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LEVERAGING SEMANTIC WEB RULE LANGUAGES TO DEFINE MODELING ASSUMPTIONS FOR THE STRUCTURAL ANALYSIS OF UNREINFORCED MASONRY BUILDINGS

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SUMMARY: *The seismic assessment of existing unreinforced masonry structures is particularly complex. Defining the correct modelling assumptions is essential when using global models to ensure valid results. Achieving this often requires the collaboration of a group of stakeholders with diverse backgrounds who can thoroughly study the structure under consideration. Field-collected data must then be compared with existing literature and regulations before proceeding to the computational model. This phase is particularly labour-intensive, and errors, data loss, or duplication are common pitfalls. The advent of new digital data management methods can improve this methodology. Specifically, a linked data approach based on web ontology language can enhance interoperability between different research areas and enable the formal and comprehensive representation of data to facilitate informed decision-making. This article presents a new method based on linked data for defining modelling assumptions for analytical models used in the seismic analysis of existing unreinforced masonry buildings. Two complementary ontologies are proposed: the Historic Masonry Ontology and the Failure Masonry Ontology. The former defines the mechanical properties of masonry material, while the latter defines the most plausible collapse modes evidenced by earthquakes. In particular, this is achieved through Semantic Web Rules Language (SWRL), which interprets geometric and material data introduced into the ontology. The methodology is successfully applied in a real case study.*

KEYWORDS: *Linked Data, Semantic Web, Semantic Web Rule Language, Historic Constructions, Structural Masonry.*

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1. INTRODUCTION

Unreinforced masonry structures are a significant part of the European building stock and were built long before the establishment of modern building codes. In the absence of contemporary regulations, these structures were built solely based on the craftsmanship of the time, following what was known as the 'rule of art'(Giuffré et al., 2010). The rule of the art encompassed a set of empirical practices ensuring the monolithic behaviour of walls and the 'box behaviour' of the overall structure. Monolithic behaviour refers to the ability of walls to resist collapse due to disintegration, a phenomenon known as 'rubble collapse'. On the other hand, box-like behaviour occurs when masonry walls offer greater resistance to horizontal forces along their mid-plane than to loads orthogonal to that plane, to the extent that these orthogonal forces can be disregarded. This is achieved when orthogonal walls are effectively interconnected and when walls are well connected to the floors (Giuffré, 1993).

Past earthquakes, such as those that affected central Italy and especially L'Aquila in April 2009 and Amatrice in August 2016, have shown the seismic vulnerability of unreinforced masonry structures, which were, in most cases, built solely to support vertical static loads. In some cases, especially when the structure is in a seismic area, traditional anti-seismic devices, such as wooden or iron components, were built to improve the bracing between orthogonal elements (Carocci, 2012). However, apart from being sporadic, these elements are often insufficient to guarantee an adequate seismic response. This is especially the case in ordinary buildings, i.e. all those buildings that are not monuments but constitute the historic urban fabric.

Over the past decades, the scientific community has studied the seismic response of traditional unreinforced masonry buildings and identified the most problematic failure mechanisms: out-of-plane and in-plane modes. The former is the most dangerous and occurs for loads of low force when the wall rotates out of its plane. The latter occurs with higher force; they are less dangerous and depend mainly on the shear capacity of the wall (Valluzzi et al., 2021). Because of their uniqueness, the structural assessment of masonry buildings typically differs from that of modern structures. Over the years, several methods have been developed to study these buildings' seismic risk and behaviour (D'Altri et al., 2020; Lourenço, 2002). Currently, these include large-scale empirical methods (Ferreira & Ramírez Eudave, 2022) methods based on masonry shear capacity (Aşıkoğlu et al., 2020), local evaluation of potential collapse mechanisms (Grillanda et al., 2021) and global models (Valente et al., 2019).

Global models can be based on different modelling assumptions and use different methods of discretising the masonry walls (D'Altri et al., 2020). They allow an in-depth assessment of structures' overall behaviour. In particular, when using the equivalent frame method, the masonry walls are discretised into panels (called macro-elements) with which specific in-plane failure mechanisms are associated, assuming that no out-of-plane failure mechanisms occur. On the other hand, the continuum finite element method allows the assessment of the strain and stress distribution in the structure and determines both in-plane and out-of-plane kinds of failures. The use of global models presents several challenges, both from a computational point of view and from the point of view of the information required to implement models that are adequate to describe the structure under consideration. In particular, the more detailed the models, the more in-depth knowledge of the structure is required to correctly assume the mechanical parameters and constitutive laws to be used.

One of the main challenges lies in the fact that masonry is a heterogeneous material composed of units (i.e. stone blocks or bricks) and joints (the dry or mortared space between the units). Consequently, its structural behaviour relies on the mechanical characteristics of these components and how they are assembled to form the wall. When employing global models, it is often impractical to model units and joints separately. Instead, homogenisation techniques represent masonry as an equivalent homogeneous material divided into Representative Volume Elements (RVE), parts of the wall with repeated features. The Italian building code addresses this issue by providing guidelines on achieving homogenization and reference values for the mechanical properties of common types of masonry (Technical Standards for Constructions, 2018).

Borri et al. (2015) developed a method to assess the capacity of masonry walls under vertical and horizontal actions (in-plane and out-of-plane). This method based on visual survey is known as the Masonry Quality Index (MQI) and allows for deriving some of the (homogenised) mechanical properties of the masonry without invasive tests, namely the compressive strength, the shear strength, the Young's modulus and the shear modulus. Furthermore, this method (Borri et al., 2020) aids in identifying potential collapse scenarios, simplifying the process of defining modelling assumptions for creating the models.

Defining properties and modelling assumptions involves adhering to various rules and requires gathering a significant amount of data managed by different stakeholders with diverse backgrounds. This data is often collected at different moments but lacks significance when considered independently since it needs systematic organisation and interpretation. The primary challenge arises from using separate management systems owned by different stakeholders, leading to the potential loss or duplication of essential information. Furthermore, the subjective nature of data interpretation, conducted by humans rather than machines, presents an additional challenge.

A current research gap is the absence of a systematic approach for the direct definition of mechanical properties and potential failure mechanisms of unreinforced masonry structures. How can a systematic approach be developed to define mechanical properties and potential failure mechanisms of unreinforced masonry structures, leveraging the latest technologies in an open, non-proprietary, and scalable manner to ensure reproducibility across various case studies?

The advent of new technologies, such as Building Information Modeling (BIM), the Internet of Things (IoT), Virtual Reality, and artificial intelligence, has introduced changes to the construction industry. To effectively use these technologies, data management must ensure interoperability across various formats, maintain conceptual clarity, and employ machine-readable language.

The open IFC format is an important tool in BIM, as it allows information to be visualized across different BIM software. However, the use of the IFC format has some limitations. Firstly, from a content perspective, the IFC format was developed primarily for new construction projects and may need adaptation to meet the requirements of historical buildings (Laakso, 2012). Furthermore, in terms of interoperability, its functionality is limited to BIM environments. Lastly, regarding efficiency, information exchange using IFC is done through file exchanges, whereas storing specific information on the web could be more effective (Gómez-Romero et al., 2015). The scientific community is exploring the benefits of using the semantic web and linked data to overcome these limitations (Pauwels et al., 2013).

The Semantic Web is an extension of the World Wide Web that enables machines to understand and interpret data by providing a structured framework. It uses standards such as RDF (Resource Description Framework) and OWL (Web Ontology Language) to encode the relationships between data so that information can be linked, queried and interpreted in a meaningful way. This facilitates data integration, interoperability and the development of intelligent applications (Błażewicz, 2000).

Linked Data is a fundamental concept that enables the Semantic Web by allowing the linking and machine readability of data on a global scale, often used alongside ontologies (Bizer et al., 2011). Ontologies are formal representations of knowledge within a domain, consisting of concepts, their properties, and the relationships among them (Pauwels & McGlinn, 2022).

The Semantic Web is essential for developing a universally accessible methodology that is interoperable with current technologies and extendable by specialists in various fields, rather than a closed system limited to specific BIM software or the IFC schema. By offering a graph database where entities are identified via unique web identifiers, this approach ensures human- and machine-readable data, facilitating integration with other technologies like machine learning. This aspect is particularly important in historic building conservation, where traditional BIM tools fall short in representing complex relationships and multidisciplinary data (Cursi et al.,2022).

This paper introduces a new methodology based on linked data for defining modelling assumptions in structural global models used for the structural assessment of unreinforced masonry constructions. Two domain ontologies were developed: the Historic Masonry Ontology (HMO) and the Failure Mechanism Ontology (FMO). The HMO describes the formal characteristics of masonry and how these relate to the mechanical properties. The FMO describes the expected failure mechanisms to understand which types of numerical modelling are most appropriate for the case study under consideration. The two ontologies were implemented taking into account existing related ontologies. Moreover, they are accompanied by rules that formalise the relationships between their constituent classes. The ontologies were published online with detailed documentation on their purpose and use. Examples of applications are presented as well. The method proposed leverages the Semantic Web to enhance interoperability and scalability, addressing the limitations of current tools and supporting a more modular and integrated approach.

This paper is organised as follows. After this introduction, chapter 2 is a critical literature review, chapter 3 outlines the methodology employed to implement the ontologies; chapter 4 details the Historic Masonry Ontology, chapter 5 details the Failure Mechanism ontology, chapter 5 shows the application to the case study and chapter 6 discusses the main conclusions.

2. CRITICAL ANALYSIS OF LITERATURE REVIEW

2.1 Challenges and opportunities in Historic Building Information Modeling

The Building Information Modeling (BIM) methodology has transformed the design process for new constructions and is now increasingly applied to various other areas, including the conservation of architectural heritage (Pocobelli et al., 2018; Volk et al., 2014). This application is often referred to as Historic Building Information Modeling (HBIM) (Maurice Murphy et al., 2009).

HBIM applications leverage the ability to accurately map damage and deformation (Barontini et al., 2021; Moyano et al., 2022), conduct simulations (Gigliarelli et al., 2017; Leonardi et al., 2024; Ursini et al., 2022), manage on-site interventions (Biagini et al., 2016) and optimise facility management (Piselli et al., 2020).

Despite its potential, the fact that the BIM methodology was initially developed for new buildings has led to numerous challenges in its application to the built heritage. In particular, one of the major problems in built heritage is the presence of very complex geometries, which are difficult to model in proprietary software and represent in the Industry Foundation Classes exchange format. In fact, since the advent of the HBIM, one of the main fields of investigation has been SCAN-to-BIM, i.e., a methodology that allows complex geometries to be derived from the point cloud to create models (Oreni et al., 2014; Skrzypczak et al., 2022).

In addition to geometry, interoperability is a significant challenge when applying BIM to historic buildings, particularly semantic interoperability, which refers to the ability of data to maintain its meaning when transferred from one system to another (International Organization for Standardization, 2013). This challenge is closely related to the difficulty of associating specific alphanumeric data for heritage objects with geometries. The main problem stems from the fact that Industry Foundation Classes (IFC) were originally designed to be concise and template-driven to match the STEP format (Laakso, 2012). When attempting to introduce specific classes or properties for new uses, placeholders such as IfcElementProxy and IfcPropertySet are often used. However, these placeholders provide semantically poor descriptions (Wagner et al., 2022), while adding new elements to the standard is quite complex (Franz et al., 2016).

2.2 Linked data and ontologies

Currently, there is a growing trend of semantic models using the linked data approach to expand the BIM model for specific domains. With the linked data approach, new information can be added to the IFC while ensuring greater interoperability with systems outside the BIM model.

In particular, the Web Ontology Language (OWL) has the advantage of describing concepts formally and semantically deeply, using human-readable, machine-readable, and queryable syntax (Błażewicz, 2000). OWL is a computational language based on the Resource Description Framework (RDF) schema, i.e., it is based on triple subject-predicate-verb relationships, thus enabling the definition of vocabularies and relationships between terms. Beetz et al. (Beetz et al., 2009) converted the entire IFC schema into OWL and developed it with Barbau et al. (Barbau et al., 2012) and Pauwels et al. (Pauwels et al., 2015; Pauwels & Terkaj, 2016) proposing the ifcOWL schema.

IfcOWL is now a standard IFC representation format. Nowadays, it is recognised that using various domain ontologies rather than one large schema allows for optimised data management. The next generation of IFC will consist of a base layer and domain-specific extensions (Berlo et al., 2020). Within this approach, more contained domain ontologies have been proposed to represent construction instances in the semantic web. In this approach, spaces are defined using the Building Topology Ontology (BOT) (Rasmussen et al., 2020), building elements are represented by the Building Element Ontology (BEO) (Pauwels, 2018), materials are represented using the Material Property Ontology (MAT) (Chávez-Feria, 2020) and damage is represented using the Damage Topology Ontology (DOT) (Hamdan et al., 2019).

In heritage preservation, ontologies have been applied to various case studies. Tibault et al. (2018) conducted a comprehensive review of ontology-based data collection in the context of Heritage Buildings (HB). They introduced a framework concept supporting the incremental development of an ontology based on diverse domain sources, which is crucial for handling complex data within different historical and cultural contexts. Quattrini et al. (2017) proposed a workflow that integrates Building Information Modeling (BIM) platforms and Semantic Web technologies for managing data related to the maintenance and management of monumental historical buildings. Their work underscored the significance of these technologies in the facility management of complex and historically valuable buildings. Colucci et al. (2020) introduced an ontological schema for representing the Historical Built Heritage (HBH) domain using international standards, vocabularies, and ontologies. They emphasized the importance of segmentation in geometric surveying, utilizing standards such as CityGML-Geography Markup Language, CIDOC-CRM, IFC, and AAT. Bonduel (2021) introduced a framework for a linked data based heritage BIM, proposing several ontologies. In a more recent development, Sartini et al. (2023) introduced an ontology focusing on the conceptualization of artistic interpretations. Their work formalized content from various theories, following the Semantic Web principles of reuse and interoperability. Meanwhile, in 2023, Cui et al. (2023) developed an ontology-based approach and HBIM for the multi-layered representation of historical archaeology and production processes.

These studies illustrate a trend toward a greater understanding and representation of cultural heritage, using advanced technologies to address challenges related to the conservation and documentation of historical assets. Moreover, there is a focus on the final representations of heritage assets depending on the purposes and scope of application, with particular attention to not revealing the interpretative path and any inconsistencies or uncertainties at the logical level of connection.

2.3 Rules and reasoning

Ontologies play a crucial role in optimising decision-making processes. This does not specifically concern the AECO field but also other domains, with major applications in medicine and biology (Bertaud-Gounot et al., 2012; Dang et al., 2008; Taheri Moghadam et al., 2022). OWL's potential for decision-making lies in its ability to describe not only the taxonomy of the represented environment but also logical rules based on descriptive logic. The latter includes, for instance, intersection, inclusion, union, negation, inverse properties, and cardinality. These rules formally describe the concept in the knowledge-based system, a decision-support system with specialised problem-solving expertise (Jacyntho & Morais, 2021).

As an extension of the original Descriptive Language rules, the World Wide Web Consortium introduced the 'Semantic Web Rule Language' (SWRL) in 2004 to give semantic models more expressive power (Parsia et al., 2005). SWRL rules consist of an antecedent (the "if" part) and a consequent (the "then" part), allowing for sophisticated reasoning over semantic data.

