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Expanding BIM Use in Assessing Fatigue Evolution of Steel Railway Bridges

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Abstract

In recent years, there has been a rising demand to integrate digital technology into Transportation Infrastructure Management and Maintenance procedures, as the success of any industry today is inseparable from the current digital technological environment. In response to this demand, there is an increasing trend to expand the scope of application of Building Information Modeling (BIM), which is traditionally used for building projects, redirecting its uses to areas such as bridge management and maintenance. One of the subcategories within the spectrum of BIM Uses is asset monitoring during its operational phase. This work uses this basis to develop an experimental model that combines a Fatigue Analysis System and a BIM model of the bridge, to form a Digital Twin. The Digital Twin can characterise the evolution of fatigue damage at any bridge connection detail at any time. The Fatigue Analysis System comprises the Linear Accumulation Damage Method for determining fatigue damage and a finite element model, implemented in commercial software. The BIM model is developed from open-source resources, allowing greater flexibility in BIM object manipulation. The database, encompassing load and geometry conditions, updates continually the global model for fatigue damage assessment, and it shows promise for bridge lifecycle management.

Keywords: BIM uses, fatigue damage, Digital Twin, steel railway bridges, openBIM, IFC standard.

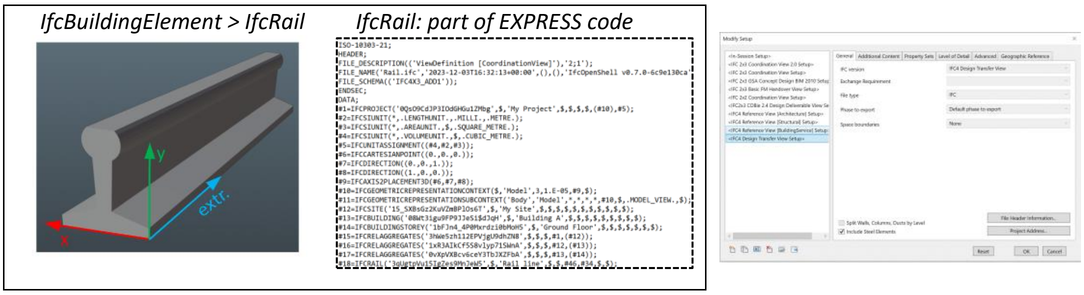
1 Introduction

Notable initiatives are currently being carried out by buildingSMART to extend BIM for linear infrastructures like roads, railways, and bridges. This entails the enlargement of standardised, object-oriented databases to include this type of infrastructure. Nonetheless, many obstacles remain to overcome when using BIM for these assets during the operation stages. This is primarily due to the lack of flexibility in the current model to handle information related to anomalies and structural behaviour over time [1]. The current BIM models realistically lack interoperable geometric components associated with various infrastructure defects. Notably, existing systems and methods of BIM modeling do not include compatible geometric features crucial for the management and operation of these structures, which relate to various infrastructure flaws. One of the most common anomalies in steel railway bridges (SRBs) is fatigue, mainly caused by trains passing over the infrastructure. This phenomenon is defined as the process of initiation and propagation of cracks in a structural member due to stress fluctuation [2]. The assessment and monitoring of this complex phenomenon may incorporate among others, the following information: prior inspection or preliminary analysis results on the state of a given structural element; and the analysis of results characterising the fatigue state of structural elements over time.

It is known that identifying damage in infrastructure such as bridges, particularly fatigue damage, is an important approach to assess the condition of these structures. However, information regarding this data can hardly be expressed (visualised, for example) in the infrastructure under consideration using traditional damage detection analysis methods [3]. In order to overcome this and other issues, BIM has been adopted in new domains. Currently, advancements and increased use in other infrastructures such as bridges and in railway systems have been observed [4]. This application extends beyond simple modelling to include infrastructure management, revealing the great potentiality of the technology [4, 5]. These potentialities are fundamentally demonstrated by digital representation (or visualisation) and the ability to integrate information [6, 7], both considered valuable for infrastructure management. However, the process of integrating information keeps raising debates, particularly regarding the type and scope of information to be integrated (for example, how the integrated information is visualised, etc.). Knowing the existence of BIM potentialities, a significant current challenge is to define processes that allow automatic and continuous BIM model enrichment with information about the state of assets, resulting in a Digital Twin (DT). This subject is addressed by various researchers (see, for instance, [8]). The efforts in this domain attempt to link BIM models with other parties that provide information, but there is no defined method or protocol to do it [8].

