UNDERSTANDING THE EFFECTS OF DOCUMENTATION DETAIL ON DIAGNOSTICS OF HISTORIC STRUCTURES

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ABSTRACT:

Before reinforcements or new construction are added to historic structures, it is important to understand how the existing damage could have arisen. Often to do this, documentation methods such as laser scanning and photogrammetry are used to capture the existing conditions and physics-based models are used to simulate the response of a facsimile structure to various responses. Something that varies quite a bit though is the level of detail used to capture the existing conditions as well as the level of detail used to represent the structure during physics-based modelling. This paper aims to understand the effects of documentation detail on diagnostics of historic structures. To do this, two masonry structures were documented with laser scanners, photographs, and thermal images. For each case study, three-dimensional models of varying fidelity were generated based on the results of simulation. The response of these models to loading conditions was then calculated using a physics-based modelling technique called finite-distinct element modelling. The results for each case study are compared to understand the impacts of geometry on diagnostics; discussion about future tools to augment current practices is included.

1. INTRODUCTION

Heritage structures and sites, such as sacred buildings, bridges, monuments, and the courtyards, complexes, as well as archaeological sites that surround them, constitute an important part of cultural legacy. Regardless of whether they are still standing, in or out of use, partially or completely collapsed, heritage structures represent important milestones in human cultural and engineering achievements, and in the scientific, political, economic, and artistic evolutions that left an everlasting impact on societies. In addition to being invaluable from a cultural perspective, historic buildings also play a role in sustainable architecture (Baskaran, 1999). Due to urban space shortages, the carbon emissions related to demolition and construction costs, as well as other reasons, there has been a resurgence in the recycling of historic infrastructure (Bullen, 2007; Shipley et al., 2006; Yung and Chan, 2012). Thus, the imperative to preserve historic structures is a multi-goal challenge.

To preserve a historic structure, the geometry and existing conditions must be properly documented, and any existing damages should be diagnosed. Currently, in the fields of architecture (Barber et al., 2006; Armesto-González et al., 2010; Barton, 2009), civil engineering (Abmayr et al., 2005; Olsen et al., 2009; Berenyi et al., 2010) and archaeology (Trier et al., 2018; Grgurić and Novak, 2018), documentation techniques such as laser scanning and photogrammetry are widely used. In addition, structural analysis techniques such as finite element modelling are coupled with documentation efforts to understand the current stability of a structure. However, since thorough analysis can often be time-consuming and computationally expensive, the geometry of a structure is commonly oversimplified during structural analysis (Napolitano et al., 2019b).

1.1 Standard levels of documentation

Letellier, 2007 first outlined the three main levels of accuracy for documentation methods as reconnaissance, preliminary, and detailed (Letellier, 2007). This was later expanded upon by Santana and Patias, 2011 (Patias and Santana, 2011). The aim of reconnaissance documentation, also sometimes referred to as initial documentation, is for initial planning, communication, and/or reference. Thus, there is not a required accuracy for documentation at this level. Introducing quantitative accuracy requirements, the preliminary level of detail for documentation is often utilized for initial condition assessments as well as pre-design stages. For this level of detail, plan drawings must have an accuracy level of $\pm$ 10 cm while details must have an accuracy level of $\pm$ 2 cm. Requiring the highest level of accuracy, the detailed documentation models are often used to document as-found condition prior to construction or to record the structure for posterity. This level of detail requires that plans have $\pm$ 1 cm whereas details must have $\pm$ 2 mm.

Level of detail	Plan accuracy	Detail accuracy
Initial	None	None
Preliminary	10 cm	2 cm
Detailed	1 cm	2 mm

Table 1. Required levels of accuracy for each level of documentation detail. Adapted from (Letellier, 2007).

