Implementing bridge model updating for operation and maintenance purposes: examination based on UK practitioners' views

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There has been a vision of creating bridge digital twins as virtual simulation models of bridge assets to facilitate remote management. Bridge model updating is one digital twin technology which can enable the continuous updating of the structural model as new monitoring data is collected. This paper examines why there is currently little industry uptake of monitoring, modelling and model updating for the operation and maintenance of bridges despite over two decades of research in these fields. The study analyses the findings from a series of semi-structured industry interviews with expert bridge professionals in the U.K. and from an extensive literature survey of bridge model updating studies to examine the disconnects between research and practice and the practical issues of implementing bridge model updating. In particular, the study found that localised damage resulting in local reduction in structural stiffness, a key assumption made in the majority of research, is subject to question by practitioners as many common types of bridge damage may not induce noticeable change in structural stiffness that existing model updating techniques would identify. Key recommendations for future research are proposed to drive adoption of bridge monitoring, modelling and model updating and thus realise their industrial value.

Keywords: structural model updating; structural health monitoring; digital twin technology; bridge operation and maintenance; industry practice

1. Introduction

Bridges are critical components of infrastructure systems, acting as points of interdependency in transportation networks. Their performance is critical to the resilience of our urban environment. However, with the growing challenges of ‘asset time bomb’ (i.e. a large number of assets approaching their end-of-life state at the same time) (Thurlby, 2013) and minimising carbon emissions from the built environment, there is a pressing need for better maintenance of bridge assets. In the U.S., as of 2019, 47,000 out of its 616,000 bridges (21%) were rated as structurally deficient and the pace of repairs of these bridges has been slow (American Road & Transportation Builders

Association, 2019). In the U.K., as of 2018, 3,177 council-maintained road bridges were rated as sub-standard and the budget for necessary repair works has been limited (RAC Foundation, 2019). Both the American Association of State Highway and Transportation Officials (AASHTO) and the U.K. Bridge Owners Forum (BOF) have identified bridge operation and maintenance (O&M) related issues as the top of their grand challenges for bridge engineering and management, as shown in Table 1 (Bridge Owners Forum, 2020; Mertz, 2013).

[Table 1 near here]

To improve bridge O&M, new materials, technologies and processes have been developed. One technology is structural health monitoring (SHM), which aims to improve asset performance by measuring and learning from in-service structural behaviour. To investigate the manner in which bridge monitoring systems are currently utilised, Webb, Vardanega and Middleton (2015) conducted a comprehensive literature survey and developed a classification framework with five categories defining the reasons why a bridge monitoring system is deployed. These are: (i) Sensor Deployment Studies, (ii) Anomaly Detection, (iii) Model Validation, (iv) Threshold Check, and (v) Damage Detection. The study found that of the 45 installations examined, only five demonstrated clear benefit to the bridge owners. Realising the practical value of bridge SHM to bridge O&M remains a key challenge to both researchers and practitioners.

Of these five categories, Model Validation was found to have the largest number of deployments but none of these installations demonstrated clear benefit to bridge O&M. In general, monitoring and modelling represent two sources of information which engineers use to better understand the real performance of bridges. The former aims to capture the in-field structural response, operational loading, environmental conditions and physical properties; while the latter, most commonly finite element (FE) modelling or grillage modelling, aims to capture the underlying engineering physics such as material behaviour, structural mechanics and soil-structure interaction. How to relate these two sources of information together to explain the observed structural behaviour or change of behaviour remains a key challenge for bridge applications. In research, model updating is commonly used as part of the Model Validation process to address this challenge. Model updating is a process by which an ‘as-is’ structural analysis model is created to closely represent the real performance of the engineering structure. It is essentially an inverse problem which updates the model parameters and sometimes other modelling assumptions by matching model predictions with sensor measurements. The fundamental concept is not new, as researchers have been conducting structural model updating and validation using experimental data for decades (Ashraf, Gardner, & Nethercot, 2006; Theofanous & Gardner, 2009; Xu, Butler, & Elshafie, 2019; Kariyawasam, Middleton, Madabhushi, Haigh, & Talbot, 2020). The key challenges lie in the complexities and uncertainties of bridges in operation (e.g. structural and material imperfections, uncontrolled environmental and operational conditions, uncertain boundary conditions), which make both their monitoring and modelling susceptible to numerous sources of uncertainty.

More recently, there has been a vision of developing bridge digital twins which have the following key characteristics:

(i) They serve as virtual simulation models which can be updated continuously as new measurement data (e.g. monitoring data) becomes available;

(ii) They are connected to the physical assets to provide real time information (e.g. structural condition) and enable remote management;

(iii) They may be used to perform ‘what-if’ scenarios for predicting asset performance and facilitating proactive maintenance.

Bridge model updating may be used as part of the digital twinning process to create virtual simulation models that closely represent the physical bridge assets.

While there has been a large amount of research on bridge model updating over the past two decades, there is little sign of industry uptake by bridge practitioners (owners, operators and consultants) to support bridge O&M related activities. The aim of this work is to address the following research question: "*What additional research is needed in order to enable industry implementation of bridge model updating?*". This research firstly identifies and examines the current challenges of implementing bridge monitoring, modelling and model updating in the U.K. based on expert practitioners' views. In particular, two types of disconnects between research and practice were investigated: (i) Disconnects between research outputs from bridge model updating studies and industry needs in bridge O&M; and (ii) Disconnects between research methodologies of bridge model updating and the industry's approach to bridge condition appraisal. Finally, the results and findings reported in this study are used to propose key recommendations for future research in order to drive future implementation of bridge model updating as a digital twin technology to improve bridge O&M.

2. Methodology

The methodology adopted for this study consists of: (i) a series of industry interviews on bridge monitoring, modelling and model updating under the broad context of bridge O&M; and (ii) an extensive literature survey on bridge model updating studies. In order to identify the disconnects between research and practice and the challenges of implementing bridge model updating: (i) research outputs were compared with industry needs; and (ii) research methodologies were compared with industry practice. The findings were then used to examine what is missing in existing research based on practitioners’ views and make recommendations for future research in order to enable industry implementation. Figure 1 provides a summary of the overall workflow and logic flow of the methodology in this study.

[Figure 1 near here]

2.1. Industry interviews

Seventeen face-to-face semi-structured interviews were conducted with nineteen expert bridge professionals in the U.K. (10 bridge owners/operators and 9 bridge consultants). The interviewees were carefully selected to be representative of those involved in bridge O&M activities in the U.K. The interviewed group sampled all typical bridge O&M scenarios, including all roles (e.g. owner, operator and consultant), all transport modes (e.g. highways and rail) and all levels of operation scope (based on level of authority: e.g. national, regional/county and local authority). All interviewees had technical background in civil and structural engineering and at least ten years’ experience in bridge O&M activities. This was to ensure that the interviewees had sufficient expertise and experience to provide insightful answers to the interview questions. Details of the interviewees are presented in Table 2.

[Table 2 near here]

The adopted methodology was consistent to those of similar studies in built environment research where semi-structured interviews were used (Baker, Moncaster, & Al-Tabbaa, 2017; Bennetts, Vardanega, Taylor, & Denton, 2019; Dadzie, Runeson, Ding, & Bondinuba, 2018; Gardner, Lark, Jefferson, & Davies, 2018). The interviews were chosen to be semi-structured in this study to allow for targeted and in-depth analysis of how bridge monitoring, modelling and model updating could be implemented in practice for better maintenance of bridges, under the broad context of the day-to-day practice and decision making in bridge O&M. Specifically, the interviews examined the following six themes:

i. Key structural components and issues that keep bridge practitioners awake at night
ii. Current practice for bridge damage detection and structural assessment
iii. Current practice for bridge monitoring and modelling
iv. Barriers and incentives to using bridge monitoring and modelling in practice
v. Industry perspectives on bridge model updating
vi. Key gaps in capability in bridge condition appraisal

The main interview questions used are presented in the Supplemental Material. The digitally recorded interviews were transcribed and then analysed by ‘coding’ against these six themes, which consisted of highlighting snippets of each interview that are related to each theme (Saunders, Lewis, & Thornhill, 2009).

The validation of the interviews followed the principles and methods in Brinkmann & Kvale (2014) for qualitative data analysis. Firstly, the representativeness of the interviewees was checked as described previously. Secondly, for five of the six themes (Themes i to iv and vi) examined, consensus or majority views among the interviewees were distilled (refer to Section 3) to ensure sufficient degree of reliability of the interview findings. Where there was a major difference in opinion on an important issue (which mainly applies to damage detection under Theme v – refer to Section 3.6), this difference was highlighted and all opinions were included. The objective of Theme v (Industry perspectives on bridge model updating) is to gather valid comments, issues or questions raised by the expert bridge professionals (refer to Section 3.5 for more details). Although these views may not be exhaustive, they are valid and may warrant additional investigation in future research. Thirdly, the distilled interview findings were sent back to a few interviewees for checking and feedback. Finally, it should also be noted that while this qualitative research was set in the U.K. context of bridge O&M practice, the findings of this interview study may be transferred to similar bridge O&M situations around the world. Specifically, the study provided insights into the types of questions and issues that can be raised by bridge practitioners worldwide as well as their perspectives on bridge model updating. Rich and specific descriptions of the context of this interview study (Themes ii and iii) are provided (refer to Sections 3.2 and 3.3) to enable the reader to judge to what degree the findings may be generalised in a new situation.

