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COMPARISON OF TWO DIFFERENT APPROACHES FOR THE SEISMIC EVALUATION OF THE BONET BUILDING OF THE NATIONAL PALACE OF SINTRA, PORTUGAL

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Abstract. *Complex masonry monuments represent an important part of the built cultural heritage and most of them are vulnerable to seismic actions. Their large scale, irregularity, and heterogeneity makes it challenging to characterize their structural behaviour.*

This work addresses the state of conservation as well as the structural behaviour and seismic vulnerability of the most ancient body of the National Palace of Sintra, Portugal: the Bonet building. This body was built on top of Arabic foundations during the reign of King Dinis, around the year 1281, and since then few alterations were made to the building.

In order to minimize the multiple uncertainties usually existing in complex masonry buildings, whether related to geometry or masonry mechanical properties, a detailed structural survey was conducted together with different in-situ experimental tests. All the tests performed were important to the adequate characterization of the building and the calibration of the numerical models. The final values adopted for the mechanical properties of the rubble stone masonry are presented and can be used as a reference for future works in ancient Portuguese monuments of the same period.

Afterwards, nonlinear static analyses were performed in two different software (3MURI and ABAQUS). Comparisons and discussion of the results are made. The differences in modelling strategies and characterization of materials between the two software are considered with regard to their realism, computational effort, data availability and applicability to large scale structures. Efforts to calibrate and obtain the same behaviour of the building for the different software were made, involving geometry, boundary conditions and characterization of the material constitutive laws.

1 INTRODUCTION

This work is part of a research project which aims to evaluate the seismic safety of the National Palace of Sintra, by identifying possible structural anomalies and vulnerability factors. This project was developed by Instituto Superior Técnico, University of Lisbon and promoted by Parques de Sintra – Monte da Lua, S.A. (PSML). The palace is an agglomerate of buildings of different volumes and styles added over time that presents a beautiful and harmonious unity, characterized by its iconic chimneys, as can be seen in Figure 1.

Figure 1: On the left: North-facing top picture of the National Palace of Sintra. On the right: Northeast view of the palace with the identification of the Bonet Building and the chapel (images captured by the drone of the IST)

This study aims at the structural safety verification of the Bonet Building, one of the oldest structures from the National Palace of Sintra, built over the foundations of an ancient Arab palace. At the request of King D. Dinis, whose reign took place between 1261 and 1326, the Bonet Building was expanded, and the adjacent Palatine Chapel building was built from scratch, both identified in Figure 1 (right).

The palace is located in Sintra, a town of the Lisbon district, which is a zone of Portugal mainland characterized by high seismic risk. The seismic assessment of complex masonry structures such as this palace, in which the Bonet building is included, presents several difficulties. One of them is the definition of the best numerical modelling option, where one needs to choose between a rational computational effort and assuring a reliable structural assessment able to characterize the building's correct behaviour. Other adversity is the lack of tools and consistent procedures to perform the seismic analysis and verification of such complex masonry structures ([1], [2]).

For the complete characterization of the Bonet building, an experimental campaign was carried out including *in-situ* experimental tests aiming for the mechanical characterization of materials and/or structural elements, and the geometric and dynamic identification of the structure [3]. A detailed geometric inspection was performed using a laser scanner that allowed to obtain data with an accuracy of up to $1x10^{-6}$ m, thus constituting a suitable methodology for cases of complex geometry. The data collection was aided by a UAV equipped with a Sony 7R digital camera so that it was possible to obtain full information of the outside of the palace. The set of data obtained gave rise to a three-dimensional point cloud (Figure 2, left), later treated and used in Revit software for the development of an H-BIM model (Figure 2, right).

The GPR (Ground Penetrating Radar) test, a non-destructive method, aims to characterize the masonry by detecting types of materials and anomalies (voids, cracks, water), using different frequencies' antennas. With this test, two major conclusions were obtained: i) "the majority of the walls are composed of two interior-filled masonry leaves, and usually the outer leaf is approximately 0.30m thick" [4]; and ii) the walls built around the rock are directly in contact with it, without empty spaces in between.

