LINKED DATA FOR THE CATEGORIZATION OF FAILURES MECHANISMS IN EXISTING UNREINFORCED MASONRY BUILDINGS

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ABSTRACT: *Assessing the structural integrity of unreinforced masonry structures is a complex and time-consuming process that necessitates the knowledge of various experts and meticulous cross-referencing of diverse data to achieve a comprehensive understanding of the building. In recent years, the Architecture and Construction Industry has witnessed a digital transformation, largely driven by Building Information Modeling (BIM). BIM has proven immensely valuable in the conservation of historic buildings. However, while it excels in new construction projects, its full potential is not fully realized when dealing with existing structures. A clear example of this limitation can be observed in the Industry Foundation Classes (IFC) format, which lacks instances necessary for accurately representing existing building features. This research contribution aims to advance the process of semantic enrichment of BIM for existing buildings, building upon findings from existing literature. Leveraging the Linked Data Approach and utilizing both existing ontologies and newly proposed domain ontologies, the objective is to facilitate the identification of vulnerabilities and potential local failure mechanisms. The geometric information of the building is represented in the IFC STEP format and enriched semantically by establishing new relationships between classes that are not present in the standard IFC. This approach is applied to a case study in the historical center of Castelnuovo di Porto, Italy. The results of this work demonstrate how the proposed model, enhancing the BIM representation of existing buildings and enabling better identification of potential weaknesses, contributes to improved preservation and seismic resilience of historic structures.*

KEYWORDS: *BIM, Linked Data, Semantic Modeling, Historic Constructions, Structural Masonry.*

1. INTRODUCTION

Before the advent of modern construction techniques, buildings were raised employing local materials and construction methods, resulting in a large percentage of the built heritage being composed of unreinforced masonry structures. The effectiveness of unreinforced masonry constructions depended on adhering to a set of empirical rules known as the 'rule of the art (Antonino Giuffré et al., 2010). This aspect becomes particularly critical in seismic scenarios, as past seismic events demonstrated that following the 'rule of the art' ensures walls exhibit a *monolithic behavior*, fundamental to being resistant to earthquakes. Furthermore, the proper connection between structural elements is another critical factor that helps prevent out-of-plane local failures. These failures can happen when walls or portions of walls collapse outward during an earthquake, posing a significant danger to both the structure and its occupants (Antonino Giuffré, 1993; Antonino Giuffré et al., 2010).

The Italian Code, which is a major reference for the assessment of historic buildings, provides three levels of analysis of the structural behavior of existing unreinforced masonry buildings: (i) Identifying the shear strength of the masonry under examination, (ii) Verifying local mechanisms, and (iii) Conducting global numerical analyses. (Norme Tecniche per Le Costruzioni, 2018). The three levels of assessment become increasingly more comprehensive, with their accuracy contingent on the modeling assumptions. Consequently, opting for the simplest level of assessment would be preferable when knowledge is limited.

Considering these principles, a precise evaluation of the structural behavior of existing non-reinforced masonry buildings, utilizing more advanced methods, necessitates a thorough examination of the structure, involving

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experts from diverse fields. (ICOMOS, 2005). Consequently, a systematic methodology is needed to allow the integration of data of different types, avoiding the repetition or defeat of pivotal information.

With the introduction of Building Information Modeling (BIM), the architecture and engineering industries have significantly changed their processes. This technology, although it was developed for the construction of new buildings, has not gone unnoticed in the field of rehabilitation of historic buildings. Today, the term HBIM (Historic Building Information Modeling) identifies the application of BIM technology to historic buildings (Maurice Murphy et al., 2009). The HBIM methodology has been explored as support to various areas of conservation (Pocobelli et al., 2018; Volk et al., 2014). Relevant efforts have been done to improve the representation of complex geometry, mainly with the integration of advanced survey acquisition methods (Cotella, 2023). HBIM applications exploit the potentiality to map damage and deformation accurately (Barontini et al., 2022; Moyano et al., 2022), conduct simulations (Gigliarelli et al., 2017; Ursini et al., 2022), manage the intervention on site (Biagini et al., 2016) and optimize facility management (Piselli et al., 2020).

Despite its widespread use, HBIM encounters challenges in its application, mainly because the original BIM methodology was primarily introduced for new construction projects. In reality, even the use of Industry Foundation Classes (IFC) needs to be enhanced to digitize existing constructions. Consequently, the semantic enrichment of HBIM models has emerged as an increasingly researched area. Due to the multidisciplinarity of the conservation field, the use of Semantic Web Languages through a Linked Data approach is gaining momentum (Cursi et al., 2022). The advantage of this methodology is that it allows modeling domain-specific information using specialized ontologies, which can be employed as external links to enhance the content of the BIM models.

