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An architecture of lifecycle fatigue management of steel bridges driven by Digital Twin

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Abstract. The fatigue of steel bridges poses a great threat to their safety and functionality. However, current approaches for fatigue management are largely based on heuristic design philosophies, physical testing, and bridge managers' experience. This paper proposes a closed lifecycle fatigue management driven by Digital Twin for steel bridges. To provide clarity around the concept, the definition of Digital Twin for steel bridges is given at first. Then eight functional modules supporting Digital Twin are outlined in detail, aiming to provide a reference for the future development of Digital Twin in fatigue management. Finally, the implementation mechanism of Digital Twin is further described over different phases during the bridge lifecycle. This paper also identifies two main obstacles for the development of Digital Twin: i) the lack of understanding of steel bridge fatigue, and ii) the insufficiency of the present technologies.

Keywords: Digital Twin; bridge maintenance; fatigue life evaluation; lifecycle management; steel bridges

1. Introduction

Steel bridges are complex engineering systems consist of a large network of steel components connected by welded joints and high strength bolts, which are under the combined effect of stochastic loads like wind and vehicle, and various environmental factors like temperature and humidity (Zhu and Zhang 2018). The complicated internal structure characteristics and the coupled external influence factors make the prediction of steel bridge behaviors difficult.

Grieves and Vickers (2017) divides system behaviors into four categories, one being the Unpredicted Undesirable (UU) category that holds the potential for serious or catastrophic problems. In a new steel bridge system, its fatigue behaviors belong to the UU category, which are hard to predict and need to be placed great emphasis on. The application of cyclic stresses induced

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by external loads causes fatigue cracks to initiate at an unpredicted point of time and location. Those cracks may finally fail the entire bridge if they come into the stage of unstable propagation (Yu *et al*. 2011). More precisely, the fatigue problem brings up the need to answer three annoying questions: (1) Whether a newly designed steel bridge will crack in its designed service life? (2) When and where will fatigue cracks occur? (3) How long is the remaining fatigue life left for bridge managers to take corresponding maintenance measures? These three irritating questions are throughout the bridge lifecycle. Capabilities and methodologies to answer these questions are urgently needed by bridge designers and managers.

Steel bridge systems get the way they are by the progression through their lifecycle. The bridge lifecycle starts bridge design, takes on its physical attributes during the building phase, and then exists as a visible entity during its service phase when its fatigue behavior is the result of how the bridge system was designed and built. Since the fatigue problems are throughout the bridge lifecycle, a reliable lifecycle fatigue management may be capable of mitigating or even eliminating the concerned issue.

After decades of development, a set of fatigue design or evaluation methodologies have been proposed. The current fatigue management during the bridge lifecycle is depicted in Fig. 1. In the design phase, bridge designers do the fatigue design for the steel components mainly according to the government or professional society standards and handbooks, including British BS5400 specification (BS 5400-3 2000), American AASHTO specification (AASHTO LRFD-8 2017), and so on. These documents are rooted in decades-old experience with laboratory tests, bridge service histories, and in-suit tests. Some of the proposed fatigue design approaches are empirical-based or over-idealized (Ajmal and Mohammed 2018). For example, fatigue loading models are proposed to verify that the designed steel bridge has a correct fatigue lifetime, which guarantees fatigue cracks will not occur in the designed bridge service life. However, some of these models have been proven not able to provide an accurate estimate of the fatigue damage accumulation for a wide range of span lengths when compared with damage predicted using the weight-in-motion (WIM) database (Chotickai and Bowman 2006), which means the generality of these proposed loading models is challenged, and the verification result of the fatigue life needs to be questioned. The building phase comes after the bridge design has been completed. Unfortunately, this phase is often neglected in the traditional fatigue management of bridge systems, while some underlying factors, such as residual stresses induced by construction error and initial faults caused during the manufacturing process, do affect the fatigue behavior of bridge systems, and the influence laws

