H-BIM Model and Seismic Assessment of Chalet of the Countess of Edla

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December 2020

ABSTRACT

The Chalet of the Countess of Edla is a remarkable building of the Portuguese heritage which stands out for its history and architecture, built in the end of the 19th century.

This study aims to assess the seismic performance of the Countess building, considering the global in-plane response of the structure, and to verify its structural safety. Therefore, non-linear static analyses were performed on the building, while being acted upon a regulatory seismic action. A model in software 3Muri was developed, in which all the main structural elements, such as rubble stone masonry walls with openings, timber floors, verandas, arches and metal frames were represented. In addition, with the purpose of understanding the parameters that most influence the model, it was performed a sensitivity analysis.

To enable the structural assessment of the building, a geometric survey using Terrestrial Laser Scanning (TLS) was conducted. A Heritage Building Information Model (H-BIM) in software Revit was built, from the ordered point cloud, in order to centralize in the digital model database all the information related to the constituent materials and their inherent physical properties.

In the context of the present work, this study demonstrates the potential of establishing a link between the application of new technologies for the acquisition of geometric data in an accurate way, the modelling in BIM of a cultural built heritage, and the study of its seismic vulnerability, which may in the future serve as a support to the conservation and maintenance activities.

Keywords: H-BIM, Seismic performance-based assessment, Non-linear static analysis, Laser Scanning, Chalet of the Countess of Edla

1 Introduction

According to the International Council of Monuments and Sites (ICOMOS, 2002), the cultural heritage has a significant importance in the identity of individuals and communities, thus transmitting social values, beliefs, religions and customs, that must be preserved for future generations. The Chalet of the Countess of Edla fits into this classification as it represents a combination of different cultures of the XIX century.

The House of Regalo, or better known for Chalet of the Countess of Edla (CCE), is a building that stands out for its history and its unusual architectural structure for the country, being one of the “maximum examples of existing romantic architecture in Portugal, and presents a very particular and singular outline” (Rebelo, 2011).

This building was built between 1869 and 1875, by D. Fernando II and his second wife Elise Hensler, according to her own project, in the western part of Pena Park in Sintra, with influences of typical Swiss Alps Chalets. The location presented a private character, serving as a space for the couple's refuge and recreation. It was abandoned years later and, in 1999, suffered a devastating fire, being only recovered in 2007 (Figure 1).

Figure 1 – Chalet of the Countess of Edla (Ncultura, 2015)

The lack of studies, from a structural point of view, carried out in the past to the building, the limited documentation and the high uncertainty in terms of construction methods used at the time, turned out to be a huge challenge for the engineers. It is in this context that emerged the need to gather and digitalize all the necessary information and make it accessible at any time, to the entities in charge of building maintenance.

The built cultural heritage represents an inestimable value in the definition of cultural identity and, therefore, it is of the utmost importance to have resources and tools to support its maintenance in an efficient manner (Bento et al., 2020).

On the other hand, the Chalet is located in one of the regions with the greatest seismic hazard in Portugal (Ferrão et al., 2016), and belongs to the typology of buildings that is most vulnerable to seismic action (masonry buildings).

Therefore, this study aims to evaluate the global seismic performance of CCE in its current state (after having undergone some structural changes), considering the in-plane behaviour of the masonry walls. To achieve this, it was developed an H-BIM model, resultant of a geometric survey carried out in the field using TLS and supported by a topographic survey.

As suggested by Bento et al. (2020), Godinho et al. (2019) and Ponte et al. (2019), the built cultural heritage requires a multidisciplinary approach for an efficient and effective analysis of the vulnerability and seismic assessment.

The methodology followed in this study starts by an extensive research of relevant historical data, in order to allow the general characterization of the building, along with a geometric survey, e.g. using terrestrial laser scanning technology and aerial photogrammetry. Afterwards, the acquired data is processed, in order to obtain an unified ordered point cloud. It is from this phase onwards, that it is possible to recreate a three-dimensional (3D) H-BIM representation of the building and to associate geometric and non-geometric data to the modelled elements. In Figure 2, the main steps necessary to the construction of most H-BIM models are highlighted.

