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## 3D-DIC analysis for BIM-oriented SHM of a lab-scale aluminium frame structure

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**Abstract.** In recent years, three-dimensional Digital Image Correlation (3D-DIC) has proven to be a reliable technique for Structural Health Monitoring (SHM) by allowing full line-of-sight, high-resolution, and contactless measurements of structures. The large amount of raw output resulting from 3D-DIC requires appropriate methods to visualise and analyse the data systematically. In this context, Building Information Modeling (BIM) emerges as a robust repository and data management tool to store, query, and assess long sequences of SHM data. Different sensors have been used to collect SHM data and digital sensors have been created in the BIM environment to mimic the behaviour of the physical ones on site. This research focuses on the BIM implementation of virtual sensors from information retrieved using 3D-DIC to store frequency and time domain data and monitor structural changes in a targeted system over time. The application of the Phase-based Motion Magnification (PMM) technique is proposed as a preprocessing tool for 3D-DIC analysis videos to obtain displacement information in specific frequency bands and make those values structurally effective. As a case study, a three-story aluminium frame structure with a damaged and undamaged configuration is used to validate the developed methodology.

### 1. Introduction

Structural Health Monitoring (SHM) is an essential tool for understanding the integrity of building and infrastructure systems. The design lifespan of any construction ranges from a few years to centuries and the maintenance is often the key factor in this difference.

Emergency events, usually referred as Sudden-Onset Disasters (SUOD) (e.g., natural as earthquake, volcanic eruption, hurricanes, floods; man-made as terrorist acts, wars, chemical explosions) can be catastrophic because of their immediate consequences on structures with little to no warning. In addition, those events cause high human, social, economic, cultural loss for a community and its identity [1,2]. To reduce the risk of loss, maintain the soundness of structures, and design a maintenance schedule, different SHM strategies have been developed. SHM techniques have been applied to condition monitoring of wind turbines [3], mill chimneys [4], offshore platforms [5], nuclear power plants [6], and to buildings and infrastructure [7]. When dealing with large-scale systems, accessibility becomes a greater issue while collecting data for non-destructive testing (NDT). Hence, in recent years, computer vision and digital image processing have proven to be two of the most promising approaches to be integrate with SHM methodologies [8].



In particular, digital image processing-based NDTs are noninvasive and faster than traditional methods and give flexibility of conducting the test at any time. Moreover, they can provide results over the whole field of view of the camera as each pixel is now a measurement point. Many researchers have been trying to incorporate optical techniques with SHM to make it more effective. Dhanasekar et al. incorporated NDT data collection using three-dimensional Digital Image Correlation (3D-DIC) for SHM of masonry arch bridges [9]. One of the reviews conducted by Jurjo et al. [10,11] focuses on the ND techniques incorporated with SHM considering slender structures. Flores et al. [12] analysed the effect of low-velocity impacts on composite materials using 3D-DIC to gather information related to damage such as deformation, strains, transverse matrix cracks initiation, and propagation. Feng et al. [13] conducted a review based on the potential of 3D-DIC approaches for SHM for a wide variety of applications starting including dynamic response of the targeted systems and damage detection. All of these researchers highlight the effectiveness of 3D-DIC for collecting full line-of-sight and high resolution damage information of the structure based on stereophotogrammetric techniques which can significantly improve the SHM strategies. Despite the promising results shown by the researchers, all of these approaches require a lot of data for the SHM techniques to properly work. While collecting enough high-quality information is one aspect of SHM, it introduces new difficulties related to the management of very large datasets. For this reason, it is of utmost importance to have tools that can help with the data management aspect.

In this context, Building Information Modeling (BIM) has emerged for its potential as an effective repository, data management, and exchange tool related to the digital representations of a built asset in all geometrical and informative features during its entire life cycle [14–18]. BIM is a set of methodologies, processes, and policies that removes the barriers between Architecture, Engineering, and Construction (AEC) disciplines by enhancing knowledge sharing throughout the project's lifecycle. It enables stakeholders to collaboratively design, construct and operate a facility [18,20]. As-Designed (AD) BIM models, which are digital representations of the design and construction phase of an asset, are developed to increase the quality of the project, reduce conflicts and waste (e.g., in time and material) [18]. On the other hand, As-Built (AB) BIM models are a challenging but necessary process for facilities not equipped with an AD BIM or whose AB conditions differ from the AD ones [20]. The AB BIM model is more than just simple geometry, and it represents the virtual equivalent of the actual building instead. AB BIM is composed of intelligent parts that are the digital prototypes of the physical elements (e.g., walls, columns, windows, doors). In this sense, BIM models should include data related to performance (e.g., structural and energy) and state of preservation to simulate and understand the building behaviour. BIM allows optimising the entire structure's lifecycle from the project phase to the construction management and maintenance because it can store, query, and assess long sequences of SHM data to define a 6D BIM model with information about anomalies and performances [21]. To enable a seamless BIM-based SHM, the first issue to be solved concerns the representation of the SHM system to facilitate a link towards the BIM environment and allow a bi-directional data flow [21].