Figure 2: Bonet Building, North Facade: Point clouds (on the left) and Revit Model (on the right)

Flat-jack tests, considered to be semi-destructive, aim to characterize the mechanical capacity of structural masonry walls. The fact that Bonet is a historical building increases the difficulty of locating the experimental tests. Despite this, the wall to be tested should accomplish still the following conditions: to present a certain level of compression and not be located near doors, windows, or another singularity that can alter the stress field. With this in mind, two locations were defined, one on the north facade of the building and the other on the south. The results of the single test indicate that the Bonet structure is poorly compressed in the tested areas, although the results may be considered with caution due to their punctual character and the physical characteristics of the walls, which present high thicknesses. From the double tests, the stress-strain curves were obtained and then the stiffness, maximum stress, and Poisson's ratio were determined. Young's Modulus values are high, justified by the boundary conditions of the walls examined, which are built against the bedrock (the only possible locations on the building to perform these tests). Therefore, this parameter obtained was taken into account only as an upper limit value during the numerical model calibration.

In addition, samples were collected in the form of cores (semi-destructive test) near to the locations were the flat-jack tests were carried out, in order to characterize the material and its constituents. However, due to the heterogeneity of the masonry, the samples can only represent the material locally. From this type of test, qualitative results were obtained, concluding that the state of degradation of the masonry in the Bonet building is quite high, even one of the worst of the entire palace [3].

The ambient vibration tests are non-destructive and suitable for the seismic assessment of existing buildings, especially for historic and heritage buildings. By measuring the structure vibrations subjected to external environmental inputs, it is possible to identify the modal dynamic characterization parameters. The dynamic characterization of the structure is crucial for the calibration of its numerical model. The processing of the obtained data was performed with the ARTeMIS Modal Pro software [5] that allowed to obtain the fundamental frequencies and the vibration modes of the structure. Results reached are available further on in Table 1 and Figure 4.

3 NUMERICAL MODEL

The Bonet Building was modelled in parallel using two software, 3Muri [6] and ABAQUS [7]. For both models, it was ensured that the structure geometry is identical, even with the required simplifications, and consistent with the data collected by the Laser Scanner.

Both ABAQUS and 3Muri models were defined based on the BIM model. It was decided to export the Revit model [8] and to import it into ABAQUS, saving time and significant manual effort. In 3Muri, this specific option is not possible. Nevertheless, one should be aware of the usual excessive detailing in BIM models for the purposes of numerical modelling, with all the architectural ornamentation, that cannot be directly used in FE software. Thus, as explained in [9], in order to achieve an adequate FE model, several manual simplifications are required to guarantee mesh compatibility, to avoid mesh local distortions or small elements, and to model complex architectural objects. With that in mind, some geometric simplifications were adopted, namely the use of the mean value of thickness in walls of variable thicknesses.

For the ABAQUS model, in solid FE elements, a 10-node tetrahedral finite element mesh with a maximum size of 700mm was defined (Figure 3, left), thus ensuring for each thickness the existence of three nodes. As presented in Figure 3 (right), the EF method is adopted in 3Muri [3], defining the walls in macroelements that consist of piers (represented in orange), spandrels (in green), and rigid nodes (in light blue).

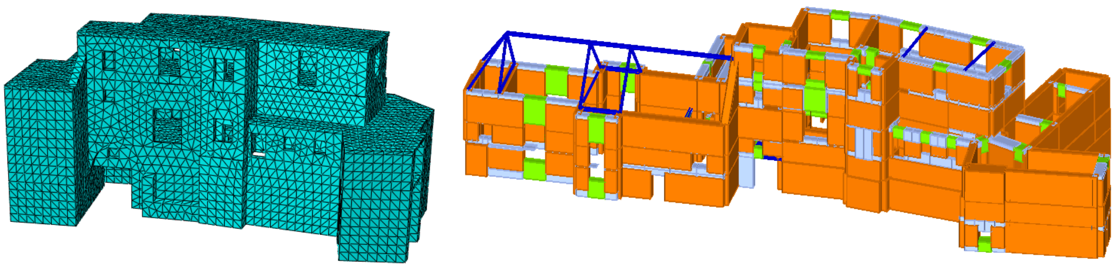

Figure 3: Bonet Building (view of the North facade): on the left, ABAQUS Model with FE Discretization; on the right, 3Muri model with macroelements discretization

