POLITECNICO DI TORINO

Master's Degree in Civil Engineering (LM-23)

Master's Degree Thesis

DIGITAL TWIN OF CULTURAL HERITAGE BUILDINGS "TORRE DELLA MOLETTA CIRCO MASSIMO ROME"

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ABSTRACT

Historic masonry towers located in areas with a lot of foot traffic and gatherings are highly susceptible to damage due to their old architecture. For example, when concerts are held nearby, the high-quality speakers generate acoustic waves, and the ground vibrations from people jumping can also impact the structure. This study focuses on conducting a detailed structural analysis by creating a digital twin of the Torre della Moletta (Moletta Tower), which was constructed before 1145 B.C. It is located in Circus Maximus, Rome, Italy. The area around the tower is known for hosting gatherings of over 4500 people during concerts. A visit on-site was important to obtain point cloud data through Laser scanners which were then fed in Autodesk Recap for optimization and transferred to Revit to develop a Building Information Model (BIM), ensuring interoperability with MIDAS Gen for advanced finite element modeling (FEM). A 3D FEM model was generated, and modal analysis was performed to determine the structure's natural frequencies. These frequencies were then validated against dynamic identification results by model updating. Furthermore, the elastic modulus of the masonry was set to 1200 MPa to refine the model and accurately reflect the natural frequencies. The final model served as a digital twin of the actual structure. In addition, a dynamic pressure analysis was conducted on the tower because of concert nearby (1st May 2024), which indicated that the displacements and velocities were higher than the acceptable range according to ISO-4866. This comprehensive approach highlights the integration of BIM methodologies with FEM analysis to enhance structural fidelity and performance assessment.

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INTRODUCTION

Preservation of architectural heritage is a crucial concern in modern societies. Analyzing historical masonry constructions is challenging due to the lack of data about the properties of their components and the impossibility of conducting destructive tests, especially because of the irregular texture of the masonry walls. Over time, existing buildings undergo degradation, making them unable to fulfill their original purpose. There is a need to adapt these buildings to new functions and improve their conditions. In developed societies, there is a growing realization of the importance of maintaining the existing building heritage. Rehabilitating and restoring heritage buildings is a form of sustainable development and an expression of culture. Generally, the cultural value of an existing building is high, especially if it is old. The repair and restoration of heritage buildings have become significant issues, particularly in developed societies. Assessing the structural safety of existing buildings is a complex task, as the methodologies used differ from those adopted in the design of new structures. Strengthening existing heritage buildings can sometimes conflict with their aesthetic value.[1]

The primary aim of this study is to create a Digital Twin of Moletta Tower, situated in Circo Massimo, Rome. The research is structured into 3 comprehensive chapters, each addressing crucial aspects of the investigation.

In Chapter 1, a thorough literature review is conducted to establish the state of the art in the field. This section explores various types of masonry, testing methodologies for masonry structures, and Properties of masonry and Finite Element Modeling. The objective is to provide a solid foundation of existing knowledge and identify gaps that this study aims to fill.

In Chapter 2, we presented a detailed case study of Moletta Tower. This involved examining available data, developing a 3D model, and applying BIM methodology. I used advanced analytical techniques such as Finite Element Modeling and Modal Analysis, and calibrated these models. Also a brief analysis of 1st MAY 2024 Concert.

Chapter 3 presents the results and presents the issues related to BIM Modelling and also shows the results of 1st May concert in term of Peak Particle Velocity.

Finally, the study concludes with conclusions and recommendations. Based on the results, this section outlines various strategies to mitigate potential Modelling problems. The recommendations aim to ensure the preservation and safety of Moletta Tower amidst the dynamic environment of large-scale events.

This structured approach not only provides a clear understanding of the research process but also highlights the significance of preserving historical structures in the face of modern-day challenges.

CHAPTER 1 LITERATURE REVIEW

1.1 HISTORIC MASONRY

Masonry is a heterogenous material made up of units and joints. These units can take many forms such as bricks, blocks, stones, and others. Mortar, which holds the units together, can be made of clay, bitumen, chalk, lime/cement-based mortar, glue, or other materials. Fig. 1 shows a simple classification of stone masonry. The wide range of possible combinations generated by the geometry, nature, and arrangement of units, as well as the characteristics of mortars, raises some doubts about the accuracy of the term "masonry." To give an example, Fig. 2 illustrates some typical combinations of brick masonry.[2]

Masonry is one of the oldest building materials that is still widely used in today's construction industry. The most significant advantage of masonry construction is its simplicity. Stacking pieces of stone, bricks, or blocks on top of each other, either with or without mortar, is a simple but effective technique that has been used successfully since ancient times. Over time, there have been numerous variations in masonry materials, techniques, and applications. The main factors that influenced these variations were the local culture and wealth, knowledge of materials and tools, availability of material, and architectural reasons.[2]

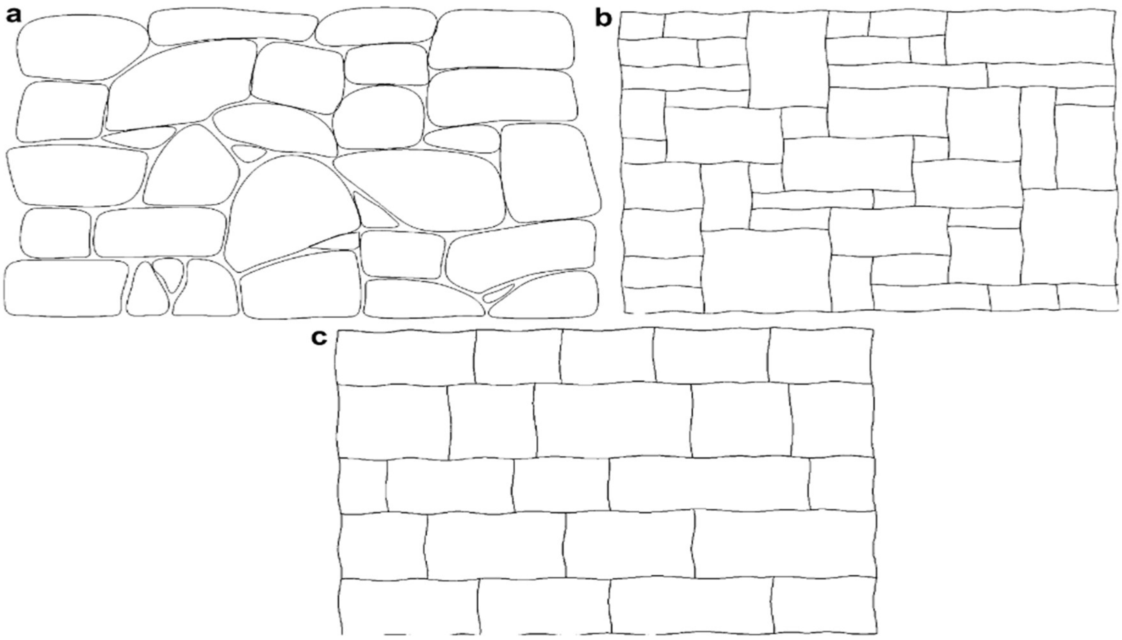


Figure 1 Different Kinds of stone Masonry: (a) Rubble Masonry; (b) Ashlar Masonry; (c) Coursed Ashlar Masonry

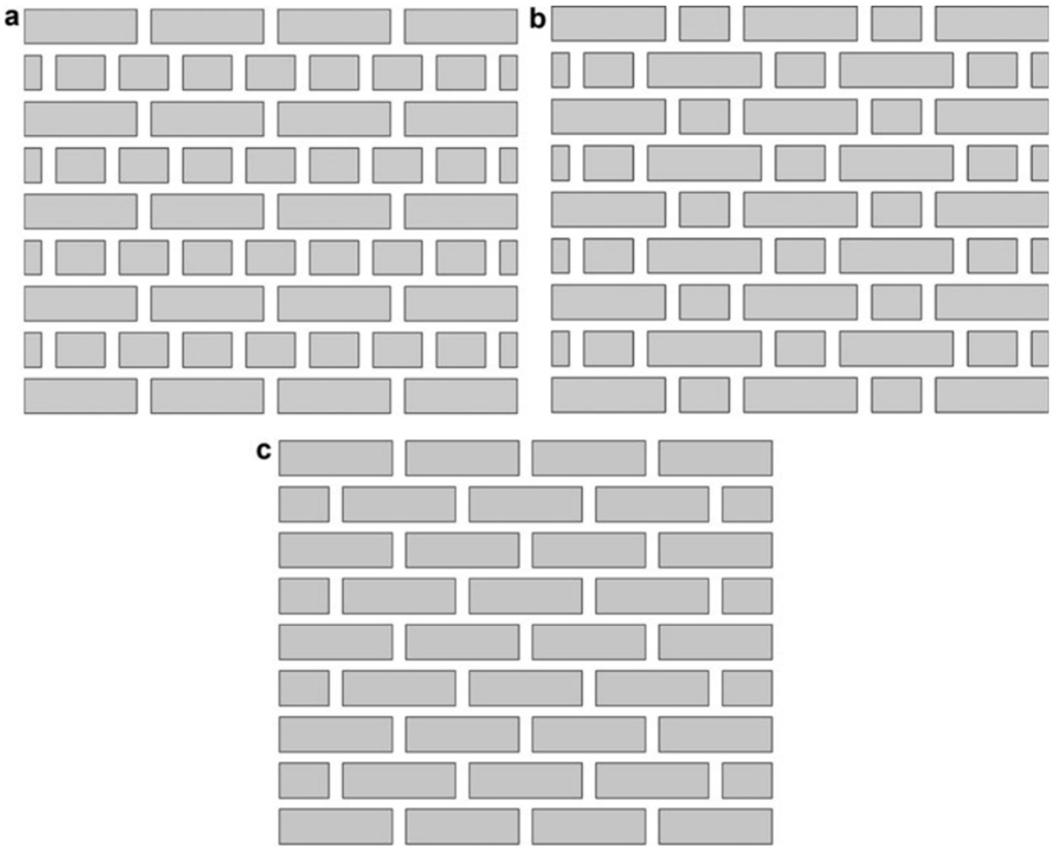


Figure 2 Different arrangements of brick masonry (a) English Bond (b) Flemish Bond (c) Stretcher Bond

The use of masonry as a building material is prominent in the modern construction practices globally. It is a configuration of units arranged in a particular courses that share a bond, usually with mortar in between. Masonry construction can either be with or without reinforcement bars depending on what is being constructed or built, and in defining this composite material, it is important to characterize each of the constituents. There are two approaches to modeling of masonry structures known as micro and macro modeling usually implemented in conjunction with other superior nonlinear analysis. The methods let themselves for seismic design and assessment of unreinforced masonry buildings in a constructive way, however the way that utilizes them depends on whether the certain building possesses box behavior in a seismic event. In other words, it is necessary for the analysis and design of masonry structures with experiments to characterize the behavior effectively and this knowledge can be obtained from literature.

1.2 MASONRY MATERIALS

STONE BRICKS

In the early ages, people have started adopting natural stones and bricks in their construction. In this centuries, the usage has been developed and adopted and used in many forms all over the world considering the culture and time factor. In most historical architectural projects the most common construction material used is stone and brick and in this case they can be laid in a bare form with no mortar or else they can be in combination with mortars. Historical construction involves physical structures that were developed before the arrival of modern cement, particularly Portland cement that emerged at the close of the nineteenth century. Nowadays, these materials are not incorporated or utilized in a building project as earlier due to continuous improvement of other forms of structural materials including concrete and steel. They are widely applied for non-load bearing situations. [3]

One must run experimental tests in order to determine the mechanical characteristics of any material or structure in question. In this way, it becomes feasible to watch the material and see how it responds from the undamaged situation and then progress on to the peak and then watch beyond the peak. It is crucial to complement the CSD with index information and mechanical properties for a comprehensive description and knowledge of the material's behavior. On numerous occasions, these material characterizations are also useful when employing accurate numerical models. There are a large number of techniques developed that allow calculating numerical results only if there is sufficient experimental data to do so. Hence, gathering the material data which are utilizable for advanced various higher non-linear numerical models is paramount.

Resistive tests for historical constructions are relatively destructive in nature and nearly impracticable. NDT is a valuable methodology and information-supporting tool, but its results are insufficient and unconvincing. Thus, testing samples made from the similar materials being used in historic constructions is more useful. An instance is that tests can be conducted on; natural stone and brick clay specimen, natural stone prisms, brick clay prisms, dry stone masonry shear wall.

The results provide valuable information on material **stress-strain behavior**, **cyclic behavior**, **stiffness degradation evolution**, **hysteretic energy dissipation**, **interaction laws**, and **failure modes**.[3]

Figure 3 Stone Masonry Structure (Hakka Indenture Museum)

CLAY BRICKS

Clay brick structural system does involve using specific types of clays that at one time are moulded into various shapes although cutting can also be used and are then put in ovens till they turn red. The firing process of the earth-plastered building material makes it to have good weathering properties as well as compressive strength. They have been used for centuries in building dwellings, houses, viaducts as well as any other structure that can be erected. [4]

MORTAR

Historic mortars are composite materials, comprised of hydraulic or aerial binding material, or a mixture of binding materials, aggregates – not always in crystalline form – and additives, passive or active, which react with the binding material and are modified during their setting, hardening and ageing. The main components used in ancient mortars are

- The first binder produced by humans was Gypsum. This was obtained by firing chalky rocks at a temperature range of 130-170°C. It has been used for centuries by the Romans, Greeks and others due to its ease of mixing and cost-effectiveness. However, its performance was not as good as lime.
- Hydrated lime is a type of binder that was previously used in the form of slaked lime. It was obtained by firing very hard compact stones that were available in the local area. For economic reasons, the stones available in the area were used, with the best ones being selected for optimal results. The mixing process required more lime because it required higher firing temperatures (around 900°C).
- During the Roman era, great significance was attached to the use of aggregates in mortar mixing. The reason for this was twofold. Firstly, it was a cost-effective measure to dilute the expensive binder with sand, ground stone and pebbles. Secondly, the inclusion of aggregates in the mortar reduced the incidence of shrinkage.

Pozzolana and cocciopesto are materials that are not classified as either a binder or aggregate. Pozzolana is a substance produced during volcanic eruptions and is primarily composed of silicon oxides, aluminum, iron, calcium, and magnesium oxides. The Romans learned from the Greeks and Etruscans that when mixed with lime, pozzolana would increase the material's mechanical strength, speed up hardening, and improve its resistance to water washout. Similarly, cocciopesto, which is finely ground bricks, was also used to achieve the same effect.

1.3 MASONRY PROPERTIES ACCORDING TO NTC 2018

This section presents the general overview of the evaluation of safety and identification of necessary measures for planning, implementation, and validation for existing buildings. The safety assessment and intervention planning must consider the following aspects of the construction:The safety assessment and intervention planning must consider the following aspects of the construction:

- It should represent efficient utilization of the knowledge available for construction at that period of time.
- A typical building may have some defects in its structure and this may be attributed to the design and construction of the building.
- It may have been confronted with numerous action variables including exceptional event impacts which have not been fully manifested.

• They may define the building's structures with signs of degradation and/or changes that are significant as viewed from original situation

Definition of mechanical properties of materials

Limited Tests (Prove Limitate)	The purpose is to allow the **identification of the types of masonry to the which to refer to for the purpose of determining the mechanical properties (from tables provided in C.8.5.II)**. This provides for the identification of the **wall texture** of and the estimation of the wall section.
Extended Tests (Prove Estese)	These are **visual, widespread investigations, accompanied by local insights.** Surveys are extended, both on the surface and in the wall thickness (also with endoscopies). Analysis of the **mortars** is also provided, together with non-destructive diagnostic surveys (penetrometric, sclerometric, sonic, thermographic, radar, etc.) and possibly supplemented by **moderately destructive techniques** (e.g. flat jacks), aimed at classifying the type of wall and its quality more accurately.
Exhaustive tests (Prove Esaustive)	In addition to what is indicated in the previous point, **direct tests on the materials are requested to determine their mechanical parameters**. The designer determines the type and quantity based on the knowledge needs of the structure. The tests should be performed either in situ or in the laboratory on undisturbed specimens taken in situ; The tests can be: • **Compression tests** (e.g. on walls or using double flat jacks); • **Shear tests** (e.g. compression and shear, diagonal compression, direct shear tests on the joint), The tests must be performed on all types of walls or to the elements which are supposed to be relevant for safety assessment.

Figure 4 Definition of mechanical Properties of Materials

NON DESTRUCTIVE TESTS

1 INFRARED THERMOGRAPHY

Infrared thermography refers to thermal imaging method of testing skills used on materials and structures. It is based on the principles of taking temperature readings at surface area through the use of an infrared camera. Thus, when utilized to measure emitted radiation, it can establish the presence or otherwise of defects, or other ground abnormality. This technology means that it is possible to detect various compositions of the masonry or even the existence of deterioration like presence of humidity or crack.

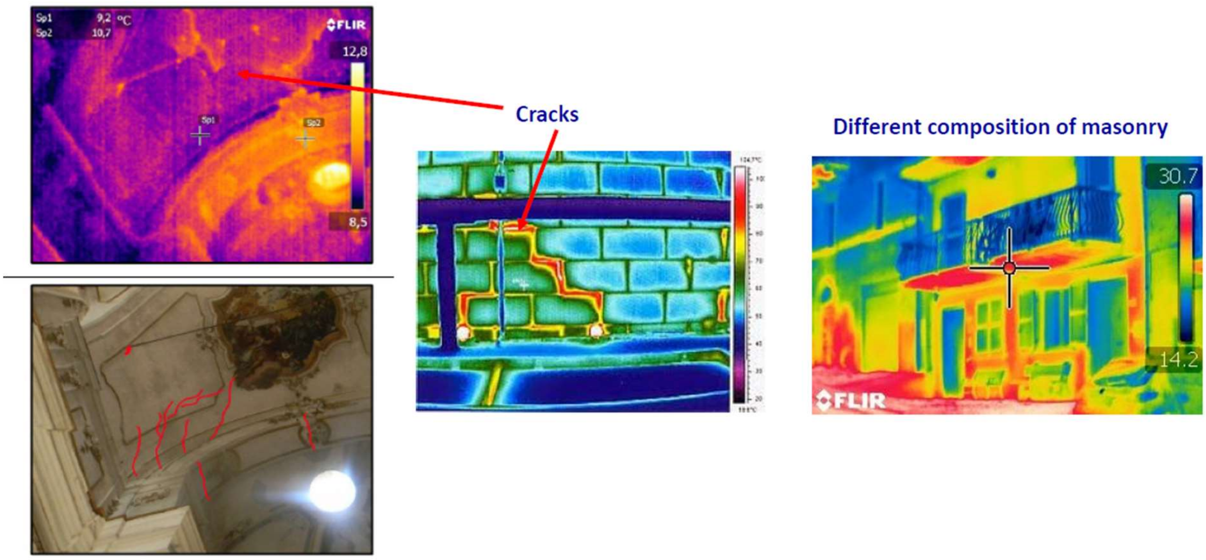


Figure 5 Infrared Theromography

2. GEORADAR

Other equipment used in this process are transmitter, receiver, control unit and magnetic recorder and graphic signal reproducer. WiFi employs certain forms of electromagnetic waves called wireless waves with a high-frequency range of 100 MHz to 1GHz. This equipment is used to establish the presence of cracks behind plasters that are invisible and it also informs on the depth of the crack, and the kind of material behind it for instance; wooden, steel and others.

Figure 6 Georadar

SEMI DESTRUCTIVE TESTS

1 DOUBLE FLAT JACK TEST

The double flat-jack test is a commonly used technique for assessing the structural properties of existing masonry structures. Horizontal slots are made in the masonry, spaced no more than 1.5 times the size of the flat jack. Two flat jacks are then inserted into these slots and pressurized using a hydraulic pump. The single flat jack assesses the acting normal stress.

The double flat jacks evaluate mechanical parameters, including the elasticity modulus of the masonry material.

Procedure:

- The first cut allows measurement of stress in a small area by inserting a flat jack.
- If additional results are needed, a second cut is made parallel to the first, and a second jack is inserted.
- The portion of masonry between the two cuts is loaded to simulate uniaxial compression stress.

Figure 7 Double Flat Jack test

CORE DRILLING

Core drilling, also referred to as diamond drilling, is a method that employs a rotary drill with a diamond drill bit. This technique is used to extract cylindrical cores from materials such as concrete, masonry, or other rigid substances. Core drilling is commonly used in construction, mining, and geological exploration due to its precision in extracting samples for analysis. The process involves rotating a tubular drill bit to cut a cylindrical core, allowing for accurate and undisturbed samples to be obtained for testing purposes.

PURPOSE:

Core drilling is used to cut large holes through masonry surfaces such as brick, concrete, cement, sandstone, stucco, and tile. It is the masonry equivalent of a hole saw for wood and plastic.

PROCESS:

A precise and non-invasive method utilized in extracting cores from concealed areas of historical structures involves the use of a rotating, diamond-tipped drill bit. This approach ensures that clean and accurate holes are made, enabling the extraction of cores while minimizing structural damage and preserving the overall integrity of the historical site.

Figure 8 Core Drilling

DESTRUCTIVE TESTS

1 IN-SITU COMPRESSIVE TEST

METHOD:

- Thin, bladder-like flatjack devices are installed in saw-cut mortar joints within the masonry wall.
- These flatjacks are designed to measure the in-situ compressive stress within the solid masonry units.
- The test provides a relatively non-destructive means of evaluating masonry properties in place.

ADVANTAGES:

- Semi-destructive: The test doesn't cause significant damage to the structure.
- Efficient: Execution times are short.
- Cost-effective: It provides valuable information without extensive expenses.

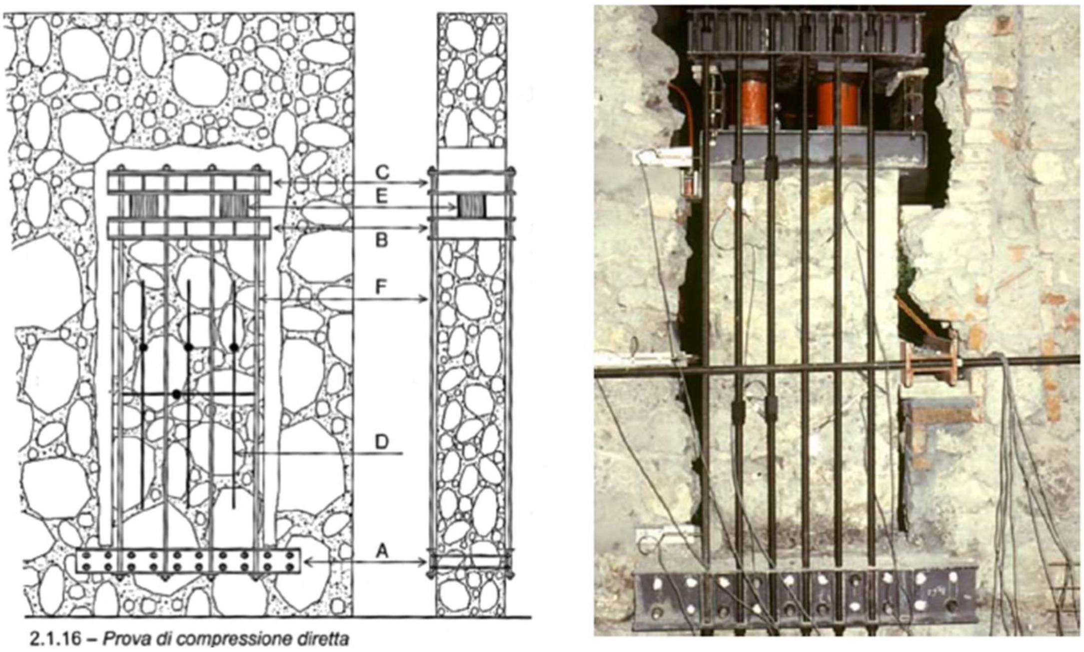


Figure 9 In situ Compressive Test

2 IN SITU SHEAR TEST

In-situ shear tests on masonry play a crucial role in assessing the shear behavior of existing masonry structures. Here's what you need to know:

PURPOSE:

The information presented below outlines the various testing methods employed to assess the shear strength and modulus of masonry within a structure. These testing methods are essential for gaining comprehensive insights into the structural behavior of masonry elements, which in turn, are crucial for conducting thorough seismic vulnerability assessments and devising effective strengthening interventions.