2.2. Literature survey

The adopted methodology was consistent to those of similar literature survey studies related to built environment research (Li, Yi, Chi, Wang, & Chan, 2018; Vagnoli, Remenyte-Prescott, & Andrews, 2018; Wang & Kim, 2019; Webb, Vardanega, Fidler, & Middleton, 2014). To systematically search and select the literature for review, a content analysis-based review method was adopted (Seuring & Gold, 2012). A number of input keywords were identified to define the scope of relevant literature, which included model updating, structural identification, bridge monitoring and finite element modelling. It was decided to focus only on case studies published as technical journal articles because their contents have been properly peer-reviewed. The literature search was facilitated through the use of Scopus and Google Scholar.

Two key selection criteria were used:

(i) The above-mentioned keywords or their synonyms should be included in the title or abstract. A brief examination of the content was conducted for each paper to assess the level of relevance.

(ii) The monitoring data utilised should be field measurement data from bridges in operation, rather than test data of scaled bridges in the laboratory or simulated data.

Both the model updating methodologies and outputs (in particular, information extracted from the updated model) were examined.

3. Industry interviews

3.1. Key structural components and issues that keep bridge practitioners awake at night

Four overarching root causes that ‘keep bridge practitioners awake at night’ have been identified based on the majority of interviewees’ responses. These are presented and explained as follows.

i. **The bridge component or issue is safety critical**

Safety critical issues can be considered from two perspectives: (a) structural integrity of the bridge; and (b) safety of people within the vicinity of the bridge (e.g. general public, inspectors or labourers on site). The former includes bridge scour, corrosion of concrete reinforcement or prestressing tendons, bearing and joint seizure, and bridge strike. The latter includes concrete spalling and insufficient load bearing capacity of bridge parapets.

ii. **The bridge component or issue is difficult to inspect**

This is commonly referred to as ‘hidden defects’ in the U.K., which includes two types of defects: (a) those which are difficult to access; and (b) those which are difficult to detect visually, even though they may be easy to access. The former includes any defects inside box girders (e.g. fatigue cracks, section loss due to corrosion), bridge scour, corrosion of concrete reinforcement or prestressing tendons, and half-joint defects. The latter includes fatigue cracks in welded sections.

iii. **The bridge component or issue is difficult to manage**

Water management related issues, such as joint leakage, were highlighted by the majority of interviewees as a key challenge in bridge O&M for two reasons: (a) it is the primary source of material degradation and structural deterioration (e.g. concrete corrosion, steel corrosion, bearing and joint seizure); and (b) waterproofing measures have often failed to perform as specified due to improper manufacturing and installation (e.g. bad detailing) or poor management and maintenance (e.g. application of de-icing salts).

iv. **There is a large degree of uncertainty in ascertaining the actual behaviour related to the bridge component or issue, which may result in the risk of sudden and unexpected failure modes**

This is often due to limited forewarning of certain structural failure modes or insufficient engineering understanding of how certain parts of the structure behave. The former includes sudden or brittle failure modes such as bucking and shear. The latter includes bridge scour, unexpected expansion joint failure, and half joint and hinge behaviour.

In addition, the most critical bridge components and structural issues in the U.K. bridge O&M activities have been identified. These are summarised in Table 3.

[Table 3 near here]

3.2. Current practice for damage detection and structural assessment

Overall, there are two major types of bridge condition appraisal activities: (i) Damage Detection: detection and evaluation of bridge damage and deterioration by means of inspection, testing or monitoring, and (ii) Structural Assessment: evaluation of reserve load capacity by means of structural assessment of bridges, which typically involves some type of structural analysis and modelling. According to the majority of interviewees, the decision of whether or not to close or partially close a bridge is governed by concern for the safety of people within the vicinity of the bridge, which is mainly determined by whether the bridge has sufficient reserve load capacity.

3.2.1. Damage detection

According to all interviewees' responses, currently there are two main ways in which damage and deterioration of a bridge can be notified in practice. These are summarised and described in Table 4. The use of testing and monitoring are mostly reactive rather than proactive. They are undertaken in a targeted manner to investigate and examine a known issue picked up by inspections rather than to detect new damage.

[Table 4 near here]

3.2.2. Structural assessment

Compared with repair work and inspection, structural assessment is currently not a high priority for many bridge owners and operators in the U.K. and it is conducted only when required (e.g. driven by immediate and targeted concerns) according to the majority of interviewees. In the U.K., it is typically conducted once every 18 years and is mainly for the purpose of load capacity assessment (Griffin & Patro, 2018; Highways England, 2019). An extensive program of bridge assessment was carried out in the 1990s when 40 tonne trucks were first introduced.

Overall, there are three levels of assessment for both highway and railway bridges in the U.K. (Highways England, 2019; Network Rail, 2018). These are summarised in Table 5. Most bridge assessment follows a similar procedure, which starts from Level I assessment and then proceeds to higher levels of assessment (e.g.

line beam method to grillage method to finite element method) until the evaluated bridge capacity is satisfactory or else actions are deemed necessary to ensure structural safety of the bridge. According to those interviewees with relevant experience, other factors to consider in bridge assessment include age of the bridge structure, original design loading, current bridge behaviour and potential failure modes.

[Table 5 near here]

Three main sources of information may be used to justify engineering assumptions made in a bridge assessment: codes and standards, inspection, and testing. Less conservative values may be used for Level III assessment based on measurements and condition survey. Frequently mentioned examples in the interviews are summarised in Table 6.

[Table 6 near here]

3.3. Current practice for bridge monitoring and modelling

3.3.1. Bridge monitoring

All interviewees agreed that overall, very few bridges have real time SHM systems in place in current practice of the U.K. Of these limited number of installations, the majority of them was put on existing bridges as a tool for further investigation and examination of a known defect or issue. Before each bridge SHM system is installed in practice, a value case needs to be made to justify the associated cost and effort. Examples of most common and useful type of bridge monitoring installation in the U.K. practice have been identified based on most interviewees’ responses. These are summarised in Table 7. One key issue for SHM of existing bridges, as raised by the majority of interviewees, is the understanding of the pre-existing conditions when the monitoring is first deployed (e.g. existing stress, existing number of wire breaks, cumulative displacement of bearings).

[Table 7 near here]

3.3.2. Bridge modelling

Structural modelling, particularly FE modelling, is rarely used for bridge O&M purposes in the U.K. According to the majority of interviewees, it is predominantly a one-off exercise after an issue has been raised, typically regarding concerns of bridge capacity deficiency due to either damage and deterioration or increased bridge loading. In certain limited cases mentioned by some interviewees, an FE model may also be used to investigate more detailed stress profiles (e.g. stress fields at critical connections), complex structural behaviour (e.g. torsional effects, live load distribution, soil-structure interaction) or the effects of key strengthening actions. Bridge FE models were typically not kept and maintained by an asset owner on a permanent basis, unless the bridge was a landmark structure of strategic importance. No examples were noted where FE models were used proactively to detect new problems (e.g. damage).

3.4. Barriers and incentives to using bridge monitoring and modelling

All interviewees were familiar with the concepts of SHM and FE modelling, and therefore they were able to provide their thoughts and comments on the use of bridge monitoring and modelling for O&M purposes.

3.4.1. Bridge monitoring

There are two types of monitoring. One is reactive monitoring for the purposes of further investigation and examination after specific issues are identified by other means such as visual inspection. Most bridge monitoring activities in practice fall under this category. The other is proactive monitoring to detect anomalous behaviour or structural damage in near real time and therefore to enable more proactive maintenance.

The most highlighted and frequently mentioned barriers to using bridge monitoring (i.e. the views shared by the majority of interviewees) are summarised as follows:

i. **Cost**

Budgets are limited for bridge O&M. Most of the budget is currently taken by condition improvement measures such as repair and replacement (e.g. bearing and joint replacement, concrete repair, strengthening against impact) to ensure structural safety and extend service life. Compared with physical repair, since bridge SHM does not directly improve bridge condition and its benefits are often unclear, it is often difficult to justify its deployment, particularly when the budget is tight. In addition to the cost of the bridge SHM system, there are also ongoing costs of maintaining the installed SHM system and employing consultants to perform data post-processing and interpretation. Another issue related to cost is the financing model, specifically, who should be paying for the bridge SHM system?

ii. **Value case for monitoring: reactive and targeted monitoring vs. proactive and untargeted monitoring**

Currently there is a dilemma between reactive monitoring and proactive monitoring.