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There are many factors which influence the level of documentation selected for a project. These include but are not limited to the scope of the project, the available budget, and the time constraints. This work seeks to illustrate diagnostic challenges that can arise when selecting a level of documentation. To do this, two historic masonry structures were used as case studies. They were documented using a combination of photogrammetry, laser scanning, and thermal imaging. Subsequently, the results of documentation were used to generate three-dimensional models in a computer aided design program Rhino. To understand the implications of different levels of documentation, three slightly different geometries were generated and subjected to the same loading conditions using physics-based modelling.

1.2 Previous work combining documentation and numerical modeling

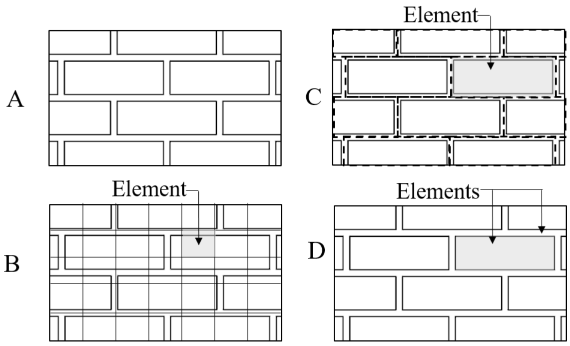

Figure 1. Illustrations of different numerical modeling levels. A) Masonry wall, B) Macro modeling, C) Simplified micro modeling, D) Detailed micro modeling

There is an abundance of literature where methods of documentation are combined with numerical modeling for assessment of historic structures. In the interest of space, only a few will be considered in this work. Specifically, a few examples of each level of numerical modeling (Figure 1 will be discussed.

Carpinteri et al, 2005 synthesized the results from both non-destructive evaluation, laser scanning, and non-linear numerical modeling to assess damages on a historical masonry tower in Alba, Italy (Carpinteri et al., 2005). In that work, the exact locations of the stones in the tower were not explicitly modeled, rather a macro element model was used (Figure 1B). Similarly, Blyth et al, 2019 used drone-based photogrammetry to capture the geometry and damage state of a historic lighthouse in Charleston, SC and synthesized the results with data from structural health monitoring. In this work, the geometry was again converted into a macro element model and was investigated using discrete element modeling.

Riveiro et al, 2011 used close range photogrammetry to capture the exact geometry of each stone in a historic masonry arch bridge. This geometry was then used to generate a simplified micro model (Figure 1C) which was examined with finite element analysis (Riveiro et al., 2011). While detailed micro modeling is the most computationally intensive approach, it has been used in several previous works. Napolitano et al, 2019 synthesized the data from terrestrial laser scanning, photogrammetry, and thermal imaging to determine the geometry of a masonry wall behind a fresco in Palazzo Vecchio. Subsequently, this work examined the structural response of the wall using a detailed micro modeling approach (Figure 1D) using finite-distinct element modeling (Napolitano et al., 2019a).

In this work, detailed micro modeling will be the level selected for numerical modeling. The case studies will be modeled using several different levels of documentation discussed in Section 4.

2. CASE STUDIES

2.1 Baptistery di San Giovanni

The first structure that was examined was the Baptistery di San Giovanni in Florence, Italy. The baptistery has an octagonal structure with eight curved ceiling panels comprising the dome of the building. While the earliest reference to the structure occurs in 897 AD; the foundations of the structure have been dated to the Roman era (Hess et al., 2018). At the present moment, the Roman foundation walls exhibit a large degree of cracking (Figure 2 (Napolitano et al., 2019c,d; Napolitano and Glisic, 2019a)).

Figure 2. Subterranean foundation wall of the Baptistery di San Giovanni showing cracks

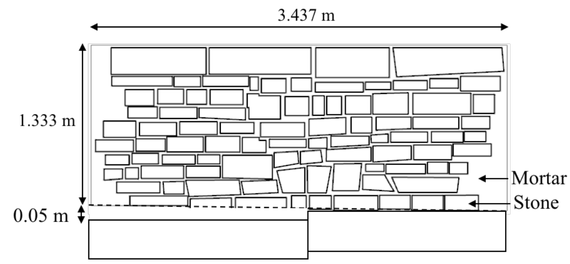

Figure 3. Front view of three-dimensional model showing existing locations of stone and mortar, overall geometry, and settlement conditions.