One of the most difficult challenges when modelling complex structures is the definition of the boundary conditions. Therefore, the necessary parts of the adjacent buildings were modelled to account for the interactions and impact they have on the overall behaviour of the Bonet Building.

3.1 Calibration

The calibration of the numerical models, in ABAQUS and 3Muri, is an important step and fundamental to reach reliable results. In this phase, an iterative process was followed, in which the values obtained in the experimental campaign [3] were considered as reference and in each step special attention was taken to the:

- definition of the boundary conditions, considering the adjacent buildings;
- type of boundary conditions when modelling the structural walls in contact with the bedrock;
- values adopted for the definition of the masses;
- values adopted for Young's modulus (E) of the materials, in particular to the masonry walls (significantly cracked on the top floor and not cracked on the other floors).

Table 1 illustrates the fundamental frequencies for the first three vibration modes obtained experimentally (ARTeMIS) and numerically (ABAQUS and 3Muri), as well the relative error obtained when comparing the numerical to the experimental results, in percentage. Figure 4 presents the corresponding vibration modes: the first and second mode represent the translational modes in the north-south direction (Y - transversal), and the third mode corresponds to the vibration in the east-west direction (X - longitudinal). It is worth noting the close similarity between the frequency values and deformed shapes obtained in the numerical models and the experimental results.

Table 1: Frequencies of first vibration modes, Relative Errors of models in ABAQUS and 3Muri (numerically) in comparison to the model in ARTeMIS (experimentally)

	ARTeMIS	ABAQUS		3Muri	
Mode:	**f (Hz)**	**f (Hz)**	**Difference (%)**	**f (Hz)**	**Difference (%)**
1st Y	5.00	5.05	0.96	4.98	-0.40
2nd Y	5.18	6.17	19.11	5.55	7.14
1st X	8.20	7.27	-11.34	7.03	-14.27