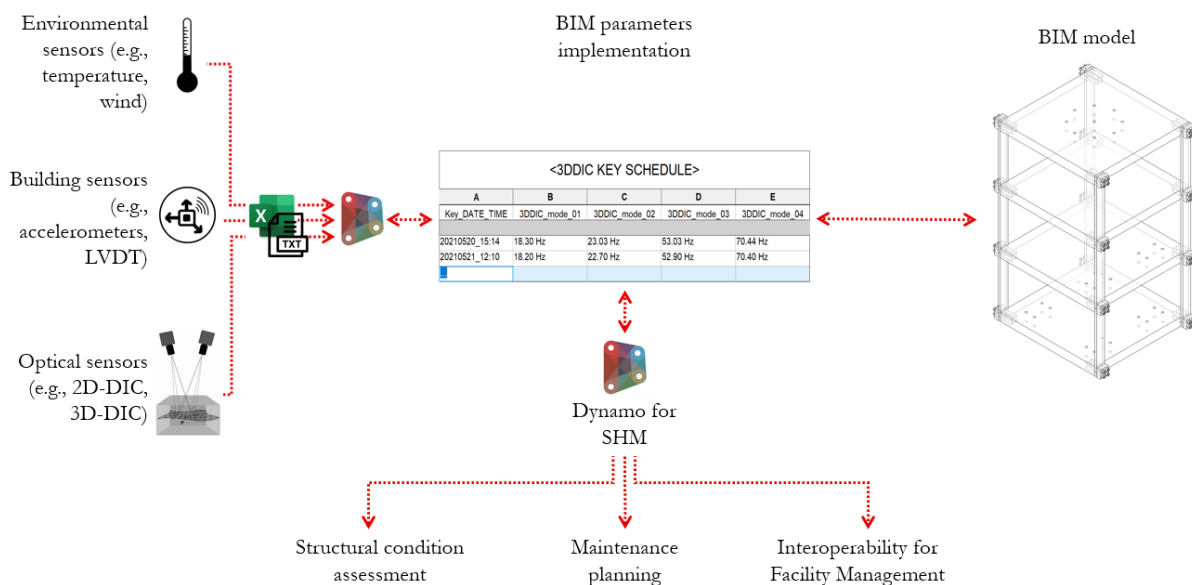
Indeed, there is a lack of standards to describe SHM systems in BIM for structural performance monitoring. In the literature, it is possible to find attempts to implement SHM data from sensors (e.g., accelerometers and strain sensors [22]) into BIM by creating custom BIM families and associating raw sensor data with them [17,18,23–26]. In some cases, these attempts are successful in exploiting the potential of BIM as a structured data repository [17,18,23,25]. Nonetheless, in most cases, the inclusion of such data as model parameters is far than standard. As reported in [27], it is common practice to translate SHM raw data in either attached documents or links to non-BIM-oriented .txt files and externally stored webpages without taking full advantage of the BIM interoperability potential.

As per the authors' knowledge, few attempts have been made to embed data from vision-based SHM analyses directly in the BIM instances and none from 3D-DIC. The present research aims at filling these gaps by integrating 3D-DIC measurements into a BIM approach. Considerations and limitations related to the implementation of a non-physical sensor BIM family for data storage are discussed. In particular, this research explores how implementation of frequency and displacement values in BIM can improve management, interpretation, analysis, and interoperability of SHM systems data.

## 2. Materials and methods

In the present research, a novel workflow between SHM sensors data and a BIM environment is structured. A stereocamera measurement system is implemented to perform a 3D-DIC analysis and identify the structural behaviour of a laboratory-scale aluminium frame structure to validate whether the predicted responses correctly match the physical ones.

The methodological bases for SHM parameters structuring in the BIM environment are herein presented (Section 2.1.). Specifically, the research moves forward, introducing innovative tools for frequency and displacement (Section 2.2.) value parameters implementation on a lab-scale experimental setup (Section 2.3.). The workflow that characterises the approach proposed in this research is summarised in **Figure 1**.



