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SEISMIC VULNERABILITY ASSESSMENT OF A 17TH CENTURY NEAPOLITAN FARM

Giovanna Longobardi & Antonio Formisano

University of Naples Federico II, Piazzale Tecchio 80, 80125 Naples, Italy
(giovanna.longobardi95@gmail.com; antoform@unina.it)

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ABSTRACT

In this paper, seismic vulnerability appraisement, restoration, and consolidation plan of a 17th century masonry building (Rossi farm) with cultural and artistic value located in a small city near Naples are reported and discussed. This case study is presented and described, providing historical data and information about its actual conditions, spaces, functions and structures. Once the crack pattern detected in the building has been appropriately traced, the knowledge is deepened by performing all the three seismic risk assessment analyses proposed by the "Italian Guidelines for the assessment and reduction of seismic risk of cultural heritage". The first evaluation level is a qualitative and simplified tool allowing for the knowledge of the risk level of the building under study. Afterwards, the structure has been subjected to more accurate investigations dealing with its local mechanisms and global behaviour in the second and the third evaluation levels, respectively. In all three analysis phases, the results have shown the high vulnerability of the masonry farm.
Based on these results, a consolidation plan, according to the Cultural Heritage Italian Guidelines suggestions, has been proposed.

KEYWORDS: Cultural heritage, seismic vulnerability, masonry building, pushover analysis, consolidation operations, restoration project.

1. CULTURAL HERITAGE AND CONSTRUCTION TRADITION IN THE VESUVIUS AREA

Masonry structures represent the most widespread type of buildings in Italy. They constitute an important part of the cultural and architectural heritage and are also evidence of the construction techniques used in the past centuries. In fact, masonry was used for centuries both for the ease of construction method (stones simply joined by mortar) and for the ease of finding material. Depending on the area, the availability, and the means, different construction techniques were spread and developed all over the world. A part of these historical masonry buildings has managed to survive and nowadays it is in an advanced state of decay: this is due not only to the poor maintenance state but also to the damage suffered over the centuries due to different natural hazards, such as earthquakes. Italy, in fact, is a very seismically active area, where most of the earthquakes caused irreparable damage to masonry buildings, as happened in the past years in L'Aquila, Emilia Romagna, and Central Italy (Borri et alia, 2019). The consequences of seismic events on the historical heritage are illustrated in detail in many literature papers (Formisano et al., 2010; Indirli et al., 2013; Carocci, 2012; Krstevska, 2010).

Survived masonry buildings usually show several problems, which could be connected to both seismic events and construction aspects, such as low-quality material, absence, or irregular connections among construction elements, etc. (D'Alpaos, 2020). In addition to crushing phenomena of walls due to the age of materials and the disintegration of mortars, there may be lesions with a vertical trend near the openings, that usually are connected to foundational settlements or ground movements. Another instability often detected is the damage on the intrados of vaults and arches. With regard to the floors, the wooden ones might present problems of deformability, with too severe deflection of the main beams or loss of planking. Still, in relation to the horizontal structures, a further problem is given by the bad connection between them and vertical walls.

Therefore, numerous problems could occur in masonry buildings and cultural heritage constructions of different types (religious or residential) all over the world (Salonikios et al., 2018; Elyamani et al., 2019; Amer et al., 2017).

For their cultural values and historical importance, today it is necessary to study these buildings and their seismic vulnerability with different methods, analysing their conditions and states of decay. These analysis phases allow developing consolidation plans to define the most appropriate intervention techniques, which should be compatible with pre-existing materials to both ensure better operation durability and preserve their artistic and historic values in accordance with cultural heritage charts and principles of the last decades (Haddad et al., 2021).

The Vesuvius area, until the first half of the 1900s, was based on a landowning system: around a land plot, it was developed a structure in which the farm laborers lived together with the owner, who belonged to the aristocratic class and invested financial resourced in that place. Because of this system and for other reasons, such as soil fertility and good climate, over the centuries, in the eastern outskirts of Naples, from Torre del Greco to Portici, including the inland areas, the urbanization of the area was characterized by a system of farms or productive villas. Nowadays, these structures testify the ancient construction art, and they are symbols of the economic and social traditions. In other words, they represent a remarkable rural, environmental, and cultural heritage which, instead of being protected or valued, is abandoned to itself, a victim of illegal building episodes.

Farms represent an expression of rural architecture, which was born in an agricultural context through a deep relationship with the surrounding environment. Being a poor architecture, the building materials are recovered nearby, and the structure is not sophisticated, but they respond essentially and effectively to their function (Cennamo, 2006). The city of Volla, in the district of Naples, where the study case (the Rossi farm) is located, belonged to this urban system, with the presence on its territory of some farms that created a production network in the past centuries.

However, the Rossi farm, thanks to architectonical features, construction materials typical of the examined area and use, could be considered an important part and evidence of this historical cultural heritage.