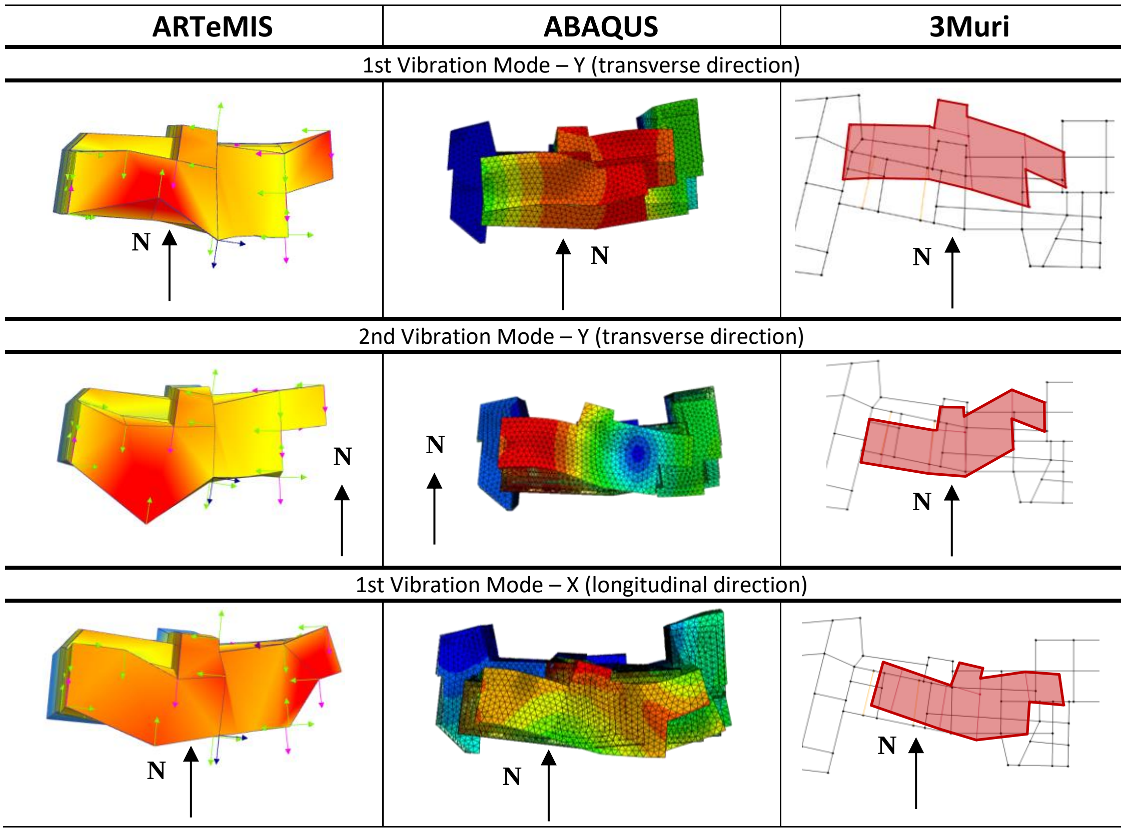

Figure 4 - Deformed shapes of the main vibration modes obtained experimentally (ARTeMIS) and numerically (ABAQUS and 3Muri) – plan view

For the verification of the seismic safety of the structure, nonlinear static analyses were performed. Different approaches were followed to model the nonlinear behaviour of the masonry panels.

For the Equivalent Frame (EF) models (3Muri program), the masonry panels were modelled as nonlinear beams with lumped plasticity and a piecewise-linear behaviour, that are able to describe the nonlinear response until very severe damage levels through progressive strength decay in correspondence with assigned values of drift [10]. In the EF models, according to the failure modes which can occur, it is possible to use specific failure criteria for the masonry panels. It is highlighted that with this modelling technique only the in-plane behaviour of the walls is considered, assessing the walls' response in terms of global stiffness, strength and ultimate displacement capacity by assuming a proper shear-drift relationship [6]. This relationship depends on the different failure modes, which in turn depend on several parameters: the geometry of the element, the boundary conditions, the axial load, and the mechanical characteristics of the masonry constituents (e.g. mortar and units).

Regarding the FE model (ABAQUS), the masonry walls have been simulated by using the Concrete Damage Plasticity Model (CDPM) and the stress-strain relationships defined separately for compression and tension. The CDPM was designed to define the plastic properties of concrete or quasi-brittle materials developed by Lee & Fenves [11]. This model uses the concepts of damaged elastic isotropic material in conjunction with the compressive and tensile plastic stress of isotropic material to represent the non-elastic behaviour of masonry, as explored in the ABAQUS Theory Manual [12]. Therefore, it is recommended to be used in masonry materials, despite being developed for concrete. The plastic model assumes that the two main collapse mechanisms are tensile diagonal cracking and compressive crushing. The evolution of the yield surface is controlled by the tensile and compressive strain, considering different types of behaviour related to the failure mechanisms under load, as explained in the ABAQUS Theory Manual. In this study, simplified constitutive laws for compressive and tensile behaviour were based on [13] and [14], respectively.

The value assumed for the masonry compressive strength was defined proportional to the calibrated Young's modulus (E), according to MIT [15] reference intervals. The value adopted for the tensile strength was defined as 3/2 of the value of cohesion. The mechanical parameters, assumed in both software, ABAQUS and 3Muri, for rubble stone masonry of the Bonet and adjacent buildings are presented in Table 2. In this table, E stands for the Young modulus, G for shear modulus, f_t for tensile strength, f_c for compressive strength, and w for the specific weight of the material.