From a broader perspective, the use of semantic web standards such as Resource Description Framework (RDF) and Web Ontology Languages (OWL) has the advantage of providing interoperability between data of different domains which are published on the web. On the other hand, IFC is written in EXPRESS language, and has a strong emphasis on the tridimensional representation of the geometry, while remaining difficult to integrate with other web sources (Rasmussen et al., 2020).

The ifcOWL ontology has been a pioneering attempt to extend the content of IFC to the semantic web (Beetz et al., 2009). However, due to its extensive length and complexity, it becomes challenging to implement and utilize in practical applications. As an alternative, other more contained ontologies have been proposed to represent construction instances in the semantic web. Under this approach, spaces are defined using the Building Topology Ontology (BOT) (Rasmussen et al., 2020), building elements with the Building Element Ontology (BEO) (Pauwels, 2018), and materials with the Material Property Ontology (MAT) (Poveda-Villalón & Chávez-Feria, 2020). The tendency of *modularization* of information based on different domains also interested the BuildingSmart Technical Room. Indeed, for the next generation of IFC, it is proposed to have a common base layer, connected to several extensions belonging to different domains (Berlo et al., 2020). In addition, the IFC base schema will be language-independent, ensuring greater interoperability with formats currently in use in other fields, including RDF.

In the past, there have been proposals for large and complex ontologies to represent historical data. The CIDOC-CRM for instance (Crofts et al., 2003), has been mainly developed for museums, but then extended to other domains such as the representation of non-destructive testing techniques (Kouis & Giannakopoulos, 2014), annotation of degradation phenomena of stones (Veron et al., 2015), and also for the semantic enrichment of HBIM models (Acierno et al., 2017). However, currently also in the field of historic constructions, there has been a recent preference for using a network of modular ontologies instead of a single complex ontology (Bonduel, 2021). This facilitates the better management of the ontology and the connection with different domains.

This paper aims to propose a method to digitize current methods for structural assessment of existing unreinforced masonry buildings. The purpose is to improve the management of the alphanumeric data associated with three-dimensional models, stressing standardization and interoperability. Two new domain ontologies are proposed: (i) Historic Masonry Ontology (HMO); (ii) Failure Mechanism Ontology (FMO). The first represents masonry material, while the second represents the vulnerabilities associated with specific types of masonry collapse. The two ontologies can be used together or combined with other domains. In particular, they can be used for the semantic enrichment of BIM models, combining geometry representation and alphanumerical data. This is demonstrated using a web app to map IFC and Turtle files (A. Donkers et al., 2023).

This paper is organized as follows. After this introduction, the next chapter is ‘Materials and Methods’, followed by ‘Results and Discussion’, and ‘Conclusions’.

2. MATERIALS AND METHODS

From a structural point of view, masonry is a heterogeneous material, constituted by *units* and *joints*. Units are bricks or stones which actively contribute to the load-bearing capacity and stability of the wall. Joints are the junctures between masonry units and can be either dry or filled with mortar. The most resistant masonry should have an arrangement of discrete elements such that monolithic behavior is ensured.

When the wall exhibits monolithic behavior, structural simulations can be conducted by considering a corresponding homogeneous material. However, even in such cases, the wall's morphology needs to be assessed, to define the most appropriate modeling assumptions. Indeed, the Italian Building Code designates specific mechanical parameters of reference, considering the type, size, materials, and arrangement of units and joints.

With these premises, it is evident that for the structural analysis purpose, it is necessary to provide a comprehensive representation of the masonry material, considering its heterogeneous features. In the already existing representation schemas, such as the IFC or the MAT ontology, there is no possibility of having such a detailed description. Wall instances are indeed associated with ‘material layers’, and to each layer, it is attributed and homogeneous or even heterogeneous material, but where the different material's constituents are not defined as classes. In this way, it is possible to represent discontinuities only along the cross-section of the wall, which is not representative of the typical configuration of masonry walls (Figure 1).

To fill this gap, a new ontology was designed. This *Historic Masonry Ontology* (HMO), was conceived as a *foundation* ontology, to be used for the structural assessment of historic masonry structures, independently from the type of analysis (i, ii, or iii level). Then, based on the specific analysis level, other ontologies can be merged into the HMO. As a proof of concept, the Failure Mechanism Ontology (FMO) was subsequently developed to model the causes and consequences of failure mechanisms in masonry walls. The FMO is linked to the HMO ontology due to the relationship between masonry quality and wall vulnerability.