Subsequently, a numerical model is developed from the previous one. It is very important at this stage to characterize the regulatory seismic action and to define the mechanical properties of the structural elements of the model, as well as to carry out a modal dynamic analysis of the structure. The building's seismic analysis is performed, considering the overall behaviour of the structure, using non-linear static analyses. In order to overcome the lack of experimental tests and to guarantee the models reliability,

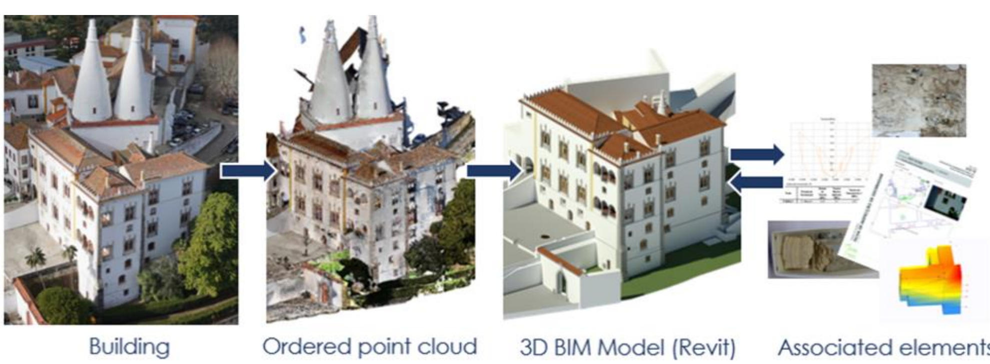

Figure 2 - Main steps to build a H-BIM model (adapted from Godinho et al., 2019)

this study ended with the performance of a sensitivity analysis (Figure 3).

All the main steps described above will be explained in more detail, in the following sections.

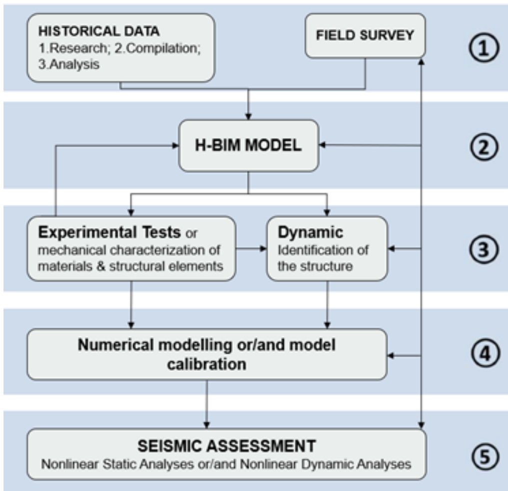

Figure 3 - Methodology applied to the study of seismic assessment of cultural heritage, and to this case study (adapted from Ponte et al., 2019)

2 Data acquisition

In the beginning of this research it was necessary to carry out a topographic and geometric survey, in order to guarantee the best possible positional quality in the construction of the digital model.

In the field work the following devices were used, provided by Instituto Superior Técnico: Laser Scanner Faro Focus S70, Drone Topcon Falcon 8+ (UAV), Leica TCR 703 Total Station and the GNSS Trimble R2 Receiver.

2.1 Topographic data

The topographic survey began with the prior preparation of a topographic support network, consisting of 3 nodes using the total station and 2 nodes with GNSS devices, coordinating a total number of 8 topographic targets. The targets were evenly distributed throughout the building, with 4 being placed on the lower floor and the remaining 4 on the upper floor.

The local coordinates were transformed into cartographic coordinates related to the PTTM06-ETRS89 system and orthometric altitude relative to the MSNM - Cascais Maregraph, which is in accordance with the current rules for cartographic production.

The positional quality of the real coordinates (shown in Table 1), obtained with GNSS, was 2 centimetres.

Table 1 – Topographical coordinates acquired by Leica Total Station, of the 8 topographic targets

	M [m]	P [m]	H [m]
Target 1	110009.80	97288.23	399.87
Target 2	109999.94	97294.93	399.79
Target 3	110004.83	97289.21	400.38
Target 4	110000.02	97287.77	402.58
Target 5	101008.29	97294.04	405.44
Target 6	109996.42	97281.84	404.95
Target 7	109998.79	97288.64	404.99
Target 8	110005.60	97283.82	404.91

2.2 Geometric data

The laser scanner field survey was conducted by using 10 flat targets placed outside and inside the building. The precise location of the checkerboard targets considered the following criteria: to be in the field of view of each scan, in order to avoid the occurrence of hidden areas; and to provide a high overlap between consecutive scans.