Table 2: Rubble stone masonry mechanical properties

	E (GPa)	**G (GPa)**	**f_t (MPa)**	**f_c (MPa)**	**w (kN/m^3)**
Disorganized irregular stone masonry					
MIT (2009)	0.69 – 1.05	0.23 – 0.35	0.030 – 0.048	1.00 – 1.80	19
Bonet Building (Last Floor) Cracked	0.40	0.13	0.018	0.62	18
Bonet Building	0.80	0.26	0.036	1.24	18
Irregular stone masonry with two external leaves and internal core					
MIT (2009)	1.02 – 1.44	0.34 – 0.48	0.053 – 0.077	2.00 – 3.00	20
Chapel	1.44	0.48	0.080	3.00	19
Brasões Room	1.20	0.40	0.063	2.43	18

In ABAQUS, damage variables for the compression and tension of each material are necessary to define to control the loss of stiffness and resistance of the material that occurs upon entering the plastic regime, increasing progressively with the stress decay. The damage variables are fundamental to represent the real behaviour of the material during the nonlinear analysis since the damaged masonry presents significant stiffness reductions. A linear progression was adopted since entering the plastic regime until the maximum strain of decay, when it was assigned the maximum damage value of 0.9.

To define the CDPM in ABAQUS, the values of the following parameters are assumed as being the typical ones for masonry, as explained in [2]: (i) the dilation angle, equal to 10°; (ii) the flow potential eccentricity, set equal to 0.1; (iii) the ratio between the initial biaxial compressive yield stress and the initial uniaxial compressive yield stress, set equal to 1.16; (iv) the ratio of the second stress invariant on the tensile meridian and the same on the compressive meridian, set equal to 0.666; (v) the viscosity parameter, which defines visco-plastic regularization, equal to 0.002.

5 NONLINEAR STATIC ANALYSES

5.1 Pushover curves

In this work, two distributions of lateral loads were considered: uniform – proportional to the mass, and inverse-triangular (named triangular for simplicity) – proportional to the product between the mass and the height of the building. The analyses are performed for the two main directions of the building (longitudinal, X, and transversal, Y), including negative and positive orientation.

Figure 5 presents the final pushover curves obtained with 3Muri and ABAQUS in terms of base acceleration, and displacement divided by global height. The last point of the capacity curves corresponds to the ultimate displacement divided by the global height. As expected, for the initial phase, similar values of initial stiffness in pushover curves were obtained for both software, since the dynamic characteristics obtained in the modal analysis were also very similar.

On the other hand, some differences in terms of maximum base acceleration exist for the curves in the X direction. For this direction, the curves in 3Muri present less acceleration, that is translated into less strength capacity. This result can be related to the different constitutive laws considered in each software; however, the most likely justification is the fact that in 3Muri the entirely of the adjacent buildings were modelled, while in ABAQUS only small parts with constraints at its extremities were modelled. The constraints do not allow to consider the damages or even the collapse of the adjacent buildings suffered during the pushover analyses, increasing the strength of the ABAQUS model. This modelling option was made taking into account the computational capacity required to model the entire adjacent buildings in ABAQUS software and the calibration of the model.