(a) The issue with proactive monitoring is that it is difficult to envisage what could go wrong with a bridge structure as there are a large number of potential issues that might arise during its service life. It is also challenging to identify at the start of a bridge's service life where the critical and vulnerable parts of the bridge are, often due to insufficient knowledge of real structural behaviour and operating conditions. In addition, it is very difficult to address the cost-benefit of untargeted monitoring where a large number of sensors may be needed (with some built-in redundancies to account for sensor failures), as the end objectives and benefits are often less clearly defined. Two main questions raised by the interviewees were: (1) Which bridge(s) and what part(s) of a bridge should be monitored when there is a large portfolio of bridge assets to manage? (2) Most bridge assets are in good condition and may not have any issues for a long period of time (e.g. 30 to 50 years) from the start of their service life, in which case what is the monitoring data used for?

(b) On the other hand, there are two main issues with reactive monitoring: (1) the structural issue (e.g. damage) needs to be picked up first by other means such as visual inspection, and (2) it is difficult to determine the pre-existing condition of the bridge or bridge component, as sensors often measure changes of state rather than the absolute state (e.g. strain, displacement, number of wire breaks).

Currently, it is much easier to establish the value case for reactive and targeted monitoring in practice as it directly addresses the specific issues of concern, particularly for existing bridges.

iii. Processing of SHM data

There are two overarching data challenges for bridge SHM: (1) How to extract useful information from bridge SHM data? (2) How to manage and process large and heterogeneous bridge SHM datasets? Most interviewees raised the issue that bridge monitoring data has often not been exploited satisfactorily due to the above-mentioned two challenges. Not much SHM data collected has been directly useful to bridge O&M. More often it is a case of ‘*measuring things just for the sake of it*’. In addition, there are many challenges for data processing such as data cleansing and data de-trending (i.e. removal of environmental trends in SHM data); and there is generally a lack of ‘*sense making*’ and engineering interpretation of SHM data to explain the underlying structural behaviour.

iv. **Reliability and futureproofing of bridge SHM system**

The most commonly raised practical issue is the reliability of the SHM system. Data quality has been found to be a common problem (e.g. due to cabling, power supply, sensor failure). False positives are not uncommon (e.g. false detection of wire breaks, false detection of over-weight vehicles). More significantly, the lifetime of sensors and sensor systems is often much shorter than that of a bridge. SHM systems have often been found to deteriorate and fail more quickly than the monitored bridges in practice, particularly for long term monitoring. Other practical issues include adaptability to future computer systems and data management platforms as well as who should manage and maintain the bridge SHM system.

Due to insufficient knowledge and appreciation of the benefits, it was difficult for the interviewees to come up with clear incentives for using bridge SHM systems as part of their bridge management processes. Most interviewees mentioned that the incentives were the opposite of the barriers if the latter could be properly addressed. A few valid incentives were raised by some interviewees and these are summarised as follows. It should be noted that this is not intended to be an exhaustive list.

i. **Cost reduction by reducing risks and uncertainties**

One common question raised by the interviewees was: Can a bridge SHM system enable more targeted and meaningful spending on maintenance and refurbishment? In other words, '*spend the right amount of money in the right place at the right time*'. For example, it is costly and sometimes physically impossible to replace all bridge bearings, and many bearings have similar appearance from the outside even though some may have deteriorated and could cause detrimental effects to the bridge. One potential use case of bridge SHM data is to provide evidence regarding which bearings should be replaced.

ii. **Better knowledge of real structural behaviour**

Many interviewees mentioned that it would be good to have better insight and engineering understanding of the real structural behaviour, such as load path and load sharing behaviour of their bridges.

iii. **Remote management of bridges**

Remote management is particularly useful when the bridge owner has a large portfolio of bridge assets to manage and maintain and these bridge assets are often difficult to access, i.e. at remote sites.

3.4.3. Bridge modelling

The most highlighted and frequently mentioned barriers to using bridge modelling for O&M purposes (i.e. the views shared by the majority of interviewees) are summarised as follows:

i. **Model type**

One key question raised by many interviewees was what type of analysis model should be used, especially if it were to be kept with the bridge.

Different use cases require different model fidelities. In addition, it may not be realistic in practice to model everything and capture every damage scenario in a model.

ii. **End benefits**

Many interviewees raised the fact that FE modelling had rarely been needed so far and it was unclear to them why there is a need to keep an FE model with a bridge and for what purposes. The most common use case for an FE model was when there is an increase in bridge loading and the model was created for bridge assessment purposes.

iii. **Practical issues**

There are three major practical issues raised by the interviewees.

(a) *Cost-benefit*: It is costly to model and analyse a large number of bridges and employ expensive consultants. It is also unclear who should keep the FE model for tens of years when the bridge remains in good condition and there appears to be no clearly defined use case.

(b) *Liability*: There is a liability issue when using analysis models created by other people or organisations. In the U.K., if the owner keeps a model, it has the obligation to check the model to ensure there is no error. The owner then needs to take legal responsibility for this model if anything goes wrong. Bridge owners in the U.K. tend to keep the drawings and technical approval documents but not the calculations and analysis models due to this liability issue.

(c) *Software package*: FE software packages have evolved over the years. If an FE model is to be kept with the bridge asset, the issue of adaptation to

> new software packages and computer systems needs to be addressed. The alternative is to build an FE model from scratch every time it is needed.

As for incentives to using FE modelling for bridge O&M, especially on a more frequent basis and if the model is to be kept with the bridge asset, it was generally very difficult for the majority of interviewees to come up with clear incentives due to insufficient knowledge and appreciation of its benefits and the above-mentioned barriers.

3.5. Industry perspectives on bridge model updating

In the current U.K. industry practice, the generation of a more realistic analysis model is not achieved through solving an ‘inverse problem’ by back calculating model parameters and modifying modelling assumptions based on sensor measurements of structural response. Rather, a direct approach is adopted by gathering as much information as possible about the physical properties of the bridge, typically through condition surveys (refer to Section 3.2.2 regarding Level III assessment). An example of this approach is provided in O’Donnell et al. (2017).

During each interview, the general research approach of solving an ‘inverse problem’ for bridge model updating and the common research goal of performing damage detection through detecting a local reduction in structural stiffness were described to each interviewee. Only eight out of the nineteen interviewees had heard of the research approach before the interview (They are C2, C11, C12, C13, C14, C15, C16, C18 – refer to Table 11). Unlike other parts of the interview where the majority or the most common views are presented, the purpose for this part of the interview was to gather valid comments and questions raised by the expert bridge practitioners, especially those who have extensive experience in bridge modelling and have familiarity with the bridge model updating concept. The gathered industry perspectives on bridge model updating are summarised as follows.

i. **On bridge model updating research methodologies**

   (a) One commonly raised issue is reliability. Specifically, there seems to be a lack of further verification and validation as well as additional engineering interpretation and evidence if the model updating results were to be fully relied on in practice. Some interviewees (C11, C12, C13, C18) raised the issue that in general, it is easy to justify the measurements by adjusting model parameters but difficult to make predictions as past predictions have often been found to be incorrect or unreliable.

   (b) In addition, the model updating approach of solving an inverse problem to detect structural damage is currently outside the framework of what most engineers would operate in terms of signing off the capacity of a bridge structure. To some interviewees (C1, C2, C13, C14, C18), it also seems to involve much more work and effort compared with the existing industry approach of demonstrating that a bridge is safe and perform satisfactorily.

ii. **On bridge model updating research outputs**

   One of the main goals of bridge model updating in current research is to perform damage detection through detecting a local reduction in structural stiffness.

   (a) Regarding the performance of damage detection using the model updating approach (i.e. detecting a local stiffness reduction by solving an ‘inverse problem’), one key feedback raised by some expert bridge professionals (C2, C6, C11, C13 and C14) was that there is a doubt on whether this approach can detect any actual damage of concern in a reliable and adoptable manner. Take corrosion of steel reinforcement bars as an example. This common type of damage mainly affects yield strength of steel rather than stiffness of the section. If this approach is to detect early stages of corrosion (e.g. 5% loss of section), the effect of reinforcement corrosion on reduction in structural stiffness may be negligible and therefore the damage may not be detected. The level of sensitivity of the sensor data to structural damage was also cast in doubt by some interviewees. On the other hand, if this approach is to detect more severe concrete corrosion and section losses, these are likely to be detected first from visual signs (e.g. signs of rust staining on the soffit of the structure) before any detectable change from bridge SHM and model updating occurs, so visual inspection may be a much more cost-effective method in this scenario based on the practitioners' views.

(b) In addition, bridge modelling in current practice is largely, if not solely, driven by capacity assessment rather than damage detection. The majority of interviewees are more interested in the actual capacity of their bridge assets and how structural damage affects bridge capacity, rather than damage detection alone.

(c) Other areas of interest mentioned by some interviewees include: (i) better understanding of real structural behaviour and the underlying causes of any structural damage or anomalous structural behaviour (C4, C9, C14); (ii) the use of reduced safety factors or load models in bridge assessment (C2, C11, C16) (an example of an industry approach is provided in Enevoldsen, 2001); and (iii) boundary condition (C2, C11).