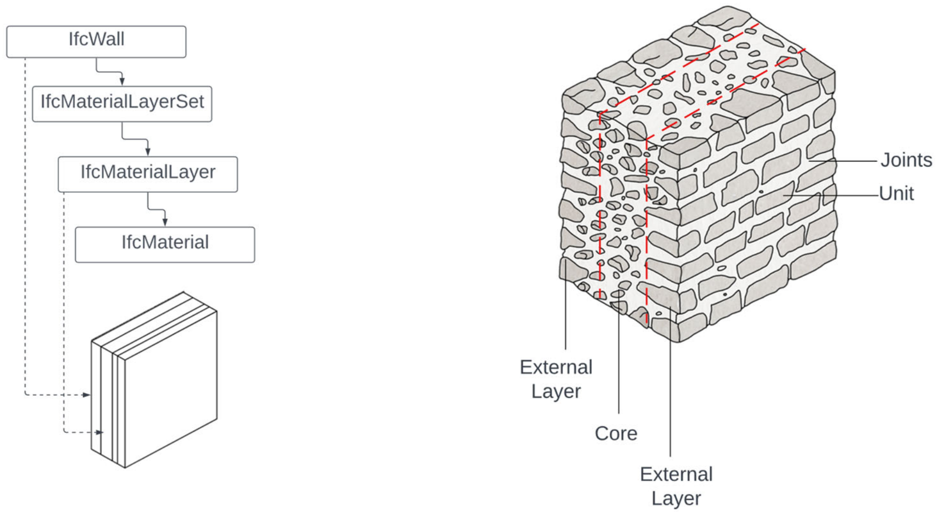


Figure 1. Morphology of an historic masonry wall compared to material modeling in IFC.

Both the HMO and the FMO ontologies were integrated with existing ontologies, exploiting the interoperability of the Semantic Web Modeling. In particular, the connection with the BEO and the MAT allows a direct mapping between the semantic model and the BIM model in IFC.

To link data between the model BIM and the model in Semantic Web Language, information is mapped between IFC model classes and corresponding ontology classes, using a common GUID. Damage elements do not have a direct equivalent in IFC, but can still be modeled as IfcElementy proxies and mapped to the ontology via GUID as well.

As shown in Figure 4, building elements, damages, and materials serve as a bridge between the IFC and the semantic model, allowing geometries to be associated with the semantic model based on the HMO and FMO ontologies.

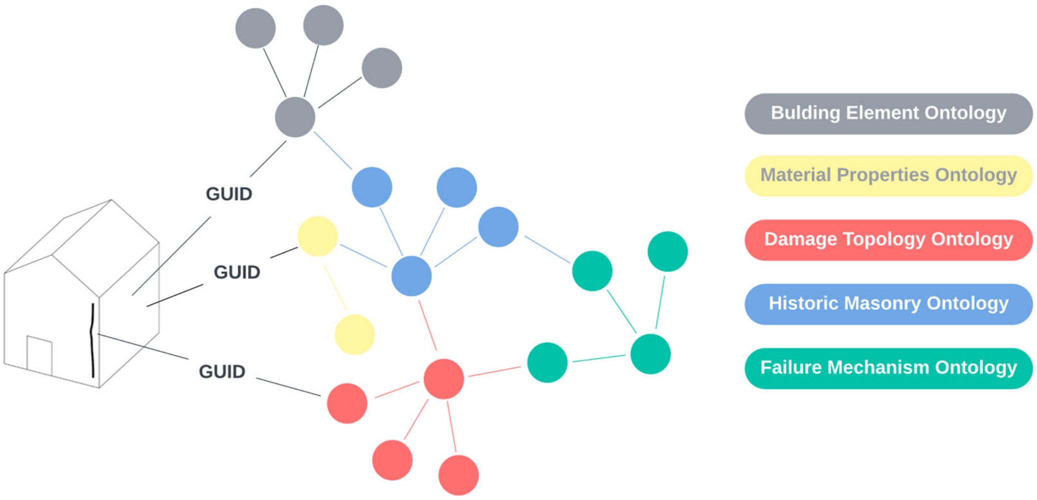


Figure 2- Methodology for the semantic enrichment of the BIM model

2.1 Historic Masonry Ontology

The Historic Masonry Ontology was implemented for the detailed modeling of masonry materials. Given the wide variety of masonry types, it was decided to propose a rather generic ontology that could be used to represent all types of masonry, regardless of units and mortar materials and morphology.