OWL and SWRL have been successfully used in various applications, including monitoring clinical patients with heart issues (Martínez-Romero et al., 2013), the definition of clinical archetypes (Lezcano et al., 2011), organising efficiency in the public sector (Antunes et al., 2024), product design (Abadi et al., 2018), power plant design (Fortineau et al., 2012), integration with IoT devices (Reda et al., 2022), for additive manufacturing (Li & Petzold, 2023) and for defining air quality in smart cities (Kumar et al., n.d.).

From the preceding discussion, it is understood that the structural analysis of unreinforced masonry buildings can gain significant advantages from using linked data approaches and ontologies, especially concerning the definition of modelling assumptions. In particular, due to its capability to allow greater integration of heterogeneous data from stakeholders with different backgrounds and better consequentiality of choices thanks to reasoning. Therefore, the authors previously proposed two: the Historic Masonry Ontology and the Failure Mechanism Ontology (Leonardi et al., 2023). These ontologies are intended to be used together to formalise information regarding the morphology of masonry structures, mechanical properties and expected failure methods. The information gathered in the ontologies can serve as semantic enrichment of BIM models and be used as input for the open BIM-based structural analysis framework proposed by the authors in (Leonardi et al., 2024a).

3. METHODOLOGY

The work presented in this paper is a continuation of the work presented in (Leonardi et al., 2023), and the ontologies previously proposed have been extended extensively and accompanied by a set of SWRL rules. The proposed methodology has two objectives:

- Defining the type of masonry behaviour and the corresponding expected failure modes, which are crucial for making modelling decisions;
- Determining the mechanical parameters to attribute to the structural elements in the analytical model.

The methodology adopted for this study consists of two main parts: 1) the definition of Historic Masonry Ontology (HMO) and Failure Mechanism Ontology (FMO) ontologies; 2) and their application for structural evaluation of unreinforced masonry buildings. The first part involves the development of the ontologies, which includes identification of key terms, definition of superclasses and subclasses, and integration with existing ontologies. The second part covers the verification and validation of ontologies through a practical case study.

During the verification phase, the ontologies were tested on a real case study to assess their ability to correctly represent the morphological and mechanical characteristics of historic masonry. Validation procedures included collection of geometric and non geometric data, implementation of the ontologies, and analysis of the results obtained against real data. Any discrepancies were used to improve and refine the ontologies.

The two ontologies were implemented using the middle-out approach (Uschold and King, 1995). Initially, key terms related to the problem were identified, forming a glossary of 'core terms'. Then, superclasses and subclasses were defined. Since representing masonry elements involves addressing various special cases, such as existing masonry types documented in literature and standards, the proposed ontologies include both a 'terminology' layer and an 'assertions' layer. Users can expand the 'assertions' layer over time.

Additionally, relationships between the classes of the proposed ontologies and other relevant existing ontologies were established. This included ontologies facilitating information mapping to Building Information Modeling (BIM) models, such as the BEO and MAP ontologies, ontologies related to value and measurement unit assignment (SAREF ontology), and the DOT ontology to represent the damage state of the element.

Along with classes and properties, several SWRL rules were proposed to connect information, deducing data necessary to define the modelling assumptions (e.g., mechanical properties and type of behaviour) from visual survey information.

Upon completing the proposed ontologies, they were made accessible on the web, together with documentation about their use. The ontologies were published with permanent identifiers through the W3C 'Permanent Identifier Community Group' service, with the assigned links at 'w3id.org' (w3c, 2024). The documentation was done using 'Widoco', a Java software designed to streamline the creation of HTML pages specifically for presenting ontologies (Garijo, 2017). The practical application to an existing case study eventually made it possible to prove the potential of the ontology and validate the functioning of the rules.

In choosing semantic rules for the model, several options were considered, including SWRL, SPIN, and SHACL Inference. SWRL (Semantic Web Rule Language) was chosen because it offers greater flexibility in defining complex rules and integrated with OWL (Web Ontology Language), which is fundamental to our ontology-based approach. Although SPIN (SPARQL Inferencing Notation) and SHACL (Shapes Constraint Language) Advanced Features are newer standards and have advantages in terms of expressing constraints and inferences, SWRL was chosen because of its maturity and wide adoption in the academic community.

SPIN, for example, uses SPARQL to express rules and constraints, but may be less intuitive for modeling complex relationships between classes and properties. SHACL, on the other hand, is primarily designed for data validation, and although it includes advanced inference capabilities, its adoption is still in its infancy compared to SWRL. In addition, the documentation and tools available for SWRL are more developed, making it easier to implement and maintain the rules in our specific context.

For these reasons, SWRL was considered the most suitable choice, providing greater compatibility and interoperability with existing ontologies and offering a robust platform for inference of mechanical properties and collapse mechanisms of historic masonry structures.

4. THE HISTORIC MASONRY ONTOLOGY

The 'Historic Masonry Ontology' is designed to allow a detailed representation of various types of unreinforced masonry, considering its heterogeneous nature, to deduce its homogenized mechanical properties. The preferred prefix for the Historic Masonry Ontology is HMO, and the proposed namespace is https://w3id.org/hmo#.

This ontology is implemented considering the current Italian regulations (Technical Standards for Constructions, 2018) and the Masonry Quality Index evaluation (Borri et al., 2015). In this ontology, the wall and its physical components, the Masonry Quality Index and the mechanical properties are modelled as classes related to each other using objected properties. The masonry types from the building codes are modelled as individuals, and SWRL rules evaluate the value of the Masonry Quality Index and mechanical properties starting from masonry features that can be easily assessed with a visual survey.

Figure 1 shows an overview of the ontology terminology, accessible at https://w3id.org/hmo (Leonardi et al., 2024b). As shown in the legend, the grey boxes indicate the owls:Class. The black arrows indicate the owl:ObjectProperties; the white boxes indicate the owl:DatatypeProperties; the dashed arrows indicate the rdfs:SubclassOf. In detail, the class 'hmo:MasonryWall' is employed to represent masonry walls, which relate to the class 'hmo:MasonryQualityIndex', via the object property 'hmo:hasMasonryQualityIndex'. The class 'hmo:MasonryQualityIndex' contains 21 data properties, aligned with (Borri, 2015). Masonry walls also relate to the class 'hmo:Layer' and the class 'hmo:RepresentativeVolumeElements', via the object properties 'hmo:hasLayer' and 'hmo:hasRepresentativeVolumeElements'. The class 'hmo:RepresentativeVolumeElements' relates to the class 'hmo:Pattern' via the object property 'hmo:hasPattern'. The latter relates to the class 'hmo:PatternEntities' with the object property hmo:hasDominantPatternEntities. The pattern entities are the discrete elements that constitute the wall: units (hmo:Units) and joints (hmo:Joints). The units have four data properties to represent their dimensional characteristics. Joints have three subclasses, which are hmo:VerticalJoints, hmo:HorizontalJoints and hmo:VerticalJoints. The following paragraphs will provide a detailed description of the specific parts of the ontology.

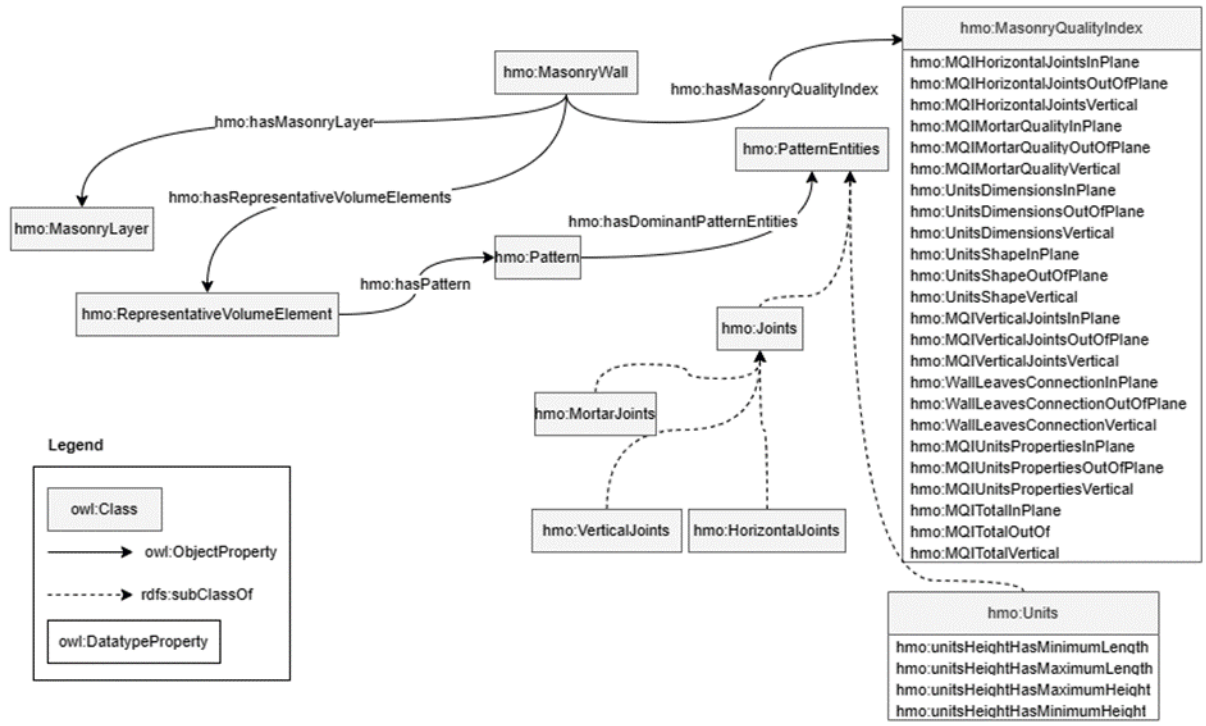

Figure 1: Overview of the historic masonry ontology.

Figure 2 shows the classes Masonry wall, masonry layer and representative volume elements in detail, showing both the terminology layer and the instances layer. In particular, the masonry walls are modelled using the class 'hmo:MasonryWall', a subclass of beo:Wall (Figure 2 - a). The class beo:Wall is a component of the Building Element Ontology (BEO) (Pauwels, 2018), which is designed to represent the IfcBuildingElement subtree of the Industry Foundation Classes (IFC) specification. Therefore, the beo:Wall class is semantically equivalent to the IfcWall class, which is interoperable with BIM platforms. By integrating the HMO ontology with beo:Wall, a comprehensive ontology model is established. This model extends the capabilities of IFC by facilitating the representation of classes and relationships within the structural analysis domain, particularly in the context of load-bearing masonry buildings. In this sense, this allows the semantic enrichment of BIM models.

An 'hmo:MasonryWall' is composed of one or more 'hmo:MasonryLayer', connected through the object property 'hmo:hasLayer'. A ‘hmo:MasonryLayer’ represents a vertical physical division within the cross-section of a wall (Figure 2 - a).

Masonry walls are divided according to similar repeating characteristics, so each masonry wall has a corresponding Representative Volume Element (RVE), i.e. a 'representative' portion of the wall whose characteristics (type of joints and units) are repeated throughout the wall, and that can be used to assign mechanical properties for the numerical simulation in homogenized condition. The RVE class relates to the masonry wall class via the object property 'hmo:hasRepresentativeVolumeElement'. (Figure 2 – b).

Furthermore, the ontology includes eight individuals belonging to the RVE class, as illustrated in Figure 2c. These individuals represent the different masonry types outlined in the Italian standard (Technical Standards for Constructions, 2018) and in the “Eurocode 8”, along with their corresponding mechanical properties provided in the standard. Table 1 includes these masonry types and their associated mechanical properties according to the standard.

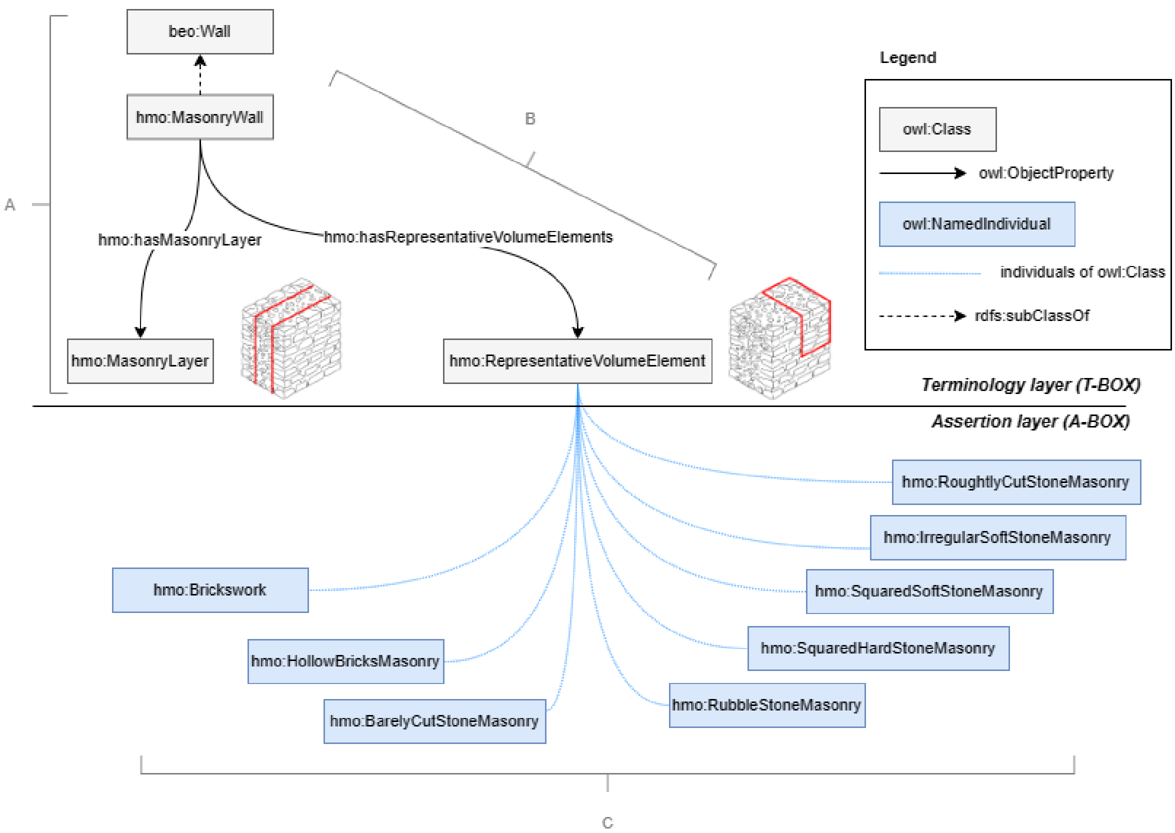

Figure 2: Masonry wall, masonry layer and representative volume elements.