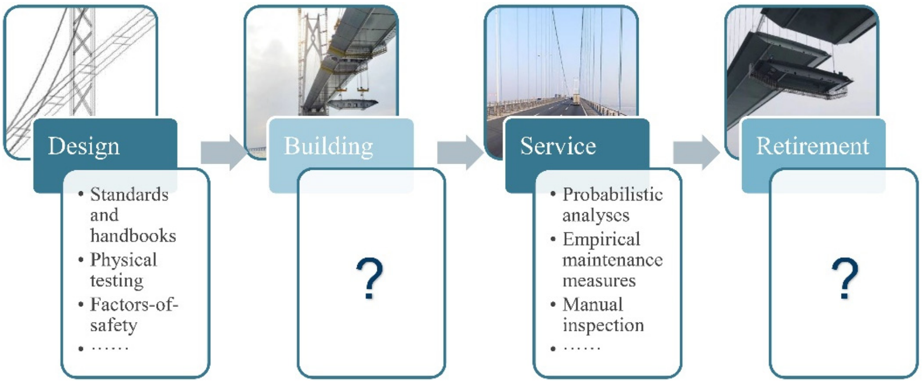

Fig. 1 Current fatigue management during steel bridge lifecycle

of these factors are still unknown and need to be further studied. During the service phase, more realistic data, such as strain from the bridge health monitoring (BHM) system or vehicle information recorded by the WIM system, is obtained, which is used to do fatigue analyses using probabilistic methods by many researchers (Cui *et al.* 2018, Lu *et al.* 2019). However, these current probabilistic and reliability analyses are inadequate because they are based on assumed similitude between the circumstances in which the underlying statistics were obtained and the environment in which the bridge operates. Additionally, many empirical maintenance measures such as the stop-hole approach (Yao *et al.* 2019) have been taken to mitigate the fatigue cracking during the service phase, but whether these measures may lead to reduced performance of steel bridges is still a question. With the increase of service life, part of those early built steel bridges come into the retirement phase. It is generally considered there is no relevance between the retirement phase and the bridge fatigue management, and this may be why there is little discussion of this phase in previous researches. However, this phase should attract our attention when considering its complete lifecycle data that provides bridge designers or managers with corresponding suggestions. Although the current fatigue management approaches are widely accepted, it has to be admitted that insufficiencies in current approaches make it hard to give a reliable answer to the three fatigue-related questions mentioned before.

This paper proposes a new concept for lifecycle fatigue management of steel bridges, called Digital Twin, that utilizes a virtual bridge system supported by eight functional modules to mirror the fatigue status of its corresponding physical bridge system. The paper outlines the Digital Twin concept for the fatigue management of steel bridges and then discusses in detail the function of each functional module. The implementation mechanism of Digital Twin is comprehensively described over different phases during the bridge lifecycle. The paper also addresses the possible obstacles to realize Digital Twin in the field of steel bridge fatigue.

2. Digital Twin concept and supporting modules

2.1 Digital Twin for fatigue management of steel bridges

The concept of Digital Twin was first introduced as a conceptual idea for product lifecycle management at a University of Michigan presentation to industry in 2002. This initial concept of Digital Twin, which was composed of real space, virtual space, and connected data or information that links real and virtual space, aims to realize a seamless connection between a physical system and its corresponding virtual system through its lifecycle (Cheng *et al.* 2020, Grieves and Vickers 2017).

Since it was proposed, Digital Twin has been applied in many fields. In the aerospace field, Digital Twin is used to predict the remaining life of an aircraft structure and guarantee its structural integrity (Tuegel *et al.* 2011). In the field of urban management, Digital Twin is proposed as a tool to do urban planning, real-time monitoring of environmental factors, and so on (Schrotter and Hürzeler 2020). In the medical field, Digital Twin is applied to personalized medicine, which has the potential to tailor healthcare to the anticipated responses of individual patients (Bruynseels *et al.* 2018).

Regardless of the multiple implementations of Digital Twin mentioned above, Digital Twin for the fatigue management of steel bridges may still be ambiguous. As shown in Fig. 2, according to the initial concept of Digital Twin, the authors define Digital Twin for the fatigue management of steel bridges as “a conceptual model consists of three parts: physical steel bridge system, virtual

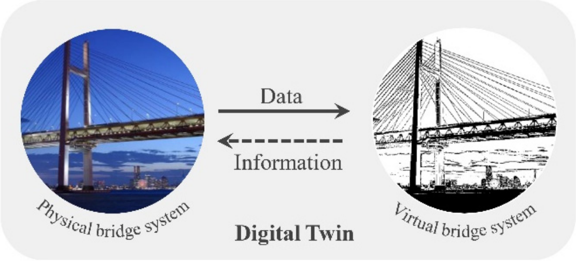

Fig. 2 Architecture of Digital Twin

steel bridge system, and connected data or information that links the physical and virtual system". In the fatigue management, Digital Twin uses the best available technology to realize a real-time mapping of physical bridges—virtual bridges containing all the information and knowledge, so that fatigue damage diagnosis and life prediction of steel bridges can be preciously performed, and then management decisions can be timely made.

2.2 Functional modules supporting Digital Twin

To specify the concept of Digital Twin and provide a reference for its future development in fatigue management of steel bridges, by referring to the general procedure for building Digital Twin proposed by Autiosalo *et al.* (2019), the authors further propose eight functional modules supporting the operation of Digital Twin, namely data link, coupling, simulation, analysis, artificial intelligence, user interface, computation, and data storage. The modules are arranged in star-structure, as shown in Fig. 3, and the specific function of each module is discussed as follows.