The walls are modeled with the class hmo:MasonryWall, which is a subclass of beo:Wall. The connection between the HMO and BEO ontologies is fundamental, both for interoperability between domains and semantic enrichment of the BIM models. An hmo:MasonryWall is defined by two data properties: (i) hmo:wallName and (ii) hmo:quality. The hmo:wallName allows the identification of different masonry walls in a human readable manner; the hmo:quality is intended to provide a qualitative description of the wall's quality to represent compliance with the rules of art in a synthetic manner.

The masonry layers are modeled by the class hmo:MasonryLayer, which is related to hmo:MasonryWall by the property hmo:isLayer of, the inverse of hmo:hasLayer. Each masonry layer may contain one or more hmo:Patterns. A pattern refers to a specific section of the layer, characterized by well-defined units and joint types that can be easily standardized.

The necessity for employing more than one pattern to describe a certain masonry type becomes especially critical when attempting to represent masonry types that involve various brick resources. These diverse brick resources contribute to the formation of walls comprising units with irregular compositions, interspersed with brick elements, as shown in Figure 1Figure 3.

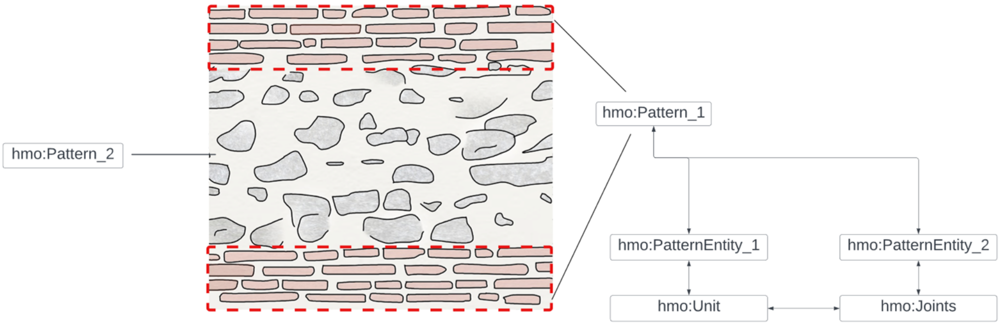


Figure 3. Elevation view of an example masonry and corresponding classes in HMO ontology modeling.

Units and joints can be modeled employing specific subclasses of the hmo:PatternEntity, which are hmo:Units and hmo:Joints. Joints are modeled as interfaces of the units, referring to the class bot:Interface. Units and joints present specific features, modeled as data properties. These classes refer in a general way to all the units and joints of the wall, so general information, such as the maximum and minimum dimensions of the units, or the horizontality and verticality characteristics of the morrtar, are assigned.

Both hmo:Unit and hmo:Joint henerith the mat:Materials from the superclass hmo:PatternEntity. The class related to the material to be associated with units and mortars does not need to be re-modeled in this ontology. In fact, it is intended to refer to and link to the MAT ontology. In addition, material characteristics can be linked to a database. This approach, derived from the Building Performance Ontology (BOP) (Donkers et al., 2021) developed for building performance assessment, is well-suited for masonry applications. The complexity of defining certain parameters leads us to rely on established Databases (Vanin et al., 2017). Finally, the ontology relates to the ontology of Damage Topology Ontology (DOT) damage, since the presence or absence of certain damage is an indicator of quality (Hamdan et al., 2019).

Figure 4 presents the Historic Masonry ontology and the link with other existing ontologies.