The acquisition of geometric data was performed using the Faro Focus S70, a phase-based laser scanner, covering a field area of 360º by 300º. The scan resolution established was 1 point by 7.7 mm, over a distance of 10 meters, from the position of the equipment. The quality of the scan was defined by the number of measurement repetitions of each point, being stipulated as 3 to 4 times, depending on the area of the captured room.

The geometric survey of the Chalet was carried out with a TLS, in a total of 95 scan stations, corresponding to 16 spaces (rooms) and surrounding environment, merged in a unique point cloud model composed by 28 million points.

For the interior compartments, at least 2 scans were executed per room, in order to be possible to join different scans afterwards, through a large common area between them.

As the surrounding area of the Chalet has many similarities, it was necessary to perform scans every 6 meters, thus guaranteeing the possibility of joining 2 laser scanning's, in the next phase, through at least 3 common targets, completing a triangulation.

It should be noted that all scans were merged with colour photography, in order to be easier to identify the details in the point cloud (Figure 4).

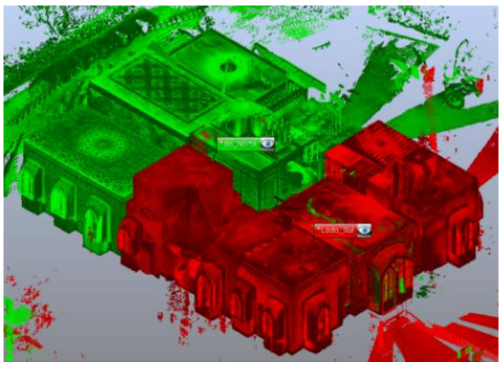

Figure 4 - Union of clusters of different rooms, corresponding to the first floor of the CCE

This described procedure was essential to ensure the accuracy of acquired data, indispensable for the construction of an accurate H-BIM model. Figure 5 shows the final ordered point cloud of the CCE.

Figure 5 – Final ordered point cloud of the Chalet of the Countess of Edla

3 H-BIM implementation

For the development of an H-BIM model, it is necessary to study exhaustively the existing building, to obtain a geometric and a non-geometric characterization of it, as close to reality as possible.

The construction of this model was supported by the material provided by *Parques de Sintra - Monte Lua, S.A.* such as old photographs (of the rehabilitation of the building), the Reconstruction Project and technical drawings.

3.1 H-BIM model

For this practical work, the adopted scan-to-BIM workflow, results on the transition of the point cloud acquired with laser scanning to the development of a BIM model, that involves three steps: (i) modelling the components geometry; (ii) defining categories to objects, and material properties and assets (graphics, appearance, physical) to components; (iii) establishing a relation between components, according to a hierarchy predefined in the software used (Godinho et al., 2019).

The H-BIM model was created in the 2020 version of Autodesk Revit program (Autodesk, 2020), consisting on the following structural elements: exterior and interior walls, steel frames, masonry arches, wooden floors, ceilings, roofs and balconies. In addition, the model was complemented with windows, doors, stairs and a chimney.

In total, 112 walls were represented, 46 roof elements (Figure 6), 40 floor elements (Figure 6), 8 structural arches and 4 steel frames.

All the elements were modelled by simplifying the geometric representation of the materials, in order to not overload the model. However, it was simultaneously guaranteed a sufficient level of detail of the individual components, for the future management activities of the building.

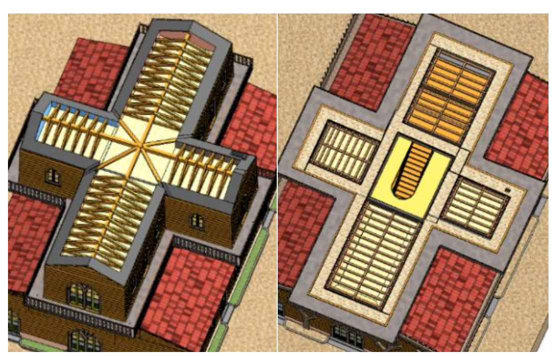

Figure 6 – Structural representation of the superior roof (left) and wood pavement of the 2º floor (right)

The complete H-BIM model of the CCE(Figure 7) provides access to the various entities involved in the maintenance and conservation activities of the building, in real time, and has the ability to provide a better global perception of the building, in its current state, without having to go to the site. In addition, the model database may be updated and completed whenever an intervention occurs.

