ADVANCED MASTERS IN STRUCTURAL ANALYSIS OF MONUMENTS AND HISTORICAL CONSTRUCTION

Master's Thesis

Maria Laura Leonardi

Integrating BIM technology in the vulnerability assessment of historic masonry aggregates.

University of Minho

Portugal | 2021

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DECLARATION

Name:	Maria Laura Leonardi
Email:	mlauraleonardi@gmail.com

Title of the Msc Dissertation:	Integrating BIM technology in the vulnerability assessment of historic masonry aggregates
Supervisor(s):	Daniel V. Oliveira and Miguel Azenha
Year:	2021

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

I hereby declare that the MSc Consortium responsible for the Advanced Masters in Structural Analysis of Monuments and Historical Constructions is allowed to store and make available electronically the present MSc Dissertation.

University:	University of Minho
Date:	07/16/2021
Signature:	

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ABSTRACT

A large part of the built heritage is represented by "groups" of buildings, also known as aggregates. These traditional dwellings have been abandoned for a long time, since they were intended for the most disadvantaged social classes, and not responding to current living standards. Nevertheless, conserving and adapting them into liveable buildings can be a winning approach to mitigate the problem of building waste. From a structural point of view, the need to rehabilitate them is urgent, as visible from the consequences of the last seismic events. Nevertheless, their diagnosis is very challenging due to the lack of adequate approaches and numerical tools. Besides, a multi-disciplinary team must be involved in the interpretation of their critical features, influencing their seismic behavior.

As a consequence, there is the need of finding a methodology to fully assess these structures, and to propose as fast as possible a rehabilitation project. Within this framework, Heritage Building Information Modeling (HBIM), applied to monuments so far, can represent a key step ahead when used in building aggregates due to its capability of coordinating the work of all the stakeholders involved in the entire life-cycle of the building. The scientific community is investigating its implementation for built heritage, but several issues are still unsolved.

This dissertation proposes an integrated framework conceived for the diagnosis and rehabilitation of masonry aggregates that takes advantage of the possibilities given by BIM. Specifically, the contribution of the dissertation is the introduction of a Product Data Template for historical masonry walls and the development of a connection between the BIM model and the structural Discrete Macro-Element model, to verify the safety of the structure and validating the strengthening project.

The methodology proposed is applied for a unit of a meaningful aggregate in Ortigia. The latter is modeled in Revit, and employing a code-link, developed in Dynamo, send to the solver of 3DMacro, to perform nonlinear static analyses, which results are sent back to Revit.

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RESUMO

Grande parte do património edificado é representado por “grupos” de edificações, também conhecidos como agregados. Estas construções tradicionais encontram-se há muito abandonadas, visto que se destinavam às classes sociais mais desfavorecidas, não podendo corresponder aos padrões de vida actuais. No entanto, conservá-las e adaptá-las em habitações seguras e confortáveis pode ser uma abordagem vencedora para mitigar o problema dos resíduos de construção. Do ponto de vista estrutural, a necessidade de reabilitar estas construções é urgente, visível pelas consequências dos últimos eventos sísmicos. No entanto, seu diagnóstico é muito desafiador devido à falta de abordagens e ferramentas numéricas adequadas. Além disso, deve estar envolvida uma equipa multidisciplinar na interpretação das suas características críticas, que condicionam o seu comportamento sísmico.

Como consequência, existe a necessidade de encontrar uma metodologia para avaliar devidamente estas estruturas e propor um projeto de reabilitação com brevidade. Assim, o “Heritage Building Information Modeling” (HBIM), aplicado até agora a monumentos, pode representar um passo importante quando aplicado a agregados devido à sua capacidade de coordenar o trabalho de todas as partes envolvidas e ao longo de todo o ciclo de vida da construção. A comunidade científica está a investigar a sua implementação no património construído, mas há várias questões ainda por resolver.

Esta dissertação propõe um procedimento integrado concebido para o diagnóstico e reabilitação de agregados de alvenaria que tira partido das possibilidades oferecidas pelo BIM. Especificamente, a contribuição da dissertação é a introdução de um “Product Data Template” para paredes históricas de alvenaria e o desenvolvimento de uma ligação entre o modelo BIM e o modelo estrutural de Macroelementos Discretos para verificar a segurança da estrutura e validar o projeto de reforço.

A metodologia proposta é aplicada a uma unidade de um agregado significativo de Ortigia. Este último foi modelado em Revit e enviado para o solver do 3DMacro, através de um algoritmo desenvolvido em Dynamo, para realizar análises estáticas não lineares, cujos resultados são enviados novamente para o software Revit.

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RESUMÉ

Gran parte del patrimonio costruito è rappresentato da "gruppi" di edifici, noti anche come aggregati. Questi edifici tradizionali sono stati a lungo abbandonati, in quanto erano destinati alle classi sociali più svantaggiate e non possono soddisfare gli attuali standard di vita. Tuttavia, preservarli e adattarli in case sicure e confortevoli può essere un approccio vincente per mitigare il problema dei rifiuti di costruzione. Da un punto di vista strutturale, la necessità di riabilitare queste costruzioni è urgente, visibile dalle conseguenze degli ultimi eventi sismici. Tuttavia, la sua diagnosi è molto impegnativa a causa della mancanza di approcci e strumenti numerici appropriati. Inoltre, l'interpretazione delle criticita di queste strutture, che ne condizionano il comportamento sismico, richiede il coinvolgimento di un team multidisciplinare.

Di conseguenza, è necessario trovare una metodologia per valutare correttamente queste strutture e proporre rapidamente un progetto di riabilitazione. In questo contesto, l' "Heritage Building Information Modeling" (HBIM), tecnologia applicata finora ai monumenti, può rappresentare un momento di svolta, grazie alla sua capacità di coordinare il lavoro di tutte le parti coinvolte e durante l'intero ciclo di vita della costruzione. Negli ultimi anni la ricerca scientifica ha sviluppato notevoli passi avanti in questa direzione, ma diverse questioni sono rimaste irrisolte, e ulteriori sviluppi sono necessari.

Questa tesi propone una procedura integrata pensata per la diagnosi e la riabilitazione degli aggregati in muratura che sfrutta le possibilità offerte dal BIM. Nello specifico, il contributo della tesi è l'introduzione di un "Product Data Template" per pareti storiche in muratura non armata, e lo sviluppo di un link tra il modello BIM e il modello strutturale, secondo un approccio basato su Macroelementi Discreti per verificare la sicurezza della struttura e convalidare il progetto di rinforzo.

La metodologia proposta viene applicata ad un'unità di un aggregato significativo di Ortigia. Quest'ultimo è stato modellato su Revit e inviato al risolutore 3DMacro, attraverso un algoritmo sviluppato in Dynamo, per eseguire analisi statiche non lineari, i cui risultati vengono riinviati al software revit.

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1. INTRODUCTION

The masonry aggregates that characterize the historical Italian centers are extremely vulnerable to seismic events and they need to be rehabilitated as fast as possible. The use of numerical models to assess these constructions can be difficult or time-consuming, but it is the most accurate way of understanding their seismic behavior. Moreover, these structures are often in a state of abandonment, still considered a form of housing for the most deprived social classes, not meeting the requirements of today's living standards. This means that, besides being seismic retrofitted, these buildings need to become liveable spaces.

Building Information Modeling (BIM) is becoming increasingly important in the design of new structures, due to its capacity of coordinating the work of all the stakeholders involved in the entire life-cycle of the building. Until now, the contribution that the scientific community has given in terms of Heritage Building Information Modeling is fragmented and unsolved (Barontini, et al., 2021). One of the main trends has been the introduction of technologies aimed at automatically importing the complex geometry of the existing structure from the point cloud to the BIM models. This was also done with the scope of use of the geometry of the BIM model to perform structural analyses, often focusing on the Finite Element Method. Within this framework, several drawbacks are still present, especially because of the complexity and the dimension of the structures being assessed. In addition, the BIM technology is sometimes denatured, since the idea of exporting only the geometry of the structure, and not the other information propedeutic to the structural analyses, is an approach that uses only a small part of the possibilities given by BIM.

This dissertation proposes a systematic methodology of diagnosis and rehabilitation of masonry aggregates that is both efficient and accessible, taking advantage of the possibilities given by BIM, in terms of data management. Within this framework, the contribution of the current work has been the introduction of a Product Data Template conceived to respond to the latest standardization requirements; and the development of a circular connection between the BIM model (in Revit) and the structural Discrete Macro-Element model (within 3Dmacro software) to verify the safety of the structure. This must be considered as part of a broader project aiming to fully understand the importance of guaranteeing interoperability between BIM and structural models. The proposed approach has advantages in terms of data management and work organization. Precisely, the proposed framework is aimed at reviewing the efficiency of the team involved in the assessment of these structures. It is an undeniable fact that dealing with the modeling of a historical building, to carry out structural analyses, or for other purposes, is one of the most time-consuming parts of the process. This feature makes the team less efficient, forcing the stakeholders to focus their effort on something where they are not specialized. Alternatively, planning to have a "BIM expert" as the only one that deals with modeling, and which is guided by the other experts, is a way to speed up the assessment and rehabilitation of these structures.

The dissertation is structured in seven chapters. This first introduction motivates the reason of explains the motivations that led to this work. Afterwords, in chapter 2 it is introduced the state of the art. Specifically, it is divided into two parts. The first part is a brief overview of the last developments that the scientific community has done in terms of seismic behavior assessment of building aggregates, illustrating the most researched methodologies, applied at different scales (urban, aggregate scale, unit scale). The second part introduces the latest innovations, but also requirements of the Building Information Modeling (BIM) methodology, with a major focus on the application of BIM for heritage (HBIM), showing the endless possibilities that this tool can give in the assessment and management of built heritage, and the related open issues that are the focus of the scientific research. Chapter 3 describes the complex construction typology that is masonry aggregates, pointing out the heterogeneity of their features, especially in the Italian territory. It is synthesized the long history of these buildings, pointing out the long period in which these were left in a state of neglect. Today's major challenges on their assessment and renovation are illustrated as well. A major detail is given in the description of the historical center of Ortigia: due to the long and complex history of the aggregates of this center, and due to the previous work done, this case study is very representative of the typology assessed. Chapter 4 focuses on the macro-element approach to assess unreinforced masonry buildings. Specifically, it is pointed out the fact that this methodology is contemplated by the building code, indicating the type of failures that this enables to assess. A major focus is given in the description of the discretization of the element to be modeled, necessary to introduce and explain the efforts done in the thesis application. Chapter 5 is aimed at inserting the contribution given by this thesis in a broader project. Indeed, ensuring the interoperability between the BIM model and the structural model provides advantages in terms of data management and speed on the entire assessment of these constructions. The approach proposed has the purpose of making easier the different aspects of the renovation project. Chapter 6 explains in detail how the communication between the two software is done, showing advantages, limitations and difficulties. This is done through an application on a little unit of a representative aggregate in Ortigia. Finally, the last chapter highlights the results achieved and the future developments of the current research.

2. ASSESSMENT OF MASONRY AGGREGATES: AN OVERVIEW

2.1 Introduction

The recent seismic events that hit the central area of Italy were an opportunity to learn from the mistakes of the past, but also opened the way to research. These disastrous events make clear the need to promptly intervene to assess and rehabilitate these constructions. Moreover, the study of the earthquake's effects makes the scientific community always more aware of the most common failure mechanisms of these buildings and their causes.

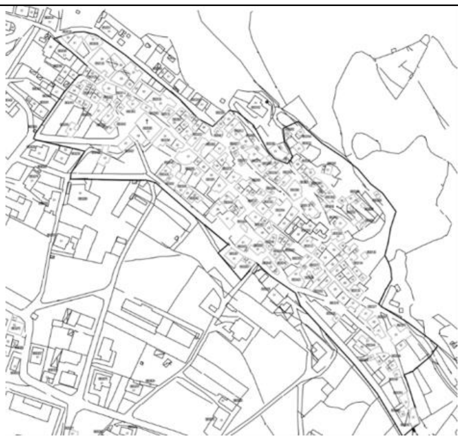
In literature, it is possible to find different approaches to the study of the behavior of this typology. Due to the difficulty of performing numerical global analyses of the entire compounds, many studies are done at a large scale. For these structures, more than ever, it is important to have in mind the final purpose of the assessment and choose the most appropriate approach to follow. The proposed literature review is based on 14 scientific papers published in the last 7 years (2014 to 2021). It mainly refers to studies done in the Italian territory, and specifically in the areas that were stroke by the earthquakes. Within the 14 papers analyzed:

- Six research papers were aimed at calibrating and testing large-scale empirical approaches, by comparing the expected damage with numerical results, (obtained by using a macro-element equivalent frame approach), or the actual damage state found on site;
- One paper compared the simplified global approach with numerical results obtained using a macro-element approach based on equivalent frame method;
- One paper compared the kinematic analyses with the global analyses obtained using a numerical finite element method;
- A total of three papers investigated the simplified kinematic approach;
- Four papers investigated the use of the Vulnus methodology;
- One paper made a full investigation taking advantage of all the aforementioned methods.

The analyzed aggregates are: Poggio Picenze, Arsita, San Pio delle Camere, Sulmona and Campotosto, all of these were struck by the 2009 L'Aquila earthquake. Campi Alti di Norcia and Sora were struck by the 2016 Amatrice earthquake. As far as concerns the morphology of these centers, this is schematized in Table 1.

Table 1- Aggregates of major focuses in the research field

Poggio Picenze: Several earthquakes have destroyed its original configuration. It is now characterized by some more regular aggregates, organized in rows, and others more complex.	
Arsita The current configuration of the aggregate dates back to the Renaissance, which explains the regularity in plan.	
San Pio delle Camere It is a medieval center. The majority of the aggregates are organized in rows, but there is a strong slope.	
Sulmona It is one of the biggest and most preserved historical centers of Abruzzo. It presents the major features of medieval cities. It went through several transformations during Renaissance and Baroque Age.	

Campotosto It was founded during the Middle Ages but was then affected by several earthquakes, which is why it has a very uniform configuration in plan, with a herringbone pattern.	
Campi Alti di Norcia Aggregates are organized in rows, according to the natural slope.	
Sora The current configuration is characterized by a certain regularity in plan, since the center was mainly re-built after the 1915 earthquake.	

As visible, all the centers that have been under the focus of the most recent research were the ones affected by the last seismic events. They are characterized by a certain plan regularity, being part of the centers that have been reconstructed after seismic events, and for this reason, they only represent a little part of the vast and heterogeneous Italian masonry aggregates.

2.1.1 Empirical approach

The empirical approach is one of the possible methods for seismic assessment of masonry aggregates at a large scale. This is applied at a large scale and aimed at evaluating the expected damage based on the application of the Vulnerability Index, introduced in 1984 (Benedetti & Petrini, 1984). This was conceived for masonry structures and considering different parameters, it takes into account the features of these constructions that affect their structural behavior. This methodology is still in continuous evolution, and recently new parameters have been introduced specifically conceived for building in aggregates. This possibility was explored in Italy as well as in other countries, such as

Portugal. A contribution was given by Ferreira and Vicente (Ferreira et al., 2012) synthesizing the parameters in five: quality of masonry fabric, misalignment of openings, irregularity in the plan, irregularity in heigh, plan geometry, location, and soil quality, to provide a first-level screening to identify the most vulnerable areas in the center, applying the methodology in Coimbra city. In Italy, a contribution was given by Formisano (Formisano et al., 2014), which, started from the 9 original parameters, added 5 more parameters and used a numerical approach to calibrate this methodology for the center of Sessa Aurunca in Campania. The methodology was further validated for Torre del Greco and applied at large scale in Poggio Picenze, which had been struck by L'Aquila Earthquake. In this way, it was possible to compare the expected damages with the effective occurred ones, showing that the methodology proposed was good for a quick assessment, especially to understand which aggregates require urgent intervention, but not conservative enough to assess the structure at the aggregate scale. In any case, even if there are still further developments required, especially related to the calibration of the method for different seismic areas, it is a methodology that can be used in case of lack of detailed information. This was pointed out for the case study in Campi Alti di Norcia (Romis et al., 2020) where four different methods of evaluating the Vulnerability Index were compared with the real damages caused by the Earthquakes. Finally, the use of the empirical method is compared with results achieved using numerical approaches, in the case of Arsita (Chieffo & Formisano, 2019), where it was noticed that, despite the empirical methodology was useful at a large scale, at the aggregate scale it was not able to fully predict the damage caused by the seismic events.

2.1.2 Simplified global approach

The previous section explained that using an empirical method can be useful when it comes to understanding which is the most vulnerable aggregates, but it is not enough to assess these structures at the local scale. At the aggregate scale, a fast assessment can be made by applying the numerical simplified approach proposed by the Italian Guidelines (MiBAC, 2011). According to this approach, the global seismic resistance evaluation of the building is based on the shear capacity of the masonry walls, in the hypothesis of the box behavior. Nevertheless, when compared with the numerical modeling, the approach became very conservative as it was demonstrated for a meaningful aggregate in San Pio delle Camere (Formisano, 2016)

2.2.2 Local mechanisms

The second approach proposed by the Italian Guidelines (MiBAC, 2011) is the evaluation of the seismic capacity of the structure based on the local collapse mechanism. This relies on the principle that the safety of the structure should be verified considering the possible activation of a local collapse mechanism. One of the first studies on this topic was carried out for the historical center of Ortigia, in Siracusa. According to this approach in the case of seismic excitation, if the seismic acceleration reaches a certain intensity, it is proven that relevant portions of a wall rotate as rigid bodies. The first step of the methodology proposed is the definition of the type of expected kinematics, which can be done by learning from past earthquakes, or by performing lab tests. In the last century, several catalogs showing the most common kinematics were proposed. Some of these types of kinematics are specifically related to the construction type in aggregates, as in the examples from Figure 1. (Giuffrè, 1993).

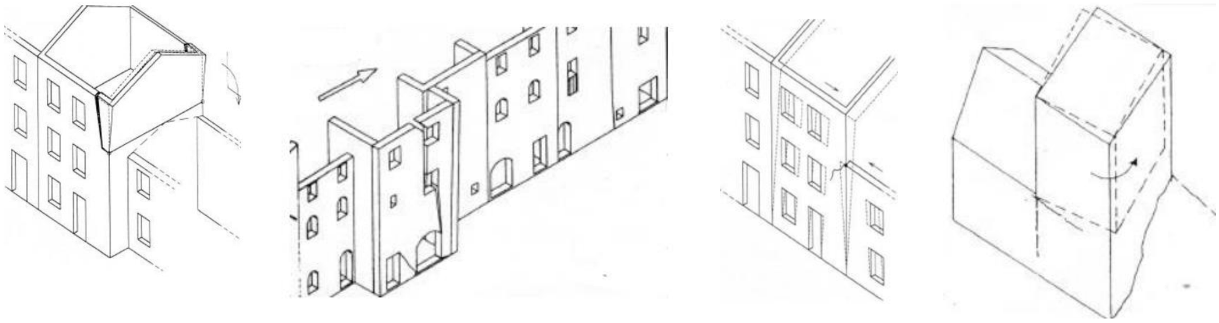


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Figure 1 - Local mechanism common in the masonry aggregates. a) out-of-plane of a wall in the case of different heigh of the units; b) out-of-plane of the corner in case of disalignment of the units; c) beating of a taller unit in a shorter one; d) rotation due to different torsional rigidity (Giuffrè, 1993).

The kinematic approach is still one of the main focuses of the research, and it is often applied in combination with methodologies aimed at evaluating the global behavior of the structure. A recent application of this methodology was applied in an aggregate of Arsita. In this case, the aim was to understand the influence of the local mechanism on large seismic vulnerability estimation, by developing a parametric kinematic analysis on masonry walls with different height/thickness ratios to estimate the collapse load multiplier for activating the main expected mechanism, and integrate the results achieved with existing survey forms (Formisano et al., 2020). Another application, always done in the center of Arsita, was done using NURBS surfaces (parametric surfaces in the tri-dimensional Euclidean space) and exported in the calculation software matlab to assess the ultimate load-bearing capacity of an aggregate. This was done using an upper-bound formulation, according to the limit analyses to solve the kinematic problem by applying the principle of virtual work (Grillanda et al., 2020).

Finally, a kinematic limit analysis was applied on the most vulnerable units of two aggregates of the center of Sora (Figure 2), after having performed nonlinear dynamic analyses in a full 3D finite element model. In this case, it was pointed out the efficiency of the kinematic approach, but also the necessity of associating the use of this method with a global numerical analysis (Valente et al., 2019).

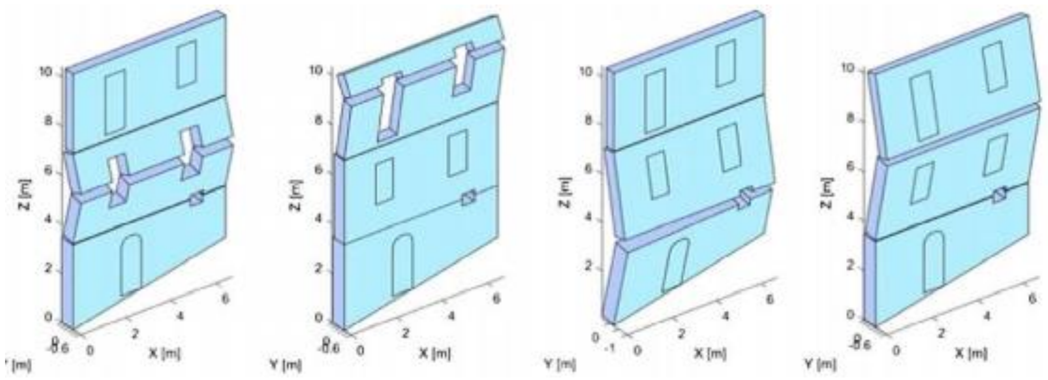


Figure 2 - Kinematic limit analysis proposed for the historical center of Sora (Valente et al., 2019).

2.2.3 Vulnus approach - an intermediate approach

An approach to the study of local mechanisms, which is becoming more and more common at the aggregate scale, is based on the use of the software Vulnus (Bernandini, et al., 2009). This methodology is a numerical approach based on the estimation of the vulnerability of the aggregate, based on three indexes. The first one is related to the in-plane strength of the walls in the weakest direction of the structure, the second is the ratio between the acceleration able to provoke the worst out-of-plane mechanism, and the third one is a parameter that accounts for specific features of the aggregate, which are considered critical. This methodology aims to understand the possible local collapse and the vulnerability of the structure (Munari, et al., 2010). Despite this approach is a simplified one, the implementation of the model in the software requires a certain knowledge of the analyzed structure. This was pointed out by the study done for the historical center of Sulmona, where the methodology was applied after having carried on the historical survey, as well as the inspection and monitoring of the structure using also NDT and MDT tests. In this case, the results were compared to the one obtained following the empirical approach, to which they are coherent. Moreover, it provides additional information, giving awareness of which are the most vulnerable units inside the aggregate, because of their position or because of the presence of efficient strengthening techniques (Munari, et al., 2010). This software was also used in the assessment of an aggregate in the center of Campotosto, and compared with the empirical approach applied at a large scale, to which it seems to be more conservative, and more near to the actual damage that can be seen in the center, struck by the earthquake of the middle of Italy in 2016 (Cocco et al., 2019). Finally, this methodology was also applied to the historical center of Arsita (Chieffo & Formisano, 2019). In this case, a quick assessment was done performing the empirical method based on the Vulnerability Index, applied at the aggregate level. Afterward, the results were compared with the numerical approach using 3Muri, based on an equivalent frame approach. As expected, the most refined results are provided by the numerical approach, followed by Vulnus, and eventually, the empirical method gives results that are not enough to establish the dynamic behavior of the structure.

2.3.4 Numerical global analyses

The performance of global numerical analyses has been recognized as the most complete way of understanding the dynamic behavior of the structural aggregates, as pointed out by the Italian Guidelines (MiBAC, 2011). The efficiency of this methodology seems to be already proven, as in the literature review this is often used to validate and calibrate other approaches (Formisano et al., 2015), (Formisano, 2016), (Chieffo & Formisano, 2019), (Grillanda et al., 2020).

Two aggregates of the historical center of Sora have been studied through a full 3D finite element model performing nonlinear dynamic analyses (Valente et al., 2019). The use of such a refined discretization approach provided a very detailed description of the dynamic response of the structure. The main drawbacks are related to the time spent to process the analyses, but also to the necessity of simplifying a lot the geometry of the structure. Indeed in this case it was required to neglect the floors. It worth also to be mentioned that the two analyzed compounds were relatively simple, being organized in rows, and being in a plane base, thus without the presence of staggering levels (Figure 3).

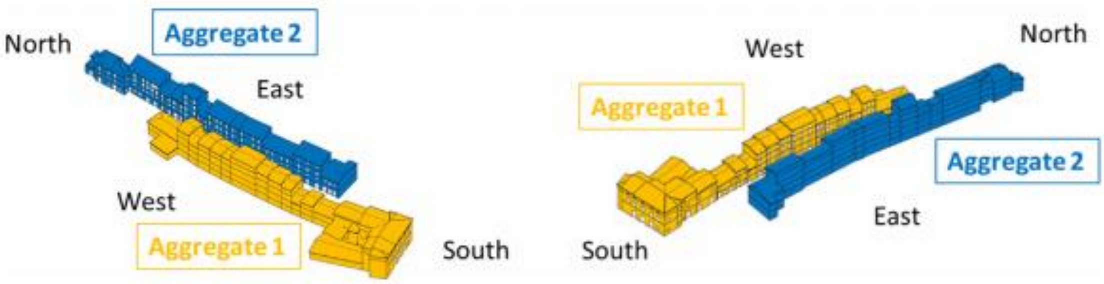
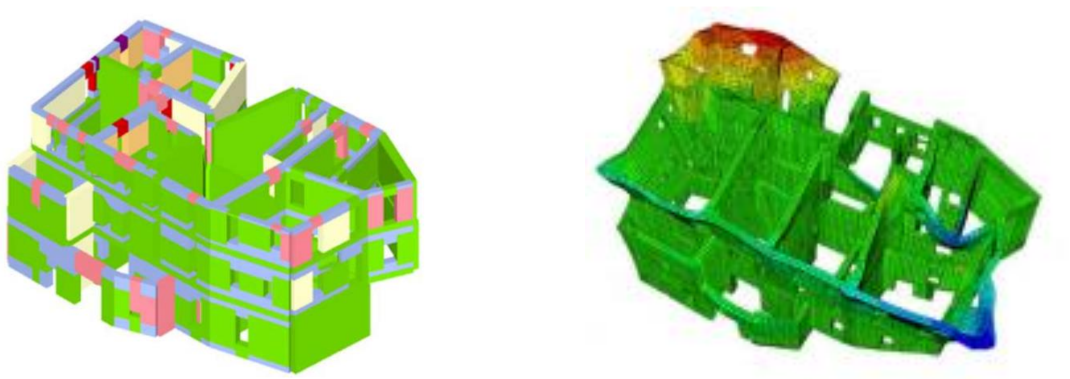


Figure 3 - Aggregates studied for the center of Sora (Valente et al., 2019).

It was stated the fact that despite the use of a Finite Element approach and dynamic analyses provides results very near to the real behavior of the structure, an alternative approach would be the use of PushOver analyses with an equivalent frame method, together with the use of kinematic limit analyses. In this way, the results obtained would be enough representative of the real behavior of the structure, with less computational effort (Valente et al., 2019).

Indeed, the use of an equivalent frame method was proposed for several centers. A representative case is again the study case of Arsita, for which different numerical strategies were applied to assess a meaningful aggregate, built in a slope and made by several residential units, some of them which are basements. It is characterized by a certain irregularity in elevation: on the south side, there are three stories, on the north side there are two stories, and the east and west sides are partially covered by the slope. Also, the different units are made with types of masonry of different quality. The use of the finite element method was compared with the use of an equivalent frame system, and in both cases, dynamic and static nonlinear analyses were performed. The main advantage given by the finite element method is the fact that it accounts for both in-plane and out-of-plane failures, whereas the equivalent frame method overestimated the seismic capacity when the box behavior is not guaranteed. On the other hand, the use of the equivalent frame approach reduced significantly the computational effort. Figure 3 shows that the two methods provide very different types of results.

However, when a global approach is followed, it is always preferred to compare the results with more detailed analyses, to better simulate details as different interlocking, pre-existing damages or even the presence of different types of masonry (Grillanda et al., 2020).

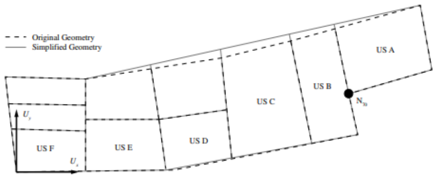


a b

Figure 4 - a) Equivalent frame method results, b) Finite element methods results (Grillanda et. al., 2020).

The numerical modeling based on an Equivalent Frame Method was also used in the assessment of an aggregate of San Pio Delle Camere (Maio et al., 2015), mainly constituted by inhomogeneous stone masonry, but also with other materials and some parts that have been added afterwards. The studied aggregate is built in a very marked slope, and some simplifications were made in the definition of the geometry. In this case, it was proven that the accuracy in the outcome provided by the nonlinear static analyses was influenced by the input parameters, such as the mechanical and the geometrical properties, pointing out the importance of having an accurate survey to obtain relatable results. In this specific case, the result obtained in the most vulnerable side were successful since they were coherent with the damage that was found on site. Also, it was done the effort of trying to considering the effect of the slope, by modifying the lateral supports of the compound, even though this assumption was considered too conservative.

a



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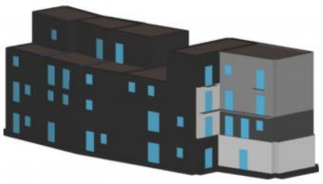


c

Figure 5 - Aggregate in San Pio Delle Camere: a) Elevation; b) Plan with simplification in the modeling; c) Equivalent frame model (Maio et al., 2015).

The same center was analysed also in other studies: different types of aggregates were assessed using once again the equivalent frame method. In this specific case, before following this approach, it was precisely defined the stiffness of the floor using a less sophisticated model with SAP2000. Also in this case the author underlined the efficiency of the method when the right information is provided. In this case, given the variety of the center, different types of aggregates were assessed (Formisano, 2017).

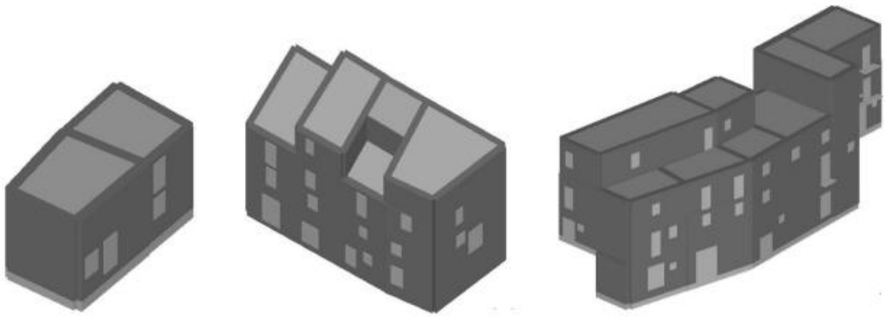
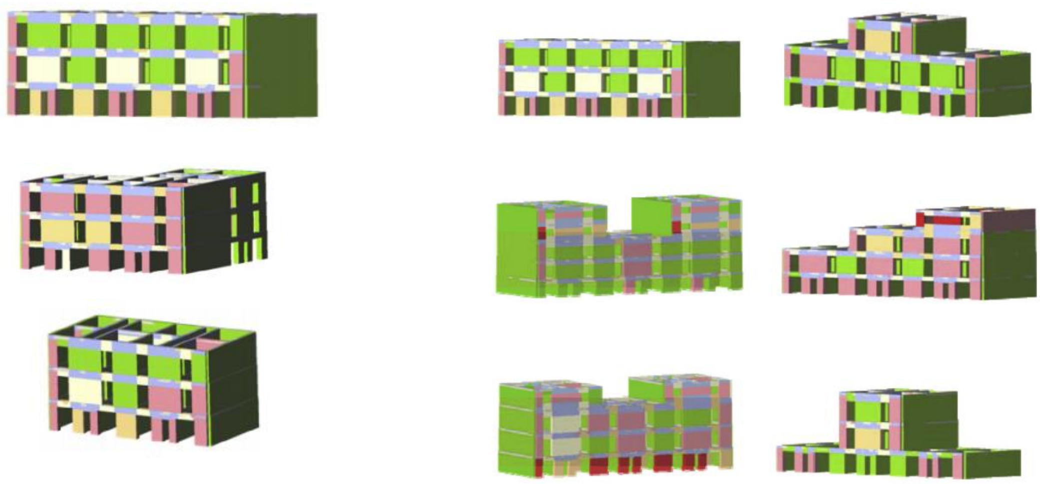


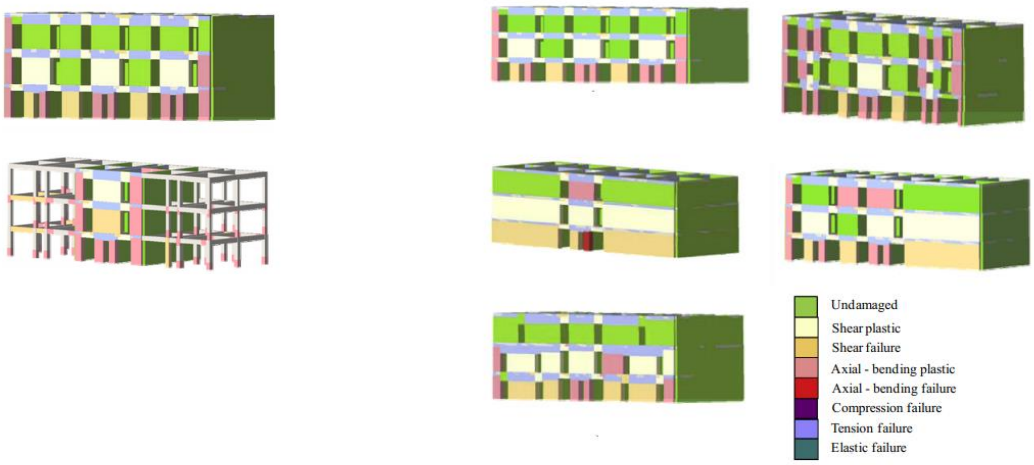
Figure 6 - Aggregate in San Pio Delle Camere (Formisano, 2017).

The equivalent frame method has been also applied to the historical center of Sessa Aurunca. In this case, the main objective of the research was not to prove the efficiency of this method but to verify a large-scale empirical method. Nevertheless, it is worth to be mentioned the fact that this tool was really easy to use in the modeling of the entire aggregate and the modeling of different configurations more or less complex of the aggregate, once again showing the suitability of such a tool in the assessment of these typologies. In this case, it was able of showing different behavior possibilities depending on the configuration of the aggregate (Formisano et al., 2014).



a b

Figure 7 - Different configurations: a) Plan irregularities, b) Elevation irregularities (Formisano et al., 2014).



b c

Figure 8 – Different configurations: a) Plan interaction b) Different positions of the opening in the adjacent units (Formisano et al., 2014).

As shown in these examples, static nonlinear analyses with an equivalent frame method are a good compromise to understand the structural behavior of masonry compounds without having unsustainable computational efforts. This is also the approach that will be used in the application proposed, and the requirement of this type of modeling, regarding the discretization of the structure, and other aspects were constraints in the definition of the algorithm used. Chapter 4 will define the main features of this strategy.

2.2 BIM AND HERITAGE BIM

2.2.1 Latest challenges

BIM is a method for communication and collaboration based on a digital representation of the built asset, applicable to several domains (architecture, structure, performance analysis, MEP, construction, and FM) to manage all the stages of the project. Amongst other wider perceptions, BIM is defined as a platform for central integrated design (European Commission, 2017). The NBS Building Information Modeling (BIM) Report 2021 has documented that awareness and adoption strongly increased in the last ten years. Precisely, it went from a bit more than 10% in 2011 to almost 70% in 2020. The benefits that are recognized by the entire community are the improvement of the coordination of the information, the improvement of productivity, the reduction of the risk, and the increase of profitability (NBS, NBS' 10th National BIM Report, 2021). Nevertheless, according to the "BIM Level", it is recognized that there are still many challenges concerning the possibility of having a "fully integrated collaboration and interoperable data". The concept of BIM levels defines the criteria required to be "BIM-compliant" (Figure 9).

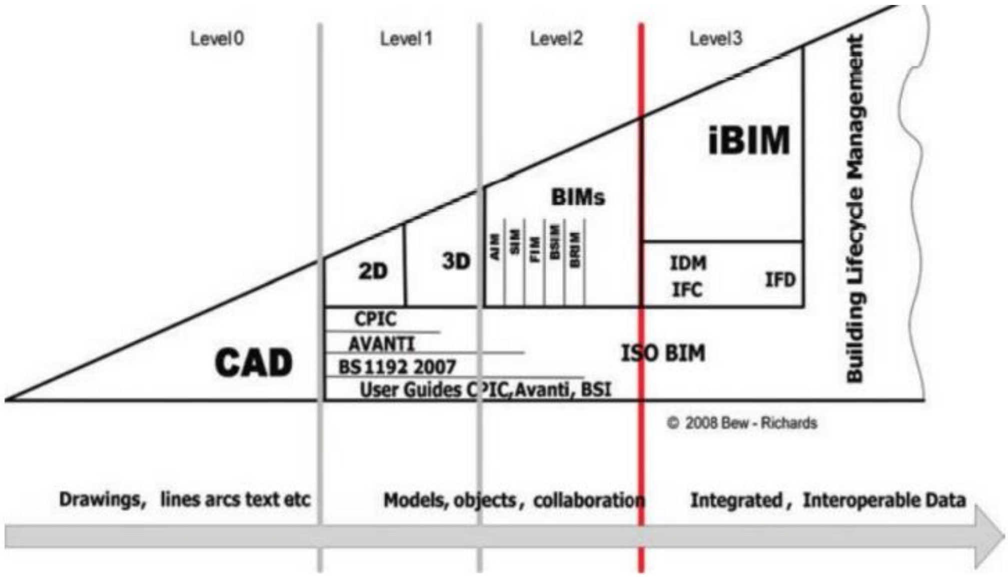


Figure 9 - BIM Maturity (Bew, M. & Richards, M. 2008).