In light of these challenges, this study presents an approach for using BIM to assist in the evaluation of fatigue damage evolution in SRBs. Data-driven modelling strategies that employ open-source tools and automatic integration of information from numerical analysis and physical assets into the BIM model to create DT are emphasised. In the context of openBIM, open-source resources (IfcOpenShell +

Python + Blender) are explored for BIM modelling, with the most recent IFC standard (IFC4x3) currently under standardisation at ISO [9]. This IFC extension includes some entities related to bridges and railways (Figure 1a). Its integration in open-source for BIM modelling is a way of overcoming the current limitations of most commercial BIM platforms, which have not yet implemented this latest version of the IFC standard (Figure 1b). IfcOpenShell is a constantly updated library for accessing and manipulating open-format IFC files [10]. The fatigue numerical analyses are carried out using powerful numerical analysis and programming software, namely ANSYS APDL® and MATLAB®. The results of these analyses are used to feed the BIM model continuously.



(a) (b)

Figure 1: (a) IfcRail modelled parametrically from IFC4x3 using open-source resources (IfcOpenShell + Python + Blender); (b) Extract from a BIM platform, in one of the recent versions limited to IFC 4.0.

2 Methods

2.1 Fatigue Analysis System (FAS) and Bridge BIM Model

Concerning the main goal of this study, which is to continuously feed a BIM model with results from numerical fatigue analyses (and relevant information that may not come from the calculation), a Fatigue Analysis System (FAS) and a BIM model for the bridge are created separately for later integration. In this process,

a) FAS - consists of two parts. In the first part, a numerical model of the bridge is created to assess its dynamic or static properties using ANSYS APDL® software. In the second part, fatigue damage is computed using the Linear Accumulation Damage Method (LADM) [2] via MATLAB® programming (Figure 2). The output results of this phase include not only the fatigue damage but also the respective identification and location along the bridge, as well as the remaining fatigue life;

b) Bridge BIM model generation - The bridge BIM model, including railway elements, is generated using the approach outlined in Figure 3 and previously discussed. This process involves creating various elements (IfcBuildingElement) and then assembling them to form the entire model.

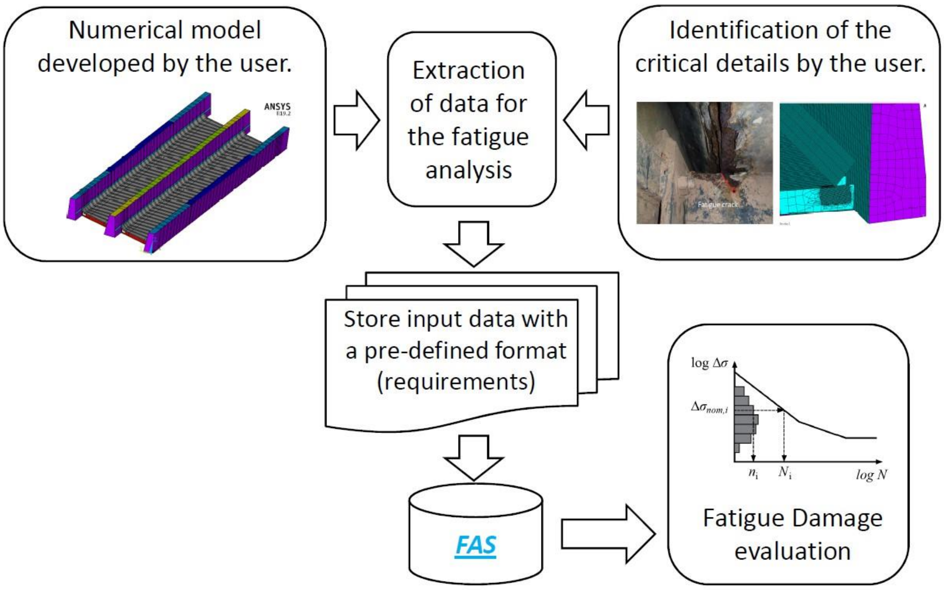


Figure 2: Overview of the Fatigue Analysis System (FAS).