TESTING METHODS:

1. **Masonry Joint Shear Strength**: ASTM C 1513 sets a standard method to evaluate the shear strength of masonry joints. This method focuses on acquiring local information related to individual joints, which is integral in understanding the behavior of masonry assemblies under shear loading conditions.

2. **Diagonal Compression Tests:** These tests serve as a valuable tool for gaining insights into the overall shear response of masonry walls. By subjecting masonry wall specimens to diagonal compression tests, researchers and engineers can obtain comprehensive data regarding the shear behavior and resistance of the entire wall assembly, enabling a more thorough assessment of its structural integrity.

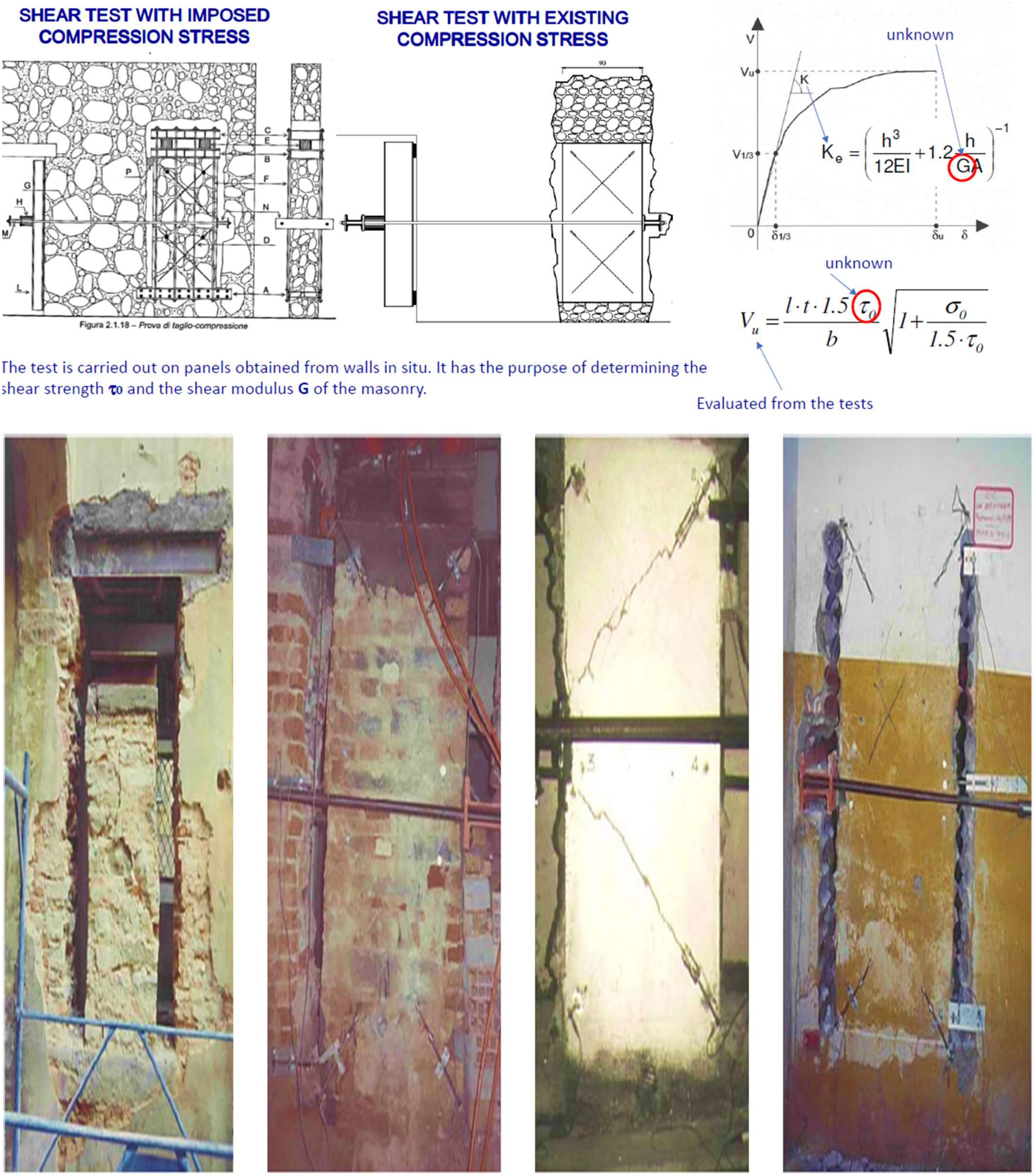


Figure 10 Diagnol Compression Test

3 LABORATORY NORMAL COMPRESSIVE TEST

The test is conducted in the laboratory. Specimens can be taken from the site or created in the laboratory using the same bricks and mortar. The test helps determine the stress-strain response and the peak strength.

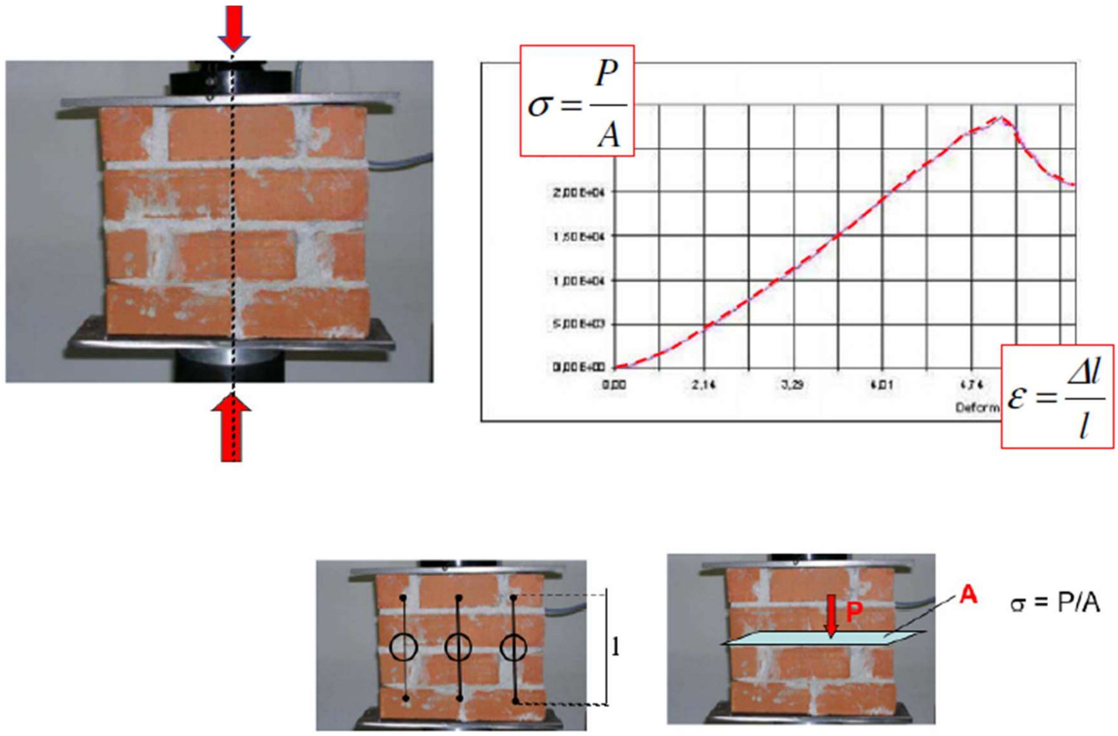


Figure 11 Normal Compressive test

4 LABORATORY SPLIT TEST ON MASONRY CORES

Laboratory split tests on masonry cores are an important way to understand the mechanical properties of masonry materials, especially in the context of existing structures. Here's an overview of the process:

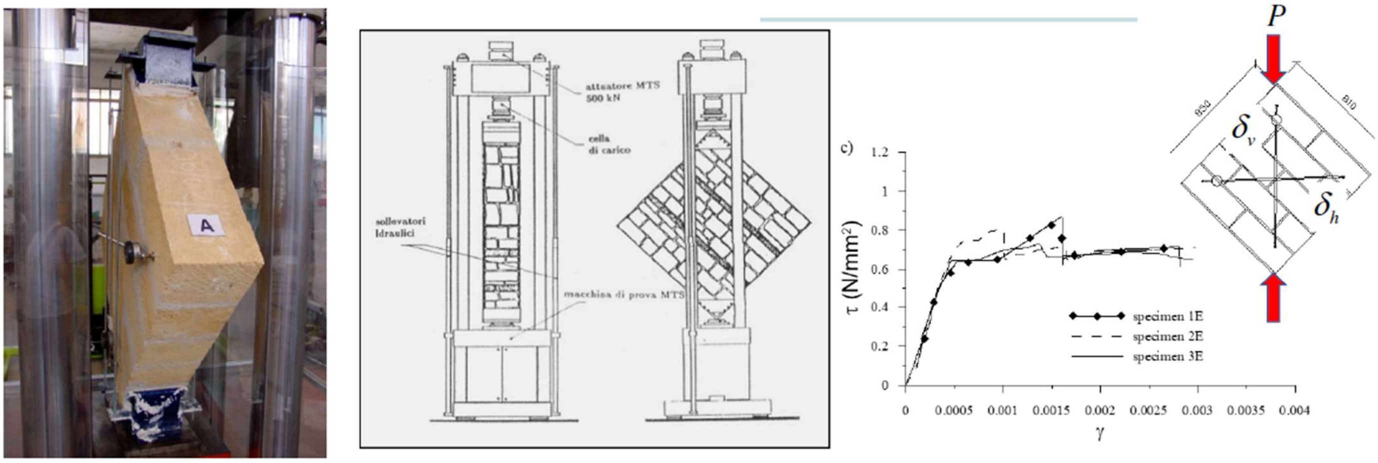
METHODOLOGY:

- Core Extraction: Cylindrical samples (cores) are carefully extracted from existing masonry walls using in-situ core drilling techniques.
- Symmetry Plane Splitting: The cores are then split along a symmetry plane to assess their behavior under shear stress.
- Axis-wise Compression Tests: In addition, compression tests can be conducted on rectified core specimens.

CHALLENGES AND BENEFITS:

- Preserving Integrity: It can be difficult to extract large prismatic samples from existing buildings due to the need to preserve structural integrity.
- Low Strength Materials: Historical materials often have low strength and poor bonding at mortar-unit interfaces, presenting challenges.

- Effective Characterization: Despite these difficulties, laboratory split tests on cores provide an effective way to understand the mechanical properties of existing masonry structures, including historical ones.



The test is carried in the laboratory.
Specimens can be withdrawn in situ or built in the laboratory using the same bricks and mortars. The test allows determining the tangential stress- sliding strain response and the peak shear strength.

$$\tau = \frac{P}{A\sqrt{2}} \qquad \gamma = \frac{\delta h + \delta v}{d}$$

Figure 12 Split Test on Masonry Cores

1.4 DEFINITION OF MECHANICAL PROPERTIES OF MASONRY

INTRODUCTION:

The conservation and preservation of historic buildings affords many challenges to those who aim to retain our building heritage. In this area, the knowledge of the mechanical characteristics of the masonry material is fundamental. However, mechanical destructive testing is always expensive and time-consuming, especially when applied to masonry historic structures. To overcome such kind of problems, a lot of investigations done.

1. THE QUALITY OF MASONRY

Historic masonry is not the result of an industrial and controlled process, in other words, to engineering process it is more an artisan product, depending on many factors (availability of the constituent materials, period of construction, importance of the building, skills of the masons, etc.). The assemblage of the two constituent materials (mortar and masonry units), either in courses or not, leads to the creation of a composite material, with elevated nonlinear stress-strain characteristics, very low tensile strength, non-homogenous and non-isotropous. Therefore, we, Structural engineers are aware of the difficulties in modeling historic buildings using FEM (Finite Element Method) methods.

according to the reference [4], The seismic behavior of a historic masonry building can be classified as it follows:

1. The material is very low quality of the masonry, the only possible collapse mechanism of the building is due to the disaggregation/crumbling of the masonry material (i.e. during the quake, wall macro-elements cannot develop).
2. the quality of the masonry material is good, and this can resist to the seismic forces without crumbling, cracking causes the formation of macro-elements of masonry joined together or arranged in a manner that permits them to move relative to one another, similarly to a kinematic chain.

2. TYPES OF MORTAR:

As mentioned in [5], there's 2 types of mortars (JMA, JMB). While, they are different in proportions of their components, and preparation process of this material. In the same reference, it was mentioned that mechanical properties of JMA is better two times than JMB.

3. TYPES OF MASONRY:

The different sizes of blocks and stone are used, together with pieces of brick, to fill the uneven gaps remaining among the stones and to obtain a kind of regularization. bricks are used to make horizontal layers gaining a better effectiveness in the irregular stonework.

According to ref [5], there are five types of masonry are mentioned as following:

– Mu1: stone masonry assembled with a good strength mortar (Fig. a): it is characterized by partially irregular stone pieces and by accurate execution that strives to achieve a horizontal layer. The masonry arrangement appears enough effective thanks to a correct use of the medium size blocks (w = 10–30 cm, h = 5–20 cm, d = 5–20 cm) assembled with JMA type mortar. The use of Mu1 masonry characterizes the original earliest residential cells. this type is mostly found at the ground floor and at the basement. For these reasons, the type Mu1 should be the oldest within the identified types.

– Mu2: stone masonry assembled with a low strength mortar (Figs. b): it is characterized by a collection of quite irregular, rounded off, roughly hewn stone blocks of variable size, bound with mortar of JMB type. The texture is certainly coarser than in the Mu1 case. The blocks (w = 10–25 cm, h = 5–15 cm, d = 5–20 cm) are mixed with rubbles to fill the gaps among the blocks, absent any cross connections. This type is recognizable in several walls of the buildings, exclusively at the ground floor and at the basement. For these reasons, the Mu2 type as well as the Mu1 type should belong to the oldest period.

– Mu3: small and irregular stones masonry assembled with a low strength mortar (Figs. c): it consists of a mass of materials, held together by the relevant contribution of JMB mortar. It is made of irregular stone blocks of various dimensions (w = 5–20 cm, h = 5–15 cm, d = 5–15 cm), where small sizes prevail, mixed with stone chips, bricks, bricks chips and roof tiles. This type of masonry is present in many parts of the building ground floors used as stables, pigsty, poultry house or as woodshed.

– Mu4: regularized stone and brick masonry assembled with a good strength mortar (Figs. d): it is made up of irregular and roughly hewn stone blocks, mixed with stone chips, bricks and roof tiles. They are bound with JMA type mortar. The sizes of the stone blocks are (w = 10–25 cm, h = 5–15 cm, d = 10–25 cm). Despite the irregularity of the blocks, the layers are arranged with some bricks or smaller stone pieces to achieve a horizontal layer. The better selection of materials and the attempt to pursue a building rule, enhanced by the attempt to create some cross connections by bricks. It is usual to find such masonry as a new addition or as a reconstruction of part of the walls in the residential building cells.

– Mu5: stone masonry improved by brick layers assembled with a good strength mortar (Figs. e): it is a mixed masonry, composed by layers of partially irregular stone blocks interrupted by a horizontal layer of bricks. The stone layers are like Mu1 type and are overlapped with courses of bricks (usually two layers of bricks per course). The presence of horizontal layers, the partial cross connection achieved by the brick work, and the use of JMA type mortar, certainly improve the mechanical behavior of the masonry.

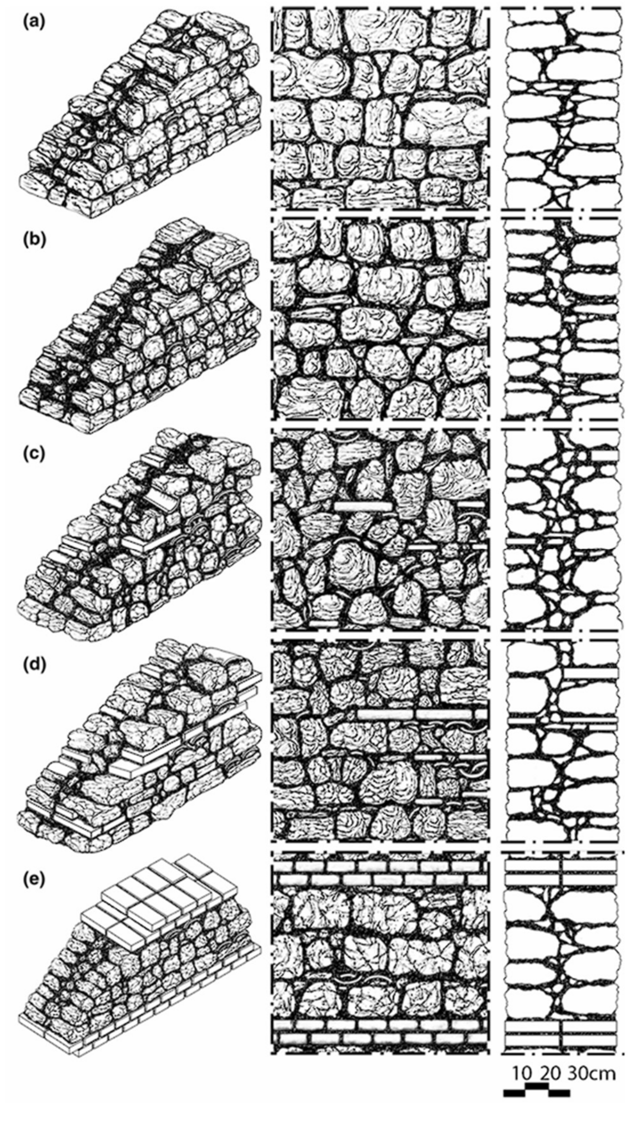


Figure 13 Plan, elevation,and axonometric cross-section of masonry types: a Mu1, b Mu2, c Mu3, d Mu4, and e Mu5 [5]

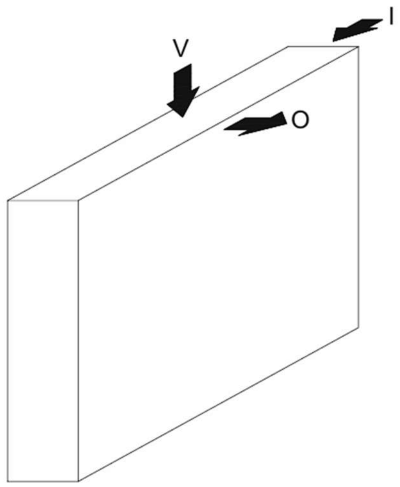
MECHANICAL PROPERTIES

The mechanical properties of masonries depend on many factors, such as properties of components (blocks and mortar), blocks shape, volumetric ratio between components and wall texture. an actual evaluation of the mechanical properties can be made only by in situ tests, as highlighted in [6]. Nevertheless, In-situ tests with semi-destructive methods are not always performable, thus an assessment of the mechanical properties of masonry walls can be carried out based on qualitative criteria, despite a certain level of approximation. The method, named MQI, which consists of the evaluation of the presence, the partial presence, or the absence of certain parameters that define the ‘‘rule of the art’’.

THE QUALITY MASONRY INDEX (MQI):

The method for the calculation of the MQI, of the historic wall is based on 8 parameters. The combination, according to eq below, of the 8 numerical values gives the value of MQI. As it can be noted from eq. (1), the r and SM parameters are factored by the summation of the values assigned to the remaining six parameters to produce the value of the final index representing the quality of the masonry, MQI

$$MQI = r \times SM \times (SD + SS + WC + HJ + VJ + MM) \qquad (1)$$



Because a single wall panel could be subjected to varying loading conditions which directly affect the masonry quality, the values assigned to the 8 parameters depend on the loading condition acting on the wall under consideration. As shown in figure 1, Three loading conditions were considered: V (vertical static loads), O (out-of-plane static and dynamic loads) and I (in-plane dynamic loads).

Fig1: Load conditions: V vertical static loads, O out of plane static and dynamic loads, I in-plane dynamic loads.[7]

4.1.The parameters to consider for the assessment:

1. Mechanical characteristics and quality of masonry units (SM parameter).
2. Dimensions of the masonry units (SD parameter)
3. Shape of the masonry units(SS parameter).

4. Level of connection between adjacent wall leaves / headers (WC parameter).
5. Horizontality of mortar bed joints (HJ parameter).
6. Staggering of vertical mortar joints (VJ parameter).
7. Quality of the mortar / contact between masonry units / pinnings (MM parameter).

Finally, the MQI value can then be used to obtain, through a correlation procedure, an estimation of the mechanical parameters (compressive strength fm, shear strength $\tau 0$ and moduli of elasticity E and G) of existing masonry. Low outcomes in one of the 8 parameters may lead to different variations of the masonry strengths depending on the loading conditions.

The estimation requires an in-depth knowledge of historical construction methods due to the demands placed upon the engineer to categorize each parameter under three possible outcomes: Fulfilled—F, Partially Fulfilled—PF, Not Fulfilled—NF. As shown in the Table, it illustrates the criteria for application of these categories relative to the seven parameters.

Parameter	Possible Outcome NF	PF	F
MM Mortar properties	– Very weak mortar, dusty mortar with no cohesion. – No mortar (dry rubble or pebble stonework). – Large bed joints made of weak mortar (thickness comparable to stone/brick thickness). – Porous stones/bricks with weak bonding to mortar.	– Medium quality mortar, with bed joints not largely notched. – Masonry made of irregular (rubble) stones and weak mortar, but with presence of pinning stones.	– Good quality and non-degraded mortar, regular bed joint thickness or large bed joint thickness made of very good quality mortar. – Masonry made of large perfectly cut stones with no mortar or very thin bed joint thickness.
WC Wall leaf connections	– Small stones compare to wall thickness. – No headers.	– For double-leaf walls: • Presence of some headers; • Wall thickness larger than stone large dimension.	– Wall thickness similar to stone large dimension.
SS Stone/brick shape	– Rubble, rounded or pebble stonework (predominant) on both masonry leaves.	– Co-presence of rubble, rounded or pebble stonework and barely/perfectly cut stone and bricks on both masonry leaves. – One masonry leaf made of perfectly cut stones or bricks. – Masonry made of irregular (rubble, rounded, pebble) stones, but with presence of pinning stones.	– Barely cut stones or perfectly cut stones on both masonry leaves (predominant). – Brickwork.
SD Stone/brick dimensions	– Presence of more than 50% of elements with large dimension < 20 cm. – Brick bond pattern made of only head joints.	– Presence of more than 50% of elements with large dimension 20-40 cm. – Co-presence of elements of different dimensions.	– Presence of more than 50% of elements with large dimension > 40 cm.
VJ Stagger properties of vertical joints	– Aligned vertical joints. – Aligned vertical joints for at least 2 large stones. – Solid brick wall made of only headers.	– Partially staggered vertical joints (vertical joint between 2 brick is not placed in the middle of adjacent upper and lower brick).	– Properly staggered vertical joints (vertical joint between 2 stones is placed in the middle of adjacent upper and lower stone).
HJ Horizontality of bed joints	– Bed joints not continuous.	– Intermediate situation between NF and F. – For double-leaf wall: only one leaf with continuous bed joints.	– Bed joints continuous. – Stone masonry wall with bricks courses (distance between courses < 60 cm).
SM Stone/brick mechanical properties and conservation state	– Degraded/damaged elements (>50% of total number of elements). – Hollow-core bricks (solid < 30%). – Mud bricks. – Unfired bricks.	– Presence of degraded/damaged elements (≥10%, ≤50%). – Hollow-core bricks (55% ≥ solid ≥ 30%). – Sandstone or tuff elements.	– Un-damaged elements of degraded/damaged elements < 10%. – Solid fired bricks. – Hollow-core bricks (55% < solid). – Concrete units. – Hardstone.