The data link (DL) module receives data from other modules, and then sends it to specific modules according to inter-service protocols. The module can realize high-efficient processing and interaction of massive multi-source data from all modules throughout the lifecycle of steel bridges. The existence of data link module enables the transformation of the communication type of different modules from the gird form to the star form (Autiosalo *et al.* 2019), which not only

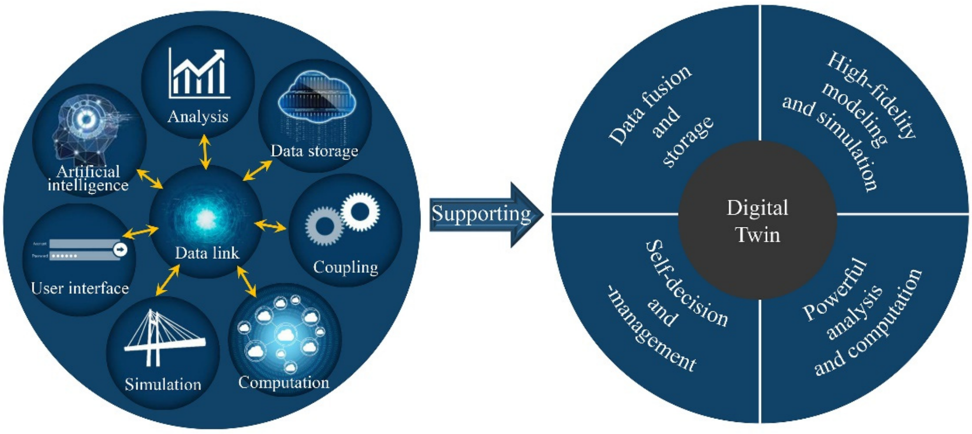

Fig. 3 Functional modules supporting Digital Twin

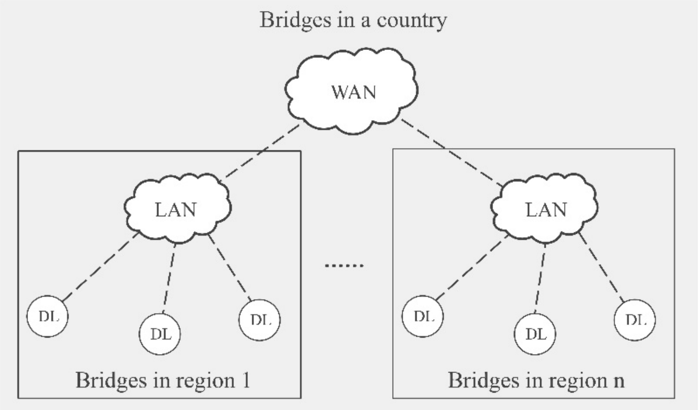

Fig. 4 DL connected network of Digital Twins

significantly lowers the number of connections, but also provides a single access point that enables the possibility of building a network of Digital Twins corresponding to different steel bridges located in a specific region or even in a country, as shown in Fig. 4, where WAN and LAN are wide and local area networks, respectively.

The coupling module provides a channel for real-time data interaction between the physical and virtual steel bridge systems. Through the coupling, the virtual system is updated continuously with the data provided by the physical system, such as the strain data from on-board BHM system, the vehicle information recorded by the WIM system, or the historical maintenance reports of the physical bridge. On the other hand, the physical system is redesigned or repaired according to the real-time information reported by the virtual system, such as the damage status, or the remaining life of fatigue details in the bridge. In fact, the most important function of this module is that it differs the bridge fatigue management driven by Digital Twin from that using the traditional approaches.

The simulation module incorporates a suite of ultra-high fidelity models of the physical bridge system and its external load systems. On the one hand, these models have a precious modeling of the as-built configuration of the bridge, including its structural configuration, physical length scale, material types, mesoscale or microscale material properties, material microstructure, fatigue defects, manufacturing anomalies, etc. (Glaessgen and Stargel 2012). On the other hand, the models accurately simulate physical behaviors of the bridge under multi-coupled external loads. More preciously, they may have the ability to simulate multi-scale fatigue crack growth under the complex dynamic interactions of vehicle-wind-bridge-temperature-etc. system during the bridge lifetime. Meanwhile, the degradation at the material, structural and system level throughout the bridge lifetime is considered in the models to return more reliable simulation results of the fatigue behaviors. In addition to the ability to do high-fidelity simulation, the simulation module can make timely adjustments to the models according to the data delivered by the coupling module and/or orders from the artificial intelligence module.