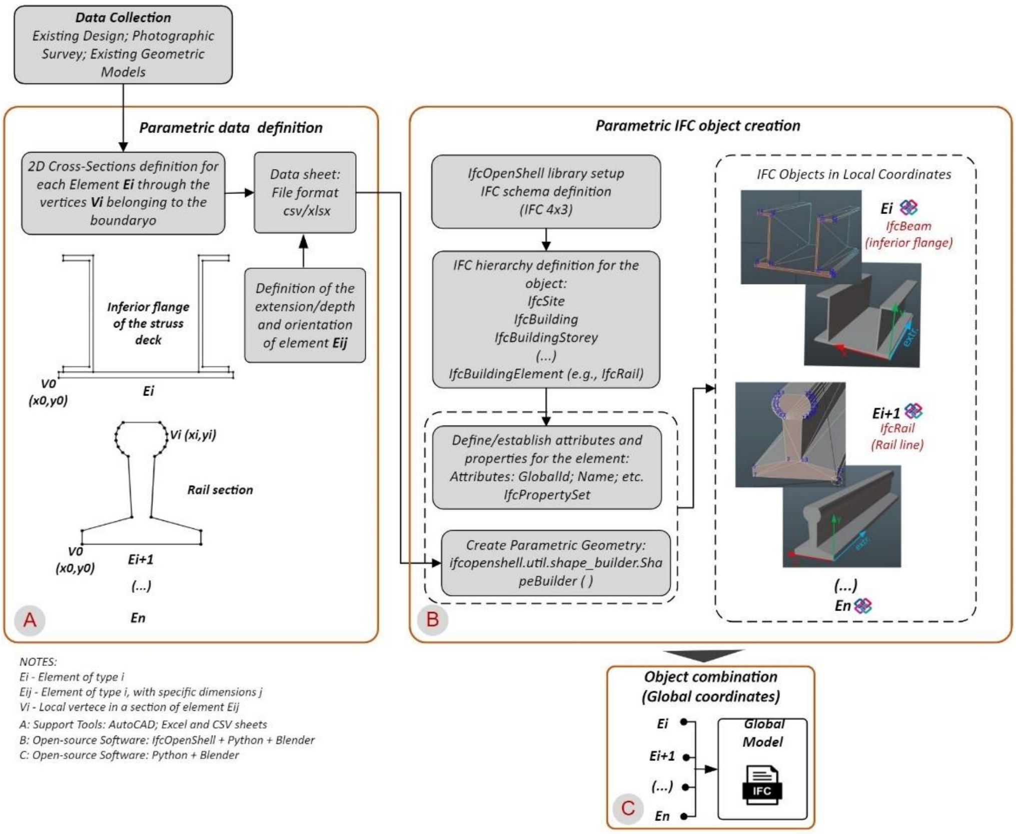


Figure 3: BIM model generation scheme for bridge and railway track.

The previously mentioned open-source resources are also proposed to model geometric representations of damage and to provide access to non-geometric information concerning damage in the BIM-based platform (Figure 4). Both the geometric representations of damage and the information query platform are empty until information about damage (or other information) is entered via the integration process (see subsection 2.2).