Figure 14 Criteria for the analysis of the seven parameters.[4]

	Vertical loading (V)			Horizontal in-plane loading (I)			Horizontal out-of-plane loading (O)		
	NF	PF	F	NF	PF	F	NF	PF	F
SM	0.3	0.7	1	0.3	0.7	1	0.5	0.7	1
SD	0	0.5	1	0	0.5	1	0	0.5	1
SS	0	1.5	3	0	1	2	0	1	2
WC	0	1	1	0	1	2	0	1.5	3
HJ	0	1	2	0	0.5	1	0	1	2
VJ	0	0.5	1	0	1	2	0	0.5	1
MM	0	0.5	2	0	1	2	0	0.5	1
r	0.2	0.6	1	0.1	0.7	1	1	1	1

Figure 15 represents the Numerical values for the assessment of the MQI [4]:

	Compressive Strength f_m (MPa)		Shear Strength τ_0 (MPa)		Young's modulus E (MPa)		Shear Modulus G (MPa)		Good quality mortar	Brick courses	Transversal connection
	Min	Max	Min	Max	Min	Max	Min	Max			
Irregular stone masonry (pebbles, erratic, irregular stones)	1.0	2.0	.018	.032	690	1050	230	350	1.5	1.3	1.5
Roughly cut stone masonry	2.0	3.0	.035	.051	1020	1440	340	480	1.4	1.2	1.5
Barely cut stone masonry, properly dressed	2.6	3.8	.056	.074	1500	1980	500	660	1.3	1.1	1.3
Irregular softstone masonry	1.4	2.2	.028	.042	900	1260	300	420	1.5	1.2	1.3
Squared softstone masonry	2.0	3.2	.040	.080	1200	1620	400	500	1.6		1.2
Squared hardstone masonry	5.8	8.2	.090	.120	2400	3300	800	1100	1.2		1.2
Brickwork (lime-based mortar)	2.6	4.3	.050	.130	1200	1800	400	600	1.27		1.3
Hollow bricks masonry (cement mortar)	5.0	8.0	.080	.170	2500	5600	875	1400	1.2		

Figure 16 mechanical properties of masonry and multiplication factors in the Italian Building Code [4].

1.5 HISTORIC MASONRY TOWERS (ST. TORCATO CHURCH)

Masonry towers, characterized by their slender design and heavy self-weight load, face significant vulnerability during seismic activity. Gravity loads exert vertical stresses, placing substantial pressure on the materials and often approaching the compressive strength of the masonry. During earthquakes, the towers' slim profile can result in considerable flexural loads and lateral drift, further intensifying the risk of local damage or potential collapse. These structural characteristics contribute to the heightened susceptibility of masonry towers to seismic forces.

In the last ten years, there has been growing interest in creating and validating tools to assess how masonry towers behave under seismic loads. Previous studies have used a range of methods, from basic static analyses to complex dynamic analyses, to understand the global behavior of these structures. Researchers have also used various techniques to determine the mechanical properties of the materials, such as non-destructive or semi-destructive tests on-site, as well as laboratory tests on samples of historic materials.. Additionally, several studies have focused on studying the out-of-plane failure mechanisms for this specific structural typology to verify their ability in attaining a global behavior. [8]

Figure 17 St. Torcato Church located in Portugal

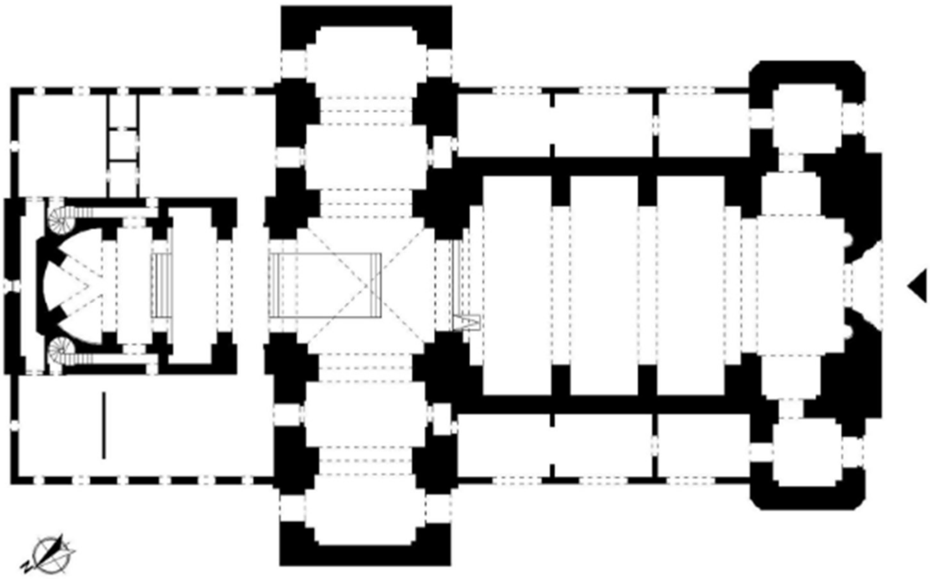


Figure 18 Plan view of the church

In this paper, the Finite Element Model of St. Torcato is developed using Point Cloud data. Different geometries are modelled by using python [9]

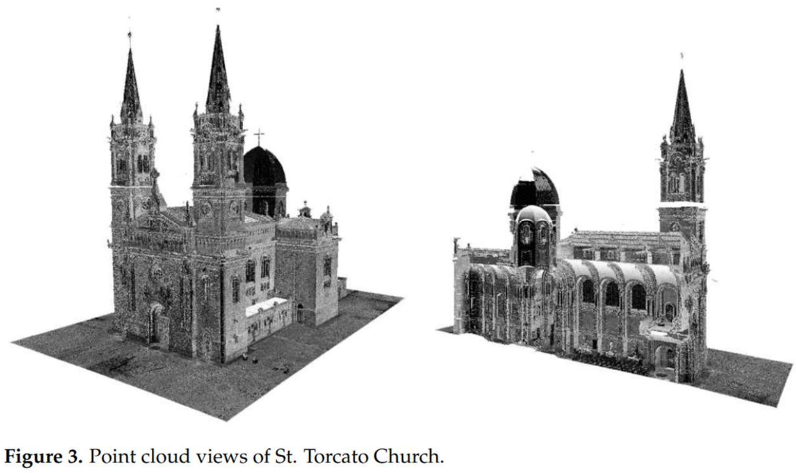


Figure 19 Point cloud of St. Torcato Church

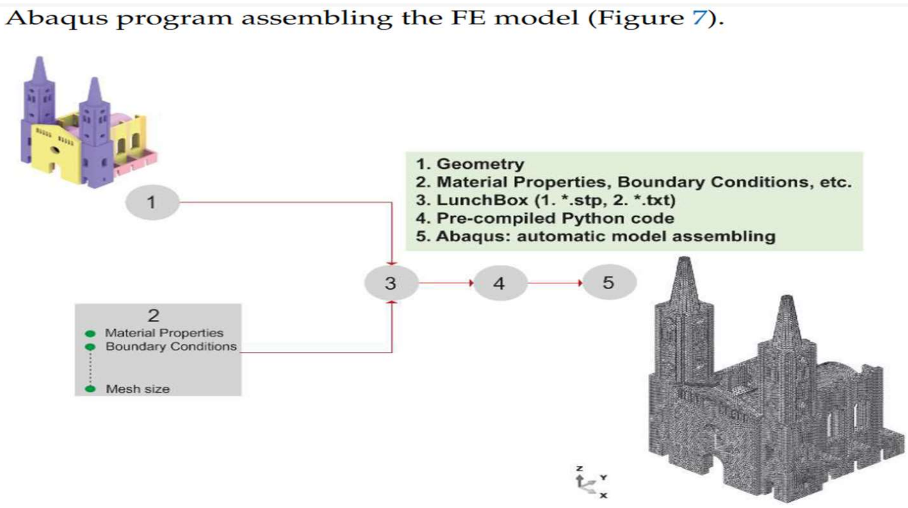


Figure 20 Workflow for FEM Modelling of the churc*h[9]*

- After getting the 3d model by using Grass Hopper it was transferred to Abaqus by using a plugin called Lunchbox.
- After providing the Material properties to Masonry they performed modal analysis on an unstrengthened Model (Without Retrofitting) [9]

  - They also performed modal analysis on the strengthened model with (Anchoring Systems + Micro piles+ Crack Injections) and compared the frequencies [9]

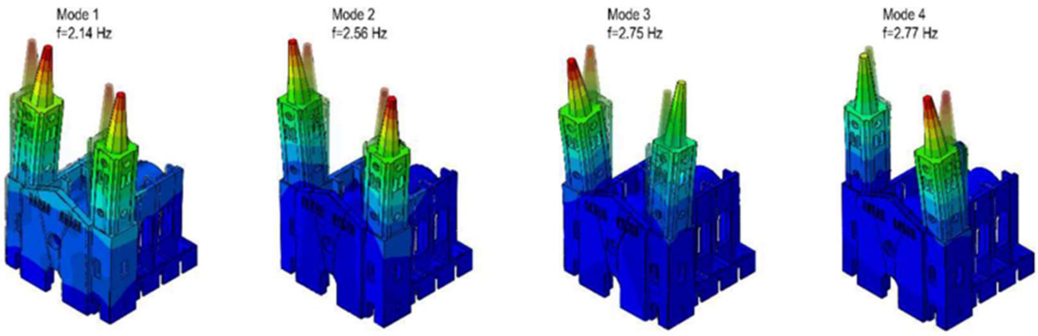


Figure 21 Mode shapes without retrofitting

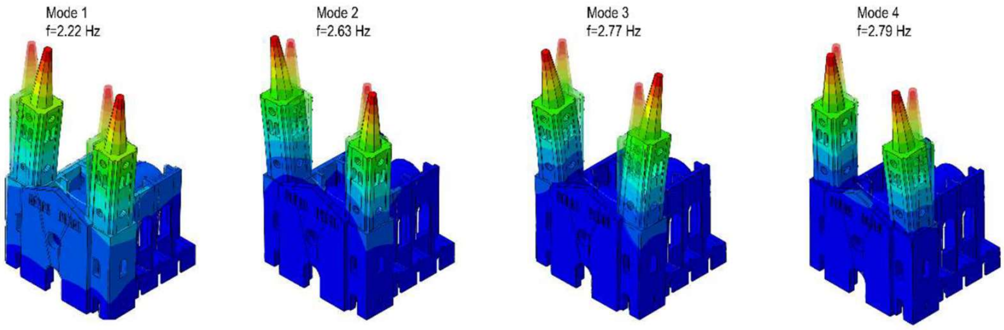


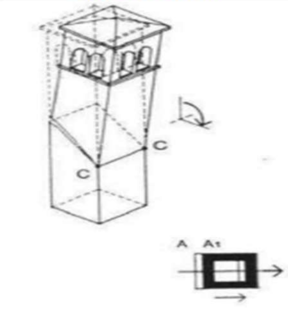
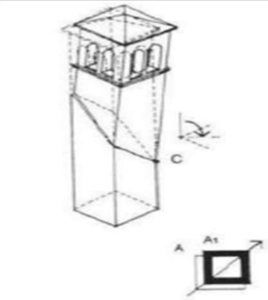
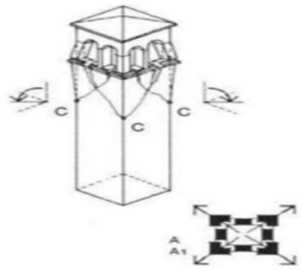
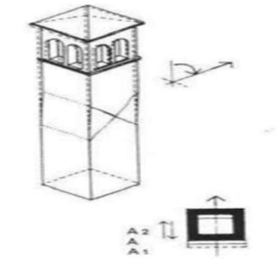
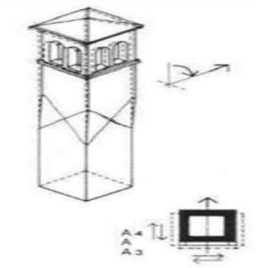
Figure 22 Mode shapes with interventions

- In particular, the first two modes are mainly affected by the interventions, i.e., +3.7% and +2.7%, because the strengthening design was devoted to locally increasing the towers' stiffness and decreasing their relative movement.[9]

This study highlights the significance of using a modeling approach based on point clouds and finite element analysis to determine mode shapes and to calibrate the model. The results indicate a slight increase in deflections and changes in frequency, demonstrating the implementation of digital twin technology and its importance in structural health monitoring.

1.6 TYPES OF FAILURES IN MASONRY TOWER

The seismic behavior of predominantly vertical structures, such as towers and bell towers, is influenced by specific factors. These factors include the degree of attachment of the wall panels, the slenderness of the structure, the possible presence of adjacent lower structures, and the presence of slender architectural elements (such as spires, bell vaults, and battlements) or vulnerable elements (such as bell cells) at the top. Vulnerability is also influenced by the presence of other types of damage, such as vibrations induced by bells or foundation problems.[10]

No	Cinematism	
1		Outward rotation of the upper wall (of the trunk) of the bell tower due to out-of-plane actions, with the formation of a cylindrical hinge with a horizontal axis or a spherical hinge at a point or an edge
2		
3		Outward rotation of "angled areas" around a hinge point formed on the angle itself, at the lower end of the part affected by the mechanism
4		Translation of the upper wall (of the trunk) of the bell tower, followed by its rotation
5		

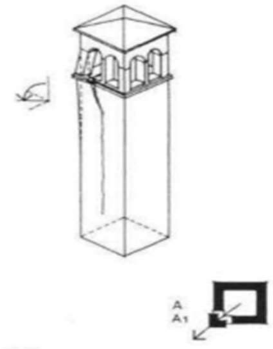
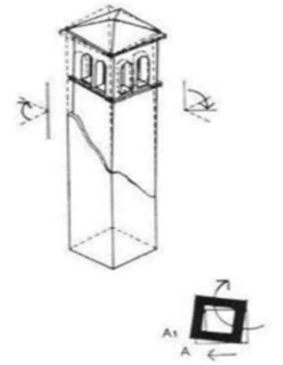
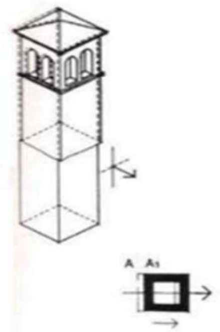
6		Outward rotation of one or more angles with horizontal rotation axis parallel to the side or diagonal
7		Rotation of the upper part (trunk) of the tower, resulting from the combination of a rotation around a vertical axis and a rotation around a horizontal axis
8		Translation of the upper part of the tower

Figure 23 Different types of Damage Mechanisms [10]

1.7 FINITE ELEMENT ANALYSIS

The field of computer-aided designing and drafting has become very advanced in the last 2 decades. In the industry related to buildings the CAD has provided efficient design and analysis technologies. High-performance programs are available to different universities for research and innovations in the field of structural engineering. [11].

FINITE ELEMENT ANALYSIS IN THE FIELD OF STRUCTURAL ENGINEERING

When we talk about Finite Element Analysis in the field of Structural Engineering. We consider a design of whole building in where there are different elements which are discussed as under

- Truss or bar Elements

- Planer Elements
- Nodes
- Rigid Links
- Supports
- Loads
- Analysis

TRUSS OR BAR ELEMENTS

Usually a structure consists of beams and columns. When a structures is designed in FEM softwares they represent beams and columns in the form of bar elements in which we can feed the data related to their properties such as dimensions, material properties etc.

Properties

- DOF: ux-uy-uz-rx-ry-rz
- Element output: axial force (Fx), torsion (Mx)
- 2 bending moments (My, Mz), 2 shear forces (Fy, Fz)
- Additional input: cross section properties

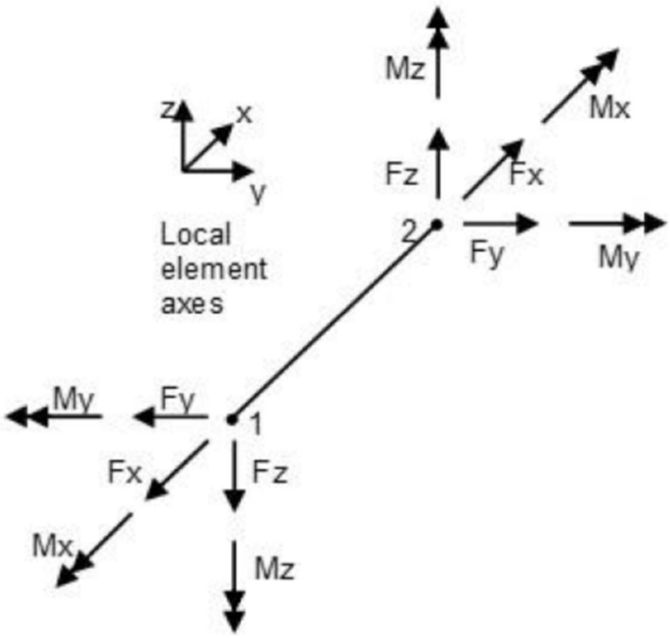


Figure 24 Beam Element

PLATE ELEMENTS

In structures when we need to analyze walls or any object with 4 sides we add the planer element which could be Plate or Shell. We provide dimensions and use material properties as required.

- DOF: ux-uy-uz-rx-ry-rz
- Element output: 8 internal actions
- (integral of tension in figure)
- Additional input: thickness (t)

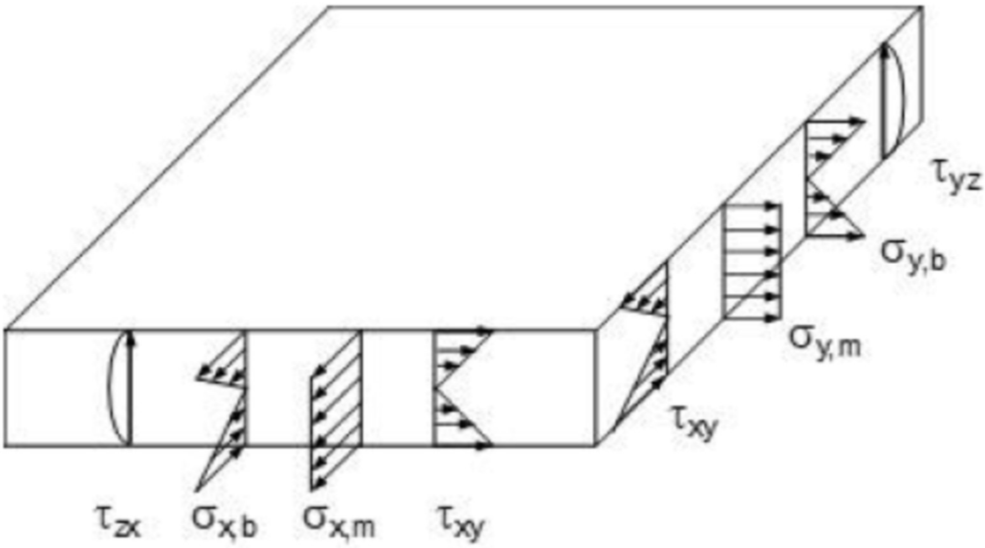


Figure 25 Plane Element

NODES

Nodes are the points at which two elements connect together. It also represents the end points of the elements. The beam elements have 2 nodes on its ends while the plane elements have 4 nodes on their ends

When a planer element is meshed so each mesh is connected with the help of nodes. We can add different properties to the nodes such as **releases** and **translations** in order to predict the accurate behaviour of structures.

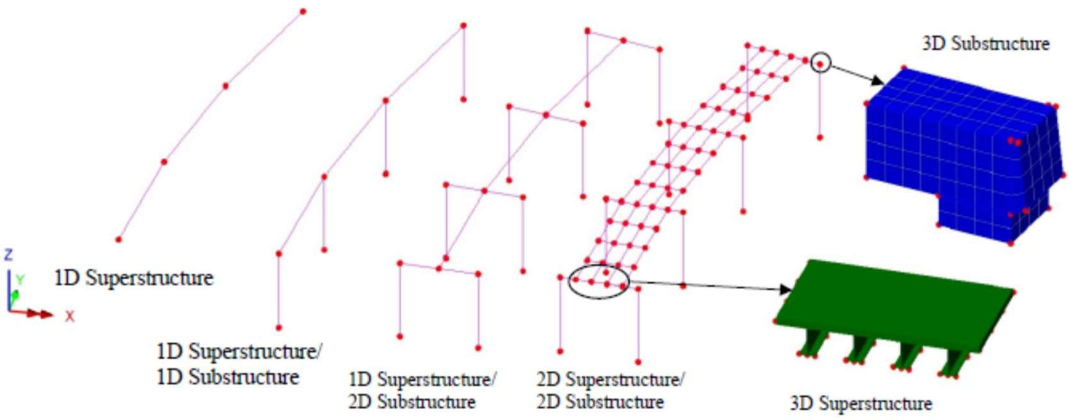


Figure 26 Nodes in a Model

RIGID LINKS

Rigid Links are used to connect two nodes of different beams together. It consists of master node and slave node. It has certain properties such fixed link, fixed in X,Y and Free in Z axis etc. When the master node translates the slave nodes follow it with the same translation. It represents the behaviour of the beams when they are connected with bolts to another member or any other supports.

- Element output: relative displacement between the nodes and
- forces exchanged between the connected body
- Additional input: depend on the link type

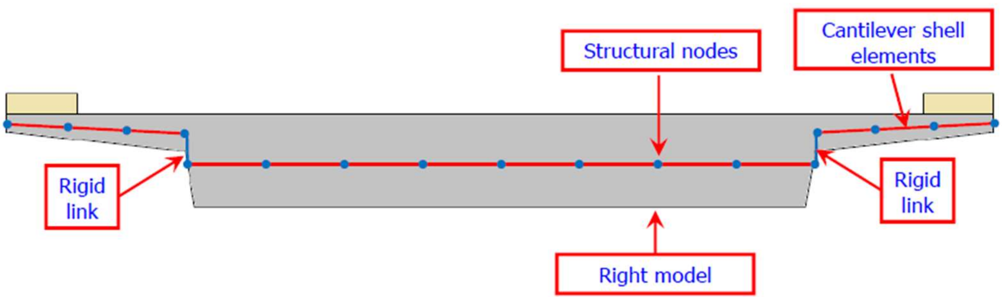


Figure 27 Rigid Links on a bridge model

SUPPORTS

Supports could be constraints and restraints. Usually they are fixed supports in any or all X,Y, and Z axis, Hinge supports with zero moment resistance and roller supports. They are critical aspects of Finite Element Modelling. Without the supports the structure would be unstable and fail.