Table 1: Mechanical properties of masonry typology according to the Italian Technical Standards for Construction and to the last version of Eurocode 8. fc = compressive strength; ft = shear strength according to Turnsec and Cacovik criterion, fvo = shear strength according to Mohr Coloumb criterion; E = Young Modulus; G = shear modulus; w =mass density.

	fc	ft	fvo	E	G	w
	MPa	MPa	MPa	MPa	MPa	kN/m^3
Barely cut stone masonry	3.2	0.09	-	1740	580	21
Brickwork	3.4	0.12	0.160	1500	500	18
Hollow brick masonry	6.5	-	0.280	4500	1138	15
Irregular soft stone masonry	1.8	0.05	-	1080	360	13-16
Irregular stone masonry	1.5	0.04	-	870	290	19
Roughly Cut Stone Masonry	2.5	0.07	-	1230	410	20
Squared Softstone Masonry	2.6	-	0.145	1410	470	13-16
Squared Hardstone masonry	7	-	0.220	2800	860	22

Mechanical properties are modelled in the ontology as subclasses of 'homogenised mechanical properties'. (hmo:HomogeneisedMechanicalProperty). The RVE class is associated with the 'homogenized mechanical properties' class with the object property ‘has homogenized mechanical properties’ (hmo.hasHomogeneisedMechanicalProperty) (Figure 3 -a).

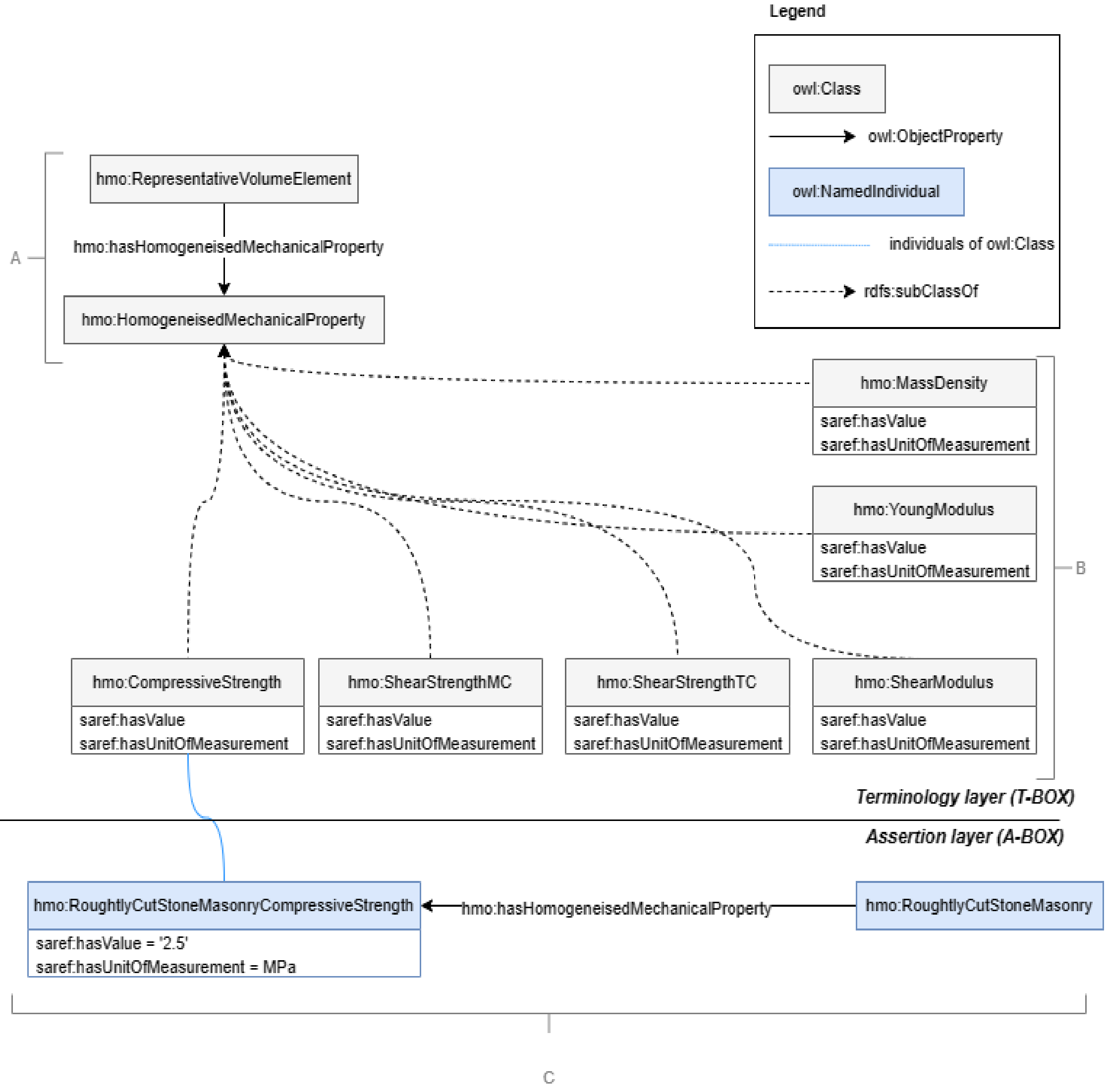

Figure 3: Application of homogenized mechanical properties in the ontology.

The fact of modeling the mechanical properties as a class allows the association of a description (rdfs:Comment), a value (saref:hasValue), and a unit of measurement (saref:isMeasuredIn). The 'homogenized mechanical properties' class has six subclasses (Figure 3-b): 1) compressive strength (hmo:CompressiveStrenght), 2) shear strength according to Turnsek and Cacovic criterion (hmo:ShearStrengthTC) 3) shear strength according Mohr Coulomb (hmo:ShearStrenghtMC), 4) Young modulus (hmo:YoungModulus), 5) shear modulus (hmo:ShearModulus), 6) mass density (hmo:MassDensity), in compliance with the standard. Figure 3 – c shows an example of the application of a mechanical property in the assertion layer.

When the masonry under examination does not fall into the regulatory types, other methods can be used to define mechanical properties, including the masonry quality index. The masonry quality index is modeled in the ontology as a class (hmo:MasonryQualityIndex), related to the masonry wall through the object property (hmo:hasMasonrtyQualityIndex). In the proposed ontology, the masonry quality index class has several data properties, including the total values of the masonry quality index for in-plane (hmo:MQITotalInPlane), out-of-plane (hmo:MQITotalOutOfPlane), and vertical hmo:MQITotalVertical) loads. These three values can be used to evaluate the mechanical properties of the masonry under examination according to formulas established in Borri (Borri et al., 2015). These formulas have been integrated into the ontology using SWRL rules. To add SWRL rules, it is necessary to define antecedents (conditions) and consequents (actions). For example, to state that *if a parent has a child and the parent's age is greater than 18, then the child is considered an adult*, the syntax to use is: hasChild(?parent, ?child) ^ hasAge(?parent, ?parentAge) ^ swrlb:greaterThan(?parentAge, 18) -> hasStatus(?child, "Adult"). As seen in the example, various properties (object and data properties) are considered in the conditions, connected with the conjunction operator '^'. Between the parenthesis, the first variable is the domain, and the second variable is the range. The '->' operator is used to define the conditions.

Figure 4 shows an example of using these rules, i.e., calculating the shear modulus using the total value of the Masonry Quality Index in-plane. The total value of the masonry quality index is multiplied by 0.1298, using the swrlb:multiply function (Figure 4 A). The resulting value is used to raise '2.72' to the power, using the function swrlb:powerOf (Figure 4 b) all this is eventually multiplied by 279.82, again using the function swrlb:multiply (Figure 4 - c).

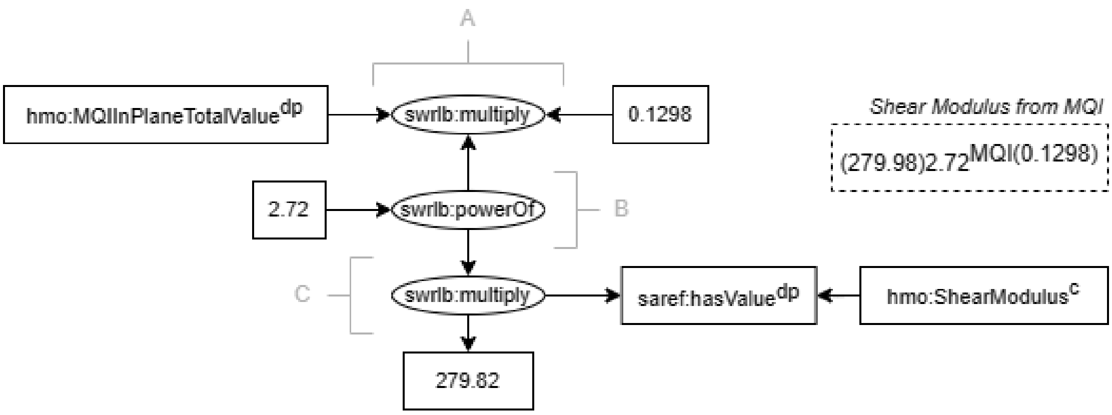

Figure 4: Evaluation of the shear modulus from the total value of the MQI in the plane. dp = data property; c = class; swrlb: prefix of math rules in SWRL.

To obtain the total masonry quality index values employed to estimate the mechanical properties, Borri proposed seven parameters: unit dimensions, unit shape, mortar quality, arrangement of horizontal joints, arrangement of vertical joints, connection between masonry layers, and unit quality. In evaluating a masonry wall, each parameter is considered for the three load directions (in-plane, out-of-plane and vertical) for 21 parameters. Each parameter fluctuates between three values, depending on the quality (average, good or bad) of the masonry under investigation concerning that specific characteristic. A mathematical formula calculates the three total values of the masonry quality index from these parameters. The 21 parameters are modelled in the ontology as data properties of the masonry quality index class, shown in Table 2, together with the definition given in the literature.

Table 2: Parameters of the masonry quality index. Part One.

Data Property	Definition in (Borri, X)	Abbreviation for the formula
hmo:MQIHorizontalJointsInPlane	Horizontality of bed joints	HJ
hmo:MQIHorizontalJointsOutOfPlane		
hmo:MQIHorizontalJointsVertical		
hmo:MQIMortarQualityInPlane	Quality of the mortar / contact between masonry units / pinnings	MM
hmo:MQIMortarQualityOutOfPlane		
hmo:MQIMortarQualityVertical		
hmo:MQIUnitsDimensionsInPlane,	Dimensions of the masonry units	SD
hmo:MQIUnitsDimensionsOutOfPlane		
hmo:MQIUnitsDimensionsVertical		
hmo:MQIUnitsShapeInPlane	Shape of the masonry units	SS
hmo:MQIUnitsShapeOutOfPlane		
hmo:MQIUnitsShapeVertical		

Table 2: Parameters of the masonry quality index. Part Two.

Data Property	Definition in (Borri, X)	Abbreviation for the formula
hmo:MQIVerticalJointsInPlane	Staggering of vertical mortar joints	VJ
hmo:MQIVerticalJointsOutOfPlane		
hmo:MQIVerticalJointsVertical		
hmo:MQIWallLeavesConnectionInPlane	Level of connection between adjacent wall leaves / headers	WC
hmo:MQIWallLeavesConnectionOutOfPlane		
hmo:MQIWallLeavesConnectionVertical		
hmo:MQIUnitsPropertiesInPlane	Mechanical characteristics and quality of masonry units	SM
hmo:MQIUnitsPropertiesOutOfPlane		
hmo:MQIUnitsPropertiesVertical		

In addition, three SWRL rules were implemented to obtain total values from each of these parameters, based on the equation 1:

$$MQI = SM\ x\ (WC + VJ + HJ + SS + SD + MM) \quad (1)$$

The formula is repeated three times for each load direction. Figure 5 shows, as an example, how the total value of the masonry quality index is derived for in-plane loads. First, the values of WC, VJ, HJ, SS, SD and MM are summed using the *swrlb:add function* (Figure 5 - a). Then, the total is multiplied with the parameter SM using the function *swrl:multiply* (Figure 5 - b).

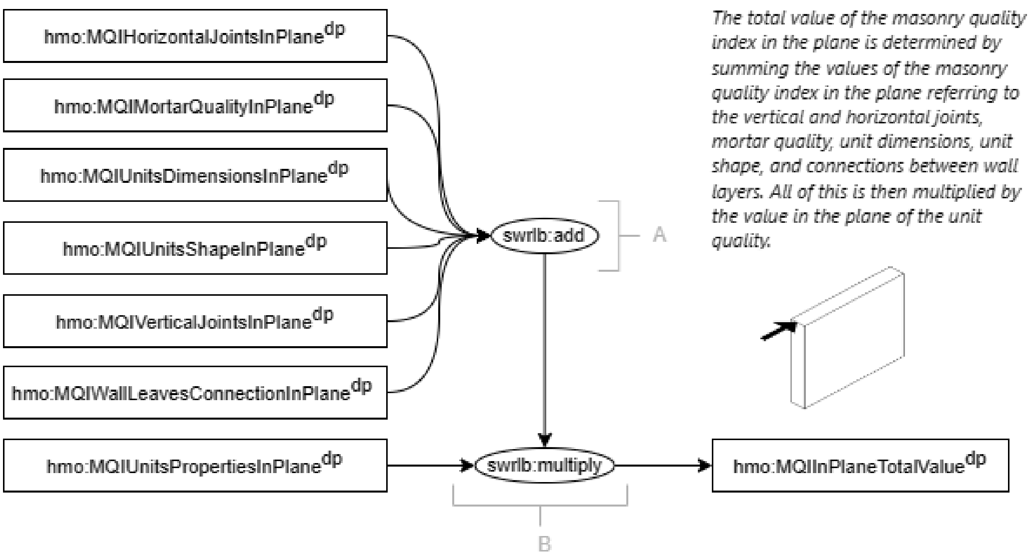

Figure 5: Evaluation of the total value of the in-plane MQI. dp = data property; c = class; swrlb: prefix of math rules in SWRL.

The 21 parameters of the masonry quality index are based on the morphological characteristics of the masonry sections and were the starting point for defining the proposed structural breakdown for the RVE. In particular, to define the MQI parameters, it is necessary to accurately identify the material and geometrical features of units and joints of the masonry under examination, as well as their arrangement.

Different types of units and joints may characterize a wall portion while still being part of the same RVE. This scenario occurs, for example, when a stone masonry is interspersed with bands of brick. Indeed, according to the Italian code, in this case, the masonry is assigned the mechanical values that the stone masonry would have but increased by a certain improvement parameter, as the presence of these brick bands increases its load-bearing capacity. The ‘pattern’ class (hmo:Pattern) is introduced in the ontology to consider cases like these.

A pattern is defined as a recurring configuration of discrete elements repeated in the RVE, which can be characterized by one or more patterns, to which relates using the object property ‘has pattern’ (hmo:hasPatten) (Figure 6 - a).

The discrete entities constituting a pattern are modeled as ‘pattern entities’ (hmo:PatternEntities). Specific pattern entities may be more or less predominantly present in a RVE. In particular, when they are present in a percentage greater than 50%, they relate to the RVE with the object property hmo:hasDominantPatternEntities. Conversely, when less than 50% are present, they relate to the RVE using the object property hmo:hasSparsePatternEntities (Figure 6 - b).

The class ‘pattern entities’ has two subclasses: ‘units’ (hmo:Units) and joints (hmo:Joints) (Figure 6 - c). The units are the stones or bricks that make the greatest resistant contribution to the wall, while the joints are the interface elements between the units. Therefore, units are related to joints via the object property 'is interface of' (hmo:isInterfacesOf) (Figure 6 - d).