The analysis module is a fundamental tool to analyze the data from each module, such as the raw vehicle data delivered by the coupling module, the fatigue cracking results given by the simulation module, and so on. For example, through the analysis module, the distribution of the vehicle parameters like vehicle type, lateral position, etc., can be obtained through fitting analysis, and then the vehicle load spectrum can be output as the input of the simulation module by Monte

Carlo simulation or other probability methods, and finally, the fatigue reliability assessment of the concerned details is conducted using the output results of the simulation module (Cui *et al*. 2018). All the analysis results will be delivered to the artificial intelligence or user interface module for decision making.

The artificial intelligence (AI) module is rare in the implementations of Digital Twin. However, the requirement for intelligent features does exist in the practical application of Digital Twin (Mohammadi and Taylor 2017, Sierla *et al*. 2018). The AI module enables Digital Twin to be a self-active model that continuously updates the high-fidelity models, timely returns key fatigue maintenance information, intelligently provides suitable daily service plan that mitigates fatigue problems, and reliably gives hours or even days of warning to the bridge managers for emergencies. Considering the various stochastic factors that the steel bridge experiences during its lifetime, the AI module greatly reduces the burden of the bridge managers.

The user interface (UI) module is the medium of interaction and information exchange between Digital Twin and the users (Schroeder *et al*. 2016), which realizes the transformation of the fatigue information form from its internal form in Digital Twin to the acceptable form of the users. The goal of the UI module is to make the users monitor and/or operate Digital Twin conveniently and efficiently to achieve two-way interaction and complete the fatigue management work with full use of the hardware. The UI and AI modules supplement each other and support the operation of Digital Twin together. The AI module makes most of the decisions, which highly reduces the burden of the users. Meanwhile, the UI allows the users to supervise the AI and make decisions beyond the AI capabilities.

The computation module is the core of Digital Twin, which provides a very high-performance computation, far beyond what is currently used for fatigue analysis of steel bridges. The high-speed characteristic of this module ensures the fatigue simulation driven by Digital Twin can be consistent with the actual service of the steel bridge, that is, a 1-hour service can be simulated in 1-hour of clock time or less (Tuegel *et al*. 2011). The powerful computation lays a good foundation for the fatigue management of steel bridges, so as to conduct advanced fatigue design, predict precise fatigue remaining life, order effective fatigue maintenance measures, and send reliable fatigue-related warning messages.

The data storage module is a container of the massive amounts of information needed by Digital Twin, which has the features of large capacity, rugged reliability, easy and fast access. During the operation, huge sensor data, maintenance reports, historical simulation or analysis results, etc. are input into the storage module. With the continuous growth of these structured and unstructured data, as well as the diversification of data sources, the traditional procedures like the block- or file-based storage need to be modified, so that the data storage module can meet the needs of big data application.

Through the cooperation of the eight modules, Digital Twin has the ability to continuously forecast the possibility of fatigue cracking, the fatigue status including the crack location and initiation time, and the remaining fatigue life of the steel bridge, which correspondingly answers the three irritating fatigue-related questions throughout the steel bridge lifetime.

3. Implementation mechanism of Digital Twin

Much research work has been carried out to study the implementation of Digital Twin in product design and verification (Tao *et al*. 2019), product manufacturing (Cheng *et al*. 2020),

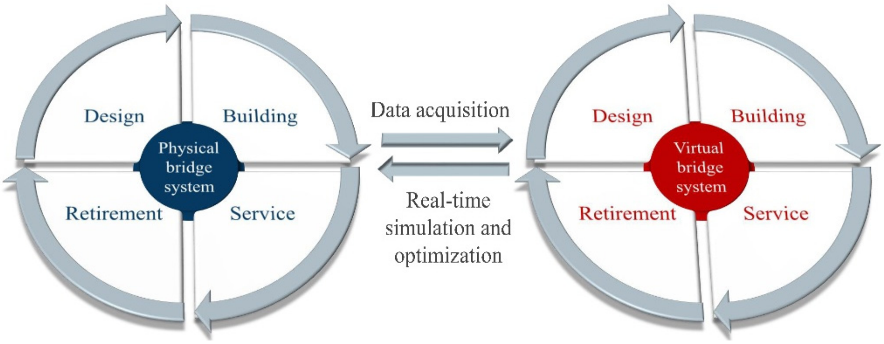

Fig. 5 Implementation of Digital Twin throughout steel bridge lifecycle

product service (Zakrajsek and Mall 2017), and product recycling (Wang and Wang 2019). Steel bridges can be treated as special engineering products. For these products, Digital Twin is a dynamic conceptual model that changes over the bridge lifecycle. The model emerges virtually in the design phase, takes physical form in the building phase, continues through the service phase, and is finally retired and disposed of (Grieves and Vickers 2017). Fig. 5 depicts the implementation of Digital Twin throughout the bridge lifecycle. To comprehensively understand the lifecycle fatigue management of steel bridges driven by Digital Twin, the implementation mechanism of Digital Twin in different phases is further described as follows.