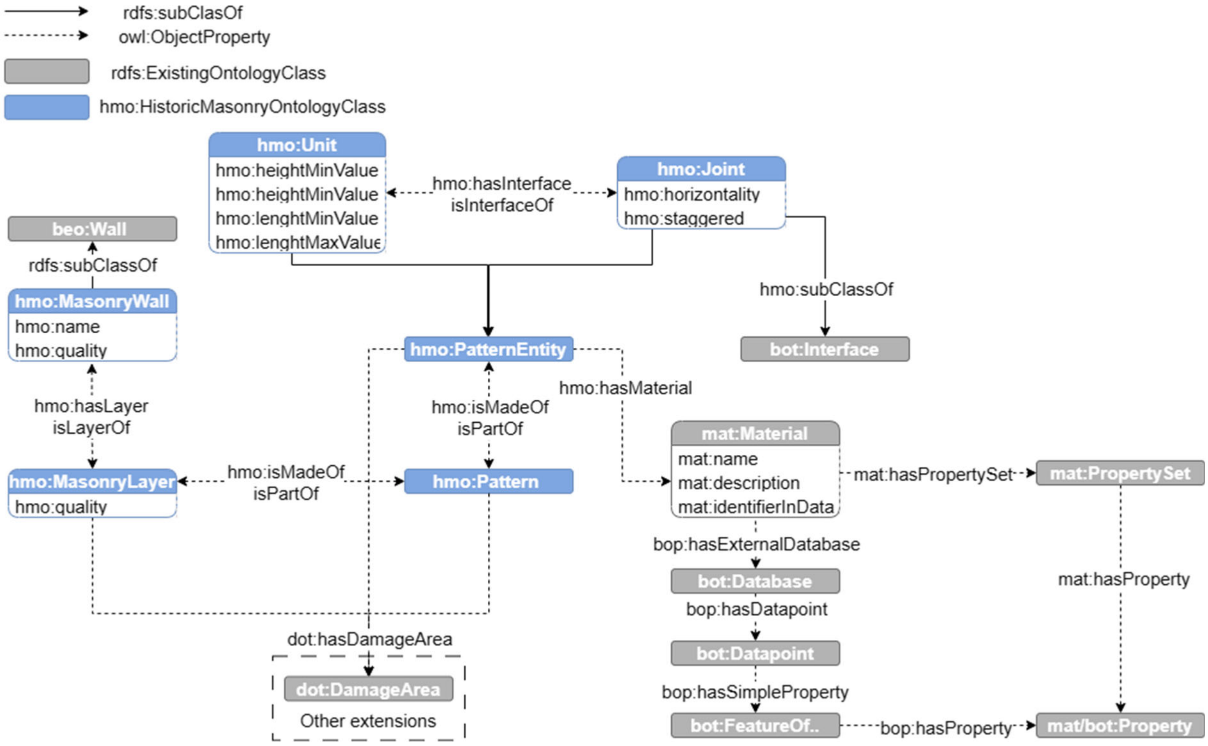


Figure 4 - Overview of the Historic Masonry Ontology

2.2 Failure Mechanism Ontology

The ontology for Failure Mechanisms enables the modeling of expected failure mechanisms by modeling the vulnerabilities that cause them.

The ontology consists of two primary classes, namely, 'fmo:Vulnerability' and 'fmo:FailureMechanism'. These classes are interconnected through the object property 'fmo:isFacilitatedBy', which establishes a relationship between mechanisms and vulnerabilities. A specific mechanism can be facilitated by one or more vulnerabilities.

To account for the qualitative nature or a combination of qualitative and quantitative aspects in vulnerability descriptions, distinct sub-classes are defined for 'fmo:Vulnerability'. This approach enhances comprehensiveness by providing dedicated classes for different types of vulnerabilities.

One of the subclasses within 'fmo:Vulnerability' is 'fmo:BadMasonryQuality', which relates directly to the previously described ontology. Defining masonry quality requires detailed description of its morphological characteristics. The object property 'fmo:isInfluencedBy' serves as a connection between the 'hmo' and 'fmo' ontologies. It is anticipated that other vulnerability subclasses can connect with various domain ontologies to address specific aspects. For example, determining whether floors are pushing and causing the presence of horizontal thrusts (e.g., 'fmo:HorizontalThrust').

Within the 'fmo:FailureMechanism' class, several subclasses exist, such as 'fmo:InPlaneFailure', 'fmo:HorizontalBending', and 'fmo:VerticalBending'. These classes require enrichment with a set of properties, which can indicate the associated load conditions for a particular mechanism. Additionally, the 'fmo:FailureMechanism' class is related to the 'dot:DamageArea' class from the DOT ontology. This relationship acknowledges that the presence of damage may be a result of an ongoing mechanism.

An overview of the complete ontology is shown in Figure 5.