Nowadays, in UK Level 2 BIM, is mandatory for all the works in the public sectors (McPartland, 2014). The warranted maturity is "collaborative working that requires an information exchange process which is specific to a certain project and coordinated between various systems and project participant". This means that every CAD software used by the different disciplines must be capable of exporting to one of the common open formats, such as IFC (Industry Foundation Classes) or COBie (Construction Operations Building Information Exchange). As it is possible to imagine, guaranteeing this type of interoperability is still very challenging for historical buildings. It suffices to think that the commercial tools conceived to export the BIM model (in Revit) into the structural software make consistent simplifications, as in Revit-Diana FEA (Barazzetti, et al., 2015); or only enable to export two-dimensional geometry, as in TreMuri (Penna et al., 2009).

Meanwhile, CEN442 in Europe (Cenelec, 2020), and EN-ISO 19650 (International Organisation for Standardization) all over the world, are making several effort in terms of BIM standardisation. Within this plan, it is demanded the creation of new international “Open Data” standards which would make easier the sharing of data within the entire market. This still requires further development even to the design of new buildings. To accomplish these requirements, each “object” of the project must be integrated into a certain classification system and associated with a Product Data Template (PDT). A PDT is a template that aids in the generation of product information for a specific manufacturer's product inside a specific category. A product data sheet (PDS) is the result of this process, which the manufacturer can make available to anyone. A PDT for a specific product category can be materialized in an electronic spreadsheet , such as Excel (CIBSE, 2017). The amount of information inside the Product Data Template depends on the Level Of Information Need correspondent to the purposes of each ‘Project Milestones’ (BSI Standard Publication, 2020).

Table 2 - Level Of Information Need. The alphanumerical information contained in the Level Of Information Need is correspondent to the data in the PDT.

Geometrical information	**Detail:** describes the complexity of the object compared to the real-world object, and goes from simplified to detailed.
	Dimensionality: describes the dimension of the object, if 2D or 3D.
	Location: can be relative or absolute.
	Appearance: similarly to the detail, indicates how much the object is faithful to reality.
Alphanumerical information	**Identification:** the name of the information shared. This is related to the Product Data Template.
	Information content: the information shared.
Documentation	**Set of documents:** all the documents that can be helpful for the achievement of the purpose.

The definition of PDTs is still ongoing, and some online platforms make available master templates to use to create templates (CIBSE, 2016; NBS, 2015). This requirement of standardization not only is improving the management of the project but the entire life-cycle of the building, especially the maintenance period. This is a fundamental concept while talking about existing buildings, which with their vulnerabilities requires to be often controlled. Table 3 shows Product Data Templates conceived for a “Rammed Earth Wall”, proposed by NBS.

Table 3 - Product Data Template for rammed earth wall (NBS, 2015).

TemplateName	Non-stabilized rammed earth system		
SuitabilityForUse ParameterName	Value	Units	Notes
	Loi2		
Description		A non stabilized rammed earth wall system typically comprises items such as suppliers preparation and foundations	
	LoI3		
Physical performance			
Fire performance			
Thermal transmittance			
Heat capacity and thermal admittance			
Water penetration prevention			
	LoI4		
Verification of performance			
System supplier			
Preparation			
Foundations			
Footings plinth			
Footings reinforcements			
Damp proof course			
Walling rammed earth type			
Walling reinforcement			
Openings lintels			
Openings sills			
Copings			
Wall plates			
External surface protective coating			
External surface render thermalInsulation			
External surface render type			
External surface cladding counter battents			
External suface thermalInsulation			
External surface vapour permeable underlay			
External surface cladding material			
Internal surface protective coating			
Internal surface plaster			
Internal surface linings battents			
Internal suface thermalInsulation			
System accessory			
	LoI6		
Accessibility Performance			
Asset Type			
Category			
Code performance			
Color			
Constituents			
Duration			
Expected life			

Grade
Manufacturer
Material
Model number
Model reference
Name
Nominal height
Nominal length
Nominal width
Replacement costs
Shape
Warranty description
Warranty duration
Warranty guarantor
Asse identifier
Bar code
Installation date
Serial number
Warranty start date

Lately, in Italy, it was introduced the obligation to use BIM for Public works. Specifically, according to the law, the introduction of this technology is required to be accomplished gradually. This is because it is hard to educate the stakeholders involved in the project with the use of such sophisticated tools. In particular, it was the Decree-Law enacted in 2017 (Ministero delle Infrastrutture e Trasporti, 2017) which introduced the obligatory use of the Building Information Modeling, according to the following:

- From 1 January 2019 it was obligatory for public bidding superior to 100 mln of euros;
- From 1 January 2020 it was obligatory for public bidding superior to 50 mln of euros;
- From 1 January 2021 it was obligatory for public bidding superior to 15 mln of euros;
- From 1 January 2023, it was obligatory for public bidding superior to 1 mln of euros.

The census made in 2019 concluded that the number of public bidding has tripled, requiring the use of BIM (OICE, 2020). The data clarifies the necessity, of concentrating several efforts to make BIM also suitable for the intervention on existing structures, and specifically on heritage, which represents a large part of the Italian buildings. The next section will point out what the scientific community did until now. The major drawbacks related to the Heritage Building Information Modeling (HBIM) are the lack of HBIM libraries and the necessity of guaranteeing interoperability between the software required in the assessment of these structures. The information must be stored in BIM complying with the requirement of ISO/CD 22014 document for library objects.

2.2.2 Literature review on HBIM

HBIM is a very trendy topic, thus large amounts of papers have been published lately. In this literature review, twelve papers published between 2009 and 2021 were consulted, from Scopus and on the International Journal of Heritage. The reason for selecting these specific papers is the fact that they are quite representative of the major focuses of the scientific community, and highlight the principal open issues.

Within this:

- Five papers are focusing specifically on the use of advanced survey techniques to create HBIM libraries (Gustavo et al., 2020; Murphy et al., 2013; Garagnani, 2013; Oreni et al., 2014; Pocobelli et al., 2018).
- Three papers are using HBIM to monitor the damage state of the analyzed structure. Among these, two are modeling the damages as objects (Lo Turco et al., 2017; Barontini, et al., 2021), one is storing the data as documentation (Quattrini, Piedricca, & Morbidoni, 2017).
- A paper explores the possibility of using HBIM to manage the rehabilitation yard (Biagini et al., 2016).
- Four papers are focusing on the interoperability between BIM and structural analyses software based on Finite Element Modeling (Barazzetti et al., 2015; Crespi et al., 2015; Lopes et al., 2021;
- A paper introduced a Product Data Template for historical masonry walls (Barontini, et al., 2021).

The results of this literature review shown that currently there is still a large part of the scientific community focusing on the first part of the definition of HBIM, which is the introduction of geometrical information, coherently with the definition of HBIM itself (Murphy & Pavia, 2009). Indeed, HBIM is defined as “a novel prototype library of parametric objects based on historical architectural data and a system of cross-platform programs for mapping parametric objects onto point cloud and image survey data”. Thus, its implementation consists of a stage of collection of data using advanced survey techniques, followed by a stage of introduction of a parametric library of objects (Murphy et al., 2013). These objects, coherently with the BIM technology, and defined as “instances” are divided into “classes” or “families”. The latter establishes the dimensions that can be parameterized, the group of relationships and rules that are followed, and how the object is generated. Having an extensive family library makes modeling faster and more natural, especially because these families are parametric elements, so they can be adapted to the project needs (Rocha et al., 2020).

The scientific community made several steps towards the implementation of “family libraries” but due to the heterogenous characteristics of the historical buildings, the advancements are often made for singular case studies (Khalil & Stravoravdis, 2019). Indeed, the procedure of the definition of families is still very laborious and for this reason, the research is working in the automatization or semi-automatization of this process (Murphy et al., 2013; Garagnani, 2013; Oreni et al., 2014; Pocobelli et al., 2018). A representative example of family created taking advantage of the interoperability throughout advanced survey techniques and BIM, is the one done for the Engine House of Paços Reais, a mixed structure of masonry, concrete, stone, and metal, located in Lisbon (Gustavo et al., 2020). In this paper, the point cloud was used to introduce families in Revit, through a long procedure, requiring first to export the point cloud as DXF and then to import the DXF in the Revit family editor, since the latter does not support the direct introduction of the coordinates from the point. It is stressed the complexity of the geometry modeled as it was not possible to edit the openings directly from the default ones, due to their chamfered nature (**Error! Reference source not found.**). This clarifies once again the major challenges that the historical structures made to the BIM, related to the complexity of the geometry, because of which, there is also the tendency of having “highly parametrized objects”. This characteristic made the modeling extremely heavy to manage, which is why it is of fundamental importance to define the purpose of the modeling, coherently with the Level Of Information needed (LoI).

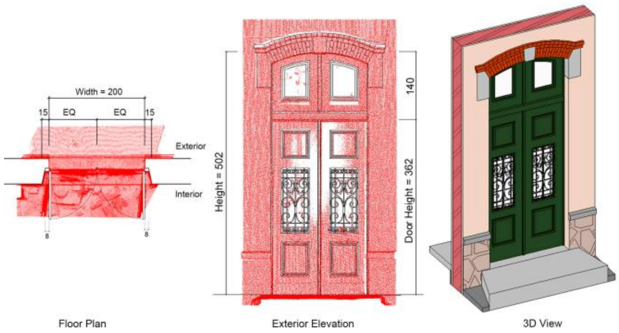


Figure 10 - Revit families of historical objects (Gustavo et al., 2020).

Within the framework of the long process required to assess historical structures, as seen in literature, in the last ten years HBIM was used to accomplish different purposes. A trending topic is the monitoring of the decay condition of the structure. To do this, a correct approach is modeling the damage as an object, to manage the information coherently with the interoperability requirements. This was done for a study case of industrial heritage, in Italy, by creating parametric objects (adaptive components) to represent the preservation status of materials (Lo Turco et al., 2017). A similar methodology was used for the Ducal Palace in Guimaraes, where once again adaptive components were used to model the existing damage (Barontini, et al., 2021).

a b

Figure 11 - Adaptive components to model damage (Lo Turco et al., 2017).

Another approach is the one applied for the Church of Santa Maria of Portonovo, Italy. In this case, the idea was not only to use the HBIM to store the information related to the damage condition, but also to associate the model with sheets containing all the information collected during the inspections, by linking them with the document, with the advantage of not having a too heavy and hard to manage model (Quattrini, Piedricca, & Morbidoni, 2017).

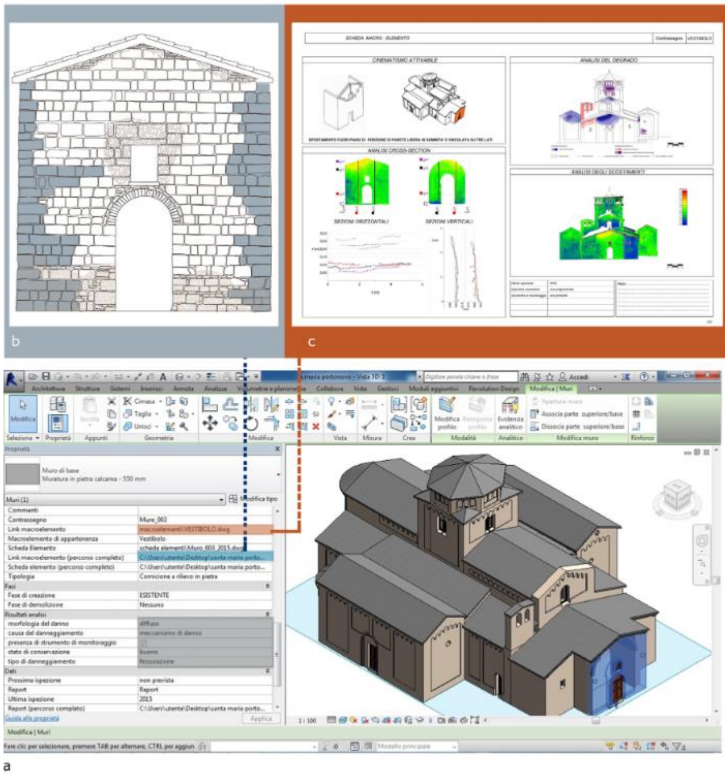


Figure 12 - Use of HBIM to store various documentation (Quattrini, et al. 2017).

Another interesting application of HBIM is the one done for the church “SS. Nome di Maria” at Poggio Rusco, in Mantua, Italy (Biagini et al., 2016). In this case, the purpose was to use the BIM model to optimize the construction site, understanding how to manage the different phases of the rehabilitation yard and the space that is required. Once again, it was necessary to introduce different new HBIM library and in this case, they were used to represent the scaffolding and the other temporary structures required.

Figure 13 - HBIM to manage the rehabilitation yard (Biagini et al., 2016).

Another topic of major interest is the interoperability between the HBIM model and the structural analyses. As known, concerning new constructions, there are several BIM software that comprehends the structural modeling (as Autodesk Revit Structure, Tekla Structures, etc.), whereas concerning historical buildings further investigation is still required. One way of allowing the BIM model to communicate with the structural analysis software is the use of a “link” software or code, to export the BIM model in the structural analysis software. For masonry structures, the Finite Element Modeling approach is very much used, and FEM-Designed is integrated with Revit structures, Tekla and Archicad, to perform the advanced static and dynamic calculation as well as earthquakes analyses. The interoperability between BIM and software for structural analyses had several applications, also for research (Lopes et al., 2021). The main issue of this methodology is the fact that this was originally conceived for new structures, meaning that the link between the BIM and the structural model creates very simplified models. To overcome this limit, recent studies worked on the development of alternative methodologies. This was done, for instance, for Castel Masegna, in Sondrio (Italy), where the BIM and its geometric information are directly turned into a tetrahedron solid mesh, by creating an auto-meshing algorithm. This contribution was very important, but it is still hard to be used since manual simplifications are required, either for the meshing and for the geometry itself (Barazzetti et al., 2015; Crespi et al., 2015). The terminology “scan-to-BIM-to-FEM” was introduced to point out the will of being as near to reality as possible.

Figure 14 - Scan-to-BIM-to-FEM (Barazzetti et al., 2015).

Moreover, the majority of the studies are focusing on geometry, not considering the new introduction related to the Level 3 of BIM. Some steps towards this direction were recently made with an application to the Ducal Palace of Guimaraes (Barontini et al., 2021), introducing a Product Data Template for historic masonry walls and the object "damage", being the latter conceived for heritage (Table 4). Even if it followed the NBS format, it was necessary to introduce parameters specifically useful for the scope, and neglecting parameters that are usually required when comes to new objects, such as "warranty" or "replacement costs". Moreover, in this specific case, the major stress is given to what data is collected in the various inspections, and to the damage mapping.

Table 4 - Template for historical masonry wall (Barontini et al., 2021)

TemplateName	Historic masonry wall		
SuitabilityForUse	Asset manager		
Template Custodian	HeritageCare		
ParameterName	Value	Units	Notes
	Masonry wall construction data		
Construction date	Years		
Construction date degree of accuracy	0 to 5		
Previous intervention dates	Years		
Intervention dates degree of accuracy	0 to 5		
	Inspection Data		
Inspection dates	Date		
Last inspection reference			
Brief descriprion			
Survey picture URL			
	Dimensional data		
Thickness	m		
Height	m		
Lenght	m		
	Wall structural data		
Load Bearing			
Compressive Strenght	MPa		
Elastic Modulus	MPa		
Type of Wall			
Morphology			
Joint Type			
Openings sills			
Copings			
Wall plates			
MQI_SS (Stone Shape)			
MQI_WC (Wall leaf connection)			
MQI_HJ (Horizontality Bed Of Joints)			
MQI_MM (Mortar properties)			

MQI_VJ (Vertical Joints)		
MQI_SM (Stone/Brick Mechanical Properties)		
MQI_SM (Stone/Brick Dimension)		
Stone characterization		
Stone Type		
Stone Origin		
Stone Origin		
Stone Hardness	kg/m^3	
Stone Density		
Stone Porosity		
Stone Compressive Strength	MPa	
Stone Tensile Strenght	MPa	
Stone Elastic Module	MPa	
Deformation		
In-plane deviation	m	From Damage Atlas HC
Out of plane deviation	m	From Damage Atlas HC
Buckling	m	From Damage Atlas HC
Leaning	m	From Damage Atlas HC
Bending/Bulging	m	From Damage Atlas HC
Excessive Deflection	m	From Damage Atlas HC
Lateral buckling		
Asset management (maintenance)		
Operation and maintenance (manual)		
Daily		
Weekly		
Monthly		
Quarterly		
6 Monthly		
Annually		
Bespoke Timeframe		

This brief literature review highlighted the fact that several efforts are being done, but also that all these studies are very heterogeneous, and it is missing an integrated framework that glues all these contributions together. What is missing is a methodology suitable for at least a certain typology of constructions, since these analyzed contributions are often only related to specific study cases. In addition, nothing has been done for masonry aggregates. A very significant research effort is still needed for PDTs and to improve the interoperability with the structural analyses software.

3. MASONRY AGGREGATES

3.1 Definition

A huge amount of existing buildings consists of dwellings, built one next to each other, creating a repetitive pattern in the landscape and defining the morphology of the historical centers. These constructions are testimonials of the habits of ancient populations, the passing of epochs, and the local manufacturing techniques used in the past, possessing an inestimable value and authenticity. This value was recognized for quite some time, and the “Convention concerning the protection of the world cultural heritage” (United Nation Educational, 1972), mention them among the heritage, defining them as “*groups of separate or connected buildings which, because of their architecture, their homogeneity or their place in the landscape, are of outstanding universal value from the point of view of history, art or science*”.

It is known that the majority of existing buildings are masonry constructions. This is why the residential buildings of the historical centers are often “unreinforced masonry aggregates”. These constructions are made of traditional materials and their efficiency depends on how much the “rule of art” is respected. Structurally speaking, they are made by adjacent residential cells (units), often sharing structural elements, and conceived to bear vertical loads. The configuration of the compound is the result of changes to which they were subjected over centuries, involving the addition of new parts, the dismantling of others, the fusion of adjacent units. The structural behavior of the system depends on the behavior of the singular unit and on the way the structural elements interact one each other. Indeed, each unit has a different role in the aggregate, depending on its position, and on how much it is connected with the others. This clarifies the important role played by the connections, which often are inefficient, due to the way the group of units developed during the centuries.

All these features made these structures extremely vulnerable to seismic events. Moreover, the parameters involved to carry out their structural assessment are various, and the data is often hard to obtain. Most of them are currently in a poor state of conservation, especially because for a very long time, they have been considered nothing more than dwellings intended for the lowest social classes. Besides, the changes in the housing needs, the raise of new different rules of urban planning, and the advent of new incompatible construction methods were extremely harmful to their preservation. In this scenario, it was not only their cultural value to be underestimated, but also their economic one, since most of them were completely abandoned.

Italy is a good study case to understand what is a masonry aggregate and why these constructions, even if having common features, can be very different. In addition, due to the seismicity of its territory, it is one of the countries where it is urgent to provide a way of assessing and rehabilitating these structures. In fact, one of the reasons why the Italian masonry aggregates are very different from each other is their age, because some centers have been reconstructed after seismic events. The history of seismic events, as will be further explained, defined the characteristics of these centers. Understand the variety of these constructions is fundamental, and it explains why to develop a methodology for their assessment is necessary that this can be adapted to all cases, especially the most complex. This is also one of the reasons why, the final application of the methodology is on a meaningful aggregate in Ortigia, due to the long history and complexity of the site that makes it very representative of the typology studied.

The following section briefly introduces different typologies of aggregates that can be found in Italy, and how the succession of historical events has defined their morphology. This is done with the scope of clarifying what a masonry aggregate is, and why a potential assessment methodology of these structures has to be proven for the most complex cases, to be always applicable.

3.2 Typology and complexity in Italy

Italy provides a considerable number of historical centers, indeed the country counts 8063 cities, which have at least one or more centers, and, from the former statement, previous studies counted around 20.000 centers. Unlike in the other European countries, these are extremely different one each other, even in the same region (Fazio, 1978) but it is possible to find some representative features between some of them, depending on when they have been founded, and on what happened in some specific historical moments. The fundamental stages in the history of the Italian masonry aggregates are the Pre-Roman and Roman Age; Middle Age; Renaissance; Baroque; 19th century and 20th century.

The majority of villages founded by Romans or Pre-roman civilization were destroyed between the 4th and 5th centuries AC, and even the ones that partly survived were deeply altered by the advent of the way of living and the idea of the city typical of the Middle-Age. In fact, in the centers founded by the Romans, the houses were arranged according to a regular net, positioned parallel to two main axes, called Cardo and Decumano Maximo. At this stage, cities founded in different regions were similar despite the different geography of the place, and the plan of the dwelling was very regular. Part of the Roman implant is still visible in the historical center of Ortigia, for example, but this was deeply changed and completely englobed with the successive transformations (Figure 15).

a b c

Figure 15 - Historical center of Ortigia, reconstruction of the evolutive phases of the urban a) Roman Implant; b) Medieval configuration; c) Actual aspect (Giuffrè, 1993).

The current configuration of a large amount of the Italian centers dates back to the Middle-Age, in particular during the 11th and 12th centuries, where the raising of the population required the construction of new dwellings. Part of the complexity and the heterogeneity of the masonry building aggregates is due to the way the cities were built in this period. Indeed, the main idea was following the natural environment of the site, and for this reason, the plan configuration of these structures had often complex shapes, that is why, nowadays, these structures look very different from each other. It is very common to see the units assembled in simple rows in the cases in which the village grew according to a uni-directional scheme or a with a herringbone pattern. Nevertheless, it is also common to see aggregates with a more complex morphology. This is due, as mentioned, to the geography of the place, but also the frequent tendency of placing the building around a central point, such as the Church. Another aspect already characterizing these structures is the fact that, depending on the topography, there could be the presence of staggered floors, one of the major vulnerabilities from the seismic point of view.

On the other hand, the residential buildings had one or two elevations and were often interspersed with courtyards and open spaces. This explains why, nowadays, medieval streets look very narrow: the original configuration of medieval buildings did not require larger streets.

The Renaissance was another turning point in the history of these structures. In particular, during this period, there was the occurrence of two phenomena, namely the existing centers were deeply changed and new cities were founded.

As far as the existing centers are concerned, the reason why these were subjected to heavy changes, is once again the population growth, and the raising of the first form of Capitalism. As a consequence, new representative buildings were raised, occupying a large part of the space in the city and the already existing residential buildings were raised until 4 or 5 stories. In addition, if during the Middle-Age there was the tendency of leaving spaces between the different units, the new demand for dwellings caused the filling of all these spaces. The consequences, from a structural point of view, are the addition of new loads to the walls of the existing structures, and the fact that their plan configuration started to become more complex, because of the will of filling any possible void. It is fundament to point out that the medieval streets were very narrow. This means that, because of the raising of these buildings, in case of seismic events, it was common that the streets were filled by the rest of the collapse buildings, increasing the dangers after these events (Fazio, 1978). Regarding the construction of new centers, these were conceived with very different criteria than the previous ones. Indeed, there was the will of following the lesson taught by the Romans, so the idea was not to adapt the constructions to the surrounding environment, but to create a regular net, and to organize the building according to this. The consequence is that the majority of the centers built during that moment presented very regular and compact aggregates. From a seismic point of view, they present less critical features in terms of plan irregularities, however, they are often characterized by irregularities in elevation (Figure 16).

a

b

Figure 16 - Complex implant of medieval aggregates compared to the regular implant of Renassaince aggregates, examples from the same region a) Venice; b) Verona

Nonetheless, not all the cities founded in this period were raised following the aforementioned criteria, since there also was the trend of the so-called “ideal cities”. The main feature of these cities was the polygonal square surrounding which all the residences were built. In this case, the aggregates were characterized by convex shapes, which may have several drawbacks from a seismic point of view. This can be seen, for example, in Palmanova, or even more in Grammichele as shown Figure 17.

a b

Figure 17 - Criticities in the aggregates of the Renaissance. a) Palmanova; b) Grammichele (Google, n.d)

It is worth mentioning that with the advent of the earthquakes that occurred cyclically, all over the country, the constructors started introducing anti-seismic details to counteract the effect of the earthquakes. Some of these antiseismic measures were characterizing the residential buildings of historical centers at least from the Renaissance (Figure 18). This means that in the history of the evolution of these centers, the Renaissance was fundamental also for the introduction of the first anti-seismic details (D'Antonio, 2019).

Figure 18 - Ancient antiseismic measurement (D'Antonio, 2019).

During the Baroque Age, the tendencies of the Renaissance were taken to the extreme. A large part of the cities was left for the most representative buildings, and the residential buildings were elevated until 6-7 stories, such as the case of Genova or even Naples. What happened in Sicily is particular and noteworthy: after the earthquakes of 1693, new cities were founded, and the aggregates from the existing ones were transformed once again, raising new floors or adding parts, as happened in

Catania or Palermo. It is for this reason, that in the same region it is possible to find centers characterized by the presence of aggregates with different dimensions and configurations. Indeed, if in the survived centers the aggregates became more and more complex, the new centers were built according to a more precise net. This is the case of Partinico and Borghetto, and Noto Nuova founded in the 17th century. In any case, despite being conceived to be very regular, even these centers were affected by several changes during the ages (Figure 19) (Tobriner, 1989).

a

b

Figure 19 - "Noto Nuova", Sicily. a) The regular net according to with it was conceived; b) The complex aggregates that can be seen today.

Later, there was the introduction of the very first anti-seismic code, after the strong 1783 earthquake, proposed by the Borbone government, among several measures, enacted an anti-seismic code. Once again, the aggregates founded after these earthquakes were different and already presented anti-seismic elements. Indeed, in some centers, they introduced the use of timber frames to help the masonry structure (Galassi et al., 2021).

Figure 20 - The first antiseismic code and the way it affected the construction of the building aggregates a) New way of building the cities; b) Prove of the effectiveness of the system (Galassi, at al., 2021).

Unfortunately, the 19th century was a critical moment for these constructions, because of the introduction of new urbanistic principles, that were based on the idea of opening new streets, thus the era of the biggest demolitions. These mainly involved the medieval tissue of the cities, and it happens in the big centers, such as Milan and Naples, but also centers with a more modest dimension. The consequence was that the aggregates were sliced and the partial reconstruction of their facades made the connections worse. This tendency was even more consolidated at the beginning of the 20th century, with the advent of Fascism, as happened in Ortigia.

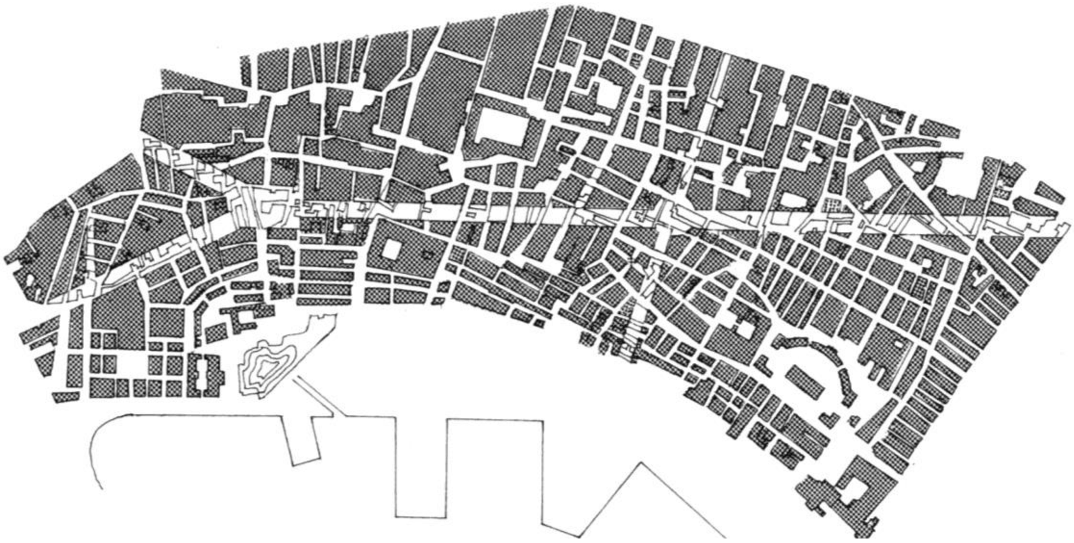


Figure 21 - Partial demolition of the aggregates (Fazio, 1978)

Finally, even during the second half of the last century, the masonry aggregates were subjected to deep changes in their structure and their configuration. This was mainly due to the advent of new technologies and new construction materials, completely incompatible with the existing ones.

Indeed, after the introduction of the reinforced concrete, the Italian manufacturer started to lose the knowledge of the masonry constructions and forgot how this worked. This had extremely negative consequences in the existing masonry group of buildings, as was learned from the past Earthquake in L'Aquila. Masonry buildings were sided by reinforced concrete ones, which have completely different behavior, especially under seismic loads. The most common transformation was the addition of concrete floors to replace the original timber ones. The consequences of this were extremely dangerous under seismic actions.

a b

Figure 22 - Bad consequences of inadequate modern interventions in the aggregates (Franchetti, 2021).

In addition, during the XX century, several centers were abandoned, since the new constructions in the suburbs were responding to the new lifestyle of the society. This contributes to the degradation of the center. The process of recognizing the value of the masonry aggregates and the necessity of being preserved, but also used as an economic value was very long. The next section will briefly go towards this process of recognizing the importance of these structures and pointing out the actual challenges.

3.3 Preservation and challenges

3.3.1 Masonry aggregates and their value: a long history

For a long time, the historical centers were so underestimated that until the end of the last century, there was not even a national census of them. The first census was done only locally, by the regions (Marche in 1967 and Friuli Venezia Giulia in 1974). On this path, when the first two laws of preservation of heritage were enacted, Nasi and Rava Rosadi in 1902 and 1909, they were not referring even mentioning the dwellings in aggregate (Ministro della Pubblica Istruzione, 1902) (Ministero della pubblica istruzione, 1909). With the first urbanistic law, in 1942, the territory of the city started to be divided into different areas according to common features, and the historical centers started to be considered as something to be preserved, through the zoning restrictions. Nevertheless, it is worth to be mentioned that the reason for the attention given to these areas was the fact that it was “the part of the city containing monuments”, without making any reference to the aggregates (Legge Urbanistica Statale -1150, 1942). Indeed, this law was enacted during a period in which the partial demolition of the masonry aggregates was often done to underline the monumentality of the building considered worthy. It was after the Second World War, in the “Convention for the Protection of

Cultural Property in the Event of Armed Conflict with Regulations for the Execution of the Convention 1954", to which Italy participated, that the group of buildings characterizing the historical aggregates started to be mentioned as something relevant (UNESCO, 2010). Later, in 2960 the "Chart of Gubbio" prohibited the demolition of the dwellings in aggregates with the specific scope of "isolating the monuments", and this was during a national congress specifically done for the safeguard of the historical centers (Soci fondatori della Carta di Gubbio, 1960). The interest in the rehabilitation of the centers continued in the '70s when they started to be considered also as an economic good. For this reason, in the Congress of Bergamo, it was stated the necessity of recovering the existing buildings of the center, as an alternative to the construction of new buildings and, as a consequence, of the building waste. With the same aim, there were introduced the "Plans for Economic and Popular Constructions", in 1971 (Ministero dell'Urbanistica, 1971). Nevertheless, still, it is noticed that these buildings were considered as potential investments for "social housing" because of the fact that the majority of people wanted to live in the new buildings of the periphery. Nowadays these centers preserved by the Code for Cultural Assets, and they are considered as heritage and part of the landscape (Figure 23) (Ministero della cultura, 2004).

Figure 23 - Masonry aggregates as part of the landscape (Padovese, 2019).

The centers are now considered as a pole of touristic attractions, and new drawbacks are raising. There is still the problem that often they are not inhabited by permanent residents, but only by tourists, and only in certain periods of the years (Padovese, 2019). One of the main reasons why these buildings are not used is the fact that many of them are not in the condition of being inhabited, either from a structural point of view or simply because of the lack of the comfortable housing to which we are accustomed today. The houses are often cold, humid, and structurally not in compliance with technical requirements. This is mainly because of the fact that these masonry compounds are extremely complex, and when an intervention is needed, this is often required to be done in the entire aggregate, or at least in a large part of it. The main problem, at this point, is that the standards to which reference should be made to preserve these buildings, give prescriptions either on a too large scale or in a too-small one. As far as concerns the structural standards, it was with the advent of the "Norme Tecniche delle Costruzioni" of 2008 (Ministero delle infrastrutture e dei transporti, 2008) that the law started to mention the aggregates. Indeed, in the previous codes referring to the masonry structures, there was no reference of it (Ministero delle infrastrutture e dei trasporti, 1987) (Ministero delle infrastruttire e dei trasporti, 1996). Nevertheless, the research community was starting to understand the necessity of studying these structures considering the entire compound, as was done for Ortigia (Giuffrè, Sicurezza e conservazione dei centri storici: il caso Ortigia, 1993).

3.3.2 Actual code and challenges

Today, in the Italian Building Code (Ministro delle Infrastrutture e Trasporti, 2018) there is an entire section dedicated to the existing masonry aggregates, and other specifications are in the Commentary of 2019 (Ministero delle Infrastrutture e dei trasporti , 2019). In particular, the code mention the fact that for a masonry aggregate it is fundamental to conduct the structural assessment considering the "structural unit". The definition given for structural unit is "part of the aggregate connected among the elevation, that have been characterized by a unitary constructive process, that has a unitary behavior with respect to the horizontal and the vertical loads, that guarantees the transfer of loads until the foundation and it is delimited by open spaces, structural joints or other units that are built with different materials, different structural systems or in different periods". As it is possible to understand, the concept of a "structural unit" can be very different. Indeed, in some cases, it can be easy to identify several structural units in an aggregate, whereas in other cases, the structural unit can coincide with the entire aggregate itself. In addition, practically it is very hard to organize a rehabilitation project, since the structural units are often not coincident with the residential unit, thus having different owners. Once again, the complexity of these constructions requires the introduction of a methodology for their assessment that can be validated for the most complex case, to be always used. The building code also mentions some characteristics that are required to be considered, as critical features: lack of connections, presence of facades not aligned in plans, presence of openings that are not aligned, presence of different heights, presence of deformable floors. All these features are very frequent and contribute to the vulnerability of the aggregates. As far as concern the way of conducting the assessment, the nonlinear static analyses are recommended in case of box behavior, otherwise, it is required to assess each singular wall, as subjected to vertical, in-plane and out-of-plane loads (Ministero delle Infrastrutture e dei trasporti , 2019).

The question of the structural assessment and rehabilitation of masonry aggregates was recently at the center of the attention within the framework of the SISMABONUS and in particular the SUPER-BONUS. The SISMABONUS was introduced in Italy in 2013 as a detraction of a percentage of 75% to 85% in the costs that the Public or Private owners must invest for the seismic retrofitting of construction located in the first three seismic areas (Agenzia delle entrate, 2013). According to the Decree-Law, for each construction it is possible to release a Seismic Certificate, indicating to which of the 8 seismic risk classes the building belongs. Until 2019, the tax detraction depended on how much the behavior of the construction is improved. Due to the crisis consequential to the Covid 2019, the government established that at this moment, irrespective of the type of intervention, the detraction is always equal to 110% of the expenses (Agenzia delle entrate, Decreto-Legge 19/05/202 - Decreto rilancio, 2020). Nevertheless, the owners of residences taking parts of masonry aggregates were not able to take advantage of these tax reductions. Indeed, with the SUPER-BONUS, for the individual houses, was possible to be obtained the advantages even only by doing some local repairs. Otherwise, referring to the case of the aggregates, given the nature of these constructions, the Italian Internal Revenue Services stated that it is required to assess the entire compound, as mentioned in the Italian Income Tax Code (Agenzia dell Entrate, 1987-updated). Several projects were rejected for this reason, as happened in Sicilia and Emilia Romagna (Edilportale, 2021). This problem has also called into question the very definition of structural unity. Indeed, in the Tax Code, with respect to the masonry aggregate, it is required the intervention precisely in the "entire compound", whereas in the building code it is mentioned also the possibility of having more than a structural unit inside the aggregate (Pagliai & Di Giovanna, 2021).

The cause of this issue can be traced once again in the absence of a precise systematic methodology aimed at structurally assess these constructions at the right scale, that is the aggregate scale. In fact, despite giving some definitions, the legislation does not provide an approach that could be used for all the types of aggregates, improving the efficiency of the assessment procedure and the intervention. On this path, considering all the components that have been mentioned until now, a winning approach could be the introduction of a methodology of assessment of these constructions that would consider not only the structural necessities but also the voluntary of making these dwellings more appealing also from other points of view, to encourage the community to live these buildings. For example, considering the energetic efficiency improvement could be another possibility, always considering what are the benefits that are now given by the Italian state to the ones that decide to improve their buildings also from this point, like ECOBONUS and again SUPER-BONUS.

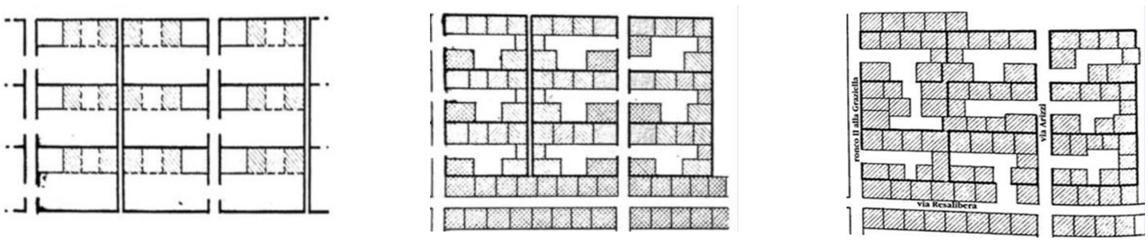
3.4 A representative case: Ortygia

3.4.1 Introduction

Within the framework of defining a methodology of assessment of masonry aggregates, it was decided to give some space to the historical center of Ortigia (Siracusa, Sicily), one of the oldest Italian villages, whose history passes through several meaningful phases. It is easy to gather information about this center, due to the work that was carried out by Giuffre at end of the last century (Giuffrè, Sicurezza e conservazione dei centri storici: il caso Ortigia, 1993). In the book "Sicurezza e Conservazione dei centri storici, Il Caso ortigia", the study case was comprehended in a very detailed way, starting from the assessment of the urban morphology, and going more and more in detail, in the study of the construction phases of the aggregates, the typical constructive elements, the damages, and the expected damage scenario in case of an earthquake. The study was highly innovative at that time, either because of the object itself, that is the masonry aggregates, but also for the consideration given. Indeed, it is pointed out the importance of having a multi-disciplinary approach on the assessment of these constructions, mentioning together numerical and empirical methods. The study stresses concepts as the rule of the art, the box behavior of a structure, the expected in-plane/out-of plane failure mechanism and the use of kinematic analysis to extimate the capacity of a wall. Eventually, intervention techniques are also proposed. Even if this contribution was given almost thirty years ago, it is still an example taken into consideration when it comes to assessing historical centers, especially if concerning their seismic vulnerability.