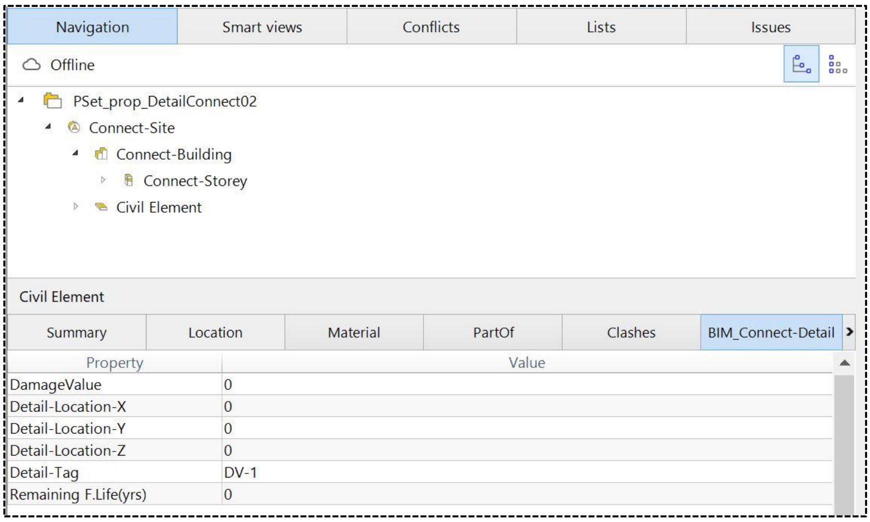


Figure 4: Platform for non-geometric information querying concerning damage at a specific connection detail.

2.2 Integration Process FAS - Bridge BIM Model

This study proposes creating the FAS separate from the BIM model, considering the complexity of each part. In the first stage, the two parts are independent, but they later become dependent when the link is established. Figure 5 illustrates the connection and interaction process comprised of two main branches:

a) Branch 1- This is a direct process in which information from the fatigue analysis results (damage value, identification, location, and remaining fatigue life) (or other available information) is automatically entered into the BIM model, updating the model's geometry and damage representation. The geometric representation of damage is carried out using an RGB (Red-Green-Blue) colour system, where the colouring changes depending on the damage index. The non-geometric representation is performed through numerical values allocated in the parameters of interest that characterise the damage. While commercial platforms such as REVIT® and RHINO® have Application Programming Interfaces (APIs), which enable connections with external environment data, in the case of this study, where the BIM model is generated through open-source software and programming, the insertion of relevant information is carried out through Python programming;

b) Branch 2 - This is an inverse process (simulation), in which the BIM model and the FAS can be updated simultaneously, generating new results and returning to branch 1, thus maintaining a continuous process. The BIM model is updated using the same process described in (a), while the FAS is updated using the APDL (Ansys Parametric Design Language) + MATLAB. APDL and

MATLAB allow access to the finite element numerical model and fatigue damage calculation algorithms, updating the geometry of FEM and traffic loads.