**Figure 1.** BIM-based workflow: sensors' data are uploaded as BIM parameters by Key schedule with each row corresponding to a measurement. From the Key schedule, a Dynamo implementation is structured for comparing and analysing the various SHM data.

### 2.1. BIM model and SHM parameters implementation

The presented SHM system considers the future interpretation of the acquired data proposing an effective SHM data structuring inside a BIM model that increases data value and usability [18]. Based on the literature, it is possible to highlight four main categories in which SHM data are represented in a BIM environment:

- (i) 3D geometry and location of sensors [17,26];
- (ii) Sensor network layout information and links [18,23,25];
- (iii) Tables and plots acquired by monitoring systems [24,26];
- (iv) Derived or post-processed information from the acquired data by means of parameters implementation [18,28].

For what concerns points (i) and (ii), the system is modelled with an object-oriented approach to closely mirror the actual physical configuration. Data are represented in units called entities to which attributes can be assigned. These entities can represent physical objects (e.g., sensors, structural elements) or abstract concepts (e.g., processes, events) [18].

Categories (iii) and (iv) are two different ways of representing SHM sensor data. Moreover, category (iv) requires a parametric hierarchy structure in the model that is achieved through shared parameters and is defined as information holders shareable in multiple projects. Shared parameters are independent .txt files, which can be transferred to allow other users to insert them into different families or projects. These parameters can be subdivided by discipline (e.g., "Structural") and are the basis for creating project parameters in the specific BIM model. Once the parametric structure is complete, the 3D-DIC data can be uploaded as BIM shared parameters and are converted into table format by Revit key schedule in which each row corresponds to a single measurement. The key schedule is a particular type of Revit schedule that allows assigning groups of parameter values to instances based on a shared key value. Therefore, the key schedule is linked to a specific instance to increase the level of information with SHM data and guarantee a correlation between the level of geometry and the level of information.

Nonetheless, BIM architectural models are mostly static representations of built assets at a particular point in time. Moreover, to fully integrate dynamic data in the models, updating attributes values at a given changes in an external data source should be set to be automatically processed. In this sense, Autodesk Dynamo is used as a Visual Programming Language (VPL) algorithm editor tool to extends BIM potentiality [21]. In the research, the SHM data and its management by means of Dynamo become the interface between the sensor data and the BIM model itself. Indeed, every data extraction processing is automated using Dynamo to import and process SHM data files.

Moreover, the Revit model automatically updates when the key schedule is added with new data measurements. Damage type and location are identified by detecting shifts in measured parameters, which could lead to structural anomalies. Indeed, from the key schedule table format, BIM checks through Dynamo are set to run and detect when monitored parameters go beyond a previously defined threshold.

In order to guarantee the successful adoption of the BIM-based workflow, the information exchange methods have to be robust and well-structured [18]. Open, non-proprietary, and publicly available standard data models have been developed to provide interoperability between the various stakeholders. For example, Building Smart develops and maintains the Industry Foundation Class (IFC) that is a standard format to give shared rules to format data and facilitate building and construction industry data interoperability. Among all IFC schema entities, ifcSensor and ifcSensorType can be selected to represent sensors.

## 2.2. *Monitoring aluminium frame natural frequencies and displacement*

The importance of monitoring frequency values is related to the fact that the response of a structure vibrating at a resonant frequency is typically amplified far beyond the design levels. With the aim of understanding a vibration problem in a structure, its resonant frequencies can be identified by defining the modes of vibration. Each mode is characterised by a natural or modal frequency, damping ratio, and a mode shape [29].

In the case study described in this paper, the natural frequencies of the aluminium frame were identified by conducting an Operational Modal Analysis (OMA) test using accelerometers signals to obtain the frequency response functions (FRF) (**Figure 6b**). Likewise, the displacement information of a DIC point identified by a marker has been processed to obtain an FFT of the signal (**Figure 6a**). In the research, the DIC FFT peak values and their shifts between undamaged and damaged configurations have been studied and parametrised in a BIM environment.