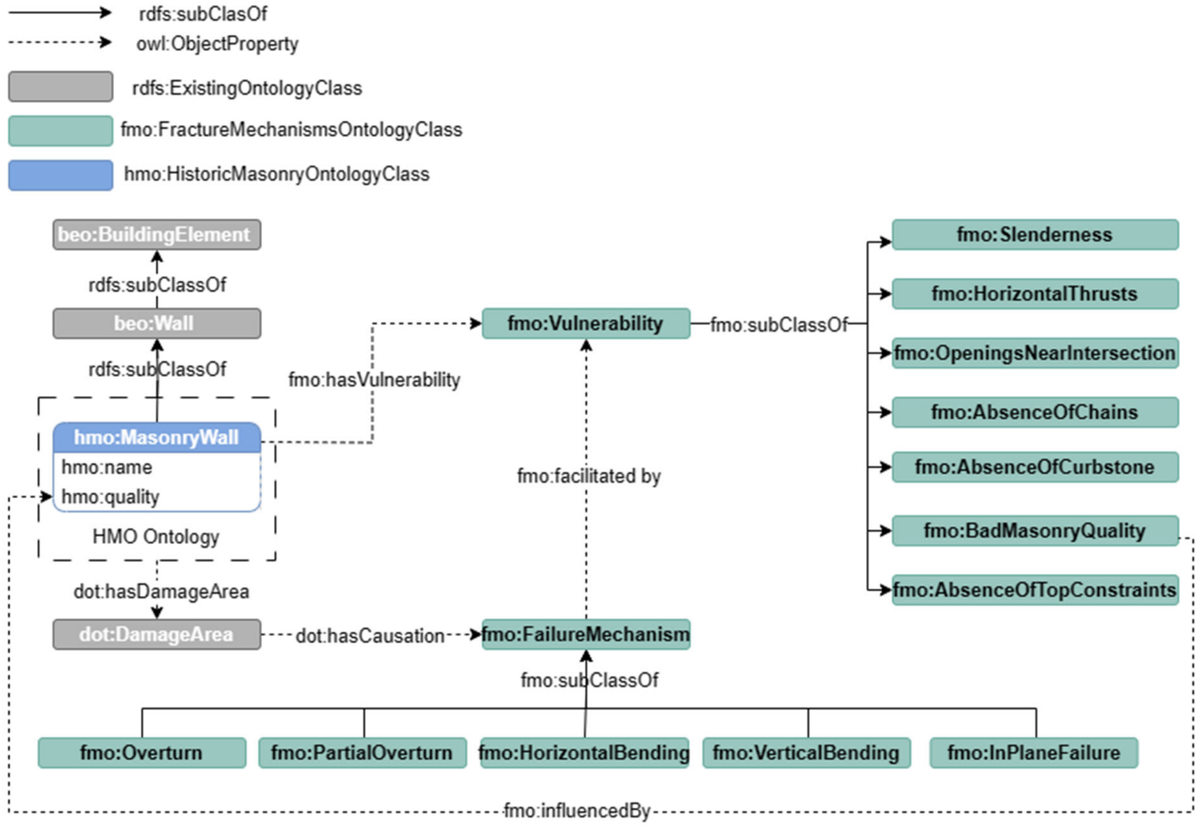


Figure 5 - Failure Mechanisms Ontology

3. RESULTS OF THE PRACTICAL APPLICATION AND DISCUSSION

To concretely illustrate the application of the proposed methodology, a residential building located in the historic center of Castelnuovo di Porto was selected. Castelnuovo di Porto is a town in central Italy known for its rich heritage of historical buildings and a diverse range of architectural styles, including residential structures, churches, and public facilities that reflect the area's rich history and architectural evolution over the centuries. The choice of Castelnuovo di Porto as a case study was driven by its structural complexity and the need to address specific challenges associated with evaluating historic buildings situated in urban environments with dense historical and cultural value.

The chosen methodological approach was particularly applied to a building that presented a set of structural and conservation challenges. This specific building, labeled as 'Wall_417_a' in the model, is part of a group of interconnected masonry structures, forming an architecturally significant complex.

In the BIM environment, the construction was modeled using proprietary software, and exported according to the IFC schema. Load-bearing walls were modeled, adding windows and doors as simple holes, modeling arches where present. Damages were included using the *IfcBuildingElementProxy* class. These elements simply serve to visualize, in the geometric model, the location of the damage. In the IFC file, there are no identified alphanumeric properties for the damages, nor any taxonomic relationship with other building elements. Regarding masonry materials, in the IFC these are identified as homogeneous, to be associated with a certain MaterialLayer.