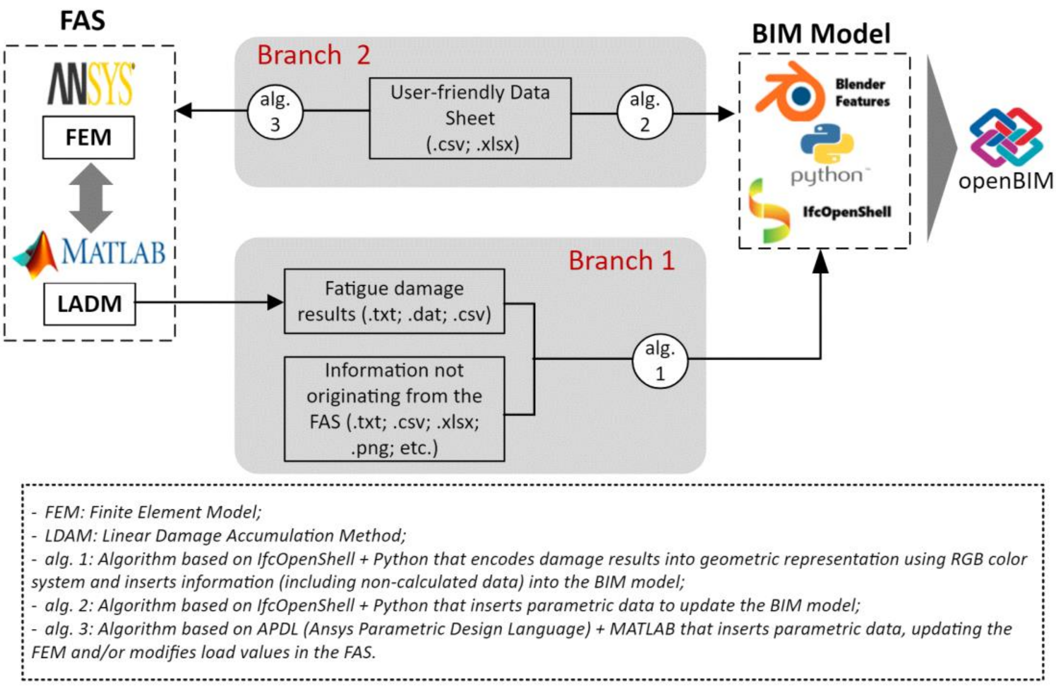


Figure 5: Schematic representation of the integration process FAS – BIM model for the bridge

3 Results

The methodology described in the previous section is applied to a real case. This is an ongoing study concerning the Várzeas Bridge, located in the district of Aveiro, Portugal (Figure 6). It is a steel bridge with a truss deck, five spans, and a total length of 281 meters. The detailed description can be found in [11, 12]. The intention is to use the BIM model to assist in assessing the evolution of fatigue damage in the main connection details of the truss deck. Different scenarios involving traffic loading and geometry properties of the structural elements may be considered for assessment.

Figure 6: General view of the Várzeas Bridge

Figure 7 depicts the framework of a DT, which has the potential to automate fatigue assessment processes and allow the visualisation of fatigue evolution for different scenarios. There are four main parts or processes involved in the Framework. Firstly, all the information about geometry, mechanical properties of the elements, and the real or typical traffic load on the bridge is collected, which allows the creation of both a numerical model (Finite Element Model - FEM) and a BIM model. The acquisition of information about real traffic that leads to the real fatigue state involves instrumenting (sensing) the bridge and applying the Bridge Weigh-in-Motion (B-WIM) technique, which is not the scope of this work. The approach and implementation of this technique can be found in [13].