LOADS

Loads are the major aspect of Finite Element Analysis. Without the proper loading we could not provide proper results on the behaviour of our structures. Some typical types of loading on the structure according to NTC 2018 are as follows,

- Dead Loads
- Live loads
- Seimic Loads
- Wind loads
- Snow loads

The equation used by NTC 18 is as follows:

$$\gamma_{G1}\mathrm{G1} + \gamma_{G2}\mathrm{G2} + \gamma_{P}\mathrm{P} + \gamma_{Q1}Q_{K1} + \gamma_{Q2}Q_{K2}\Psi_{02} + \gamma_{Q3}Q_{K3}\Psi_{03} + \ldots.$$

Where:

- G1: Structural permanent load
- G2: Non- Structural permanent load
- P: Action due to pre-compression (generally not considered)
- Q: Dominant and secondaries variable loads
- Ψ: Variable loads corresponding coefficient
- γ: Partial load coefficient

MODAL ANALYSIS

Modal analysis is a technique in engineering which is used to determine the natural frequencies characteristics of the structure. It takes into account the dynamic properties of the structure in terms of its natural frequencies, mode shapes and damping ratios.

- Natural frequency is the frequency at which the system oscillates in the absence of any driving or damping forces.
- Model shapes are the vibrations and torsions which the structure assumes due to the loads and properties.
- Damping ratio is a measure of how the oscillations in a system decays after a disturbance.

STEPS INVOLVED

- Construct a FEM of a structure which takes maximum physical details of the structure.
- Run the eigen value analysis in order to compute Mass and Stiffness matrix
- Select the number of modes usually 10 are taken.
- Run the analysis and check the natural frequencies of each modes.
- Check the mode shapes of the structure if they are irregular or some points are disconnected you can update the model by adding rigid links over disconnections.

- Compare the results with the experimental frequencies calculated through Time and Frequency domain algorathms.
- If the difference is much more then adjust the model because it has mistakes
- If the difference is less then adjust the masonry properties according to MQI tables NTC 2018. And add values in the range provided by NTC 18 untill the FEM frequencies match with the experimental Frequencies.

1.8 DIGITAL TWIN

A digital twin could therefore be described as an accurate replica of an object, process or a system that is used in what is termed as digital modeling to act as a ready reference for the actual physical model indicating how the model should perform. Digital twin refers to a virtual representation of a built structure which is utilized in structural engineering at the company to represent the structural and functional features of the physical built environment. Also, it is a dynamic model that integrates data obtained from other sources and used for further monitoring, analyzing, and enhancing.[12]

KEY CHARACTERISTICS OF A DIGITAL TWIN

HIGH FIDELITY REPRESENTATION:

A digital twin gives exactly the picture of the physical structure and most of the details can be observed here. These consist of the geometry, material, and the dynamics of the structure in relation to its design. Thus, Point cloud data and retrofitting drawings were used for Moletta tower for developing its Digital twin in the context of our study to address its geometric properties and structural detail.[13], [14]

REAL-TIME DATA INTEGRATION

What makes a digital twin unique is that it is a combination and integration of real-time data gathered from sensors as well as monitoring systems placed throughout the physical structure. Some of the data that can be measured are temperature, relative humidity, load stresses, vibrations, etc. This means that the flow of data is constant and the digital twin is always an updated model of the physical structure and its performance.

SIMULATION AND ANALYSIS:

Behind every digital twin is always the power of functioning and analyzing simulations and possibilities… The digital twin can be employed by engineers to run different tests based on the changes which can be observed from the various parameters of the situation, including dynamic loads, environments, and failure modes among others. This for enables prediction of the specific behaviour of the structure in certain situations, and to plan accordingly for prevention.[15]

OPTIMIZATION AND PREDICTIVE MAINTENANCE

Thereafter, the analysis and simulation data from the generated digital twin can aid in enhancing the productivity and reliability of the structure. Optimum maintenance can be planned since existing problems could be detected prior to the rise of high extent damages, hence postponing the need for maintenance thus improving the structure’s life cycle.[14]

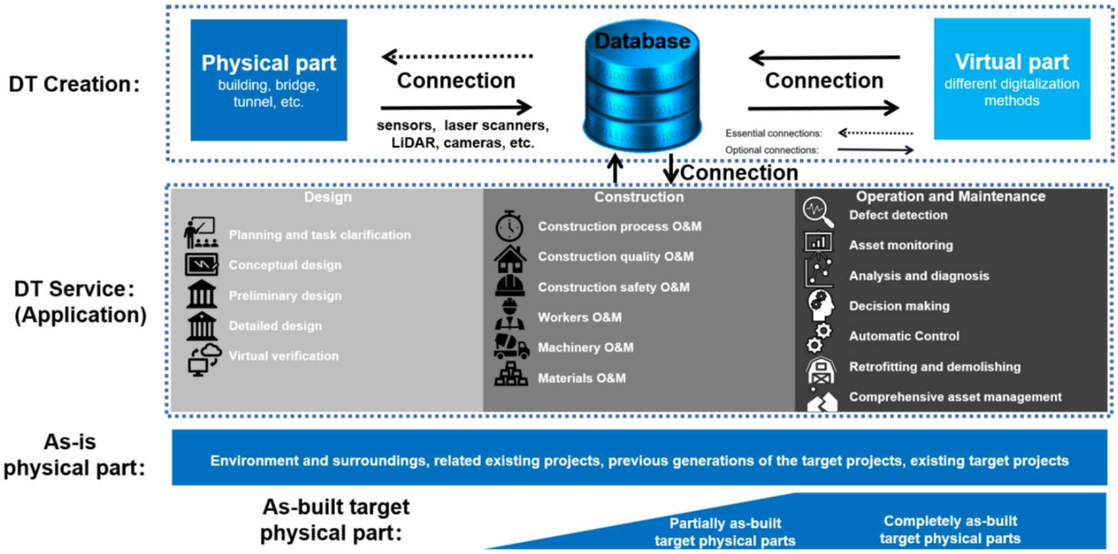
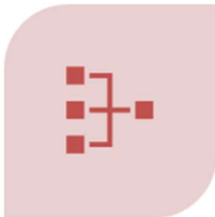


Figure 28 Digital twin Flow Chart

DIGITAL TWIN IS THE REPRESENTATION OF A REAL STRUCTURE IN SOFTWARE AS A BIM MODEL SUCH AS IN REVIT, ETC.;

THERE IS A DIFFERENCE BETWEEN ONLY A BIM MODEL OF A STRUCTURE AND A DIGITAL TWIN. A BIM MODEL CAN BE DEVELOPED FOR A NON-EXISTING STRUCTURE, BUT A DIGITAL TWIN IS A BIM MODEL OF AN **EXISTING STRUCTURE.**



A DIGITAL TWIN OF A STRUCTURE IS A VIRTUAL MODEL THAT REPLICATES THE PHYSICAL STRUCTURE IN REAL-TIME.

CHAPTER 2 CASE STUDY OF MOLETTA TOWER

2.1 TORRE DELLA MOLETTA

The Torre della Moletta, also known as Turris in Capite Circi or Turris de Arco, is a fascinating structure situated within the archaeological complex of the Circus Maximus in Rome. It is named after its proximity to a mill that was powered by the water of the Fosso di San Giovanni. The tower has been owned by the Frangipane family since at least 1145, showcasing its rich historical significance. It features a square plan and is constructed from tuff with limestone splinters, flint, and irregular courses of bricks, reflecting the building materials and methods of its time. Moreover, historical records suggest that the tower was once surrounded by modest buildings and was likely part of a fortification system that was dismantled in 1943, adding to its historical importance.[16]

The Circus Maximus, located in the Murcia Valley, has a rich history dating back to the time of Julius Caesar. Under his rule, the venue was transformed into a masonry structure, measuring an impressive 600 meters in length and 140 meters in width. It served as the main host for popular Roman competitive contests, including gladiatorial games and chariot races featuring the revered quadrigas. Additionally, the circus was used for various political, social, and religious gatherings, such as triumphal processions and public executions, providing insight into the diverse events held at the venue.[16]

Throughout its history, the Circus Maximus faced several challenges, including destruction by fire. However, it was almost entirely rebuilt during the rule of Emperor Trajan in the second century AD, with many of the structures we see today dating back to this period. Notably, in 357 AD, Emperor Constant II had a massive obelisk installed at the site, which is now located in the Lateran, adding an intriguing architectural element to the venue. While the Circus was in use until the first half of the sixth century, it was later repurposed as an agricultural area before becoming the location for the "Gazometro" plants and warehouses in the 19th century. The area then underwent significant transformation in the early 1900s when efforts began to create an archaeological walk in the region.[16]

Excavations during the 1930s revealed a large portion of the hemicycle and the remains of the Arch of Titus, shedding light on the historical significance of the site. Following World War II, the area was transformed into green space, with the ancient structures largely abandoned. However, a notable effort took place in 2016, when Roma Capitale, Capitoline Superintendence for Cultural Heritage, and Zetema Progetto Cultura undertook archaeological investigations and restoration interventions, resulting in the creation of new visitor routes with special lighting systems, allowing for enhanced exploration and appreciation of the rich historical heritage of the Circus Maximus and its surroundings. [16]

Figure 29 Torre Della Moletta

2.2 ENCOUNTERED PROBLEM WITH THE TOWER

Frequent concerts near the Moletta Tower have raised concerns about the vibrations affecting the structure. These events, which draw over 4500 people, involve significant activities such as jumping and loud noises from speakers. It is important to understand the impact of these vibrations on the tower's structural integrity. Therefore, our study focused on creating a digital Twin of the tower and conducting detailed analyses to assess the effects of these concert-induced vibrations.[16]

2.3 POINT CLOUD DATA OF MOLETTA TOWER

Point cloud data of Moletta Tower is collected by on different data points in a three-dimensional coordinate system. These points represent the external and internal surface of the tower or space and have specific X, Y, and Z coordinates that accurately describe a part of the object's surface. When combined, these points create a "cloud" that forms a detailed 3D model of the Tower.[17]

Our team conducted a thorough site visit to Moletta Tower. We strategically placed sensors inside and outside the tower to collect detailed structural geometry.

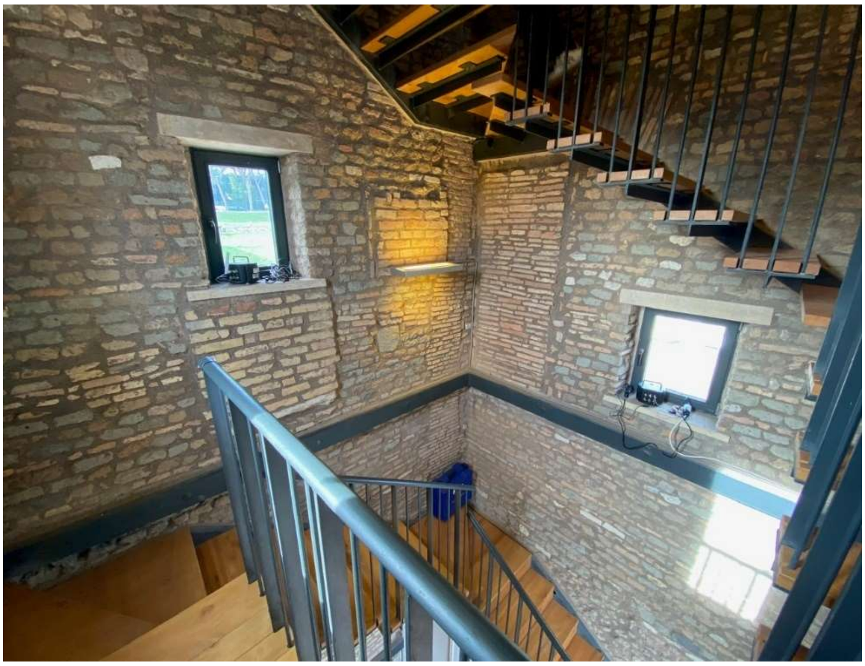


Figure 30 Inside view of the tower

Figure 31 Sensors for collecting the Point clouds

2.4 AUTODESK RECAP PRO (POINT CLOUD OPTIMIZATION)

After collecting the point cloud data from the site with LiDAR sensors, we inputted them into Autodesk Recap Pro. This software helps us remove glares on the mirrors and unwanted point clouds for 3D modeling in Revit. Autodesk Recap Pro provides us with an .rcp file which is compatible with Revit for 3Dmodeling.

Figure 32 Point cloud of the entire Circus Massimo

Figure 33 Point clouds of the tower from all directions

2.5 HISTORY OF RETROFITTING INTERVENTIONS ON THE TOWER

We have received a document from the Sovrintendenza Capitolina ai Beni Culturali, the Dipartimento Programmazione e Attuazione Urbanistica, and ATI (Associazione Temporanea di Imprese). This document contains several drafts for the retrofitting of Torre della Moletta. These drafts can help us identify the types of beams and provide details related to structural modeling. Here is a brief introduction to these departments.

Dipartimento Programmazione e Attuazione Urbanistica: This department is responsible for urban planning and implementation in Rome, overseeing the planning, development, and regulation of urban spaces to ensure sustainable and strategic growth of the city's infrastructure.

Zetema Progetto Cultura S.R.L.: Zetema is a company that oversees cultural projects in Rome. It is involved in organizing and executing cultural events, exhibitions, and restoration projects, with the aim of enhancing and promoting the city's cultural heritage.

ATI (Associazione Temporanea di Imprese): ATI, or Temporary Association of Companies, refers to a consortium of companies that come together to carry out specific projects. In this case, ATI is responsible for the executive design and construction work, coordinating various aspects of the project.

ROMA

SOVRINTENDENZA CAPITOLINA
AI BENI CULTURALI
Sovrintendente: dott.Claudio Parisi Presicce

DIPARTIMENTO PROGRAMMAZIONE E
ATTUAZIONE URBANISTICA
Direttore: Dott.ssa Annamaria Graziano

APPALTO INTEGRATO PER I LAVORI DI REALIZZAZIONE DELL'INTERVENTO DI
"RIQUALIFICAZIONE AMBIENTALE E VALORIZZAZIONE DELLE EMERGENZE ARCHEOLOGICHE DEL CIRCO MASSIMO E DEI CONNESSI SPAZI PUBBLICI DI VIA DEI CERCHI E PIAZZA PORTA CAPENA"
codice b.2.8 OP1110790001

APPALTO PRINCIPALE
DIPARTIMENTO PROGRAMMAZIONE E ATTUAZIONE URBANISTICA
DIREZIONE E PIANIFICAZIONE DEL TERRITORIO
U.O. CITTA' STORICA
Direttore: Arch. Porfirio Otticlini
Responsabile del Procedimento: ing. Angelo di Stefano

OPERE COMPLEMENTARI
SOVRINTENDENZA CAPITOLINA AI BENI CULTURALI
DIREZIONE TECNICO TERRITORIALE
Direttore: arch. Porfirio Otticlini
U.O. MONUMENTI DI ROMA, SCAVI, RESTAURI, SITI UNESCO
Dirigente: arch. Caterina Ferraro Pelle
Responsabile del Procedimento: ing. Silvio De Bellis
Indirizzo Storico Archeologico:
dott. Giovanni Caruso
dr.ssa Marialetizia Buonfiglio (resp.)
dott. Gianluca Zanzi (coll.)
dr.ssa Stefania Pergola (coll.)
dr.ssa Elena Federico (coll.)

PROGETTAZIONE DEFINITIVA E DIREZIONE DEI LAVORI
ZETEMA PROGETTO CULTURA S.R.L.
Dott. Arch. Guido Ingrao (direttore lavori)
Dott. Arch. Daniela Marinelli
Strutture: Dott. Ing. Luigi Serio
Impianti: Dott. Ing. Danilo Sofia
Coord. Sicurezza in fase di progett.ed esecuzione: Dott. Ing. Davide Guidi

PROGETTAZIONE ESECUTIVA
ATI
Celletti Costruzioni Generali S.r.l. (mandatario)
GRA S.r.l (mandante)
GRUPPO DI PROGETTAZIONE ESECUTIVA APPALTO PRINCIPALE
Prof. Arch. Tancredi Carunchio (coordinatore)
Dott. Arch. Ivano Ferraro (per gli aspetti di restauro ed architettonici)
Dott. Ing. Giancarlo Carlone (per gli aspetti idraulici)
GRUPPO DI PROGETTAZIONE ESECUTIVA OPERE COMPLEMENTARI
Arch. Ivano Ferraro (capogruppo)
Arch. Federico Celletti,
Strutture: Arch. Michela Esposito
Impianti: ing. Fabrizio Bargoni

AS BUILT

OGGETTO: Torre della Moletta: Piante, prospetti e sezioni

Giugno 2016
Scala 1:50
21

Figure 34 Dipartimento Programmazione e Attuazione Urbanistica

2.6 CROSS SECTION DRAWINGS WITH DETAILINGS

In this section we can view the drafts provided by the above mentioned companies

Figure 35 Autocad Drafts of the tower

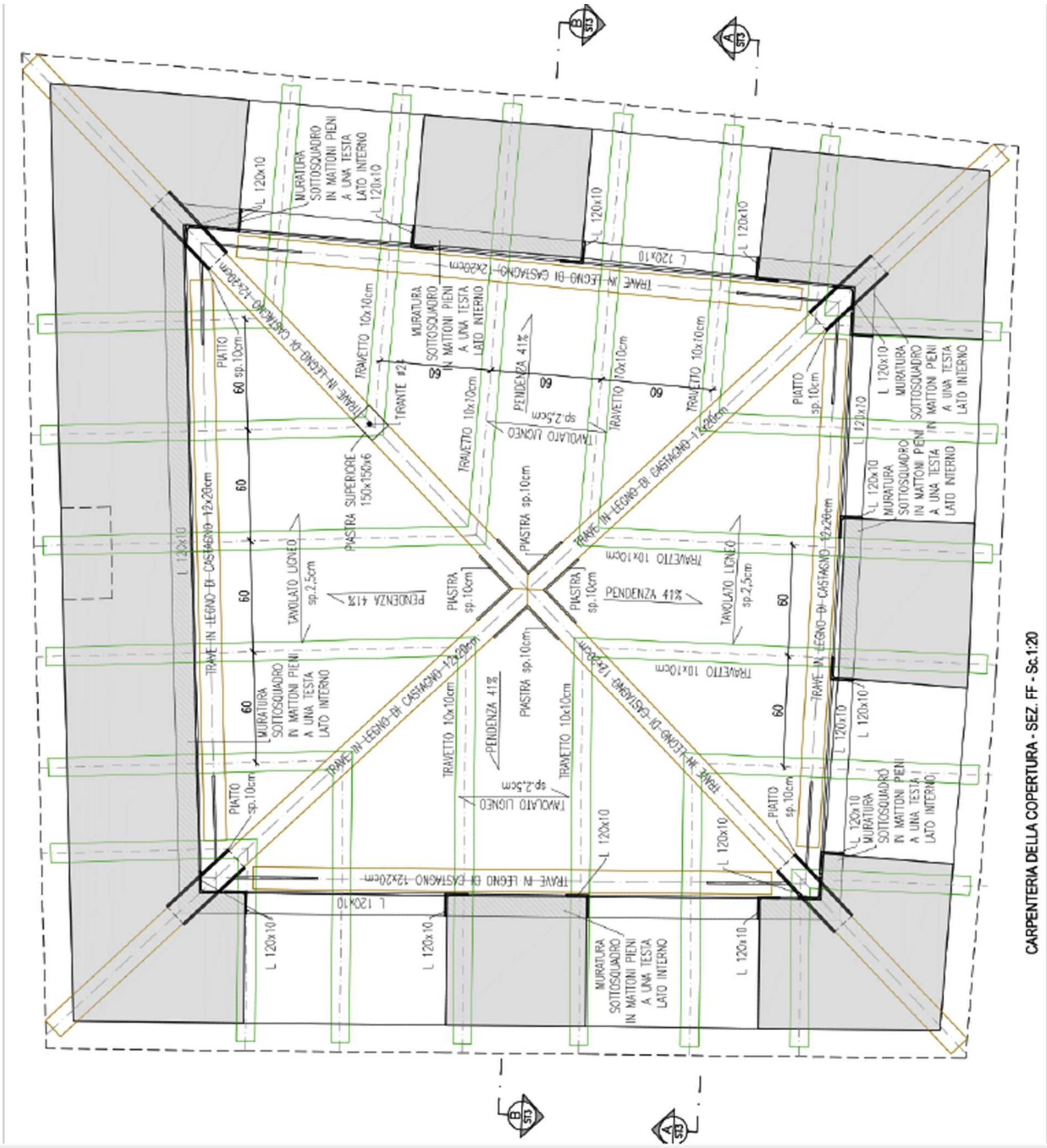


Figure 36 Details of the Roof

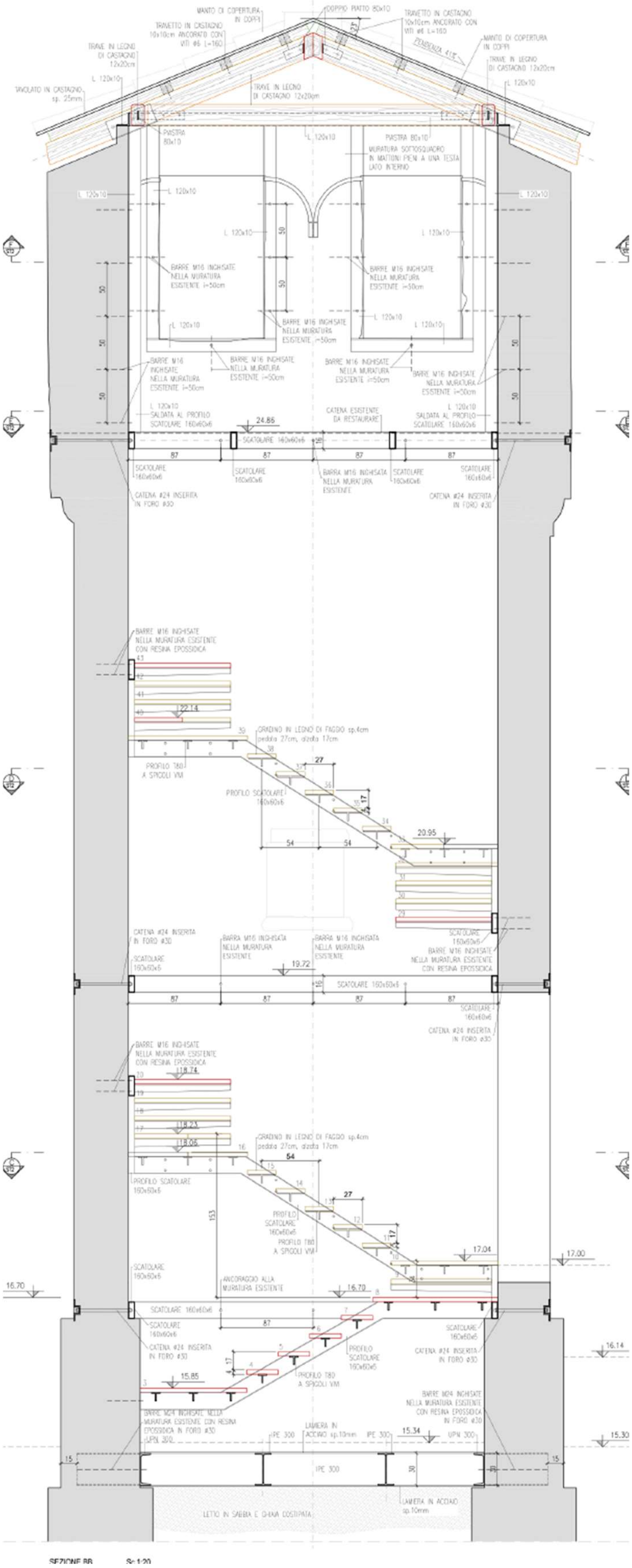


Figure 37 Section A-A of the tower

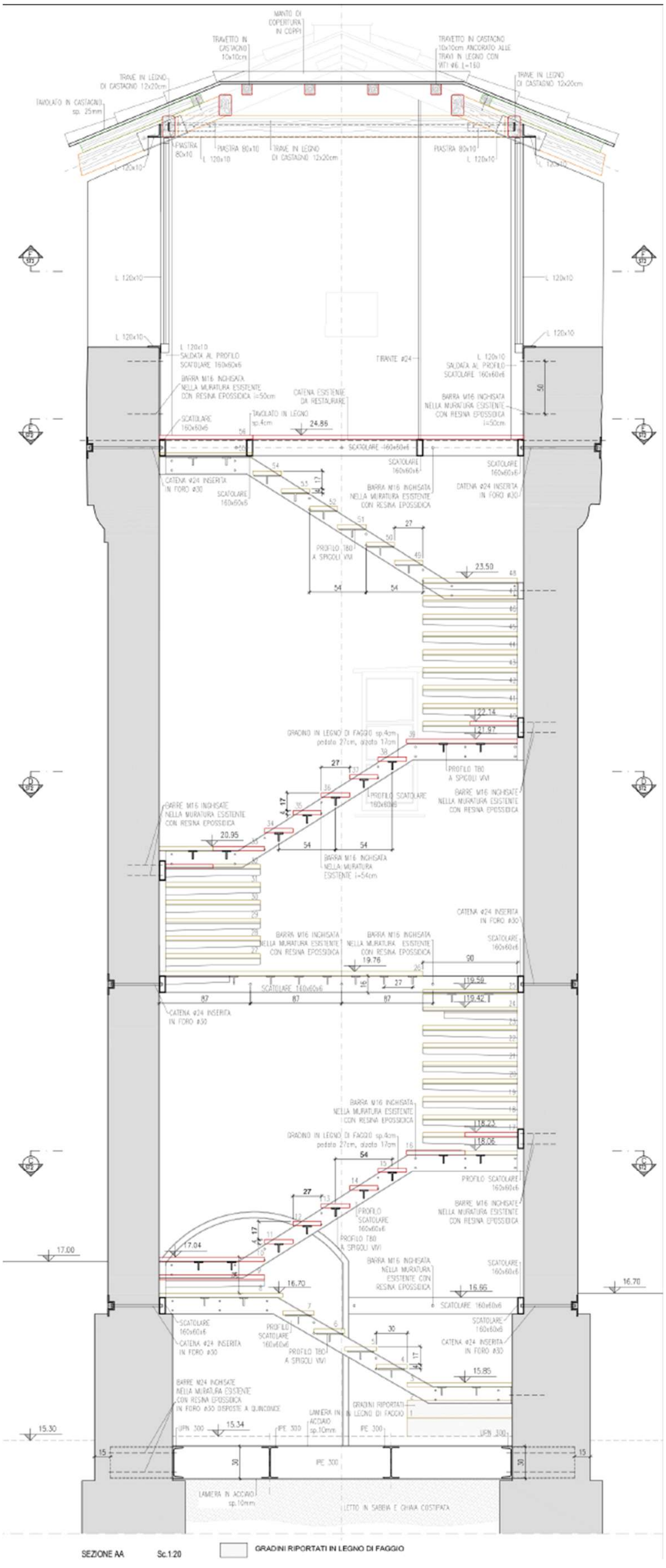


Figure 38 Section B-B of the tower

Types of beams are used as under

Floor beams	UPN 300
	IPE 300
Stair Beams	Scatolare (BOX Cross Section): 160x60x60
Roof Timber beams	Joist 10x10
	Main beams 12x20 and secondary beams 120x10