In addition to frequency monitoring, the displacement of a marker identifying a DIC point maximum displacement at specific frequency bands was studied. For time-domain analyses, a Phase-based Motion Magnification (PMM) technique [30] was used as a 3D-DIC preprocessing tool because it acts as a bandpass filter while making a magnified version of the motion in a narrow frequency band. Therefore, at subsequent measurements, the 3D-DIC videos can be used to obtain the displacements in the specific frequency band. In the literature, there are examples where the choice of the frequency band to be magnified is either subsequent to a preliminary modal analysis [31] or independent from it, and a small

bandwidth is considered [28]. In the first case, the modal analysis could identify the band center with the natural frequency value and the bandwidth as a fixed value. In the second case, a wide frequency range is divided into more frequency bands with the same width, and the displacement measured after the PMM application is monitored to take into account possible shifts in frequency due to structural changes. In this research, a hybrid approach between the two presented in [28,31] is structured in the following steps:

- (i) Individuation of frequency response of both Undamaged and Damaged configuration with 3D-DIC FFT or Accelerometers FRF;
- (ii) Selection of narrow bandwidth with natural frequencies as centre frequencies;
- (iii) PMM analysis of both Left and Right high-speed cameras videos within the selected frequency bands;
- (iv) 3D-DIC analysis with magnified videos;
- (v) Operational Deflection Shape (ODS) identification.

### 2.3. Experimental Setup

As shown in **Figure 2a**, a three-story aluminium frame was used for the experimental campaign, and a shaker was employed to generate broadband white noise excitation. The structural response to the shaker excitation was measured with accelerometers installed at each slab of the frame and with two high-speed cameras (Photron SA2) recording at a sampling rate of 250 fps. Additional LED illumination was supplied to enhance vision-based analysis quality. A black and white speckle pattern and some optical targets, necessary for DIC analysis, have been applied to the frame. Two tests were performed with two different configurations to capture structural changes in the system. The first test was conducted with the undamaged configuration, while the second had the pillars of the structure replaced with notched ones to simulate a damaged condition (**Figure 2b**).

For what concern the 3D-DIC analysis, the images were analysed by means of GOM correlate professional software v2020, while Autodesk Revit and Autodesk Dynamo v2022 were employed respectively as main BIM authoring and tool software.

The Revit BIM model was used to define the real-time dynamic behaviour of the frame used for visualisation of long-term monitored SHM data.



**Figure 2.** (a) Three-story aluminium frame setup with the stereocamera vision system for vision-based analysis and a shaker to generate broadband white noise excitation; (b) details of the notches in the pillars representing the damaged configuration.

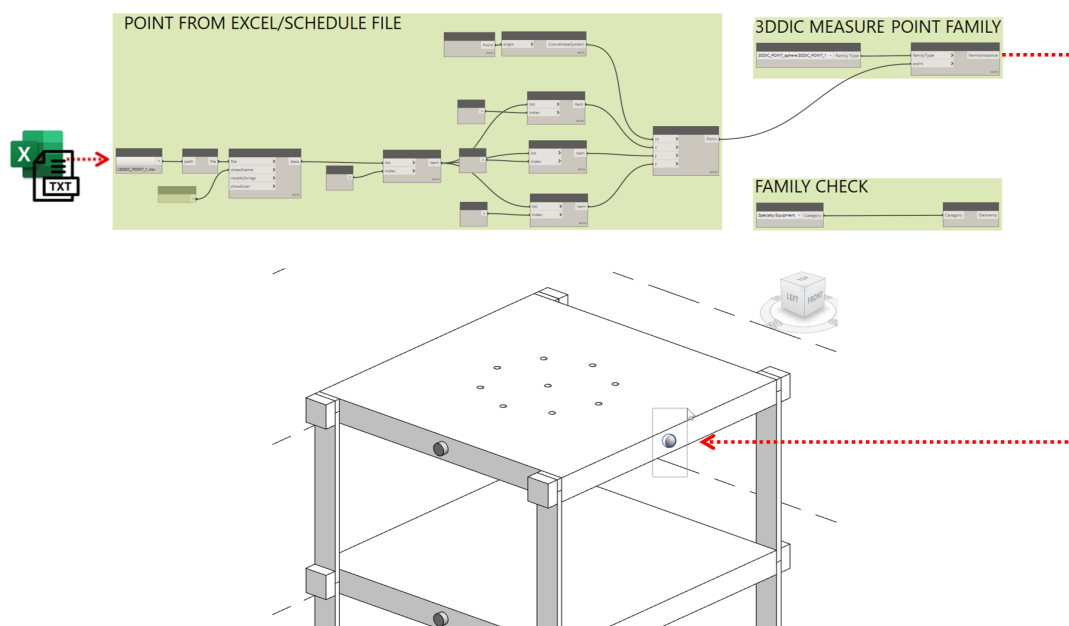
### 3. Results

#### 3.1. BIM model and SHM parameters implementation

The frame is modelled in BIM using an object-oriented approach. Data are represented in specific family instances and can have specific attributes. In particular, the BIM family for 3D-DIC data storage is implemented as a point-based sphere whose centre corresponds with the 3D-DIC optical target. This sphere family is linked to the 3D target used for DIC processing to create a BIM virtual sensor. The junction between one of the pillars and the slab of the aluminium frame was chosen as the origin to set a shared coordinate system for GOM Correlate Professional and Autodesk Revit to locate the virtual sensor in the same measurement point for both the 3D-DIC software and the BIM model. Moreover, a VPL algorithm in Dynamo is structured to automatically import the sensor's location and displacement data in the BIM virtual sensor to allow little-to-no user manual interaction (see **Figure 3**).