While the origins of these cracks were not originally known, in prior works (Napolitano et al., 2019c,d; Napolitano and Glisic, 2019a) multiple causes were computationally explored. It was found that a combination of settlement on the left side of the wall (Figure 3 and an earthquake with an epicentre on the left caused the existing damages.

2.2 The Room of the Elements in Palazzo Vecchio

Also located in Florence, Palazzo Vecchio functions as the current city hall. Since the Middle Ages, the structure has been built up based on the needs of its occupants. This work considers a room in the Southeast corner of Palazzo Vecchio, the Room of the Elements. Starting in 1558, there were concerns with the structural stability of this section of the building and steel reinforcing bars were added. Presently, there is cracking on a stone wall in the Room of the Elements which is visible through a layer of fresco (Figure 4 (Napolitano et al., 2019a)).

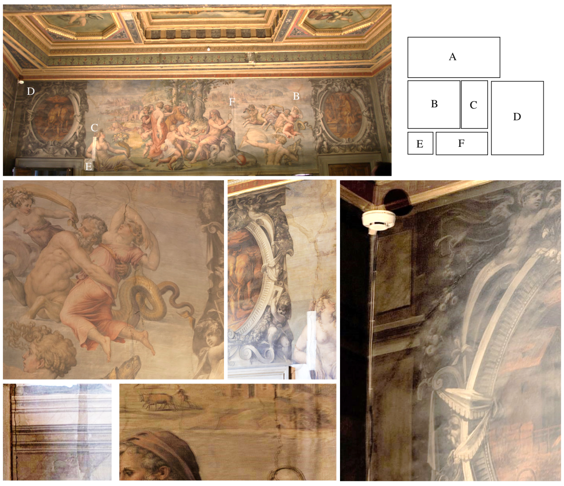

Figure 4. Cracks on fresco in the Room of the Elements in Palazzo Vecchio.

Similar to the foundation wall of the Baptistery, several combinations of loads were explored for this structure in a previous work (Napolitano et al., 2019a). Napolitano et al, 2019 found that settlement of the middle of the wall (Figure 5 on the order of 0.05 m caused the existing damage.

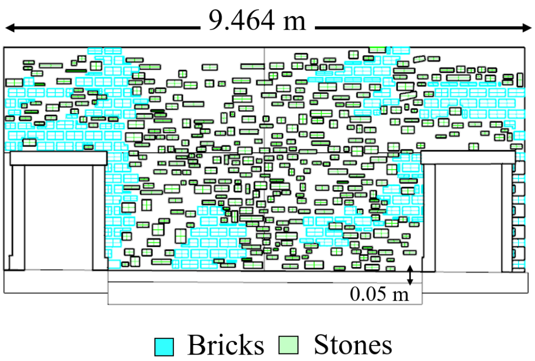

Figure 5. Front view of three-dimensional model showing existing locations of stone, brick, and mortar, overall geometry, and settlement conditions.

3. DOCUMENTATION OF GEOMETRY AND EXISTING CONDITIONS

To understand how different levels of detail in the documentation of historic structures can affect diagnostics, three different levels of modeling were used to document a foundation wall in the Baptistery di San Giovanni in Florence, Italy as well as a wall in Palazzo Vecchio in Florence, Italy. Terrestrial laser scanning (TLS) was used in combination with archival construction research to capture the current geometry and conditions of the Baptistery di San Giovanni. 14 scans were taken in the region surrounding the foundation wall using a Faro Focus 3D × 130 laser scanner with 1-2 mm resolution. Cloud-to-cloud alignment was used in Faro Scene to align the different scans. In addition to TLS, high-resolution photographs were taken to capture the existing damages (Hess et al., 2018). An orthographic projection of the resulting 3D model was imported into a CAD program to extract the exact geometry of the stones and mortar. Three different levels of detail were used to generate different 3D models for structural analysis. The first level of detail captured the exact locations of each stone in the wall; the second level of detail made small perturbations to the joints in one section of the wall; the third level of detail was an idealized, isodomic pattern (Figure 6A-C). The locations of the existing cracks in the wall can be seen in Figure 6D.