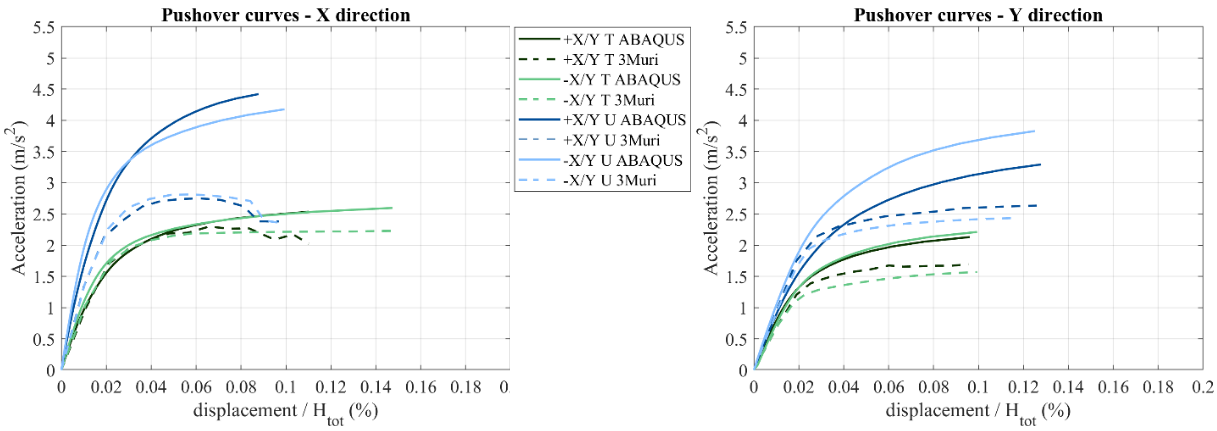

Figure 5: Final Pushover Curves, X direction (left) and Y direction (right), ABAQUS and 3Muri

5.2 Ultimate displacement definition

The ultimate displacements of the pushover curves obtained in 3Muri were calculated based on two-level multiscale approach: global damage, measured when achieving a decay of 20% of the base shear force on the pushover curve; and local damage, defined when a collapse mechanism occurs.

The CDPM implies that for each time increment the applied load is also increasing and, regardless of the damage variables defined, the total strength of the structure does not decrease. Thus, with the ABAQUS software, there is a difficulty in determining the ultimate displacement, becoming necessary to define a criterion for its definition.

Since one of the main objectives of the ABAQUS model is to compare the results with the 3Muri model, in addition to performing the seismic evaluation of Bonet building, the ultimate displacement calculated in 3Muri was used in the corresponding curves obtained in ABAQUS. Subsequently, the ultimate displacement was verified using the Italian Standard [16] criterion - the ratio between the ultimate displacement value and the yield displacement must be between 3 and 6 - and, if necessary, a correction was implemented.

5.3 Safety verification – N2 method

Safety is verified using the N2 method, as suggested in Part 3 of Eurocode 8 [17] and defined in its Part 1 [18]. In this study, for the safety verification, the ratio of the maximum acceleration compatible with the fulfilment of each limit state ($a_{g,max}$) and the reference ground acceleration (a_{gR}) is evaluated and analysed. The ration between the ultimate displacement and the target displacement was not analysed for the safety verification, since the definition of the ultimate displacement is one of ABAQUS limitations. For the definition of the equivalent single degree of the system (SDOF), a transformation factor needs to be evaluated; as opposed to 3Muri, ABAQUS does not automatically calculate the transformation factor, for this reason, it was obtained manually for each direction, which is a demanding process for complex structures such as the Bonet Building. The degrees of freedom were considered at the floor levels of the structure that are not restrained by the bedrock. The mass associated with each degree of freedom was calculated considering the displacements of each floor associated with the vibration modes.

The seismic action was defined according to EC8-1 [18], complemented by the Portuguese Annex. According to EC8-3, three limit states should be considered for the seismic safety verification: Limit Damage (LD), Severe Damage (SD), and Near Collapse (NC).

Safety is verified when the ratio is greater than 1. Figure 6 shows the safety verifications for the type 1 earthquake, the most demanding one, and the near collapse limit state (the one with the highest requirements) of the equivalent SDOF system in ABAQUS and 3Muri. It is then possible to state that safety is not verified for the Bonet Building, with Y direction being the most vulnerable for both models. It should be added that, due to the restrictions of ABAQUS when defining the ultimate displacement, it is more useful and interesting to compare the results of both software in terms of damage patterns, as will be commented below.