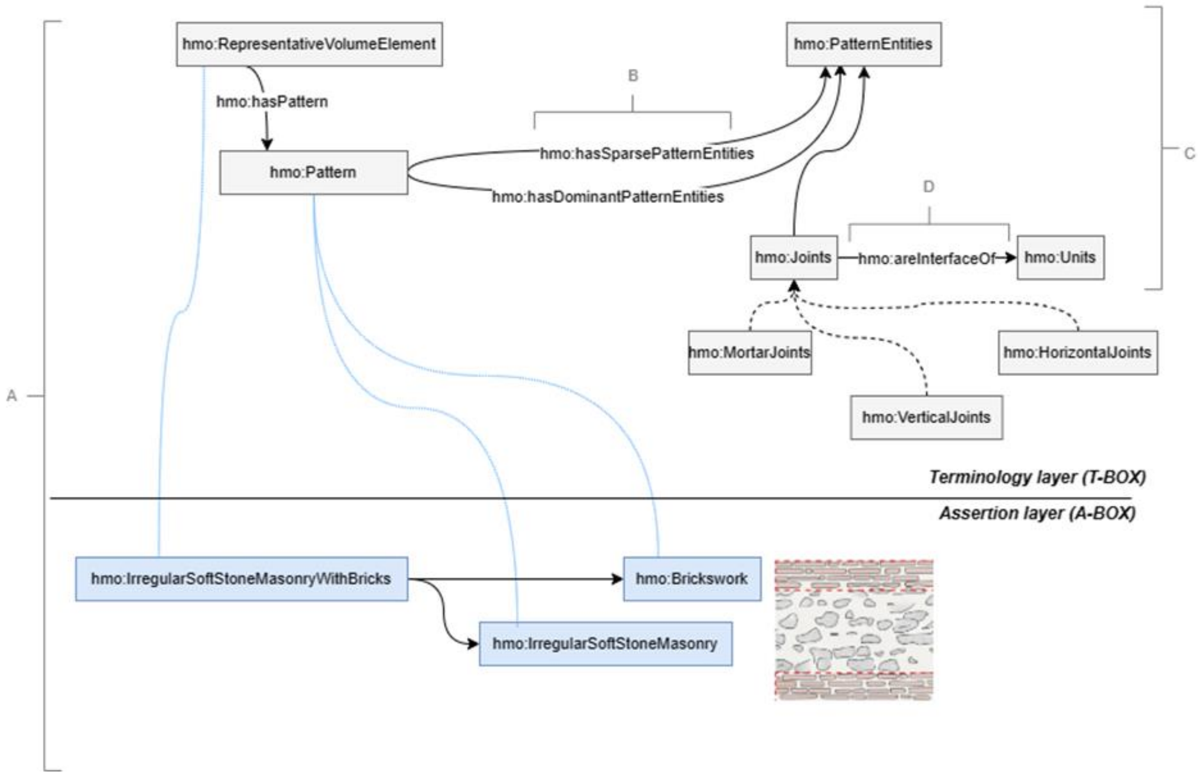

Figure 6: Relationship between representative volume elements, patterns and pattern entities.

The units are characterized in the ontology by their dimensional properties, modeled in the ontology has data properties. Being historical masonry, very often the size of a certain type of unit varies over the course of the masonry, for this reason, the author refers has maximum/minimum dimensions, as shown in Table 3.

Table 3: Data type properties associated with units.

Owl:dataTypeProperty	Description
hmo:unitsHeightHasMaximumValue	Maximum measured value of the height of the units (in cm).
hmo:unitsHeightHasMinimumValue	Minimum measured value of the height of the units (in cm).
hmo:unitsLengthHasMaximumValue	Maximum measured value of the length of the units (in cm),
hmo:unitsLengthHasMinimumValue	Minimum measured value of the length of the units (in cm).

The 'average' size of the units allows the MQI 'stone dimensions' to be defined. This is done in the ontology automatically, a SWRL rule, shown in Figure 7. First, using swrlb:add and swrlb:divide, the average width dimensions of the units are calculated. This average is compared to standard values using the built-ins swrlb:greaterThan, and swrlb:lessThan. Specifically, if the value is greater than or equal to 40 cm, the three MQI values are equal to 1, if the average is between 20 cm (inclusive) and 40, the three MQI values are equal to 0.5, finally, if the average is less than 20, the three values are 0.

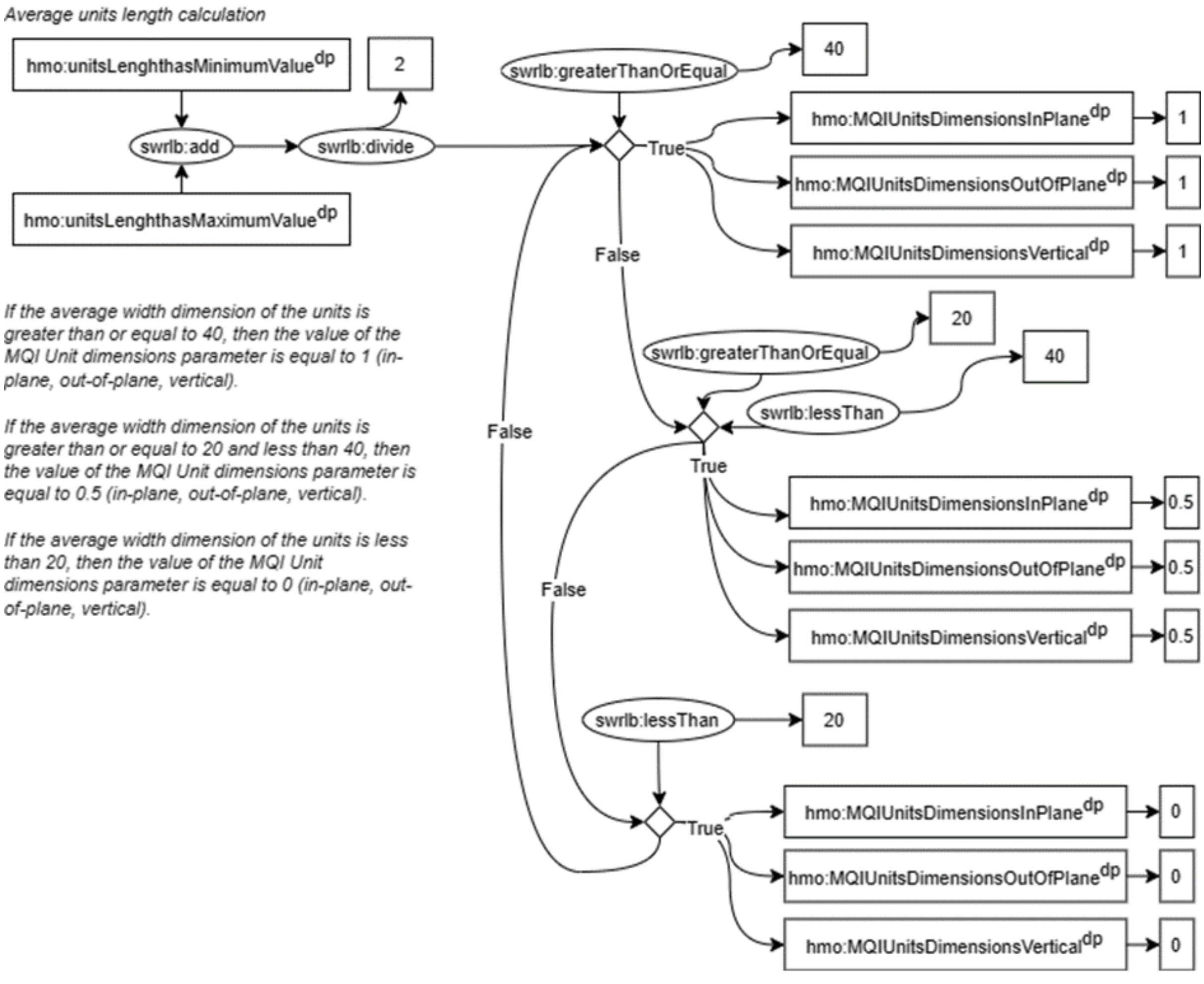

Figure 7: Evaluation of MQI parameter 'unit dimensions' based on the datatype properties of the units.

Proposed ‘units’ individuals include ‘barely cut stones’ (hmo:BarelyCutStone), bricks (hmo:Bricks), irregular soft stone (hmo:IrregularSoftStone), roughly cut stones (hmo:RoughtlyCuteStones), rubble stones (hmo:RubbleStones), squared softstone (hmo:SquaredSoftSrone), squared hardstone (hmo:SquaredHardStone), hollow bricks (hmo:HollowBricks) and pinning stones (hmo:PinningStones), headers bond units (hmo:HeaderBondUnits). The first height types correspond to the regulation masonry types, whereas the ‘pinning stones’ are very little stones that fill the voids when the joints are with no mortar, and the ‘header bond units’ are units disposed with the long part inside the cross sections, helping the clutching of different masonry layers.

The unit's features influence the unit shape and properties of the masonry quality index. For example, if the units are 'rubble stones', then the 'unit shape' parameter will have low values. Similarly, the unit material (soft stone, hard stone, brick) determines the 'unit quality'. Therefore, SWRL rules are implemented in the ontology to assign the most suitable 'units shape' and 'unit properties' data properties based on the features of the units. For instance, if the units are 'rubble stones', low values of 'unit shape are assigned, while if the units are 'squared hard stones', high values are assigned (see annexe 1 for more detail).

Joints subclasses includes 'vertical joints' (hmo:VerticalJoints), 'horizontal joints' (hmo:HorizontalJoints), and 'mortar joints' (hmo:MortarJoints).

Horizontal and vertical joints are modelled separately because different characteristics influence different masonry quality index parameters. Horizontal joints individuals include 'continuous horizontal joints' (hmo:ContinuousHorizontalJoints), 'non - continuous horizontal joints' (hmo:NonContinuousHorizontalJoints) and 'partially continuous horizontal joints' (hmo:PartiallyContinuosHorizontalJoints). The ideal situation is when the horizontal joints are continuous along the pattern, and this occurs when the stone dimension is pretty much the same along the pattern. The horizontality of the joints is a feature considered in the masonry quality index parameters. Hence, SWRL rules assign high values to the 'joint horizontality' parameters in the case of 'continuous horizontal joints', medium values in the case of 'partially continuous horizontal joints and bad values in the case of 'non - continuous horizontal joints' (annexe 1).

Vertical joints individuals include 'partially staggered joints'(hmo:PartiallyStaggeredJoints), 'properly staggered joints'(hmo:PropertlyStaggeredJoints), and 'vertically aligned joints' (hmo:VerticallyAlignedJoints). This also influences masonry quality, as properly staggered joints allow good bonding between wall layers, vertical joints ensure no bonding at, and partially staggered joints are a compromise. Based on this, SWRL rules assign high, low, or medium values to the 'joint verticality' (annex 1).

Joints can be dry or mortared joints. Dry joints are modelled as a particular individual of the class 'joints' (hmo:DryJoints). Conversely, for the mortar joints, it is defined as a specific 'mortar joints' class (hmo:MortarJoints), and particular individuals are 'mortar joints' of a specific material. The mortar joints proposed individuals are earth mortar (hmo:EarthMortar), lime mortar (hmo:LimeMortar), hydraulic mortar (hmo:HydraulicMortar), and roman cement mortar (hmo:RomanCementMortar). Different materials mortars correspond to different values of the masonry quality index 'mortar quality', assigned with SWRL rules. For instance, earth mortar has a lower quality of hydraulic mortar and of roman cement mortar (see annexe 1). The fact of having 'dry mortar' also influences the mortar quality, but in such case, it is important also to take into account the types of units. For instance, if units are very regular (e.g. 'Squared hard stone), then the dry joints are thin. Thin dry joints are favourable since they reduce the vulnerability part of the wall (there are more units 'area', which provides better mechanical properties. Conversely, the presence of dry units in rubble stones is unfavourable because it has less bonding than mortar. In such case, only with the presence of 'pinning stones' the values of the parameters referred to as 'mortar quality' can be medium (annexe 1).

5. THE FAILURE MECHANISM ONTOLOGY

The Failure Mechanism Ontology aims to provide an initial estimation of the possible collapse mechanisms of the structure under examination. This allows for the definition of the most appropriate modelling assumptions. The preferred prefix for this ontology is FMO, and the proposed namespace is https://w3id.org/fmo#.

The FMO ontology is utilized to indicate whether the structure is more prone to collapse out of the plane or if in-plane failures are the most probable scenario. Consequently, it becomes possible to decide, for instance, whether to utilize an equivalent frame model or to opt for a more sophisticated model capable of capturing out-of-plane behaviour as well. In scenarios involving out-of-plane failures, the ontology also facilitates the location and type of failure mechanism, thus enabling the modelling of any discontinuities between elements.

The FMO ontology works complementarily with HMO, of which it represents an extension, as shows in Figure 8, where it is seen that all the classes of the failure mechanism ontology are related to the class hmo:MasonryWall. The file and the comprehensive documentation is accessible at https://w3id.org/fmo (Leonardi et al., 2024c).

Figure 8 illustrates the three main classes introduced with FMO: fmo:Vulnerability, fmo:Behaviour, and fmo:FailureMechanism. These three classes are related to the class hmo:MasonryWall, via the object properties fmo:hasOccurringFailureMechanism, fmo:hasVulnerability and fmo:hasBehavior. The fmo:Vulnerability class is related to the fmo:FailureMechanism class via the property fmo:Facilirates. Additionally, it demonstrates how the ontology is also linked to the existing DOT ontology to model structural damage possibly associated with a specific mechanism. Individuals were proposed based on (ReLuis, 2011).

Vulnerabilities are characteristics of the wall under examination (or of adjacent elements) that facilitate the activation of a specific failure mechanism. The ontology includes individuals for both the failure mechanism class and the vulnerability class. Table 4 lists the individuals proposed for vulnerabilities along with their descriptions.

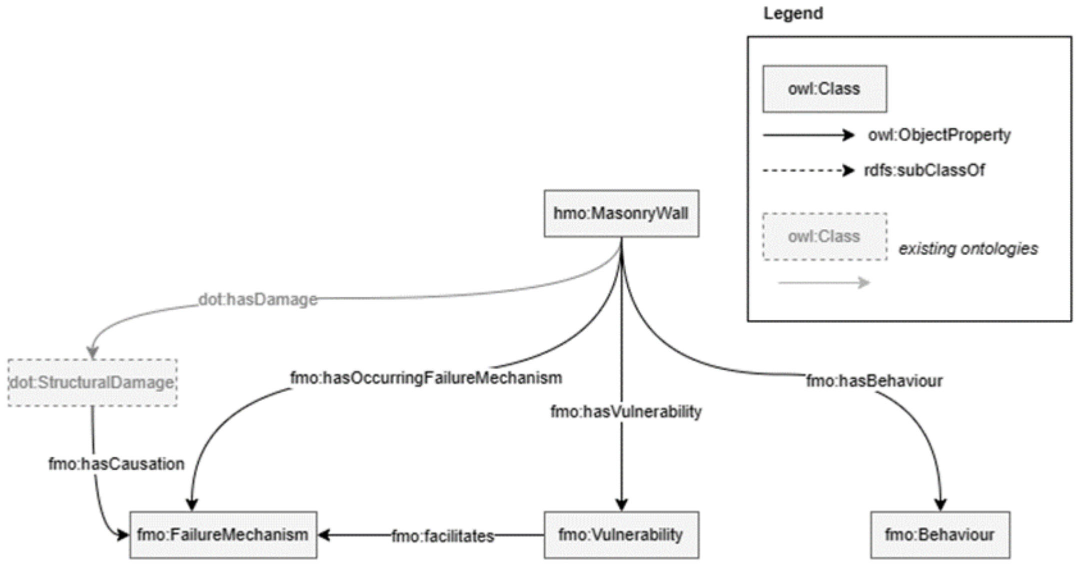

Figure 8: Overview of the failure mechanism ontology.