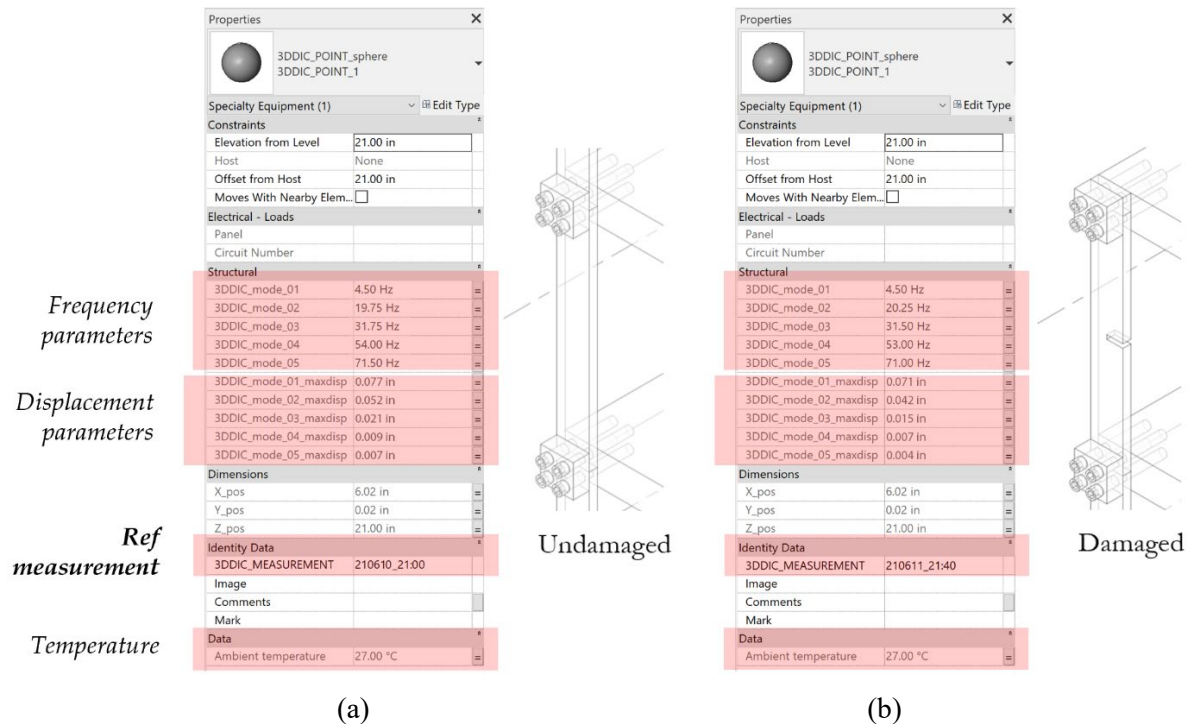
Sensors modelling and simulation are mainly aimed at allowing data interoperability with external tools. Without this step, sensors modelling can be used only for storage and visualisation purposes. To create a fully interoperable dynamic system, the sensor information needs to be embedded in the IFC output. In the research, the sensors were modelled as Revit families under the specialty equipment family category. The IFC class *ifcSensor* and *ifcSensorType* were used for IFC interoperability. Currently, there are 32 defined, one user-defined and one undefined sensor types in the IFC 4.3 Schema. The user-defined type was used because no other one is dedicated to vision-based virtual sensor analyses yet.

Moreover, a user-defined Property Set named *Pset\_SensorType3DDIC* was created to propose 3D-DIC sensors integration into the IFC schema and convert the defined project parameters into IFC parameters. For creating *Pset\_SensorType3DDIC*, frequency was used as Frequency IFC parameter, Real data type was used for Displacement IFC parameters, ThermodynamicTemperature was used for Ambient Temperature IFC parameter, and Label was used for Date and Time IFC parameter. Therefore, the FRF plot has been parametrised, and specific BIM parameters were defined and assigned to each 3D-DIC family instance in Revit. Specific BIM project parameters, derived from a shared parameter file, have been created for the frequency peak values. The Revit plug-in Paramanager by DiRoots [26] was used for the conversion process between the shared and project parameters.