Figure 7 - H-BIM final model of the Chalet of the Countess of Edla, in software Autodesk Revit

4 Numerical Model

4.1 Non-linear numerical model in 3Muri software

Based on the Revit model of the Chalet of the Countess, a 3D numerical model was developed in 3Muri software (S.T.A. DATA, 2020), with the aim to assess its seismic behaviour by means of non-linear static analyses.

The 3Muri software uses the Equivalent Frame Method approach by applying macro-elements, in which follows the assumption that masonry walls with openings have in-plane behaviour. The contribution of the out-of-plane wall behaviour is neglected (Penna et al., 2013).

The macro-elements used to model the structural masonry elements are divided into three structural components: piers (vertical elements) and spandrels (horizontal elements), a set of deformable elements, and rigid nodes, which are the rigid regions of the building where no damage occurs, serving only as a link between spandrels and piers (Lagomarsino et al., 2013).

4.2 Mechanical properties

In an initial phase, the main walls of the Chalet, which surrounds the entire building and the stairs atrium, and its respective openings were modeled. The walls are made of ordinary stone masonry and lime, with pebbles and irregular stones. The partition walls of the first floor were also represented, however given the varied thickness and constructive complexity, they were simplified and modeled as *tabique* walls (Simões, 2018).

The mechanical properties adopted in the 3Muri model for exterior walls are defined according to the Italian regulations (MIT, 2019), and for the partition walls, based upon experimental results of Rebelo et al. 2015 and Simões (2018). Table 2 shows the chosen values.

It should be noted that two of the rubble stone masonry parameters, the modulus of elasticity (E) and the distortion modulus (G), must be reduced to 66% of their value, in order to take into account the cracking defects on the masonry structures non-linear analyses (pushover) (Simões, 2018).

Table 2 – Masonry and tabique walls mechanical properties

Materials	f_c [Mpa]	τ_0 [MPa]	E [GPa]	G [GPa]	γ [KN/m^3]
Rubble Stone Masonry Wall	1.00	0.018	0.69*	0.23*	19.0
***Tabique* Wall**	0.54	0.010	0.11	0.002	13.5

The wooden pavement structure was completely replaced by a new one and reinforced using steel angles, attached to the masonry by threaded rods, and by two steel profiles placed in the smallest direction of the building (parallel to the wooden beams).

The pavements mechanical properties, such as the compressive strength (f_c), the modulus of elasticity parallel and perpendicular to grain (E_0 e E_{90}) and the volumetric weight (γ), were defined using values proposed by Part 2 of the Italian Standard UNI 11035 (2003). These properties are presented in Table 3.

The value of the distortion modulus (G) suggested by the Italian Standard, is relatively high (0.95 GPa) and is usually applied to rigid pavements. Therefore, the value suggested by Giongo et al. (2014) was adopted, for flexible pavements (of wood) with good connections to masonry walls.

Table 3 – Wood pavement mechanical properties

	f_c [MPa]	E_0 [GPa]	E_{90} [GPa]	G [GPa]	γ [KN/m^3]
Chest nut wood	22	11.0	0.73	0.021	5.4

According to Part 3 of Eurocode 8 (EC8-3) (CEN, 2017), the level of knowledge relatively to the Chalet's mechanical properties of the materials is very limited (level of knowledge KL1). For this reason, it is recommended to divide the material properties considered by a confidence factor of 1.35, in order to take into account the uncertainties associated.

4.3 Modal Analysis

The first analysis to be carried out in the 3Muri software was the modal analysis, which allows to estimate frequencies and their respective vibration modes of the structure. The main periods of the building for the longitudinal (Y) and transverse (X) directions, were chosen accordingly to the mass participation factors of each mode. Table 4 shows the two main vibration modes of the structure, associated to each direction.

Table 4 – Periods, frequencies and mass participation factors (M_x and M_y), relative to the main vibration modes

Vibration mode	Period [s]	Frequency [Hz]	M_x [%]	M_y [%]
1	1.02	0.98	31.71	0
4	0.40	2.48	0	48.81

The structural walls in the transverse direction (X) of the building present a shorter length than the walls in the longitudinal direction (Y). In addition, the conciliation of the structural elements such as the resistant walls, the 6 stone masonry arches and the 4 steel frames, provides a higher stiffness to the structure in the Y direction. Therefore, it can be concluded that the results obtained are as expected, since the direction with the lowest stiffness (X) is associated with the lowest frequency mode.