Table 4: Individuals of the fmo:Vulnerability class.

fmo:Vulnerability	Description
fmo:AbsemceOfTopChain	When chains are not present in the upper floor, and the roof is not well anchored to the wall under examination.
fmo:AbsemceOfTopCurbstone	When curbstone is not present in the upper floor, and the roof is not well anchored to the wall under examination.
fmo:AbsemceOfIntermediateChain	When chains are not present in the intermediate floor, and the slab is not well anchored to the wall under examination.
fmo:AbsemceOfIntermediateCurbstone	When curbstone is not present in the indermediate floor, and the slab is not well anchored to the wall under examination.
fmo:DeformableFloors	When floors are not rigid, not allowing the box behaviour of the structure.
fmo:OpeningNearIntersections	When windows are present in areas near to the orthogonal elements.
fmo:PresenceOfHorizontalThrusts	When pushing elements are present, such as beams that are not well connected.
fmo:InadequateVerticalBehaviour	When, according to the masonry quality index, the wall does not behave adequately when subjected to vertical loads.
fmo:InadequateOutOfPlaneBehaviour	When, according to the masonry quality index, the wall does not behave adequately when subjected to out of plane loads.
fmo:InadequateInPlaneBehaviour	When, according to the masonry quality index, the wall does not behave adequately when subjected in plane loads.

The individuals fmo:InadequateVerticalBehaviour, fmo:InadequateInPlaneBehaviour and fmo:InadequateOutOfPlaneBehaviour in addition to belonging to the class 'fmo:Vulnerability', are also part of the class 'fmo:WallBehaviour'. This class is related to the masonry wall through the object property 'fmo:hasBehaviour' and is used to determine, based on the total values of the Masonry Quality Index (vertical, in-plane, and out-of-plane), whether the behaviour of the wall under consideration is 'inadequate', 'average', or 'good' for each of the three types of loading. Figure 9 shows how an SWRL rule determines that the out-of-plane behaviour of a specific wall is ‘inadequate’, based on the values of the masonry quality index. The other rules are detailed in Annex 2.

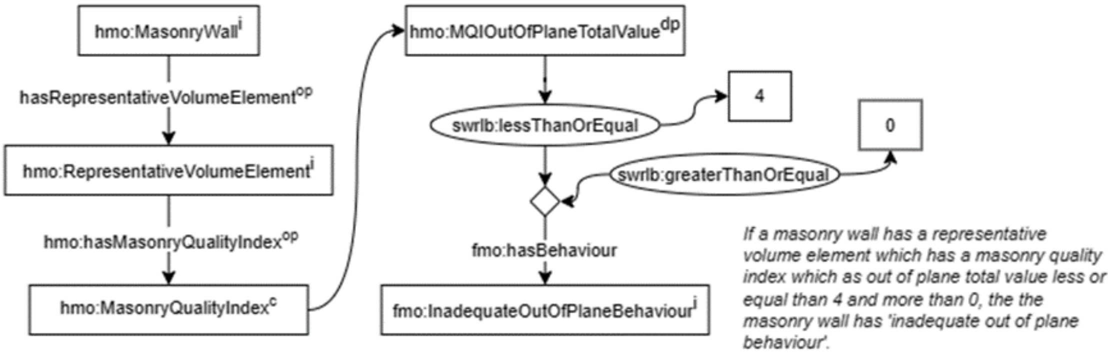

Figure 9: Definition of the masonry wall behaviour from the masonry quality index.

The proposed individuals in the 'failure mechanism' class are described in Table 5.

Table 5: Individuals of the fmo:FailureMechanisms class.

fmo:FailureMechanisms	Description
fmo:HorizontalBending	A fmo:FailureMechanism manifested by the expulsion of material from the top zone of the wall and the detachment of wedge-shaped bodies, accompanied by the formation of oblique and vertical cylindrical hinges due to out-of-plane actions.
fmo:VerticalBending	A fmo:FailureMechanism manifested with the formation of a horizontal cylindrical hinge that divides the wall into two blocks and is described by the mutual rotation of the same around this axis by out-of-plane actions.
fmo:PartialOverturn	A fmo:FailureMechanism consisting of the total rotation of part of a wall out of the plane.
fmo:TotalOverturn	A fmo:FailureMechanism consisting of the total rotation of the entire wall out of the plane.
fmo:InPlaneFailure	A fmo:FailureMechanism that does not involve out-of-plane overturning, but in-plane craking/failure.

SWRL rules allow for the derivation of specific mechanisms from vulnerabilities. For example, as shown in Figure 10, a' total overturn' may occur with the 'absence of top curbstone' and with the 'absence of an intermediate chain'. Conversely, if only the 'absence of top chain' vulnerability is present, this implies that intermediate connections are present, and therefore, a partial overturn is expected.

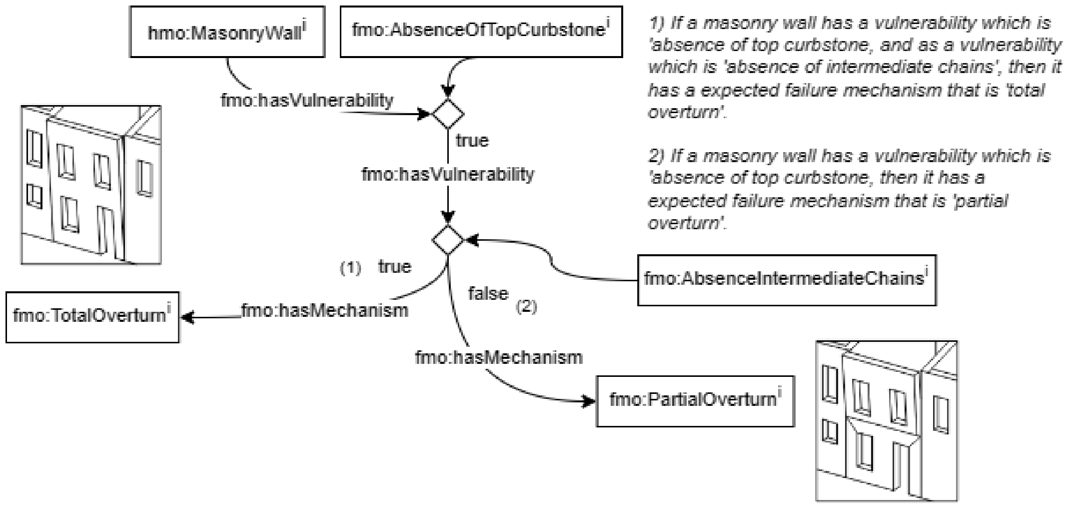

Figure 10: Evaluation of the expected mechanism based on the wall vulnerability (Drawings of the mechanisms adapted from (ReLuis, 2011)).

A specific structural damage is often a sign of an ongoing mechanism. In particular, the type of cracks indicates the type of mechanism. For example, a vertical crack at wall intersections is often a sign of overturning, while horizontal and vertical cracks in the wall under examination are symptoms of horizontal flexure. Using existing classes from the DOT ontology is proposed to model these damages. The DOT ontology already has the 'Structural damage' class. Therefore, the 'crack' class is added as a subclass of structural damage, and various types of cracks are modelled as individuals to be associated with ongoing mechanisms. The proposed individuals are 'vertical crack', 'diagonal crack', and 'horizontal crack'. Since 'crack' is modelled as a subclass of 'structural damage', it is related to the wall through the object property 'has damage'. Furthermore, specific types of cracks are related to specific mechanisms, with the object property ‘fmo:hasCausation’. An SWRL rule was added to ensure that when a wall has damage associated with a specific mechanism, the wall is also related to that mechanism, with the object property ‘fmo:hasOngoingMechanism’.

6. PRACTICAL APPLICATION

The proposed ontologies were applied to a case study to showcase their functionality while validating the accuracy of the rules. The selected case study is a portion of a large unreinforced masonry structure situated in the historic center of Castelnuovo di Porto, north of Rome (Italy). This structure is built on terraced ground, featuring three elevations to the south and only one to the north. The authors studied this building during several site visits, conducting visual analysis of the masonry, photographic surveys, on-site drawings, and laser scanner surveys.

These data were used both to model in the BIM environment the buildings and to implement, using Protégée software, the ontologies developed. The use of several existing ontologies allowed us to complete our models; namely, the Building Element Ontology (BEO) to represent structural elements and the Material Property Ontology (MAT) to define material properties. The integration of these ontologies enabled a comprehensive and consistent representation of building characteristics.

The information collected on-site was compared with existing written and graphical documentation, both related to the case study itself (Centroni & Castanoli, 2007; Clementi & Panepuccia, 1991) and to the geographical area (Daniela Esposito, 1997). An overview of the geometry of the building under study is presented in Figure 11.

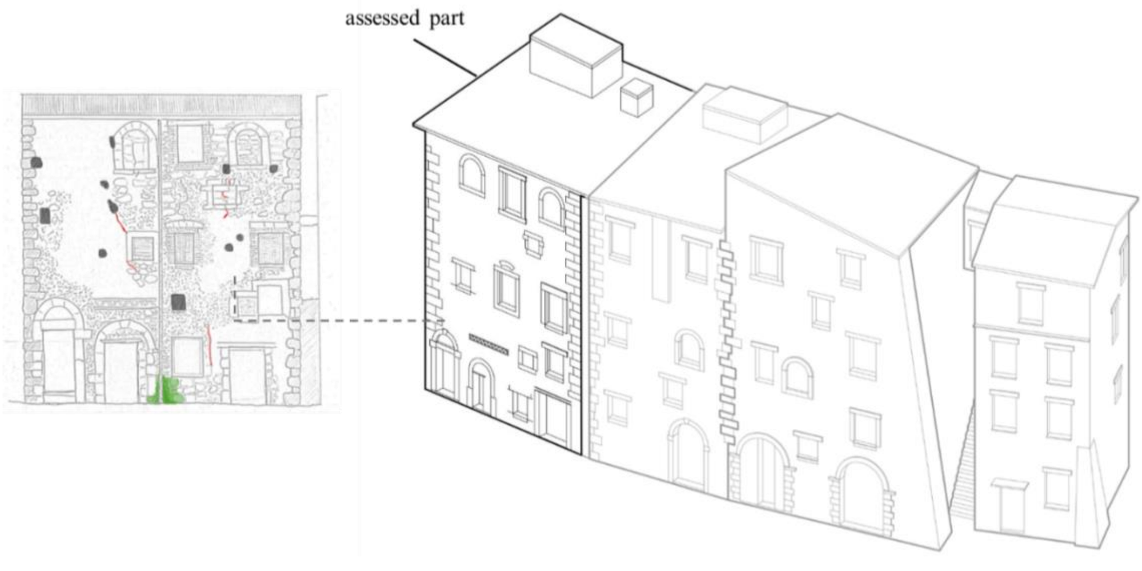

Figure 11: Case study.

The external facades of the building under investigation are made of irregular tuff masonry, interspersed with some smaller-sized brick elements and pozzolanic mortar. This type of masonry corresponds to that observed in the study by Centroni & Castanoli (2007) and is part of a variant of 'tuff masonry', extensively studied (Daniela Esposito, 1997). Figure 12 is a graphical representation of this masonry type, showing how it was modelled in the ontology.

Geometric data of the building were collected using laser scanners. Non-geometric information, related to the types of materials, was gathered through the mentioned literature review. The Assertional Box (A-BOX) ontology was expanded using the open-source software Protege. In particular, to model this type of masonry, it was sufficient to add five new individuals to the ontology proposed in the methodology: hmo:SurveyedWall (hmo:MasonryWall), hmo:SurveyedWallMQI (hmo:MasonryQualityIndex), hmo:IrregularBricks (as a subclass of hmo:Units), hmo:IrregularSoftStoneWithSomeBrick (as a subclass of hmo:Pattern), and hmo:CastelnuovoDiPortoMasonryType6 (as a subclass of hmo:RepresentativeVolumeElement).

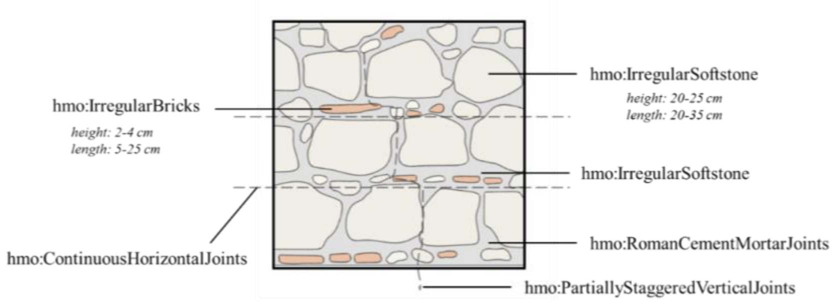

Figure 12: Assessed masonry type.

The hmo:IrregularSoftStoneWithSomeBricks class was modeled as a variant of 'hmo:IrregularSoftStone', which was already present in the base version of the ontology (as it exists in the building code). This pattern was associated with the following pattern entities: 'hmo:IrregularSoftStone', 'hmo:PartiallyStaggeredJoints', and 'hmo:ContinuosHorizontalJoints' (all three were associated using the object property 'hmo:hasDominantPatternEntities', and already exist in the proposed ontology). The 'hmo:IrregularSoftStones' were customized for the study case by adding dimensions using the data properties 'units height has minimum value', 'units height has maximum value', 'units length has minimum value', and 'units length has maximum value'.

The joint material was modeled by associating the pattern with 'hmo:RomanCementMortarJoints' RomanCementMortarJoints' (also using the object property 'hmo:hasDominantPatternEntities'). Finally, the 'hmo:IrregularBricks' were added to the pattern using the object property 'hasSparsePatternEntity', since they have a distribution in the pattern of less than 50%.

When creating this pattern, most of the instances to be associated with the object properties were already present in the proposed asserted ontology. It was only necessary to associate the irregular bricks and detail the dimensions of the 'softstone' units. Therefore, the pattern modelling process was very fast. Figure 10 (left – asserted properties) depicts the Protege model at this stage, where it can be observed that only the geometric and material properties of the pattern components have been asserted. At this stage, neither the individual properties of the Masonry Quality Index (MQI) nor the mechanical properties have been added.

Once the modelling of the elements constituting the pattern is completed, the rule engine of Protege (Drools) is used to infer new properties through SWRL rules. The Drools -> OWL function subsequently allows the rules to be incorporated into the ontology. Figure 13 (right – inferred properties) shows the Protege model after applying the rules.

The SWRL rules inferred all the values of the Masonry Quality Index parameters from the geometric and material characteristics of the masonry. Based on these parameters, they finally inferred the mechanical properties of the masonry. The rule engine runs in less than one second.