2.7 BUILDING INFORMATION MODEL (REVIT)

"We used point clouds and Retrofitting Drafts to create a 3D model of the tower in Revit 2024. To achieve this, we followed a step-by-step procedure:

- Imported the point cloud in .rcp format into Revit from Autodesk Recap Pro.

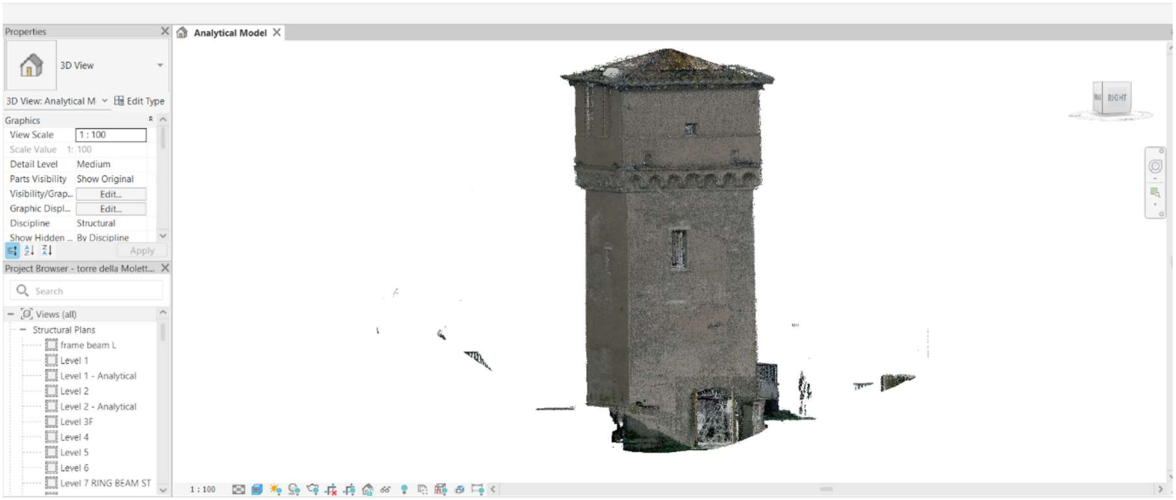


Figure 39 Point cloud transferred in Revit

- Aligned and rotated the point cloud data to the center of the compass (North, East, South, West).

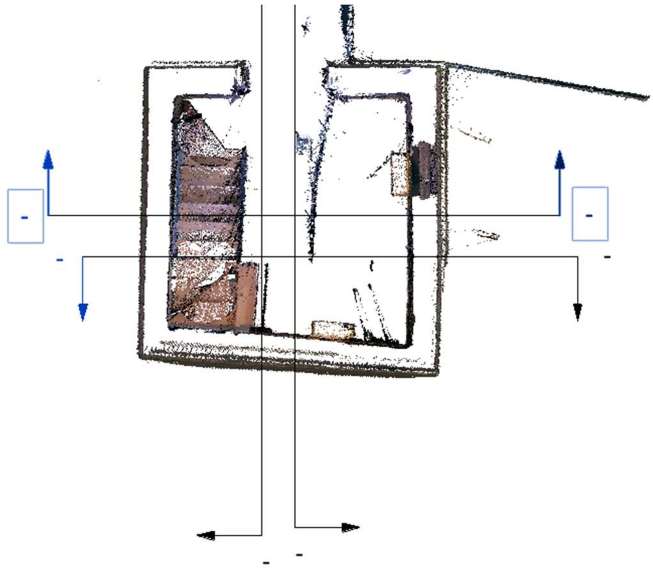


Figure 40 Plan view of point cloud after rotating

- Started modeling using the point clouds to determine wall thickness and beam locations.

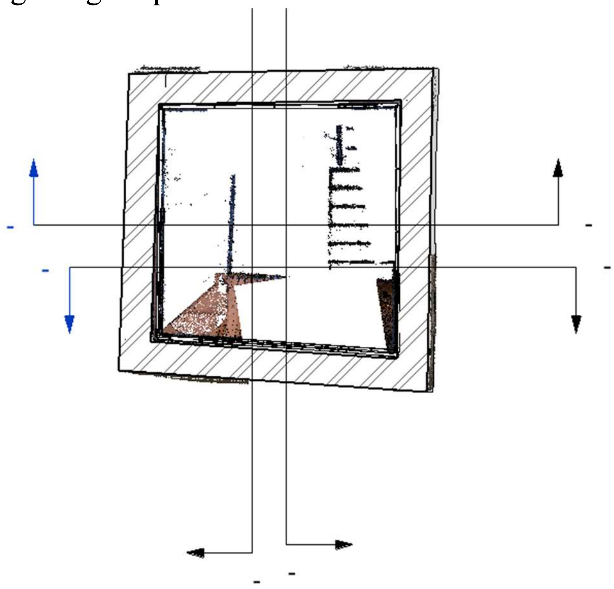


Figure 41 walls traced on the point cloud

- Added material properties to the drawn geometries to ensure alignment with the point clouds.

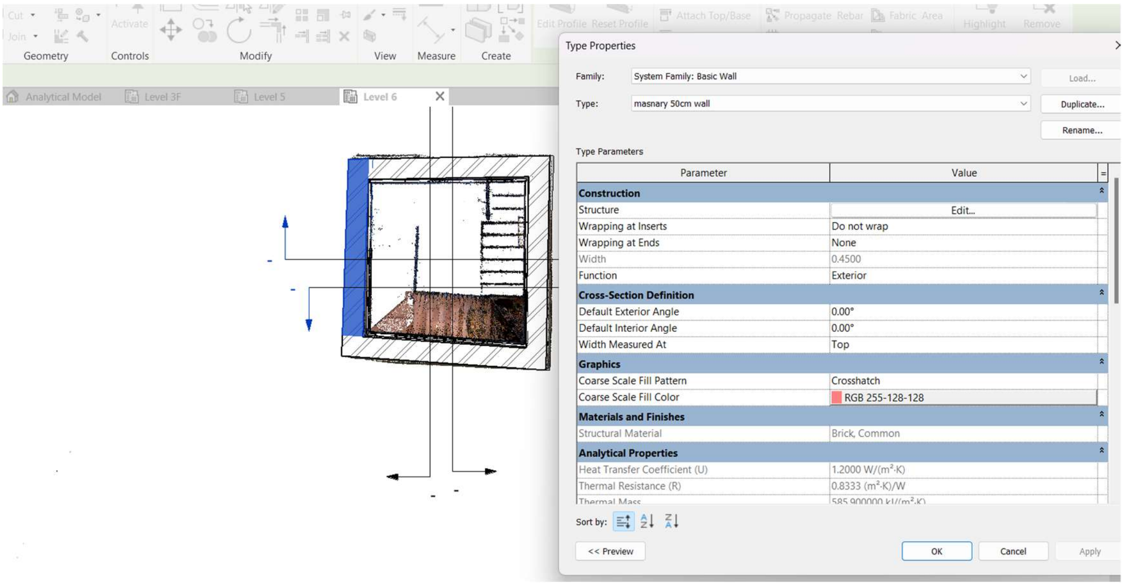


Figure 42 wall thickness

- Reviewed the walls from all sides and plan views to ensure accurate alignment with the point clouds.

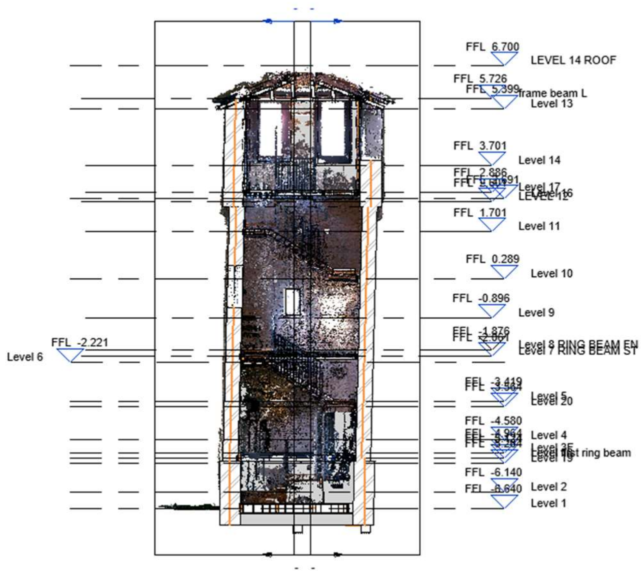


Figure 43 section view in Revit

- Aligned the walls with the point clouds and then added beams based on the provided locations in the point clouds.

Figure 44 Beams in point cloud and alligned

- Added types and properties of the beams by reviewing the details provided by the company.

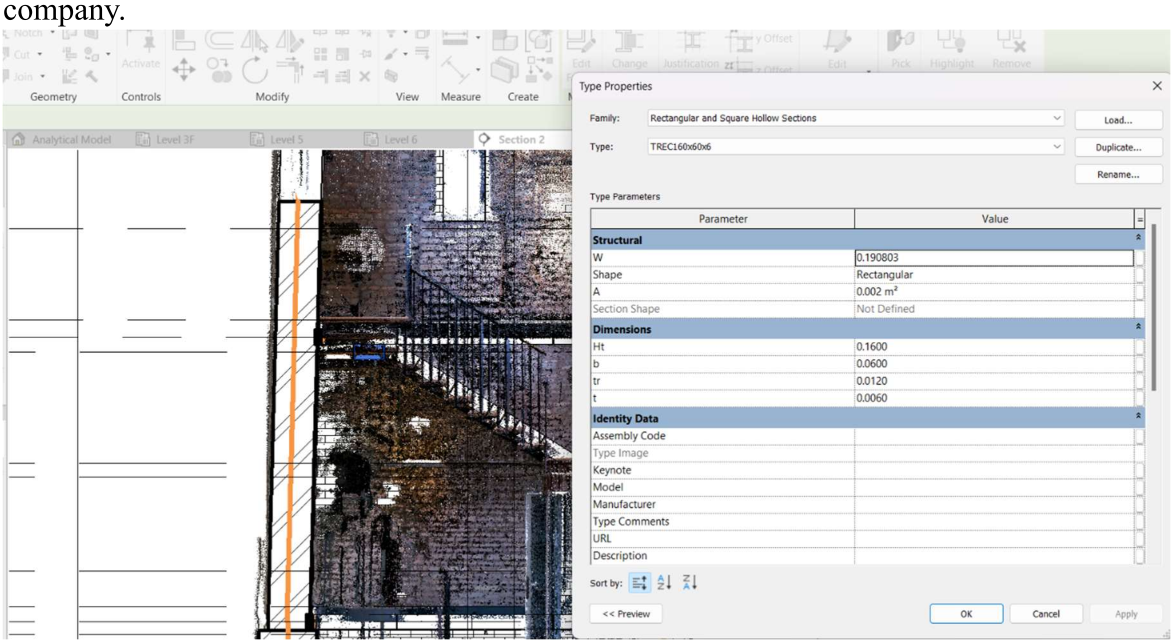


Figure 45 Beam properties

- Once the walls and beams were accurately aligned and connected, we proceeded with analytical modeling for structural analysis.

- The analytical model represented beams as line elements with 2 nodes and walls as planar elements with 4 nodes.

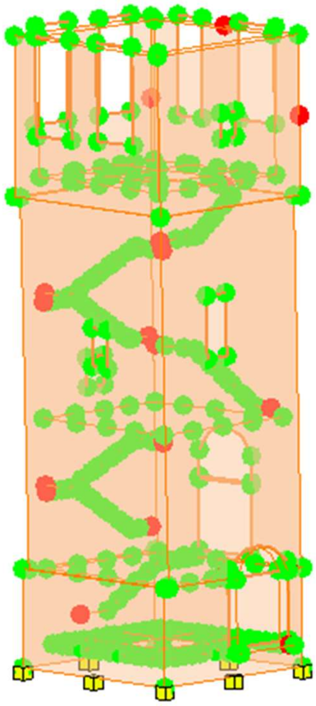


Figure 46 Analytical Model Revit

- Aligned the analytical model with the physical model to accurately represent the position of elements.

Figure 47 analytical model and physical model

- After completing these steps, the model was ready for structural analysis.

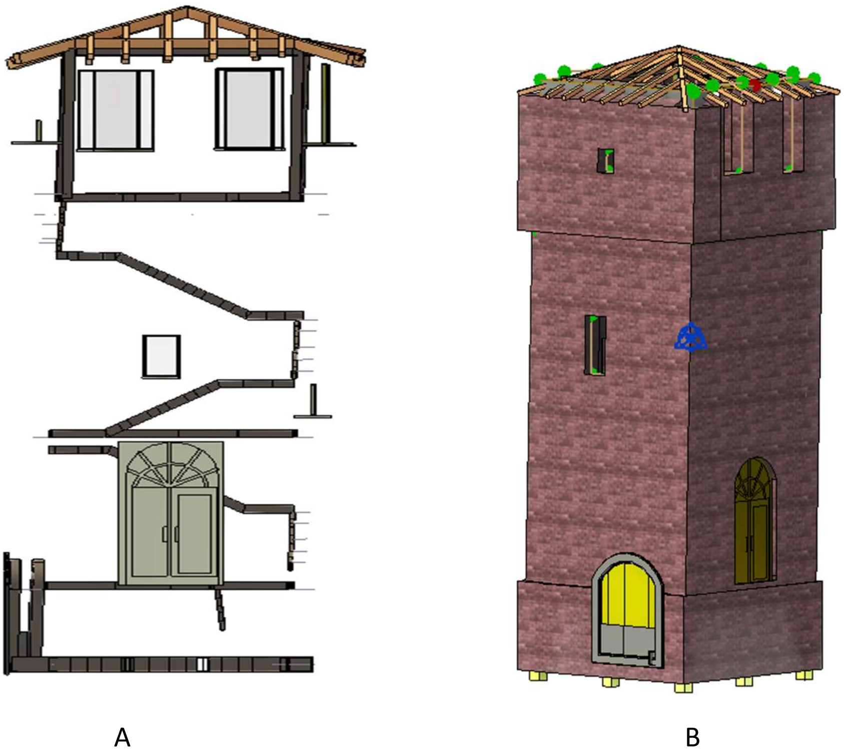


Figure 48 3d Model of the tower A) Steel Structure B) Full Model

Figure 49 point cloud and the 3d model

IMPORTANCE AND USEFULNESS OF REVIT FOR 3D MODELLING

"By using Revit for both physical and analytical modeling with the BIM Methodology, we were able to obtain a direct FEM model without having to construct it node by node in FEM software. This approach to creating a 3D model in Revit is much easier compared to direct FEM Modeling in software like MIDAS Gen or SAP 2000."

2.8 INTEROPEROABILITY (REVIT TO MIDAS GEN)

After the creation of 3d model in revit we used a plugin which helps us to transfer the model from revit to MIDAS gen for Finite Element Analysis.

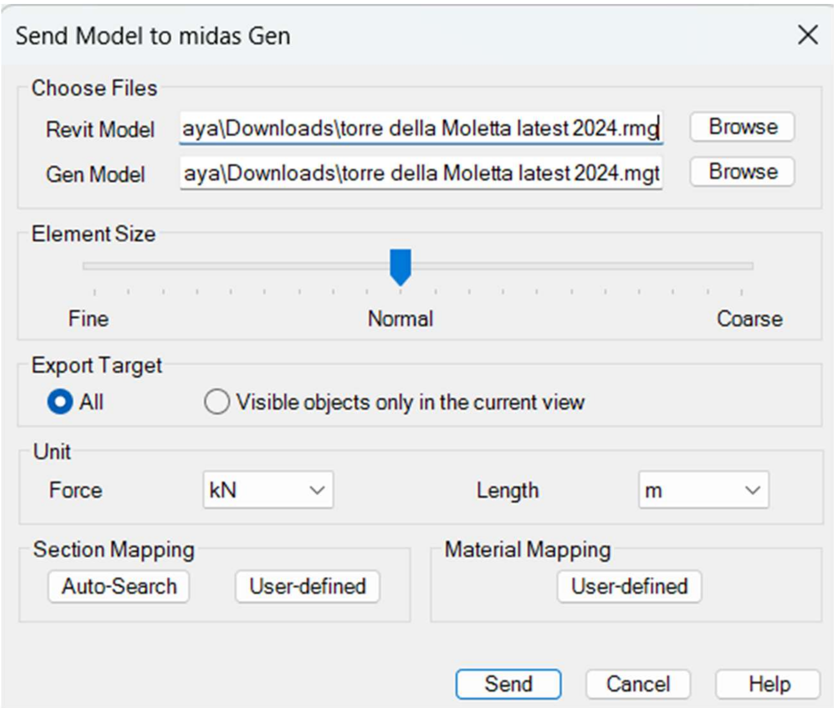


Figure 50 Revit - MIDAS Plugin

- After adjusting the mesh for our walls we have to do section mapping which is the dimensions of steel beam should be the same in midas gen.

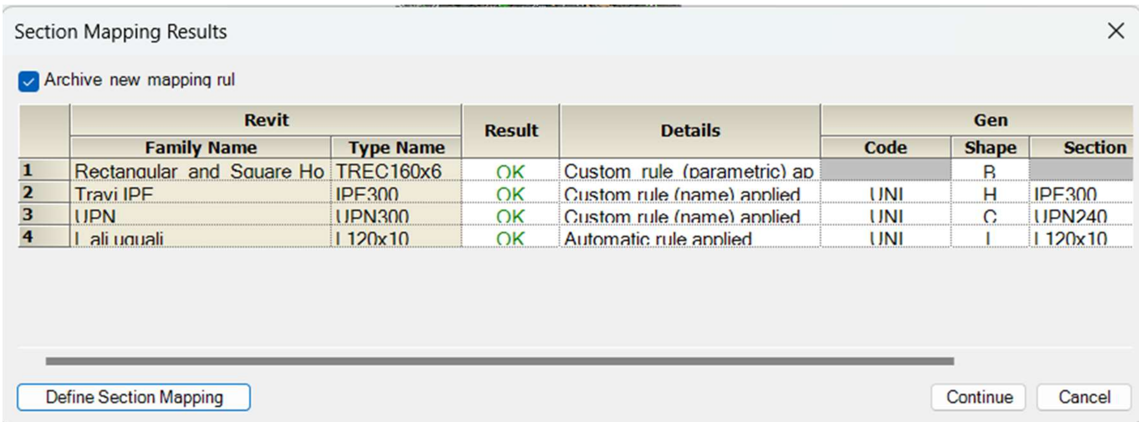


Figure 51 Section Mapping

- After this step the model could be transferred directly to MIDAS below are the list of interporabiliy between Revit and MIDAS.

	Functions	Revit < > Gen
Linear Elements	Structural Column	< >
	Beam	< >
	Brace	< >
	Curved Beam	>
	Beam System	>
	Truss	>
Planar Elements	Foundation Slab	< >
	Structural Floor	< >
	Structural Wall	< >
	Wall Opening & Window	>
	Door	>
	Vertical or Shaft Opening	>
Boundary	Offset	>
	Rigid Link	>
	Cross-Section Rotation	>
	End Release	>
	Isolated Foundation Support	>
	Point Boundary Condition	>
	Line Boundary Condition	>
	Wall Foundation	>
	Area Boundary Condition	>
Load	Load Nature	>
	Load Case	>
	Load Combination	>
	Hosted Point Load	>
	Hosted Line Load	>
	Hosted Area Load	>
Other Parameters	Material	< >
	Level	>

> da Revit a Midas

< da Midas a Revit

Figure 52 Revit Midas Interoporability Matrix

2.9 ISSUES OCCURRED DURING INTEROPERABILITY BETWEEN REVIT AND MIDAS GEN:

- After Creating the structural Model we need to transfer it to FEM software for Structural Analysis
- The first issue we encountered was due to the rigid links needed to demonstrate the connection between the walls and the beams. Since Revit does not have an option for meshing panels, we attempted to mesh them manually and connect with rigid links through Revit analytical properties. However, when we transferred them from Revit to MIDAS, each panel was meshed again differently. This led to numerous mesh incoherent errors. Additionally, some panels that appeared connected in Revit showed as disconnected in the FEM software, resulting in thousands of errors. **To address this,**

we adjusted our approach and applied rigid links directly in the FEM software after meshing the panels.