Figure 8 shows the deformed shape of the two main vibration modes, for the X and Y directions, with the aim to better understand the dynamic behaviour of the building.

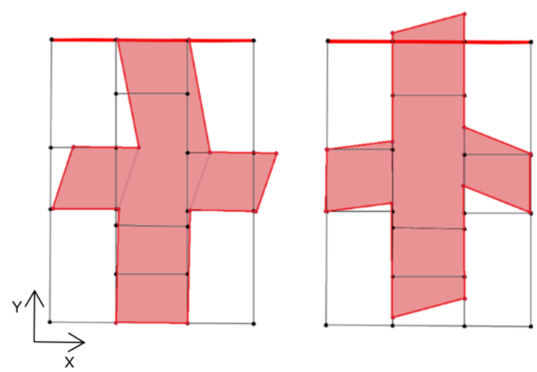

Figure 8 - Translation mode in X direction (left) and in Y direction (right)

5 Seismic Assessment

The seismic assessment of the CCE is carried out through non-linear static analyses (pushover) according to EC8-3, using the 3Muri software.

The National Annex of EC8-3 (CEN, 2017) establishes that buildings classified with an importance class III (as is the case of the Chalet), are required to verify the limit states of Near Collapse (NC), Significant Damage (SD) and Damage Limitation (DL), for two types of seismic action, type 1 and type 2.

5.1 Capacity curves

The pushover analysis is characterized by a resistant capacity curve, which is a function of the base shear force and the respective displacement of the structure in the control node.

The capacity curve is obtained by applying two types of horizontal force distributions to the building, in the positive (+) and negative (-) directions and for each main direction of the structure (X and Y). The uniform distribution is proportional to the mass of the building's floors, and the pseudo-triangular distribution, proportional to the product between the mass and the height of each floor. These forces are representative of regulatory seismic actions.

It is based on the capacity curve that it is possible to describe the inelastic response of the structure, when subjected to horizontal seismic forces, and to obtain information such as stiffness, resistant capacity and ultimate displacement capacity (Lagomarsino et al., 2013).

The ultimate displacement of the structure is established according to the following criteria: (i) global level criterion, defined when the maximum value of the base shear force shows a 20% reduction, as indicated in EC8-3 (CEN, 2017) and the Italian Standard (MIT, 2019); (ii) local level criterion, corresponding to the collapse of the first vertical element of the structure (pier). The most conditioning criterion will define the ultimate displacement of the structure.

Analysing the capacity curves (Figure 9) of this case study, although it is not so obvious, it is possible to conclude that the uniform loading is the most conditioning distribution in the X direction, since it has the lowest values of the ultimate displacement for the same direction and orientation, which prevails over the slightly superior value of the base shear force. For the Y direction, the pseudo-triangular loading is the most conditioning when compared to the distribution of uniform loads.

Regardless of the type of lateral forces applied, it appears that it is in the longitudinal direction that the building presents the greatest resistance (as previously verified), in which the base shear force values are much higher compared to the transversal direction (Figure 9). This is due to the presence of walls with greater length in the Y direction, giving greater inertia force and consecutively, greater stiffness. Additionally, it is also possible to observe that the Y direction is more ductile than the X direction, since it has a greater capacity to redistribute non-linear behaviour across the different macro-elements in that same direction, until it reaches the collapse.

5.2 N2 Method – Safety Verification

The N2 method was originally developed by Fajfar (2000) and is the method recommended in EC8-1 (CEN, 2010) to perform non-linear static analyses. It is based on this method that the performance point is determined, defined by the intersection of the bilinear capacity curve with the elastic response spectrum of the seismic action, in the ADRS (Acceleration Displacement Response Spectrum) format.

The evaluation of the seismic performance of a structure is performed through the ratio between the ultimate displacement (du) and the performance point (dt). The safety is only verified when this value is greater than 1, which means that the ultimate displacement of the structure must exceed the displacement imposed by the seismic action on the building ($du\ /dt$ >1). Figure 10 shows the safety verification of the heritage building under study, according to the $du\ /dt$ ratio, for seismic action type 1 and type 2.