The wall modelled in the HMO ontology is then imported to the FMO ontology, together with the total values of the Masonry Quality Index. In the FMO ontology, the dot:hasDamage relates the wall to 'fmo:VerticalCrackEntireWallIntersection', a dot:StructuralDamage. The object property ‘fmo:hasCausation’ relates the structural crack to the ‘fmo:TotalOverturn’.

Without introducing further information, the drools engine is run. The SWRL rules inferred with the wall behaviour from the MQI total values. In particular, the rules identify that the wall has an 'average vertical behaviour', an 'average in-plane behaviour', but an 'inadequate out-of-plane behaviour'. Furthermore, they relate the ‘fmo:TotalOverturn’ to the wall (Figure 14).

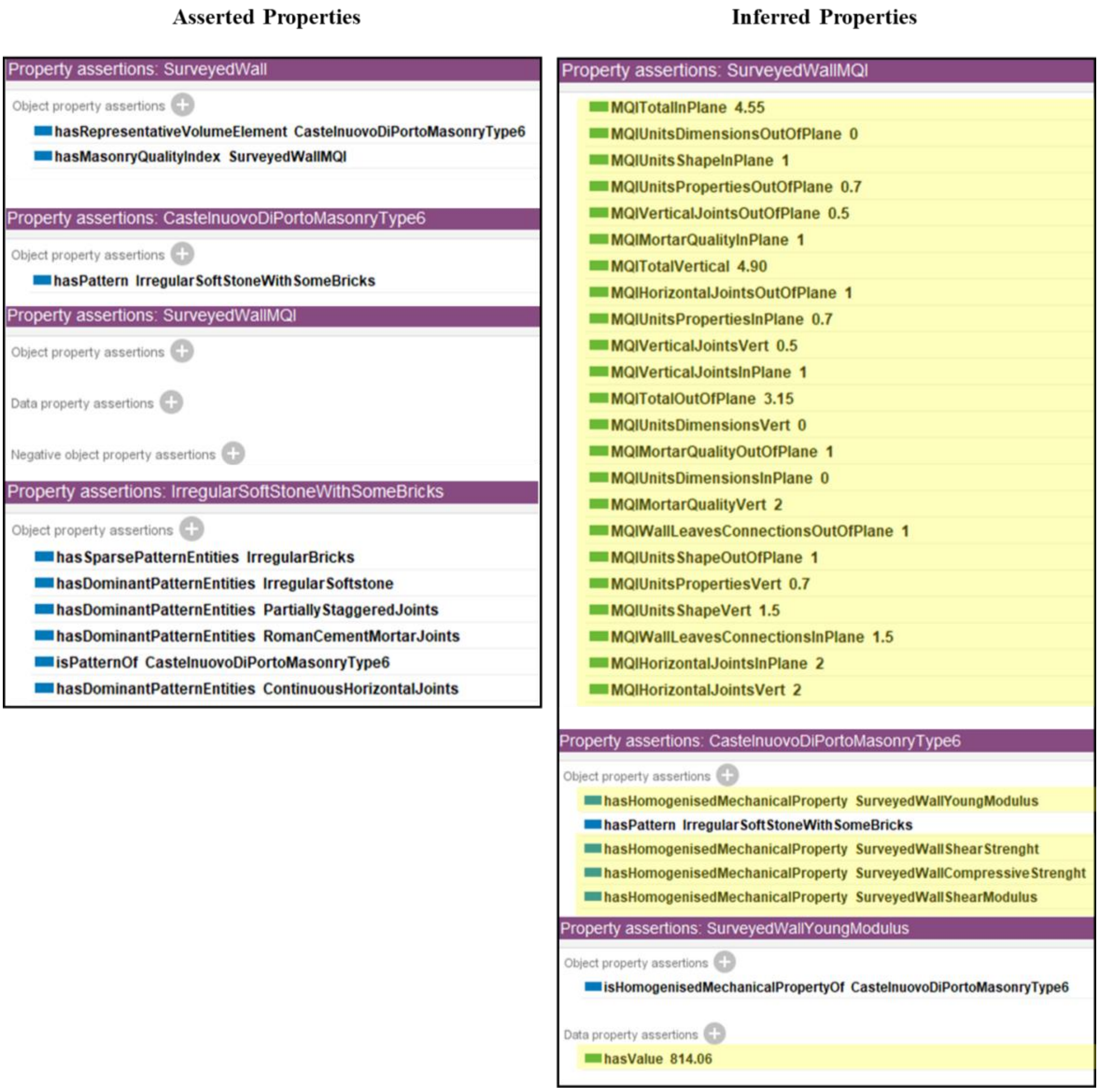

Figure 13: Asserted and inferred properties - HMO ontology.

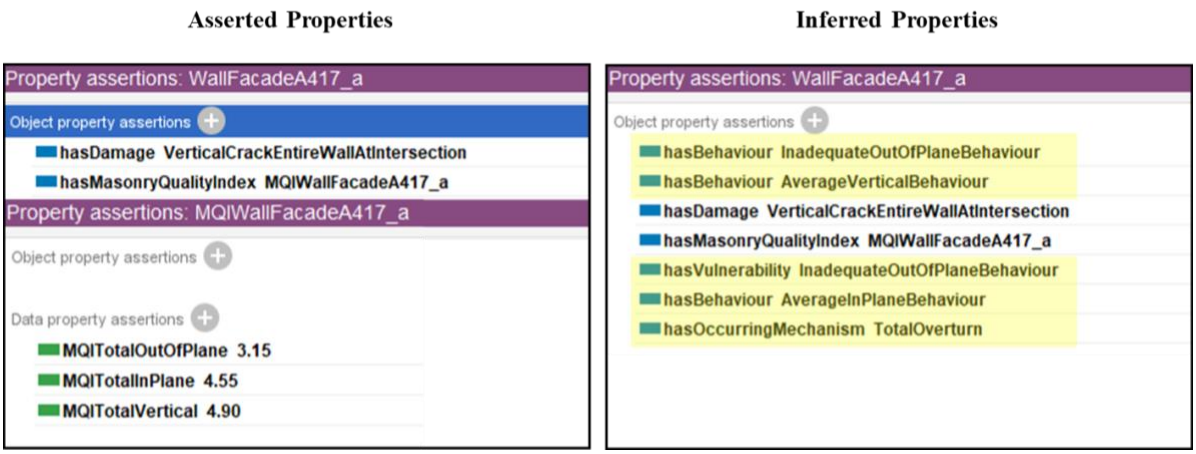

Figure 14: Asserted and inferred properties – FMO ontology.

The application of the ontologies made it possible to infer the most likely mechanical properties and collapse mechanisms for the building under consideration. Specifically, the implemented SWRL rules allowed the mechanical properties to be automatically inferred from the morphological and material data of the masonry.

The ontological model provides valuable insights into the mechanical properties of masonry and alerts us to potential out-of-plane movements. To accurately capture these movements, it's important to use a modeling approach that can handle them effectively. A continuous finite element model is a valid option for this purpose.

The results showed that the proposed approach is effective in representing the complex characteristics of historic masonry and predicting collapse mechanisms. However, some critical issues emerged during the implementation and analysis of the data:

1. Quality of Data: The accuracy of the inferences strongly depends on the quality and completeness of the collected data. In the case of historic buildings, the data may be incomplete or inaccurate due to undocumented structural changes or unseen damage.

2. Complexity of SWRL Rules**: The creation and maintenance of SWRL rules can be complex and require in-depth knowledge of both the application domain and the rule language. Errors in rule definition can lead to incorrect or incomplete inferences.

3. Scalability: Although the approach was effective for a single case study, the scalability of the approach to multiple buildings or larger complexes needs further investigation. Inference of properties and mechanisms for larger structures or those with greater variability may require further optimization.

The developed ontologies and SWRL rules have enabled automatic inference of mechanical properties and collapse mechanisms, improving the accuracy and efficiency of the analysis process. However, the critical issues that emerged highlight the need for further studies to improve the data quality, interoperability and scalability of the proposed method.

The application of the case study illustrated the value of using an ontology reasoner to extract critical information, such as the mechanical properties and potential collapse mechanisms of an unreinforced masonry building. The current methodology requires users to be familiar with the ontology concepts and the software required to work with them.

To make this process more accessible, the next phase of our work is to develop a front-end interface for interacting with the ontology. The aim is to create a platform that allows users to work directly with both the ontology and the BIM model. This platform will allow users to add data one by one without the need for specialised knowledge of ontologies, thus extending the usability of the platform. A promising approach for building this platform is the use of JavaScript in combination with the 'comunica' library, as shown in Donkers et al. (2023). This choice is particularly advantageous because JavaScript can also interact with the 'ifc.js' library, ensuring smooth communication between the BIM model and the ontology.

7. CONCLUSIONS

Unreinforced masonry structures have been demonstrated to be particularly vulnerable to seismic events. Moreover, it is particularly challenging to assess their structural behaviour. One of the major difficulties concerns the definition of the modelling assumptions, namely the identification of the most suitable type of discretization and the most adequate mechanical model. This requires a deep understanding of the assessed structure and the cooperation of stakeholders with different experts to interpret the diverse data collected.

This article addresses the lack of a systematic approach for assessing the structural behavior of unreinforced masonry buildings through a series of SWRL rules, to define the 1) mechanical properties and 2) failure mechanisms for this type of building using the HMO and FMO ontologies. The results from the practical application responded to the research questions, demonstrating that it is possible to use an open system, leveraging the latest technologies, to define mechanical properties and potential failure mechanisms of unreinforced masonry structures.

The HMO is aimed at representing in detail the morphology of masonry materials, with the scope of defining the most plausible mechanical properties. The FMO assesses the most plausible failure mechanisms that a masonry wall may undergo based on the quality of the masonry and on the presence of specific features identified in the literature as causing particular mechanisms. The two ontologies were built upon existing ontologies to promote interoperability with other data systems, namely the BIM model. Indeed, the ontologies were implemented to work in combination with the ‘IFC to finite element analysis framework’ proposed by the author in a previous contribution. The two ontologies were published on the web together with documentation.

The implementation of SWRL rules was a key aspect of the proposed methodology. These rules, based on existing standards and guidelines, enable the automatic deduction of mechanical properties and failure mechanisms from the description of the wall under consideration. The use of SWRL enabled the implementation of particularly complex rules, including mathematical rules and "if statement" rules, while promoting a language with high interoperability.

The practical application of the methodology to a real case study proved the potentiality of the combination of the ontologies together with the SWRL rules to help the stakeholders involved in the knowledge process of a construction to manage the generated data in a standard data space. It was possible, from a few geometrical and material features of the components of specific masonry walls assessed, to deduce the mechanical properties and the most plausible collapse mechanism. This was facilitated by the presence, in the ontologies, of the data from existing standards, stored as individuals of specific classes related to each other with SWRL rules.

This application marks the initial phase of implementing our methodology. The next step involves applying the ontology to various cases to validate it with more complex scenarios further. Additionally, it would be beneficial to incorporate new rules associated with additional mechanical parameters or features not covered in the standard but documented in the literature.

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APPENDICES

Appendix 1 - Rules of the Historic Masonry Ontology

MQI_HJ_ContinuousHorizontalJoints

If a wall has a representative volume element which has a pattern which has a homogeneous pattern entity that is 'continuous horizontal joints', then the value of MQI Horizontal Joints is equal to '2' for vertical loads, '1' for out of plane loads and '2' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:ContinuousHorizontalJoints) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIHorizontalJointsVert(?MQI, 2) ^ hmo:MQIHorizontalJointsOutOfPlane(?MQI, 1) ^ hmo:MQIHorizontalJointsInPlane(?MQI, 2)

MQI_HJ_NotContinuousHorizontalJoints

If a wall has a representative volume element which has a pattern which has a homogeneous pattern entity that is 'not continuous horizontal joints', then the value of MQI Horizontal Joints is equal to '0' for vertical loads, '0' for out of plane loads and '0' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:NotContinuousHorizontalJoints) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIHorizontalJointsVert(?MQI, 0) ^ hmo:MQIHorizontalJointsOutOfPlane(?MQI, 0) ^ hmo:MQIHorizontalJointsInPlane(?MQI, 0)

MQI_HJ_PartiallyContinuousHorizontalJoints

If a wall has a representative volume element which has a pattern which has a homogeneous pattern entity that is 'continuous horizontal joints', then the value of MQI Horizontal Joints is equal to '1' for vertical loads, '1' for out of plane loads and '0.5' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:PartiallyContinuousHorizontalJoints) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIHorizontalJointsVert(?MQI, 1) ^ hmo:MQIHorizontalJointsOutOfPlane(?MQI, 1) ^ hmo:MQIHorizontalJointsInPlane(?MQI, 0.5)

MQI_MM_EarthMortarJoints

If a wall has a representative volume element which has a pattern which has dominant pattern entities 'earth mortar joints', then the value of MQI Mortar Quality is equal to '0' for vertical loads, '0' for out of plane loads and '0' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:EarthMortarJoints) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIMortarQualityVert(?MQI, 0) ^ hmo:MQIMortarQualityInPlane(?MQI, 0) ^ hmo:MQIMortarQualityOutOfPlane(?MQI, 0)

MQI_MM_HydraulicMortar

If a wall has a representative volume element which has a pattern which has dominant pattern entities 'hydraulic lime mortar', then the value of MQI Mortar Quality is equal to '2' for vertical loads, '1' for out of plane loads and '1' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:HydraulicLimeMortarJoints) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIMortarQualityVert(?MQI, 2) ^ hmo:MQIMortarQualityInPlane(?MQI, 1) ^ hmo:MQIMortarQualityOutOfPlane(?MQI, 1)

MQI_MM_LimeMortar

If a wall has a representative volume element which has a pattern which has dominant pattern entities 'lime mortar joints', then the value of MQI Mortar Quality is equal to '0.5' for vertical loads, '1' for out of plane loads and '0.5' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:LimeMortarJoints) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIMortarQualityVert(?MQI, 0.5) ^ hmo:MQIMortarQualityInPlane(?MQI, 1) ^ hmo:MQIMortarQualityOutOfPlane(?MQI, 0.5)

MQI_MM_RomanCementMortar

If a wall has a representative volume element which has a pattern which has dominant pattern entities 'roman cement mortar', then the value of MQI Mortar Quality is equal to '2' for vertical loads, '1' for out of plane loads and '1' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:RomanCementMortarJoints) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIMortarQualityVert(?MQI, 2) ^ hmo:MQIMortarQualityInPlane(?MQI, 1) ^ hmo:MQIMortarQualityOutOfPlane(?MQI, 1)

MQI_MM_RubbleStones_DryJoints

If a wall has a representative volume element which has a pattern which has dominant pattern entities 'rubble stones', and dominant pattern entities 'dry joints', then the value of MQI Unit Shape is equal to '0' for vertical loads, '0' for out of plane loads and '0' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:RubbleStones) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:DryJoints) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIVerticalJointsVert(?MQI, 0) ^ hmo:MQIVerticalJointsInPlane(?MQI, 0) ^ hmo:MQIVerticalJointsOutOfPlane(?MQI, 0)