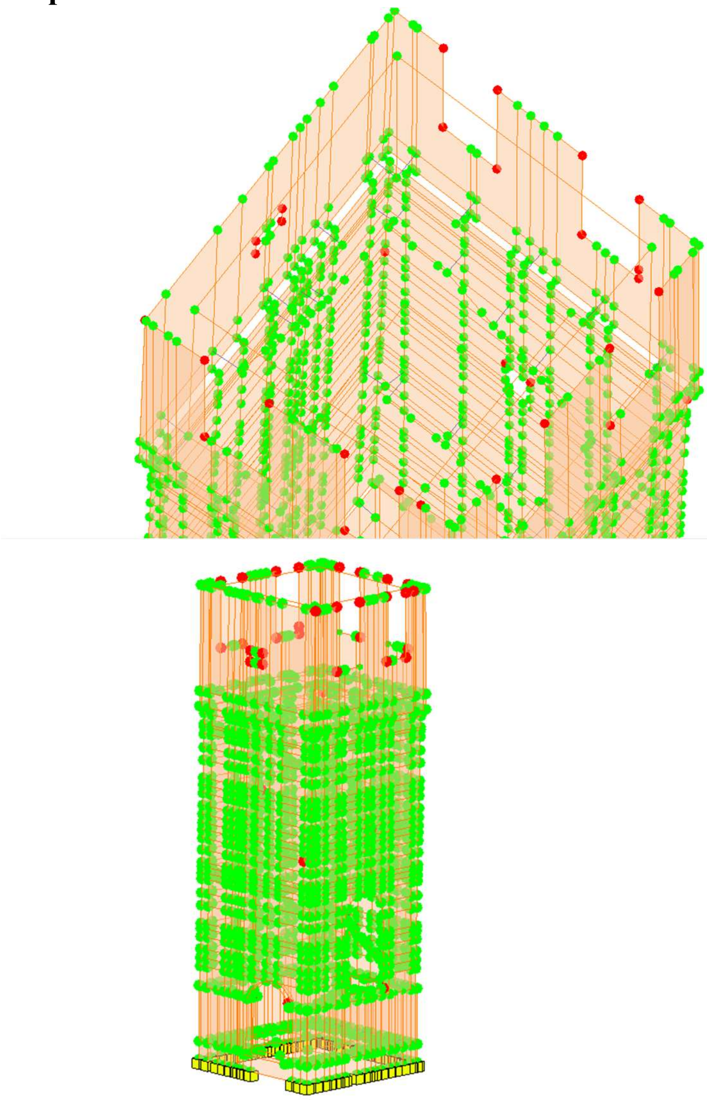


Figure 53 manual meshing to solve rigid Link Problem

- Another issue was about the global and local coordinates of panels each panel looks completely in proper orientation but their local axis does not coincide with the global axis which gave error of Instability. **Just align the local axis with global axis and the problem will be fixed.**
- Another issue was with the support conditions that **should lock the movement along the 3d.**

2.10 FEM MODEL (MIDAS GEN)

After transferring the model from revit we got the FEM model in MIDAS gen the following actions were taken on our structure

FEA MODEL PROPERTIES

Our structure contains **4018 Elements** and **4378 Nodes** also **248 rigid links**

Walls are **42cm, 40cm, 50cm** and **62cm** thick which are taken from point clouds in Revit.

The beams which are used for foundations are **UPN 300** and **IPE 300** whereas for the stairs they are box **(Scatolare 160x60x60)**

- Applying Material Properties of Masonry while the other properties of steel were automatically transferred from Revit by selection the desired section

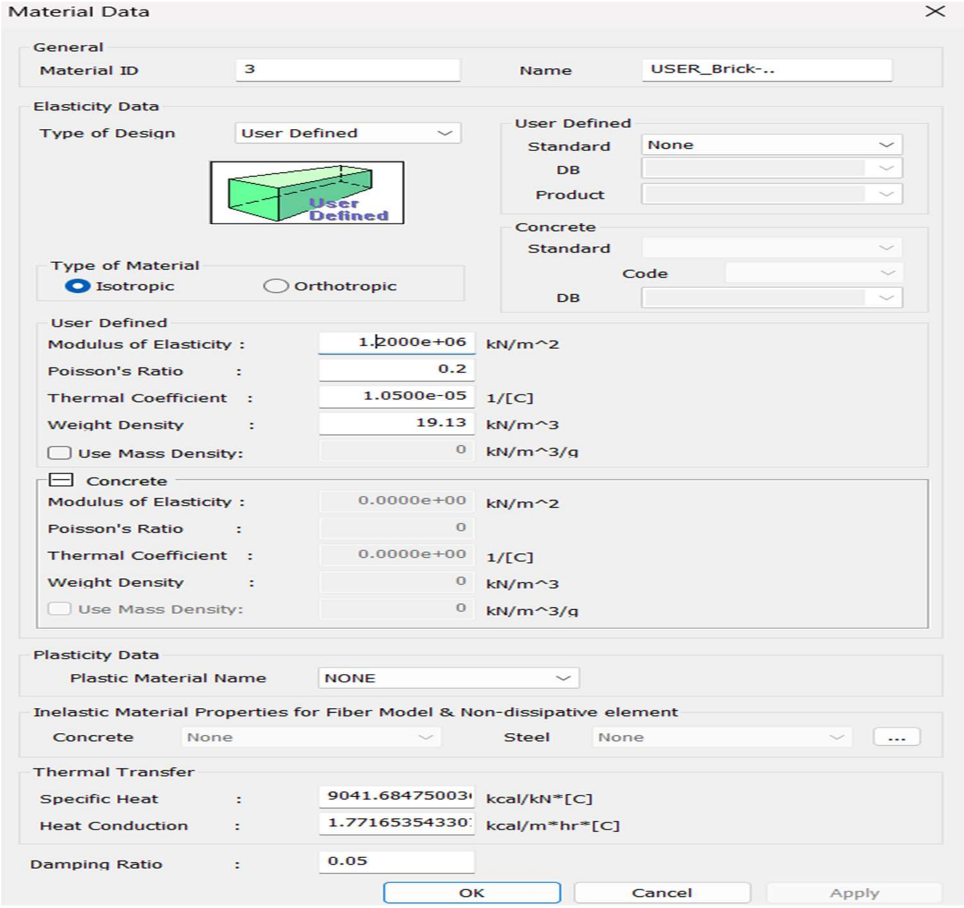


Figure 54 Material Properties

- We added the linear supports below walls fixed on global x,y and z axis.

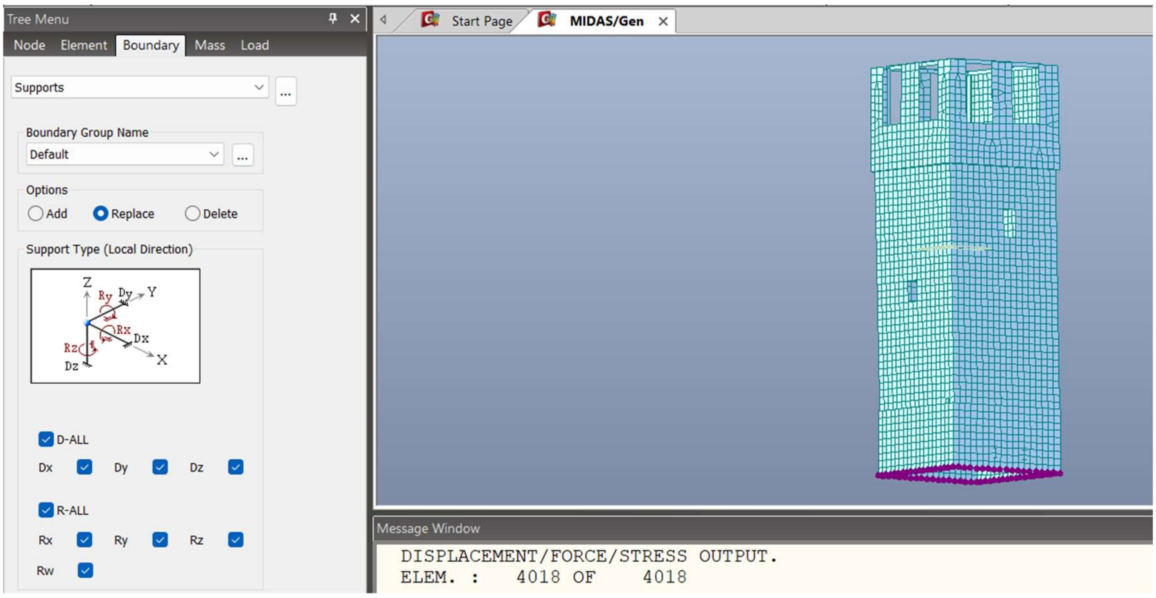


Figure 55 Fixed Supports

- Then we provided rigid links on each connecting interface because we have different thickness so we connected the walls together with rigid links and also we connected the beams with walls using rigid links.

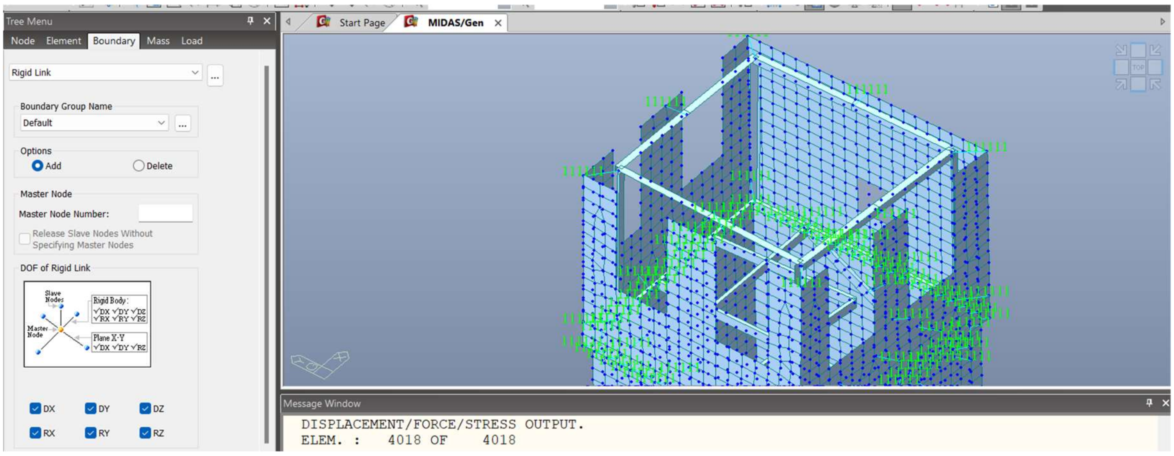


Figure 56 Rigid Links

- After that we applied loads on beam (Dead Load and Live load) also we applied the roof loads.
  DL= 0.1 KN/m^3
  LL= 1.0 KN/m^3
  Roof Load= 3.6 KN/m^3

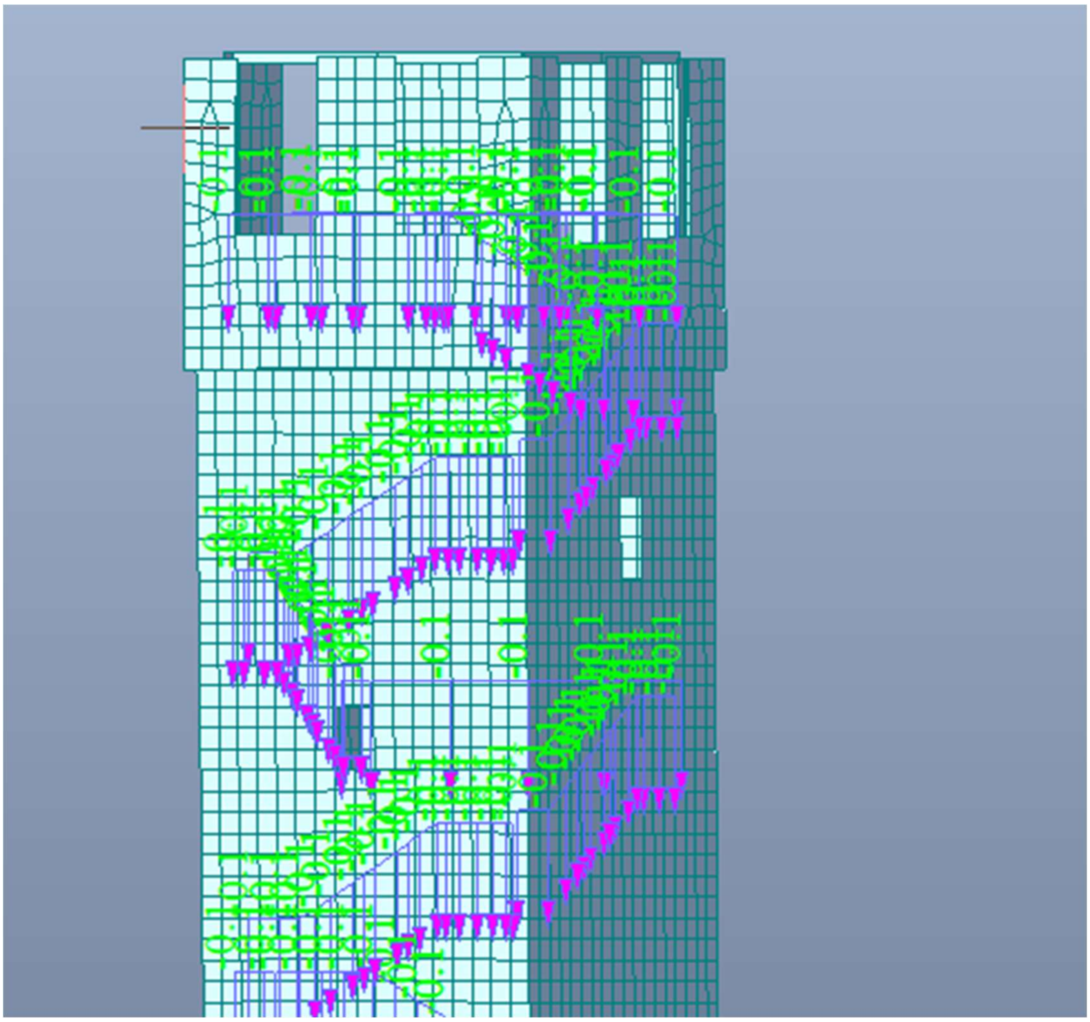


Figure 57 Dead Load on stairs

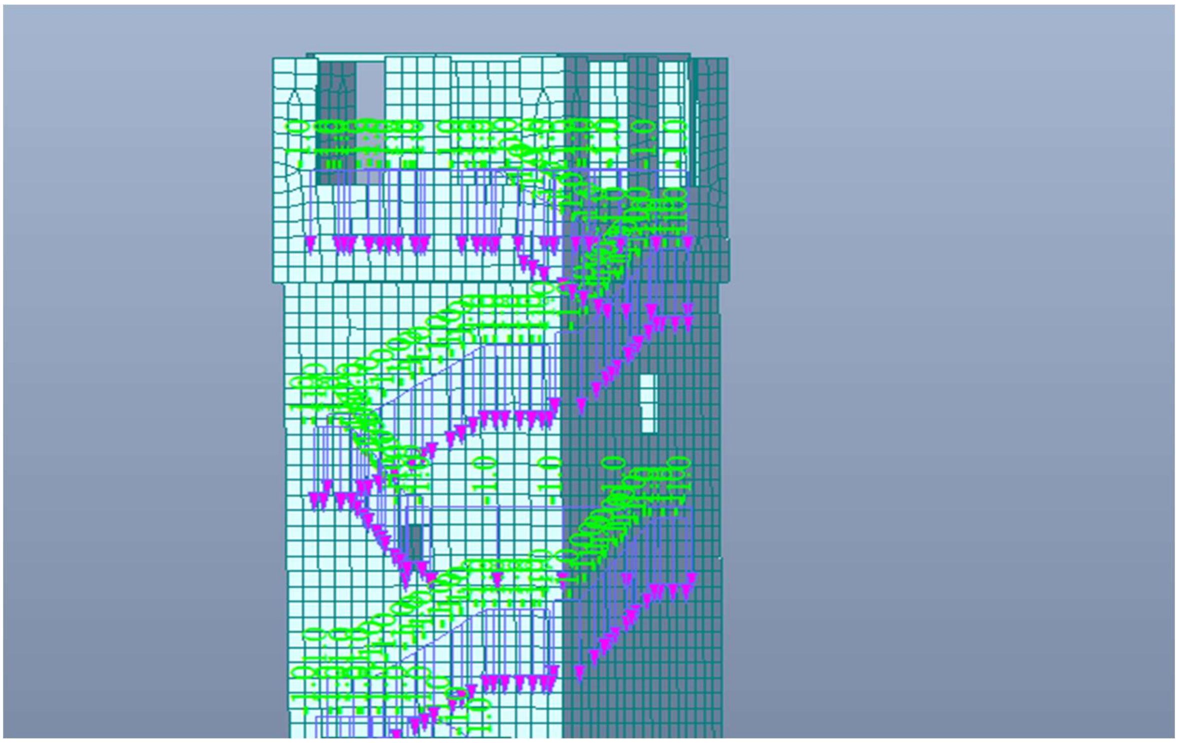


Figure 58 Live load on Stairs

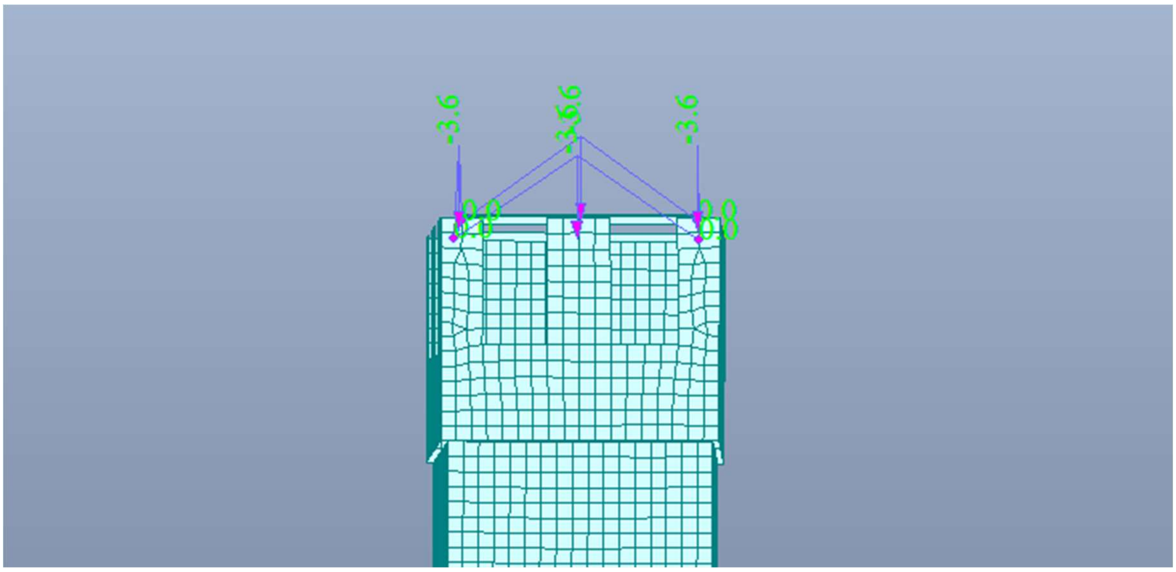


Figure 59 Roof Loads

- After applying loads and rigid links we ran the eigen value analysis to calculate the Natural frequencies of each Mode.

2.11 MODEL UPDATING:

DYNAMIC CHARACTERIZATION OF TORRE DELLA MOLETTA BY POLITECNICO DI TORINO

This portion was written by my senior colleague, Amir Reza Elahi, in his master's thesis. He is currently pursuing a Ph.D. from Politecnico di Torino. His study involves designing an innovative Structural Health Monitoring (SHM) campaign for monitoring Circo Massimo and Torre della Moletta. Three separate sensor configurations have been defined for dynamic characterization to evaluate the effect of spatial distribution on modal properties. Additionally, the thermal influence on modal parameters was assessed through continuous long-term monitoring. Fault Detection and Diagnosis (FDD) and Automated Fault Detection and Diagnosis (AFDD) were applied to derive natural frequencies and mode shapes. Furthermore, the correlation between natural frequencies and temperature variation has been acquired through statistical analysis. The following concluding remarks are drawn:[18]

• The analysis of the ambient vibration response on July 9 revealed natural frequencies lower than those recorded in the previous 2019 campaign, which could indicate potential damage under specific environmental conditions.

Table 3: Summary of the extracted frequencies for all configuration.

Puzzilli et al. (2019)		Politecnico di Torino 09.07.22		Politecnico di Torino 21.10.22		Politecnico di Torino 30.11.22	
X-dir	Y-dir	X-dir	Y-dir	X-dir	Y-dir	X-dir	Y-dir
3.25	3.00	3.10	2.92	2.95	2.95	3.01	3.01
5.80	5.80	5.36	5.36	3.13	3.12	3.22	3.22
-	-	-	-	5.51	5.51	5.89	5.89

In the final part of this section, the 3D modes are presented. Since there are not two sensors at the same level, the rotation of the tower is not captured.

Figure 60 Summary of the tower frequencies extracted by Polito

• Long-term monitoring has shown that natural frequencies are highly influenced by changes in temperature. Statistical analysis has indicated a decreasing trend in frequencies as temperature increases. It is possible that the decrease in frequency is due to temperature changes rather than damage[18].

For the model updating these are our reference frequencies calculated by experiment results by **Amir Reza Elahi**

- **Mode 1 2.95**
- **Mode 2 3.13**
- **Mode 3 5.51**

After performing the modal analysis we performed model updating in order to co-relate the frequencies computed by experimental methods and by Finite element analysis so that our structure acts as a digital twin of real structure in order to perform further acoustic static and dynamic pressure analysis on our digital twin so that we can predict its behaviour.

Steps followed for model updating were as followed,

- We had 2 types of data available one was experimental frequencies and the other was the properties of masonry by the Masonry Quality Index

Table 3: Summary of the extracted frequencies for all configuration.

Puzzilli et al. (2019)		Politecnico di Torino 09.07.22		Politecnico di Torino 21.10.22		Politecnico di Torino 30.11.22	
X-dir	Y-dir	X-dir	Y-dir	X-dir	Y-dir	X-dir	Y-dir
3.25	3.00	3.10	2.92	2.95	2.95	3.01	3.01
5.80	5.80	5.36	5.36	3.13	3.12	3.22	3.22
-	-	-	-	5.51	5.51	5.89	5.89

In the final part of this section, the 3D modes are presented. Since there are not two sensors at the same level, the rotation of the tower is not captured.

Figure 61 Experimental Frequencies recorded by Polito [18]

	Compressive Strength f_m (MPa)		Shear Strength τ_0 (MPa)		Young's modulus E (MPa)		Shear Modulus G (MPa)		Good quality mortar	Brick courses	Transversal connection
	Min	Max	Min	Max	Min	Max	Min	Max			
Irregular stone masonry (pebbles, erratic, irregular stones)	1.0	2.0	.018	.032	690	1050	230	350	1.5	1.3	1.5
Roughly cut stone masonry	2.0	3.0	.035	.051	1020	1440	340	480	1.4	1.2	1.5
Barely cut stone masonry, properly dressed	2.6	3.8	.056	.074	1500	1980	500	660	1.3	1.1	1.3
Irregular softstone masonry	1.4	2.2	.028	.042	900	1260	300	420	1.5	1.2	1.3
Squared softstone masonry	2.0	3.2	.040	.080	1200	1620	400	500	1.6		1.2
Squared hardstone masonry	5.8	8.2	.090	.120	2400	3300	800	1100	1.2		1.2
Brickwork (lime-based mortar)	2.6	4.3	.050	.130	1200	1800	400	600	1.27		1.3
Hollow bricks masonry (cement mortar)	5.0	8.0	.080	.170	2500	5600	875	1400	1.2		

Figure 62 Material Properties of masonry according to NTC 2018 [4]

Figure 63 wall texture of Moletta Tower

As checking the picture above we can see that our structure masonry lies in type B **(Roughly Cut Stone Masonry)** which E ranges from (1020-1440) MPA where as while the value of ν was directly obtained though the well-known relationship

$$G = E/(2(1 + \nu));$$

the value of the Poisson ν ratio being calculated is approximately ν = 0.33. A damping ratio ξ = 5% was assumed for all modes, which is a realistic value for masonry.