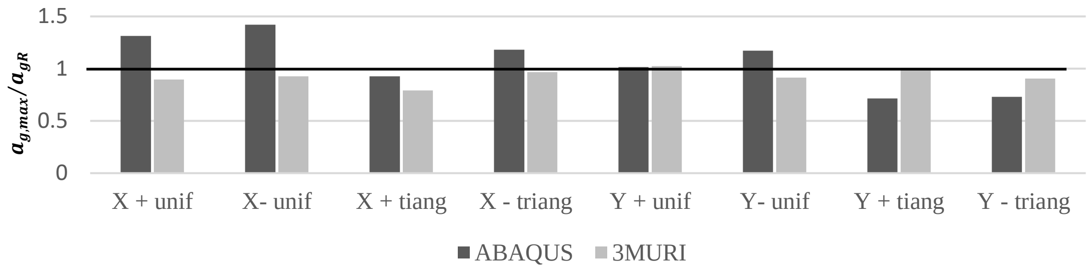

Figure 6: Safety Verification, NC, Earthquake Type 1

5.4 Damage pattern

A comparison is made between the damage patterns results obtainable from the FE model developed in ABAQUS, and those obtainable from the Equivalent Frame approach, by using the 3Muri software. Here only the most demanding case is presented: + Y, triangular lateral load distribution (Figure 7 and Figure 8). The damage patterns depicted correspond to the ultimate displacement.

According to the 3Muri results presented in Figure 7, it is possible to identify in the Bonet building a concentration of damaged elements at the top floor, even with a pier collapsed due to shear on the western sidewall. The walls of the top floors along the Y direction present damage mainly due to shear behaviour. As expected, the type of collapse is severely influenced by the height/length ratio; walls with lower values are controlled by shear, while walls with higher ratio values tend to present flexural damage.

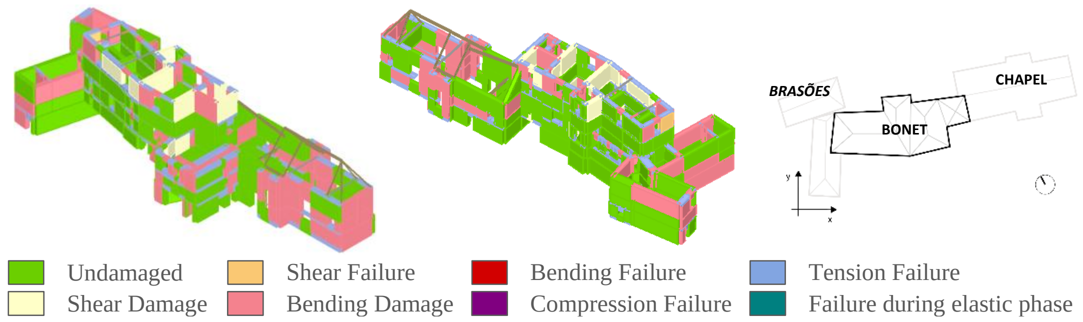

Figure 7: Damage Pattern, 3Muri (+Y, triangular distribution) – damage in Equivalent Frame Model