3.1 Implementation mechanism in bridge design phase

In the design phase, the physical bridge does not yet exist, and the construction of Digital Twin mainly relies on the basic design parameters in blueprints. Besides, the closed-loop characteristic of the fatigue management (Fig. 5) also benefits the generating of Digital Twin in this phase, because it enables the recycling of the data from the bridge lifecycle, which enables Digital Twin to have full knowledge of how last-generation steel bridges have been operated and the condition of all structural components in terms of material state and fatigue damage distribution. As shown in Fig. 6, during the design phase, preliminary design, detailed design, and virtual verification are mainly considered. Firstly, the general layout, bridge type, and cross-section design of the bridge are discussed. Because a bridge is a complex and major project, various factors have to be considered, including the bridge location, the operation environment, the needed span length, the strength of available material, the building cost, and the beauty and harmony with the location. The historical knowledge generally helps the designers choose a better preliminary design scheme. Then, the detailed design, such as the selection of material, the configuration design of some important inner components or joints, is further conducted to ensure the bridge safety in terms of stiffness, strength, and stability of the whole bridge or each bridge components. It is also in the detailed design of steel bridges, the configuration of some critical fatigue details, such as the deck to U-rib welded joints or the U-rib to diaphragm welds in an orthotropic steel bridge decks, are adjusted to meet the requirement of fatigue resistance during the bridge lifetime. Finally, based on the existing data, Digital Twin provides a high-fidelity simulation for the virtual verification of the current design scheme. The vehicle-bridge-environment coupling system is erected and set to operate virtually through the bridge lifetime to estimate the possible fatigue vulnerable details, the crack initiation time, the remaining fatigue life, and/or the effect of fatigue cracks on the bridge

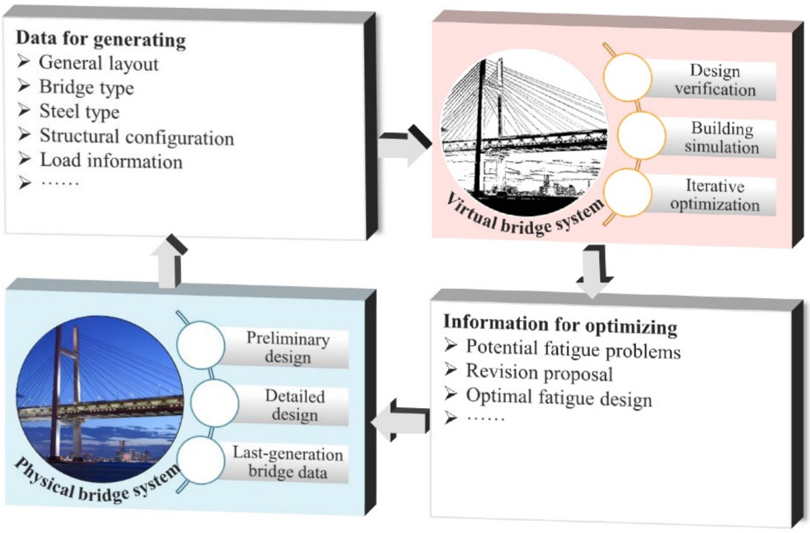

Fig. 6 Implementation of Digital Twin in the design phase

safety. Therefore, the fatigue reliability of some newly designed structures, such as the thickened edge U-ribs (Heng *et al*. 2019), the innovative rib-to-diaphragm detail (Zhang *et al*. 2018), etc. can be thoroughly analyzed using computer simulation, so as to save wasted physical resources and the time-consuming and costly production of testing prototypes. In addition, the bridge-building process is also simulated by Digital Twin. If the simulation result does not satisfy the design requirements, revisions will be conducted immediately, which highly reduces the construction errors caused by design mistakes, thereby lowering the uncertainties of fatigue inducements. The firm coupling between the virtual and physical space allows the optimal fatigue design of steel bridges. Through multiple iterations, the final bridge design scheme can be determined.

3.2 Implementation mechanism in bridge building phase

In the building phase, the bridge engineers start to build the physical bridge. Fig. 7 shows the implementation of Digital Twin in the bridge construction. With the help of Digital Twin, the engineers can fully understand the exact specification and makeup of the bridge components without having to consult a great deal of abstract design data. Moreover, bridge construction is very challenging, which usually requires the collaboration work of multiple engineering teams. Therefore, a unified blueprint, Digital Twin, enables the standardized bridge construction and avoids the construction errors that may cause local stress concentration, which will greatly improve the construction efficiency and quality, and shorten the project period and cost. During the building phase, pre-installed bridge construction monitoring devices will continuously record the real-time construction data, such as construction errors, construction environmental factors, and various types of residual stresses. These data about how the physical bridge was built is transmitted to the virtual bridge system through the coupling module, which timely refines Digital Twin, and finally, builds a virtual representation of the exact physical bridge system, so that reliable fatigue assessment of the steel bridge can be performed while considering various construction factors.