MQI_MM_SS_RubbleStones_DryJoints_PinningStones

If a wall has a representative volume element which has a pattern which has dominant pattern entities 'rubble stones', and dominant pattern entities 'dry joints' and 'pinning stones', then the value of MQI Unit Shape is equal to '0' for vertical loads, '0' for out of plane loads and '0' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:RubbleStones) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:DryJoints) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:PinningStones) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIVerticalJointsVert(?MQI, 0.5) ^ hmo:MQIVerticalJointsInPlane(?MQI, 0.5) ^ hmo:MQIVerticalJointsOutOfPlane(?MQI, 1) ^ hmo:MQIUnitsShapeVert(?MQI, 1.5) ^ hmo:MQIUnitsShapeInPlane(?MQI, 1) ^ hmo:MQIUnitsShapeOutOfPlane(?MQI, 1)

MQI_SS_Bricks

If a wall has a representative volume element which has a pattern which has a homogeneous pattern entity that is 'bricks', then the value of MQI Unit Shape is equal to '3' for vertical loads, '2' for out of plane loads and '2' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:Bricks) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIUnitsShapeVert(?MQI, 3) ^ hmo:MQIUnitsShapeOutOfPlane(?MQI, 2) ^ hmo:MQIUnitsShapeInPlane(?MQI, 2)

MQI_SS_HollowBricks

If a wall has a representative volume element which has a pattern which has a homogeneous pattern entity that is 'hollow bricks', then the value of MQI Unit Shape is equal to '3' for vertical loads, '2' for out of plane loads and '2' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:HollowBricks) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIUnitsShapeVert(?MQI, 3) ^ hmo:MQIUnitsShapeOutOfPlane(?MQI, 2) ^ hmo:MQIUnitsShapeInPlane(?MQI, 2)

MQI_SS_IrregularSoftStones

If a wall has a representative volume element which has a pattern which has a homogeneous pattern entity that is 'roughly cut stones, then the value of MQI Unit Shape is equal to '1.5' for vertical loads, '1' for out of plane loads and '1' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:IrregularSoftstone) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIUnitsShapeVert(?MQI, 1.5) ^ hmo:MQIUnitsShapeOutOfPlane(?MQI, 1) ^ hmo:MQIUnitsShapeInPlane(?MQI, 1)

MQI_SS_RoughlyCutStone

If a wall has a representative volume element which has a pattern which has a homogeneous pattern entity that is 'roughly cut stones, then the value of MQI Unit Shape is equal to '1.5' for vertical loads, '1' for out of plane loads and '1' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:RoughlyCutStone) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIUnitsShapeVert(?MQI, 1.5) ^ hmo:MQIUnitsShapeOutOfPlane(?MQI, 1) ^ hmo:MQIUnitsShapeInPlane(?MQI, 1)

MQI_SS_RubbleStone

If a wall has a representative volume element which has a pattern which has a homogeneous pattern entity that is 'rubble stones, then the value of MQI Unit Shape is equal to '0' for vertical loads, '0' for out of plane loads and '0' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:RubbleStones) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIUnitsShapeVert(?MQI, 0) ^ hmo:MQIUnitsShapeInPlane(?MQI, 0) ^ hmo:MQIUnitsShapeOutOfPlane(?MQI, 0)

MQI_SS_SquaredSoftStone

If a wall has a representative volume element which has a pattern which has a homogeneous pattern entity that is 'squared soft stones', then the value of MQI Unit Shape is equal to '3' for vertical loads, '2' for out of plane loads and '2' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:SquaredSoftstone) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIUnitsShapeVert(?MQI, 3) ^ hmo:MQIUnitsShapeOutOfPlane(?MQI, 2) ^ hmo:MQIUnitsShapeInPlane(?MQI, 2)

MQI_SD_PresenceOfLargeUnits

If a wall has a representative volume element which has a pattern which has a homogeneous pattern entity that are 'units', and the average length of the units is greater or equal than '40', then the value of MQI Unit Dimensions is equal to '1' for vertical loads, '1' for out of plane loads and '1' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, ?unt) ^ hmo:unitsLengthHasMinimumValue(?unt, ?minVal) ^ hmo:unitsLengthHasMinimumValue(?unt, ?maxVal) ^ swrlb:add(?sum, ?minVal, ?maxVal) ^ swrlb:divide(?avg, ?minVal, ?maxVal) ^ swrlb:greaterThanOrEqual(?avg, "40.0"^^xsd:float) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIUnitsDimensionsVert(?MQI, 1) ^ hmo:MQIUnitsDimensionsOutOfPlane(?MQI, 1) ^ hmo:MQIUnitsDimensionsInPlane(?MQI, 1)

MQI_SD_PresenceOfLittleUnits

If a wall has a representative volume element which has a pattern which has a homogeneous pattern entity that are 'units', and the average length of the units is less than '20', then the value of MQI Unit Dimensions is equal to '0' for vertical loads, '0' for out of plane loads and '0' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, ?unt) ^ hmo:unitsLengthHasMinimumValue(?unt, ?minVal) ^ hmo:unitsLengthHasMinimumValue(?unt, ?maxVal) ^ swrlb:add(?sum, ?minVal, ?maxVal) ^ swrlb:divide(?avg, ?minVal, ?maxVal) ^ swrlb:lessThan(?avg, "20.0"^^xsd:float) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIUnitsDimensionsVert(?MQI, 0) ^ hmo:MQIUnitsDimensionsOutOfPlane(?MQI, 0) ^ hmo:MQIUnitsDimensionsInPlane(?MQI, 0)

MQI_SD_PresenceOfMediumUnits

If a wall has a representative volume element which has a pattern which has a homogeneous pattern entity that are 'units', and the average length of the units is greater or equal than '20' and less than '40', then the value of MQI Unit Dimensions is equal to '0.5' for vertical loads, '0.5' for out of plane loads and '0.5' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, ?unt) ^ hmo:unitsLengthHasMinimumValue(?unt, ?minVal) ^ hmo:unitsLengthHasMinimumValue(?unt, ?maxVal) ^ swrlb:add(?sum, ?minVal, ?maxVal) ^ swrlb:divide(?avg, ?minVal, ?maxVal) ^ swrlb:greaterThanOrEqual(?avg, "20.0"^^xsd:float) ^ swrlb:lessThan(?avg, "40.0"^^xsd:float) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIUnitsDimensionsVert(?MQI, 0.5) ^ hmo:MQIUnitsDimensionsOutOfPlane(?MQI, 0.5) ^ hmo:MQIUnitsDimensionsInPlane(?MQI, 0.5)

MQI_SM_Bricks

If a wall has a representative volume element which has a pattern which has dominant pattern entities that are 'bricks' units, then the value of MQI Unit Properties is equal to '1' for vertical loads, '1' for out of plane loads and '1' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:Bricks) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIUnitsPropertiesVert(?MQI, 1) ^ hmo:MQIUnitsPropertiesInPlane(?MQI, 1) ^ hmo:MQIUnitsPropertiesOutOfPlane(?MQI, 1)

MQI_SM_Damage

If a wall has a representative volume element which has a pattern which has dominant pattern entities (units) that have a damaged area then the value of MQI Unit Properties is equal to '0.3' for vertical loads, '0.5' for out of plane loads and '0.3' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, ?unt) ^ autogen0:hasDamageArea(?unt, ?dmg) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIUnitsPropertiesVert(?MQI, 0.3) ^ hmo:MQIUnitsPropertiesInPlane(?MQI, 0.3) ^ hmo:MQIUnitsPropertiesOutOfPlane(?MQI, 0.5)

MQI_SM_HollowBricks_LessEqualThan55_GreaterEqualThan30

If a wall has a representative volume element which has a pattern which has dominant pattern entities (hollow bricks) that have a pergentage of volume equal or greater than 30% and less or equal than 55 % then the value of MQI Unit Properties is equal to '0.7' for vertical loads, '0.7' for out of plane loads and '0.7' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, ?brk) ^ hmo:bricksHaveVolumePercentage(?brk, ?vlm) ^ swrlb:greaterThanOrEqual(?vlm, 0.30) ^ swrlb:lessThanOrEqual(?vlm, 0.55) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIUnitsPropertiesVert(?MQI, 0.7) ^ hmo:MQIUnitsPropertiesInPlane(?MQI, 0.7) ^ hmo:MQIUnitsPropertiesOutOfPlane(?MQI, 0.7)

MQI_SM_HollowBricks_LessThan30

If a wall has a representative volume element which has a pattern which has dominant pattern entities (hollow bricks) that have a pergentage of volume less than 30% then the value of MQI Unit Properties is equal to '0.3' for vertical loads, '0.5' for out of plane loads and '0.3' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, ?brk) ^ hmo:bricksHaveVolumePercentage(?brk, ?vlm) ^ swrlb:lessThan(?vlm, 0.30) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIUnitsPropertiesVert(?MQI, 0.3) ^ hmo:MQIUnitsPropertiesInPlane(?MQI, 0.3) ^ hmo:MQIUnitsPropertiesOutOfPlane(?MQI, 0.5)

MQI_SM_HollowBricks_MoreThan55

If a wall has a representative volume element which has a pattern which has dominant pattern entities (hollow bricks) that have a percentage of volume equal or greater than 55 % then the value of MQI Unit Properties is equal to '1' for vertical loads, '1' for out of plane loads and '1' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, ?brk) ^ hmo:bricksHaveVolumePercentage(?brk, ?vlm) ^ swrlb:greaterThan(?vlm, 0.55) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIUnitsPropertiesVert(?MQI, 1) ^ hmo:MQIUnitsPropertiesInPlane(?MQI, 1) ^ hmo:MQIUnitsPropertiesOutOfPlane(?MQI, 1)

MQI_SM_IrregularSoftStone

If a wall has a representative volume element which has a pattern which has dominant pattern entities that are 'irregular softstone' units, then the value of MQI Unit Properties is equal to '0.7' for vertical loads, '0.7' for out of plane loads and '0.7' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:IrregularSoftstone) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIUnitsPropertiesVert(?MQI, 0.7) ^ hmo:MQIUnitsPropertiesInPlane(?MQI, 0.7) ^ hmo:MQIUnitsPropertiesOutOfPlane(?MQI, 0.7)

MQI_SM_SquaredHardStone

If a wall has a representative volume element which has a pattern which has dominant pattern entities that are 'squared hardstone' units, then the value of MQI Unit Properties is equal to '1' for vertical loads, '1' for out of plane loads and '1' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:SquaredHardstone) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIUnitsPropertiesVert(?MQI, 1) ^ hmo:MQIUnitsPropertiesInPlane(?MQI, 1) ^ hmo:MQIUnitsPropertiesOutOfPlane(?MQI, 1)

MQI_VJ_PartiallyStaggeredJoints

If a wall has a representative volume element which has a pattern which has a homogeneous pattern entity that are 'propertly staggered units', then the value of MQI vertical joints is equal to '0.5' for vertical loads, '1' for out of plane loads and '0.5' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:PartiallyStaggeredJoints) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIVerticalJointsVert(?MQI, 0.5) ^ hmo:MQIVerticalJointsInPlane(?MQI, 1) ^ hmo:MQIVerticalJointsOutOfPlane(?MQI, 0.5)

MQI_VJ_ProperlyStaggeredJoints

If a wall has a representative volume element which has a pattern which has a homogeneous pattern entity that are 'propertly staggered units', then the value of MQI vertical joints is equal to '1' for vertical loads, '1' for out of plane loads and '2' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:ProperlyStaggeredJoints) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIVerticalJointsVert(?MQI, 1) ^ hmo:MQIVerticalJointsInPlane(?MQI, 2) ^ hmo:MQIVerticalJointsOutOfPlane(?MQI, 1)

MQI_VJ_VerticallyAlignedJoints

If a wall has a representative volume element which has a pattern which has a homogeneous pattern entity that are 'vertically aligned units', then the value of MQI vertical joints is equal to '0' for vertical loads, '0' for out of plane loads and '0' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:VerticallyAlignedJoints) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIVerticalJointsVert(?MQI, 0) ^ hmo:MQIVerticalJointsInPlane(?MQI, 0) ^ hmo:MQIVerticalJointsOutOfPlane(?MQI, 0)

MQI_WC_FrequentHeaders

If a wall has a representative volume element which has a pattern which has a dominant pattern entity that is 'headers bond units, then the value of MQI Wall Connections is equal to '1' for vertical loads, '3' for out of plane loads and '2' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:HeadersBondUnits) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIWallLeavesConnectionsVert(?MQI, 1) ^ hmo:MQIWallLeavesConnectionsOutOfPlane(?MQI, 3) ^ hmo:MQIWallLeavesConnectionsInPlane(?MQI, 2)

MQI_WC_IrregularSoft

If a wall has a representative volume element which has a pattern which has a homogeneous pattern entity that is 'rubble stones, then the value of MQI wall leaves connections is equal to '0' for vertical loads, '0' for out of plane loads and '0' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:IrregularSoftstone) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIWallLeavesConnectionsVert(?MQI, 1) ^ hmo:MQIWallLeavesConnectionsOutOfPlane(?MQI, 1) ^ hmo:MQIWallLeavesConnectionsInPlane(?MQI, 1.5)

MQI_WC_RubbleStones

If a wall has a representative volume element which has a pattern which has a homogeneous pattern entity that is 'rubble stones, then the value of MQI wall leaves connections is equal to '0' for vertical loads, '0' for out of plane loads and '0' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:RubbleStones) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIWallLeavesConnectionsVert(?MQI, 0) ^ hmo:MQIWallLeavesConnectionsOutOfPlane(?MQI, 0) ^ hmo:MQIWallLeavesConnectionsInPlane(?MQI, 0)

MQI_WC_SparseHeaders

If a wall has a representative volume element which has a pattern which has a sparse pattern entity that is 'headers bond units, then the value of MQI Wall Connections is equal to '1' for vertical loads, '1.5' for out of plane loads and '1' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasSparsePatternEntities(?Pttr, hmo:HeadersBondUnits) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIWallLeavesConnectionsVert(?MQI, 1) ^ hmo:MQIWallLeavesConnectionsOutOfPlane(?MQI, 1.5) ^ hmo:MQIWallLeavesConnectionsInPlane(?MQI, 1)

MQ_SS_SquaredHardStone

If a wall has a representative volume element which has a pattern which has a homogeneous pattern entity that is 'squared hardstone', then the value of MQI Unit Shape is equal to '3' for vertical loads, '2' for out of plane loads and '2' for in plane loads.

hmo:hasRepresentativeVolumeElement(?wl, ?RpV) ^ hmo:hasPattern(?RpV, ?Pttr) ^ hmo:hasDominantPatternEntities(?Pttr, hmo:SquaredHardstone) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) -> hmo:MQIUnitsShapeVert(?MQI, 3) ^ hmo:MQIUnitsShapeOutOfPlane(?MQI, 2) ^ hmo:MQIUnitsShapeInPlane(?MQI, 2)

MQI_Vertical

hmo:MasonryQualityIndex(?MQIv) ^ hmo:MQIHorizontalJointsVert(?MQIv, ?HJv) ^ hmo:MQIVerticalJointsVert(?MQIv, ?VJv) ^ hmo:MQIMortarQualityVert(?MQIv, ?MMv) ^ hmo:MQIUnitsShapeVert(?MQIv, ?SSv) ^ hmo:MQIWallLeavesConnectionsVert(?MQIv, ?WCv) ^ hmo:MQIUnitsDimensionsVert(?MQIv, ?SDv) ^ hmo:MQIUnitsPropertiesVert(?MQIv, ?SMv) ^ swrlb:add(?sum, ?HJv, ?VJv, ?MMv, ?SSv, ?WCv, ?SDv) ^ swrlb:multiply(?mlt, ?SMv, ?sum) -> hmo:MQITotalVertical(?MQIv, ?mlt)