**Figure 3.** Automatic Revit family instance placement through Excel/schedule and Dynamo integration for 3D-DIC data storage.

The first five resonant frequency values of both undamaged and damaged tests have been uploaded in a Key schedule linked to the BIM instances for storing each 3D-DIC measurement and allowing other SHM sensors data to be added in the future. The results of this BIM implementation can be used as reference values in SHM perspective after other measurements are performed during the structure's life.



**Figure 4.** Integration of 3D-DIC data into BIM: Aluminium frame BIM model in Autodesk Revit and Instance properties of 3D-DIC BIM family selected for the undamaged (a) and damaged (b) configuration.

**Figure 4** shows all the parameters implemented in Revit for the two configurations herein described. By changing the reference measurement value, all parameters will be updated all at once, and the old ones will be stored in the 3D-DIC key schedule (see **Figure 5**). When the updated frequency or displacement values are loaded into the BIM model, the system can send an alert if the frequency shift ( $\Delta f_{i-s}$ ) or displacement shift ( $\delta\Delta f_i^S/\delta\Delta f_i^I$ ) exceeds a specific threshold as shown in Equations (1) and (2). Moreover, the temperature of each monitored structural element has also been recorded over time in order to compensate for strain variations between measurements at different temperatures. In this research, frequency, displacement, and ambient temperature parameters were implemented, but the same approach could be extended to other types of data input.

<3DDIC_POINT_1>									
A	B	C	D	E	F	G	H	I	J
Key Name	X_pos	Y_pos	Z_pos	3DDIC_mode_01	3DDIC_mode_02	3DDIC_mode_03	3DDIC_mode_04	3DDIC_mode_05	Ambient temperature
210610_21:00	6.02 in	0.02 in	21.00 in	4.50 Hz	19.75 Hz	31.75 Hz	54.00 Hz	71.50 Hz	27.0 °C
210611_21:40	6.02 in	0.02 in	21.00 in	4.50 Hz	20.25 Hz	31.50 Hz	53.00 Hz	71.00 Hz	27.0 °C
210612_...									

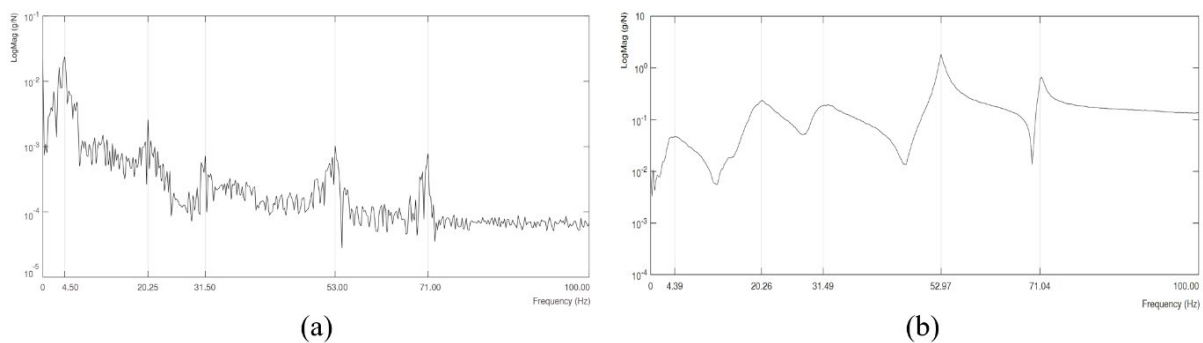
**Figure 5.** Revit key schedule with the initial (i.e., undamaged) and recurring (i.e., damaged) frequency values.



### 3.2. 3D-DIC analysis for monitoring natural frequencies in the aluminium frame

The images captured with the two Photron cameras have been analysed in GOM correlate to perform a 3D-DIC analysis and extract the displacement time history of a single point corresponding to the sphere defined in the BIM model. It should be noticed that the monitoring can be done by tracking every point derived from the speckle pattern or optical targets.

The 3D-DIC output was used both for **i)** locating the selected point in the DIC-BIM coordinate system and **ii)** retrieving displacement information to perform a modal analysis. The first five frequencies of the structure have been identified, and the values of 4.50 Hz, 19.75 Hz, 31.75 Hz, 54.00 Hz, and 71.50 Hz were selected as representative for the undamaged configuration. For the damaged configuration, the values of 4.50 Hz, 20.25 Hz, 31.50 Hz, 53.00 Hz, and 71.00 Hz were identified (see **Figure 6**). Compared with accelerometers FRF values, the percentage difference between the optical and accelerometer data is equal to 0.48% and 0.50%, respectively for undamaged and damaged configuration with a maximum difference of 2.51%.