3.6. Key gaps in capability in bridge condition appraisal

Overall, based on all interviewees' responses, bridge owners and operators in the U.K. are mostly interested in four areas:

i. Is the bridge safe? (i.e. margin of safety)
ii. How long will the bridge or bridge component remain safe? (i.e. remaining service life)
iii. What is happening with the bridge? (i.e. real structural behaviour and performance)
iv. When and how to intervene? (i.e. optimal maintenance routines)

Based on all interviewees' responses, five categories of capabilities in bridge condition appraisal were derived, which can be useful to bridge O&M. These are: (i) Damage detection, (ii) Damage criticality evaluation, (iii) Reserve load capacity assessment, (iv) Remaining service life prediction, and (v) 'What-if' scenarios simulation. These are summarised and described in more details in Table 8. It should be noted that while these are some common areas of interest, the specific capabilities required often depend heavily on the individual bridge structures and specific cases.

[Table 8 near here]

4. Literature survey

4.1. Overview of academic research on model updating of bridges in operation

A total of 96 journal papers were identified using the methodology described in Section 2.2. It should be noted that while these may not provide full coverage of all relevant papers, they provide a good representation of existing research studies in this field. Figure 2 shows the number of papers collected by year of publication. It can be seen that as bridge SHM technologies and model updating techniques have developed, more research papers have been published in this field over the years.

[Figure 2 near here]

Based on the surveyed literature and the issues and questions raised in the industry interviews, six overarching questions for bridge model updating have been identified. These are the decisions that need to be made when implementing bridge model updating in practice.

- i. How to construct an appropriate model for updating?
- ii. What model properties should be updated?
- iii. What monitoring data can be utilised?
- iv. What model updating technique should be used?
- v. How to verify and validate the updated model?
- vi. What information can be extracted from the updated model?

The answers to these six questions may depend on the exact end applications, and therefore there may not be a one-size-fits-all strategy for bridge model updating. Details of the surveyed journal papers based on these six questions are provided in the Supplemental Material. The findings of the literature survey are summarised as follows under these six questions.

4.2. Bridge model updating methodologies

4.2.1. How to construct an appropriate model for updating?

A bridge design FE model is established under ideal and simplified conditions, e.g. rigid joints, homogeneous material, perfect alignment. The idealised model may serve as a baseline for engineering design. However, it has been found to be challenging to generate an appropriate bridge model for the purposes of performing model updating and supporting bridge O&M. On the one hand, the model needs to be sophisticated enough to describe the structural behaviour or diagnose structural damage. On the other hand, the model also needs to be sufficiently simple so that the model updating inverse problem is well-posed. To develop an appropriate model is a multiplex decision to make and depends on many factors such as the monitoring data collected and the exact end applications.

Overall, it has been found that this question is not often explicitly addressed in the surveyed literature. Some early research on bridge model updating using measurements of dynamic properties found that for the updated model parameters to be physically meaningful, the fidelity of the initial model should be sufficiently high (Brownjohn & Xia, 2000; Xu & Xia, 2012). Different types of model with different model fidelities have been attempted in existing research, for example:

- 2D vs 3D (most research uses a 3D model; examples of using a 2D model: Bentz & Hoult, 2017; Okasha, Frangopol, & Orcesi, 2012)
- linear vs nonlinear (most research uses a linear model; examples of using a nonlinear model: Ding, Hao, Xia, & Deeks, 2012; Okasha et al., 2012)
- multi-scale or hybrid model (e.g. Zhu, Xu, & Xiao, 2015)
- surrogate model (e.g. Xiao, Xu, & Zhu, 2015)

Meanwhile, there has been an increasing amount of research on the selection of model class (Kontoroupi & Smyth, 2017; Yuen, Kuok, & Dong, 2019), although this has not often been applied in the surveyed bridge model updating studies.

4.2.2. What model properties should be updated?

The discrepancy between model predictions and sensor measurements for a bridge may be the result of a combination of different sources of uncertainty. These are discussed and summarised in a number of papers (Goulet, Kripakaran, & Smith, 2010; Mottershead, Link, & Friswell, 2011; Simoen, De Roeck, & Lombaert, 2015). Table 9 provides a summary of these uncertainties.

[Table 9 near here]

Based on the surveyed literature, it is common practice to minimise model structure uncertainties first (specifically, select the appropriate model type or model class: e.g. which structural components or details to be included, boundary condition, element type, mesh size) to prepare the initial model for bridge model updating. Data uncertainties also need to be addressed (e.g. data cleansing, data synchronisation, data de-trending) before model updating. Currently, these are achieved primarily by manual examination of design and modelling assumptions, initial data interpretation and engineering judgement (e.g. Bentz & Hoult, 2017; Ding & Li, 2008; Goulet et al., 2010).

Existing model updating techniques mainly deal with uncertain model parameters. In terms of selecting which parameters to update, a large number of papers adopted the general principle given in Brownjohn, Xia, Hao and Xia (2001) which states that the selected parameters should satisfy two conditions: (i) their values must be uncertain; and (ii) changes of the monitored output response should be sufficiently sensitive to changes in these parameters. In many cases, a parametric study (i.e. sensitivity analysis) is performed to assist in the selection of updating parameters.

4.2.3. What monitoring data can be utilised?

'*What should be measured and why?*' is a fundamental question raised by many bridge practitioners for bridge SHM. The answer to this question depends on how the SHM data would be interpreted to extract useful information once it is collected.

Overall, there are two types of measured bridge response or properties which are most commonly used in the surveyed bridge model updating studies. One is to use identified modal properties (e.g. modal frequency, mode shape) from the dynamic response, typically obtained using accelerometer data, under ambient or forced vibration tests (e.g. Brownjohn & Xia, 2000; Xu & Xia, 2012). Real time operational data may be used under ambient vibration tests with minimal traffic disruption. However, as modal properties represent the global condition of a structure, they have generally been found to be relatively insensitive to localised structural change or damage (Xu & Xia, 2012). The other is to use strain or displacement data under controlled load tests (e.g. Okasha et al., 2012; Xiao et al., 2015) where the loading can be measured with relatively high accuracy. However, controlled load tests would either require bridge closure and thus cause traffic disruption or need to be performed prior to bridge opening. In addition, a few studies use geometry-based model updating for masonry arch bridges. This uses geometry measurement (e.g. laser scanning for arch geometry) to evaluate permanent deformation and thus to inform the underlying deformation mechanism and detect structural damage (e.g. Conde, Eguía, Stavroulakis, & Granada, 2018).

There are two additional challenges when interpreting bridge SHM data: (i) data quality, and in particular, whether the sensor data is sufficiently sensitive to detect any structural change or damage of interest; and (ii) it may be difficult to distinguish between the effects due to changes of environmental or operational conditions and the effects due to physical changes of the bridge (Farrar & Worden, 2012; Ni, Wang, Chen, & Ko, 2007; Vagnoli et al., 2018).

Figure 3 shows the number of collected papers based on the monitoring data utilised. It can be seen that the majority of the existing research is based on modal properties under vibration tests, although recently there have been more attempts of using strain or displacement response under load tests.

[Figure 3 near here]

4.2.4. What model updating technique should be used?

Based on the surveyed literature, the model updating techniques can be categorised into four main groups: manual tuning, residual minimisation, Bayesian model updating, and error-domain model falsification. A brief description is provided for each group as follows:

i. **Manual tuning**: This type of approach involves selecting and updating model parameters based on engineering knowledge, judgement and experience as well as in-field monitoring data. Other sources of information may also be used, such as visual examination and material testing. Iterative trial-and-error processes may often be involved to refine the model. Example applications include Bentz and Hoult (2017) and Daniell and Macdonald (2007).

ii. **Residual minimisation**: This type of approach involves framing the model updating problem as a multi-variate deterministic optimisation problem to optimise the model parameters. Constrained optimisation is often used to ensure the updated model does not lose physical meaning. The objective function is some measure of discrepancy between model predictions and sensor measurements of structural response. In the case where more than one type of structural response data is used, a weighted sum of the discrepancies for these structural responses is commonly used. Detailed work flow and example applications can be found in Brownjohn et al. (2001) and Živanović, Pavic and Reynolds (2007).

iii. **Bayesian model updating**: The updating procedure of the Bayesian approach is developed based on Bayes' theorem: *posterior probability density function (pdf) = prior pdf* × *likelihood function / (integral of prior pdf* × *likelihood function over the entire parameter space)*. In the context of model updating: *p(model parameter* | *data) = p(model parameter)* × *p (data* | *model parameter) / p(data)*. The prior probability density function shows the prior information of the uncertain model parameters without using the SHM data, and the likelihood function reflects the information extracted from the SHM data. The Bayesian approach provides not only the optimal estimates but also the quantification of estimation uncertainty in the form of probability distribution. The theoretical framework and an example application can be found in Beck and Katafygiotis (1998) and Jang and Smyth (2017), respectively.

iv. **Error-domain model falsification**: This type of approach involves first generating a pool of candidate models with all possible input parameter values and then falsifying the models from this pool by performing a threshold check on the discrepancy between model predictions and sensor measurements. The threshold value is set based on the sum of the effects from multiple sources of modelling errors and data errors. The objective is to narrow down the number of candidate models as new monitoring data becomes available. Detailed work flow and example applications can be found in Goulet et al. (2010) and Goulet & Smith (2013).