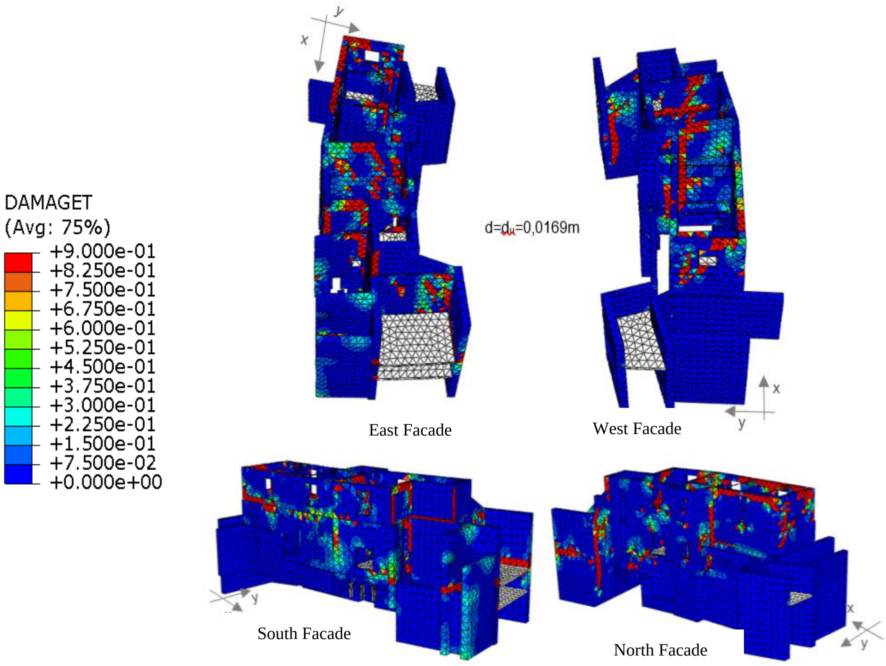

Figure 8: Damage Pattern, principal inelastic Tensile strains, ABAQUS (+Y, triangular distribution)

Finite element analysis in the ABAQUS model allows studying the local evolution of the damage in detail in terms of strains, which can be increased if necessary, with mesh refinement. On the other side, refining the mesh will require more computational effort and time, which for complex structures of this size can be unportable. Moreover, it is worth noting that ABAQUS does not identify the type of damage or collapse the walls suffer as in 3Muri, making the analysis less user-friendly. This program presents the damage through the separate interpretation of the damage caused by tension or compression. Analysing the damage parameter in ABAQUS for the tensile strains (Figure 8), it can be concluded that most of the damage is also concentrated on the walls of the top floor. The diagonal inclination of the cracks at the top floor walls along the Y direction clearly indicates the activation (or close to the activation) of shear failure, as seen in 3Muri damage patterns. It is worth mentioning that the maximum tensile damage is presented in the upper spandrels of the last floor walls, in both facades, where the tie rods are located. This effect cannot be identified in 3Muri since a global analysis is performed, without considering the out-of-plan behaviour.

In the past, some numerical comparisons have already been carried out for masonry walls ([19], [20]) and the results have shown generally good agreement in terms of damage pattern. This is in accordance with the observed in the Bonet building analyses for FE and EF models.

6 CONCLUSIONS

Regardless of the numerical software used, the point cloud based on the laser scanner survey is essential for the correct geometric characterization of a complex building. As the construction of complex structures in ABAQUS is very difficult, it is suggested, whenever possible, to import a BIM model of the structure directly into the software. Otherwise, it may not be advisable to use ABAQUS to assess this type of structures, as the effort of building the numerical model will not be worthwhile. Moreover, the BIM model has to be architecturally simplified and built in order not to create distorted finite elements when generating the mesh in the FEM software. On the other hand, 3Muri is a program developed for masonry building modeling and analysis, leading to a simplified process of construction and alteration of the geometric characteristics of the structure.

In general, good correspondence is observed between the predictions of the two numerical models considered. Note that ABAQUS presents a high graphical ability to observe the results. In the modal analysis, it is possible to rigorously study the deformed structure for the various vibration modes. The same conclusion can be drawn when interpreting the damage pattern since one can observe the damage evolution for each finite element node, while 3Muri presents the damage evolution for each macroelement. However, 3Muri designates the type of damage or collapse in each element, which is very useful to the user.

In addition, 3Muri is a more suitable program for performing pushover analysis and subsequent security verifications. The program proposes for each analysis an ultimate displacement and automatically calculates the transformation factor of the models from MDOF to SDOF. These two points are of high difficulty in ABAQUS, involving a complex calculation, especially for complex buildings. On the other hand, in ABAQUS, non-linear analyses performed with refined FE discretizations of the critical regions and with more sophisticated material models, are useful to deepen the knowledge of the behaviour of complex structures under seismic actions.

Lastly, 3Muri does not require the large computational effort and time that ABAQUS requires, which is a very important aspect to take into account when dealing with very large and complex structures. In the end, it will be necessary for the user to choose between more geometry accuracy and detail with ABAQUS or less computational effort with 3Muri.

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