3.4.2 History and morphology of the quarter of “La Graziella”

In the VIII century BC, Ortigia was a Greek colony, already intensely built. In particular, the original configuration of the residential buildings consisted of the so-called “elementary Domus”. This type of construction, typical of the Greek tradition, was characterized by a squared enclosure, with a length of 12-15 meters for side, that surrounded the residential units, and some open spaces that consisted in the courtyard. Over the centuries, mainly because of demographic growth, these open spaces started to be occupied by new residential units, up to the present complex plan (Figure 24) (Giuffrè, Sicurezza e conservazione dei centri storici: il caso Ortigia, 1993).



a b c

Figure 24 - Different evolution phases in the plan; a) Phase 1; b) Phase 2; c) Phase 3 (Giuffrè, 1993).

Until the XVIII century, these constructions only had an elevation. In the XIX century, the aggregates began to grow in height and the remained courtyards completely lost their function, at the point that the portals were inglobed in the new constructions (Figure 25) (Giuffrè, Sicurezza e conservazione dei centri storici: il caso Ortigia, 1993).

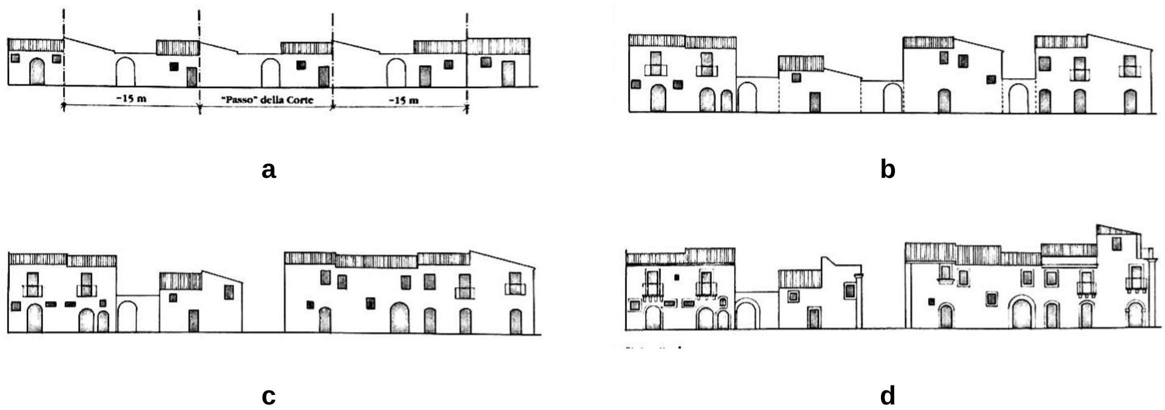
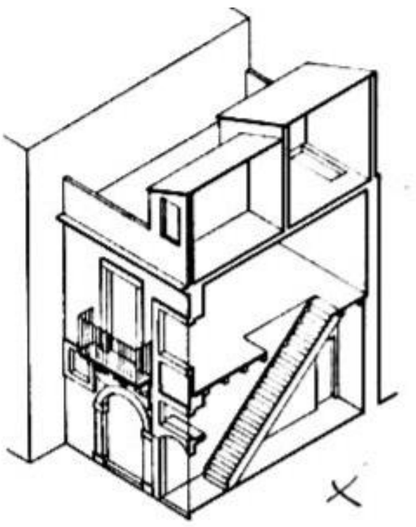
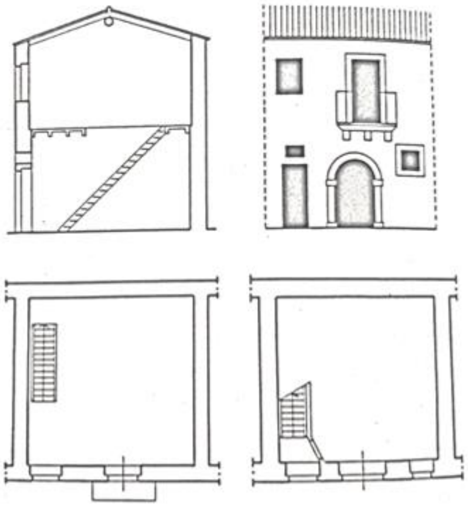


Figure 25 - Phases in elevation; a) End of XVIII century; b) Half of XIX century; c) 1877; d) 1993 (Giuffrè, 1993).

The 70% of construction is made of load-bearing two leaves masonry walls, with a thickness that goes from 45 cm to 75 cm. The span between walls is always about 4.5 m to 6 m. Usually, the external walls are made by several openings, whereas the internal ones do not. The foundations of these structures were realized with stones of big dimension, the roofs were made in timber, with brick tiles (coppi). During the XIX century, with the new elevation, there was the introduction of intermediate timber floors, and of the stairs, also made in timber. When this happened, the main opening of the second floor was often not aligned to the inferior one, due to the internal configuration of the residence.In the last century, as in several other historical centers, there was the use of replacing some of the existing floors with concrete slabs and the stairs with steel profiles. This is due to the internal architectural configuration of the plan, and in particular to the presence of the stairs. In addition, during the Fascismo, also the historical center of Ortigia was characterized by several demolitions aimed at opening big streets. (Giuffrè, Sicurezza e conservazione dei centri storici: il caso Ortigia, 1993).





a b

Figure 26 – a) Axonometric section of a typical unit; b) Misalignment of the openings (Giuffrè, 1993).

In the last year, the aggregates became always more complex, due to the continuous addition that has been done in elevation. Most of them, in a very disorganized way (Figure 27).

Figure 27 - Complexity of the roofs in Ortigia (Google, n.d.).

Regarding the typical damage pattern of Ortigia, it is visible the soil settlement, due to the way the compound grew in the plan, due to the addition of new elevation, but also due to the characteristic of the soil itself. Also, are often cracks found due to the disconnection between the elements as well as the presence of beating roofs. In addition, it is common to see alveolarization due to the presence of sea salt (Figure 28).

a b

Figure 28 - Typical damages a) Corner crack; b) Alveolisation (Google, n.d.).

The historical center of Ortigia is divided into quarters, and a very interesting one is “La Graziella”(Figure 29), which was even at the center of the studies done by Giuffre. As visible in the picture, the aggregates of this center are extremely complex, and it is hard to define the different structural units, often coincident with almost the entire compound (Comune di Siracusa, n.d.).

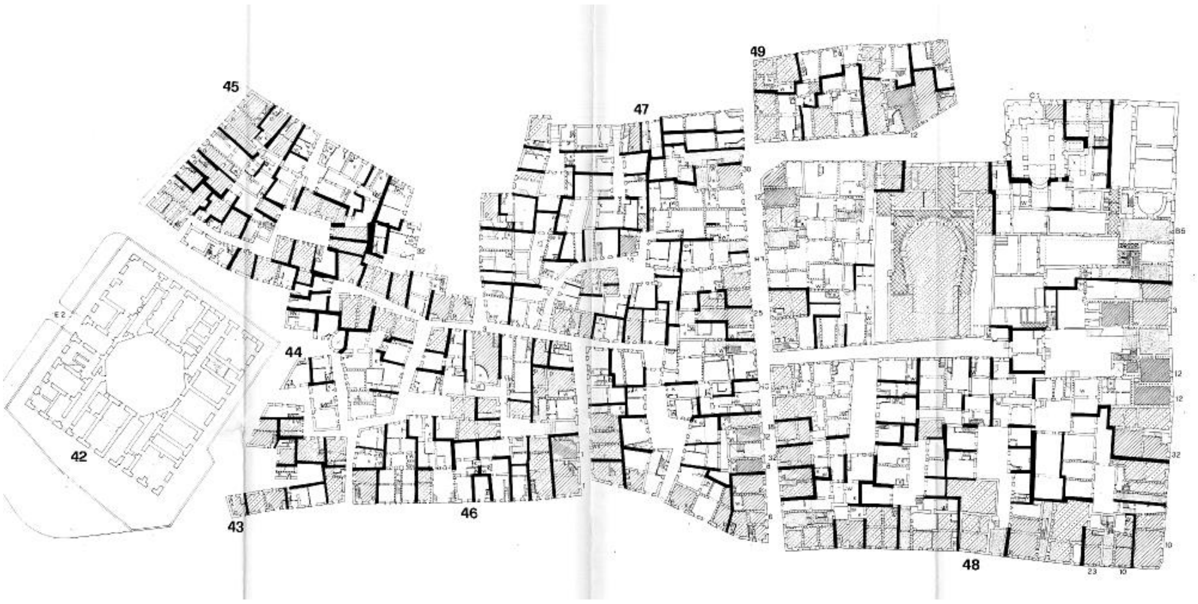


Figure 29 - Graziella quarter (Comune di Siracusa, n.d.)

A meaningful aggregate of this quarter is the one shown below. As shown in Figure 30, the entire urban block can be divided into five structurally independent units, two of which are extremely big.

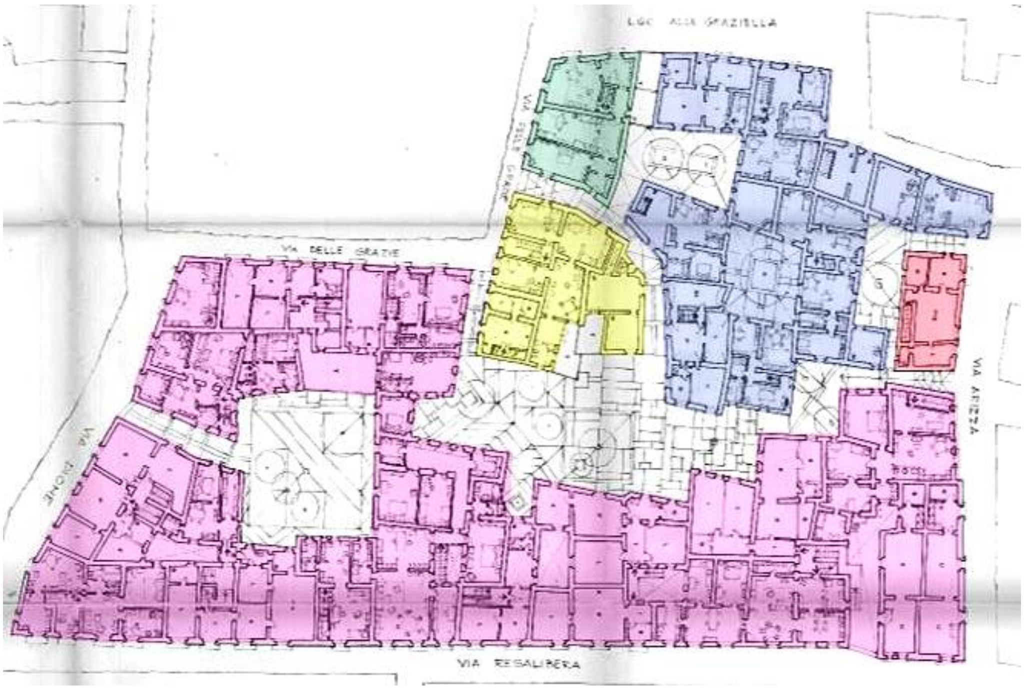


Figure 30 - Complexity of the aggregates in Ortigia (Comune di Siracusa, n.d.)

What is visible, is not only the presence of very big structural units but also the fact that the morphology of the compound is extremely complex. Indeed, there are severe misalignments in the façade on the courtyards, and often some convexities. Critical features can also be seen in elevation (Figure 31).

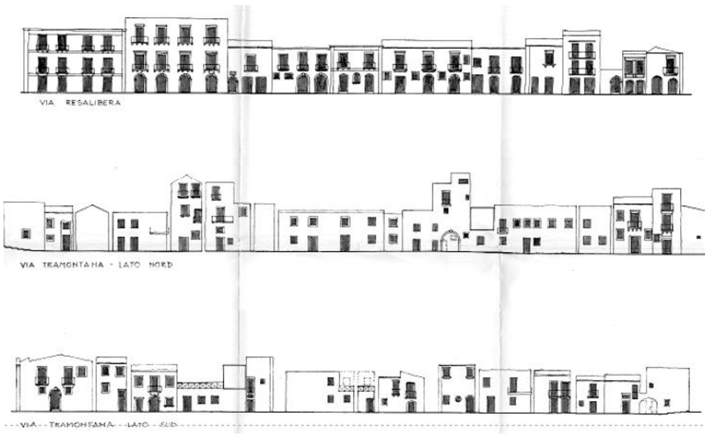


Figure 31 - Elevation of the aggregate in Ortigia (Comune di Siracusa, n.d.).

This aggregate was meant to be part of a requalification project, at the end of the XX century, but the project was never done, and the compound is still in very bad conditions, as it how it was found by surveying Google Earth (Google, n.d.).

a

b

c

d

Figure 32 - Some pictures from the survey. a) Material loss; b) Various Damages, material loss/vandalism; c) Presence of temporary support to prevent out-of-plane; d) Presence of most recent additions (Google, n.d.).

3.4.3 Description of a representative unit

The work carried out by Giuffre provided a lot of information regarding the aggregates of Ortigia. In particular, here, is described the unit that was modeled in Revit and used in the application. The considered unit is a “header” (three free sides) unit located in one of the biggest aggregates of Ortigia (Figure 33).

Figure 33 - Position of the studied unit in the aggregate (Comune di Siracusa, n.d.).

The building has two elevations, it is characterized by the presence of walls of different thicknesses, and one of the walls is shared with the adjacent units. The plan is rectangular, with dimensions of 8 m length on the longest side and 5 m length on the shortest (Figure 34 and Figure 35).

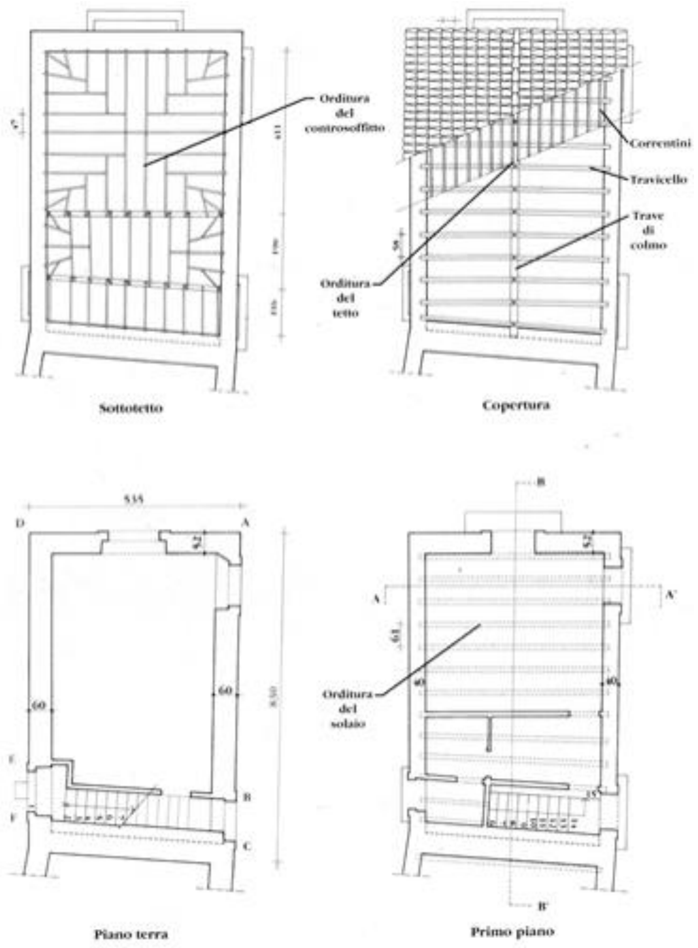


Figure 34 - Examined aggregate (Giuffre, 1993)

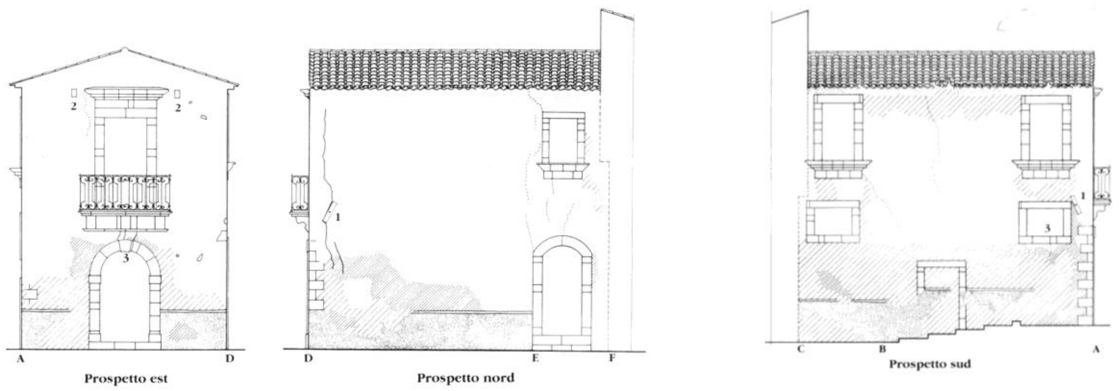
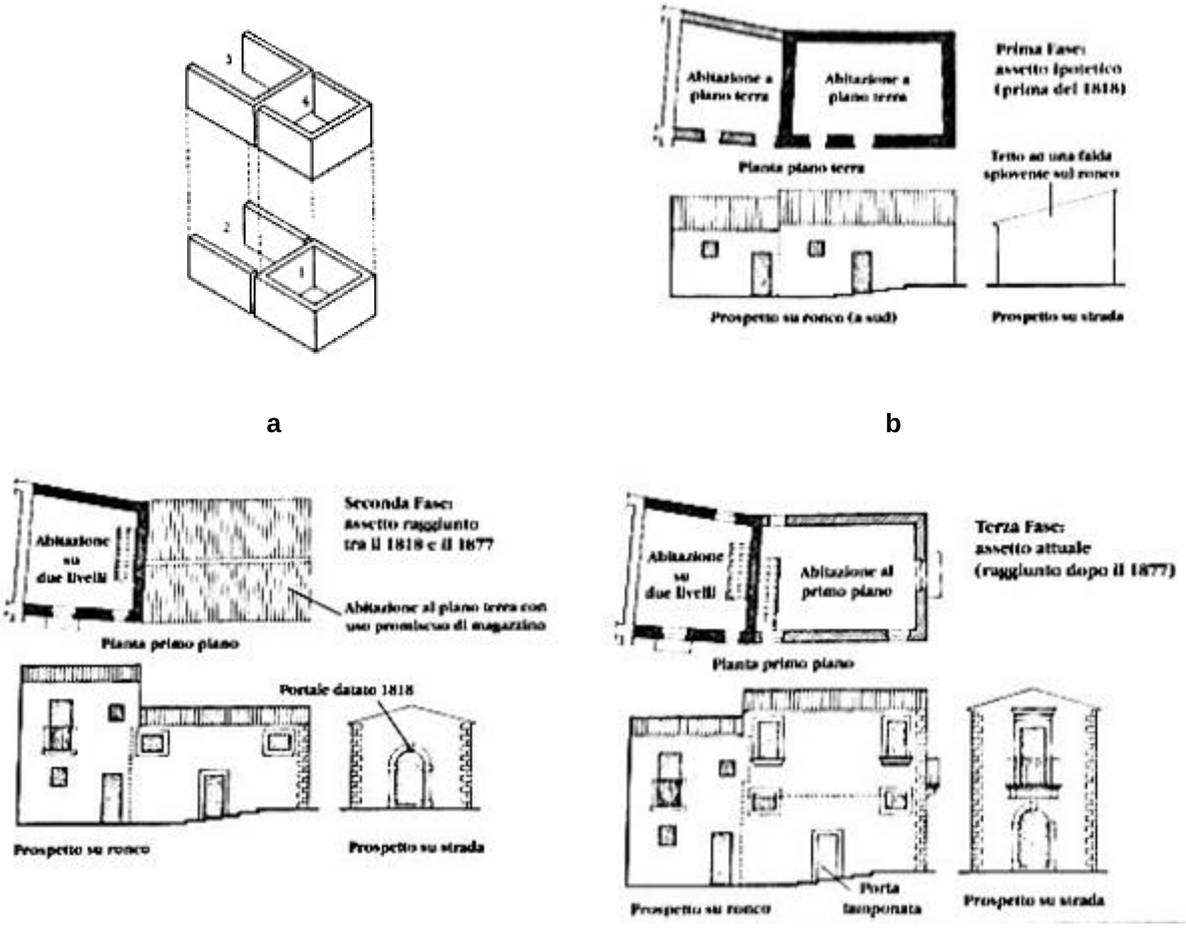


Figure 35 - Examined aggregate (Giuffre, 1993)

The morphological characteristic of the walls is the ones previously described, typical of Ortigia. The structure of the floor is characterized by little timber joints, covering a span of about 5 meters and spaced of about 60 cm. The roof presents two slopes with the main timber beam, and little joists in the other direction, spaced of about 40 cm. Originally had to be an isolated unit to which new buildings were added. Moreover, as in the majority of the cases, it was originally only consisting of an elevation, and, in a second case, an additional level was added. The construction phases contributed to the presence of a lack of connections between the walls (Figure 36).



a b

c d

Figure 36 - Constructive phases a) Way of construction; b) Phase 1; c) Phase 2; d) Phase 3 (Giuffre, 1993)

The constructive phases that characterize it would probably provide problems related to the lack of connections between walls. It was decided to model this unit because of the presence of information.

4. THE MACRO-ELEMENT APPROACH

4.1 Theory and normative indication

When the structural arrangement of a masonry building guarantees a box-like behavior, the seismic response of the compound depends mainly on the in-plane performance of its walls. The latter can be estimated using a macro-element method. According to this approach, the structural behavior of a wall can be assessed by studying the behavior of portions thereof. In particular, by considering the presence of openings, the horizontal alignment of the openings are the piers, the vertical alignments are the spandrels and the cross element connecting piers and spandrels are cross panels (Gambarotta & Lagomarsino, 1997). The introduction of this approach is related to what are the typical failure or cracks that are seen in the site.

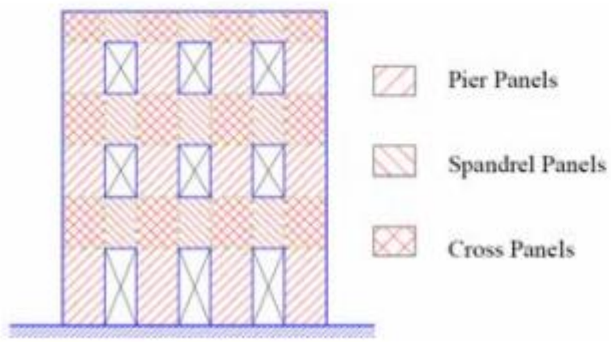


Figure 37 - Piers, spandrels, and cross panels (Marques & Lourenço, 2014).

A pier element has a load-bearing function, it absorbs directly the horizontal actions and receives the vertical loads from the spandrels, through the cross panels. For this reason, it is considered the element that controls the behavior of the wall. However, also spandrels have consistent importance since they also contribute to providing strength and stiffness to the wall (Marques & Lourenço, 2014).

The possibility of using a macro-element approach is one of the options considered by the Italian Building Code, (Ministro delle Infrastrutture e Trasporti, 2018) and explained in detail in the Commentary 2019 (Ministero delle Infrastrutture e dei Trasporti, 2019). Precisely, it is mentioned that for this type of modeling, the shear-displacement diagram is bilinear (Figure 38) and the resistance of the walls is based on the assessment of the type of failure of the elements. In particular, it is required to understand which kind of failure occurs first, reaching the limit of deformation associated with the different Limit States.

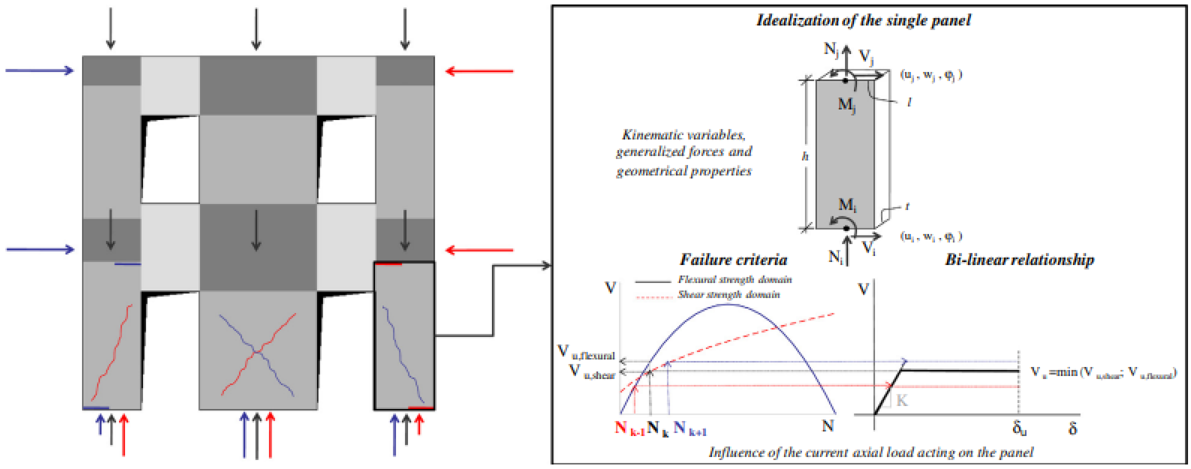
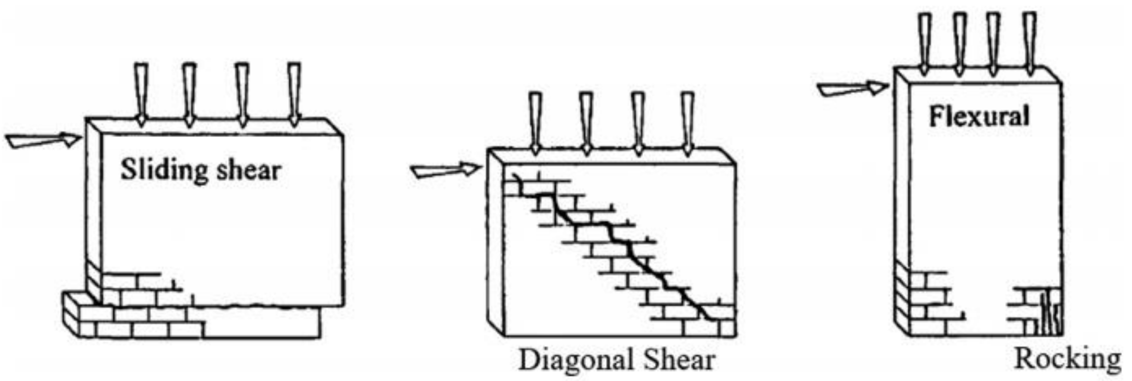


Figure 38 - Bilinear characterization of the Shear/displacement relation and idealization of the panel (Lagomarsino, et al., 2007)

The Italian Building code (Ministero delle Infrastrutture e dei trasporti , 2019) considers three main in-plane failure mechanisms, as far as concern the piers (**Error! Reference source not found.**).

- Bending-rocking;
- Shear-sliding;
- Shear with diagonal cracking.



a **b** **c**

Figure 39 - a) Bending – rocking, b) Shear-sliding, c) Shear with diagonal cracking (Asikoglu, et al., 2020)

The bending-rocking failure can be evaluated using the following formula:

$$M_u = \left(l^2 \cdot t\frac{\sigma_0}{2}\right)\left(1 - \frac{\sigma_0}{0.85 f_d}\right) \tag{1}$$

Where:

M_u is the moment correspondent with the collapse for bending-rocking.

l is the length of the wall.

σ_0 is the average normal stress referred to the total area in the section, with =N/(lt) with N axial force positive if compression and if N is tension Mu=0

$\sigma_0 = \frac{N}{lt}$ N is the axial force positive in case of compression

In case of tension Mu=0

$f_d = \frac{f_k}{\gamma_M}$ is the design compressive strength of the wall.

The last displacement allowed is evaluated depending on the rotation of the distance between the extremities of the pier, and for the ultimate limit state, the value is equal to 0.01. The distance is evaluated as follow:

$$\theta_i = \left|\varphi_i - \frac{u_i - u_0}{h_i}\right|$$
$$\theta_j = \left|\varphi_j - \frac{u_0 - u_j}{h_j}\right| \tag{2}$$

Where θ_j and θ_i are the rotation, u_j and u_i are the horizontal displacement, u_o is the displacement at the inflection point and h_j and h_i are evaluated considering that the height of the pier is $h = h_j + h_i$. The two failures associated with this mechanism are the crushing of the masonry (in compression) and the cracking (in tension).

The shear-sliding mechanism is less usual and it can occur in case of low normal stresses and participation of the section. The shear sliding resistance is given by:

$$V_t = l \cdot t \cdot f_{vd} \tag{3}$$

Where:

l is the length of the compressed part of the panel obtained on the base of a linear diagram of the compression and in absence of resistance to the tension stress

t is the thickness of the wall.

$$f_{yd} = f_{vmo} + 0.4\,\sigma_n \leq f_{y,lim} \tag{4}$$

$$f_{V,lim} = \frac{0.065 f_b}{0.7} \tag{5}$$

Where:

f_b is the compressive resistance of the masonry

f_{vmo} depends on the type of masonry.

The value of f_{v0} depends on the type of masonry used and f_b is the compressive resistance. The last displacement is defined for the rotation of the distance in the extremities, calculated as for the bending-rocking failure, and its equal to 0.005.

As far as concerns the shear with diagonal cracking, there are two cases:

- Irregular masonry with shear failure depending on the value τ_0.
- Regular masonry, in which the failure corresponds with the failure of the joints;

The shear with diagonal cracking is very common, and mainly due to the poor tensile resistance of the masonry. In the case of the regular irregular masonry, the shear resistance is evaluated according to the following formula:

$$V_t = l \cdot t \frac{1.5\tau_{0d}}{b}\sqrt{1+\frac{\sigma_0}{1.5\tau_{0d}}} = l \cdot t \frac{f_{td}}{b}\sqrt{1+\frac{\sigma_0}{f_{td}}} \tag{6}$$

Where:

l is the length of the block.

t is the thickness of the block.

σ_0 is the average normal stress referred to the total area in the section:

$\sigma_0 = \frac{N}{lt}$ N is the axial force positive in case of compression

τ_{0d} *and* f_{td} are the design value for the tensile resistance of the panel for diagonal failure and the shear failure.

b a corrective coefficient depending on the slenderness of the panel.

As far as the piers are concerned, the ultimate angular deformation at the limit state of collapse is equal to 0.005, and evaluated from **Error! Reference source not found.**. In the case of regular masonry, the shear resistance is given by:

$$V_t = \frac{l\,t}{b}\left(\tilde{f}_{v0d} + \tilde{\mu}\sigma_0\right) = \frac{l\,t}{b}\left(\frac{f_{v0d}}{1+\mu\phi} + \frac{\mu}{1+\mu\phi}\sigma_0\right) \leq V_{t,\lim} \tag{7}$$

Where:

$\tilde{f}_{v0d}$ is the shear resistance.

$\tilde{\mu}$ is the friction coefficient (depending on cohesion and friction angle).

ϕ, is the friction angle.

$V_{t,lim}$ is a limit value that can be approximated in the function of the tensile failure of the units, and considering the geometry of block, as:

$$V_{t,lim} = \frac{lt}{b}\frac{f_{btd}}{2.3}\sqrt{1+\frac{\sigma_0}{f_{btd}}} \tag{8}$$

In the spandrels, the in-plane failure mechanisms are:

- Bending-rocking;
- Shear with diagonal cracking.

A critical aspect is given by the axial component, influenced by the interaction with the horizontal diaphragm and from the kinematics interaction between the rotation and the axial deformation in the spandrel themselves, and that can be influenced, for example, by the presence of ties. The bending-rocking resistance for the spandrels is different from the one related to the piers. Indeed, it can be determined considering the tensile resistance that is generated in the extremities due to the adjacent portions of masonry, and the failure occurs when the tensile resistance of the units is reached or because of the sliding along the horizontal joints. The tensile resistance can be given by the formula:

$$f_{ftd} = min\left(\frac{f_{btd}}{2}; \bar{f}_{v0d} + \frac{\mu\sigma_y}{\Phi}\right) \tag{9}$$

Where:

σ_y is the average of the normal stress acting in the horizontal joints in the extremity section.

f_{v0d} is the shear resistance of the masonry in absence of shear stress.

$\phi,$ is the friction angle.

$\tilde{\mu}$ is the friction coefficient (depending on cohesion and friction angle).

The last displacement for the SLC is evaluated by calculating the angular deformation in the two sections of the extremity of the panel, according to **Error! Reference source not found.**. In this case, the limit is 0.02, and if there is an element coupled with this, like a beam, or 0.015 in the other cases.

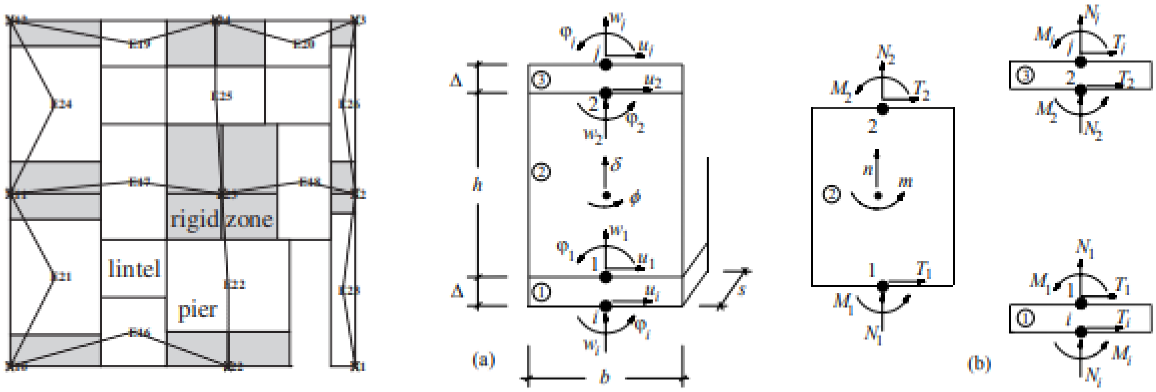
Regarding the shear with diagonal cracking, the criteria are the same as the ones used for the piers, but the angular deformation that corresponds with the limit of collapse is not superior to 0.0015. (Ministro delle Infrastrutture e Trasporti, 2018).

4.2 Numerical modeling software

To simulate the masonry panels mechanism and their interactive behavior, different types of macro-elements have been proposed, and recently several modeling software based on this approach have been released. Lagomarsino introduced 3Muri (Penna et al., 2009), based on an equivalent frame method approach, thus modeling the macroelement as monodimensional. Calio introduced 3dMacro (Gruppo Sismica, 2011) based on the discretization of the macro-elements as bidimensional discrete elements. Based on a presentational approach, these models can predict the aforementioned in-plane failures of masonry. Their capability of accounting for the shear-sliding damage evolution allows estimating the reduction of the strength of the elements (softening), as well as their stiffness deterioration (Lagomarsino et al., 2007). The affordable computational costs, and the easy way of modeling these structures, satisfy new important challenges addressed today such as the sustainability of the assessment and the validation of the rehabilitation intervention (Marques & Lourenço, 2014).

4.2.1 Equivalent frame approach

In the simplified macro-element modeling proposed by Gambarotta and Lagomarsino (Gambarotta & Lagomarsino, 1997), the piers and the spandrels are connected by a rigid node, similar to what happens in the frames structures. Masonry panels are modeled as 2D elements assuming a bi-linear relation with a cut-off in strength and stiffness decay in the nonlinear phase, for monotonic action. The initial stiffness is computed based on the geometrical and mechanical properties of the panel. Moreover, the loads are applied in the nodes only, not acting among the elements (Lagomarsino et al., 2013). To simulate the presence of damage, it is possible to model a reduction of the initial stiffness. The macro-element is divided into three sub-structures, as shown in Figure 40. In the two extremities, there is the concentration of bending and axial effects, whereas the central part is affected by shear and sliding effects. In this case, the kinematic of the macro-element is described by 8 degrees of freedom: in each extremity, there are 3 degrees of freedom, and in the middle part there are two degrees of freedom, displacement, and rotation (Lagomarsino et al., 2007).



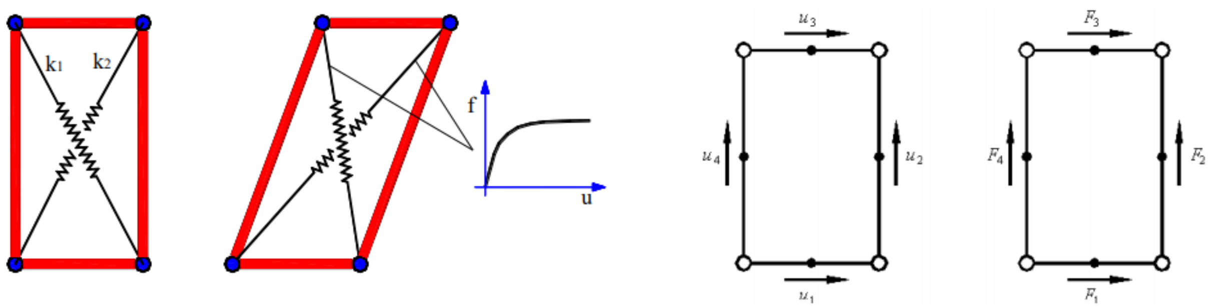
a **b**

Figure 40 - Macro-element approach based on the Equivalent Frame method a) Discretisation of the structure; b) Kinematic of the panel (Lagomarsino, Galasco, & Penna, 2007).