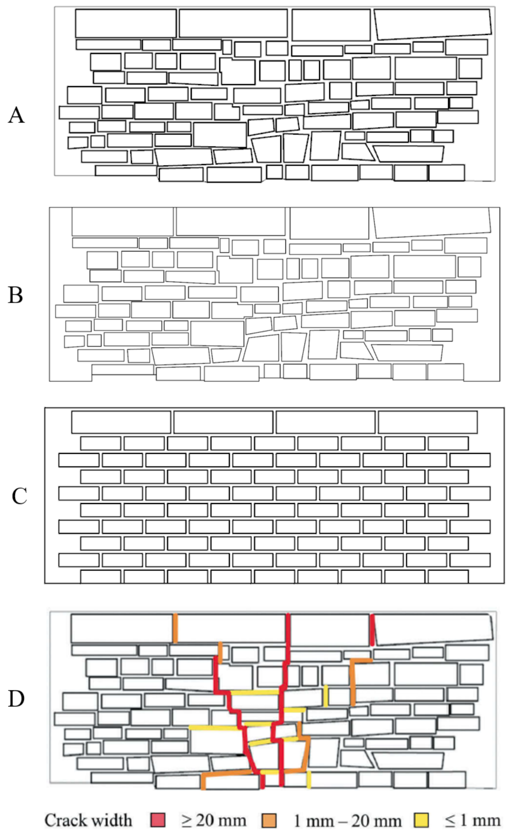

Figure 6. Existing geometry of the wall, B) Perturbed geometry, C) Isodomic geometry, D) Crack map. Figures adapted from (Napolitano et al., 2019c).

For documentation of the damaged wall in Palazzo Vecchio, the same Faro Focus 3D × 130 laser scanner was used with 1-2 mm resolution. In addition, 200 high-resolution images were taken of cracks in the frescoes using a Canon 5D DSLR camera. Furthermore, as damages to the wall were masked by layers of fresco, non-destructive evaluation techniques were also used to map existing damage conditions. 72 thermal images were taken using a FLIR A615 camera with a resolution of 640 ± 480 pixels, a thermal sensitivity of 0.05 °C, and an accuracy of ± 2 °C (Hess et al., 2015). A combination of the geometry captured using line-of-sight methods as well as thermal imaging was used to generate the 3D models for structural analysis. Again, the first level of detail was the exact location of the stones in the wall; the second level of detail was a semi-idealized model where the stone and mortar dimensions from the exterior of the building were used; the idealized model organized the stones into an isodomic pattern (Figure 7A-C). The locations of the existing cracks in the wall can be seen in Figure Figure 7D.

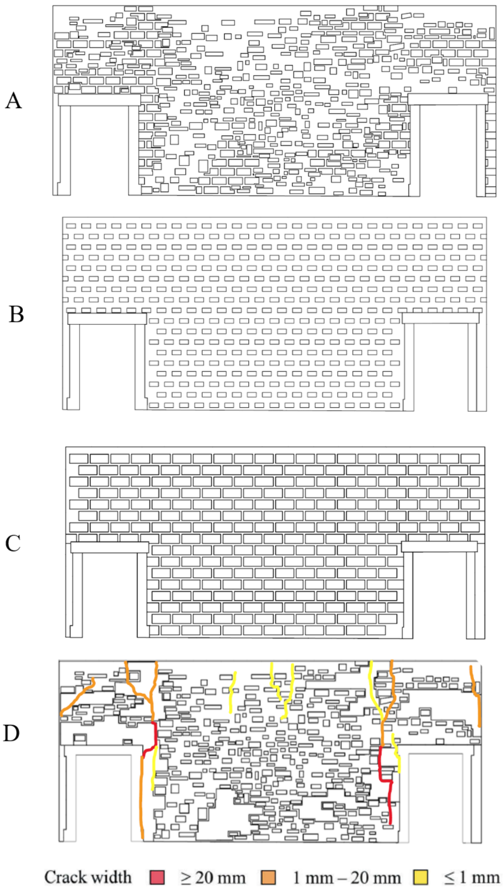

Figure 7. A) Existing geometry of the wall, B) Semi-Idealized geometry, C) Idealized geometry, D) Crack map. Figures adapted from (Napolitano et al., 2019c).