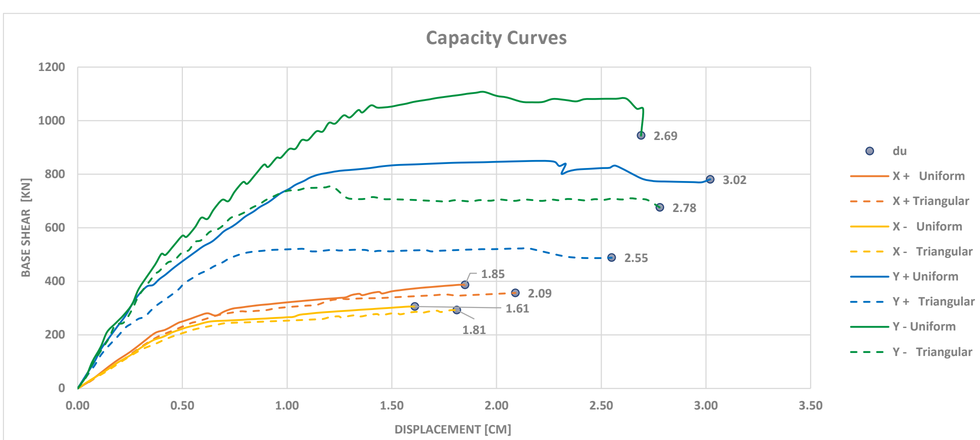

Figure 9 - Resistant capacity curves of the Chalet of the Countess Edla up to the ultimate displacement (d_U), for X and Y directions

It is important to note that according to EC8-3 (CEN, 2017), the global capacity of the structure for the Near Collapse limit state (NC), should be equal to the capacity of the ultimate displacement (d_u), for the Significant Damage limit state (SD), the value must be reduced to ¾ of its value, and for the damage limitation (DL) the yielding displacement (d_y) should be considered.

The safety verification of the structure is verified, for a seismic action type 2 with a return period of 975 years (NC) or 308 years (SD), for the considered values of the mechanical properties. However, the safety is not verified when subjected to the most conditioning seismic action (type 1), being the near collapse limit state the most demanding for the structure.

In the next section, a sensitivity analysis will be carried out, in order to study the variation impact on the material's mechanical properties, assumed for the 3Muri structural model.

6 Sensitivity Analysis

The adequate definition of the materials mechanical properties is essential for the development of the seismic assessment of the built cultural heritage. Historical buildings have many aleatory uncertainties, due to the limited knowledge and poor models reliability, which may directly affect the seismic analyses of the structure (Cattari et al., 2015). Therefore, appropriate tools must be used in order to verify the initial values adopted for the material's mechanical properties, through experimental tests or in existing scientific literature to homologous buildings.

The sensitivity analysis has as main objective study the aleatory parameters that most affect the structural response to the seismic action, thus reducing the inherent uncertainty in the models.

For this study, the sensitivity analysis uses non-linear static analyses and the previously obtained pushover capacity curves, which are characterized by: (i) load distribution (uniform or pseudo-triangular); (ii) direction of the seismic action (X and Y); (iii) and orientation of this action (positive or negative). Even though for the non-linear analyses the various options are analysed and the safety verification of the structure to seismic action is studied, only the most conditioning cases defined in the pushover analyses are considered for the sensitivity analysis. Thus, the number of analyses to be performed is limited and the computational effort is reduced (Cattari et al., 2015).

2N + 1 analyses are carried out, being firstly adopted as reference the average value of all the parameters. Subsequently, a set of 2N analyses is performed (where N is the number of parameter groups), in which each group of random variables X_k is alternated, one by one, to its lower or upper limit of the previously defined interval (depending on the type of sensitivity analysis to be studied), keeping all the other variables with average values.