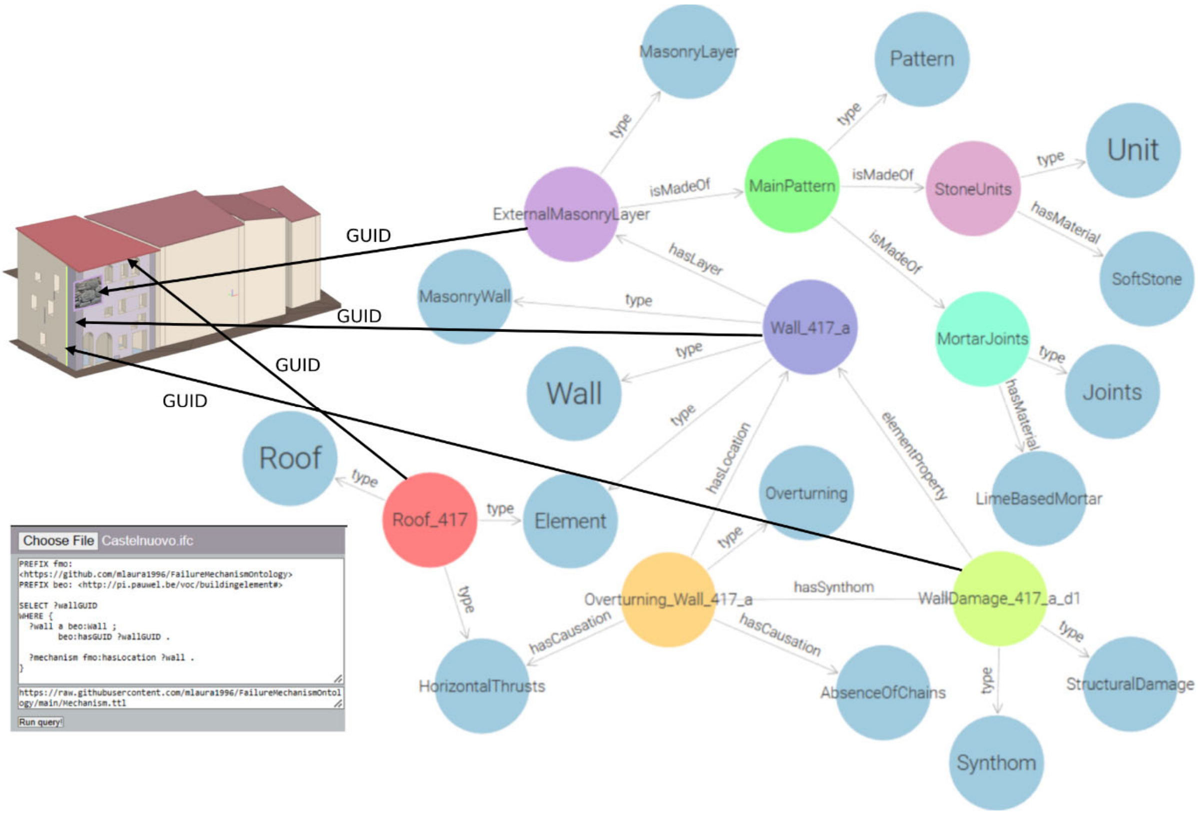
A turtle file was created to proceed with the semantic enrichment. This particular application concentrates on the main facade of the building, referred to as 'Wall_417_a,' which is modeled using the BEO ontology. The name attributed to the façade refers to the number of the urban parcel: *417*, followed by the letter *a* as it is the first façade assessed. The wall is further represented in the model as a *hmo:MasonryWall* along with its corresponding *hmo:MasonryLayer*. Due to the initial survey's limited accessibility, only the external layer was accounted for. Therefore, the focus remained on modeling the *hmo:ExternalMasonryLayer* and associating it with a *hmo:Pattern*. The details regarding the entities of the *hmo:PatternEntity* are shown in Figure 6.

The structural damage is modeled as both *dot:StructuralDamage* and as a *fmo:Symptom*, since the presence of a crack could be a symptom of an out-of-plane mechanism. In detail, the presence of damage in one facade can be indicative of an out-of-plane mechanism occurring on the orthogonal facade. Through semantic modeling, this can be made explicit, as it was done for this model.

The roof was added to the semantic model as a *beo:Roof*, modeled as a *fmo:HorizontalThrust*, which is a subclass of *fmo:Vulnerabilities*, since a 'pushing' roof can cause the overturning of a wall. Consequently, the mechanism was modeled as *fmo:Overturning*, associating the mechanism instance to (i) the wall where it occurs; (ii) the pushing roof that caused it, (iii) the structural damage which represents its symptom.

The interactive mapping of the IFC model to the semantic model can be facilitated through web-based integration, leveraging JavaScript modules like IFC JS and COMUNICA. In this process, elements from both models are correlated using their respective GUIDs, allowing seamless cross-referencing between the two representations. This approach has been already proposed in the literature (A. Donkers et al., 2023) to query the information of the semantic model by clicking on the IFC geometry.

Figure 6 presents a comprehensive overview of what is described above. Within the IFC model, the classes corresponding to the semantic model are visually indicated by distinct colors. Notably, the semantic model consists of a network of interrelated classes, showcasing its capacity to define relationships that surpass the limitations of the IFC model. An example of the query interface is shown as well.



```
PREFIX fmo:
<https://github.com/mlaura1996/FailureMechanismOntology>
PREFIX beo: <http://pi.pauwel.be/voc/buildingelement#>

SELECT ?wallGUID
WHERE {
  ?wall a beo:Wall ;
        beo:hasGUID ?wallGUID .

  ?mechanism fmo:hasLocation ?wall .
}
```

```
https://raw.githubusercontent.com/mlaura1996/FailureMechanismOntol
ogy/main/Mechanism.ttl
```

Figure 6. Mapping the IFC and the Semantic Model.