MQI_InPlane

hmo:MasonryQualityIndex(?MQIiP) ^ hmo:MQIHorizontalJointsInPlane(?MQIiP, ?HJiP) ^ hmo:MQIVerticalJointsInPlane(?MQIiP, ?VJiP) ^ hmo:MQIMortarQualityInPlane(?MQIiP, ?MMiP) ^ hmo:MQIUnitsShapeInPlane(?MQIiP, ?SSiP) ^ hmo:MQIWallLeavesConnectionsInPlane(?MQIiP, ?WCiP) ^ hmo:MQIUnitsDimensionsInPlane(?MQIiP, ?SDiP) ^ hmo:MQIUnitsPropertiesInPlane(?MQIiP, ?SMiP) ^ swrlb:add(?sum, ?VJiP, ?HJiP, ?MMiP, ?SSiP, ?WCiP, ?SDiP) ^ swrlb:multiply(?mlt, ?SMiP, ?sum) -> hmo:MQITotalInPlane(?MQIiP, ?mlt)

MQI_OutOfPlane

hmo:MasonryQualityIndex(?MQIoP) ^ hmo:MQIHorizontalJointsOutOfPlane(?MQIoP, ?HJoP) ^ hmo:MQIVerticalJointsOutOfPlane(?MQIoP, ?VJoP) ^ hmo:MQIMortarQualityOutOfPlane(?MQIoP, ?MMoP) ^ hmo:MQIUnitsShapeOutOfPlane(?MQIoP, ?SSoP) ^ hmo:MQIWallLeavesConnectionsOutOfPlane(?MQIoP, ?WCoP) ^ hmo:MQIUnitsDimensionsOutOfPlane(?MQIoP, ?SDoP) ^ hmo:MQIUnitsPropertiesOutOfPlane(?MQIoP, ?SMoP) ^ swrlb:add(?sum, ?HJoP, ?VJoP, ?MMoP, ?SSoP, ?WCoP, ?SDoP) ^ swrlb:multiply(?mlt, ?SMoP, ?sum) -> hmo:MQITotalOutOfPlane(?MQIoP, ?mlt)

Shear strength

hmo:RepresentativeVolumeElement(?RpV) ^ hmo:hasMasonryQualityIndex(?Rpv, ?MQI) ^ hmo:MQITotalInPlane(?MQI, ?MQIi) ^ hmo:ShearStrengthTC(?Sst) ^ hmo:hasHomogenisedMechanicalProperty(?RpV, ?Sst) ^ swrlb:pow(?MQIisq, ?MQIi, 2) ^ swrlb:multiply(?factor1, ?MQIisq, 0.0005) ^ swrlb:multiply(?factor2, ?MQIi, 0.0074) ^ swrlb:add(?S, ?factor1, ?factor2, 0.0192) -> saref:hasValue(?Sst, ?S)

Young modulus

hmo:RepresentativeVolumeElement(?RpV) ^ hmo:hasMasonryQualityIndex(?Rpv, ?MQI) ^ hmo:MQITotalVertical(?MQI, ?MQIv) ^ hmo:YoungModulus(?Y) ^ hmo:hasHomogenisedMechanicalProperty(?RpV, ?Y) ^ swrlb:multiply(?factor1, ?MQIv, 0.14) ^ swrlb:roundHalfToEven(?factorR, ?factor1) ^ swrlb:pow(?factor2, 1, ?factorR) ^ swrlb:multiply(?YM, 814.06, ?factor2) -> saref:hasValue(?Y, ?YM)

Shear modulus

Evaluation of the shear modulus from MQI

hmo:RepresentativeVolumeElement(?RpV) ^ hmo:hasMasonryQualityIndex(?Rpv, ?MQI) ^ hmo:MQITotalInPlane(?MQI, ?MQIi) ^ hmo:ShearModulus(?S) ^ hmo:hasHomogenisedMechanicalProperty(?RpV, ?S) ^ swrlb:multiply(?factor1, ?MQIi, 0.1298) ^ swrlb:pow(?factor2, 2.72, ?factor1) ^ swrlb:multiply(?SM, 279.82, ?factor2) -> saref:hasValue(?S, ?SM)

Compressive strength

hmo:RepresentativeVolumeElement(?RpV) ^ hmo:hasMasonryQualityIndex(?Rpv, ?MQI) ^ hmo:MQITotalVertical(?MQI, ?MQIv) ^ hmo:CompressiveStrength(?C) ^ hmo:hasHomogenisedMechanicalProperty(?RpV, ?C) ^ swrlb:multiply(?factor1, ?MQIv, 0.1572) ^ swrlb:pow(?factor2, 2.72, ?factor1) ^ swrlb:multiply(?Cs, 1.6841, ?factor2) -> core:hasValue(?C, ?Cs)

Appendix 2 - Rules of the Failure Mechanism Ontology

Average in plane behaviour

If a Masonry Wall has a Masonry Quality Index, which has a Masonry Quality Index Total In Plane Value less or equal than 5 and greater than 3, than the Masonry Wall has an average in Plane behaviour.

hmo:MasonryWall(?wl) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) ^ hmo:MQITotalInPlane(?MQI, ?MQIv) ^ swrlb:lessThanOrEqual(?MQIv, 5) ^ swrlb:greaterThan(?MQIv, 3) -> hasBehaviour(?wl, AverageInPlaneBehaviour)

Average out of plane behaviour

Out Of Plane Value less or equal than 7 and greater than 4, than the Masonry Wall has an average out of Plane behaviour.

hmo:MasonryWall(?wl) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) ^ hmo:MQITotalOutOfPlane(?MQI, ?MQIv) ^ swrlb:lessThanOrEqual(?MQIv, 7) ^ swrlb:greaterThan(?MQIv, 4) -> hasBehaviour(?wl, AverageOutOfPlaneBehaviour)

Average vertical behaviour

If a Masonry Wall has a Masonry Quality Index, which has a Masonry Quality Index Total Vertical value less or equal than 5 and greater than 2.5, than the Masonry Wall has an average vertical behaviour.

hmo:MasonryWall(?wl) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) ^ hmo:MQITotalVertical(?MQI, ?MQIv) ^ swrlb:lessThanOrEqual(?MQIv, 5) ^ swrlb:greaterThanOrEqual(?MQIv, 2.5) -> hasBehaviour(?wl, AverageVerticalBehaviour)

Good in plane behaviour

If a Masonry Wall has a Masonry Quality Index, which has a Masonry Quality Index Total In Plane Value less or equal than 10 and greater than 5, than the Masonry Wall has an good in plane behaviour.

hmo:MasonryWall(?wl) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) ^ hmo:MQITotalInPlane(?MQI, ?MQIv) ^ swrlb:lessThanOrEqual(?MQIv, 10) ^ swrlb:greaterThan(?MQIv, 5) -> hasBehaviour(?wl, GoodInPlaneBehaviour)

Good out of plane behaviour

If a Masonry Wall has a Masonry Quality Index, which has a Masonry Quality Index Total out of plane value less or equal than 10 and greater than 7, than the Masonry Wall has an good out of plane behaviour.

hmo:MasonryWall(?wl) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) ^ hmo:MQITotalOutOfPlane(?MQI, ?MQIv) ^ swrlb:lessThanOrEqual(?MQIv, 10) ^ swrlb:greaterThan(?MQIv, 7) -> hasBehaviour(?wl, GoodOutOfPlaneBehaviour)

Good vertical behaviour

If a Masonry Wall has a Masonry Quality Index, which has a Masonry Quality Index Total vertical value less or equal than 10 and greater than 5, than the Masonry Wall has a good vertical behaviour.

hmo:MasonryWall(?wl) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) ^ hmo:MQITotalVertical(?MQI, ?MQIv) ^ swrlb:lessThanOrEqual(?MQIv, 10) ^ swrlb:greaterThan(?MQIv, 5) -> hasBehaviour(?wl, GoodVerticalBehaviour)

Horizontal bending - absence of top chains

If a masonry wall has a vulnerability that is 'excessive slenderness' and a vulnerability that is 'absence of top chains' and a vulnerability that is 'presence of horizontal thrusts' and a behaviour that is 'inadequate out of plane behaviour', then it has an occurring mechanism that is 'horizontal bending'.

hasVulnerability(?wl, ExcessiveSlenderness) ^ hasVulnerability(?wl, AbsenceOfTopChains) ^ hasVulnerability(?wl, PresenceOfHorizontalThrust) ^ hasBehaviour(?wl, InadequateOutOfPlaneBehaviour) -> hasOccurringMechanism(?wl, HorizontalBending)

Horizontal bending - absence of top curbstone

If a masonry wall has a vulnerability that is 'excessive slenderness' and a vulnerability that is 'absence of top curbstone' and a vulnerability that is 'presence of horizontal thrusts' and a behaviour that is 'inadequate out of plane behaviour', then it has an occurring mechanism that is 'horizontal bending'.

hasVulnerability(?wl, ExcessiveSlenderness) ^ hasVulnerability(?wl, AbsenceOfTopCurbstone) ^ hasVulnerability(?wl, PresenceOfHorizontalThrust) ^ hasBehaviour(?wl, InadequateOutOfPlaneBehaviour) -> hasOccurringMechanism(?wl, HorizontalBending)

In plane failure

If a masonry wall has a vulnerability that is 'inadequate in plane behaviour', than it has an occurring mechanism that is 'in plane failure'.

hasVulnerability(?wl, InadequateInPlaneBehaviour) -> hasOccurringMechanism(?wl, InPlaneFailure)

Inadequate Out Of Plane Behaviour Vulnerability

If a masonry wall has a vulnerability that is 'inadequate out of plane behaviour', then it has an occurring mechanism that is 'out of plane failure'.

hasBehaviour(?wl, InadequateOutOfPlaneBehaviour) -> hasVulnerability(?wl, InadequateOutOfPlaneBehaviour)

Inadequate Vertical Behaviour Vulnerability

If a masonry wall has a behaviour that is 'inadequate vertical behaviour', then it has a vulnerability that is 'inadequate vertical behaviour'.

hasBehaviour(?wl, InadequateVerticalBehaviour) -> hasVulnerability(?wl, InadequateVerticalBehaviour)

Inadequate in plane behavior

If a Masonry Wall has a Masonry Quality Index, which has a Masonry Quality Index Total in plane value less or equal than 3 and greater or equal than 0, than the Masonry Wall has an inadequate In plane behaviour

hmo:MasonryWall(?wl) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) ^ hmo:MQITotalInPlane(?MQI, ?MQIv) ^ swrlb:lessThanOrEqual(?MQIv, 3) ^ swrlb:greaterThanOrEqual(?MQIv, 0) -> hasBehaviour(?wl, InadequateInPlaneBehaviour)

Inadequate vertical behaviour

If a Masonry Wall has a Masonry Quality Index, which has a Masonry Quality Index Total vertical value less or equal than 2.5 and greater or equal than 0, than the Masonry Wall has an inadequate vertical behaviour

autogen0:MasonryWall(?wl) ^ autogen0:hasMasonryQualityIndex(?wl, ?MQI) ^ autogen0:MQITotalVertical(?MQI, ?MQIv) ^ swrlb:lessThanOrEqual(?MQIv, 2.5) ^ swrlb:greaterThanOrEqual(?MQIv, 0) -> hasBehaviour(?wl, InadequateVerticalBehaviour)

Inadequate out of plane behaviour

If a Masonry Wall has a Masonry Quality Index, which has a Masonry Quality Index Total out of plane value less or equal than 4 and greater or equal than 0, than the Masonry Wall has an inadequate out of plane behaviour

hmo:MasonryWall(?wl) ^ hmo:hasMasonryQualityIndex(?wl, ?MQI) ^ hmo:MQITotalOutOfPlane(?MQI, ?MQIv) ^ swrlb:lessThanOrEqual(?MQIv, 4) ^ swrlb:greaterThanOrEqual(?MQIv, 0) -> hasBehaviour(?wl, InadequateOutOfPlaneBehaviour)

Mechanism and damage

If a wall has a damage, and the damage is caused by a specific mechanism, than the wall has a ongoing mechanism.

dot:hasDamage(?wl, ?dmg) ^ dot:hasCausation(?dmg, ?mcn) -> hasOccurringMechanism(?wl, ?mcn)

Partial overturn – chains

If a masonry wall has a vulnerability that is 'absence of top chains', then it has an occurring mechanism that is 'partial overturn.

hasVulnerability(?wl, AbsenceOfTopChains) -> hasOccurringMechanism(?wl, PartialOverturn)

Partial overturn – curbstone

If a masonry wall has a vulnerability that is 'absence of top curbstone, then it has an occurring mechanism that is 'partial overturn.

hasVulnerability(?wl, AbsenceOfTopCurbstone) -> hasOccurringMechanism(?wl, PartialOverturn)

Vertical bending

If a masonry wall has a vulnerability that is 'excessive slenderness' and has a vulnerability that is 'presence of horizontal thrusts', and has a vulnerability that is 'deformable floor, and it has a behaviour that is 'inadequate out of plane behaviour', then it has an occurring mechanism that is 'vertical bending'.

hasVulnerability(?wl, ExcessiveSlenderness) ^ hasVulnerability(?wl, PresenceOfHorizontalThrust) ^ hasVulnerability(?wl, DeformableFloors) ^ hasBehaviour(?wl, InadequateOutOfPlaneBehaviour) -> hasOccurringMechanism(?wl, VerticalBending)

Total overturn – chains

If a masonry wall has a vulnerability that is 'absence of intermediate chains' and has a vulnerability that is 'absence of top chains', then it has an occurring mechanism that is 'total overturn'.

hasVulnerability(?wl, AbsenceOfIntermediateChains) ^ hasVulnerability(?wl, AbsenceOfTopChains) -> hasOccurringMechanism(?wl, TotalOverturn)

Total overtun – curbstone

If a masonry wall has a vulnerability that is 'absence of intermediate curbstone and has a vulnerability that is 'absence of top curbstone, then it has an occurring mechanism that is 'total overturn'.

hasVulnerability(?wl, AbsenceOfIntermediateCurbstone) ^ hasVulnerability(?wl, AbsenceOfTopCurbstone) -> hasOccurringMechanism(?wl, TotalOverturn)

Total overturn - curbstone -chain

If a masonry wall has a vulnerability that is 'absence of intermediate curbstone' and has a vulnerability that is 'absence of top chains', then it has an occurring mechanism that is 'total overturn.

hasVulnerability(?wl, AbsenceOfIntermediateCurbstone) ^ hasVulnerability(?wl, AbsenceOfTopChains) -> hasOccurringMechanism(?wl, TotalOverturn)

Total overturn chain – curbstone

If a masonry wall has a vulnerability that is 'absence of intermediate chains' and has a vulnerability that is 'absence of top curbstone', then it has an occurring mechanism that is 'total overturn.

hasVulnerability(?wl, AbsenceOfIntermediateChains) ^ hasVulnerability(?wl, AbsenceOfTopCurbstone) -> hasOccurringMechanism(?wl, TotalOverturn)