There are two types of sensitivity analyses carried out by the software 3Muri. The cognitive analysis investigates the combination of parameters that lead to more conditioning results than the average. This analysis gives an indication of the parameters that are most promising to reduce the

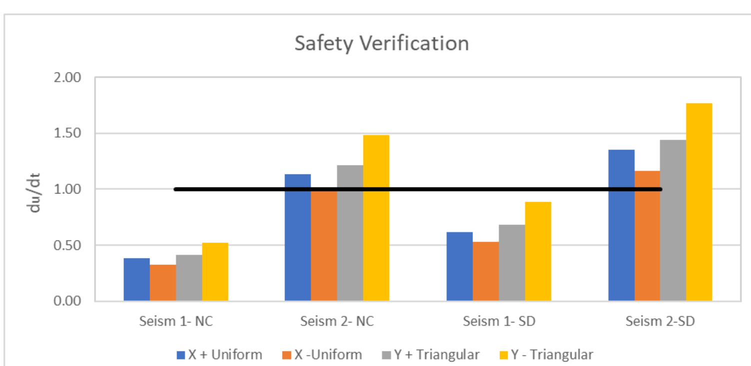

Figure 10 – Safety verification for seismic action Type 1 and Type 2

uncertainties in the model and, in turn, serve as a guide to the choice of structural elements that may be important to carry out experimental tests. The improvement analysis seeks the combination of parameters that will bring better results than the average, whose purpose is to indicate the structural elements that are useful to intervene and reinforce, thus improving the behaviour of the structure.

6.1 Definition of the aleatory uncertainties and mechanical properties of the materials

The parameters applied for this case study, are defined according to Badalassi et al. (2017) and Simões da Silva et al. (2009) for the structural steel mechanical properties, for the exterior walls of irregular stone masonry, according to the Italian Ministry of Infrastructure and Transport (MIT, 2019), and for the partition walls, based on Simões (2018). In detail, 3 groups of aleatory variables are defined (Table 5):

• set X_1 – The mechanical properties of structural steel S275 JR, such as yielding strength (f_y), Young modulus (E) and shear modulus (G);

• set X_2 and X_3 – the material properties of irregular stone masonry and partition walls, respectively, such as Young's modulus (E), distortion modulus (G), compressive strength (f_c) and tangential stress (τ_0).

In this context, for this sensitivity analysis study the variation of the timber floors parameters was neglected. It does not have a significant influence on the overall behaviour of the structure, due to the greater stiffness of the masonry walls and its enormous contribution in the seismic performance of the building, as mentioned by Milosevic et al. (2018).

6.2 Sensitivity analysis of the seismic performance results

For this sensitivity analysis, it can be concluded that the low sensitivity of the group of variables X_1 and X_3 and the high sensitivity of X_2, leads the focus of this investigation to be around the mechanical properties of stone masonry. Therefore, the variation of this last group of variables has a great influence on the cognitive and improvement sensitivity (corresponding to the highest sensitivity index I_s), as expected, since it is the element with the greatest expressiveness in the model. In order to make the model's seismic assessment as accurate as possible, it is necessary to have a high level of knowledge of the group of variables X_2.

Comparing the impact of group X_2 parameters on the main directions of the building, although both indicate a high sensitivity, it is according to the X direction that these parameters significantly affect the structural response of the building due to seismic action, as it is the most vulnerable direction.

On the other hand, this sensitivity analysis proves that the use of a conservative model and that, although the results of the pushover analyses did not verify the safety verification to the type 1 seismic action, the variation of the masonry mechanical properties will have a

Table 5 - Mechanical properties of the materials (aleatory uncertainties)

Materials	**Groups** X_k	Variables	$X_{k,min}$	$X_{k,max}$	$X_{k,med}$
Steel grade S275 JR	1	f_y [MPa]	222.90	254.70	238.80
		E [GPa]	192.29	218.65	205.47
		G [GPa]	73.96	84.10	79.03
Rubble stone masonry walls	2	f_c [MPa]	1.00	2.00	1.50
		τ_0 [MPa]	0.018	0.050	0.032
		E [GPa]	0.455	0.693	0.574
		G [GPa]	0.152	0.231	0.192
***Tabique* walls**	3	f_c [MPa]	0.40	0.72	0.54
		τ_0 [MPa]	0.010	0.020	0.015
		E [GPa]	0.060	0.200	0.110
		G [GPa]	0.001	0.003	0.002

major impact on the final results of the 3Muri structural model. The results of the sensitivity analyses returned by software 3Muri, are shown in Figure 11.

7 Conclusions

For this case study two types of 3D models of the Chalet of the Countess of Edla, were built according to its purpose: a H-BIM model (Revit tool) and a simplified geometry model (3Muri tool). A H-BIM model was built, with high positional quality achieved through terrestrial laser scanning (geometric survey) supported by a topographic survey. This model centralized all the information related to geometric and mechanical characterization of the building's structural elements and supported the numerical simulation in 3Muri, to assess the seismic vulnerability of the building. In addition, this model was designed to serve as a tool for future management activities of the building, guaranteeing the safeguard of the built cultural heritage.

