL ** 4) - (BL1 ** 3) * (4 * BL - 3
* BL1) / (BL ** 4)) / 12
    elif LoadType == 4:
        W1 = PM[ieL][0]
        W2 = PM[ieL][1]
        BL1 = PM[ieL][2]
        BL2 = PM[ieL][3]
        a1 = BL - BL1
        FSB = W1 * (a1 ** 3) * ( (7 * BL + 8 * BL1) - BL2 * (3 * BL
+ 2 * BL1) * (1 + BL2 / a1 + (BL2 / a1) ** 2) / a1 + 2 * (BL2 ** 4)
/ (a1 ** 3)) / (20 * (BL ** 3)) + W2 * (a1 ** 3) * ( (3 * BL + 2 *
BL1) * (1 + BL2 / a1 + (BL2 / a1) ** 2) - (BL2 ** 3) * (2 + (15 * BL
- 8 * BL2) / a1) / (a1 ** 2)) / (20 * (BL ** 3))
        FMB = W1 * (a1 ** 3) * (3 * BL + 12 * BL1) - BL2 * (2 * BL +
3 * BL1) * (1 + BL2 / a1 + (BL2 / a1) ** 2) / a1 + 3 * (BL2 ** 4) /
(a1 ** 3)) / (60 * (BL ** 2)) + W2 * (a1 ** 3) * ( (2 * BL + 3 *
BL1) * (1 + BL2 / a1 + (BL2 / a1) ** 2) - 3 * (BL2 ** 3) * (1 + (5 *
BL - 4 * BL2) / a1) / (a1 ** 2)) / (60 * (BL ** 3))
        FSE = (W1 + W2) * (BL - BL1 - BL2) / 2 - FSB
        FME = (BL - BL1 - BL2) * (W1 * (-2 * BL + 2 * BL1 - BL2) -
W2 * (BL - BL1 + 2 * BL2)) / 6 + FSB * BL - FMB
    else:
        FSB = FMB = FSE = FME = 0
    QF[0] += FSB
    QF[1] += FMB
    QF[2] += FSE
    QF[3] += FME
```

```
    return QF


# utility function to store element fixed-end force vector into
structure load vector P
def STOREPF(JB, JE, NCJT, NDOF, NSC, QF, P):
    i = 0
    while i < 2 * NCJT:
        if i < NCJT:
            i1 = (JB - 1) * NCJT + i
        else:
            i1 = (JE - 1) * NCJT + (i - NCJT)
        N1 = NSC[i1]

        if N1 <= NDOF:
            P[N1 - 1] = P[N1 - 1] - QF[i]
        i += 1
    return P


# main function to integrate stiffness matrix and fixed-end forces
def element_to_cracked_structure(NE, NEL, NDOF, NCJT, EPRP, EM, CP,
COORD, MP, PM, NSC, ieCracked, coeffi):
    # generate stiffness matrix
    S = np.zeros((NDOF, NDOF))  # structure stiffness matrix
    P = np.zeros(NDOF)  # structure force vector (including moments)

    ie = 0  # loop for elements
    while ie < NE:
        JB = EPRP[ie][0]  # joint number of beginning
        JE = EPRP[ie][1]  # joint number of end
        iE = EM[EPRP[ie][2] - 1]  # material property of element i
        iZI = CP[EPRP[ie][3]-1] #cross sectional property of element
i
        if ie == ieCracked:
            iZI = iZI*coeffi
        XB = COORD[JB - 1]  # X coordinate of beginning joint
        XE = COORD[JE - 1]  # X coordinate of end joint
        iBL = abs(XE - XB)  # make sure the length of element is
positive
        BK = ESTIFF(iE, iZI, iBL)
```

```
        S = STORES(JB, JE, 2, 3, BK, S)

        if NEL > 0:  # for ith element
            QF = np.zeros(2 * NCJT)
            ieload = 0
            while ieload < NEL:  # number of element loads=2
                if ie == MP[ieload][0]-1:
                    QF = EFEFLL(ieload, iBL, MP, PM, QF)
                    ieload += 1
                else:
                    ieload += 1
            P = STOREPF(JB, JE, 2, 3, NSC, QF, P)
        ie += 1
    #print(S, P)
    return S, P #P is the aggregated vector of fix-end forces