4.2.2 Discrete macro-element approach

The aforementioned limitations are partly overcome in the approach used in 3DMacro, in which, through a set of non-linear springs, it is possible to simulate the planar response of masonry panels and its interaction and cracking within the entire elements. This section is aimed at explaining the theory on which this software is based since it establishes the base and constraints for the definition of the algorithm developed in this Dissertation.

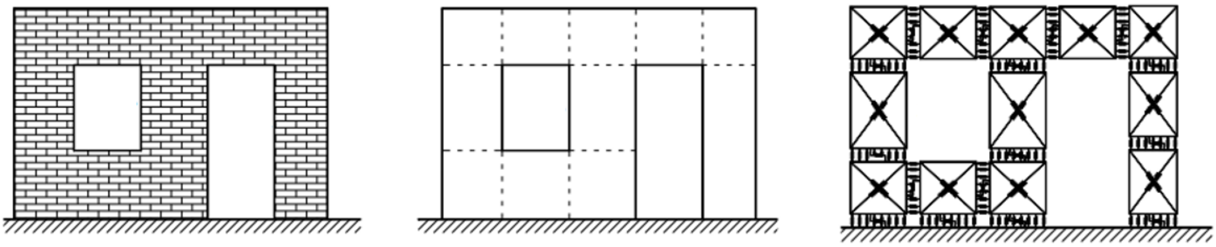
In 3DMacro, a wall is discretized as a panel in which the vertexes are connected by diagonal springs, simulating the shear deformability (Figure 41). Each panel is identified in the model by four vertexes, a relative reference system, the specific weight, and the mass. It is characterized by 4 degrees of freedom.



a b

Figure 41 - Discretization of the panels (Gruppo Sismica, 2011).

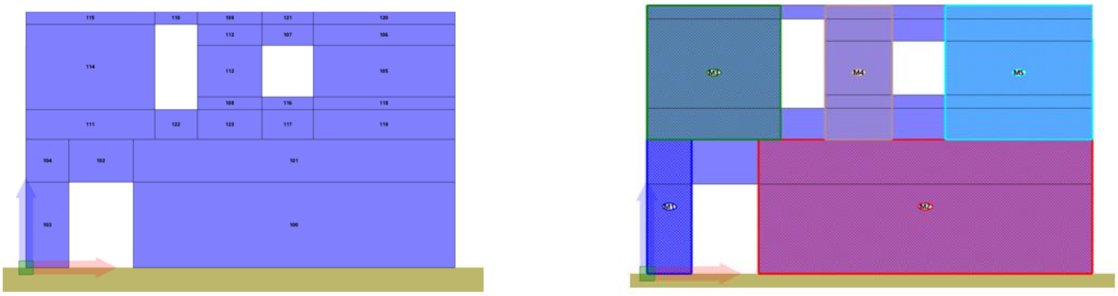
The mesh of macro-elements that discretize the wall is defined depending on the position and dimension of the openings in the wall, in a very simple way, as shown in (Figure 42) and this is usually done automatically by the software.



a **b** **c**

Figure 42 - Mesh of macro-elements (Gruppo Sismica, 2011).

In the model it is possible to identify different elevations, corresponding to the height of the floors, in which they will be located the control points of the PushOver curve. The macro-element mesh is done for each floor. In addition, each wall is associated to a local coordinate system (Figure 43).



a **b**

Figure 43 - Mesh of a wall. a) Macro-elements; b) Piers (Gruppo Sismica, 2011).

As previously briefly mentioned, the macro-elements are not connected through rigid nodes but interface elements characterized by 6 degrees of freedom (Figure 44).

a b

Figure 44 - Degree of freedom at the interfaces. a) Between two elements; b) Panel with external support (Gruppo Sismica, 2011).

These elements are modeled as a set of non-linear springs that allows simulating the in-plane response of masonry panels, as well as the interaction and cracking within the entire elements. The presence of these interface elements provides a major computation effort, concerning the other models, but it also gives a more accurate representation of the behavior of the wall. In particular, the interfaces have to simulate two behaviors: the sliding between the two macro-elements and the axial-flexural behavior connecting two adjacent panels (Figure 45).

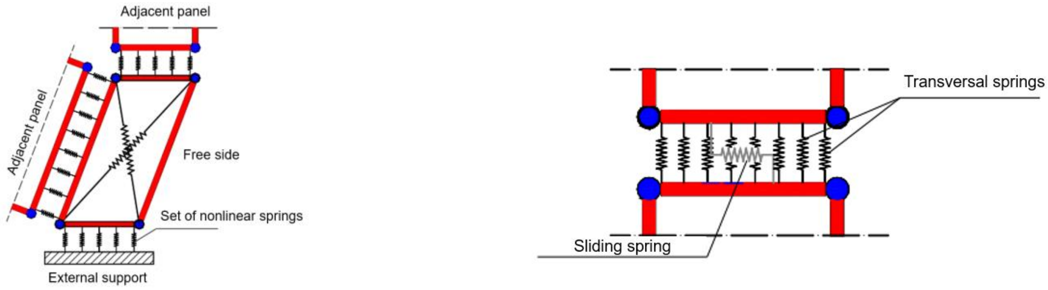


Figure 45 - Nonlinear spring simulating the interfaces (Gruppo Sismica, 2011).

The springs are associated with the in-plane failure mechanism of the wall, and it is required to define three constitutive laws to represent them. Thus, it must be taken into account the values of the mechanical parameters referred to the panel itself for the diagonal springs, and the average between the two adjacent panels for the interfaces. Regarding the values of the mechanical characteristics, it is possible to refer to the ones proposed by the Italian code, in particular in the Commentary 2019 (Ministero delle Infrastrutture e dei trasporti , 2019), and select the appropriate level of knowledge, always referring to the prescription of the code.

In the interfaces, the transversal springs describe the bending-rocking failure, thus they present a limited resistance in compression and a fragile behavior in tension (Figure 46). The crushing of the masonry is modeled as the progressive plasticization of the spring, whereas the cracking is modeled as the tensile failure of the latter (Gruppo Sismica, 2011).

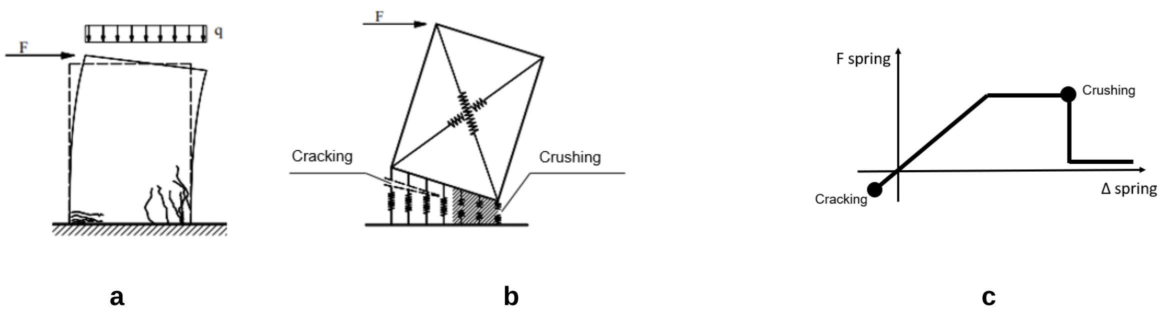


Figure 46 - Flexural failure a) Typical cracking pattern; b) Discretization; c) Constitutive law (Gruppo Sismica, 2011).

To describe the flexural behavior it is required the Young Modulus, the compressive strength, and the tensile strength in the two main directions of the wall. Indeed, the material is modeled like orthotropic-elastoplastic, as explained previously. In addition, as far the unloading condition is concerned, for the tensile behavior it is oriented on the origin, whereas for the compressive behavior, it maintains the stiffness as the original (same as the loading). This information is needed for the solver to run the analyses (Gruppo Sismica, 2011).

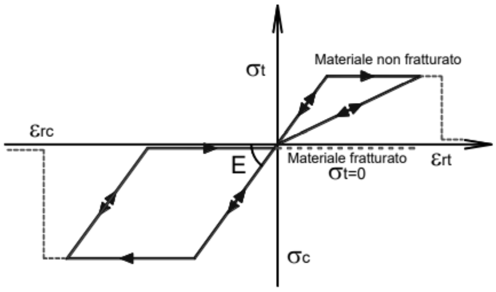


Figure 47 - Unloading condition for tensile and compressive stresses (Gruppo Sismica, 2011).

The shear with diagonal cracking, which is the most common type of failure, is modeled with nonlinear behavior associated with the diagonal springs (Figure 48).

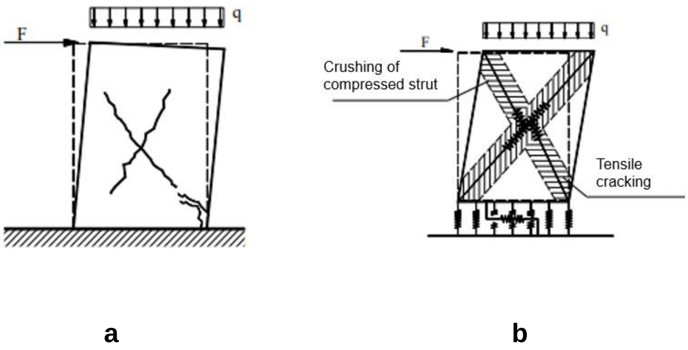


Figure 48 - Shear failure of the panel. a) Typical crack pattern; b) Discretisation with the springs (Gruppo Sismica, 2011).

As suggested from the NTC (Ministro delle Infrastrutture e Trasporti, 2018), the diagonal cracking depends on the type of masonry, thus in the case of regular masonry, it is possible to consider the Coulomb criterion. Otherwise, the modeling is based on Turnsek and Cacovic. Apart from the shear modulus and the shear resistance (depending on the criterion), other parameters are required. Indeed, it is demonstrated that this type of failure does not only provide a stiffness decrement, but also a strength decrement. The unloading condition is thus represented by a degrading model, through a damage function (Figure 49) (Gruppo Sismica, 2011).

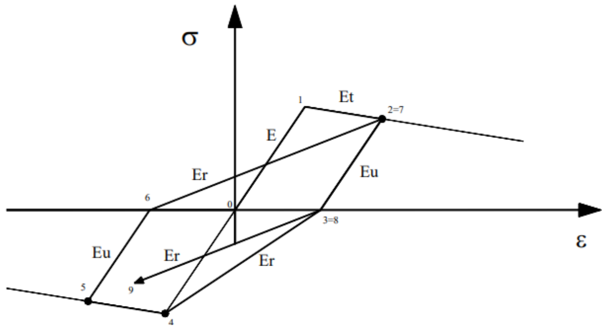


Figure 49 - Degrading model in the load-unload cycle (Gruppo Sismica, 2011).

This hysteretic law is described by three elastic moduli, that is the initial one, the unload elastic modulus (Eu), and the re-load elastic modulus (Er).

$$E_u = \beta \cdot K_I + (1-\beta) \cdot K_0 \tag{10}$$

$$0 \leq \beta \leq 1; \tag{11}$$

$$E_r = \frac{\sigma_y(\varepsilon_p^-)}{\varepsilon_r^+ + |u_{\max}^-|} \cdot (1 - \gamma \cdot D) \tag{12}$$

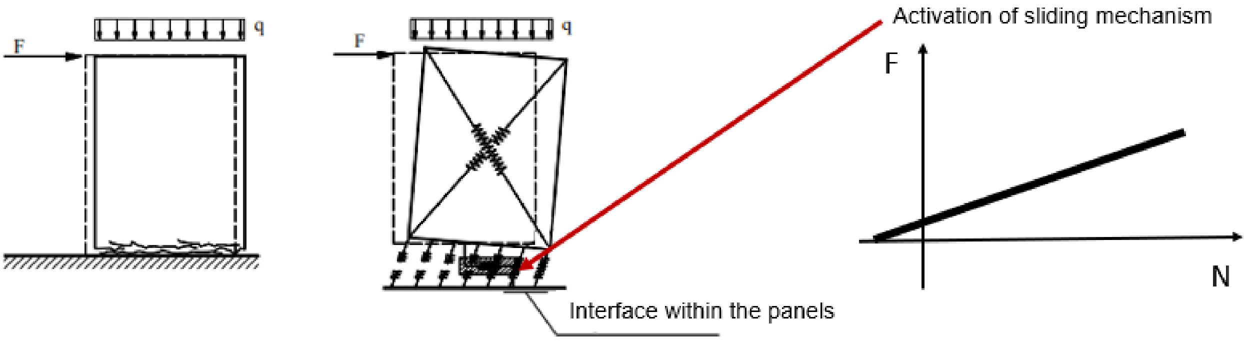
$$0 \leq \gamma \leq 1 \;;\quad 0 \leq D \leq 1; \tag{13}$$

Where:

σ_y	Yelding stress
ε_r^-	Plastic deformation
ε_r^+	Residual deformation
K_0	Initial Stiffness
K_I	Originally oriented stiffness

For this reason, it is necessary to introduce other parameters, β, γ, and D. Otherwise, for default the unloading condiction is origin-oriented, not considering this strength decrement.

Finally, the sliding behavior is modeled through the elastic behavior of the longitudinal spring and its elastic behavior.



a b c

Figure 50 - Sliding failure. a) Typical pattern, b) Discretization of the panel: c) Diagram F-N (Gruppo Sismica, 2011).

The shear-sliding behavior is described by the Coulomb criterion (described before), and the material is characterized by two resistance parameters, which are the cohesion and the friction angle and which are considered in the two directions. The unloading condition maintains the initial stiffness.

Depending on the geometry of the structure, it can be necessary to use a type of element of different shapes (Figure 51 a). These elements are modeled as rigid elements with six degrees of freedom, that is the three translations and the three rotations of the local reference system, with the origin in its barycenter (Figure 51 b). This can be used to model, for instance, the triangular panels of the roof, and since it does not have the internal springs, only bending and sliding behavior are associated with it.

a b

Figure 51 - Rigid element. a) Typical rigid elements on these structures; b) Degree of freedom (Gruppo Sismica, 2011).

The floors and the roofs can be modeled in different ways: rigid diaphragms, stiff diaphragms, and deformable diaphragms (Ministro delle Infrastrutture e Trasporti, 2018).

The rigid floors are connected to the adjacent panels with two interfaces, one superior and one inferior. This is the case, for example of a concrete slab that is in between the masonry, which is why the connection is simulated by two dinsting interfaces. The kinematic of these elements provides sliding and vertical displacements, as shown in Figure 52.

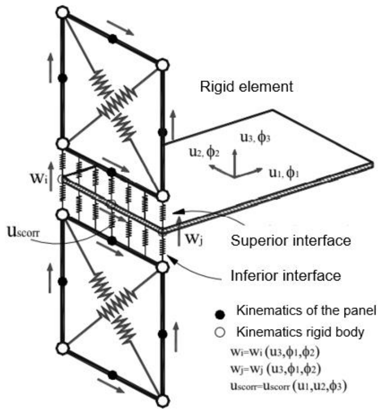
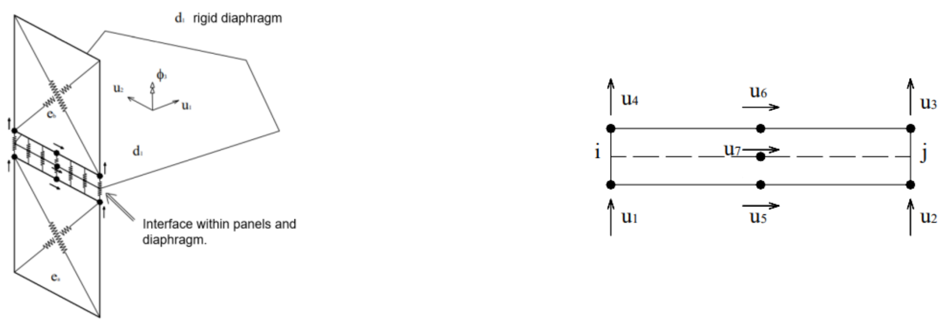


Figure 52 - Kinematics of rigid floors (Gruppo Sismica, 2011).

The rigid diaphragms are elements that only have three degrees of freedom on their plane, applied to the barycentre of the plane itself. They are connected to the vertical panel through a special type of interface, which has an additional degree of freedom (Figure 53) aimed at connecting the diaphragms to the interfaces, to simulate the sliding interaction of the latter with the panels to which it is connected. This is the case, for example, of a timber floor that have been strenghtened to gain stiffness.

For historical buildings, the hypothesis of a rigid diaphragm sometimes is far from reality, especially in the case of masonry aggregates. Nevertheless, it reduces substantially the computational costs. This can be used, for example, in the case of timber floors in which the in-plane stiffness and strength has been improved.



a **b**

Figure 53 - Rigid diaphragms a) Degree of freedom; b) Interfaces

Finally, the deformable diaphragms are characterized by a larger degree of freedom. Indeed, each element is constituted by n triangular meshes of six nodes (n is the number of the sides). Each element is characterized by 12 degrees of freedom, two translations for each node. These 12 degrees of freedom are condensed into 8 (Figure 54). This is, for example, a traditional timber floor.

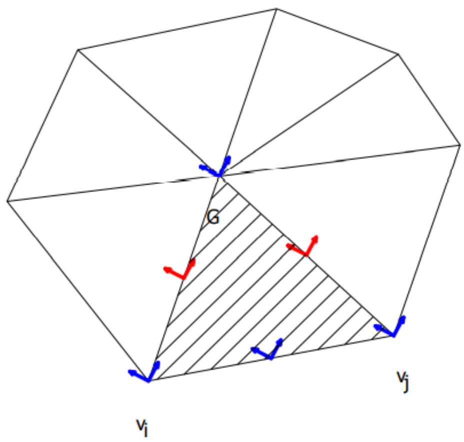


Figure 54 - Mesh for deformable diaphragms

The foundations are modeled as beams (2D elements with axial and flexural behavior), placed between two interfaces. The top interface is representing the wall deformability and the bottom one is the one of the ground and it can be considered as elastic.

4.2.3 Nonlinear static analyses

As mentioned in the literature review, nonlinear static analyses are considered a good approach for the structural assessment of masonry aggregates. To perform this type of analysis, appropriate load patterns are applied to the numerical model, increasing their amplitude in a stepwise fashion. The analysis is performed at each step until the failure of the structure or until reaching limit conditions, as the one considered in the Italian code (refer to the previous chapter). The software does the PushOver analysis after having applied the vertical loads, which is afterward redirected horizontally, according to the X or Y directions of the global reference system. In particular, the horizontal actions are determined according to two different ways of distributing the forces: uniform pattern, modal pattern. In the first case, the intensity of the forces is equal to the vertical load; in the second case, it is assumed to have a linear variation with the height (the reverse triangular distribution is representative of the fundamental mode of the structure).

As far as the masonry panels are concerned, the vertical loads are assigned directly to the element. They are automatically evaluated based on the geometry of the panel and the assigned material characteristics. The vertical loads (structural and nonstructural) on the diaphragms are distributed to the adjacent panels, according to the floor warping. Also for the horizontal loads, the forces are applied to the pertinent elements. Regarding the horizontal elements, in the case of rigid floors or rigid diaphragms, the actions are concentrated on the barycenter of the element, whereas in the case of the deformable diaphragms, the forces are redirected on each node of the element. Indeed, in each triangular sub-element of the mesh, there is a load, proportional to the area that can be redirected to its vertex.

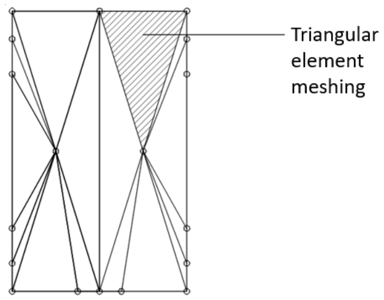


Figure 55 - Triangular meshing

The analysis is subdivided into steps to apply all the load. Each analysis needs to be called by an identification name to call the analysis itself, an identification that calls the previous analysis, the discretization, a value that indicates if the analysis is executed or not, the load distribution, a control point to be monitored in order not to go beyond the maximum displacement, and finally, if the analysis is a displacement control, a list of points that are the degree of freedom of the model.

The control points are assigned in the horizontal elements. In particular, in the case of rigid floors or rigid diaphragms, the control point is in the barycenter of the element. In the case of deformable diaphragms, the control point is assumed as the average of the displacement of all the points that define the diaphragms. In addition, in case there are more the one horizontal element in a certain seismic elevation, that elevation is characterized by more than one control point. If one elevation does not have any horizontal elements, the control point is assumed as the middle point in the displacement that occurs in the two extreme nodes of the wall. The selection of the control point is extremely important since it conditions the phase of displacement control in the case of nonlinear static analyses.

The nonlinear static analyses are finally divided into two phases, a force control analysis and a displacement control analysis. In the first phase, the load is applied (depending on the configuration selected) and in the second phase, there is a displacement control phase. This phase allows redistributing the actions after the failure of some elements and understanding the residual ductility of the structure. This approach will be followed in the application.

5. METHODOLOGY PROPOSED TO ASSESS THE MASONRY AGGREGATES

5.1 Introduction to the workflow

In this chapter, it is introduced the methodology proposed for the comprehensive assessment of masonry aggregates, explained through the workflow shown in Figure 58. The workflow is structured into different phases, as “project milestones”. The first four are coincident with the ones recommended by ISCARSAH: *historical survey*, *inspection*, *monitoring*, and *structural analysis*. In addition, it is stressed the requirement of consulting the Italian Building Code, on which the modeling assumptions are based. The reference to the Italian Building Code is not only done because of the fact that the study case is located in Italy, but also because it is the most complete normative as far as the existing structures are concerned. Moreover, the logic followed by the software proposed for the structural analysis, 3DMacro, has common points with the legislation mentioned (see also Chapter 4).

Once the structural analyses are performed, the following phase consists of the design of the structural intervention and its validation. Finally, the workflow opens the possibility to other aspects of the intervention, such as cost-benefit analyses, as well as energy efficiency. Even though these aspects have not been studied in-depth, it is fundamental to consider them inside the workflow, to understand how working on the interoperability between structural analysis software and BIM would provide great benefit to the entire intervention on the structure. The workflow is calibrated by a team of experts of different backgrounds, that share information through the Product Data Templates, and the BIM model. Due to the nature of the current application, it is considered the presence of the structural engineer, the BIM modeler, and the other experts. As mentioned, introducing an expert on the BIM modeling would allow the other stakeholder to focused on their field of expertise. In this way, there is no requirement of having every stakeholder expert in BIM, and there is also a lot of time gained. One of the major contribution given by this approach is in the fact that each specialist can be focused on its field of application, without spending his time in the attendance of other tasks, such as the modeling of the geometry. This concept is very important especially when dealing with existing structures, as the level of expertise is growing, and consequentially the requirement of having experts with in-depth knowledge about a specific field.

The main difficulty found in the development of this framework was due to the nature of the rehabilitation project itself, extremely different from the design of new structures. For a new structure, during the different Project Milestone, there is the passage from a very simplified and conceptual model, to an“as-built” model.

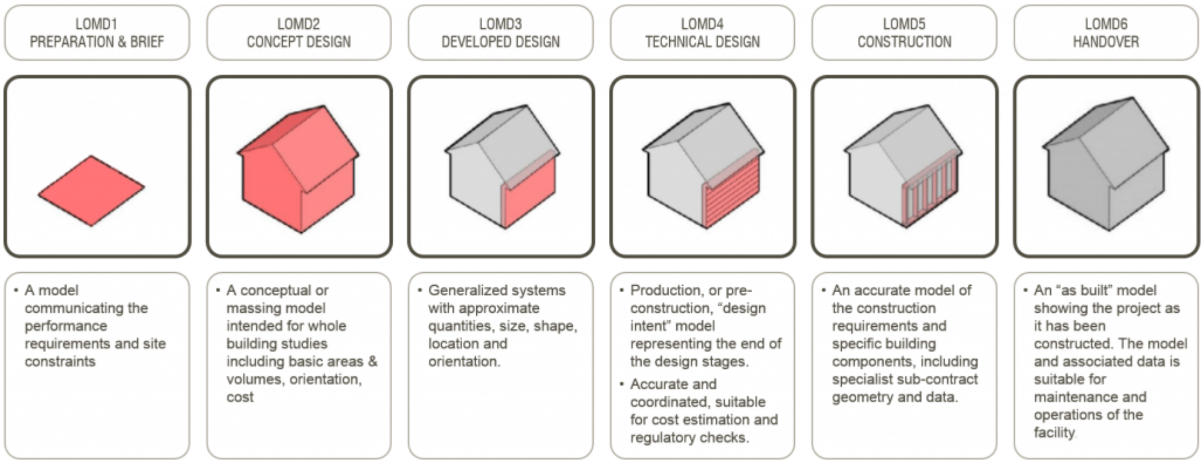


Figure 56 - Phases of the model for a new structure (Evolve Consultancy, 2014)

As far as concerns an existing structure, especially when the scope of the structural assessment, the methodology followed is completely different. The structural model is the arrival point of long research work and is usually characterized by simplifications, especially in terms of its geometry, due to the specific modeling assumptions to be followed. A geometrically simple model often come after that very detailed drawing are done (Figure 56).

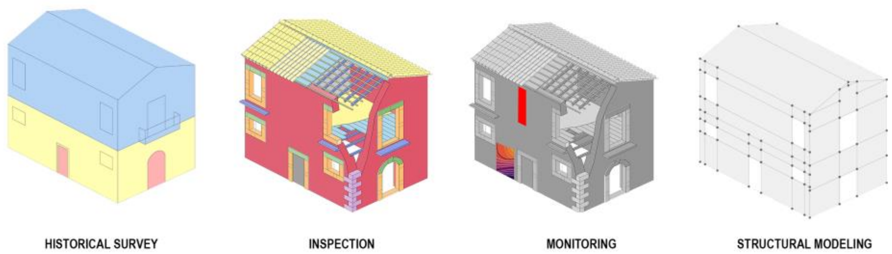


Figure 57 - Information gathered during the various phases of structural assessment of a historical structure

The way the workflow was conceived is aimed at managing the modeling in such a way of having an always more detailed model, making the modeling process more fluid, avoiding repetition or loss of data, and improving the cooperation among stakeholders (Figure 58).

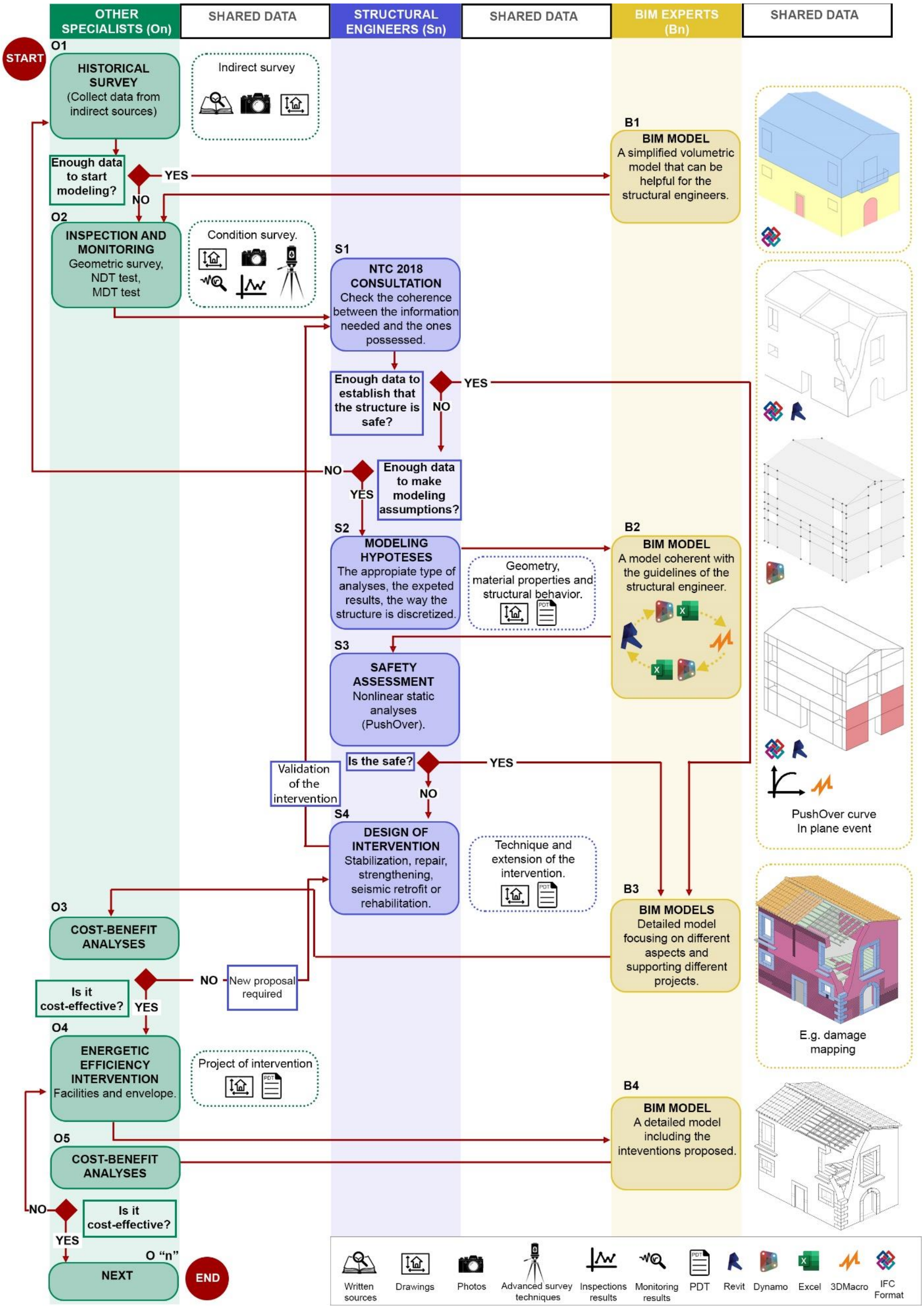


Figure 58 - Workflow of the methodology

5.2 Historical survey

The first project milestone is the historical survey, whose main goal is gathering data, not directly looking at the building, but through indirect sources, such as the written ones, photos, existing drawings, existing projects or previous analyses. At this stage, it may occur that the stakeholders are already dealing with a certain typology of data that is convenient to store in a BIM model. If the case, the model will be simplified and following the requirement of the Level Of Information need. A possible outcome is a model showing the construction phases of the building. The Level Of Information need, related to the historical survey is shown in Table 5.

Table 5 - Historical survey LOI

Historical survey	
Purpose	Identification of the constructive phases
Actors	Architect – Historian – Archeologist
❖ **Object:**	**“Wall"**
➢ Geometrical information:	
▪ Detail:	Volume representation including openings.
▪ Dimensionality:	2D
▪ Location:	Absolute
▪ Appearance:	Symbolic colours based on the period.
➢ Alphanumerical information:	
▪ Identification	“Wall age”
▪ Information content	Period of construction.
➢ Documentation	
▪ Set of document	Old pictures, old plants, sketches providing details that help to understand the period.
Object:	**Opening**
➢ Geometrical information:	
▪ Detail:	Void.
▪ Dimensionality:	Void in the 2D element

- Location: Absolute
- Appearance: Symbolic colors based on the period.

➢ Alphanumerical information:

- Identification “Opening period”
- Information content Period of construction.

➢ Documentation

- Set of document Old pictures, old plants.

Object: **Infilled in the opening**

➢ Geometrical information:

- Detail: Surface
- Dimensionality:
- Location: Absolute
- Appearance: Symbolic colors based on the period.

➢ Alphanumerical information:

- Identification “Infill period”
- Information content Period of construction.

➢ Documentation

- Set of document Old pictures, old plants.

Object: **Stairs**

➢ Geometrical information:

- Detail: Simplified surface
- Dimensionality: 2d
- Location: Absolute
- Appearance: Symbolic colors based on the period.

➢ Alphanumerical information:

- Identification “Stair age”
- Information content Period of construction.

➢ Documentation

▪ Set of document	Old pictures, old plants.
Object:	**Floors and roofs**
➢ Geometrical information:	
▪ Detail:	Surface
▪ Dimensionality:	2D
▪ Location:	Absolute
▪ Appearance:	Symbolic colors based on the period.
➢ Alphanumerical information:	
▪ Identification	“Floor age”
▪ Information content	Period of construction.
➢ Documentation	
▪ Set of document	Old pictures, old plants.

5.3 Inspection and monitoring results

In the phase of inspection and monitoring, plenty of information is gathered on-site. It is a crucial moment and the loss or overlapping of data is not unusual. The information gathered in this phase are drawings, photos, results on situ tests, but also outcomes of the most advanced techniques of survey, such as photogrammetry and laser scanning. Various site visits can be required and several stakeholders are involved.

These records are sent to the structural engineer, which compares them with the requirement of the reference standards. At this point, he can do a first safety assessment, for example performing some hand calculations. Afterwards, since the scope is the performance of the global numerical analysis, the structural engineer proceeds with the modeling assumption, or if required, asks for further data. A possibility is having different experts on the various construction materials of the structures. Each of them, starting from the information gathered from the inspectors, fills Product Data Templates to send to the BIM modeler (Figure 59). The passage of sharing of information between inspectors and structural engineers is fundamental: the latter can filter only the information necessary to made the structural model, and sent them to the bim modeler. This is done to maintain the efficiency of the workflow since it is known that a too complex model is often slow, especially if this is made with the purpose of structural analyses. Moreover, it is way more efficient to start with a simpler model, and adding details when it is needed, instead of preparing a huge model and after simplifying it.

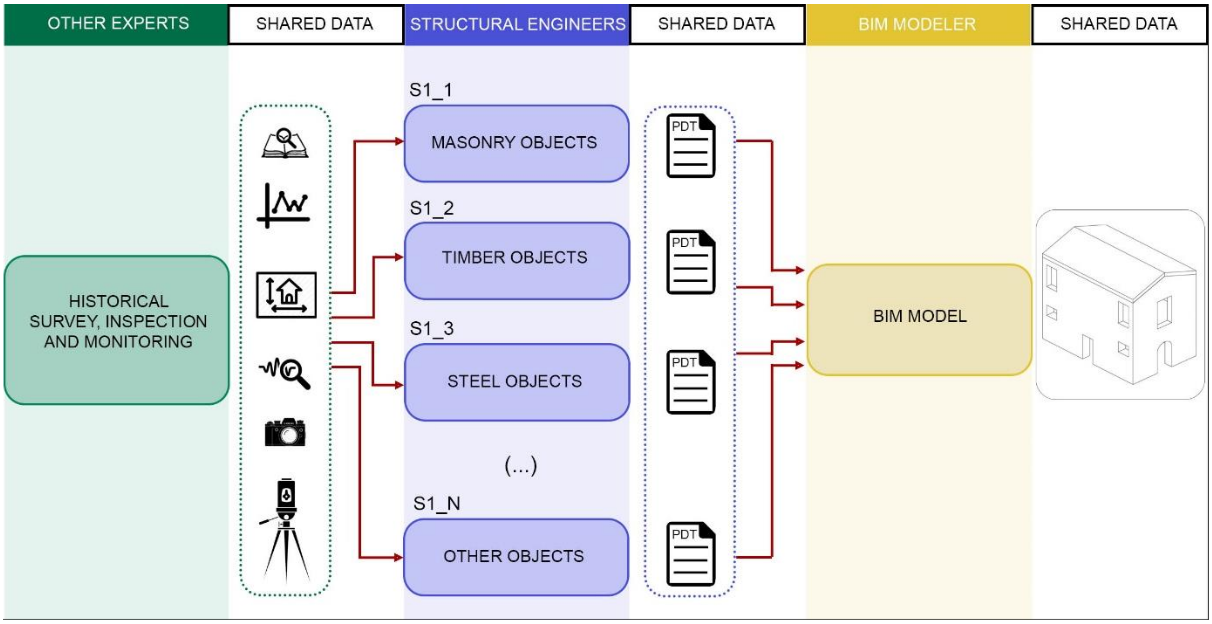


Figure 59 - Cooperation between stakeholders during the definition of the structural model

To give a contribution in this phase, it is proposed a PDT conceived for the object "Historic masonry wall", following the model proposed by NBS. The parameters required are structured into groups, depending on the project milestone in which they are introduced, but also depending on the modeling assumptions made. As far as the two groups of parameters (HistoricalSurvey-InspectionAnd Monitoring) are concerned further developments are recommended since this was not the major focus of the thesis.

More effort was done in the definition of the parameters grouped under "MechanicalCharacteristics", "FlexuralBehavior","ShearAndSlidingBehaviour","CorrectiveCoefficients"and"StrengtheningIntervention Coefficients". Once again, these parameters are the one that the NTC 2018 proposes for the assessment of existing unreinforced masonry structures. To be more precise, as far as concerns the "MechanicalCharacteristics", "CorrectiveCoefficients" and "StrengtheningInteventionCoefficients", these coefficients are applicable regardless of the choice of the behavioral model of the structure. As far as concerns the "FlexuralBehavior" and "ShearingAndSlidingBehavior", also these parameters are considered by the NTC, but they refer to specific modeling assumptions, the discretization of the structure in piers and spandrels, and the different failures of these elements.

It was decided to add the "CorrectiveFactors" and the "LevelOfKnowledge" as parameters, instead of including them already in the "MechanicalCharacteristics". This is due to the will of ensuring as much transparency as possible in the choices and the assumptions, but also to simplify the updating of the wall characteristics, in case of additional testing, or also in case of application of strengthening measures. Finally, the last group of Parameters is specifically related to 3Dmacro software. The PDT is shown in Table 6.