More recently, there has also been research involving the use of machine learning based techniques (e.g. Gaussian processes, neural networks) in bridge model updating (e.g. Gokce, Catbas, Gul, & Frangopol, 2013; Hasançebi & Dumlupınar, 2013; Soyoz & Feng, 2009; Yin & Zhu, 2019) to identify model parameter values by incorporating a data-driven approach. The data-driven approach is used to characterise the relationship between output model response or properties of interest and relevant input model parameters.

Figure 4 shows the number of collected papers based on the main model updating technique used. Some research used a combination of more than one technique, in which case the main technique used is chosen for categorisation purpose. Manual tuning is sometimes applied as a prior step to automated model updating in order to generate an appropriate initial model for further updating. A typical example is the identification of appropriate boundary fixities (e.g. Bentz & Hoult, 2017; Okasha et al., 2012; Robert-Nicoud, Raphael, Burdet, & Smith, 2005). Overall, it can be seen that the majority of existing research is on automated model updating techniques. Of the three automated techniques, residual minimisation is most commonly adopted, and recently there has been more applications of other automated techniques for bridge model updating.

[Figure 4 near here]

4.2.5. How to verify and validate the updated model?

Based on the surveyed literature, there are two main methods for verifying and validating the updated bridge model. One is to use other measurement data (e.g. structural response at other locations, other types of structural response, material properties from material testing) to test whether there is a close match between the predictions of the updated model and these other measurements. The other is mainly based on engineering interpretation and judgement (i.e. physical explanation) to evaluate whether the associated structural changes based on the bridge model updating make engineering sense. Other methods mentioned in the surveyed literature include checking convergence by updating perturbed models (James M. W. Brownjohn et al., 2001) and comparison with results from other model updating techniques (Weng, Xia, Xu, & Zhu, 2011).

One question which has not been properly addressed yet is whether the updated model, if it were to be used for making predictions, is valid for other loading scenarios and ambient conditions of interest. For example, a model updated using monitoring data under small load cases (e.g. normal traffic loading, normal weather conditions) is not necessarily valid for extreme load cases (e.g. severe wind loading, earthquake loading).

Figure 5 shows the percentage of each model verification and validation method adopted in the surveyed literature. It can be seen that the majority of these studies have not specifically mentioned model verification and validation. Around a third of the papers used other measurement data, and engineering interpretation and judgement is not very often used.

[Figure 5 near here]

4.3. Bridge model updating outputs

Based on the surveyed literature and industry interviews, five potential capabilities, which are related to bridge monitoring and model updating and can be useful to bridge O&M (particularly bridge condition appraisal), have been identified. These are: (i) Damage detection; (ii) Damage criticality evaluation; (iii) Load capacity assessment; (iv) Remaining service life prediction; and (v) ‘What-if’ scenarios simulation. The surveyed papers were examined to identify the information extracted from bridge model updating based on these five categories. Figure 6 shows the percentage of each category of information extracted from the surveyed bridge model updating exercises. Some research had more than one type of output information, in which case the main type is chosen for categorisation purpose. It can be seen that of the papers which specified the outputs of model updating for bridge O&M, the two most common ones are damage detection and load capacity assessment. Some research coupled model updating with other analyses such as reliability analysis (e.g. Gokce et al., 2013; Okasha et al., 2012) and fragility functions (e.g. Li, Spencer, & Elnashai, 2013). The surveyed papers on remaining service life prediction and damage criticality evaluation are based on fatigue analysis of critical bridge elements (e.g. Lee & Cho, 2016; Pasquier, Goulet, Acevedo, & Smith, 2014).

As for damage detection, the majority of the surveyed model updating studies on this topic rely on the assumption that localised damage results in a local reduction in stiffness, which can then be detected from sufficient change of structural behaviour. Some research did not specify the exact type of damage that can be detected. Others investigated specific types of bridge damage, which include:

- Boundary condition: e.g. pier settlement (Teughels & De Roeck, 2004), support stiffness reduction due to scour (Garcia-Palencia, Santini-Bell, Sipple, & Sanayei, 2015)
- Significant section loss: e.g. introduced torch cuts to girders (Perera & Ruiz, 2008), steel corrosion of steel truss bridges (Jang, Li, & Spencer, 2013)
- Cable damage (e.g. cable slack) of cable-stayed bridges (Degrauwe, De Roeck, & Lombaert, 2009)
- Crack pattern of masonry arch bridges (Conde et al., 2018)

The majority of the surveyed studies, especially early ones, used modal frequencies and mode shapes to perform model updating and damage detection, which were generally not sensitive to local damage. Recently, there have been attempts of using potentially more damage sensitive features or measurements such as damping (Mustafa, Matsumoto, & Yamaguchi, 2018), mid-span displacement and strain (Jesus et al., 2019).

As for capacity assessment, the surveyed studies investigated a number of assumptions typically made in bridge assessment, which include:

- Boundary condition (Bentz & Hoult, 2017; Brownjohn, Moyo, Omenzetter, & Lu, 2003; Gokce et al., 2013; Goulet et al., 2010)
- Contribution of secondary elements: e.g. guardrails and safety curbs (Brownjohn et al., 2003; Goulet et al., 2010; Sanayei, Phelps, Sipple, Bell, & Brenner, 2012), fill materials of masonry arch bridges (Conde, Ramos, Oliveira, Riveiro, & Solla, 2017)
- Material stiffness (Bentz & Hoult, 2017; Conde et al., 2017; Goulet et al., 2010)
- Geometry of masonry arch bridges (Conde et al., 2017)

In addition, load testing is sometimes used to facilitate bridge assessment (Bentz & Hoult, 2017; Sanayei et al., 2012; Zhou et al., 2012).

[Figure 6 near here]

5. Key findings and recommendations

5.1. Disconnects between research and practice

Based on the results of both industry interviews and literature survey, the disconnects between research and practice were identified and examined under two categories: (i) Disconnects between research outputs from bridge model updating studies and industry needs in bridge O&M; and (ii) Disconnects between research methodologies of bridge model updating and the industry's approach to bridge condition appraisal.

The disconnects between research outputs and industry needs are summarised as follows.

i. **On damage detection**

One of the key end objectives in bridge model updating research is to perform damage detection and assessment through detection of local reduction in structural stiffness. By examining the research outputs or results (refer to Section 4.3) based on the expert practitioners' views in this area, a number of key issues have been identified.

(a) Existing bridge model updating research for damage detection often assumes that localised damage results in a local reduction in stiffness, which can then be detected from sufficient change of structural behaviour. This may not be the case for many types of bridge damage such as corrosion of reinforcement bars inside concrete, which mainly affects yield strength of steel rather than elastic stiffness of the section under normal operating conditions (refer to Section 3.5 for more details).

(b) Based on the research outputs or results from the surveyed research studies (refer to Section 4.3), most bridge model updating research methodologies may not be able to specify the exact types of bridge damage that can be detected and whether there are certain types of bridge damage that may not be detected. In particular, there is little research on addressing those specific damage concerns that keep bridge practitioners awake at night (refer to Section 3.1 for more details). Therefore, it is difficult to evaluate the relative performance of damage detection by the model updating approach in research compared with that by the current visual inspection approach in industry. Key performance evaluation criteria of damage detection, summarised based on the expert practitioners' views (refer to Section 3.6), include: detection accuracy and reliability, capability of early detection, capability of detecting hidden defects cost-benefit analysis.

(c) In addition, based on the industry interviews, many bridge practitioners are more interested in the underlying cause of any identified damage and the criticality of each damage to structural integrity (i.e. how structural damage affects structural capacity) (refer to Section 3.6 for more details). These issues have not been adequately addressed in existing bridge model updating research for damage detection, which are of greater interest to many bridge practitioners than damage detection alone as they are critical for optimising maintenance actions.

ii. **On capacity assessment**

Based on the industry interviews, bridge practitioners are mainly interested in the margin of safety and structural integrity of their bridge assets, which are directly related to the actual bridge loading and load capacity. Moreover, structural modelling of bridges in the current framework of the U.K. industry is driven by capacity assessment (refer to Sections 3.2.2 and 3.3.2). A limited amount of research in bridge model updating has so far been focused on improving capacity assessment. Since bridge FE modelling for O&M purposes is costly and involves a great amount of effort in practice, it may be difficult to establish the value case for implementing bridge model updating purely for the purpose of damage detection. Key areas of interest for capacity assessment, based on the expert practitioners' feedback (refer to Sections 3.5 and 3.6), include: (i) how structural damage affects load capacity; (ii) real structural behaviour such as load path and load sharing behaviour; (iii) boundary condition; and (iv) the use of reduced safety factors or load models.