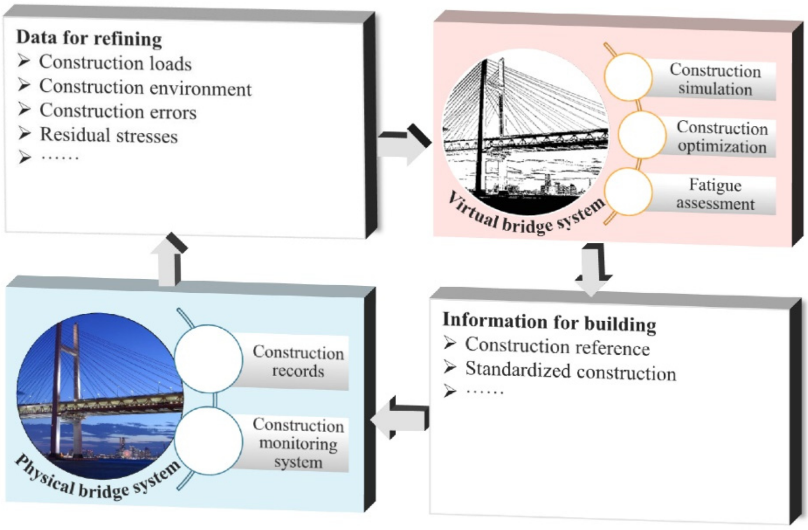

Fig. 7 Implementation of Digital Twin in the building phase

3.3 Implementation mechanism in bridge service phase

In the service phase, the physical and virtual bridge systems maintain their linkage. It is during this phase, the bridge managers find out whether the bridge designers eliminated the undesired fatigue problems. If the designers have done a good job to mitigate the risk of fatigue cracking, and the recycled service data from the last-generation bridge is suitable for the high-fidelity simulation in the design phase, then there will be a tiny risk of fatigue damage during the bridge service, but this is an idealized assumption after all. The facts are i) human brain has certain limitations for complex projects, and designers can not foresee and consider all the adverse conditions steel bridges may experience in the future, and ii) many external factors, such as the average daily traffic volume, change with the development of the regional economy, so there must be a big difference in the operation environment between the last-generation bridge and the contemporary bridge. Therefore, bridge fatigue should not be underestimated during the operation phase, and Digital Twin will continue to play an essential role in mitigating fatigue problems. As shown in Fig. 8, during the service phase, Digital Twin uses its on-board monitoring systems to update the simulation module and produces continuously refined predictions of bridge health and fatigue reliability of steel bridges. Before fatigue cracking, Digital Twin can be used to predict future fatigue status of the bridge, such as the fatigue cracking location, the crack initiation time, and the possible crack propagation path. After getting this information, fatigue optimization measures, like reducing the geometric mutation of welds by grinding treatment (Cao *et al*. 2019), reinforcing the bridge deck using ultra-high-performance concert layer (Yuan *et al*. 2019), and introducing favorable compressive residual stress into fatigue vulnerable details by hammer penning (Fu *et al*. 2018), will be taken correspondingly. After fatigue cracks have been observed in steel bridges, Digital Twin uses the crack parameters detected by the acoustic emission method (Leaman *et al*. 2020, Nowak *et al*. 2017) or the computer image recognition technology (Xu *et al*. 2019) to calibrate the fatigue crack growth simulation to further predict the remaining fatigue useful life of structural components and system. Accordingly, the bridge managers can take a series of fatigue maintenance measures, such as the stop-hole approach (Yao *et al*. 2019), the