In a second phase, a global seismic assessment of the building was carried out when subjected to a code seismic action, according to non-linear static analyses. Analysing the pushover curves results, the walls in the longitudinal (Y) direction of the structure showed greater resistance, greater stiffness and greater ductility, since it has a bigger capacity to redistribute the forces and direct them to the building's foundations. Subsequently, the safety of the structure was checked based on the N2 method, concluding that for the near collapse ultimate limit state, significant damage and damage limitation, it satisfies the safety for seismic action type 2. However, the safety verification is not verified when subjected to the most conditioning seismic action, type 1, for the longitudinal and transversal direction of the building.

To conclude, a sensitivity analysis was performed, with the purpose of understanding which aleatory variables adopted in the model would have the greatest impact on the seismic assessment of the structure. The group of aleatory variables adopted for the irregular stone masonry walls were the ones that presented the highest sensitivity index for the cognitive and improvement analyses.

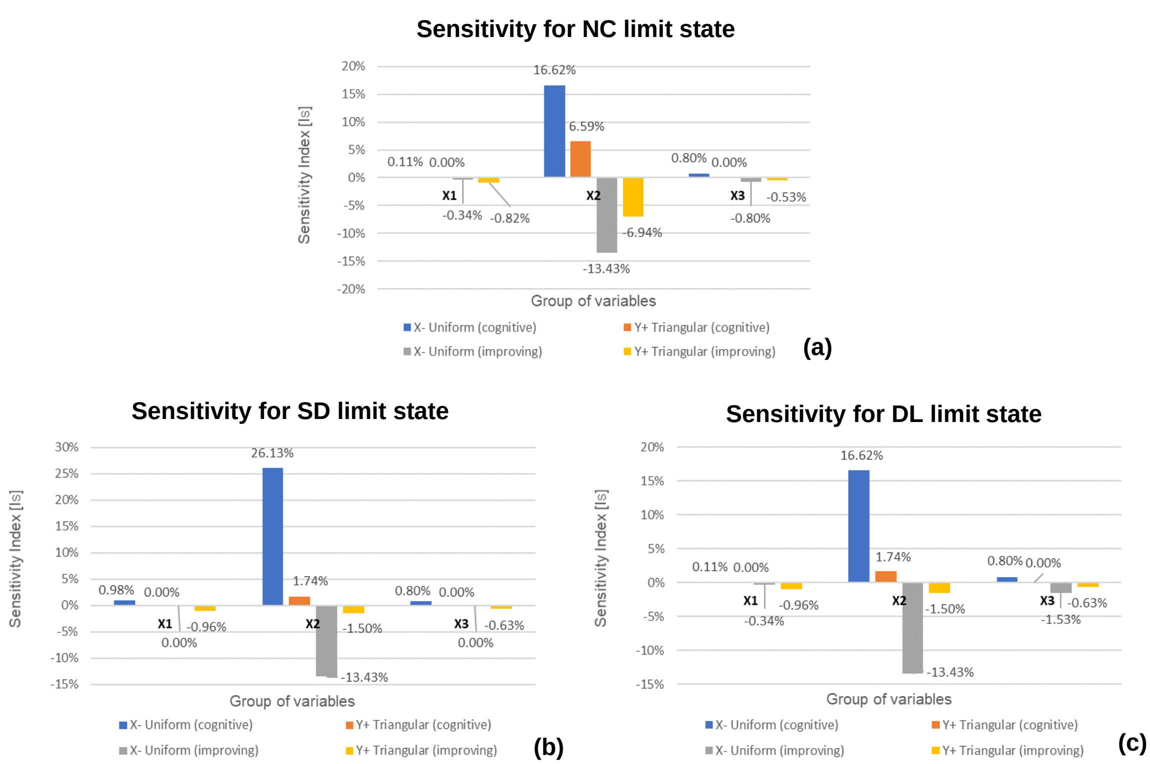

Figure 11 - Cognitive and Improving sensitivity analysis results, according to the most conditioning scenarios, in the X and Y direction, for (a) near collapse (NC),(b) significant damage (SD) and (c) damage limitation (DL) limit states

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