1ST ITERATION

In our first iteration, we used the masonry properties as E= 1440 MPA and v= 0.33

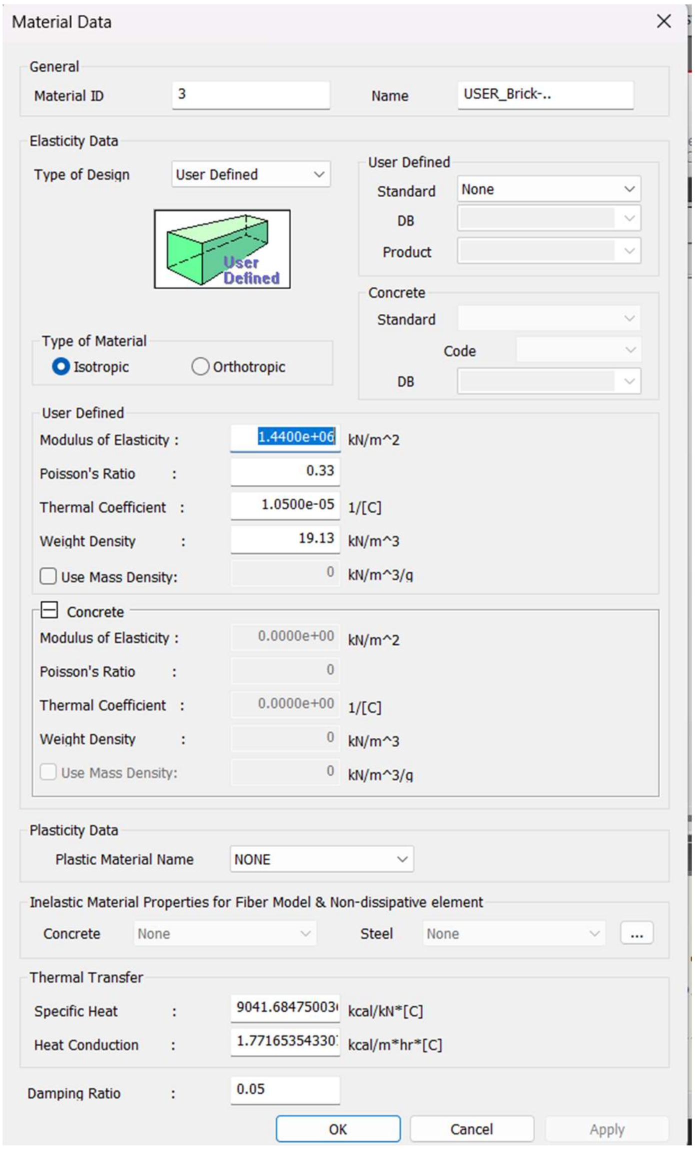


Figure 64 1st iteration with E= 1400 MPA

Node	Mode	UX	UY	UZ	RX	RY	RZ
EIGENVALUE ANALYSIS							
	Mode No	Frequency (rad/sec)	Frequency (cycle/sec)	Period (sec)	Tolerance		
	1	22.0724	3.5129	0.2847	0.0000e+00		
	2	25.8586	4.1155	0.2430	0.0000e+00		
	3	43.4520	6.9156	0.1446	1.7339e-76		
	4	50.7576	8.0783	0.1238	1.9636e-67		
	5	67.5594	10.7524	0.0930	8.8687e-50		
	6	71.3965	11.3631	0.0880	1.4429e-45		
	7	78.3242	12.4657	0.0802	2.1306e-40		
	8	81.6717	12.9985	0.0769	6.8101e-37		
	9	86.8502	13.8226	0.0723	2.5586e-33		
	10	88.1603	14.0311	0.0713	3.3588e-31		

Figure 65 1st iteration Modal Frequencies

Here we can see that our frequencies of first 3 modes are,

- 3.51 Hz
- 4.11 Hz
- 6.91 Hz

These frequencies are very high as compared to experimental frequencies so we need to change the material properties.

2ND ITERATION

In our 2nd iteration, we changed the value of E= 1300 MPA

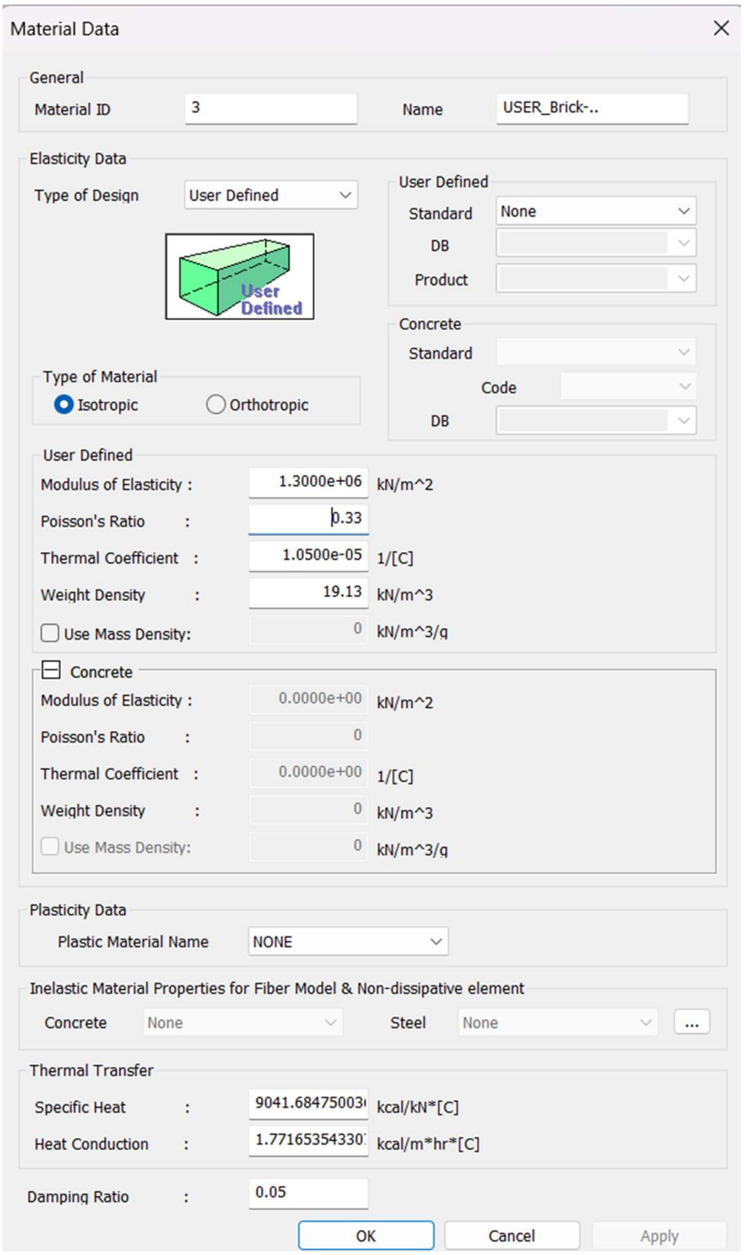


Figure 66 2nd Iteration with E=1300MPA

Node	Mode	UX	UY	UZ	RX	RY	RZ
EIGENVALUE ANALYSIS							
	Mode No	Frequency (rad/sec)	Frequency (cycle/sec)	Period (sec)	Tolerance		
	1	20.9936	3.3412	0.2993	0.0000e+00		
	2	24.5885	3.9134	0.2555	0.0000e+00		
	3	41.6699	6.6320	0.1508	1.6391e-76		
	4	48.2707	7.6825	0.1302	6.5416e-68		
	5	64.3155	10.2361	0.0977	2.0625e-50		
	6	68.0684	10.8334	0.0923	1.2374e-45		
	7	74.8164	11.9074	0.0840	5.2593e-41		
	8	79.0849	12.5868	0.0794	1.2780e-36		
	9	83.7900	13.3356	0.0750	1.3884e-33		
	10	87.7981	13.9735	0.0716	8.8823e-29		

Figure 67 Modal frequencies recorded with 1300 MPA

Here we can see our frequencies have been reduced but still our structure is stiffer than real structure we need to reduce the Elastic Modulus more.

3RD ITERATION

In our 3rd Iteration, we changed the value of E to 1200 MPA

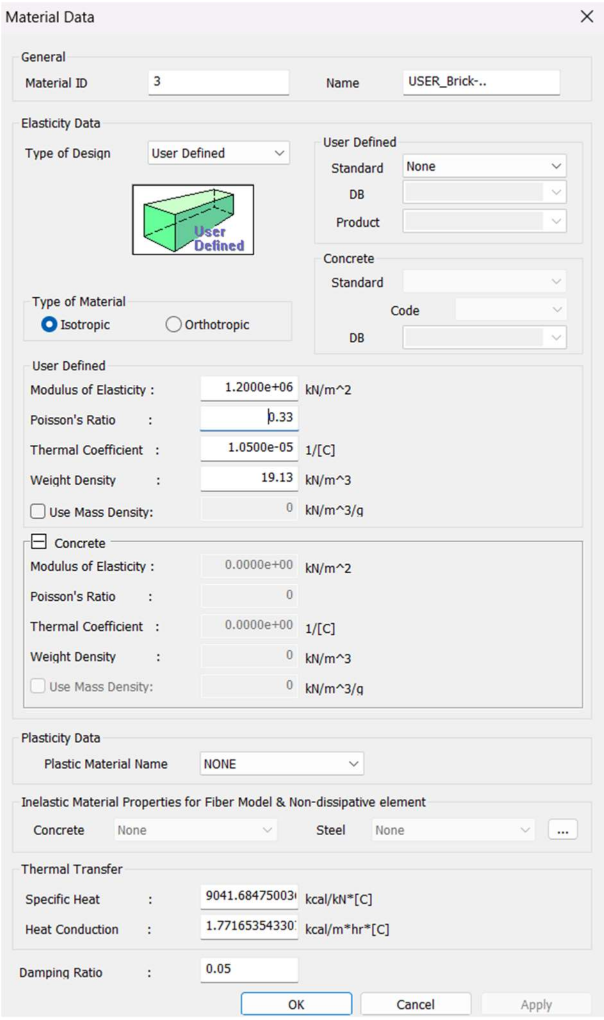


Figure 68 3rd Iteration with E=1200 MPA

Node	Mode	UX	UY	UZ	RX	RY	RZ
EIGENVALUE ANALYSIS							
	Mode No	Frequency (rad/sec)	(cycle/sec)	Period (sec)	Tolerance		
	1	18.5873	2.9583	0.3380	0.0000e+00		
	2	21.8189	3.4726	0.2880	0.0000e+00		
	3	37.8053	6.0169	0.1662	4.8625e-76		
	4	43.6916	6.9537	0.1438	1.9640e-67		
	5	57.3007	9.1197	0.1097	3.1092e-51		
	6	60.5895	9.6431	0.1037	2.9952e-47		
	7	66.5718	10.5952	0.0944	3.1667e-42		
	8	74.1955	11.8086	0.0847	2.3536e-34		
	9	77.1086	12.2722	0.0815	3.8349e-32		
	10	78.7036	12.5261	0.0798	5.9035e-31		

Figure 69 Correct Modal Frequencies with 3rd Iteration

The figures show that our frequencies match the experimental frequencies calculated using sensors, and our mode shapes are also accurate. This means that our structure now has the properties of a real structure. As a result, we can conduct static and dynamic acoustic pressure analysis on our structure to study how it will behave in real-life conditions.

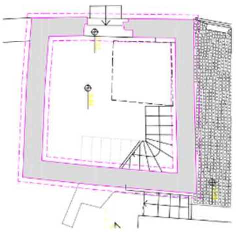
Table 1 Natural frequencies Before and After Caliberation

odes	Numerical frequencies FEM (Hz)		Experimental frequencies (Hz)	Maximum difference between frequencies (%)	
	Before calibration	After calibration		Before calibration	After calibration
1	3.51	2.95	2.95	11.8	0.1
2	4.11	3.47	3.22	12.7	7
3	6.91	6.0	5.89	11.7	1.03

2.12 MODEL CREATED BY AUTOCAD DATA ONLY BY FOLLOWING THE PREVIOUS PROCEDURES

REVIT MODEL

By using the AutoCAD drawings we constructed another model in Revit in which we can study the difference in behaviors the difference in model is discussed in the table below.



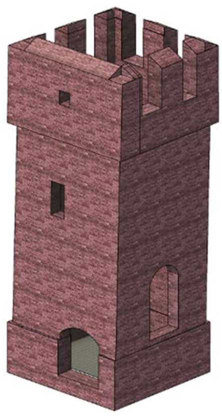


Figure 70 Model generated by Autocad in Revit

DIFFERENCE BETWEEN TWO MODELS

The Main differences between the models are thickness and inclination of walls.

Table 2 the difference in thickness of walls for both models

Type of walls	Thickness of walls (Point clouds) cm	Thickness of walls Autocad cm
Foundation Wall	62	75
Center Wall	45	50
Top floor wall	63	72

The inclination of 2 walls in point clouds was taken as **1.5** degrees to align them accurately with the point clouds

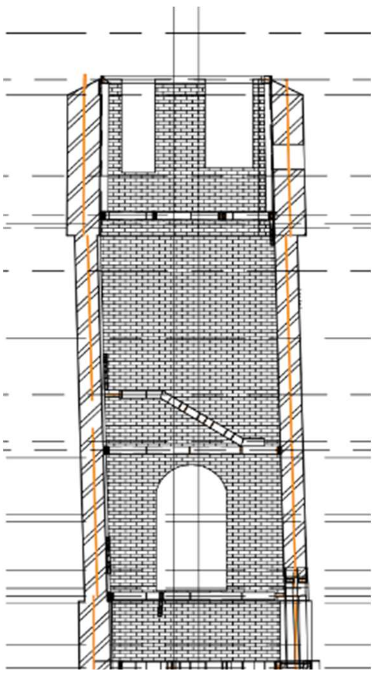


Figure 71 Section view of the tower where you can see the inclination

MODEL CALIBERATION RESULTS IN MODEL CONSTRUCTED BY USING AUTOCAD DRAWINGS

After creating the model using AutoCAD drafts in Revit, we transferred them to MIDAS Gen and repeated the same steps with the same loads as described above. We then performed a modal analysis in order to obtain the frequencies. After obtaining the natural frequencies, we calibrated the model in a similar manner. The table below shows the results:

Table 3 Model Caliberation results of model based on Autocad Drawings

odes	Numerical frequencies FEM (Hz)		Experimental frequencies (Hz)	Maximum difference between frequencies (%)	
	Before calibration	After calibration		Before calibration	After calibration
1	3.31	2.96	2.95	12.2	0.3
2	3.85	3.12	3.22	19.6	3.0
3	6.99	6.2	5.89	18.7	5.2

2.13 ACCELAROGRAMS REGISTERED DURING 1st MAY 2024 CONCERT

We installed sensors on the tower door to monitor its behavior during the concert. We incorporated a time history dynamic function into our model using MIDAS gen and calculated the Peak Particle Velocity.

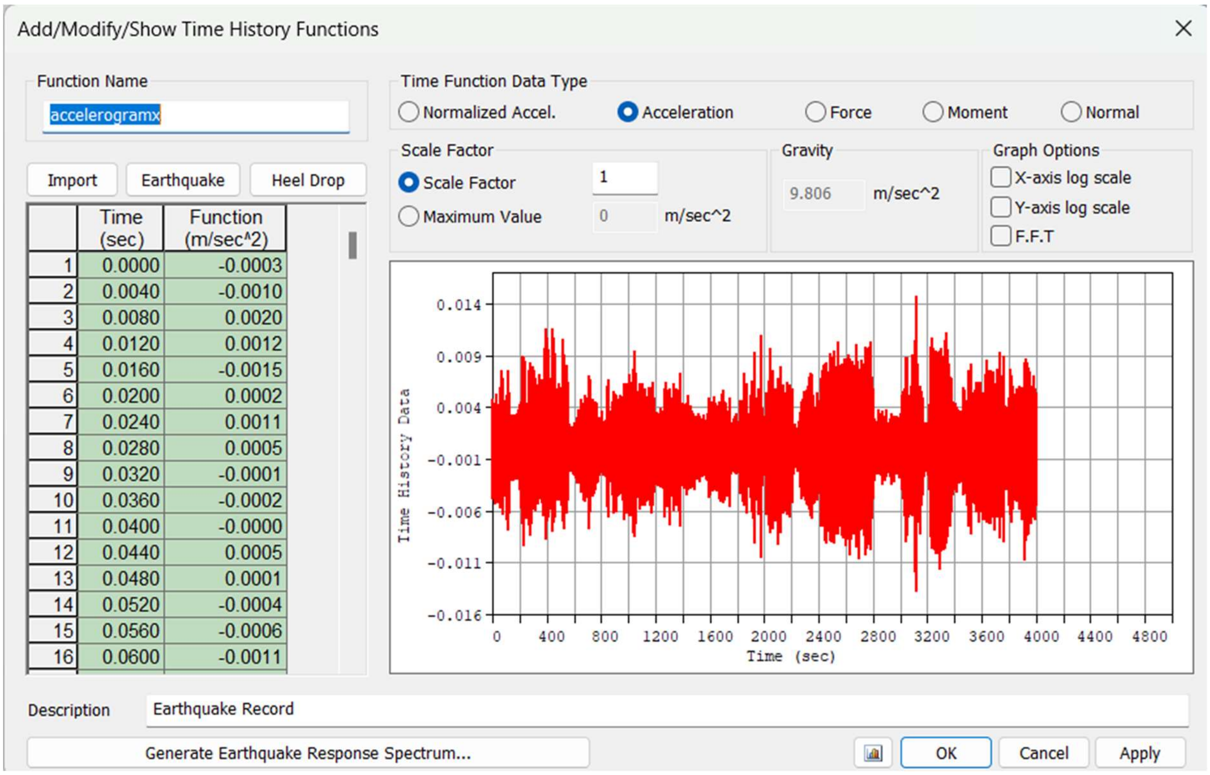


Figure 72 Accelerogram Recordings

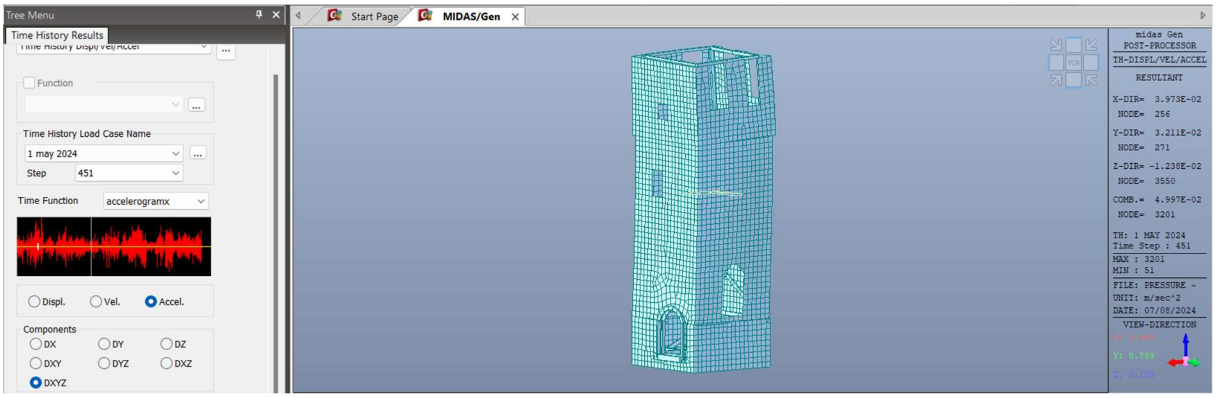


Figure 73 Maximum Accelaration recorded during concert

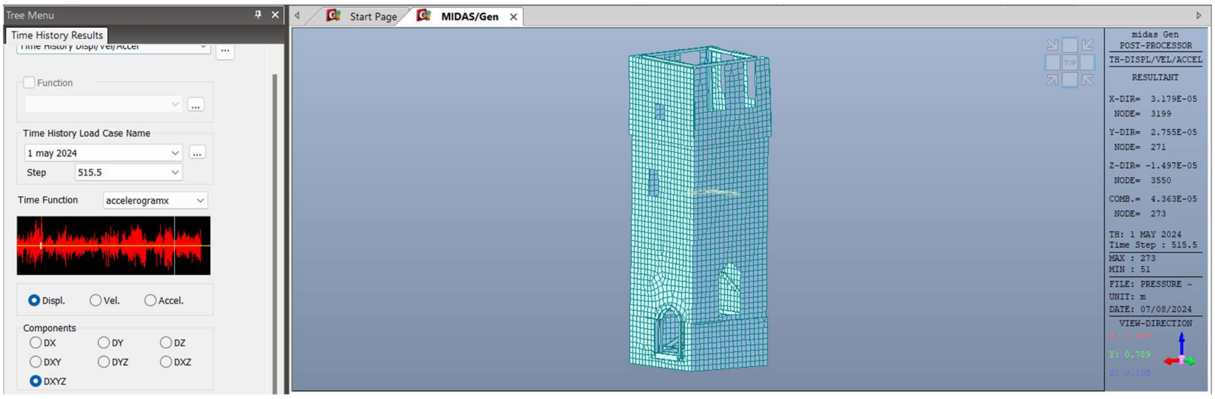


Figure 74 maximum displacement generated during the concert

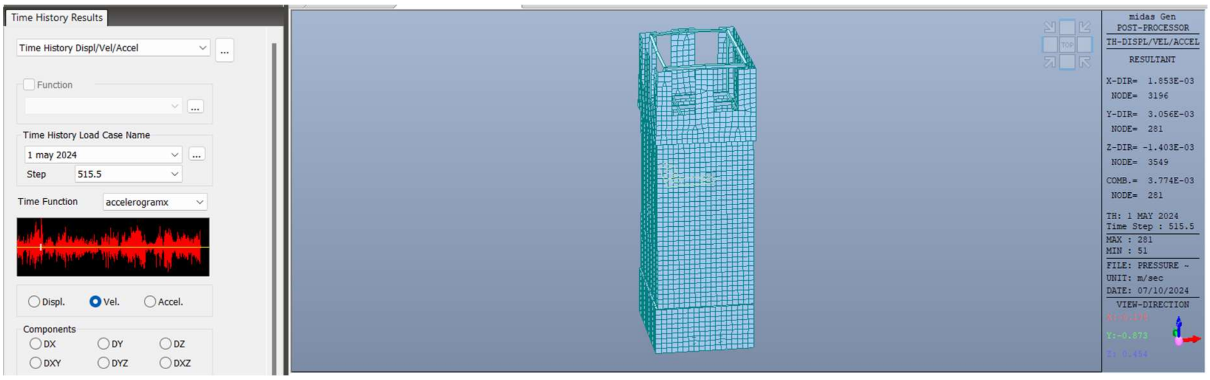


Figure 75 Maximum velocity by the concert

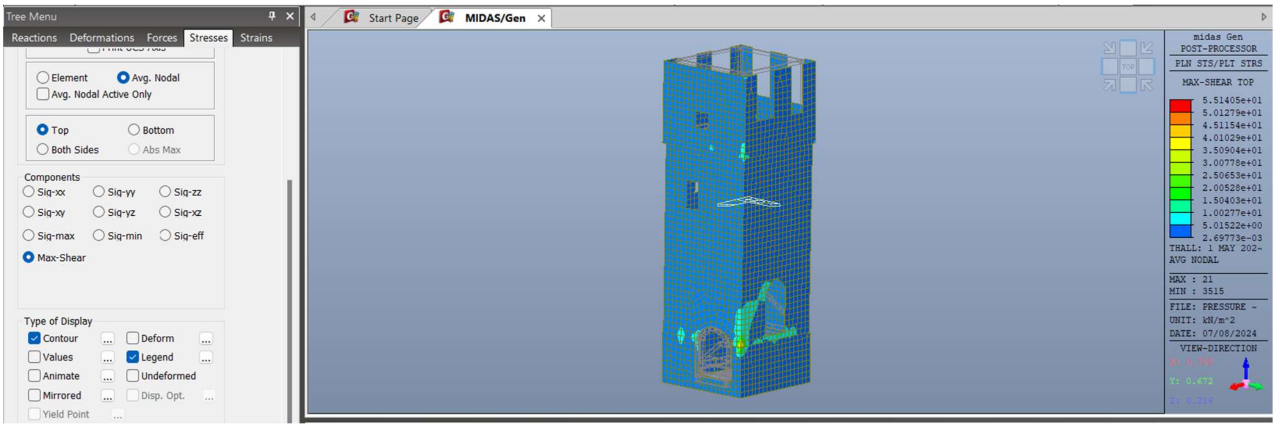


Figure 76 Maximum Shear

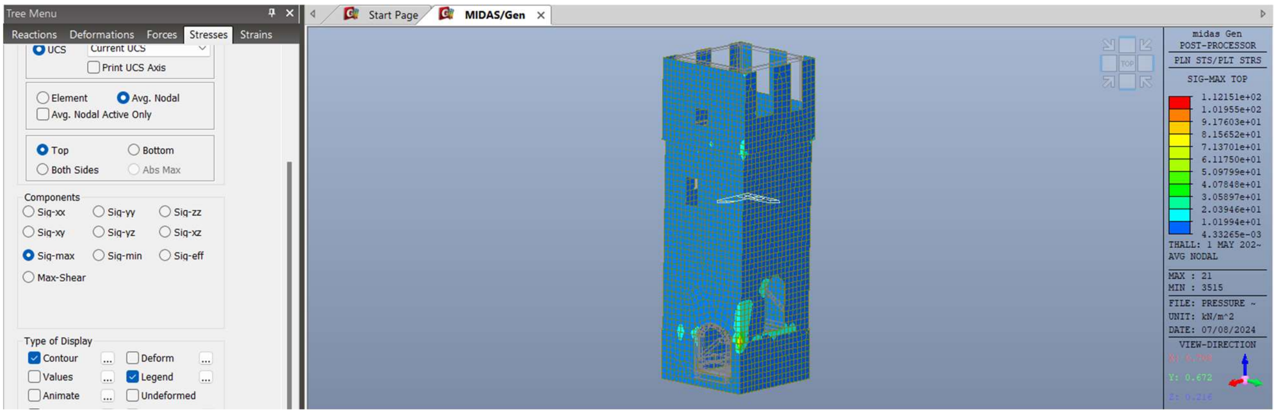


Figure 77 Maximum Stress

In the figures above we have shown the MAX Displacements, Velocities and Accelerations. Also, we have shown the MAX Shear and MAX Stress acting on the structure due to the 1st May concert.