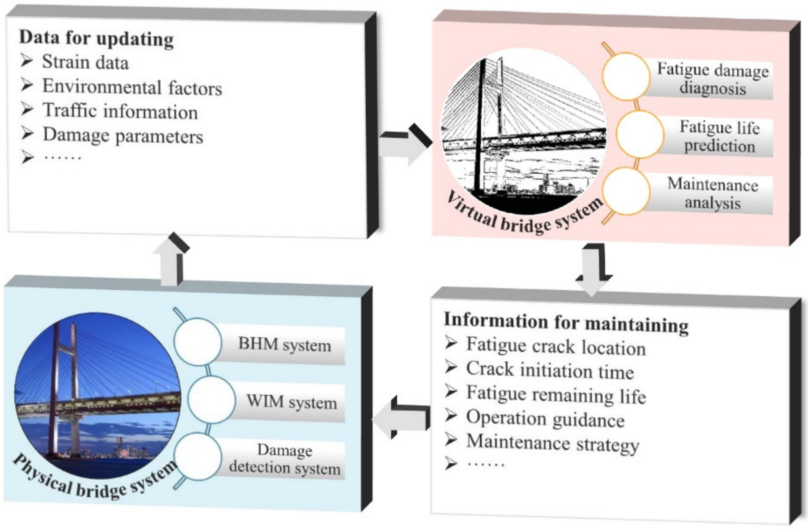

Fig. 8 Implementation of Digital Twin in the service phase

Crack-closure Retrofit technique (Zhiyuan *et al*. 2016), the re-welding method (Fu *et al*. 2017), and the carbon fiber reinforced patch (Karamloo *et al*. 2019). Thanks to the coupling module, changes to the physical bridge caused by fatigue maintenance will be reflected in Digital Twin accordingly, and then Digital Twin can do impact investigation to answer the questions regarding the impact of the maintenance measures on all future performance of steel bridges and the option for the best maintenance measure that effectively prevent the crack growth while hardly lowers the structural performance. Besides, Digital Twin can also analyze the influence of accidental loads, such as earthquakes, typhoons, and impacts, on the fatigue performance of steel bridges and issue a warning if necessary, so that necessary measures can be timely taken to ensure safety and normal operation of the bridge.

3.4 Implementation mechanism in bridge retirement phase

Fig. 9 presents the implementation of Digital Twin in the retirement phase. As mentioned earlier, the final phase, retirement, is often ignored as an actual phase. In the context of this topic, there are two reasons why the retirement phase should receive enough attention. The first is that the bridge retirement provides us with more comprehensive fatigue damage information. Researchers' understanding of the fatigue mechanism is often limited by the development of damage detection techniques. For example, the inner fatigue cracks of a closed U-rib are hard to be detected, which slows down the corresponding research and simulation. However, with the dismantling of the bridge, the former undetected fatigue damage is uncovered, and more vital fatigue-related information is obtained. This additional information will be recorded and further benefits the fatigue management driven by Digital Twin. Second, the abundant information deposited in this phase is of great significance to the disposal of the old steel bridge and the fatigue design of the next-generation steel bridge. While the steel bridge needs to be retired, owing to the large capacity of the storage module, the information through the bridge lifetime can be saved at little cost. The collection of information about how the bridge is built, operated and dismantled enables people to fully understand the fatigue status of all components, which not only facilitates

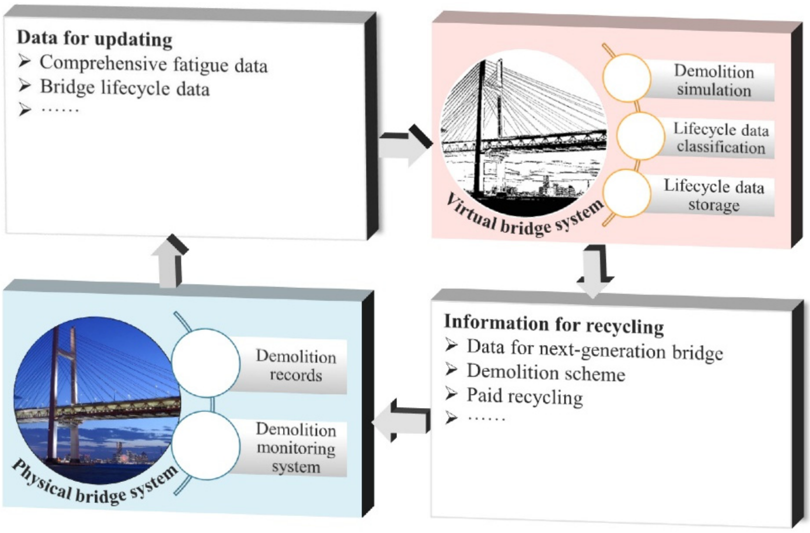

Fig. 9 Implementation of Digital Twin in the retirement phase

the disposal of old components but also earns capital income for the bridge management company. On the other hand, based on this information, Digital Twin can simulate all possible operating environments the next-generation bridges will experience, and then optimize the fatigue design to avoid most of the fatigue problems.

Digital Twin realizes real-time data fusion throughout the bridge lifetime, so as to build a one-to-one mapping between the virtual bridge system and its corresponding physical bridge. Based on the data fusion, corresponding design optimization, fatigue evaluation, maintenance support, etc. can be performed by Digital Twin. The implementation of Digital Twin provides closed fatigue management for steel bridges, which fully utilizes the available information and reduces the uncertainties during the fatigue management effectively.

Compared with the existing system constructed by Digital Twin, the Digital Twin-driven fatigue management system integrates the diversity of fatigue data throughout the bridge lifecycle and forms the close-loop characteristic enabling the recycling of historical fatigue information after the bridge retirement, which realizes intergenerational data fusion and provides great convenience for the design of new steel bridges.