**Figure 6.** Frequency response measured for damaged configuration of the test article: (a) FFT obtained from 3D-DIC data; (b) FRF obtained from accelerometers data.

In the case of existing structures, it is not possible to measure the value of the undamaged state of the structure rather monitor the evolution of damage. Therefore, a precise mathematical formulation based on Vibration-Based Inspection (VBI) [32] is hardly inferable. For this reason, in the present research, the relationship between the natural frequency at the initial measurement and natural frequency at a subsequent measurement is assessed as follows:

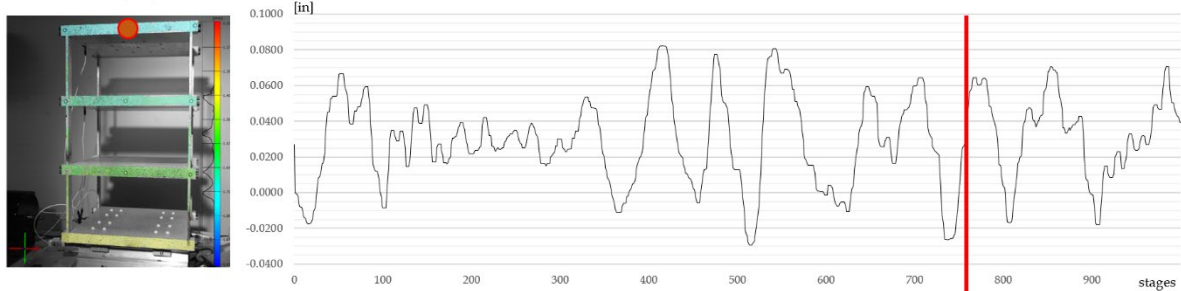
$$\begin{cases} \text{if } |\Delta f_{I-S} - 1| < \gamma \rightarrow \text{NO ALARM} \\ \text{if else} \rightarrow \text{ALARM} \end{cases} \quad (1)$$

where  $\Delta f_{I-S}$  is the frequency shift between the initial measurement I and the subsequent measurement S.

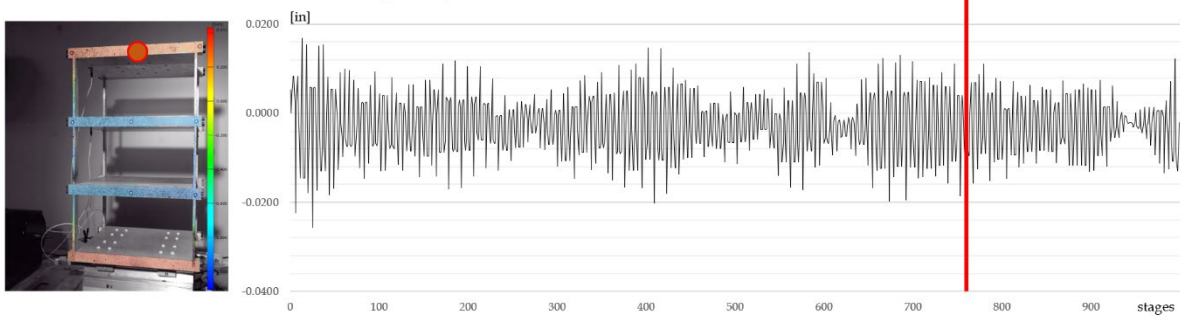
### 3.3. 3DDIC for monitoring displacements at aluminium frame natural frequencies

For what concerns displacement data implementation, before performing the 3D-DIC analysis, the images captured with the two Photron cameras have been preprocessed with PMM technique to magnify specific frequency bands. The 3D-DIC analysis was used to obtain the displacement of a point corresponding to a DIC target. The choice of PMM frequency bandwidth influences the resolution of the potential frequency shift in time, which can be a damage indicator [33]. Moreover, the narrower the bandwidth, the more focused the amplification and the lower the noise amplified are. Hence, bands of 5 Hz were chosen to allow both adequate discretisation and resolution for all the five frequencies identified.

Without PMM



With PMM (50.50 – 55.50 Hz frequency-band)



**Figure 7.** Displacement time history plot of the point highlighted by the red dot and representation of the DIC output at a specific timeframe, before (top) and after (bottom) PMM technique application (magnification factor  $\alpha=10$ ).