Table 6 - Product data template proposed for an historical masonry wall

TemplateName			
SuitabilityForUse			
ParameterName	Value	Units	Notes
HistoricalSurvey			
WallAge		Years	
Inspection (WallConstructionDetails)			
Height			
Lenght			
Thickness			
Morphology			
JointType			
MQIStoneShape			
MQIWallLeafConnections			
MQIHorizontalBedJoints			
MQIMortarProperties			
MQIVericalJoints			
MQIUnitsMechanicalPropertiesAndConservationState			
MQIUnitDimensions			
MechanicalCharacteristics(FromNCT2018)			
CompressiveStrengthH			
CompressiveStrengthV			
TensileStrengthH			
TensileStrengthV			
ShearStrengthH			
ShearStrengthV			
SpecificWeigth			
ElasticModulusH			

ElasticModulusV			
ShearModulusH			
ShearModulusV			
KnowledgeLevel			
FlexuralBehavior			
FlexuralBehavior			
FlexuralLimitRotation			
CompressiveDuctilityH			
CompressiveDuctilityV			
TensileDuctilityH			
TensileDuctilityV			
UnloadingConditionCompression			
UnloadingConditionTension			
ShearAndSlidingBehavior			
ShearBehavior			
SlidingBehavior			
ShearLimitDeformationH			
ShearLimitDeformationV			
UnloadingCondictionShear			
A			
B			
Alpha			
Beta			
Gamma			
PhiV			
PhiH			
CorrectiveCoefficients			
GoodQualityMortar			

GoodInterlock PresenceOfListing			
StrenghteningIntervetionCorrectiveCoefficients			
Injections			
ReinforcedPlaster JointsRepointingWithInterlockImprovement MaximumCorrectiveCoefficient			
3DMacroParameters			
NameOfMaterial NameOfWall			

5.4 Modeling

Once that the structural engineers filled the PDTs, these will be shared with the BIM expert. The latter will also be provided with the data collected in situ regarding the geometry of the structure. At this point, it is necessary to develop a model coherent with the Level Of Information needed in the project milestone.

Being BIM based on object-oriented modeling, the BIM expert has to introduce families, and at this moment it is important to have in mind what is required and what is not, since these objects are developed with a series of parameters, and having too many of them makes the model unnecessarily slow. The example below shows two ways of modeling a type of opening that is very common in Ortigia (Figure 60).

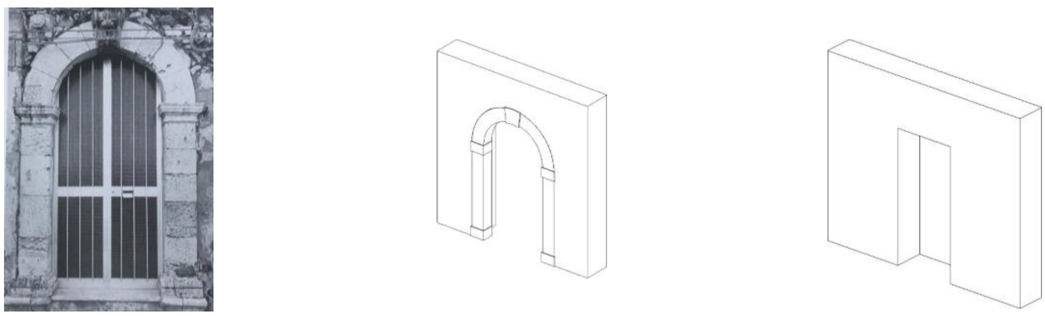


Figure 60 - Different ways of modeling the same opening

Despite the first example being more representative of reality, the detail of the second one is enough to the scope of structural assessment. This does not mean, that at a certain point, proceeding with the design of other aspects of the rehabilitation project, there will be no need for more detail, but again, following the right order of information integration makes the methodology more efficient. To this scope, together with the PDTs, the BIM expert encharged of preparing the structural model is provided with the Level Of Information needed for this stage of modeling, as indicated in Table 7.

Table 7 - LOI required for the structural modeling

Structural Modeling	
Purpose	Modeling a simplified geometry and introducing the required parameters.
Actors	
❖ **Object:**	**“Historical masonry wall"**
➢ Geometrical information:	
▪ Detail:	Volumetric representation including openings. Some simplifications are done.
▪ Dimensionality:	3D
▪ Location:	Absolute
▪ Appearance:	-
➢ Alphanumerical information:	
▪ Identification	“Wall flexural behavior”, “Wall shear and sliding behavior”.
▪ Information content	Type of behavior(flex), Young Modulus, compressive strength, ultimate compressive resistance, tensile resistance, limit rotation, tensile ductility, compressive ductility, specific weight, Type of behavior (shear), shear modulus, failure criterion, shear resistance, friction coefficient, last shear deformation, coefficient b, initial condition,
➢ Documentation	
▪ Set of document	Italian code and information from the previous project milestones.

❖ **Object:**	**Window**
➢ Geometrical information:	
▪ Detail:	Void.
▪ Dimensionality:	3D
▪ Location:	Absolute
▪ Appearance:	-
➢ Alphanumerical information:	*Not required.*
➢ Documentation	*Not required.*
❖ **Object:**	**Door**
➢ Geometrical information:	
▪ Detail:	Void.
▪ Dimensionality:	3D
▪ Location:	Absolute
▪ Appearance:	-
➢ Alphanumerical information:	*Not required.*
➢ Documentation	*Not required.*
❖ **Object:**	**Infilled opening**
➢ Geometrical information:	
▪ Detail:	Volume
▪ Dimensionality:	3D
▪ Location:	Absolute
▪ Appearance:	-
▪ Alphanumerical information:	
➢ Identification	*Not required.*
➢ Set of document	*Not required.*
❖ **Object:**	**Timber floor – Timber roof.**
➢ Geometrical information:	
▪ Detail:	Volume containing the overall thickness of the

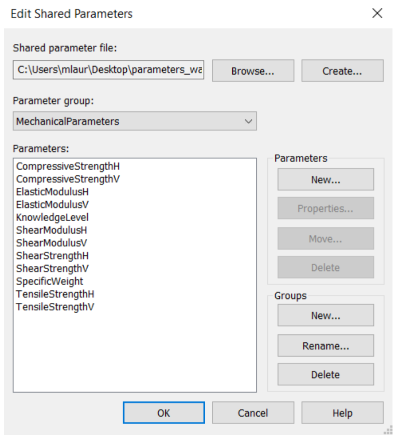
	structural part of the floor.
▪ Dimensionality:	3D
▪ Location:	Absolute
▪ Appearance:	-
▪ Alphanumerical information:	
➢ Identification	"Floor/Roof Structural information"
▪ Information content	Material behavior, structural behavior, loads (permanent and variable).
▪ Documentation	Information from the previous project milestones, Italian code.
➢ Set of document	Pictures and drawing from the visual grading, test results.

By comparing the Level Of Information needed at this stage, with the one related to the Historical Survey, it is clear how the model is growing in terms of geometry and information content. Also, the breakdown structure is different. Indeed, at this stage, it is required a division in objects that contemplate the different materials present and their structural role.

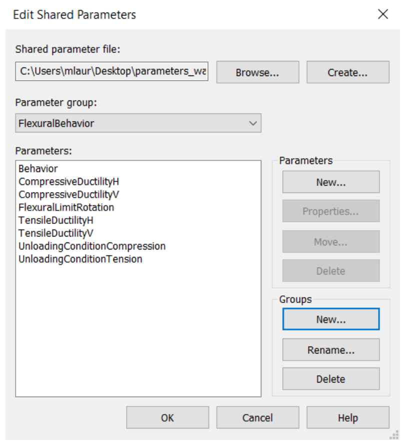
As far as the parameters of the PDT are concerned, these have been implemented in Revit, as "Shared Parameters", and already provided in the current work. The introduction of Shared Parameters is quite useful, indeed, they are saved in a file and they can be used by everyone, both in Revit family file and in Revit Project file and that can be associated with each Category.

It would certainly be more coherent to associate some of these, such as the ones relative to the mechanical properties of the materials, with the "Material Category". Nevertheless, it was preferred to associate all of them to the Category of the object described by the PDT, the walls, for instance. Indeed, inside Revit, it is still hard to manage the material properties, but also when a material is associated with a certain category, in the instance parameters of the objects, the parameters related to the material are not visible. Also, in Revit it was used the PascalCase nomenclature, even though Revit gives the possibility of saving the parameters with any possible name.

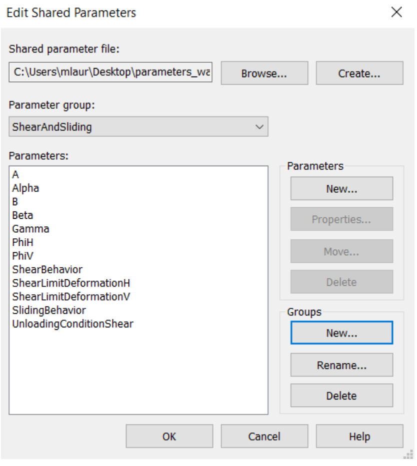
The shared parameters in Revit can be organized under "Groups" which are called with the same name of the groups of parameters of the PDT. As shown, the shared parameters are saved in a file that can be always upload to the model (Figure 66).



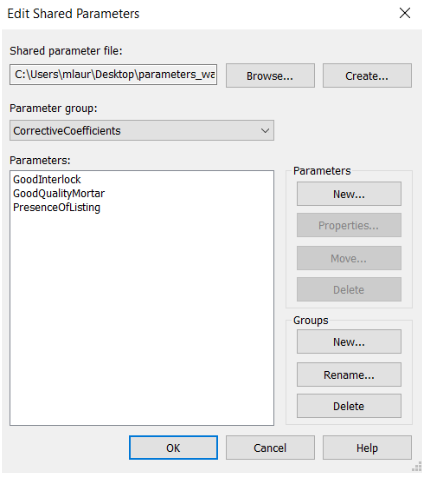
a



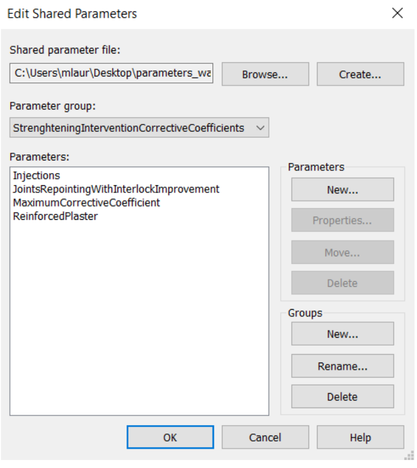
b



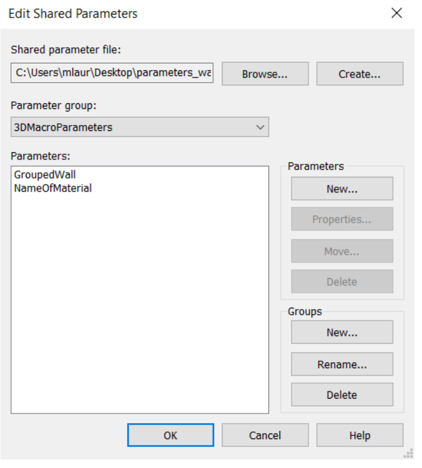
c



d



e



f

Figure 61 - Shared parameters in Revit

Once the shared parameters are introduced, these are associated with the object, as “Instance” parameters, thus they can be modified for each wall, as in Figure 62. Please notice that the units are the same as proposed by the NTC.

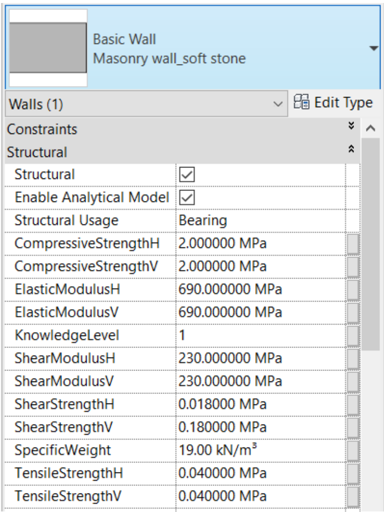


Figure 62 - Instance wall

An important contribution of the current work, aside from introducing the shared parameters file, was the development of a Dynamo script that allows to directly set the values of the parameters from the Product Data Template to the Revit Object. Despite this can seem not of primary importance, it makes faster the modeling procedure, it avoids mistakes, and makes the work less repetitive. In fact, in this way, the data are filled only by the structural engineer and not also by the BIM modeler. This will be described in detail in Chapter 6.

5.5 Structural analyses and safety assessment

The final purpose of the BIM model defined in the previous stage is the structural analyses that are done throughout the solver of 3DMacro. Precisely, the scope is performing nonlinear static analyses, which results are sent to the BIM model. The Dynamo code was implemented in Revit, but the possibility of saving in IFC format makes this procedure applicable to other software.

Currently, the procedure to run the analyses and obtaining the results is semi-automatic. The first and the second part of the code, aimed at exporting the coordinates of the geometry and at discretizing the structure, required the implementation of long algorithms. As the code was implemented, it was realized its length and complexity, meaning that the use of another coding language would be probably more appropriate. It is hard, using visual programming such as Dynamo, to manage such complex algorithms. Nevertheless, the problem was partially solved by concatenating all the codes within an importing/exporting of data internal in Dynamo. In this way, the user only has to run the codes, and the data will be saved all in the same file, with the correct order, and open the final txt file using 3dMacro.

The results obtained applying this methodology are the PushOver curve, which appears in the interface of 3dMacro once the code is run, and the damage state occurring at the piers at a certain Limit State. As the latter is obtained as a text file, a Dynamo code was implemented to show the results in the Revit model.

The workflow illustrated in (Figure 63) shows in detail the different passages required to exchange the information from a BIM model and 3dMacro. The workflow of the code generated will be explained in detail in Chapter 6, by showing a demonstration.

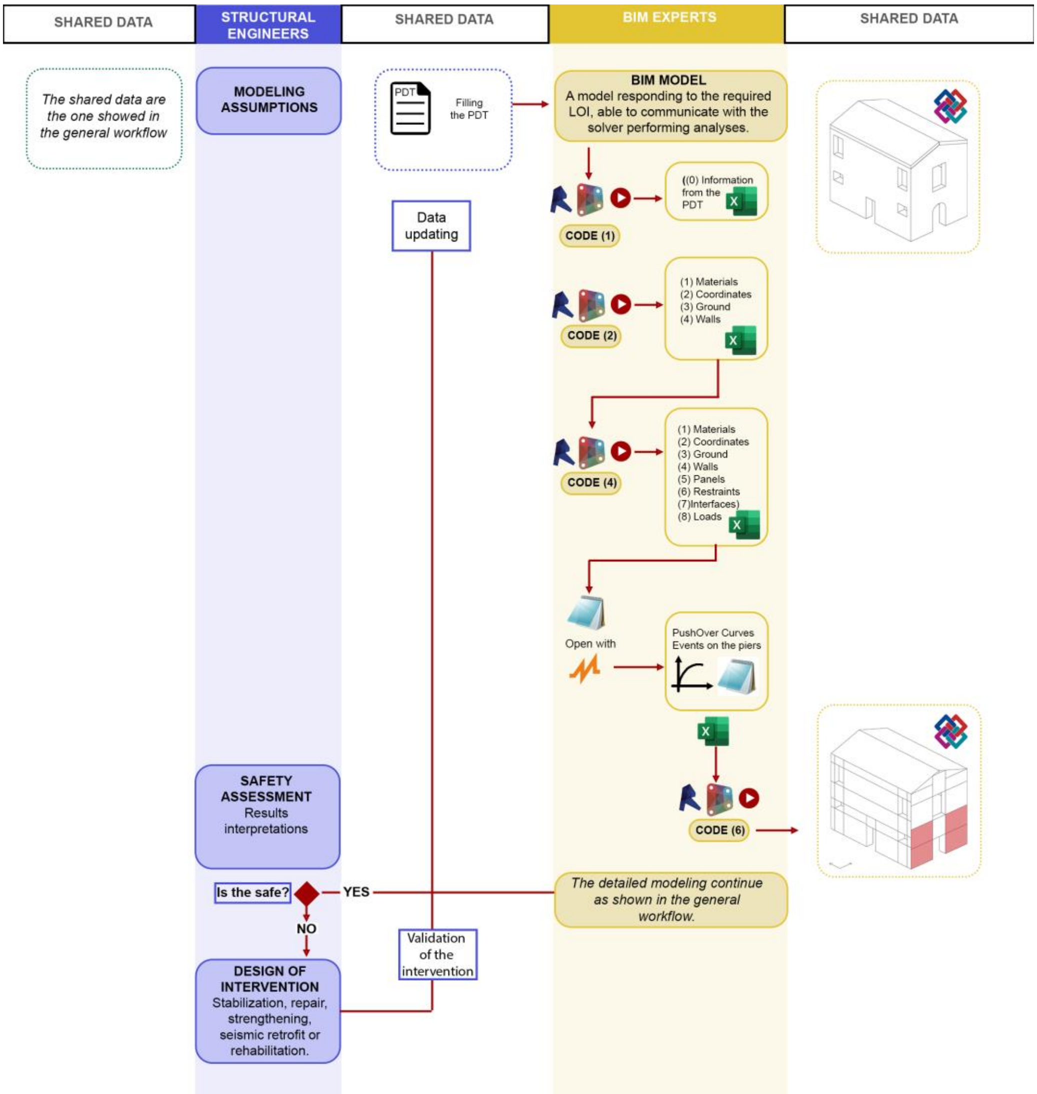


Figure 63 - Structural analysis

The results of the analyses (PushOver Curve and In-Plane events) are read from the structural engineer, which is the one that decides if the structure is safe or not safe, and which is the eventual intervention needed. Once that this is done, the previous model can be updated, by changing the mechanical parameters associated with it. The dynamo code can be run again, a new safety assessment can be done. The advantage of the methodology which is proposed is the fact that for example of being able of validating the project faster than usual, and then make a ponderation with other aspects such as the cost, or even the invasiveness of the different approach proposed.

5.6 Further development of the model

As mentioned, and also as shown in the workflow, once the structural intervention is defined and it is also validated, it is possible to consider other aspects of the rehabilitation project. It is at this point that the BIM modeler is asked to fulfill new requirements in terms of the Level Of Information Need. If the first step of the design of the structural intervention was defining what type of intervention is required, now it is time to quantify the project, and when required, integrating the structural intervention with nonstructural intervention. In the workflow, it is mentioned the possibility of understanding the cost of the intervention by really quantify the amount of material required to rehabilitate the structure. In this path, one of the points of strength of this workflow is the fact that by changing some parameters in the PDT, it is possible to easily consider various interventions and how they change the overall capacity of the structure. This means that different interventions may be proposed, validated, and compared, in terms of cost, but also in terms of compatibility with other features that characterize the structure.

Proposing a way of integrating easily the structural analysis of these constructions with the progressive development of more detailed model does not only improve the way the structural assessment and the structural intervention is done, but it can improve the overall assessment of these structures and is meant to be inserted inside a broader scope. This is why, for example, in the very end it is proposed the possibility of providing an energy-efficiency intervention. In particular, this aspect is mentioned because of the latest bonus that has been introduced in Italy, to combine the seismic retrofit with the energetic renovation of the buildings, which is mentioned in Chapter **Error! Reference source not found.**, and it is even more important when it comes to historical buildings of the city center.

6. INTEROPERABILITY BETWEEN BIM AND STRUCTURAL MODEL: CODE AND APPLICATION

This chapter shows the workflow created to allow the communication between Revit and 3DMacro, through an application done for the unit described in Chapter 3. As mentioned, to develop the link between the two programs, it was used Dynamo. Precisely, the approach was creating a 3DMacro file in a standard text file (data file), by exporting the data from Revit to Excel. To do that, several simplified models have been first created in 3DMacro (Figure 64) to understand the structure of the text file.

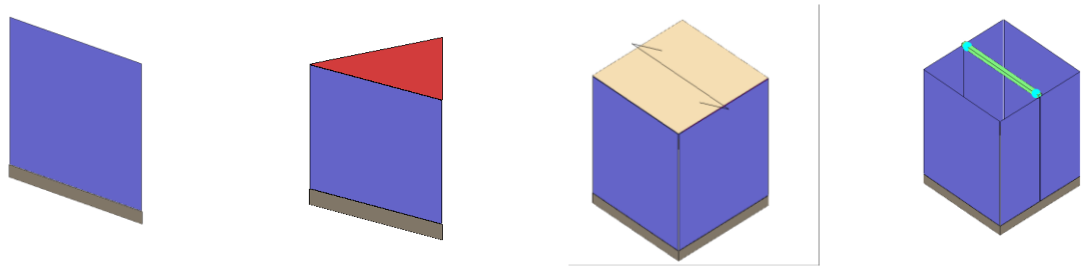


Figure 64 - First simplified models

6.1 Model on Revit

The unit model is the one presented in Chapter 3. The objects modeled were walls, floors, roofs, and openings. The geometrical information associated with them, according to the Level Of Information need for the structural analyses, in the one mentioned in Chapter 3. The wall objects are characterized by the parameters mentioned in Chapter 6, thus the data contained in the Product Data Template and associated with the Revit shared parameter file. The walls were modeled like volumes, according to the requirements of the Level Of information need. Despite simplifications have been done, it was decided to maintain some peculiar characteristics, such as misalignments on the windows, or the presence of windows almost at the floor level, to provide a code that is useful for each configuration. The orthogonal walls were considered with a perfect angle of 90º((Figure 65). As far as concerns the horizontal elements, it was assumed an orthotropic correspondent slab, to which associate the mechanical parameters. Also, there were introduced other parameters required by the software as the Span, the ID of the load-bearing walls, and the name of the floor (Figure 66).

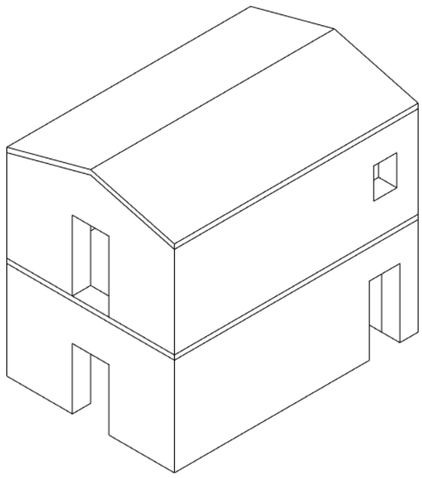


Figure 65 - Geometry of the model

Structural Analysis	
Span	5.0000 m
YoungModulusH	48000.000000 MPa
YoungModulusV	8000.000000 MPa
LoadBearingWall	2-3
OrthotropicSlabCorrespondentThickness	0.0500 m
OrtotropicSlabWeight	
NameOfTheFloor	

Figure 66 – Parameters of roofs and floors

The openings were simplified in their geometry, not considering their chamfered natured, using the built-in Revit families. At this stage, the only parameters required for the openings are the geometrical ones: height and width for the doors; height, width, and sill height for the windows (Figure 67).

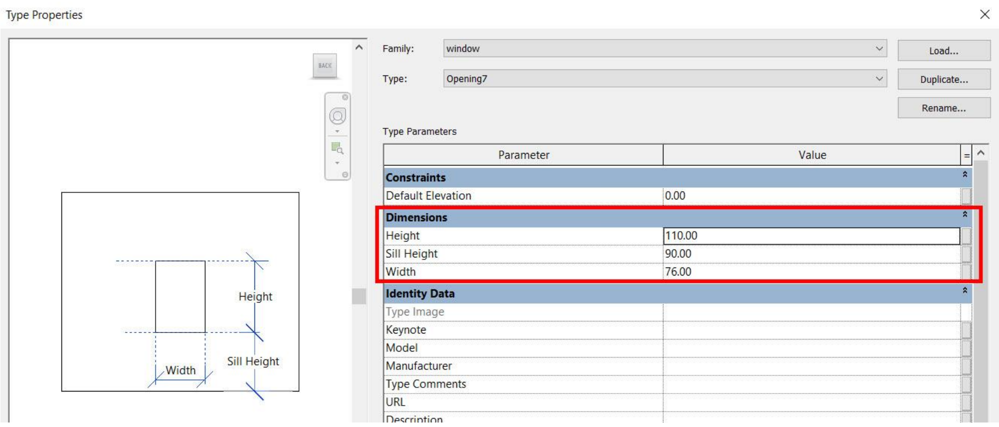


Figure 67 - Parameters of the windows

6.2 Structure of the file

Every string of the text is structured as in Figure 68. Moreover, the entire file is structured in 9 groups, as shown in Table 8. The units used are kN and cm.

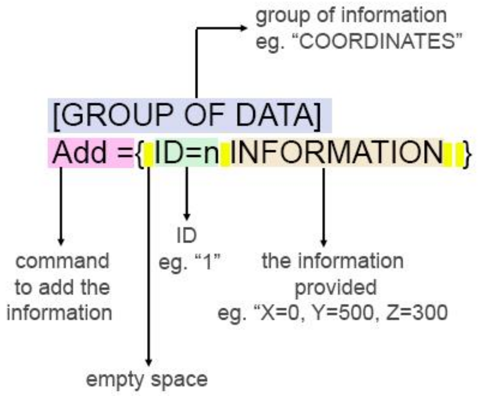


Figure 68 - Syntax required

Table 8 – Group of information

Name of the group	Information contained
Model	General information. The name of the model, the type of behavior (in-plane or 3d), the type of structure (masonry or mixed). Information related to the solver (version used).
Materials	The constitutive laws of the materials.
Coordinates	The coordinates of each point of the model (the four vertexes of the macro-elements), referring to the global coordinate system.
Ground	The type of foundation used.
Walls	The direction of each wall according to its internal coordinate system.
Panels	The information associated with each element. For the masonry macro-elements, it is indicated the ID of the vertex (recalling the ID of the coordinates previously implemented), the thickness of the wall, and the constitutive law related to the associated nonlinear springs. For the rigid elements, it is indicated the number of vertexes, their ID, and the constitutive law related to bending and sliding. For the floors and the diaphragms, it is indicated the number of the vertexes, their ID, the corner vertexes, the type of the cross-section, the thickness of the equivalent orthotropic slab, the material, the degree of freedom, the barycenter, and the total area.
Restraints	The boundary condition of the model, indicated for base vertexes, showing

	the six degrees of freedom.
Interfaces	Type of the interface used.
Loads	The first load type is the vertical load. For each load element, it is indicated the panel that is loaded, how it is distributed (for each panel in the vertexes 3 and 4), and the direction. Then it is indicated the redirection of the load in the horizontal direction of the load.

6.3 Code workflow

The following section will show, using the modeled example, how was implemented the code. Please consider the following legend to read the flowchart.

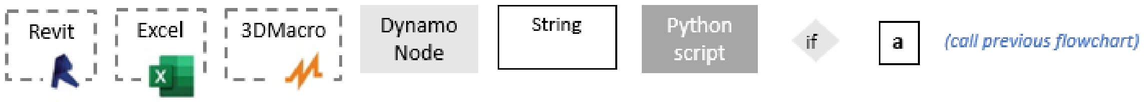


Figure 69 Flowchart legend

6.3.1 Materials

The first algorithm implemented helps the user to provide the material information to the walls. This is done by importing the excel file of the PDT in Dynamo and using the node "Set Parameter Value by Name". For each wall, it is associated the parameter of the product Data Template with the Parameter in Revit. This is a semi-automatic procedure since the user has to select each wall and upload each PDT, but it is helpful to save time, and above all, to avoid mistakes. Indeed, each wall is defined by several parameters.

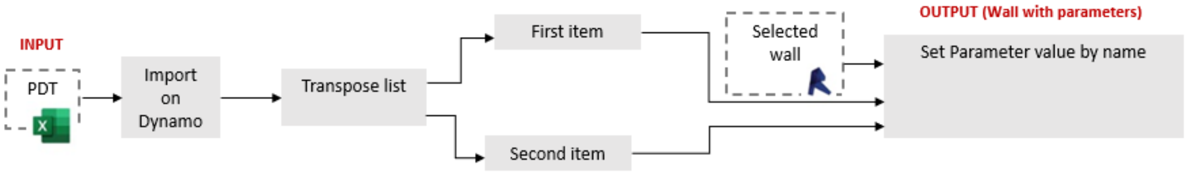


Figure 70 - Provide parameters to the wall (Flowchart 1)

The second algorithm implemented was aimed at extrapolating the material information. As far as the masonry is concerned, three different constitutive laws were defined, respectively related to the flexural behavior, sliding behavior, and diagonal cracking.

In Figure 71 and Table 9 show the correspondence between the parameters in Revit and the information required by 3DMacro. Please notice that for each constitutive law there is also the necessity of insert the “Generation” parameter, this is just to give the output of generating the material.

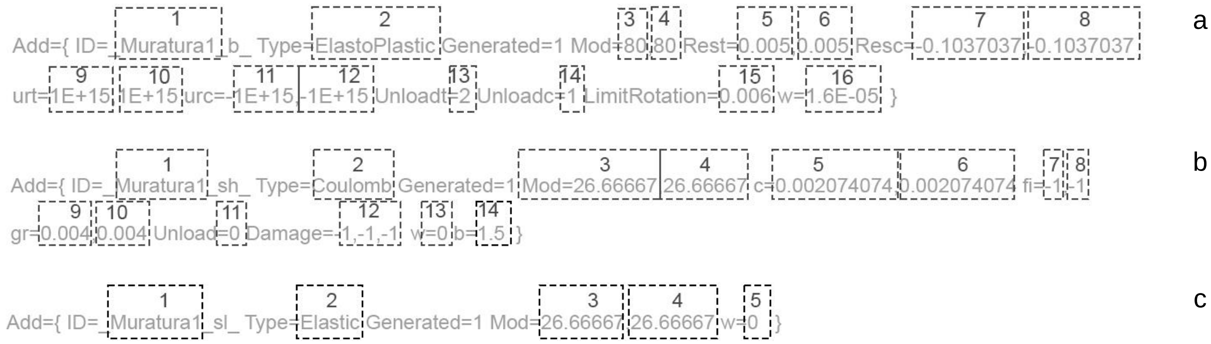


Figure 71 - Strings for the three constitutive laws of masonry; a)Bending; b)Shear with diagonal cracking; c)Shear with sliding

Table 9 - Correspondence between parameters

Name in the Figure	**PDT/Revit**
	Bending
1	NameOfMaterial
2	FlexuralBehavior
3	YoungModulusH
4	YoungModulusV
5	TensileStrenghtH
6	TensileStrenghtV
7	CompressiveStrenghtH
8	CompressiveStrenghtV
9	TensileDuctilityH
10	TensileDuctilityV
11	CompressiveDuctilityH

12	CompressiveDuctilityV
13	UloadingConditionCompression
14	UnloadingConditionTension
15	LimitRotation
16	Density
Shear (with diagonal crack)	
1	NameOfMaterial
2	ShearBehavior
3	ShearModulusH
4	ShearModulusV
5	ShearStrenghtH
6	ShearStrenghtV
7	PhiV
8	PhiH
9	ShearLimitDeformationH
10	ShearLimitDeformationV
11	A, Alpha, Gamma
12	Beta
13	B
Shear (sliding)	
1	NameOfMaterial
2	Behavior
3	ShearModulusH
4	ShearModulusV
5	Beta

To define the algorithm, all elements of the category *Walls* were first selected and for each parameter necessary to define the constitutive law, it was got the value and converted to the unit required. This is a very long algorithm since all the parameters are called using the node “Get Parameter value by the name". When necessary, the mechanical parameter is divided for the confidence factor. By adding this functionality, it is given the user the possibility of easily improving the level of knowledge. Another important aspect is related to the unit used. Indeed, it is introduced a function that converts the unit into the ones required by the solver.

This passage is necessary to allow managing the data using canonic units (eg. MPa) and not the ones related to the solver. Also, for each masonry element, it was got the value of *KnowledgeLevel*. Indeed, some of the parameters must be divided for it. **Error! Reference source not found.** refers to the algorithm used to define the mechanical properties. As visible, in the majority of the cases, the name of the parameter required by the solver of 3DMacro is not the same as the one inserted in the PDT, but the code does the transformation. For example, the Young modulus is called "YoungModulus" in the PDT, but to be read by the solver must be called "Mod".

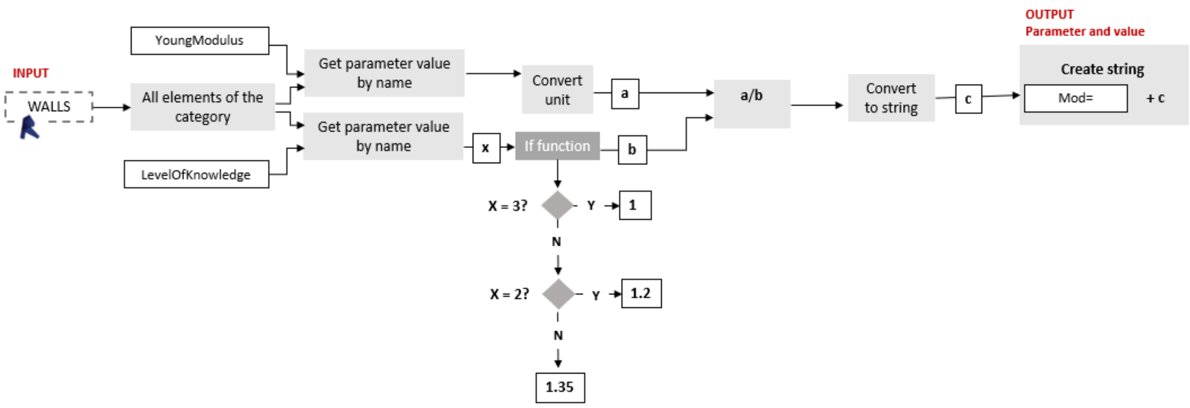


Figure 72 - Mechanical parameters (e.g. Young Modulus) (Flowchart 2)

Regarding the other parameters, it was done the same thing, without adding the division of the confidence factor, and without the requirement of converting units, in case of coefficients, or for the name of the material. An exception is in the definition of the unloading conditions, explained in Chapter 4. Indeed, it was necessary an algorithm that when the unload condition is assumed with stiffness equal to the initial one, insert the value "2", when the unload condition is oriented in the origin, it is associated with the value "1" and when it is defined by the damage function, it is associated to the value "0" Figure 73.

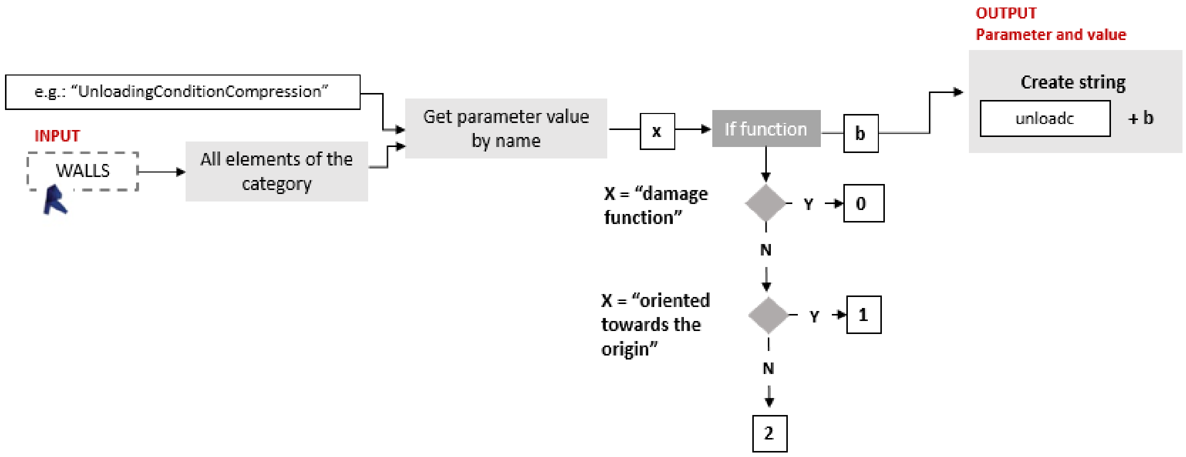


Figure 73 - Unload conditions (Flowchart 3)

In what concerns the timber elements, the constitutive law defined was linear elastic and the only required parameters are the density and the elastic modulus. In this application, it was not prepared a Product Data Template for the timber elements, but the parameters were directly implemented in Revit as shared parameters.

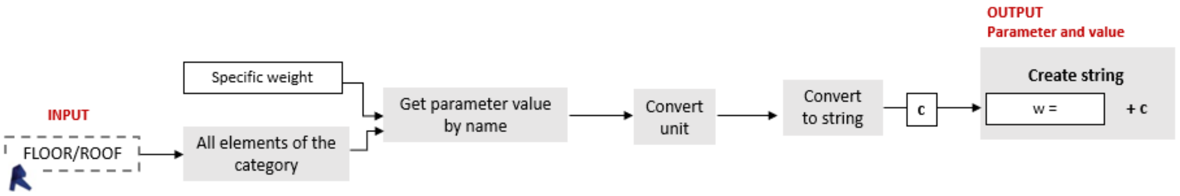


Figure 74 - Timber material, example (Flowchart 4)

Once that all the data are gathered in Dynamo, for each material constitutive law it is created a string coherent with the syntax shown in Figure 63. This is done by associating together all the strings containing the parameter name and their value.

Once that all the parameters are associated with the correct nomenclature, the final string for each constitutive law is created by linking the parameters in a unique string, maintaining the syntax shown in Figure 68.

6.3.2 Coordinates

The second group of information extrapolated is the coordinates of the vertexes of the elements. Each point must be defined by three coordinates in the space and identified with an ID.

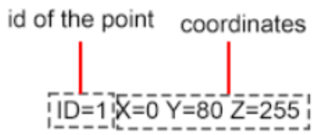


Figure 75 - Coordinates of the points

This passage required a lot of effort in the code since it was necessary to pass from the simple model to a model with mesh discretization. From this moment onwards, please consider two different types of coordinates. shown in Figure 76.