4. Obstacles to Digital Twin

Currently, the implementation of Digital Twin mainly faces two obstacles: one is the lack of understanding of steel bridge fatigue, and the other is the insufficiency of the present technologies, as shown in Fig. 10.

The lack of understanding of steel bridge fatigue is mainly manifested in two aspects: fatigue mechanism and fatigue assessment. In the study of fatigue mechanism, researchers mainly focus on the fatigue degradation in the service phase, and only a set of specific fatigue factors are considered. For example, the comprehensive study on the coupling effect of fatigue and corrosion on a steel component with initial defects and welding residual stresses is rare. That is to say, the fatigue mechanism after fully considering the combined effect of multiple fatigue factors that

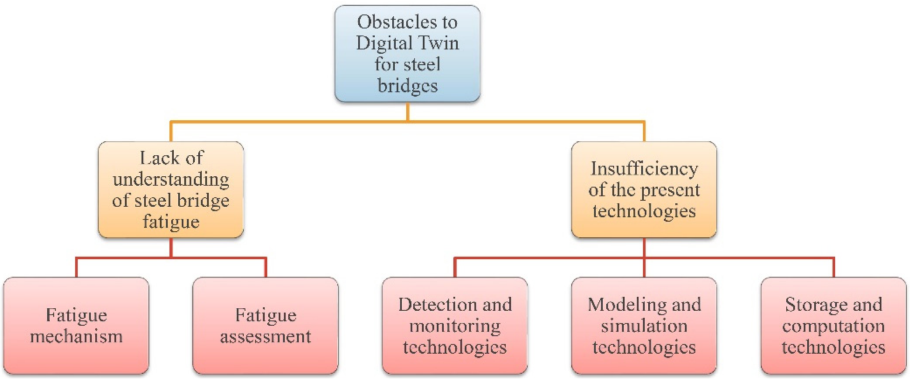

Fig. 10 Obstacles to Digital Twin for steel bridges

occur in each phase of the bridge lifecycle is still unknown. In the aspect of fatigue assessment, the S-N curve and fracture mechanics are usually used to evaluate the fatigue initiation life and the crack growth life, respectively (Wang *et al*. 2020, Zhu and Xiang 2019). However, the calculation results based on the S-N curve is very sensitive to the local geometry characteristics, which means the various geometry characteristics in steel bridges pose a great challenge to the versatility and reliability of the S-N curve. Besides, the accuracy of the evaluation results based on fracture mechanics highly depends on the parameters in the evaluation model, while the relevant parameters have great variability due to the external environment and the intrinsic material properties, which aggravates the discreteness of the results.

The insufficiency of the present technologies presents a very big obstacle to the implementation of Digital Twin. First, the current detection and monitoring of fatigue cracks in the steel bridge are mainly based on manual inspection. The high-intensity work and harsh site environment make the manual inspection not efficient enough to keep up with the update of Digital Twin, which means advanced detection and monitoring technologies should be put forward, including the high-reliability and high-sensitivity sensor technology, sensor layout, and co-measurement optimization technology, and low-latency communication technology (Cheng *et al*. 2020). Second, in the current fatigue analysis of steel bridges, the structural dynamic analysis, the thermodynamic analysis, the fatigue stress analysis, and the crack growth analysis are performed based on their own physical models, respectively. Information is passed between two analyses by writing the result from the former analysis to a file that can be read as input by the latter one. This process fails to develop a synchronized fatigue stress spectrum under the coupling effect of multi-physics (Tuegel *et al*. 2011). To realize the ultra-high fidelity simulation in Digital Twin, more advanced modeling and simulation technologies need to be developed, mainly including the multi-physics modeling technology, the multi-scale modeling technology, and the damage-stress coupling technology. In addition to the insufficient technologies mentioned above, the lack of high-performance storage and computation technologies also confines the development of Digital Twin. To achieve efficient processing and interaction of big data form the bridge lifecycle, computation and storage technologies like the new cloud service technology are urgently needed, mainly including the distributed and parallel computing technology and the high-performance, high-throughput, and large-capacity storage technology.

5. Conclusions

Since current approaches cannot meet the needs of fatigue maintenance of steel bridges, the Digital Twin-driven lifecycle fatigue management is presented, so as to revolutionize the fatigue maintenance pattern during the bridge lifecycle. The main contributions of this paper are concluded as follows. (1) A novel mode of fatigue management driven by Digital Twin towards steel bridges is proposed, and the concept and supporting modules of Digital Twin for steel bridges are outlined in detail. (2) The implementation mechanism of Digital Twin is discussed over four phases during the bridge lifetime: design, building, service, and retirement. (3) The obstacles for the development of Digital Twin are illustrated from two aspects: i) the lack of understanding of steel bridge fatigue, and ii) the insufficiency of the present technologies.

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