**Figure 7** shows the difference in wavelength and amplitude of the displacement signal, before and after the application of the PMM technique in the 50.50-55.50 Hz range. For the PMM preprocessing, a magnification factor of  $\alpha=10$  was used. Moreover, isolating the frequency band and adding an attenuation filter to the other frequencies make it possible to emphasize the specific ODS in the selected band. Indeed, as can be observed in the bottom part of **Figure 7**, the representation of the DIC output at a specific timeframe shows that the first bending ODSs is clearly visible, with little presence of noise and contribution from other modes. The displacement value was divided by the magnification factor.

As described in Section 3.1., the same considerations about displacement difference between the initial measurement and a subsequent measurement can be done:

$$\begin{cases} \text{if } \left| \frac{\delta_{\Delta f_i^S}}{\delta_{\Delta f_i^I}} - 1 \right| < \gamma \rightarrow \text{NO ALARM} \\ \text{if else} \rightarrow \text{ALARM} \end{cases} \quad (2)$$

Where  $\delta_{\Delta f_i^I}$  is the maximum displacement in a 5 Hz frequency band  $i$  during the initial measurement I, and  $\delta_{\Delta f_i^S}$  is the maximum displacement in the same frequency band  $i$  during the successive measurement P.

#### 4. Discussions

As observed from the results listed in **Figure 4** and **Figure 5**, the 3D-DIC analysis for undamaged and damaged configurations made structural changes in the aluminium frame visible. Frequency value shifts between the undamaged and damaged configurations are consequent to the stiffness reduction caused by the damage in each pillar of the first-floor frame. The contribution to the frequency shift due to the reduction in mass is negligible compared to the decrease in stiffness. Indeed, experimental results confirm an overall reduction in natural frequencies in the damaged configuration.

These considerations, which are usually displayed on plots similar to those shown in **Figure 6**, are herein implemented as discretized data in Revit key schedules, read and interpreted using Dynamo. For what concerns the visual-based analysis, the accuracy of 3D-DIC system is used not only to address structural aspects, but also to locate the measurement point in the space due to the shared reference system between the BIM model and the 3D-DIC software.

As reported in **Figure 6**, DIC is noisier than the contact-based measurement because of inherent characteristics and because it is an output-only measurement where results are not normalised to the input. Nevertheless, it allows to recognise and identify all the frequency peaks easily.

Moreover, the 3D-DIC preprocessing with PMM technique generated a magnified time history (**Figure 7**) clearly showing a tinier displacement than in the non-magnified one because a high-frequency component is isolated and the rigid body motion effects are negligible [34]. The time history shows that the choice of 5 Hz bandwidth was effective because it provided a good compromise between processing time, natural frequency component isolation, and reduced influence of other modes. A Magnification factor  $\alpha=10$  has also proved to be correct according to the results obtained. Indeed, similar researches show that no particular error occurred while processing DIC video after applying such magnification factor [34]. It could be possible to reach a higher magnification factor to see the ODSs with a naked eye, but this would introduce artefacts that could worsen the quality of the 3D-DIC analysis.

## 5. Conclusion

In the present study, the potential of overcoming Structural Health Monitoring (SHM) data repository issue is studied implementing a Building Information Modeling (BIM)-based approach. The perspective of creating peak frequencies and displacements parameters for discretised points from 3D Digital Image Correlation (3D-DIC) analysis is presented.

A static BIM repository is moved toward a dynamic BIM implementation to propose a quasi-real-time SHM application. The presented approach has shown that 3D-DIC analysis output can be imported as BIM virtual sensor families to store structural parameters. In particular, it was possible to measure and describe in BIM the frequency and displacement for selected frequency bands information of rigid body motions and natural frequencies.

The combination of 3D-DIC and Phase-based Motion Magnification (PMM) provided an essential advance in visualising the displacements for asset managers, engineers, or project owners by providing them with updated information. In the research, the BIM implementation of a single point is presented, but the automation could be extended to a larger set of points without increasing the operator manual interactions.

The proposed framework utilises the potential of 3D-DIC, PMM, and BIM to achieve an automation-prone SHM system by structuring custom Visual Programming Language (VPL) tools. The BIM tool Dynamo within the BIM authoring software Revit has been used to import and automatically process the recorded data from the subsequent measurements in the SHM network. A more streamlined path between structural monitoring and data management was shown to be possible, and it provides an effective visualisation tool for updated monitoring information.

Future works will extend the methodological tools presented to take full advantage of 3D-DIC full-line-of-sight features. 3D-DIC point clouds will be used to increase the quantity of monitoring data and propose a proper BIM oriented solution. The methodology will be tested on real-world building to verify its feasibility on real-world scenarios.

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