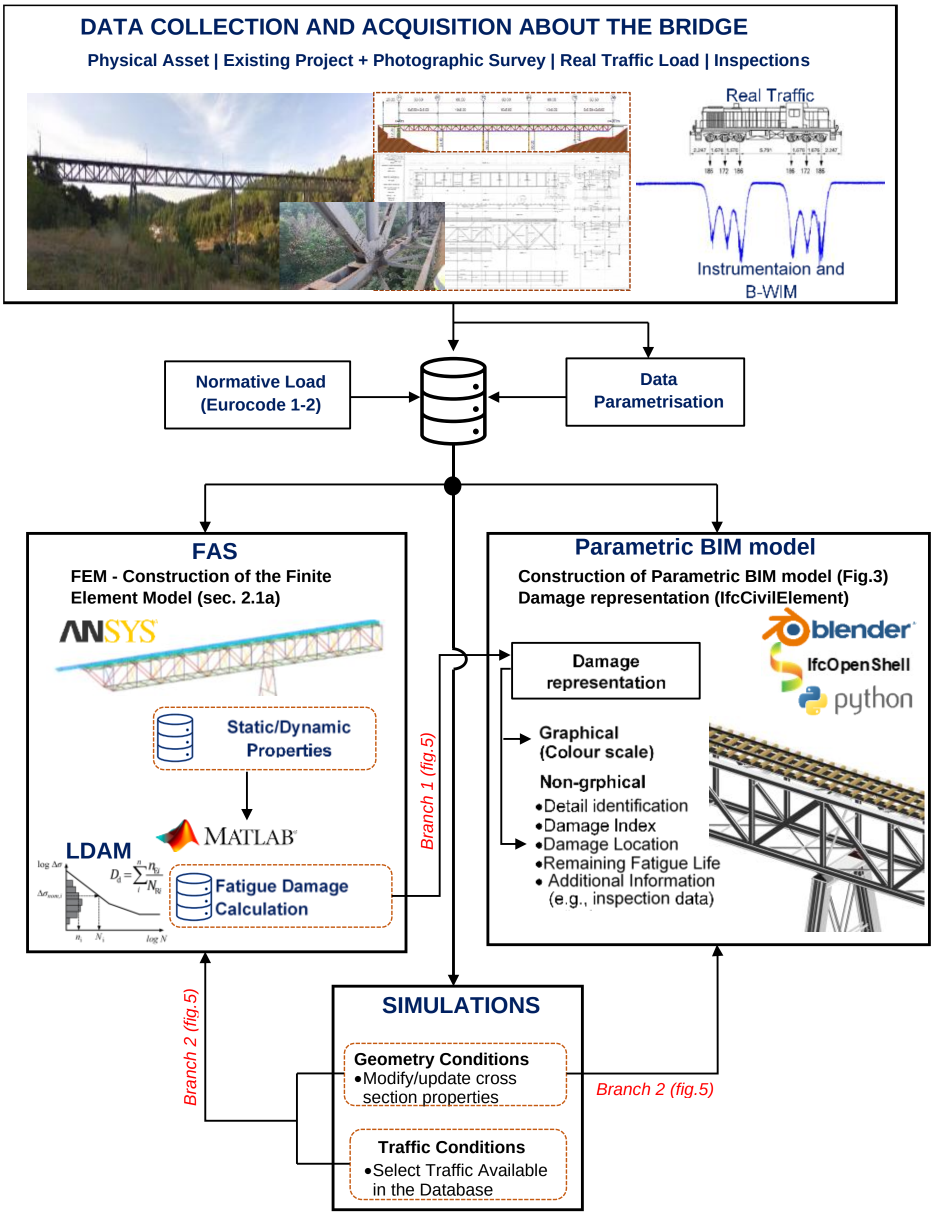
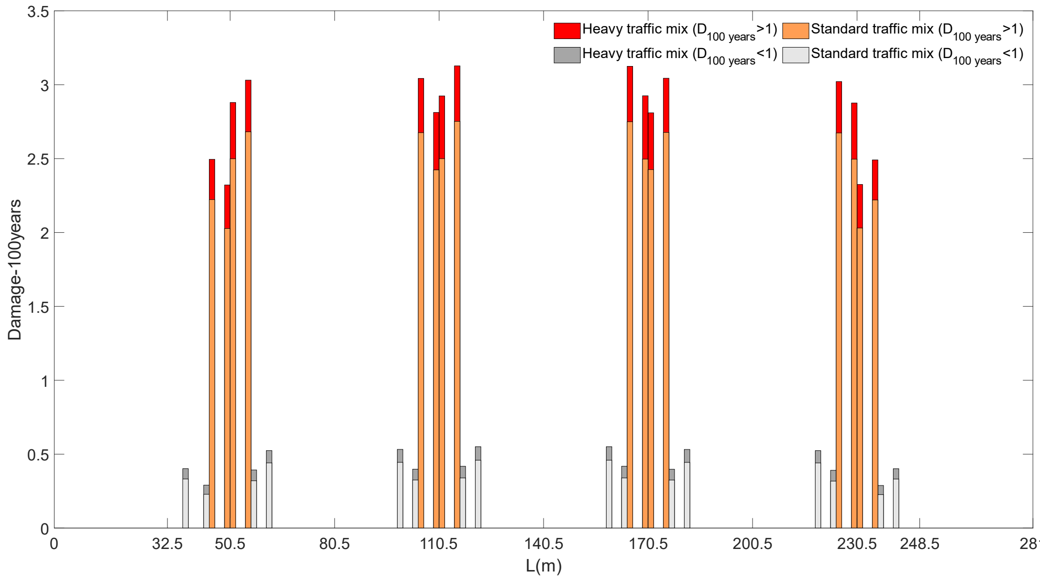