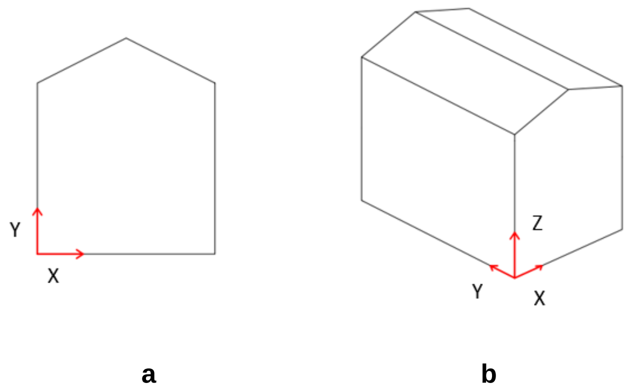
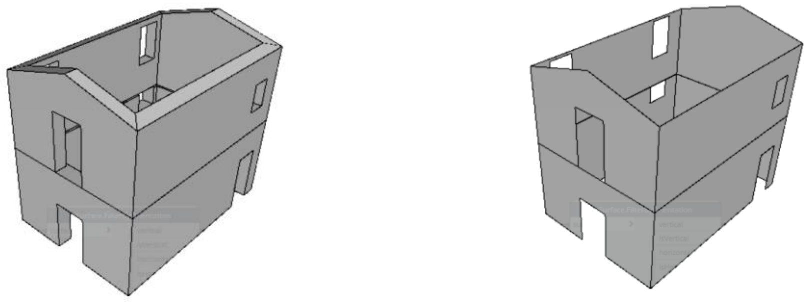


Figure 76 – Coordinates of Dynamo environment; a) Global coordinates; b) Local coordinates

The first algorithm created is aimed at extrapolating the wall footprint. To do that, the first attempt was done using the node “Element.GetLocation”. Nevertheless, this approach was subsequently discarded since it provides the location of the wall centerline whereas to extrapolate the geometry of a masonry aggregate, it is more appropriate to consider the outer edge of the wall. This is because this type of structure is often characterized by the presence of walls of different thicknesses, in the height, and in that case, a misalignment between the walls would be created. To avoid this problem, the best solution was to extrapolate in Dynamo the solid geometry of the wall and filtering the external surface. This was done by using a customized node aimed at obtaining the direction of the external surface of a wall, and from it filtering the surface of the solid previously extrapolated. At this point, the implemented code creates a BoundingBox, which is a virtual cuboid surrounding a certain geometry. The base curve of this cuboid provides the coordinates of the wall footprint.



a b

Figure 77 – From dynamo interface: a)Solid geometry of the wall; b) External surfaces of the wall

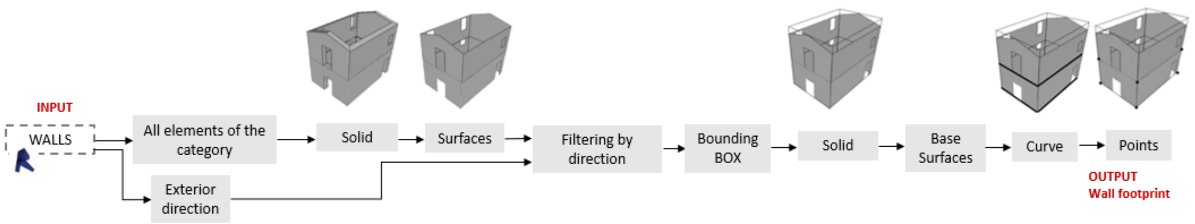


Figure 78 - Wall footprint (Flowchart 5)

The next step was allowing to get the coordinates of the roof. Dynamo does not provide a way of taking directly the position of the roof. The approach followed was similar to the one regarding the roof. Then the algorithm extrapolated the solid geometry of the floors, filter the top surfaces, extrapolates the perimeter curves, and finally the nodes (Figure 79). Nevertheless, these points are not enough to define the triangular panels of the top part of the wall: other two points, with the same coordinates of the ridge, but at the height of the perimeter are needed. To provide them, it was defined a Bounding.Box surrounding the solid of the roof, this was converted into a Cuboid, then into Surfaces, and finally the bottom surface was used to define a plane, in which the ridge points were pulled out.

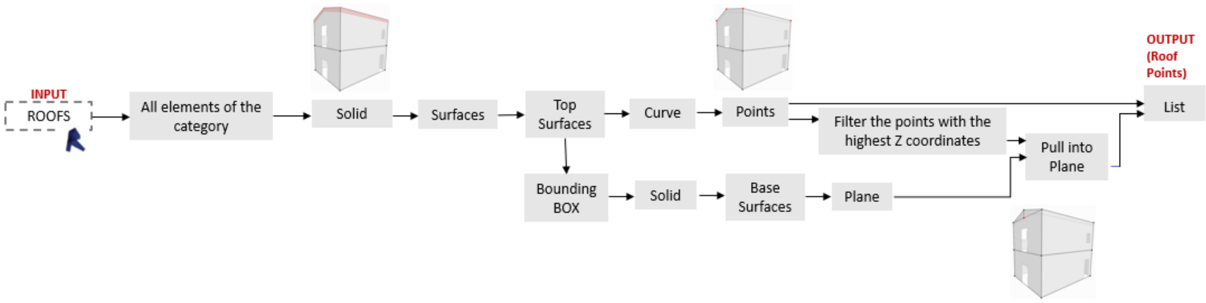


Figure 79 - Roof points (Flowchart 5)

Subsequently, was defined the algorithm to provide the mesh. As mentioned in Chapter 4 in the macro-element approach the definition of the mesh derives from the position of the openings. Therefore, it was implemented a code that, given the coordinates of an opening, it creates the coordinates of the panel above, below, and next to the opening itself.

To do that properly, the approach followed was to create an algorithm that communicates with the openings in Revit, and their hosting families, which are the walls (Figure 80).

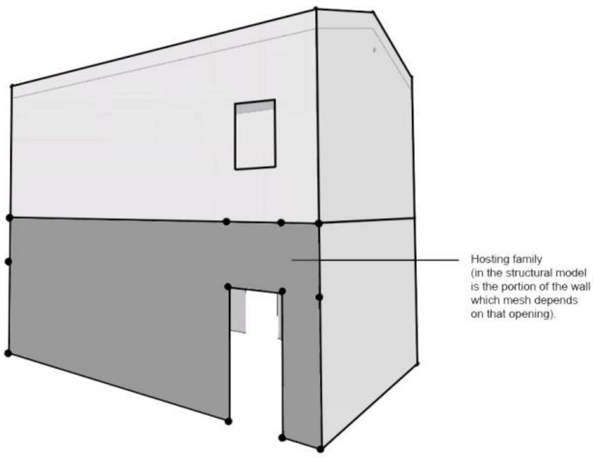


Figure 80 - Dependences of the mesh from the openings

Concerning the doors, the procedure simple. The first step was selecting all the elements of the family type, then obtaining the host family (the wall) and its geometry. From the solid, it was derived the external surface, its perimeter curve, and finally the points. These points were filtered using a boolean filter to only select the points lying at the base of the wall. Then, they were vertically translated of a distance equal to the height of the door and also translated of a distance equal to the height of the hosting wall. As clarified, to create the mesh properly, it was required to input some of the parameters related to the opening object and the hosted family. This necessity is the reason why it was implemented a code specifically considering these objects.

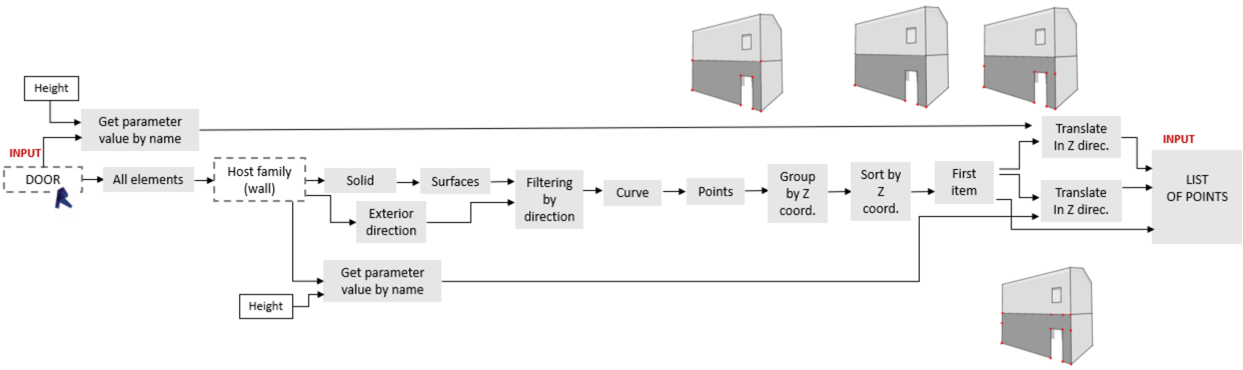


Figure 81 - Door coordinates and panels in proximity (Flowchart 6)

Also for the windows, it was reasonable to define a code directly related to the family type. In this case, the procedure was a bit more complex, since in the case of the window there is also the definition of a panel below. The first passage of the procedure was individuating the location point of the window.

Using the node "get location", Dynamo provides the middle point at the base of the window, aligned with the centerline of the hosting wall. From the location point, it was possible to define the four corners of the openings. This was done using the parameters of the opening family "height", "width" and "sill height". From the location point, a node subtracts to the local X coordinates half of the width of the window, another node adds half of the width of the window. This is done inside a for cycle, to be done for all the windows existing, to introduce the base corner of the window. To have the top corners it was only necessary to translate the base corners along the Z direction, of a value equal to the height of the window (Figure 82).

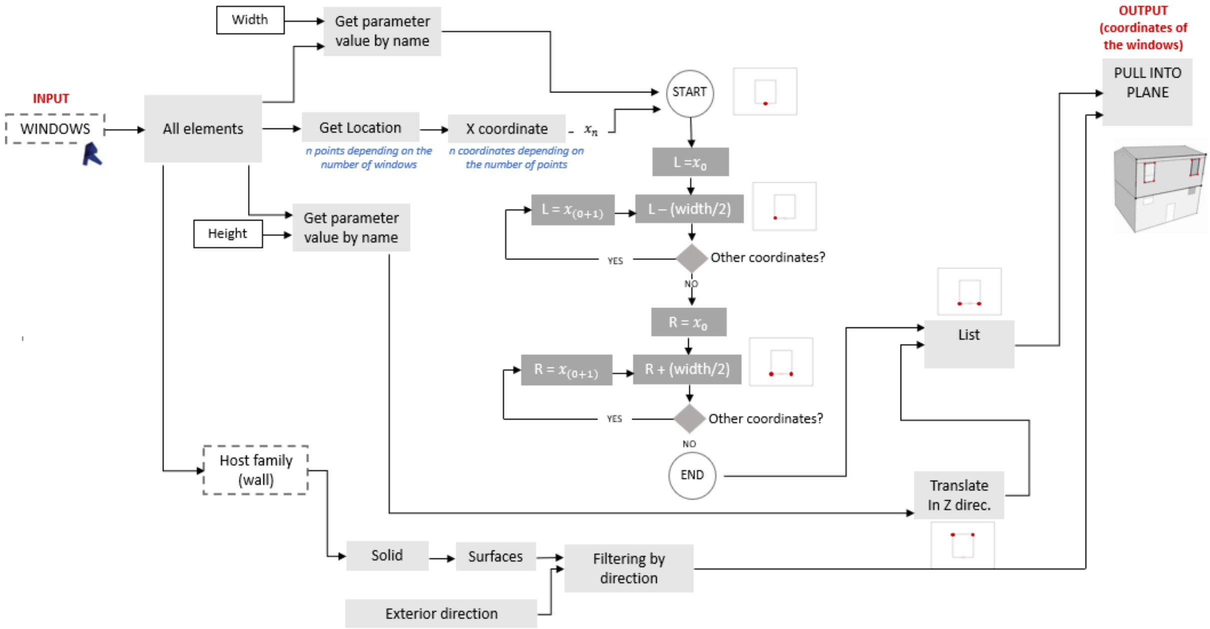


Figure 82 – Openings (Flowchart 7)

At this point, it was necessary to define the coordinates of the panels above and below the window. This was done translating the top corners of the window along the Z direction, of a distance equal to the height of the host element minus the height of the window, minus the sill height (to find the macro-element above). Finally, the latter was translated again along the Z direction, with a distance equal to the negative height of the wall, to have the one below. Please notice that since the location of the window was given at the hosting wall centerline, the final points were pulled into the plane adjacent to the surface of the hosting wall (Figure 83).

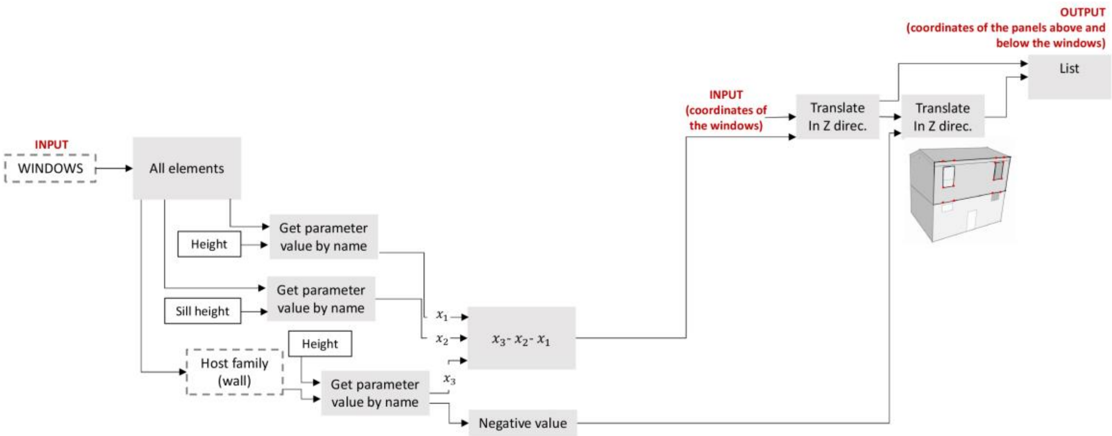


Figure 83 - Coordinates of the windows, and panels above and below (Flowchart 8)

Finally, it was required to find the macro-element within the openings. To do that, it was considered the hosting wall solid, then the surface, the curve, and finally the base points. These were translated along the Z direction of a distance equal to the sill height of the window. The latter points were finally translated of a distance equal to the height of the window (Figure 84). The entire sequence of the window procedure is shown in Figure 85.

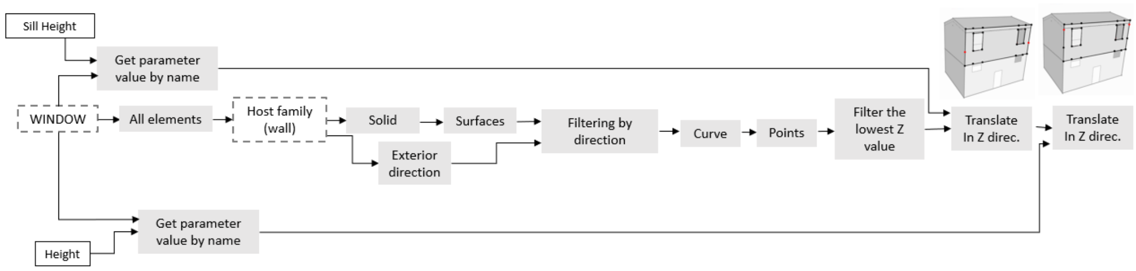


Figure 84 - Coordinates of the panels within the openings (Flowchart 8)

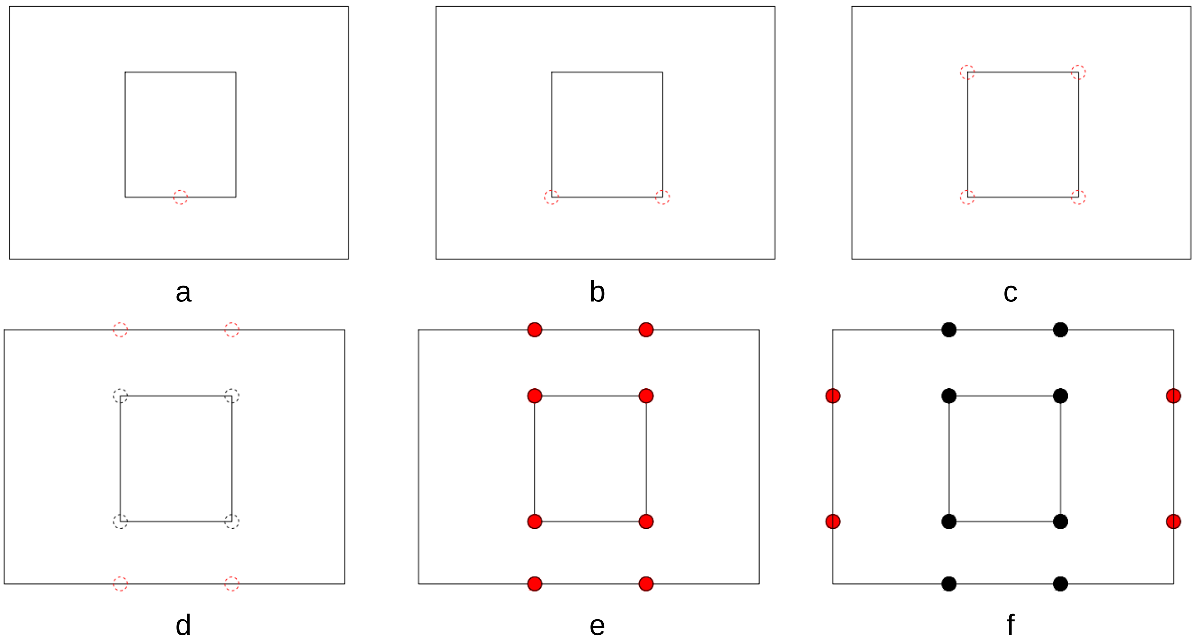


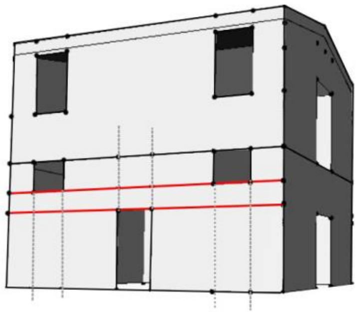
Figure 85 - Sequence of the definition of the window vertexes and dependent panels; a) Location point of the window; b) Base vertexes; c) Top vertexes; d) Vertexes of the panels above and below; e)Pulling into the plane the points; f)Vertexes of cross panels and

As known, in the same wall, there are often openings of a different type, a possibility that the algorithm afore defined does not consider. To solve this issue, it was implemented another passage in the code, aimed at providing the intersection between verticals coming from different openings (Figure 86 a).

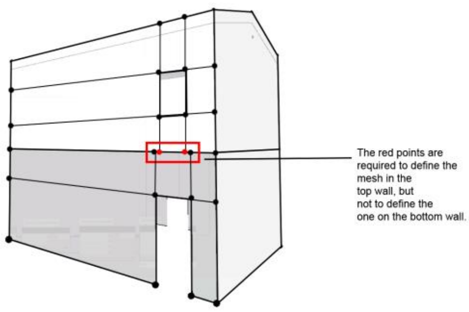
To do that, all the points extrapolated have been gathered according to the wall of belonging. Then, from the list corresponding to the wall, it was defined a sub-list containing all the points having Z-coordinate equal to the level elevation and it was drawn a line passing by them (Figure 86 b). The line was translated along the Z-axe, to intersect the points corresponding to the windows (sill height and height) and the door (height) (Figure 86).

Figure 86 - Intermediate panels; a)Intersection between openings; b) Base line; c) Translated lines

These lines need to be intersected with vertical lines to define the panels' vertex as shown in (Figure 87 b). To create these lines, it was first required to exclude from the list of the wall all the points that are on the edge. This is to avoid taking the point that should not interfere with the definition of the mesh of the specific wall (Figure 87 b).



a



b

Figure 87 - a) Panel to be created; b) Points to be excluded

To exclude these points it was only necessary to sort and group the points depending on the Z coordinates, and then exclude the first and the last item. At this point, it was possible to create the vertical lines and take the intersection point with the horizontal ones previously traced, as shown in Figure 88 and Figure 89.

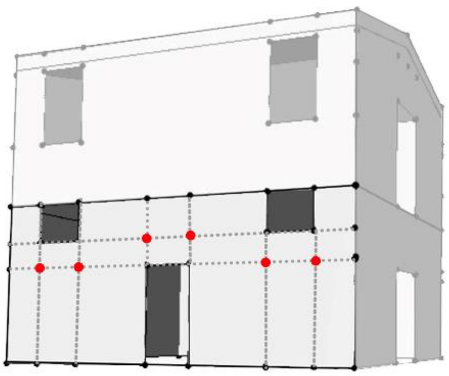


Figure 88 - Final points of the panels

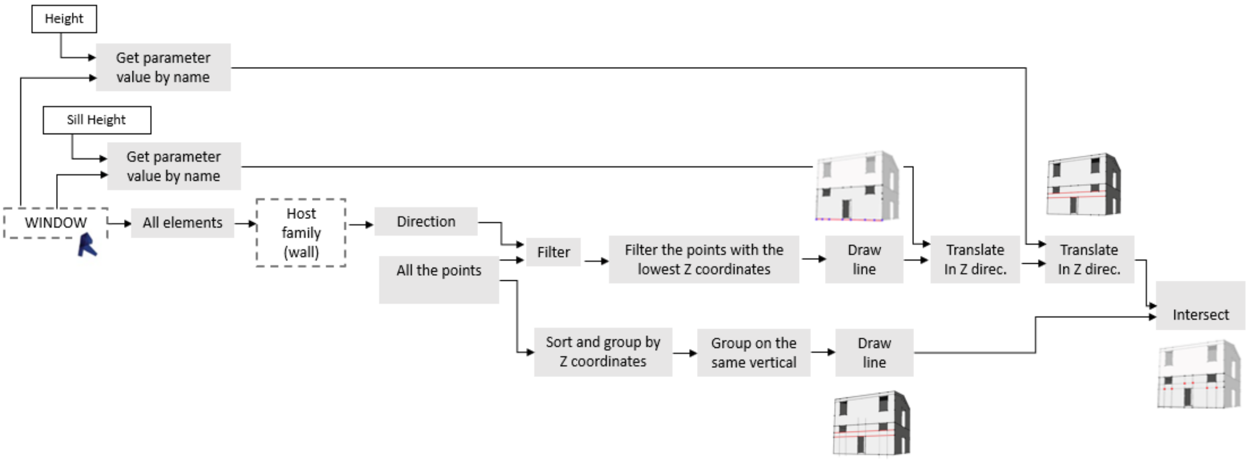


Figure 89 - Point intersection (Flowchart 9)

For each point is was required to add an ID, that will be recalled for doing the panels.

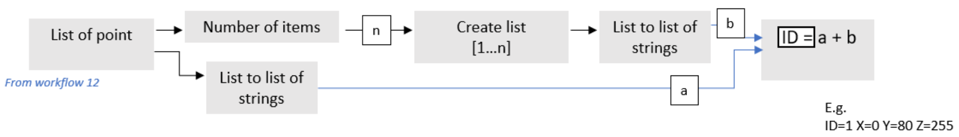
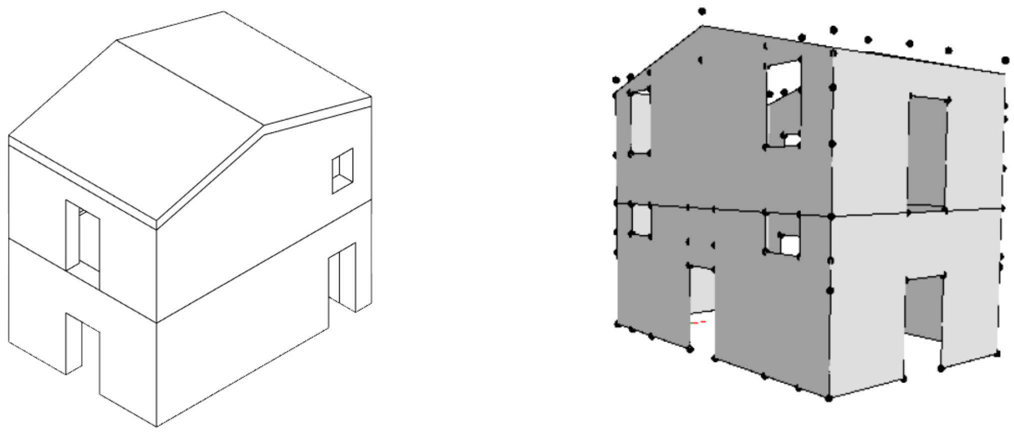


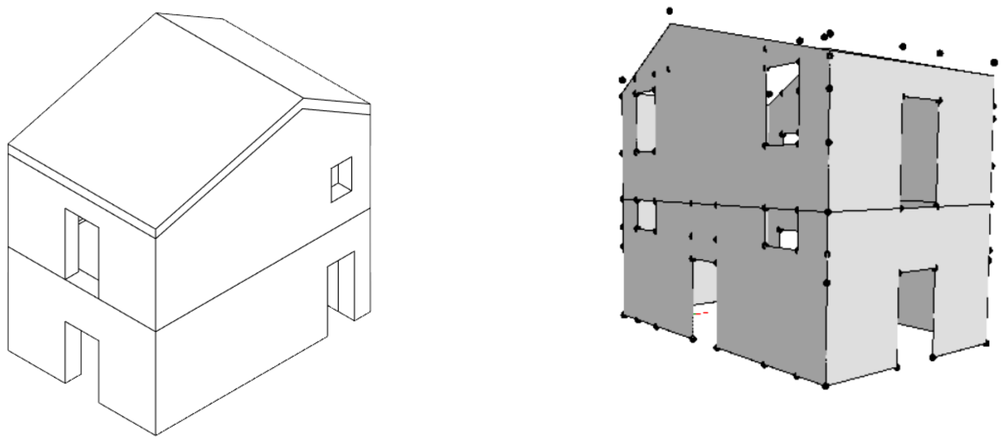
Figure 90 - List of points

Having defined this algorithm, it was possible to export the coordinates of the point in Excel. Before this, the algorithm was validated for different unit roof configurations, and for a little aggregate, as shown in Figure 91, Figure 92, Figure 93, and Figure 94.



a b

Figure 91 - Slopes of the roof in the other direction a) Revit, b) Dynamo



a b

Figure 92 - Irregular slopes a) Revit, b) Dynamo

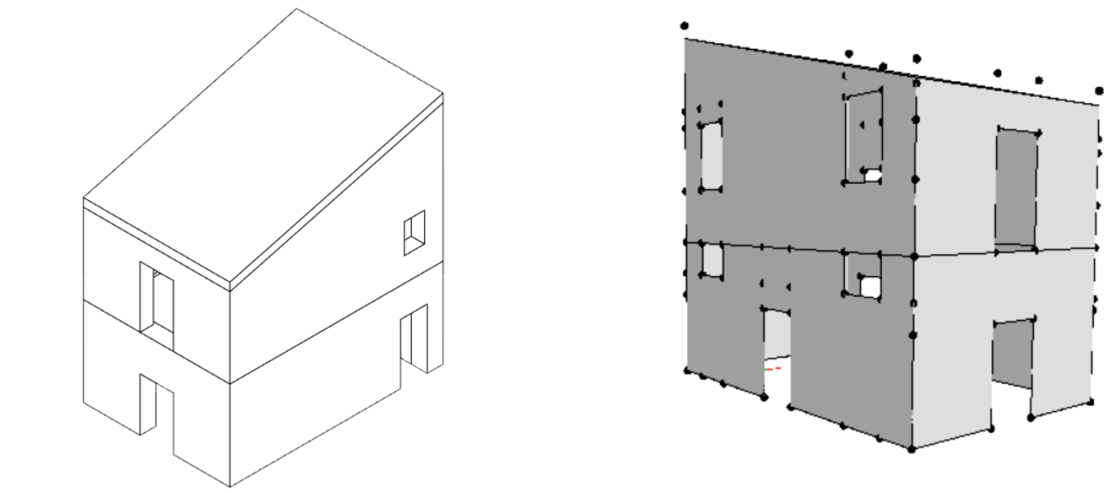
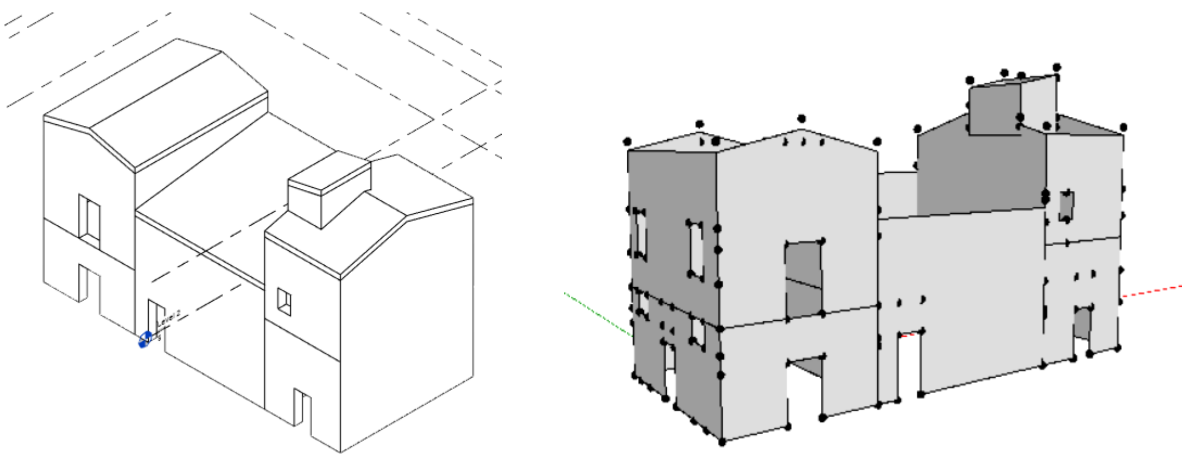


Figure 93 - Only one slope a) Revit, b) Dynamo



a b

Figure 94 - Little compound a) Revit, b) Dynamo

6.3.3 Boundary conditions

At this point, it was required to introduce the type of foundation. This aspect was not deepened in detail, but for the application, it was only introduced a string at the end of the coordinates with the following information as shown in Figure 95.

```
[GROUNDS]
Add={ ID=FondazioneLinea1 Type=0 E=0.05 }
```

Figure 95 - String for the ground

6.3.4 Walls

Proceeding with the code implementation it was necessary to associate with each wall of the model an ID and the vector of their local coordinates, as shown in Figure 96.

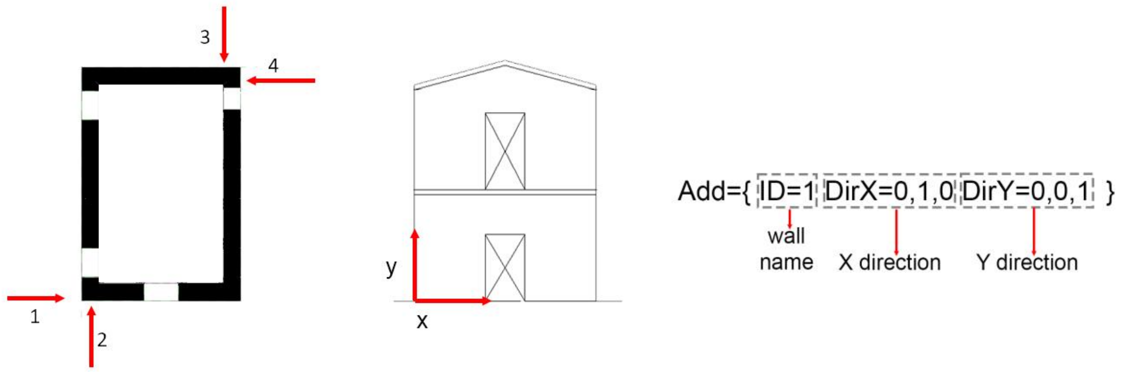


Figure 96 - Walls and ID local coordinates

To name the wall, it recalled the parameter “NameOfWall”. To define the wall according to the local coordinates, it was used a Dynamo node that provides the direction cosines of the wall plane (Figure 97).

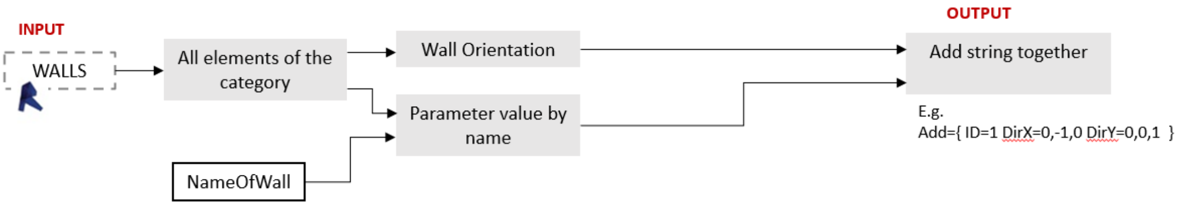


Figure 97 - Direction of the walls (Flowchart 10)

6.3.5 Panels

The following passage was to group the previously extrapolated points to define the element. Different procedures are implemented for the different types of panels: quadrangular panels, rigid panels, rigid diaphragms, and deformable diaphragms. At this point, unfortunately, it was required to break the code, because it was already very heavy, thus it is required an export-import through Excel (Figure 98).

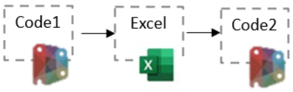


Figure 98 - Export/Import

The information required for the quadrangular panels is shown in Figure 99.

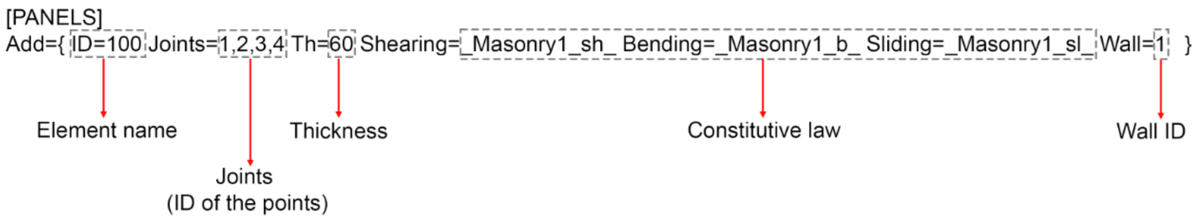


Figure 99 – Information required to define the quadrangular panels

As shown, the panel vertexes are defined as recalling the points of the model through their ID. For this reason, it was decided to define a “Dictionary” internal to Dynamo, to directly associate the points with their ID. This was done by converting the coordinates of the point as a string and defining them as “key” of the dictionary, whereas their ID was used as “value” (Figure 100). The second step was ordering the points of the panels in a clockwise manner (Figure 101). To do that, the points were first of all group per wall. Then, for each wall, they were grouped according to the x and y local coordinates, and finally, it was used a while cycle to group them according to Figure 101 b. The algorithm is in Figure 102.

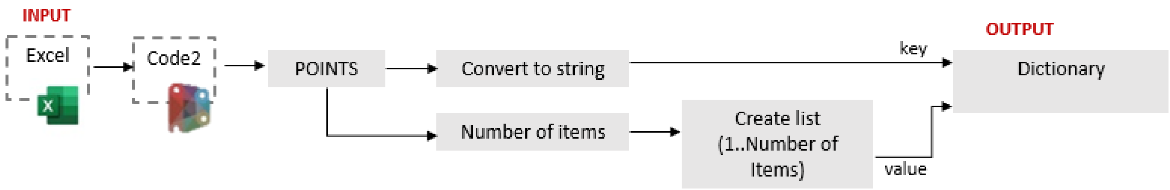


Figure 100 - Definition of a dictionary to call the ID (Flowchart 11)

Figure 101 – a) Panels in a wall; b) Order of the vertex in the panel.

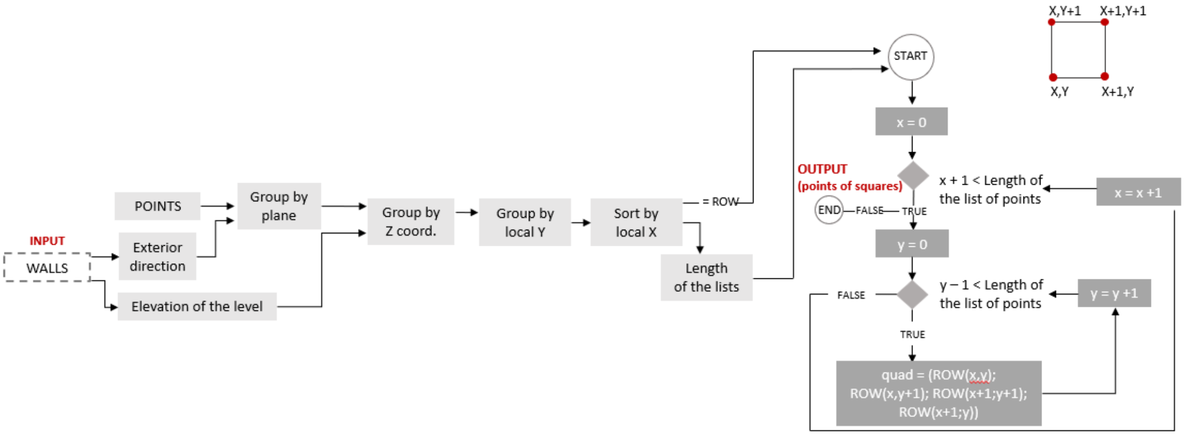


Figure 102 - Points of the squares (Flowchart 12)

The while cycle shown in the **Error! Reference source not found.** provides a list of list with all the squares vertexes. From this list it is needed to exclude the openings. This was done by recalling the opening's coordinates (Output of Figure 81 and Figure 82).

At this point it was required to recall the dictionary, to have the ID of the points. This was recalled both for the openings and for the panels in order to subtract the list of the ID of the opening to the one of the ID of the panels (Figure 103).

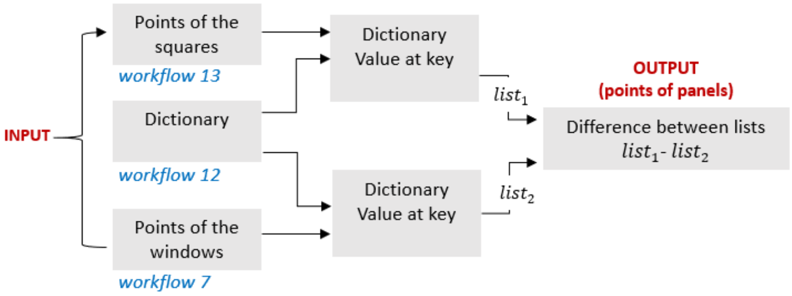


Figure 103 - Points of the panels ((Flowchart 13)

Finally, the required strign was created as shown in Figure 104.