4. PHYSICS-BASED MODELING

It has been shown that regions of interest on a structure can be examined individually if the proper boundary conditions are applied (Lemos, 2007; Kavanaugh et al., 2017; Roca, 2004; Clemente, 2006; Asteris et al., 2015). Thus, to examine only the walls shown in Figures 6 and 7 and not the whole structure, linear finite element modelling was carried out first to calculate the boundary conditions and finite-distinct element modelling was used second to examine detailed displacements and cracks on the walls.

4.1 Background on Finite-Distinct Element Modeling

Distinct element modelling (DEM) and finite-distinct element modelling (FDEM) have been widely applied to masonry construction (Fang et al., 2018; Napolitano et al., 2019e; Napolitano and Glisic, 2019b) and proven to correspond with experimental testing (Giamundo et al., 2014; Napolitano and Glisic, 2019a). In this numerical method, the individual stones and mortar within the walls were allowed to develop stress and can be deformed as occurs with linear finite element modelling. In addition however, individual stones can rotate and displace so that crack patterns are evident.

4.2 Applications to case studies

As stated, previous studies have compared the existing crack patterns for these two cases studies with the results of the simulation to a response of several loading combinations (dead load, settlement, earthquake) (Napolitano et al., 2019a,d). The loading combinations which were found to have most probably caused the existing conditions were used to compare the three different levels of modeling.

Figure 8 shows the three geometries for the Baptistery settled 0.05 m on the left side. In the model where the locations of the stones match the existing geometry, it can be seen that the cracks are concentrated in the middle of the wall which closely aligns with the existing conditions. When small perturbations are added to the geometry however, not only do the locations of cracks change but so does the magnitude of cracking. There are many regions of the wall which were uncracked in the initial, more accurate model which are now exhibiting minor cracking (on the order of 1 mm). Thus this shows, that even small perturbations in the geometry of a historic structure can affect the results of structural analysis and diagnostics. Lastly, if the isodomic pattern is considered, it can be seen that the magnitudes and locations are now significantly different than the first two geometries as well as significantly different from the existing damage. Thus, this shows that if idealized, isodomic patterns are used for structural analysis of historic structures, a practitioner must understand the diagnostic limitations of the tools they are using.

A similar analysis was carried out for the wall in Palazzo Vecchio. The existing conditions documented using TLS, thermal images, and high-resolution images were directly compared to the outputs of the simulations to see if the level of detail would change the results of diagnostics. Figure 9 is a plot of the simulated crack widths for all three geometries under 0.05 m settlement of the middle (found in previous work to be the cause of existing damages). Again, it can be seen that the crack patterns change with the level of detail in the analysis model. For the existing geometry and isodomic geometry, cracking can be seen in the middle of the wall on the order of 1-9 mm. However, in the semi-idealized case, these cracks are not present which could change the outcomes of diagnostics.

5. CONCLUSIONS AND FUTURE WORK

As can be seen in Figures 8 and 9 as the level of detail for the model is changed, the resulting crack pattern varies. Thus if a model is to be used for diagnostic purposes, it should be at least at the preliminary level, if not the detailed level, depending on the scope of the project. When the initial levels are used the ensuing crack patterns tend to spread further in the highly-regularized model with smaller values. This could lead to the assumption that only minor cracking would take place. However if the same loads are examined on the existing geometries, it can be seen that in both case studies, the highly irregular geometries lead to stress concentrations. These stress concentrations can manifest as larger cracks on the order of a couple centimeters. Since in diagnostics, the difference in a couple of millimeters and a couple of centimeters is a large one, this could significantly alter preservation planning and rehabilitation plans.