The summary of the results lie on the following table

Table 4 Max shear and Max Stress of the tower due to 1st Mat 2024 Concert

Max shear stress [KN/m^2]	Max compression stress [KN/m^2]
55.1	112.15

Table 5 Max Displacement, Velocity and Accelaration due to 1st May concert

Max displacement [mm]	Max velocity [mm/s]	Max acceleration[cm/s2]
0.04	3.77	4.99

CHAPTER 3 RESULTS AND DISCUSSIONS

3.1 3D BIM MODEL ALIGNED WITH POINT CLOUDS IN REVIT

In the beginning we had only 2 sets of data in order to create the 3d model in revit. Our main focus was using point clouds for the dimensioning of walls where as using the drawings to get the details and properties of beams. Here is the final result of the model from all directions.

- At the top you can see al 4 sides in point clouds
- In the middle we can see all 4 sides according to the drafts provided by the company.
- In the bottom you could see all 4 sides constructed in Revit.

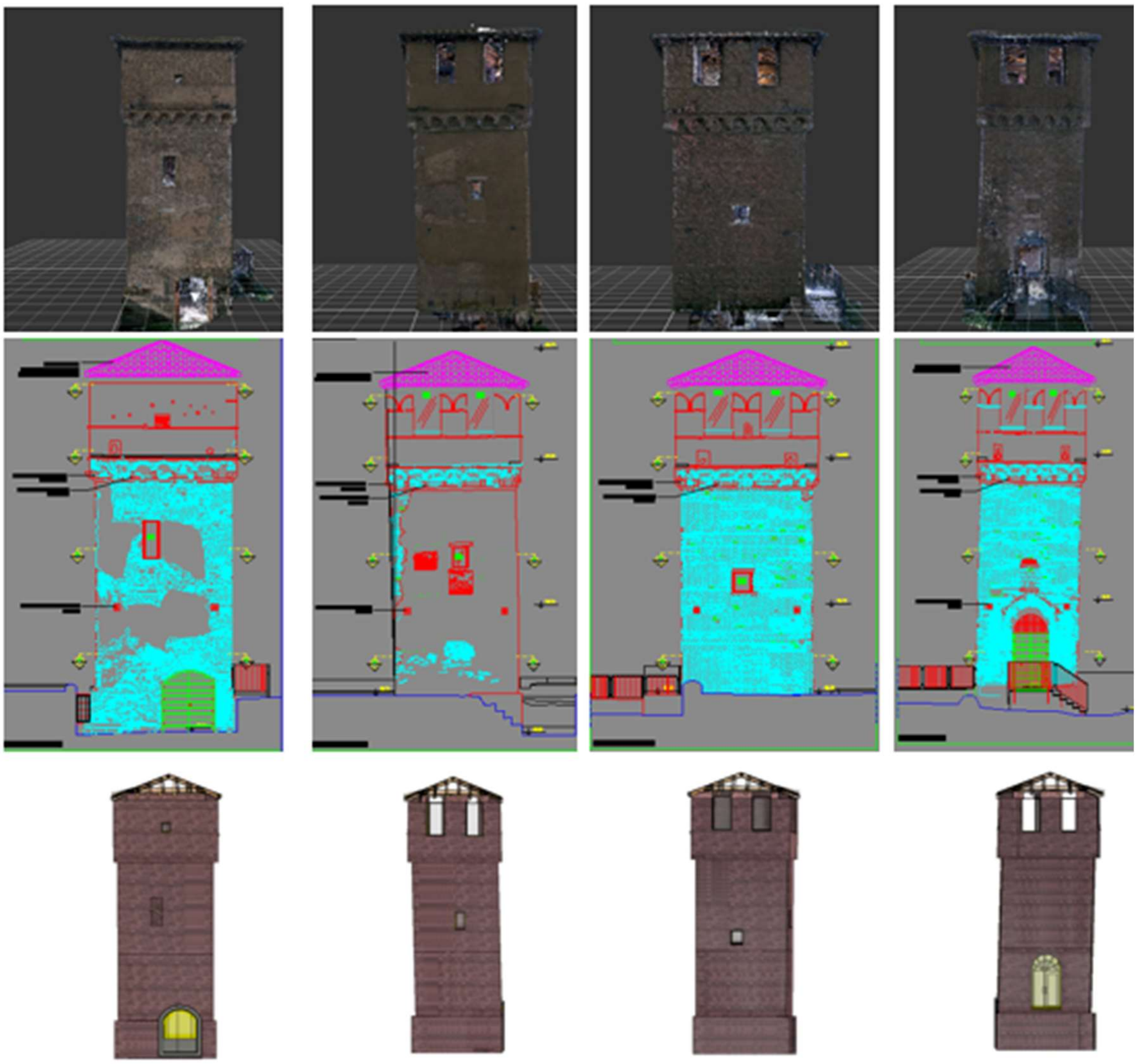


Figure 78 N E W S sides of the tower

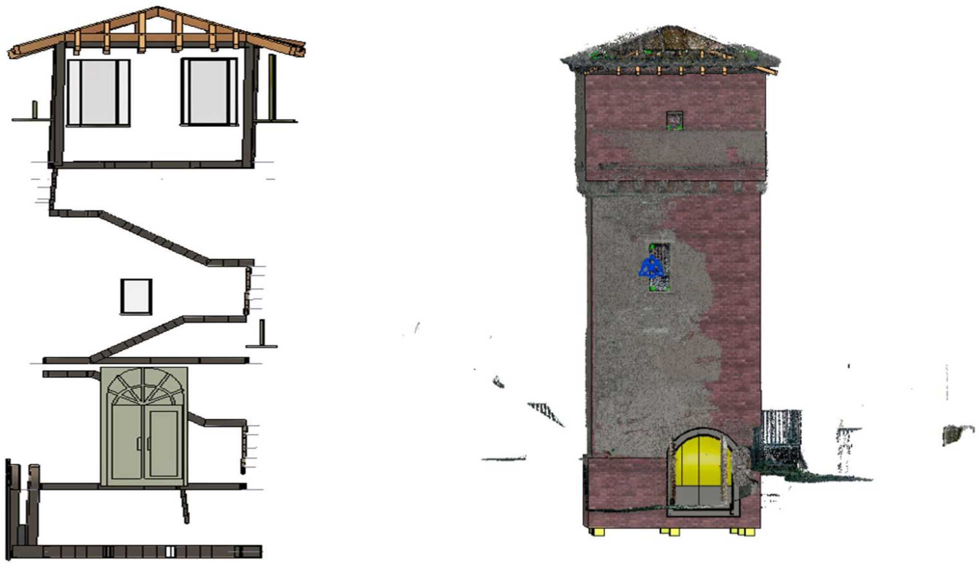


Figure 79 3d Model of the Tower with steel structure

This the model which we transferred to MIDAS gen for the analysis by using the BIM Methodologies.

3.2 MODAL ANALYSIS (MIDAS Gen)

Dynamic testing is increasingly important as a valuable tool that provides a validation to refine and eventually update numerical simulation models and gives information about the response to an external stimulus (e.g., ground motion).

Numerical and experimental frequencies are comparatively presented in Table. The calibrated FE model of the tower is attained by altering in elasticity modulus of masonry walls. Before calibrating, differences between numerical and experimental frequencies of first, second and third modes were 12.2%,19.6 % and 18.7 %, respectively. Modulus of elasticity of brick masonry wall decreased from 1452 MPa to 1200 MPa. After updating, differences between numerical and experimental frequencies of first, second and third modes were 0.3%, 3% and 5.2 %, respectively. Calibrated and non-calibrated first three numerical and experimental natural frequency values of the tower are presented in Tab 11. As results of calibrating process, it was observed that numerical and experimental results were quite close to each other's.

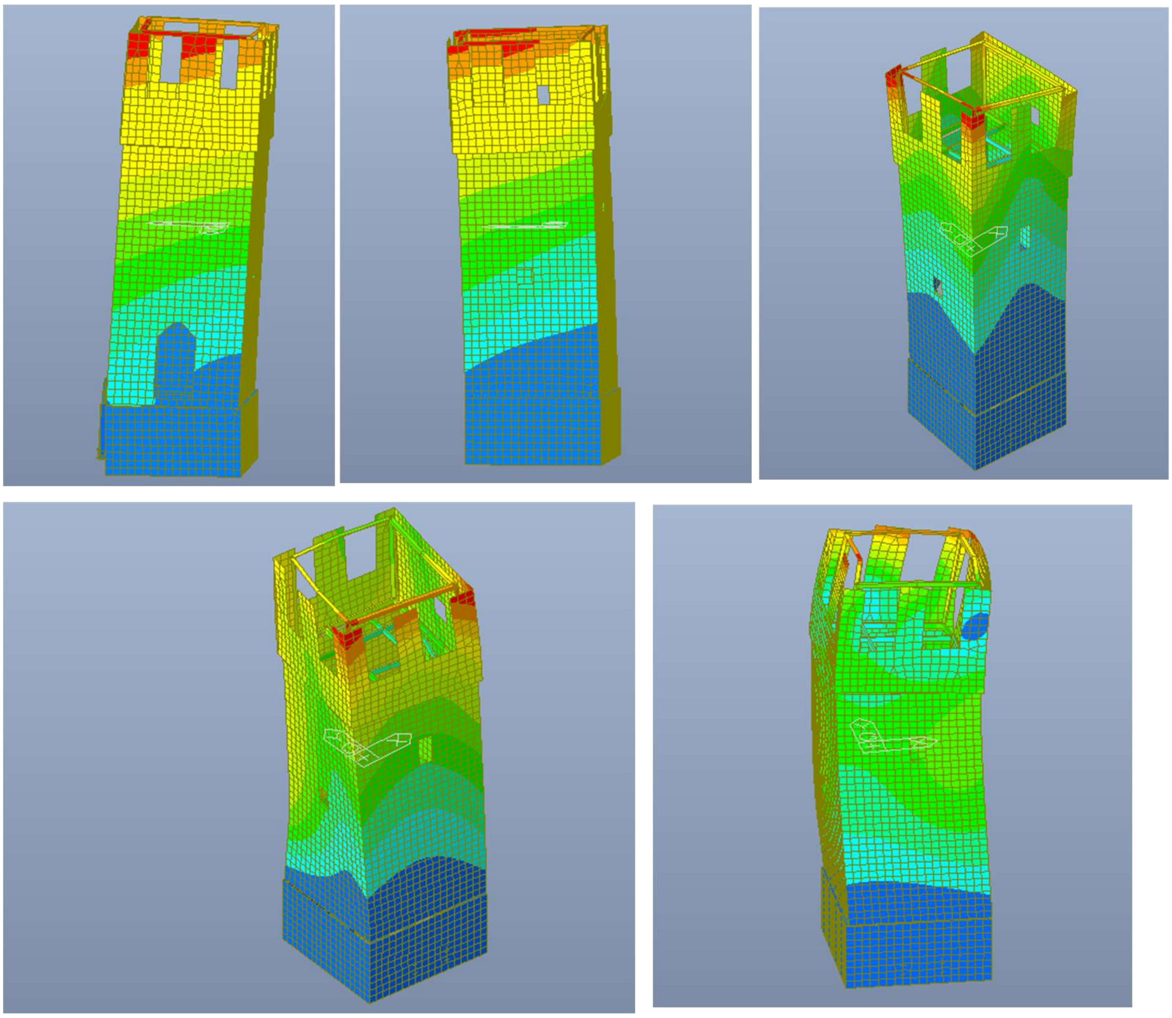
The dynamic characteristics obtained before and after the FEM calibration compared with experiments frequencies.

Table 6 Modal frequencies before and after caliberation

Modes	Numerical frequencies FEM (Hz)		Experimental frequencies (Hz)	Maximum difference between frequencies (%)	
	Before calibration	After calibration		Before calibration	After calibration
1	3.51	2.95	2.95	11.8	0.1
2	4.11	3.47	3.22	12.7	1.077
3	6.91	6.0	5.89	11.7	1.03

Mode shapes of the tower. the figure below represents the first five mode shapes of the updated FE model:

a b c



d e

Figure 80 First 5 mode shapes of our tower a) 1st mode b) 2nd mode c) 3rd mode d) 4th mode e) 5th mode

These figures show the maximum displacement occurs at the top part.

3.3 RESULTS COMPARISON BETWEEN MODELS GENERATED BY POINT CLOUD AND AUTOCAD DRAWINGS

Two models were generated one with point clouds and another with drawings provided by the company. Both were transferred to MIDAS gen for modal analysis and model updating.

Table 7 Different thickness of walls in both models

Type of walls	Thickness of walls (Point clouds) cm	Thickness of walls Autocad cm
Foundation Wall	62	75
Center Wall	45	50
Top floor wall	63	72

- The mode shapes appear to be similar between both of them.

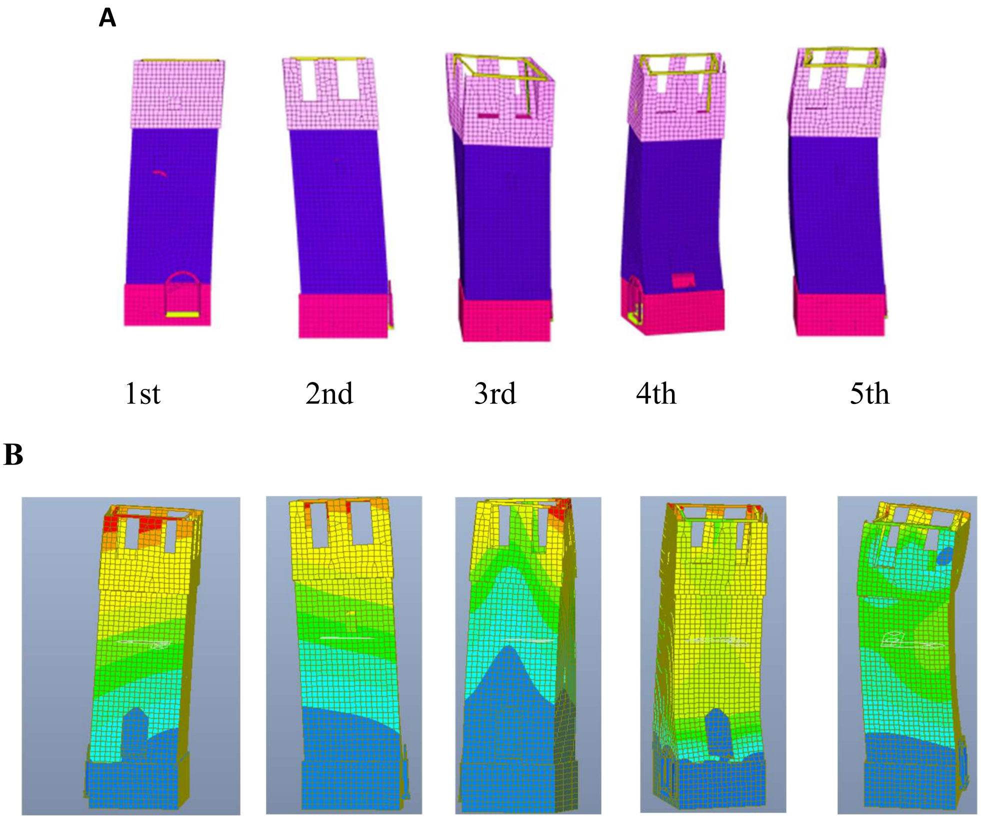


Figure 81 First 5 Mode shapes of both models A) Generated by model made from AutoCAD drawings B) Generated by model made from point cloud

"The figures above represent the first 5 mode shapes of the model generated by AutoCAD, while the bottom 5 represent the mode shapes of the tower generated by point clouds. The mode shapes are almost identical, indicating that there is no significant difference in the analysis caused by variations in thicknesses of 10cm and a 1.5-degree inclination."

3.4 MODEL UPDATING OF TWO MODELS RESULTS

Model Updating was performed by using the same iterations and techniques followed as discussed above in the case study.

Table 8 Calibration results of the model generated by Point Clouds

odes	Numerical frequencies FEM (Hz)		Experimental frequencies (Hz)	Maximum difference between frequencies (%)	
	Before calibration	After calibration		Before calibration	After calibration
1	3.51	2.95	2.95	11.8	0.1
2	4.11	3.47	3.22	12.7	7
3	6.91	6.0	5.89	11.7	1.8

Table 9 Calibration results of the model generated by AutoCAD drawings

odes	Numerical frequencies FEM (Hz)		Experimental frequencies (Hz)	Maximum difference between frequencies (%)	
	Before calibration	After calibration		Before calibration	After calibration
1	3.31	2.96	2.95	12.2	0.3
2	3.85	3.12	3.22	19.6	3.0
3	6.99	6.2	5.89	18.7	5.2

After comparing the results of both models, we found that the numerical frequencies are very similar with only a small difference. This means that if an architect provides us with AutoCAD drawings, we can use them directly to create a structural numerical model. However, when we look at the point clouds result, it aligns more accurately with the experimental frequencies. After calibration, our output for the masonry modulus is E=1200MPa.

3.5 1ST MAY 2024 CONCERT RESULTS

Table 10 Max shear, Stress, Displacements, Velocity and Acceleration on the tower due to 1st May Concert

Max shear stress [KN/m^2]	Max compression stress [KN/m^2]
55.1	112.15

Max displacement [mm]	Max velocity [mm/s]	Max acceleration[cm/s2]
0.04	3.77	4.99

UNI 9916 LIMITS

According to UNI 9916[19], the maximum allowable velocity of particles for historical buildings is 2.5 mm/s. However, our measured velocity during the concert was 3.77 mm/s, which exceeds the allowable range. This could potentially cause damage to the walls. Therefore, crowd control, limits on excessive noise, and structural health monitoring should be implemented.

After comparison between the stresses induced by concert, it’s noticed that the effect of the dynamic pressure could result in unwanted damage so Structural Health Monitoring is required.

CONCLUSIONS AND RECOMMENDATIONS

In summary, this comprehensive study provides a detailed analysis of the Digital TWIN of Moletta Tower. The study utilizes advanced techniques such as point cloud data, REVIT software, MIDAS GEN, and BIM features to create two Finite Element (FE) models of the tower. One model is based on point cloud data, and the other is based on AutoCAD details provided by the company. These models are then refined and validated using various techniques, such as calibrating the elastic modulus of masonry, to create a digital twin. Dynamic time history analysis is performed to represent the effects of the concert on May 1, 2024, on the real structure. Thus, the main conclusions of this study are:

- Using point clouds of a structure when developing a BIM model is advantageous because they can show the positions of walls and beams, and detect any changes in wall positions over time, such as tilting of walls by over 1.5 degrees as observed in our case. Point clouds can also help pinpoint where and when retrofitting is needed. Additionally, they are beneficial in showing the actual 3D shape of the building, including its height and position.
- Using point clouds for 3D modeling is quicker than traditional modeling with AutoCAD. In AutoCAD, we need to develop layers for both 2D and 3D, whereas point clouds can be directly transferred to Revit to create the 3D BIM model directly over the point clouds.
- Point clouds to generate the 3D model in Revit enables us to apply BIM Methodologies to directly obtain the finite element model without the need for additional modeling and we can conduct analysis.
- From the dynamic analysis of the concert happened on 1st May 2024 near the tower, It was discovered that the sound levels of the concert (3.77 mm/s) may have exceeded the peak particle velocity limit (2.5mm/s) set by UNI 9916[19], which could potentially cause damage to the tower.

  Based on these conclusions mentioned above here are the recommendations based on the findings:

- BIM Modeling: If point clouds are available, we can use the data to model geometries, as it can show any tilting of walls or other details that may have occurred over time. This will allow us to create a more accurate model for analysis and checks after calibration. However, point clouds are not always available, so we can also use 2D drawings to generate 3D drawings. In our case study, the difference between the two was very minor.

- Interoperability: It's crucial to review the interoperability matrix between two software programs like REVIT-ROBOT and REVIT-MIDAS. In our analysis, we found that we can transfer the Revit model to Midas Gen, but the walls are automatically meshed and cannot be updated from Midas to Revit. However, it is possible to do so in Robot Structural Analysis.

- After reviewing the outcome of the concert on May 1, 2024, we recommend implementing regular structural health monitoring for Moletta Tower. This will facilitate the early detection of any potential damage and allow for timely intervention.

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