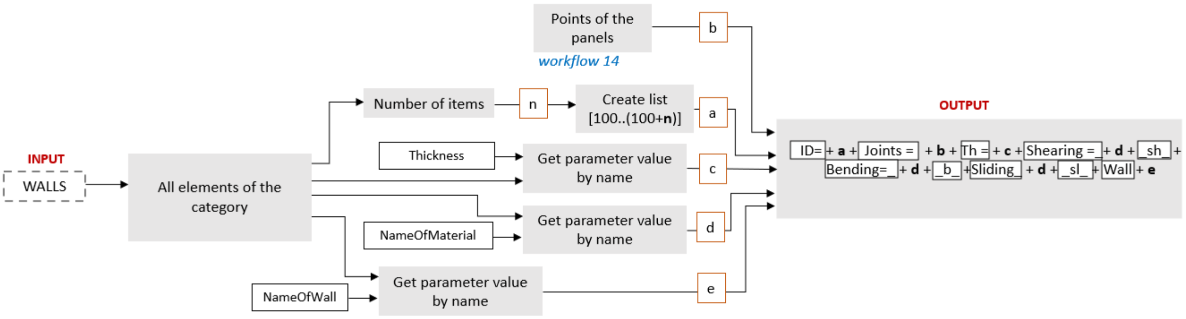


Figure 104 - String of the panel (Flowchart 14)

Afterward, it was defined the algorithm for the triangular panels of the roof, according to the requirements of Figure 105. As shown, in this case, it is required to indicate the number of joints. Moreover, the panel is rigid to shear.

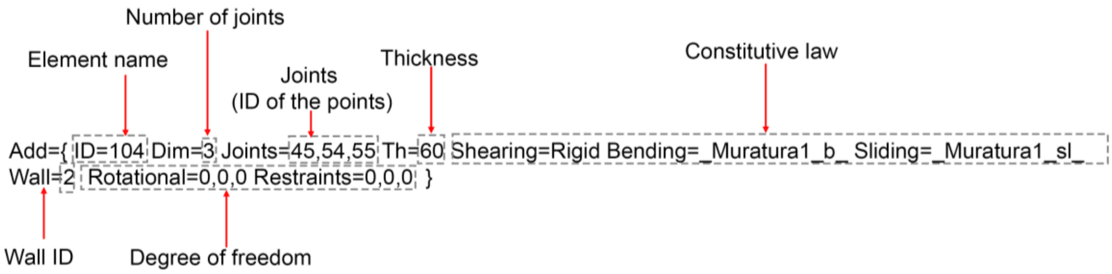


Figure 105 - Information required to define the rigid panels

In this case, the algorithm groups the points according to their local X coordinates. Then, it combines group 1 with group 2, and group 2 was combined with group 3 (Figure 106). This algorithm works properly for the most common roof configurations shown in **Error! Reference source not found.**.

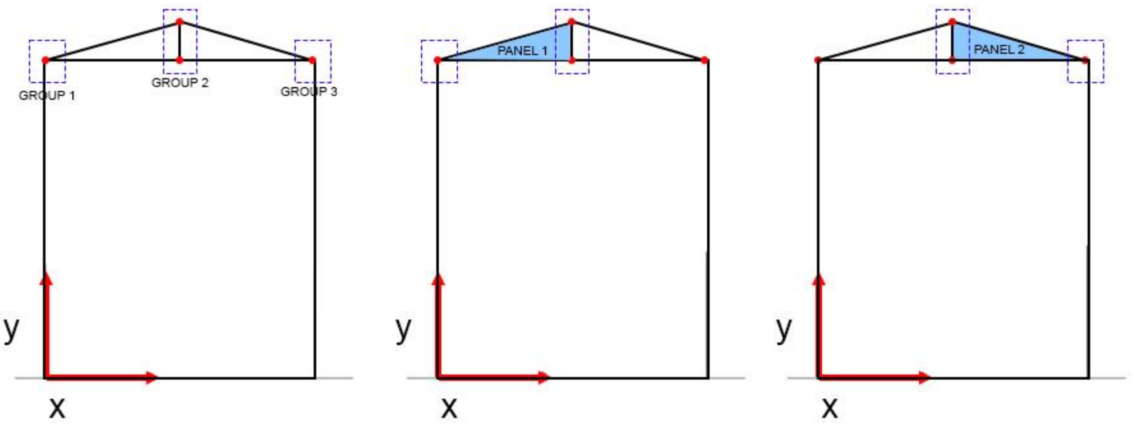


Figure 106 - Rigid panels of the roof

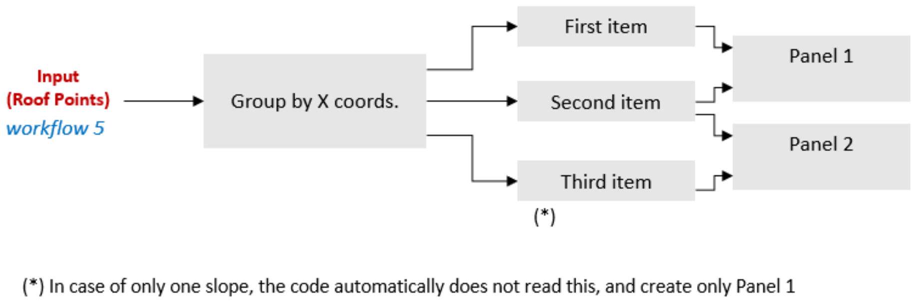


Figure 107 - Triangular rigid panels (Flowchart 15)

Finally, algorithm gathers the information together (Figure 108).

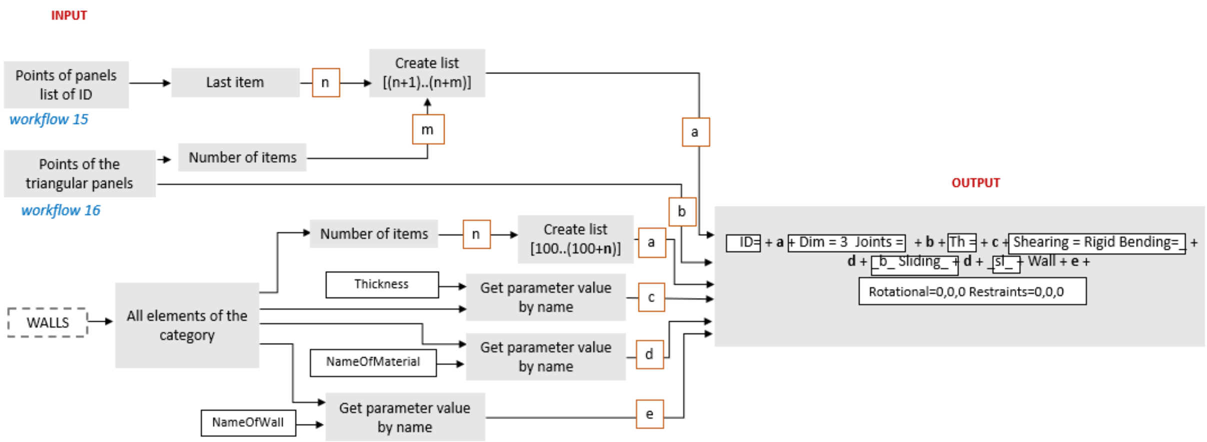


Figure 108 - String of triangular rigid panel (Flowchart 16)

The following step was to implement an algorithm to export the information regarding the diaphragm. This are the name, the number of points located at the level floor (organized in a counterclockwise manner), the corner point, the name of the floor type, the behavior, the type of horizontal element (floor or diaphragms), the area, and the barycenter (Figure 109).

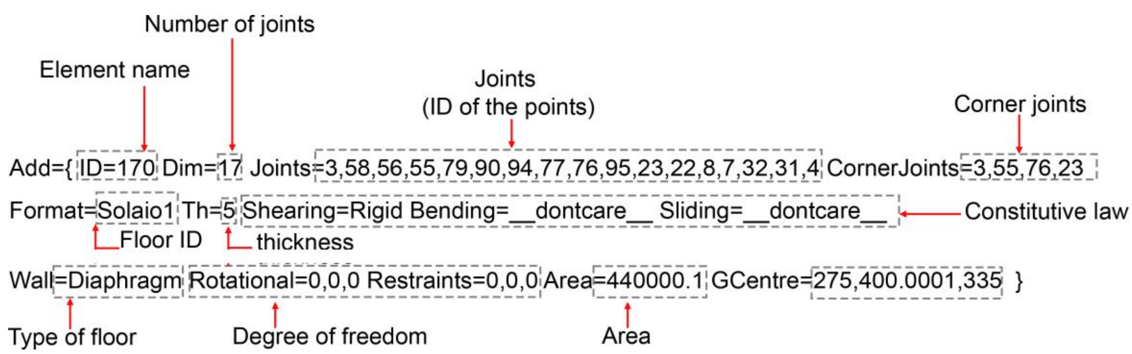


Figure 109 - Diaphrams

The first step was filtering all the points of the elevation, and organize them as required. To do that, the point has been grouped according to the wall of belonging and sorted according to their local X coordinates. Subsequently, the order of the points in the first two lists was inverted to have the counterclockwise order. This algorithm works for every type of four-sided floor and considering the typical configuration of the units of the study case, it is considered suitable (Figure 110 and Figure 111).

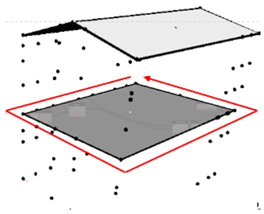


Figure 110 - Points of the floor

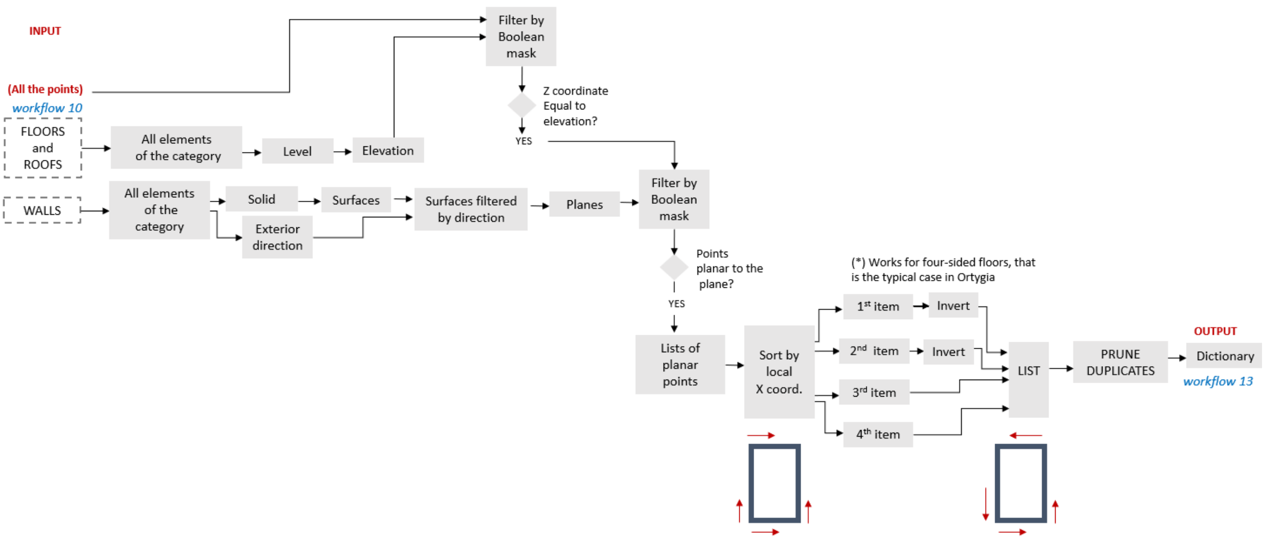


Figure 111 - Vertexes of the floor and the roof (Flowchart 17)

Subsequently, the algorithm defines the corner points, by selecting the points from the footprint, (Figure 78) and filtering the ones at the level of the floor.

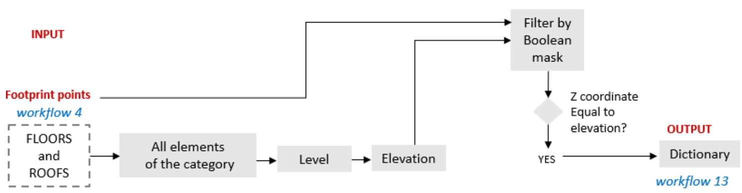


Figure 112 - Corner points (Flowchart 18)

Finally, it adds the area and the barycenter of the floors and gathers the information together.

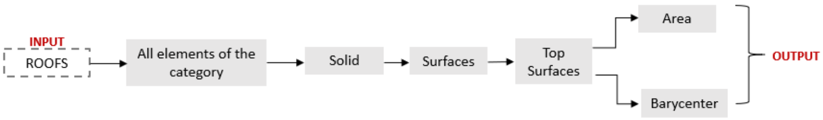


Figure 113 - Area and baricenter

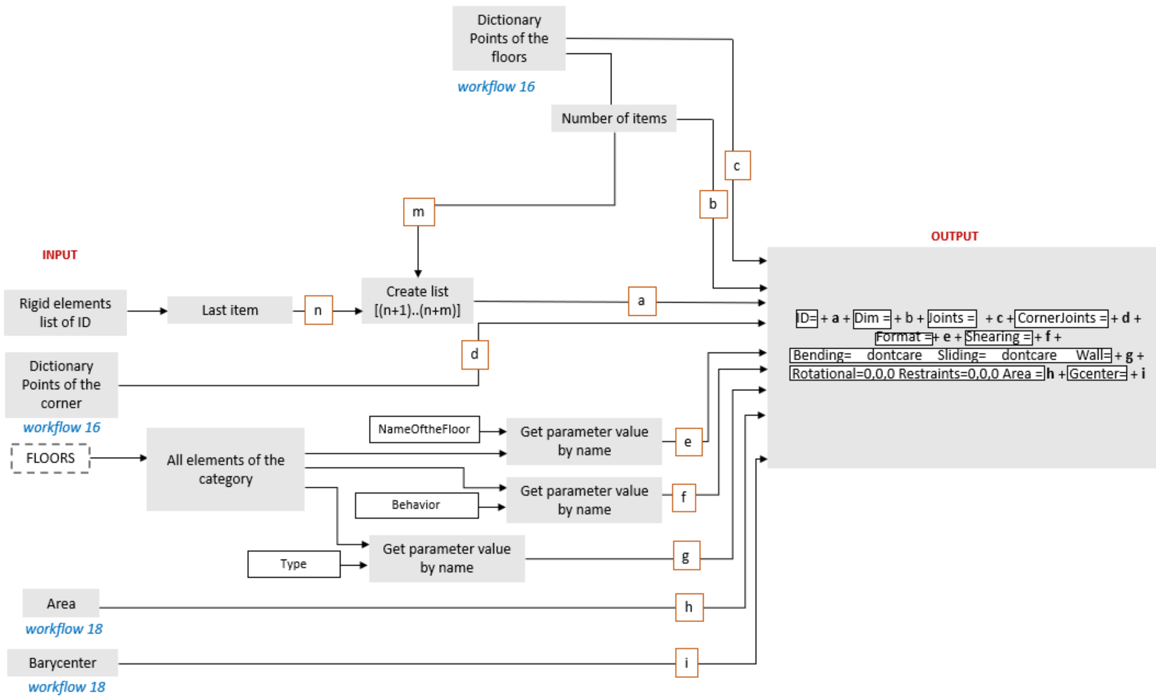


Figure 114 - String of the horizontal panel (Flowchart 19)

6.3.6 Restraint

To introduce the constraints, it is required to fix displacements and rotation of the two vertexes of the panels in contact with the ground (Figure 115).

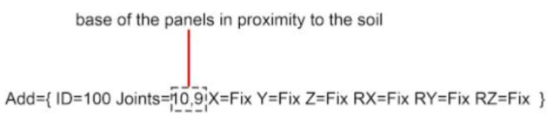


Figure 115 - Restraint

To do that, the algorithm calls all the points of the model and filters the ones that have Z coordinate equal to zero. From the points, it obtains the vertexes name by using the dictionary of **Error! Reference source not found.**. Then, it calls the list of strings of the panels and looks for the strings containing the vertexes called from the dictionary. Finally, it split these strings to obtain the vertexes 0 and 1. These are the ones related to the constraints. Once it has it, it creates the string by adding the information to block the degrees of freedom. To add the ID, it counts the number of items to add and creates a list that goes from 100 to 100 minus the number of items (Figure 116).

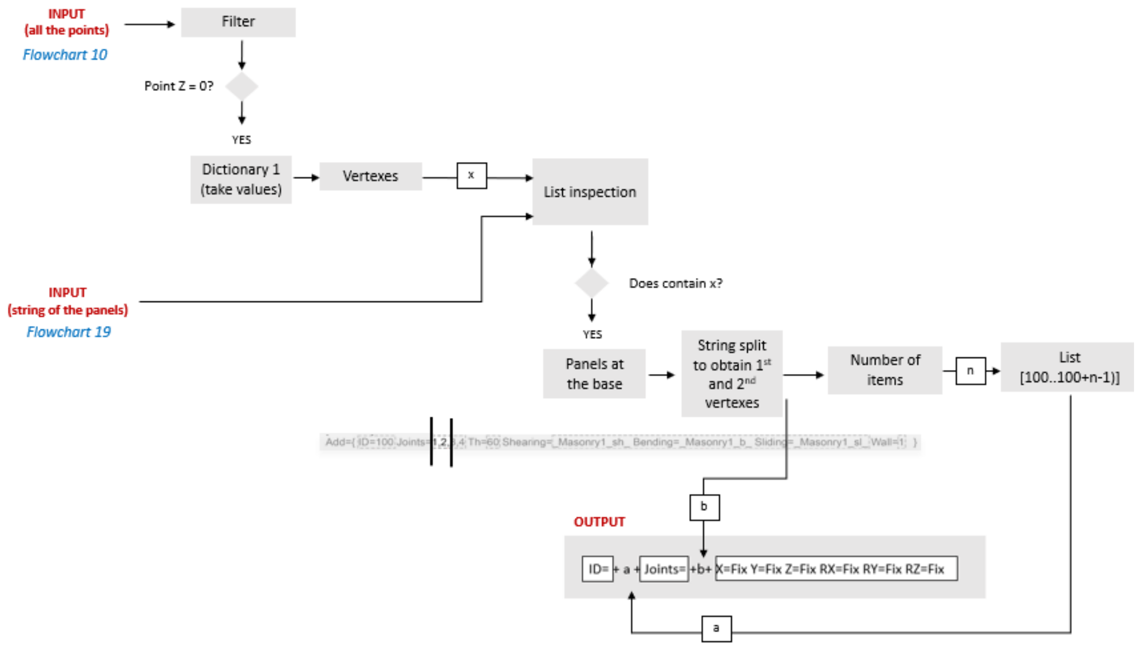


Figure 116 - Restraint definition (Flowchart 20)

6.3.7 Interfaces

To set the interfaces is only required to add the following string to the file. It would be possible to have various types of interfaces, but this aspect was not deepened (Figure 117).

```
[INTERFACES]
Set={ Int=All IMax=50,15 Mat=Elements }
```

Figure 117 - Interfaces

6.3.8 Loads

Once that the geometry can be exported, it is required to create an algorithm that to define the loads acting on the structure. The final goal is to run the PushOver analyses, thus it is required to apply the vertical loads, and then redirect them horizontally. The source of load considered in the application was only the self-weight of the structural elements.

The first algorithm defined, is the one that provides the vertical loads. The load deriving from the weight of the floors is distributed on the panels right below, according to its orientation, as shown inFigure 118 - Vertical loads distribution

, divided into the two top vertexes. Precisely, it was investigated a specific case, in which there is the presence of windows right below the floor itself. It was noticed, that the little portion of the weight of the floor on top of it is neglected. This portion of the load is negligible, especially if considering the ratio between the weight of the walls and the timber floors.

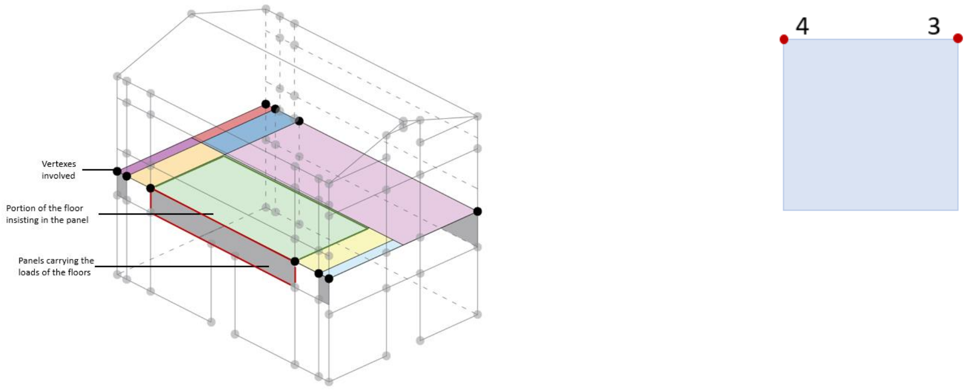


Figure 118 - Vertical loads distribution

As mentioned, one of the parameters of each floor is “LoadBearingWalls”, which indicates the “NameOfWall” in which the floor transfers the load. As shown in **Error! Reference source not found.**, from the panel string, the code takes the string containing Wall=n, where n is the value of “LoadBearingWall”. The string is split to obtain the name of the vertexes 3 and 4 and using the dictionary, from this are recalled the points. At this point, it provides the lines passing by each group of points, and finally its length. Then the code provides the value of the “Span” parameter of the floor. The latter is multiplied by the afore calculated length, providing the portion of the floor insisting on each panel. This is multiplied by the value of the parameter “SpecificWeight” and divided by two since the load is distributed in the two upper vertexes of the panel (Figure 199) and finally, the two outputs are linked together to obtain the string (Figure 120).

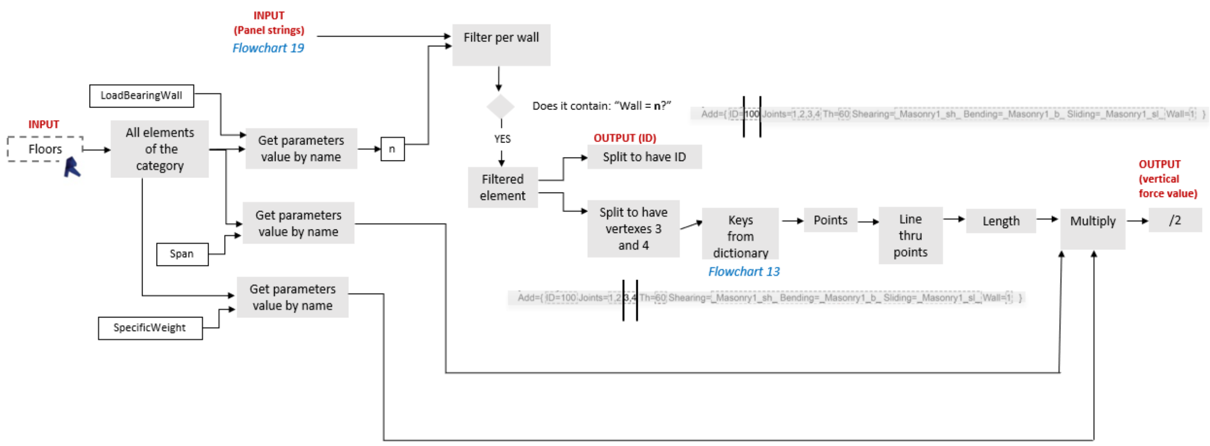


Figure 119 - Load of the floors (Flowchart 21)

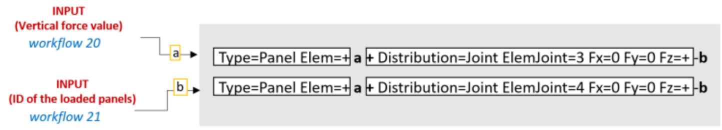


Figure 120 - ID of the loaded panel (Flowchart 22)

As far as concern the self-weight of the masonry panels, this is associated with the panel itself. To do that, the input was the list of the Panels, obtained from **Error! Reference source not found.**. Each string was split to obtain the ID of the wall and split again to have the vertexes. From the vertexes, they were taken the point, defined a square, and evaluated the area. Finally, the algorithm filtered the wall from the parameter NameOfWall equal to the one of the string, and it was taken the parameter "specific weight"(Figure 121).

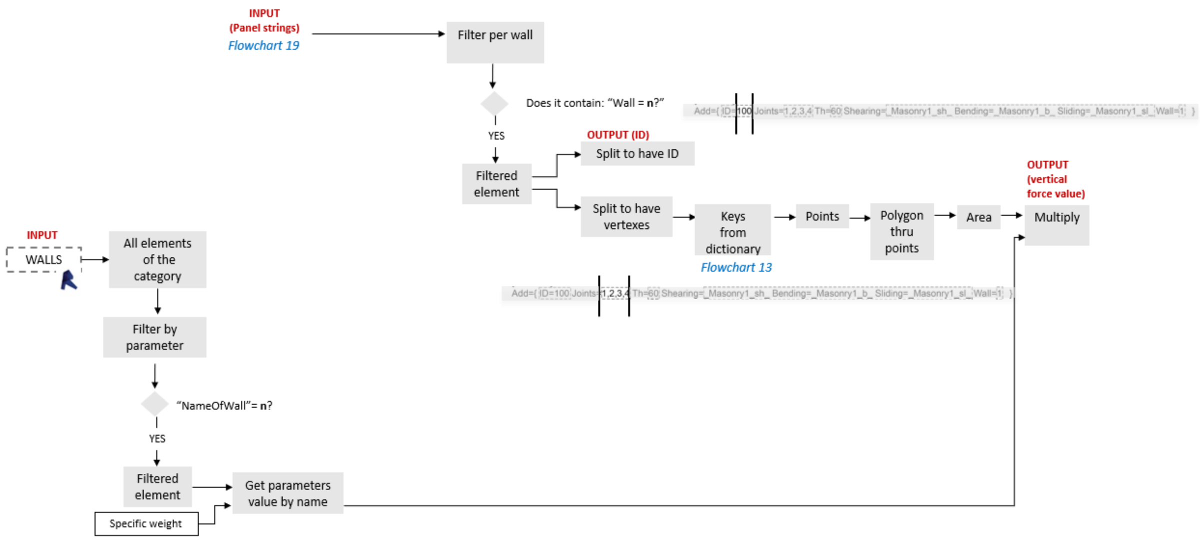


Figure 121 - Vertical forces of the panels (Flowchart 23)

The following algorithm creates defines the string of the load (Figure 122).

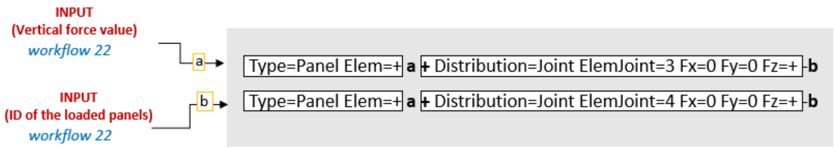


Figure 122 - String of vertical loads of the panel (Flowchart 24)

On top of the groups of strings of the loading, the algorithm introduces the strings shown in Figure 123.

```
[LOADS]
Add={ ID=GRAVITY  }
Add={ ID=__f__Vert LoadType=Force  }
```

Figure 123 - Group of strings introduced by the algorythm

To get the PushOver analyses, the load must be direct horizontally in the four directions (+X, -X, +Y, and -Y), and associated with the control points. For the rigid diaphragms, the control point is the barycenter of the element. For the deformable diaphragms, the number of control points depends on the mesh that is defined, as will be further shown. Moreover, to each floor, it is associated with the load of the element above it. The following algorithm is the one related to the rigid floors. The first thing to do is define a new dictionary because it will need to recall the name of the ID of each panel, to calculate the total load (Figure 124).

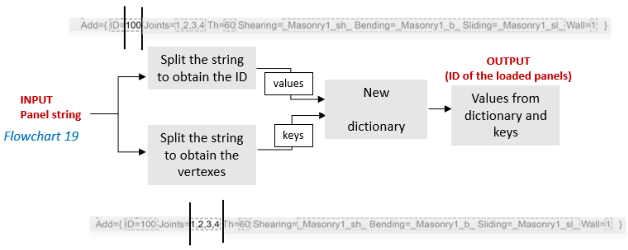


Figure 124 - New dictionary (Flowchart 25)

Once that this is done, the panel string is called again, and in this case, they are taken the vertexes, from which the algorithm recalled the points, that are finally filtered, taking only the ones that have the Z coordinate lower than the elevation level, considered as a parameter of the floor. Then, the code passes again to the vertexes, and recalls the ID of the panels, using the dictionary of **Error! Reference source not found.**. In this way, they are called all the panels that are above the elevation level. Afterward, the code calls the strings of the vertical load, and it filters the ones that contain those IDs. These strings are split to obtain the vertical loads, that are summed and applied to the barycenter. Finally, it was required to have the ID of the horizontal panel. To do that, the code calls the vertexes of the floor, calls the string of the horizontal panels, and filter the latter, taking the ones containing the floor points, and splitting the string to have the ID (Figure 125).

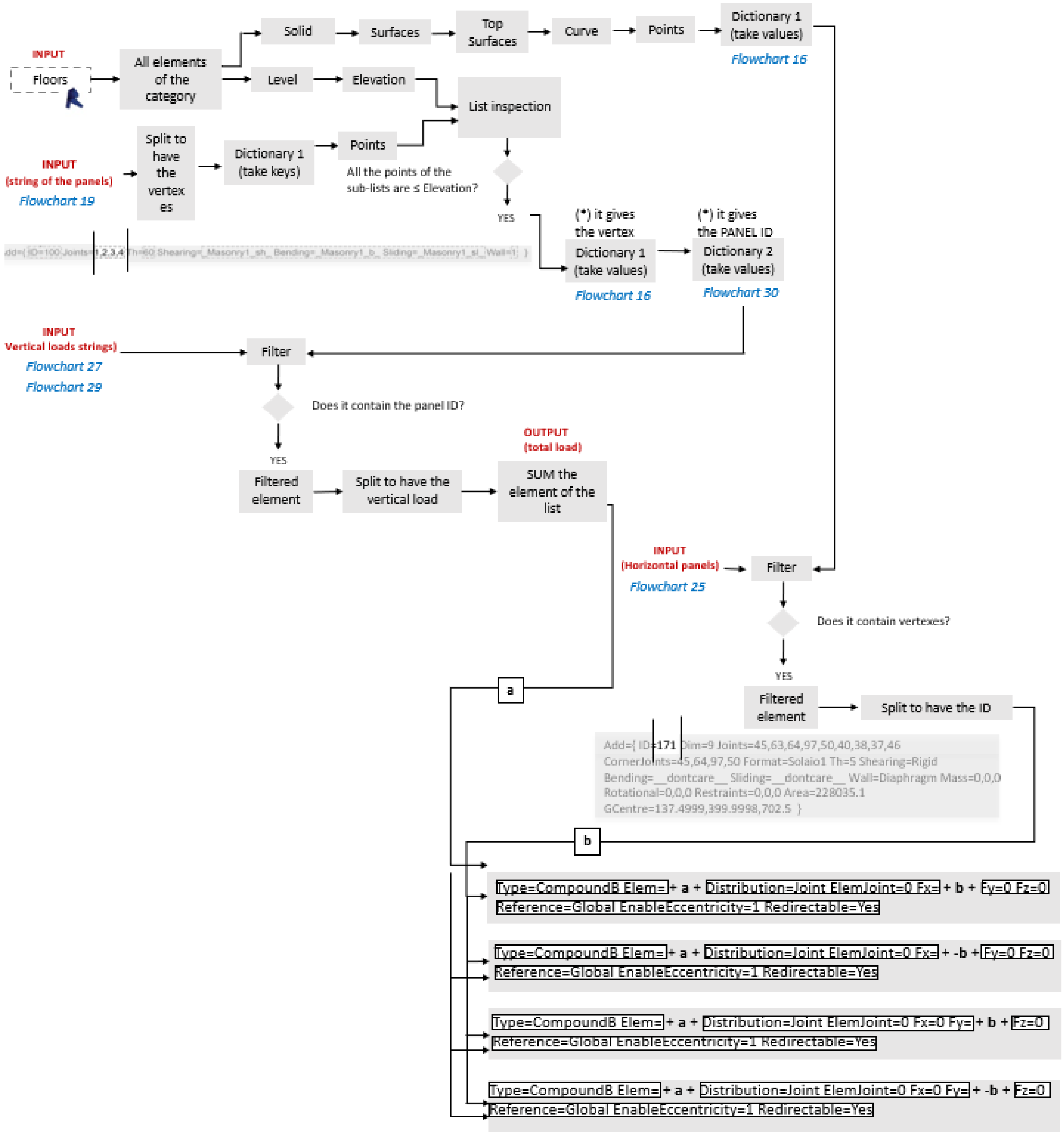


Figure 125 - All the horizontal load redirected in the barycenter of the rigid diaphragms (Flowchart 26)

If the diaphragm is deformable, the total load to be associated with insists for 1/3 in the barycenter of the element, and 1/3 is redistributed in the barycenter of the mesh of the floor. The mesh must be defined considering all the nodes insisting in the element, and the barycenter, as in Figure 126.

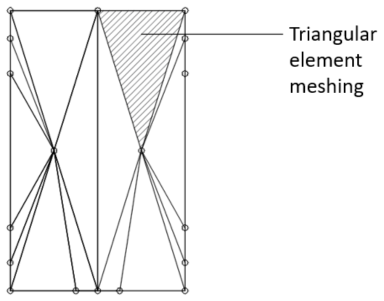


Figure 126 - Plans of the roof with mesh

To define the mesh, it was implemented the following algorithm. First, the code selects the horizontal element, in this case, the roof, the correspondent surfaces, and planes and it filters all the points of the model that belong to that plane. Subsequently, it provides the barycenter of the element and connects the latter with all the points previously collected. The lines that are created are translated above and below to create a set of planes. These planes are used to cut the roof geometry, proving the mesh elements. It was calculated the area of the mesh element, the total area of the panel, and finally the percentage between the two. This was done to evaluate the amount of load that must be associated with the barycenter of each mesh.

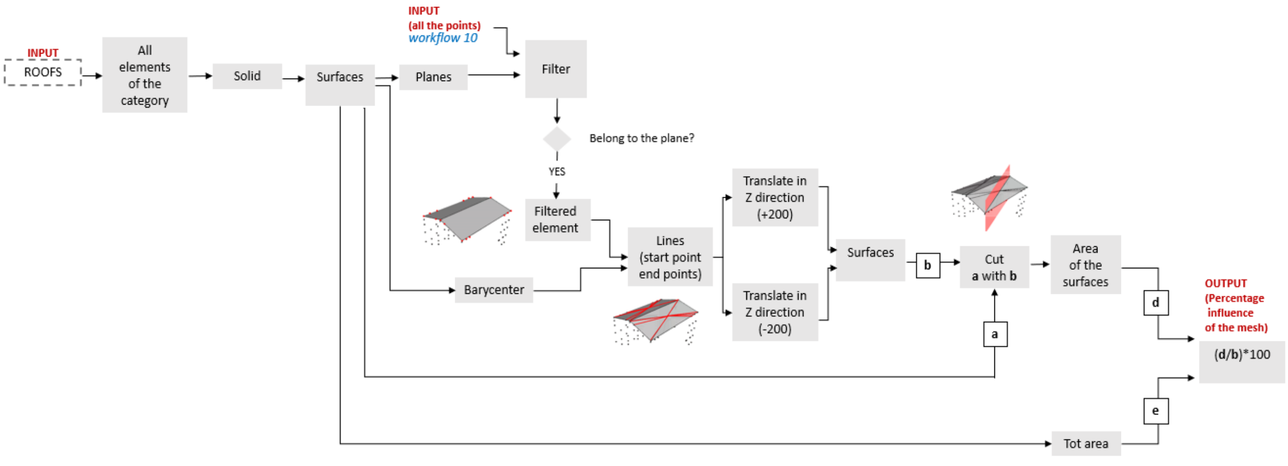
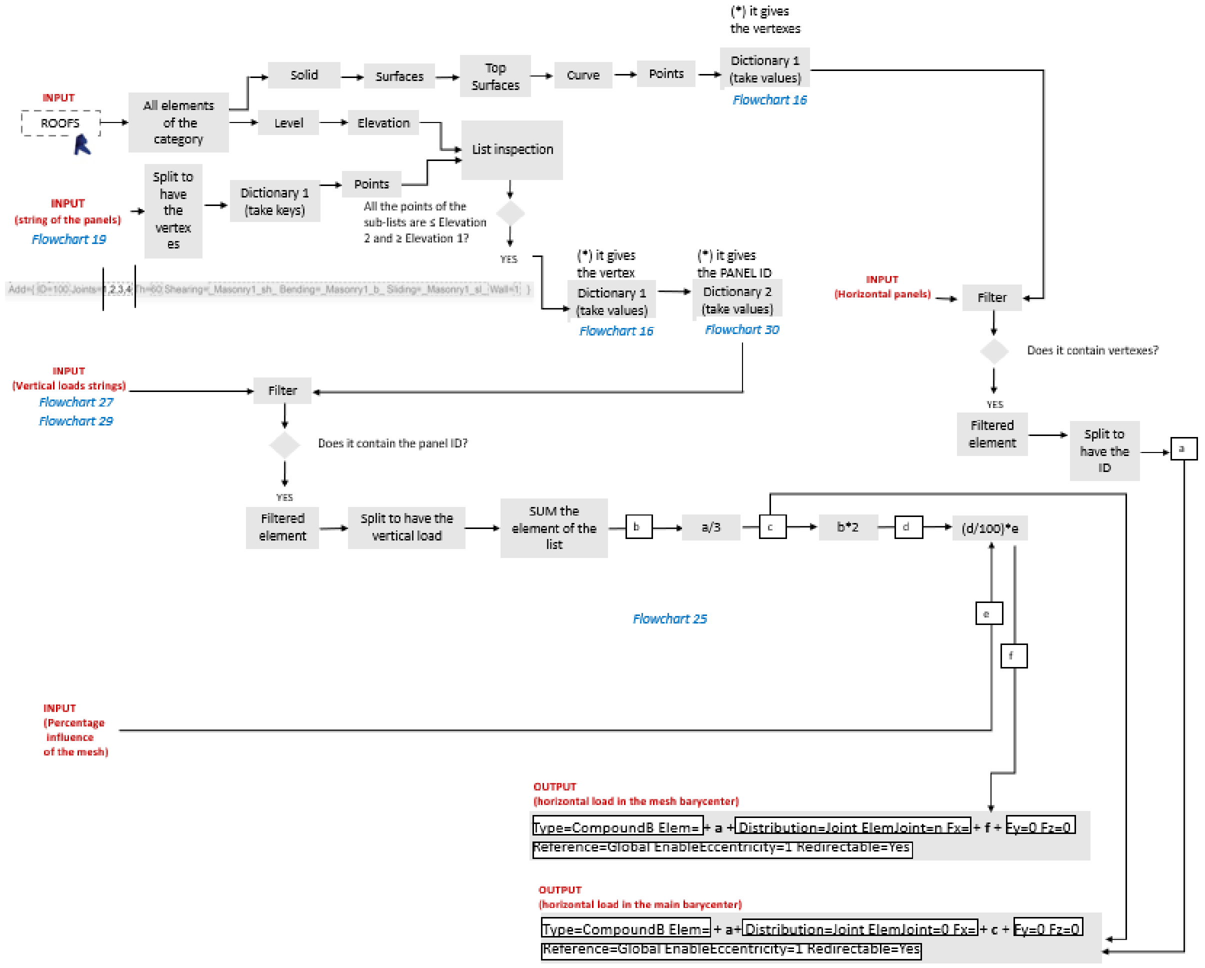


Figure 127 - Triangular mesh for deformable floors (Flowchart 27)

The sum of the total load that is concentrated at the roof elevation is calculated in the same as it is done for the rigid diaphragms. Then, this is divided by three, to associate one-third of the load with the overall barycenter and the other two-thirds with the barycenter of the mesh elements.