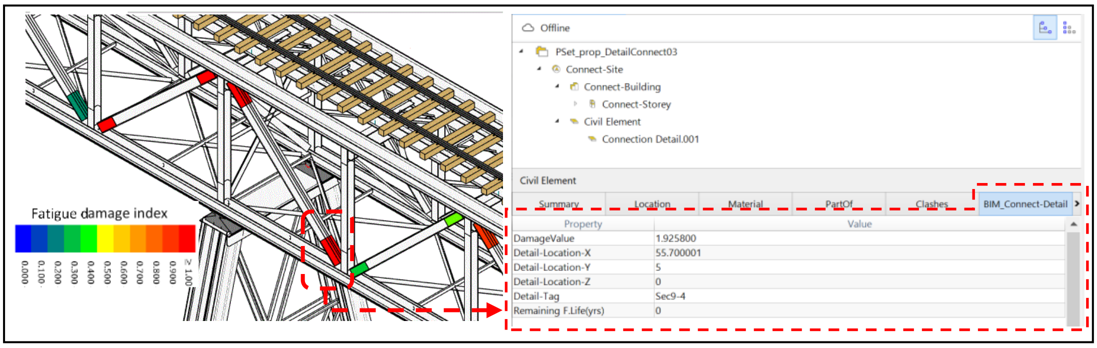
Figure 7: Framework of BIM Use, forming DT for characterising the evolution of fatigue damage in the Várzeas Bridge.

The FEM and the BIM model are parametrically built independently (using APDL for the numerical model and open-source tools for the BIM). Parametrisation enables automated model changes and accelerates the creation of similar models. The FEM allows the static or dynamic properties of the bridge to be determined and, when combined with the LADM, the FAS is formed. This system allows for the computation of fatigue damage at specific connections based on input data (traffic load and geometry properties). The integration between the FAS and the BIM Model, including visualisation and querying of damage evolution, is depicted in this framework and is briefly described in Section 2.

Figure 8a shows the values of computed fatigue damage for connection details belonging to the diagonal members located next to the bridge supports, and 8b illustrates part of the representation of the respective information in a BIM viewer. Besides BIM viewers, other BIM platforms within the openBIM spectrum may be used.



(a)



(b)

Figure 8: (a) Values of computed fatigue damage for diagonal connection details located next to the bridge supports; (b) Example of graphical and non-graphical representation of damage information on one of the diagonals - BIM Viewer.

As detailed earlier, this representation is carried out following the integration of information and the generation of the BIM model in IFC format. The computed damage data corresponds to the loading scenarios for the "Standard Traffic Mix" and

"Heavy Traffix Mix" fatigue trains of normative traffic as specified in Eurocode 1-2 [14]. As the bridge consists of riveted connections, the S-N curve detail category 71, proposed by several researchers for such cases [12], was adopted in the fatigue assessment. With the aid of the BIM viewer, it is possible to identify critical details or places in good condition and access quantitative data regarding the specified detail.

4 Conclusions and Contributions

Within the range of the potentialities of BIM, this work has demonstrated how BIM can be used to assist the process of assessing fatigue evolution in SRBs and is, therefore, a way of extending its use. The global model combines the FAS and the bridge BIM model, with the FAS responsible for fatigue damage computing, continuously feeding the BIM model. Normative and real traffic are some scenarios that provide input information for fatigue computing. The latter, which is not used in this work but may result in a more complete DT, entails instrumenting the bridge (bridge sensing) and using the B-WIM approach, as illustrated in the framework in Figure 7. Unlike the traditional fatigue assessment system, which is characterised by a high level of manual work, this model makes the system more open and automated, allowing new input data related to traffic loads or geometry properties to be entered automatically. This results in an automatic representation of the evolution of fatigue damage, accelerating the process and making decision-making more flexible.

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