Regarding the disconnects between research methodologies (refer to Section 4.2) and industry practice (refer to Sections 3.2 and 3.3), there are many practical issues involved when implementing the research methodologies of bridge model updating in practice. These are described in more details in Section 3.4. In summary, these include: liability issue of keeping FE models, adaptability to future upgrade of software packages and computer system, reliability and futureproofing of the installed SHM system, FE model and SHM system ownership, cost-benefit analysis. In addition, FE modelling is rarely used in current bridge O&M practice and it is predominantly used in a reactive and one-off manner to address specific and known issues, while the academic vision of bridge 'digital twinning', which updates the model in near real time as new monitoring data becomes available, requires more frequent and proactive use of the analysis model in order to realise its value.

5.2. Recommendations for future research and deployment

In light of the identified disconnects between research and practice as well as key gaps in capability in bridge condition appraisal, recommended 'Research Questions' (RQs) are posed where additional research is needed in order to enable industry implementation of bridge model updating. These RQs are grouped under four categories: (i) confidence and interpretability, (ii) use case and usefulness, (iii) efficiency, and (iv) practicality. (i) and (ii) mainly address the disconnects between research outputs and industry needs, while (iii) and (iv) mainly address the disconnects between research methodologies and industry practice.

i. **On confidence and interpretability**

RQ1: *How can bridge model updating results be validated and presented in a way more intuitive and interpretable to bridge engineers (e.g. by improving the engineering knowledge and understanding of real structural behaviour)?*

Ultimately, better models give better predictions. The key difficulty lies in evaluating how much better the updated model is, and more specifically, the level of confidence in the updated model and its predictions. In order for bridge engineers to understand and appreciate the model updating results, more structural engineering interpretation (in particular, the underlying structural behaviour and the reasons behind change of structural behaviour) are needed in the model verification and validation processes. The issue of whether the updated model remains valid in a loading scenario different to the one used for the model updating process also needs to be addressed. In addition, machine learning based techniques may assist engineers with interpreting large and heterogeneous monitoring datasets by identifying patterns and correlations within these datasets.

ii. **On use case and usefulness**

RQ2: *How can bridge model updating be used to improve damage detection by addressing specific damage concerns which keep bridge practitioners awake at night (e.g. corrosion, fatigue, bearing and joint seizure, scour)?*

RQ3: *How can bridge model updating be used to improve capacity assessment by enabling less conservative assumptions in bridge assessment and/or addressing how structural damage affects load capacity?*

Based on the literature survey, it is not often clear what specific types of structural damage can be detected using the model updating approach and to what degree of sensitivity and reliability. The majority of bridge model updating research for damage detection has not been focused on addressing specific damage concerns of the bridge practitioners. More case studies on detection of specific bridge damage would be helpful in providing real evidence and thus improving confidence in the model updating approach. Future research should focus more on addressing specific structural issues and concerns (e.g. those identified in Section 3.1) as well as gaps in capability in bridge condition appraisal (refer to Section 3.6). Further investigation on relating detected structural damage to its impact on bridge capacity would also help establish the value case for implementing bridge model updating.

iii. **On efficiency**

RQ4: *How can bridge model updating be automated without losing engineering insight?*

Many bridge practitioners consider bridge modelling and model updating exercises as involving too much cost and effort and thus would rather not include it as part of their standard bridge management routine. Advanced computational tools, such as machine learning based techniques, may be used to improve automation and thus efficiency of data processing. The key challenge lies in achieving automation without losing engineering knowledge and interpretation, which needs to be addressed in future research.

iv. **On practicality**

RQ5: *How to address the identified practical issues (refer to Section 3.4 for more details) and thus establish the value case of implementing bridge model updating in industry practice?*

RQ6: *How to incorporate the academic research outcome of bridge model updating into practice to assist bridge engineers for more efficient and informed decision making in bridge O&M?*

There are many practical issues related to implementing bridge model updating for O&M purposes. These are identified and explained in Section 3.4 and need to be addressed in future research and deployment. In addition, recent technological developments such as the Internet of Things (IoT), cloud data storage and cloud-based analysis platforms may improve the integration of different sources of information to enable bridge engineers to make more informed decisions in an efficient manner. It may be realistic to ensure that, at least as the first step, the adoption of bridge model updating and 'digital twinning' is compatible with the existing bridge O&M practice by mapping out where it can assist and contribute to the current practice and address current issues and concerns.

6. Conclusions

With a growing need for better maintenance of bridges and growing research interests in developing bridge digital twins as digital representation of these bridges, it is important to examine existing research on bridge model updating and investigate how it can be implemented in practice to deliver value to industry. This paper identifies and examines the disconnects between academic research on bridge model updating and industry practice of bridge condition appraisal in bridge O&M. It consists of an extensive literature survey of bridge model updating research studies and a series of industry interviews with expert bridge professionals to enable targeted and in-depth analysis of implementing bridge monitoring, modelling and model updating for better maintenance of bridges.

In summary, the literature survey and industry interviews have revealed two overarching disconnects between research and practice in this field. These disconnects include:

1. Disconnects between research outputs from bridge model updating and industry needs in bridge O&M: The assumption that localised damage results in local reduction in stiffness is subject to question, as many common types of bridge damage may not induce noticeable change in structural stiffness that existing model updating techniques would identify. In addition, compared with damage detection, many bridge practitioners are more interested in bridge capacity assessment as well as real structural behaviour.
2. Disconnects between research methodologies of bridge model updating and the industry's approach to bridge condition appraisal: Bridge model updating is outside the current framework in which bridge practitioners operate. Structural modelling for bridge O&M in practice is driven by capacity assessment, and it is mostly a one-off exercise rather than a routine practice. There are also many practical issues, including cost, liability of keeping FE models and adaptability to future system upgrade.

Research questions are posed in this study for future research to address the following issues: (i) validation and interpretability of bridge model updating results, (ii) use cases for addressing specific damage concerns, (iii) relating structural damage to structural capacity, (iv) automation without losing engineering insight, (v) practical issues with implementing bridge model updating, and (vi) incorporation of bridge model updating into bridge O&M decision making process. It is recommended that these issues need to be addressed in order to foster future implementation of bridge model updating and ‘digital twinning’ and thus realise its potential value to industry.

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Table 1. Top grand challenges of bridge engineering and management identified by AASHTO and BOF.

No.	Grand challenge	
	Identified by AASHTO	**Identified by BOF**
1	Extend bridge service life	Prevent bridge failures
2	Assess bridge condition	Extend the life of existing structures

Table 2. Details of the interviewees.

	Interview	Role	Sector	Scope
C1	1	Highway sector lead	Highways	National
C2	2	Senior bridge engineer	Highways & Rail	Regional
C3	3	Principal structures advisor	Highways	National
C4	4	Principal engineer	Rail	National
C5	5	Head of bridge engineering	Highways & Rail	National
C6	6	Head of profession – bridges & structures	Highways	Local authority
C7	6	Project manager	Highways	Local authority
C8	7	Major bridge manager	Highways	Regional
C9	8	Independent consultant	Highways & Rail	Regional
C10	9	Independent consultant	Highways & Rail	Regional
C11	10	Professor (independent consultant)	Highways & Rail	National
C12	11	Professor (independent consultant)	Highways & Rail	National
C13	12	Head of profession	Highways & Rail	National
C14	13	Head of structures policy	Highways	Regional
C15	14	Instrumentation and monitoring lead	Highways	National
C16	15	Head of profession – structures	Highways	Regional
C17	16	Bridge master	Highways	Local authority
C18	17	Major bridges manager	Highways	Regional
C19	17	Technical director	Highways	Regional

Table 3. Most critical bridge components and structural issues identified in the U.K. bridge O&M activities.

	Description	**Examples and comments**
1	Material degradation, such as corrosion and fatigue	*(a) Corrosion of reinforcement bars or prestressing tendons embedded within concrete* • Currently very difficult to detect and quantify satisfactorily • No satisfactory remedial measures to treat concrete bridge corrosion in current practice *(b) Determination of yield strength of reinforcement bars in concrete bridges* • Directly related to structural integrity • Existing non-destructive testing (NDT) techniques are limited in their accuracy and reliability in estimating this property *(c) Fatigue prone steel structures* • The internal condition of steel box type structures is difficult to inspect • The length of weld to inspect on large bridges is significant
2	Joints and bearings	Joints and bearings are directly influenced by water management. It has been found that they often fail unexpectedly and well before the specified design service life in practice. *(a) Half-joints (for some bridges)* • Critical to structural integrity • Difficult to access and inspect *(b) Expansion joints* • Often fail unexpectedly • Its failure can induce build-up of local stresses and bending moments *(c) Bearing seizure* • Reduce the capacity for accommodating temperature and traffic load variations, and thus accelerate the failure of bearing components • Could lead to structural failure if the adjacent components are not originally designed for the induced local stresses and bending moments
3	Bridge scour	Scour is one of the most common causes of bridge failure worldwide (Wardhana & Hadipriono, 2003). • Currently difficult and sometimes dangerous to inspect for scour • There is often limited forewarning of impending failure and the consequence can be catastrophic (e.g. bridge collapse)
4	Other key issues	(a) *Concrete spalling* • Pose safety threats to people and live traffic underneath the bridge *(b) Bridge strike* • Pose immediate concern to structural integrity • Difficult to assess quickly and satisfactorily the structural condition after a bridge strike

Table 4. Two main ways for bridge damage detection in the U.K. practice.