The employment of the Historic Masonry Ontology enables the modeling of diverse wall thicknesses while considering the patterns formed by units and joints. This domain ontology offers versatility and conciseness, accommodating various masonry typologies. Moreover, its seamless integration with established ontologies like BEO, MAT, and DOT enhances its utility, particularly in enriching IFC models with semantic data. Addressing the limitation of standard representations, it allows accurate association of material properties with specific masonry elements, such as bricks, stones, or mortar.

The adoption of semantic language within these ontologies results in enhanced interoperability, with the potentiality of extending into fields like chemistry and facilitating the assessment of material degradation. The possible interaction with databases presents valuable opportunities for deriving mechanical properties from data and integrating ontologies into practical applications, including inspections and monitoring processes. By integrating the Historic Masonry Ontology with the Failure Mechanism Ontology it was possible to consider, in a single semantic model, masonry characteristics and vulnerabilities. This comprehensive view allows for an objective definition of masonry quality by comparing qualitative and quantitative data.

The systematic organization of masonry quality data with other relevant wall-related information, such as near-wall damage or the presence of lateral thrusts, is another innovative aspect. These data are presented as instances of classes, incorporating a range of characteristics. For instance, the damage is described not just descriptively but also as a potential symptom of an ongoing mechanism. Similarly, the representation of the roof as a structural element and a possible pushing element further enhances the objectivity of assessments.

4. CONCLUSIONS

This contribution belongs to the field of research debating the role that digital tools assume in the activities of investigation, documentation, representation, and analysis of the built heritage. In particular, the illustrated work proposes a workflow that aims to integrate the HBIM digital environment with an ontological structure, seeking to raise the semantic level offered by current digital models for the built heritage and in particular for the analysis of building systems from a structural point of view.

In the last decade, various solutions for collecting, organizing, and managing cultural heritage information have given rise to a series of tools each with its database classification system, dedicated to representing a cultural artifact and its diverse contexts of investigation and interpretation. However, the same cannot be said of the built heritage, where on the one hand the complexity of the artifact itself and its historical evolution, and on the other hand, the presence of multiple disciplines in its processes of investigation, recovery, and intervention, have left the field effectively unexplored and lacking an organic approach to knowledge modeling. In this context, this article discusses the progressive adoption of two specific techniques - computer ontologies and the and HBIM models - highlighting their possibilities and ability to balance on the one hand the flexibility in dealing with the different disciplines involved on the other hand the rigor in information management necessary to effectively document the artifact.

The real change, therefore, is not to be found in new models for cataloging and documenting the building and its aspects but, rather, in approaches capable of integrating and making consistent the different cognitive models of the built heritage, fostering mutual understanding and collaboration among the different skills involved in such a complex process as that of investigation and documentation.

In this application, the primary focus was on the structural assessment of historic load-bearing masonry buildings. To achieve this goal, two new domain ontologies were developed, one for modeling masonry as a heterogeneous material and the other for defining vulnerabilities and related local mechanisms. This innovative contribution enables the semantic enrichment of BIM models using a Linked Data approach, effectively mapping the IFC and semantic model.

The results obtained from applying the proposed methodology allowed for the identification of its strengths and existing open issues. Among the advantages achieved, the methodology provides a more objective basis for structural assessments by considering diverse modeling assumptions. Moreover, it offers potential benefits in training new preservation experts, as the inclusive representation of the structure, materials, and preservation state fosters a better understanding of the structural behavior in existing unreinforced masonry buildings.

However, certain open issues require further development. One crucial aspect pertains to the integration of new domain ontologies into the methodology, especially for the development of global numerical models. This pioneering contribution lays the groundwork for future developments in this regard. Additionally, enhancing the user experience with the ontology is essential, and the creation of a platform that presents the ontology representation in the backend, capable of working with queries, and offering user-friendly interactions, would be highly valuable.

Furthermore, applying the proposed methodology to a larger case study with more extensive data could yield additional insights and demonstrate further benefits. Such an expanded application would reinforce the methodology's effectiveness and real-world applicability.

In conclusion, the development of the new domain ontologies and the application of the methodology present promising advancements in the field of structural assessment for historic masonry buildings. While it demonstrates numerous advantages, ongoing efforts to address open issues and explore potential enhancements will undoubtedly contribute to the continuous improvement and adoption of this innovative approach.

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