Flowchart 1 - Horizontal load associated with the deformable diaphragms (Flowchart 28)

Similar to what is done for the vertical loads, on top of the horizontal load group it is required to add these strings. As shown, first it provides the first load distribution, and then this is redirected in the required directions.

Add={ ID=__f__Pushover_+X_Massa LoadType=Force }

strings of the load of the pushover +x

Add={ ID=__f__Pushover_+X_Massa_wall LoadType=Force }

CopyLoad={ Source=__f__Vert Redirect=1,0,0 DeltaInfo=DeltaX Eccentricity=0 }

Add={ ID=__f__Pushover_+X_Massa_gravity_1 LoadType=Force }

CopyLoad={ Source=Gravity_1 Redirect=1,0,0 }

Add={ ID=__f__Pushover_-X_Massa LoadType=Force }

strings of the load of the pushover -x

Add={ ID=__f__Pushover_-X_Massa_wall LoadType=Force }

CopyLoad={ Source=__f__Vert Redirect=-1,0,0 DeltaInfo=DeltaX Eccentricity=0 }

Add={ ID=__f__Pushover_-X_Massa_gravity_1 LoadType=Force }

CopyLoad={ Source=Gravity_1 Redirect=-1,0,0 }

Add={ ID=__f__Pushover_+Y_Massa LoadType=Force }

strings of the load of the pushover +y

Add={ ID=__f__Pushover_+Y_Massa_wall LoadType=Force }

CopyLoad={ Source=__f__Vert Redirect=0,1,0 DeltaInfo=DeltaY Eccentricity=0 }

Add={ ID=__f__Pushover_+Y_Massa_gravity_1 LoadType=Force }

CopyLoad={ Source=Gravity_1 Redirect=0,1,0 }

Add={ ID=__f__Pushover_-Y_Massa LoadType=Force }

strings of the load of the pushover -y

6.4 Analyses

Finally, to send the software to call the analyses, and this was done by inserting manually strings with the required information (number of step, step increment, condition to stop the analyses). Plase notice that the first string is to define the analyses information, and the others are required to associated the loads to the analyses, adding the following information.

This aspect was not the major focus and requires further development. Indeed, the information of the analyses would be managed in Revit as global parameters.

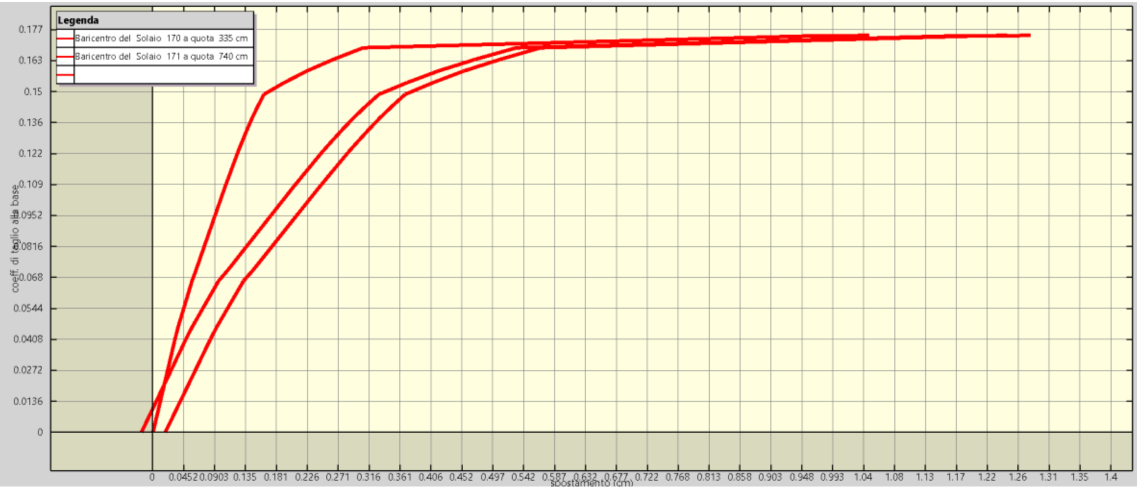
6.5 The results of the analyses

The final file can be opened using the Command Prompt, to run the analyses.

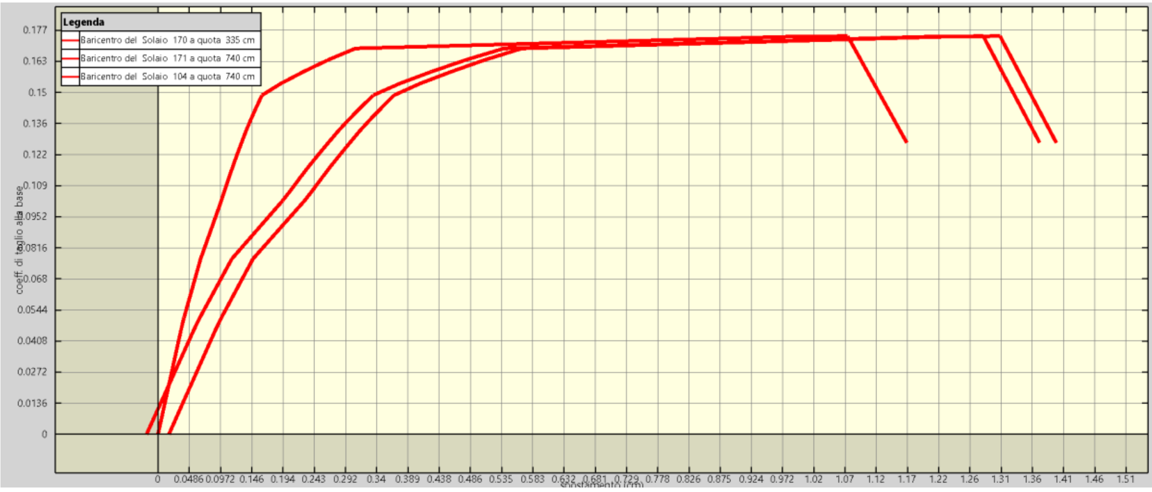
Until now it was possible only to have limited results on the analyses. This was done because of the limitation of the software used, clearly, further, development is need, in the perspective of reading some other results.

The type of results obtained is the PushOver curves for the four directions and the InPlane events associated with the final step. The PushOver curves can be seen throughout the interfaces of

3Dmacro that opens once that the file is opened using the command prompt (Figure 128 and Figure 129).

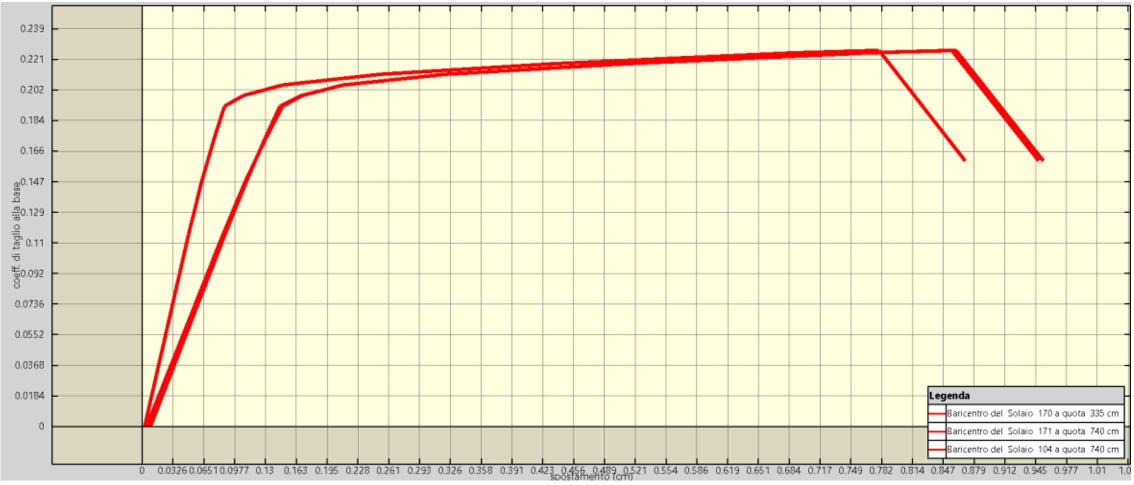


a

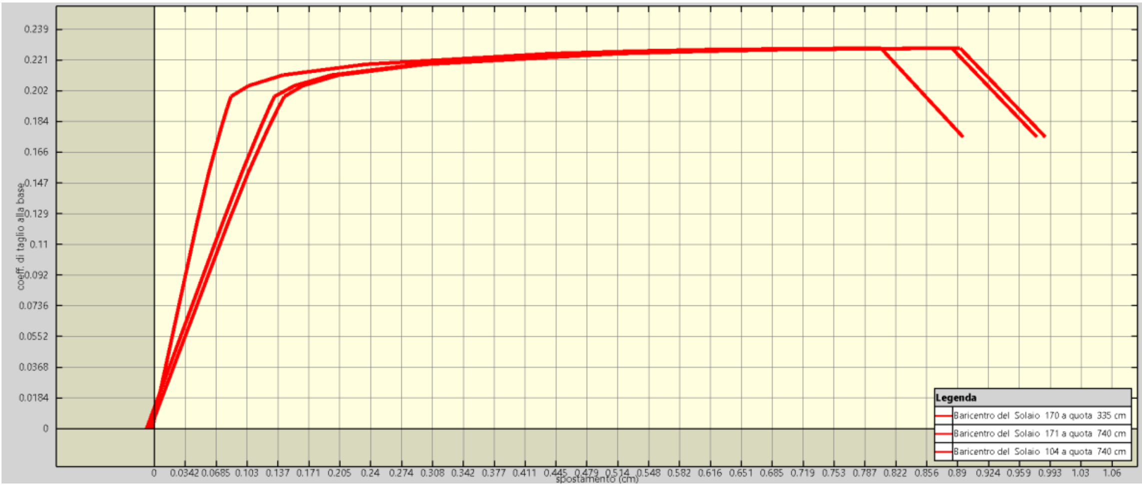


b

Figure 128 - PushOver results a) PushOver +X; b) PushOver- X



a



b

Figure 129 - PushOver results a) PushOver +Y; b) PushOver- Y

In addition, once that the analyses run, the results are saved in a text file. In particular, for each PushOver, there is a text file that shows the in-plane events occurring at the last step of the analysis. To complete the workflow, it was implemented a code that reads the results and sends them back to the Revit model.

The text file with the results of the analyses is structured as shown in Table 10, which is repeated for each in-plane event occurring.

Table 10 - Results of the in-plane events

Last step of the analysis	step = 37
In plane event	evt = PIERS_SHEAR_FAILURE

Id of the wall	wall_id = 1
Level	elem_level_id = 0
Panel name	elem_sub = 101,104

As visible, the results are reported for the macro-elements. The approach followed to send the results back to Revit was to introduce a new family of objects, corresponding to the macro-elements. This family corresponds to the category “mass” and is defined in its geometry by length and height (instance parameters). With the panel are associated the parameter related to the macro-elements (the Panel ID, the ID of the vertex, and the wall to which the panel belongs) and all the parameters related to the possible in-plane failure. These are named differently depending on the analyses, as shown in the picture, so all the results can be associated with the same Revit file (Figure 131).

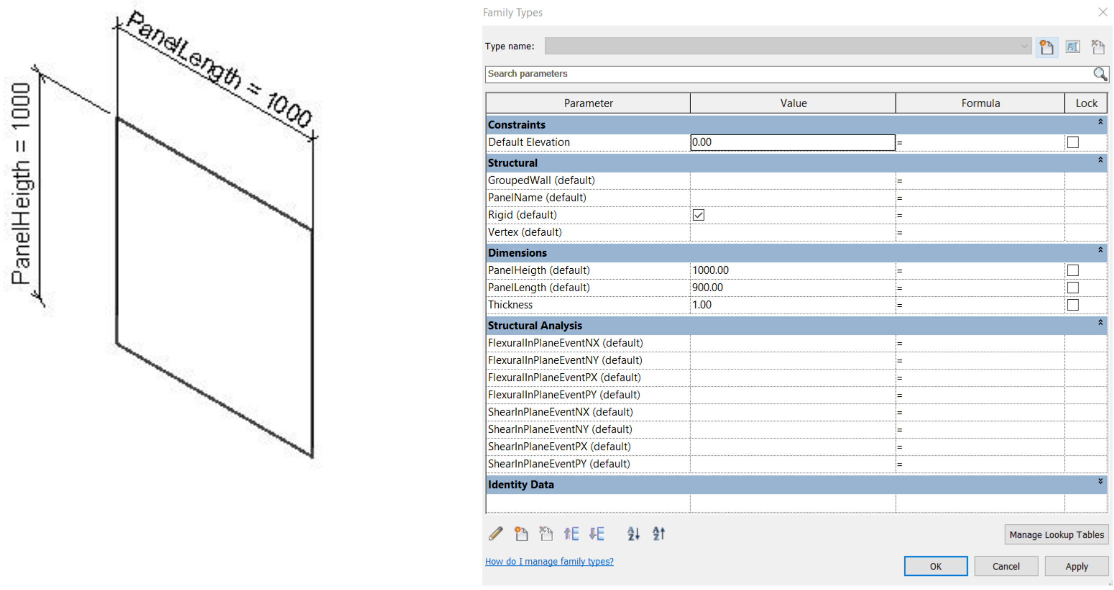


Figure 130 - Name of the parameters of the panels

It was implemented an algorithm to introduce the objects “panels” in the model. This is done by creating a new code, associated with the analysis results. Inside the new code, there are already implemented dictionaries that connect the points with their ID and also the vertexes. The code calls the string of the panel from the Excel file that was implemented to run the analysis. From the string, it takes the ID of the panel and the vertexes. In particular, it takes the first vertex and uses the correspondent point to place the panel. In addition, it set the parameters of the length and the height of the panel. For the length, it takes the first and second vertexes, provides the correspondent points, draws a line between, and measures the length. For the height, it takes the second and third vertexes, provides the points, creates a line between them, and measures its length (Figure 132).

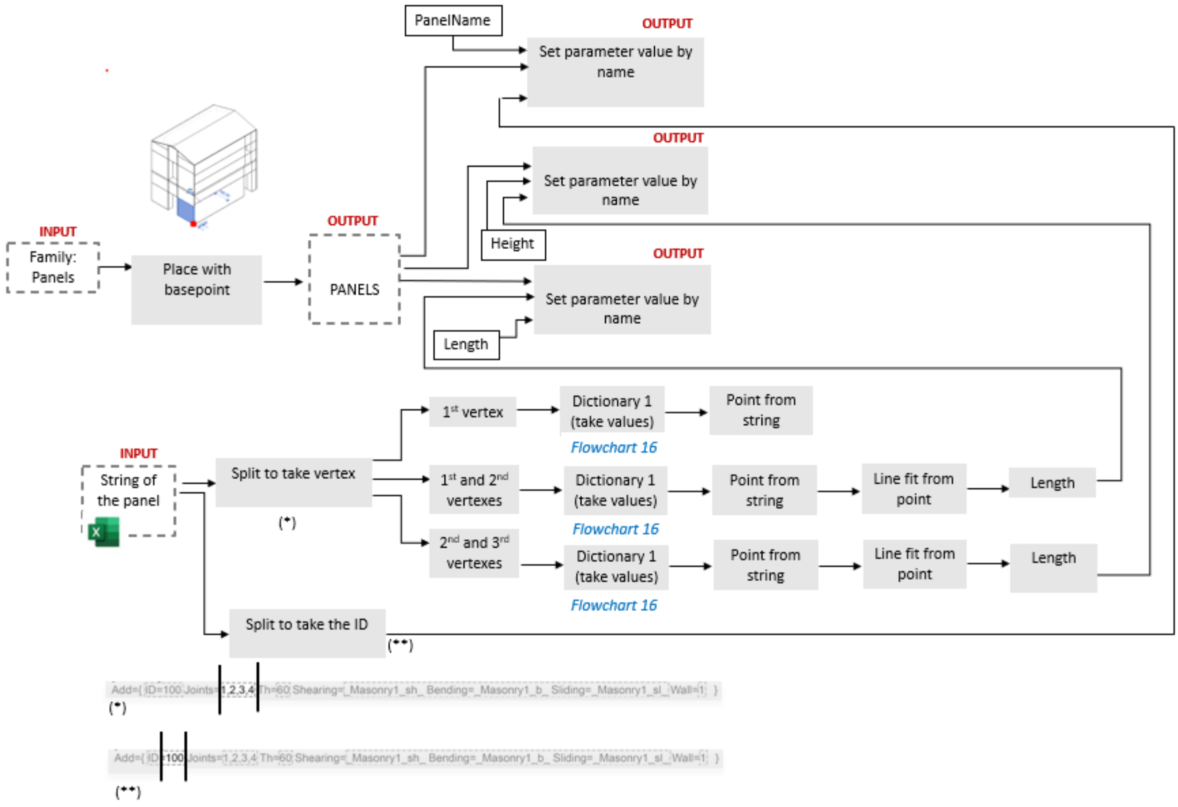


Figure 131 - Placing the panels (Flowchart 29)

The algorithm imports all the panels in Revit. (Figure 132).

a b

Figure 132 - Panels in Revit

At this point, it was defined the algorithm to send the results to the Revit panels. The results from the text file are imported on Excel in different sheets, named respectively “PushOver+X”, “PushOver+Y”, “PushOver-X” and “PushOver-Y”. For each sheet is implemented an algorithm that sends the results to the panels. To do that, it subdivides the list of results into groups of 5 elements, to take separately each event. The second element of each list is taken to introduce the type of event in the panel, and the fifth element of each list is taken to select the panel to which associate the damage (Figure 132).

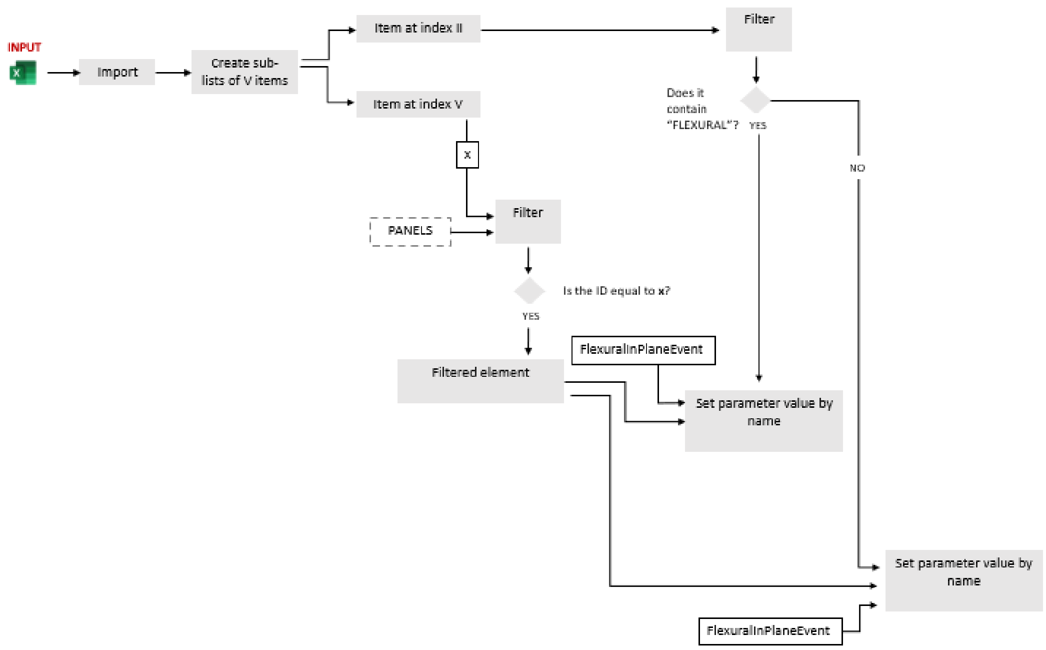


Figure 133 - In plane damage of each panel (Flowchart 30)

At this point, each damaged macro-element is associated with the type of event occurring in all the analyses, that can be read in the Revit interfaces. In addition, inside Revit, it is possible to introduce four different 3D Views, associated with the four analyses done. Each of these has different graphic settings, showing the damage associated with the analysis itself. To be more precise, it was defined a legend for each type of damage, as shown in **Error! Reference source not found.**. Since there is the possibility of having shear failure and flexural failure in the same panel, and in the same analyses, the flexural damage is indicated with a hatch with a transparent background, to eventually superpose two damages.

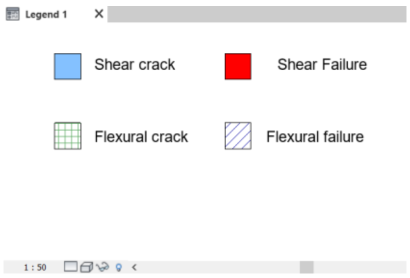


Figure 134 - Legend of the panel

The different graphic settings associated with the different views are defined using different filters. The example in Figure 134 shows, for example, the filter created for the PushOver-Y.

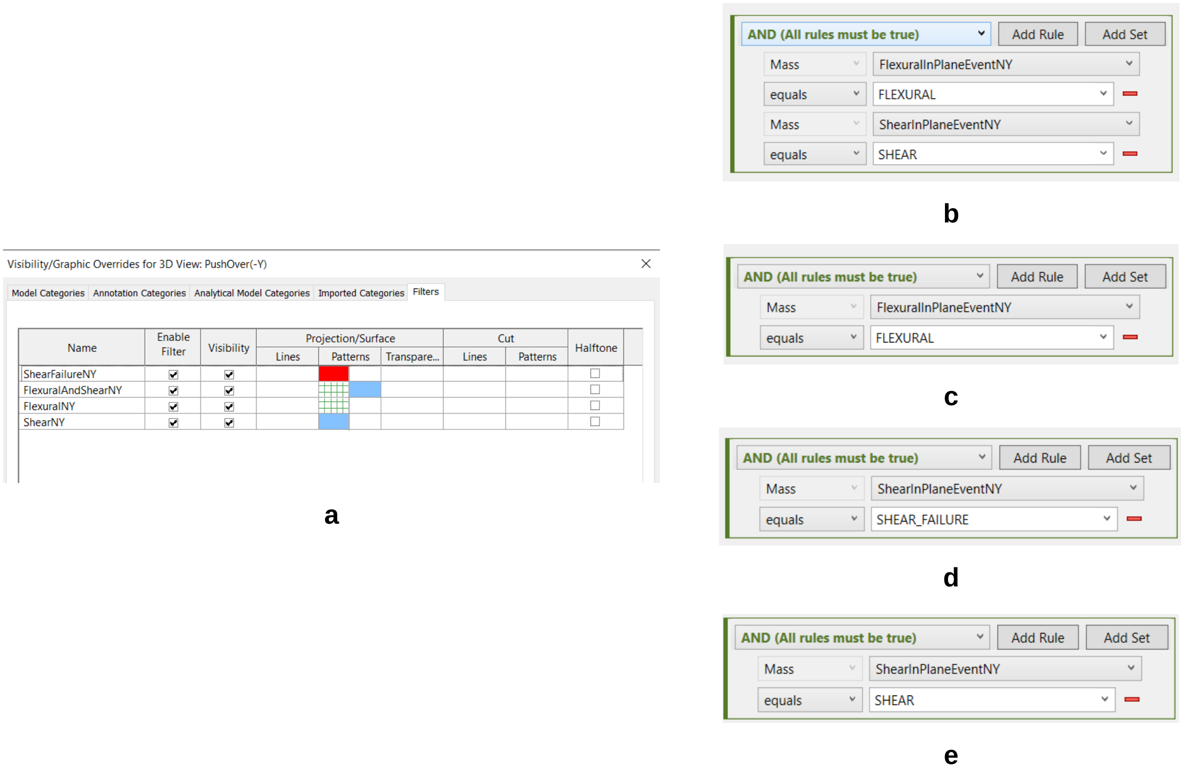


Figure 135 - Application of the filter for the PushOver-Y

In 136 is visible the Revit interfaces and the results related to the various analyses.

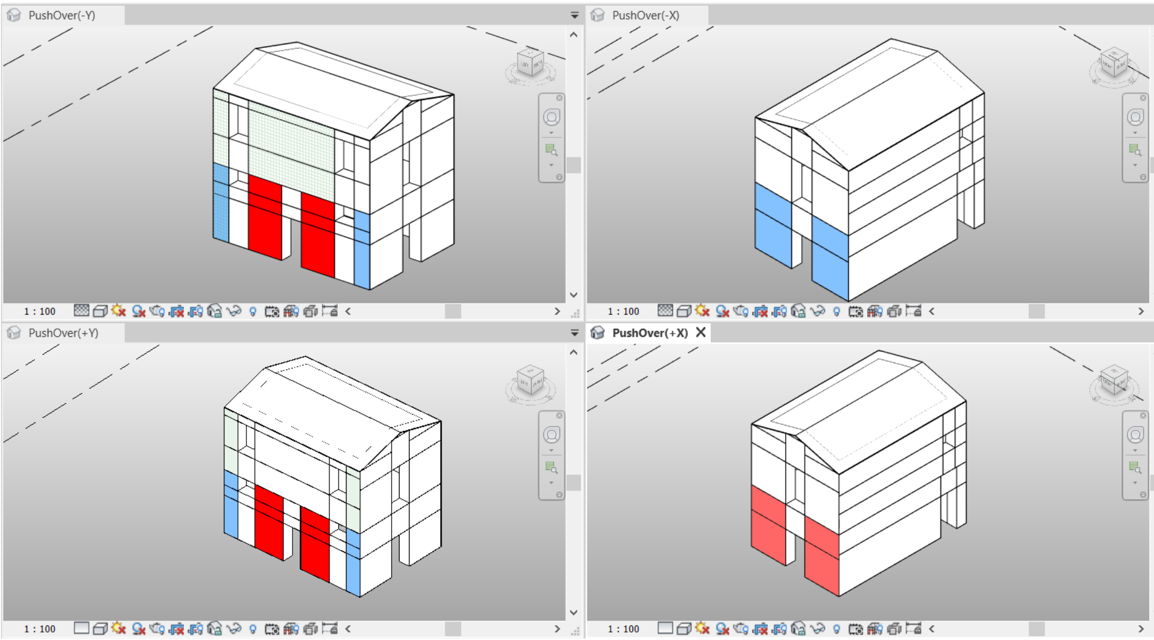


Figure 136 - Revit interface with the results

7. CONCLUSIONS AND FURTHER DEVELOPMENT

The Dissertation investigates the question of the masonry aggregates and the main objective is to integrate the assessment of these structures with the new technologies available, introducing a methodology based on the use of BIM to improve the cooperation within the different stakeholders involved. In the first part of the document, the state of art is pointed out, the aggregates that have been studied more, in Italy, are the ones located in the center of the country, especially after being stroke by earthquakes. A lot of studies were done recently to assess them quickly and at a large scale, whereas fewer studies focus on the use of numerical models. In addition, the structural assessment and the structural intervention on these constructions are often considered as an independent part of the project, instead of being considered together with a broader intervention, to make the centers liveable from all points of view. On the contrary, the masonry aggregates, that aside from being heritage, have an important economic value, are still often considered as destined to the lowest social classes.

A few attempts were made to exploit the BIM to increase cooperation between the various parts of the project and a way of greatly speed the intervention on these centers. Nevertheless, the BIM environment still needs to be ready to model existing structures, by introducing class of objects conceived specifically for these constructions. Also, a lot of work must be done in the management of data through the use of a Product data template. In this sense, a contribution was given, proposing a Product data template that covers the information required for the structural assessments of these constructions, but there is still the need of introducing parameters related to other aspects of the projects, and also introducing Product Data templates conceived for other objects.

As far as the question of the interoperability and the structural analyses is concerned, it is given a demonstration on how implementing a code, the BIM can be the unique environment in which the structure is modeled, and the information can be sent to an external solver that runs the analyses and send the result back to the model. In this way, modeling the geometry can be something managed by an expert on the sector, and the other stakeholders can focus on other aspects. Clearly, the implemented code is still rudimental: the connection done between the two software is partly manual, and the application was demonstrated for a small unit, and not for the entire compound, even though it was shown that the implemented code could export some more complex geometries. Some open issues were left because of the lack of time, and because of the use of a too simple coding language. Nevertheless, more than finding the final solution, the scope of the application was to demonstrate that the connection between BIM and the structural model is possible, and it is something worth investing in. Indeed, the aspect of understanding that this concept is addressable was successfully achieved. Now, implementing larger objects using this methodology, is just at the distance of adding new work, and is not anymore a new concept. Several further developments can be seen. First of all, within the idea of cooperation of structural model and BIM model, introducing new objects inside the workflow can be an interesting approach. For instance, it could be beneficial to model the strengthening intervention objects. In this way, it is easy to understand how much the intervention designed is compatible with the existing building (in the BIM model), and at the same time, have a quick validation of it (with the structural software). Another development of the entire framework, in a wider perspective, is the improvement of the way the information is collected during the inspection, in a way of making them be easily inserted in the BIM model.

To conclude, the definition of an integrated framework, based on HBIM, to fully assess the masonry aggregate can be seen as feasible and something on which the scientific community should investigate.

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9. ANNEXES

Annex 1: string to send the analyses.

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AddLoad={ Load=__f__Vert Mult=1 }

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AddLoad={ Load=__f__Pushover_+X_Massa_wall Mult=1 }

AddLoad={ Load=__f__Pushover_+X_Massa Mult=1 }

[STATIC]

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Stage=1 autosavestep=10 AnalysisExecuted=0 Frestart=0 }

AddLoad={ Load=__f__Pushover_-X_Massa_gravity_1 Mult=1 }

AddLoad={ Load=__f__Pushover_-X_Massa_wall Mult=1 }

AddLoad={ Load=__f__Pushover_-X_Massa Mult=1 }

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AddLoad={ Load=__f__Pushover_-Y_Massa_wall Mult=1  }

AddLoad={ Load=__f__Pushover_-Y_Massa Mult=1  }
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Annex 2: Damages

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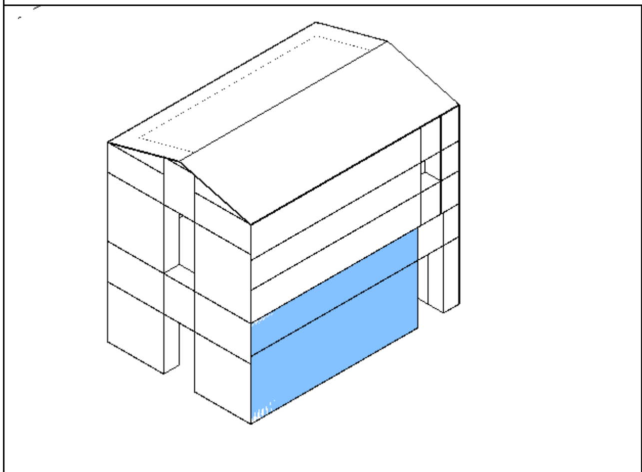	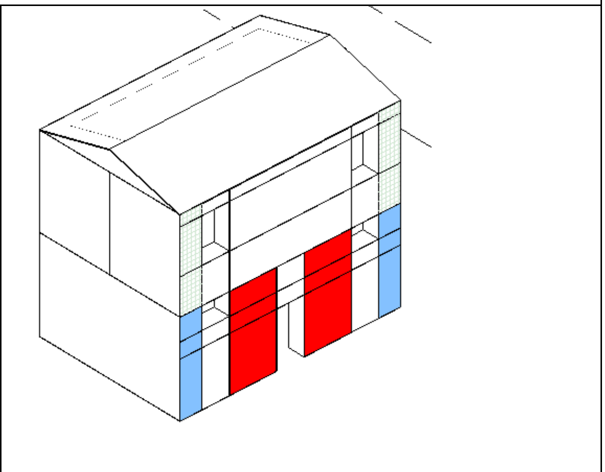
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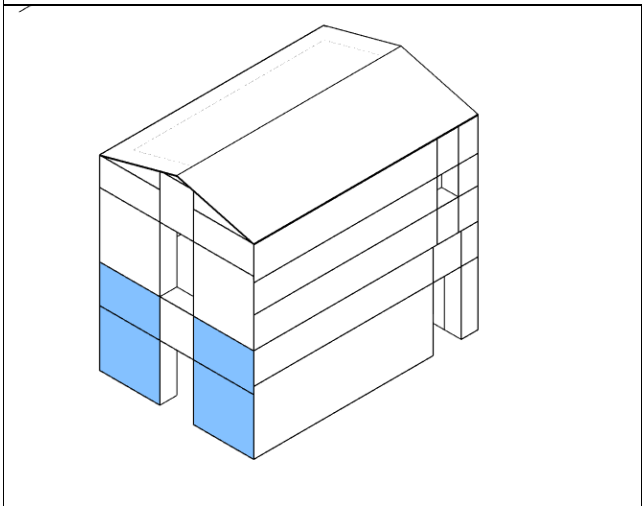	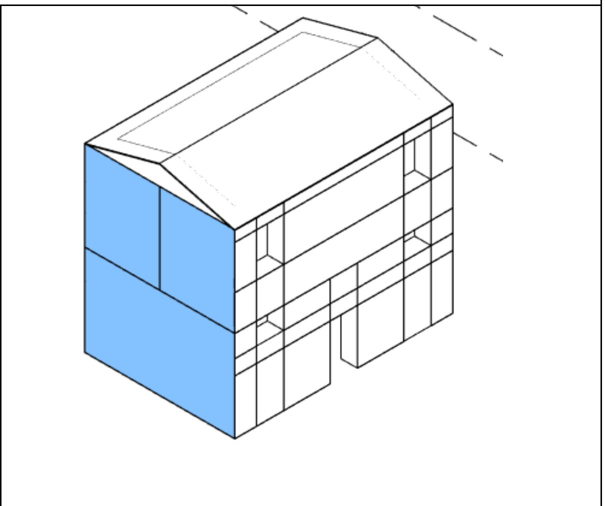
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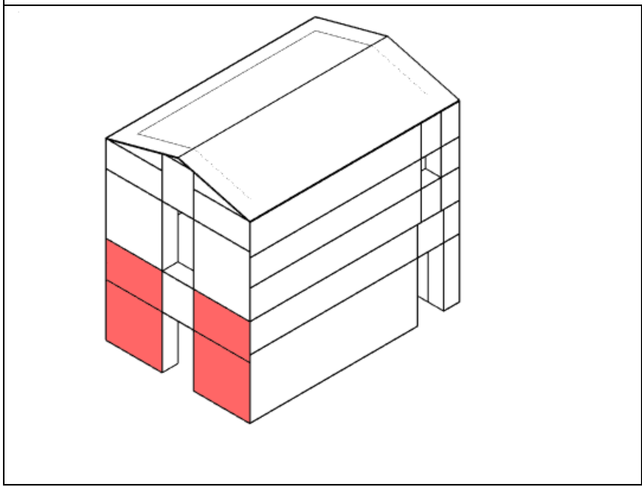	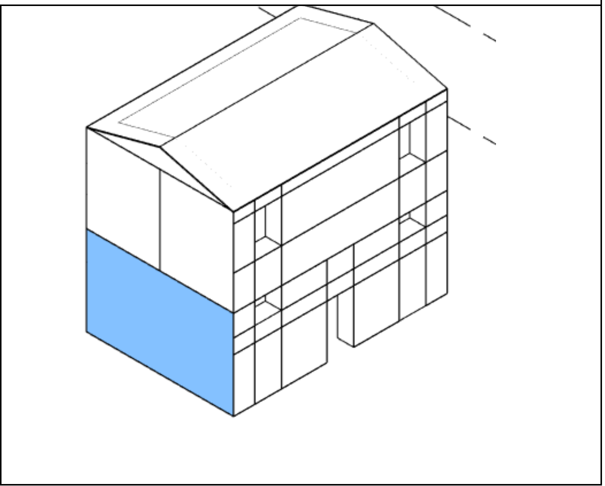

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