Presently, there are many applications of machine learning for the derivation of structural analysis models from documentation models. In the future, a method using Convolutional Neural

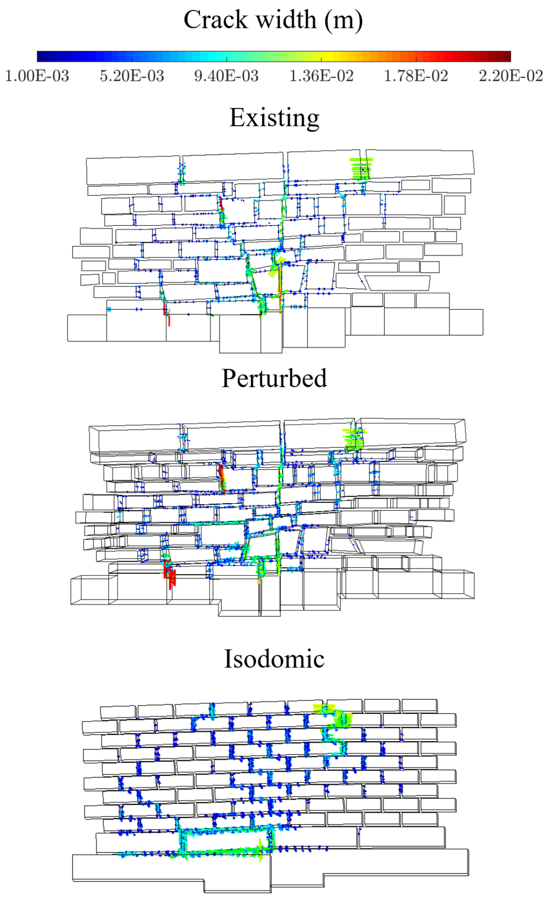

Figure 8. Results of simulation for existing, perturbed, and isodomic

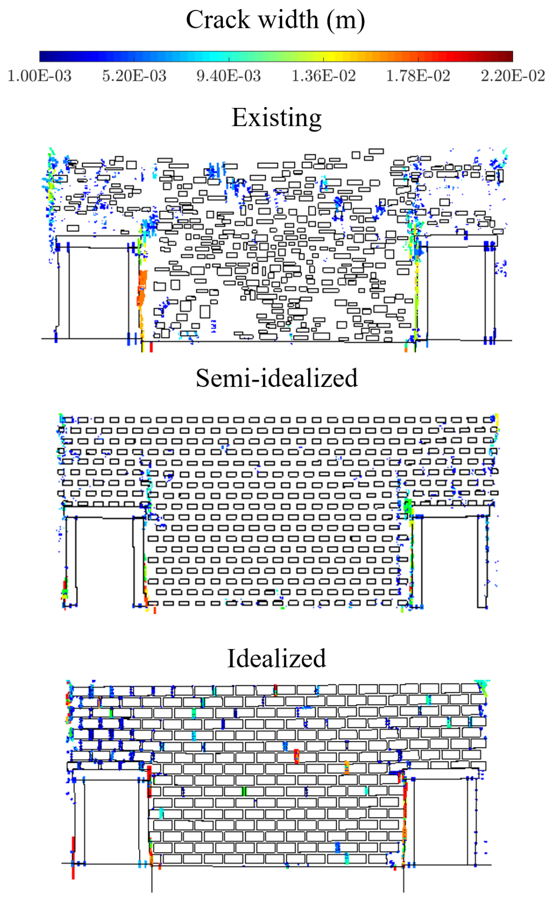

Figure 9. Results of simulation for existing, perturbed, and isodomic

Networks to extract the location of stones in orthographic photographs generated from photogrammetry should be developed. By tracing out the exact geometries and locations of stones in a wall, the process of creating more detailed, accurate models can be augmented so that diagnostic processes can be more rigorous.

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