	Method	**Description and comments**
1	Bridge inspection	Ongoing damage and deterioration of bridges are predominantly notified through standard inspection regimes and very rarely from monitoring systems. Routine visual inspection records should observe bridge defects, typically in terms of type, location, extent, severity, and possibly cause (based on engineering judgement and investigation) (Highways England, 2017). These current practices are not automated and do not provide notification of damage in real time. In addition, they rely on bridge inspectors to be competent and consistent in carrying out their inspections. Visual inspections have been found to be subjective and inconsistent (Highways England, 2011; Lea & Middleton, 2002), and hidden defects are particularly difficult to inspect.
2	Public reporting and other reporting	Another main source of bridge condition information comes from the general public, police or managing agents. For example, every single bridge of Network Rail in the U.K. has a telephone number for the public to call and report any observed damage or incidents (e.g. pieces of loose concrete, concrete falling off from the bridge, bridge strike).

Table 5. Three levels of bridge assessment in the U.K. practice.

Level	Description
I	Simple structural analysis methods, with conservative assumptions for material properties (i.e. using code values)
II	Refined structural analysis methods, such as non-linear or plastic analysis methods
III	Less conservative assumptions for material properties and bridge loading are used, based on measurements (e.g. material properties from testing samples, live traffic loading data)

Table 6. Examples of less conservative assumption used for Level III bridge assessment in the U.K.

Assumption	**Examples and comments**
Material properties	• These are obtained from material testing: e.g. compressive testing of concrete cores.
Section geometry	• This is obtained from measurement of dimensions: e.g. web thickness by electronic thickness gauge, arch barrel thickness by drawing cores and taking measurements, concrete cover by covermeters. • One key issue raised by many interviewees is the quantification of concrete corrosion, in particular, corrosion of reinforcement bars or prestressing tendons inside concrete. This is an important piece of information in bridge assessment and is difficult to obtain. The current practice for determining the remaining amount of reinforcement bars or prestressing tendons is by exposing them, performing visual inspection and where possible, measuring loss of section on specific sample areas.
Boundary conditions	• This is determined by visual examination of bearing and joint conditions. However, it is very difficult to quantify the stiffness and restraining effect of these components on the structural performance of the bridge.
Bridge loading	• Bridge-specific assessment live loading models (BSALL) are derived from load measurement data: e.g. weigh-in-motion (WIM) data. • Load testing may also be performed for some bridges.

Table 7. Examples of most common and useful type of bridge monitoring installation in the U.K. practice.

	Area of interest	**Examples and comments**
1	Wind and flooding	(a) Wind speed and direction are monitored using anemometers. Wind speed is used as a parameter for a threshold check, particularly for long span bridges. Certain actions (e.g. bridge closure, traffic restriction, special investigation) are triggered when the wind speed is above certain threshold value. However, threshold values are usually set based on historical experience and maintenance manual rather than scientific reasoning. (b) Flood level is monitored and used as another parameter for a threshold check where certain actions are triggered (e.g. bridge closure, scour assessment, assessment of impact of debris or water pressure uplift) when the flood level is above certain threshold value.
2	Bearing and joint movement	The main area of concern is to check whether the bearings or joints (e.g. expansion joints, saddles and anchorages of a suspension bridge) have their full range of movement as intended to accommodate the effects of variations in temperature and live load. Restricted movement indicates lock-up or seizure, which could have detrimental effects on the bridge structure. Temperature is often also monitored and correlated with bearing and joint movement data, which can then be used to investigate bearing and joint fixity (Webb et al., 2014).
3	Dynamic response	Monitoring of bridge dynamic response, such as global vibrations and bridge cable vibrations, has been used in some cases as a means of checking whether sufficient damping is in place to reduce fatigue problems and ensure serviceability, and thus inform whether extra damping is needed.
4	Wire breaks	Acoustic emission (AE) sensors have been used in certain limited cases to detect number of wire breaks in prestressing tendons or suspension bridge tendons. The data is used to perform a threshold check for maximum permissible number of wire breaks to maintain structural integrity and sustain traffic loading. The key challenge is to understand the pre-existing condition (i.e. number of wires left) before the monitoring system is installed.
5	Bridge loading	Weigh-in-motion sensors are used in some cases to monitor traffic loading for a threshold check (i.e. detecting over-weight vehicles) and for bridge assessment purposes (e.g. generation of a realistic live load model).
6	Others	Other useful monitoring activities mentioned by some interviewees include: tell-tales for monitoring crack width, extensometers for monitoring foundation movement, CCTV cameras for traffic monitoring, strain gauges at fatigue critical locations for assessing fatigue risks, and corrosion sensors for measuring corrosion status.

Table 8. Key gaps in capability in bridge condition appraisal in the U.K.

Capability type	**Comments and examples**
Damage detection	Some interviewees were not particularly interested in developing new capabilities for damage detection itself but are more interested in how damage affects capacity. Others were interested in targeted damage detection where there are specific issues with inspection. Specifically: • Early warning and detection of damage, particularly hidden defects • Real time detection of critical damage, particularly when the bridges are at remote sites and the bridge owner/operator has a large portfolio of bridge assets to manage In terms of specific damage types, these are summarised in Section 3.1.
Damage criticality evaluation	Evaluation of damage criticality is of great interest to many interviewees as it directly informs which damage should be intervened first from a large list of damage recorded. Examples include: • Which bearings should be replaced first when they may have similar appearance from the outside? • Which cracks should be refurbished first when there are numerous cracks on a bridge? • Which bridge components or details are most critical from a fatigue sensitivity point of view? • How to measure concrete durability of a bridge in a non-destructive manner? It has been found that it is often a key challenge for many bridge practitioners to identify the critical parts and the critical damage of their bridge structures.
Reserve load capacity estimation	The primary concern for all interviewees is structural safety, which depends directly on both bridge loading and load capacity. Load testing is sometimes used in practice to evaluate load capacity. • Some interviewees raised the issue that a stronger link between condition (e.g. damage and deterioration) and capacity needs to be established, as currently it is difficult to understand exactly how condition affects capacity.
Remaining service life prediction	Remaining service life is another key area of interest as it is particularly useful for optimising maintenance and refurbishment routines (specifically, '*when does a bridge component reach a state when intervention is needed and what sort of intervention is needed?*'). For example, many interviewees raised the issue that some bridge components, especially bearings and joints, tend to fail well before their specified design life and often in an unexpected manner. Commonly raised examples include: • Propagation of cracks over time • Durability model for concrete • Durability model for sliding materials such as bearings
'What-if' scenarios simulation	Some useful 'what-if' scenarios identified by the interviewees include: • Change of loading: e.g. additional traffic loading • Extreme events: e.g. extreme winds, successive extreme heat • Hypothetical damage scenarios: e.g. bearing seizure, bridge strike, concrete corrosion

Table 9. Key model and data uncertainties.

Model uncertainties		**Data uncertainties**
Model parameter uncertainties	**Model structure uncertainties**	
• Material properties • Section geometry • Boundary and continuity conditions • Operational and environmental loading	• Modelling assumptions and simplifications • Discretisation and approximations	• Random measurement noise • Systematic error due to faulty sensors, improper sensor installation or data transmission • Systematic error in data pre-processing • Validity of indirect measurement