#main function - complete the structure force vector P by adding
joint loads (i.e., external forces)
def structure_force_vector_formation(NJL, NCJT, NDOF, JP, PJ, P):
    i = 0
    while i < NJL: #1
        i1 = JP[i]
        i2 = (i1-1)*NCJT -1
        j =0
        while j<NCJT:
            i2 += 1
            N = NSC[i2]
            if N <= NDOF:
                P[N-1] = P[N-1] + PJ[i][j]
                j += 1
            else:
                j+=1
        i += 1
    #print(P)
    return P

#step 2 - solve the P=Sd equation
#main function - obtain structure joint displacement vector by
solving P = Sd
def structure_displacement_vector_formation(NDOF,S,P):
    i = 0
```

```
    while i<NDOF:
        Z1 = S[i][i]
        j=0
        while j<NDOF:
            S[i][j] = S[i][j]/Z1
            j += 1
        P[i] = P[i]/Z1
        k = 0
        while k<NDOF:
            if k == i:
                k += 1
            else:
                Z = S[k][i]
                m = i
                while m<NDOF:
                    S[k][m] = S[k][m]-S[i][m]*Z
                    m+=1
                P[k] = P[k] - P[i]*Z
                k += 1
        i += 1
    #print(P)
    return P
#P here represents the joint displacements at the structure level

##step 3 - determine element-level end forces and support reactions

#utility function to retrieve end displacements U at element level
def EDISPL(JB,JE,NCJT, NDOF, NSC, d):
    U = np.zeros((2*NCJT))
    j = (JB-1)*NCJT -1
    i = 0
    while i < NCJT:
        j += 1
        N = NSC[j]
        if N <= NDOF:
            U[i] = d[N-1]
            i+=1
        else:
            i+=1
    j = (JE-1)*NCJT -1
    i = NCJT
```

```
    while i <2*NCJT:
        j += 1
        N = NSC[j]
        if N <= NDOF:
            U[i] = d[N-1]
            i += 1
        else:
            i += 1
    return U

#utility function to determine element load force vector Q
def EFORCE(NCJT, BK, U, QF):
    Q = np.zeros((2*NCJT))
    i = 0
    while i <2*NCJT:
        Q[i] = QF[i]
        i+= 1

    i = 0
    while i<2*NCJT:
        j = 0
        while j < 2*NCJT:
            Q[i] = Q[i] + BK[i][j]*U[j]
            j += 1
        i+=1
    return Q

#utility function to calculate the reactions at supports
def STORER(JB, JE, NCJT, NDOF, NSC, Q, R):
    i=0
    while i <2*NCJT:
        if i < NCJT:
            i1 = (JB-1)*NCJT + i
        else:
            i1 = (JE-1)*NCJT + (i-NCJT)
        N = NSC[i1]
        if N>NDOF:
            R[N-NDOF-1]  = R[N-NDOF-1] + Q[i]
            i += 1
        else:
            i += 1
```

```
    return R

#main function to calculate element-level displacements and forces &
obtain Reaction vector
def structure_reaction_vector_formation(NCJT, NJ, NDOF, NE, NEL,
EPRP, EM, CP, COORD, MP, PM, NSC, d):
    ie = 0
    R = np.zeros((NCJT*NJ - NDOF)) #initialize R vector
    u_dict = {}
    eforce_dict = {}
    while ie < NE:
        JB = EPRP[ie][0] #joint number of beginning
        JE = EPRP[ie][1] #joint number of end
        iE = EM[EPRP[ie][2]-1] #material property of element i
        iZI = CP[EPRP[ie][3]-1] #cross sectional property of element
i
        XB = COORD[JB-1] #X coordinate of beginning joint
        XE = COORD[JE-1] #X coordinate of end joint
        iBL = abs(XE-XB)
        iU = EDISPL(JB, JE, 2, 3,NSC, d) #end displacements
        u_dict[ie] = iU
        iBK = ESTIFF(iE, iZI, iBL)
        iQF = np.zeros(2*NCJT) #fixed-end force vector of each
element
        if NEL > 0:
            ieL = 0 #ith element load
            while ieL <NEL:
                if ie == MP[ieL][0]-1:
                    iQF = EFEFLL(ieL,iBL,MP,PM,iQF)
                    ieL+=1
                else:
                    ieL +=1
            #internal forces at ends (including external force and
stiffness * displacement)
        Q = EFORCE(2, iBK, iU, iQF)
        eforce_dict[ie] = Q
        R = STORER(JB,JE,2, 3,NSC,Q,R)
        ie += 1
    #print(R)
    return R, u_dict, eforce_dict
```