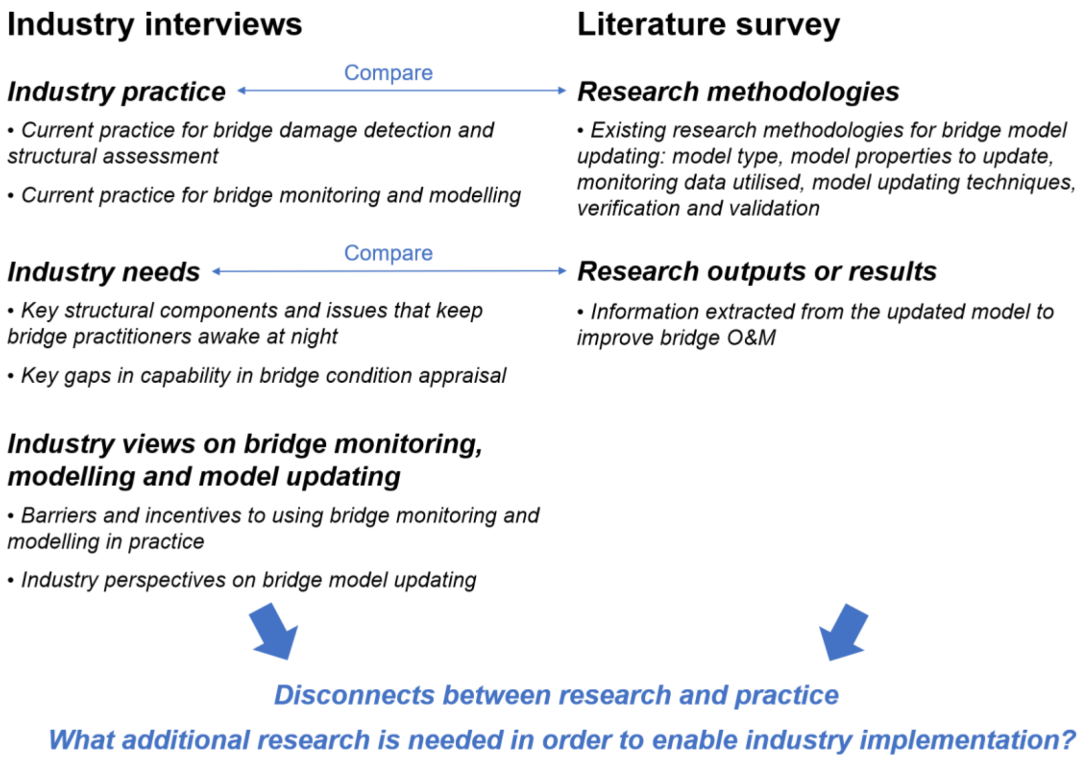


Figure 1. Overall workflow of this study.

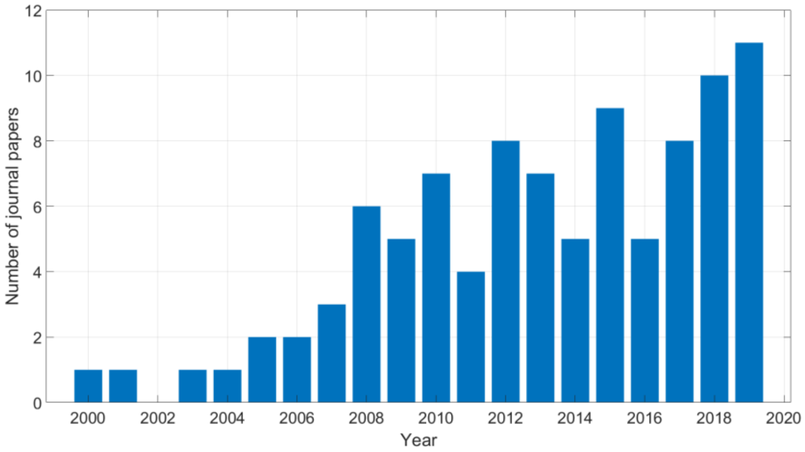


Figure 2. Number of collected journal papers per year on bridge model updating studies.

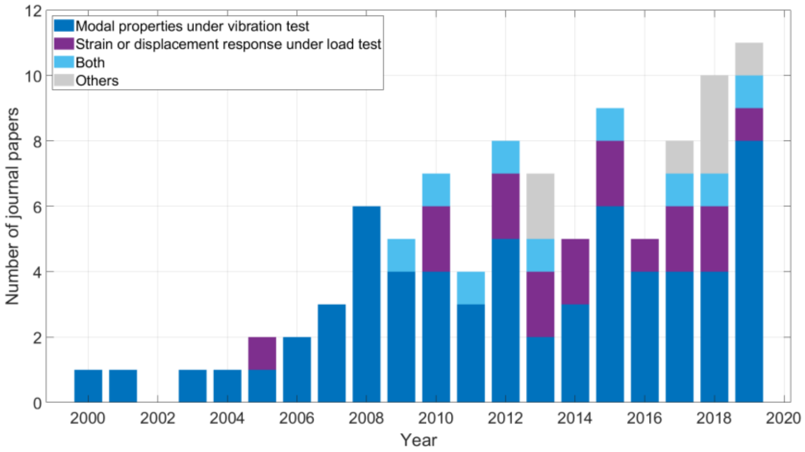
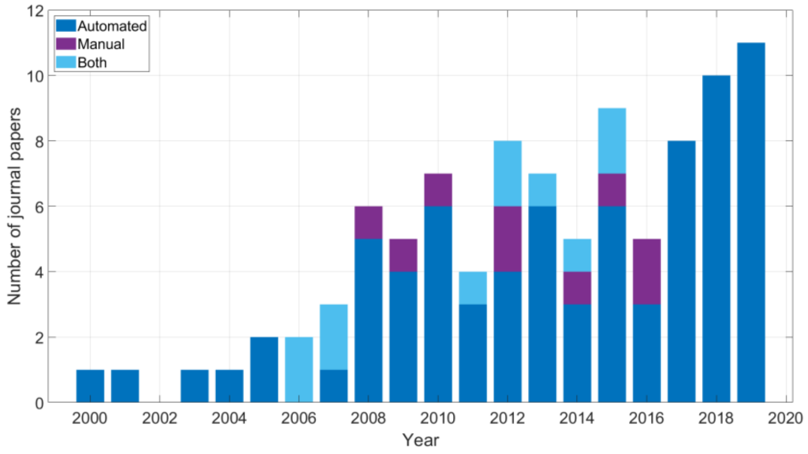
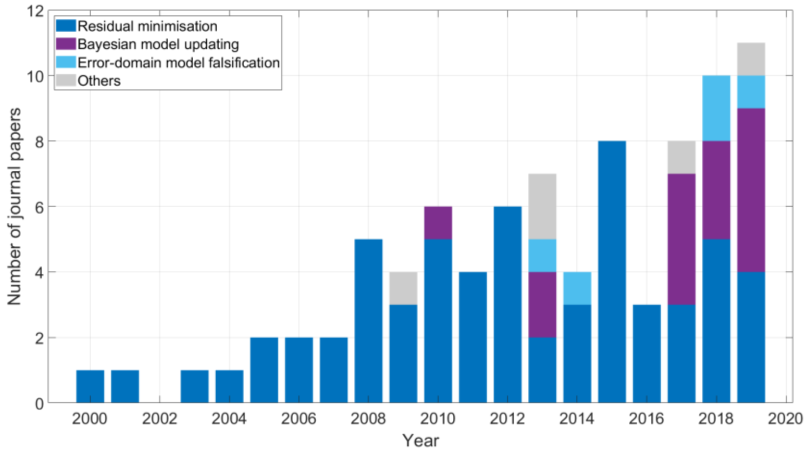


Figure 3. Number of collected papers per year based on the type of monitoring data utilised.



(a) Manual vs. automated



(b) Automated model updating techniques (based on the main technique used)

Figure 4. Number of collected papers per year based on the model updating technique.

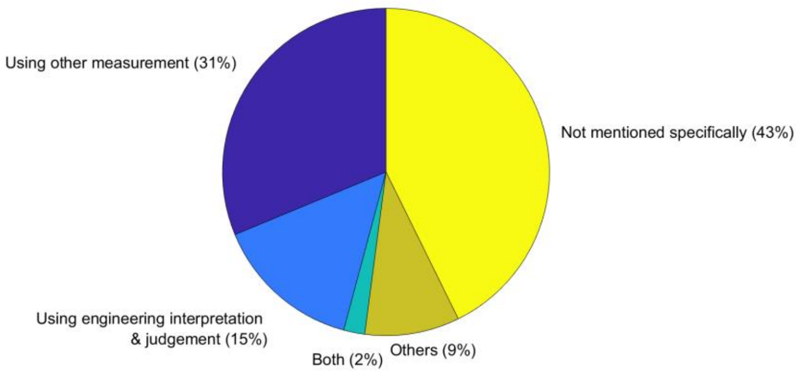


Figure 5. Percentage of each model verification and validation method adopted in the collected papers.

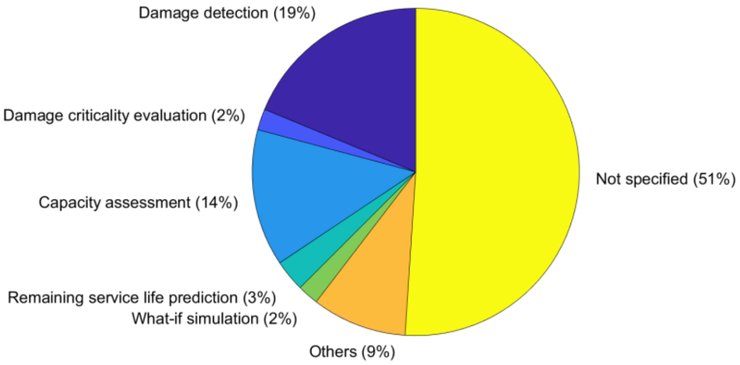


Figure 6. Percentage of each category of intended or actual bridge O&M related output from bridge model updating exercise in the collected papers.