Therefore, the current work is aimed to both analyse the seismic assessment of a typical Neapolitan farm, highlighting its vulnerability due to a lack of maintenance, and recover the structural integrity through some specific consolidating operations.

2. THE CASE STUDY: THE ROSSI FARM

The Rossi farm, an isolated building with an internal chapel, is placed in the eastern area of the city of Volla. In particular, the building stands at the intersection of two road axes placed to the east and the south. To the north, the farm is delimited by a green area, formerly used for grazing, while to the west, there is an agricultural relevance.

According to the consulted sources, the founding of the building occurred around 1670. It was born as a residence for the farmhands of San Sebastiano al Vesuvio, a near feud.

In 1772, a rich Neapolitan family bought the building as a country residence and started many changes, like the construction of two new levels.

After the last eruption of Vesuvius, in 1944, the weight of ashes caused the collapse of a part of the coverage, which was rebuilt, some years later, with modern techniques.

Nowadays, a local manager, who bought the building, has returned attention to the farm, abandoned for many years, for requalifying it.

Since 2005, the structure and its agricultural relevance, due to their historical and architectural features (Italian Law n. 1089, 1939), were under the protection of the Superintendence for the Metropolitan area of Naples.

The structure of Rossi farm reproposes the typical scheme of Mediterranean courtyard houses: the rooms are arranged so to individuate two internal courtyards, usually used as yard in the past centuries. Before abandonment, on the ground floor, there were stables for animals and stores for fodder and agricultural tools. Here there were also two ovens to produce bread and a little chapel dedicated to Saint Michele.

The structure has an underground floor, which hosts food stores and pools for the collecting of meteoric water necessary for animals. At the first level, on one side there were the lodgings for laborers and on the other one a terrace overlooking the internal courtyard and, before the collapse of the roof, the servants' rooms. There were the master bedrooms and a second panoramic terrace at the last level.

The structure occupies an area of about 1000 m^2 and it is developed on three levels. The ground floor of the building is shown in Figure 1a. The vertical structure is made of tuff stones, a common construction material in the Neapolitan area. Internally, there are most masonry vaults covering locals, whereas only three rooms have chestnut wooden floors as horizontal structures. Two external views of the farms are plotted in Figure 1b.


(a)


(b)

Figure 1. Ground floor layout (a) and external views (b) of the Rossi farm

3. ANALYSIS OF CRACK PATTERN AND DEGRADATION PHENOMENA

The Neapolitan area is classified as a high-risk area not only under the seismic viewpoint but also under the volcanic one. The historical seismic events and a lack of maintenance in the past decades have led to the appearance of cracks, injuries, and failures, both of global and partial type. Through a careful observation of the artifact by site inspections and photographic surveys, it was possible to trace the crack pattern and degradation phenomena as follows:

- Earthquake damage, which led to detachments between vertical masonry and floors. (Fig. 2)

- Injuries on the first level's intrados of vaults and arches produced by past seismic events. (Fig. 3)
- Crushing of masonry walls, due to the increasing of loads and the age of materials. (Fig. 4)
- Detachment among walls dating back to different periods and between vertical walls and horizontal floors.
- Reduction of the resistant section of load-bearing elements due to humidity problems.
- Widespread phenomena of wooden floors decay with their partial or total collapse, the fall of planking, and excessive inflection of main beams leading to unwarranted deformability. (Fig. 5 – 6 - 7)
- Collapse of a part of staircase due to the failure of the roof after Vesuvius eruption. (Fig. 8)

Figure 2. Earthquake damage

Figure 3. Injuries on the intrados of masonry vaults

Figure 4. Crushing phenomena on masonry walls

Figure 5. Widespread phenomena on the wooden floor – Partial collapse

Figure 6. Widespread phenomena on the wooden floor – Inflection on the main beam

Figure 7. Widespread phenomena on the wooden floor – The fall of the planking

Figure 8. Collapse of a part of staircase

4. SEISMIC VULNERABILITY ASSESSMENT

Once the crack pattern and the deterioration state of the farm have been identified, the study is deepened by evaluating its seismic vulnerability. To do this check, all the three seismic safety evaluation levels proposed by the Italian Guidelines on Cultural Heritage have been applied to the case study (DPCM 09/02/11).

4.1. Evaluation Level 1

The first analysis tool is the Evaluation Level 1 (EL1), which has been applied to the farm using, between the two simplified mechanical models proposed in the Guidelines, the provisions given in Section 5.4.2 "*Palaces, villas and other structures with transverse walls and intermediate floors*". This kind of analysis allows studying the overall seismic performance of the structure using a simplified approach that involves a limited knowledge of the geometrical and mechanical parameters. (Torelli et alia, 2020). This method calculates the return period corresponding to the Life Safety Limit State (SLV) under the hypothesis that this is accomplished due to the breakage of walls in their own plane.

Therefore, with reference to the condition that leads to the attainment of SLV, it is possible to calculate the value of the collapse acceleration of the elastic response spectrum with the following equation:

$$S_{e,SLV} = \frac{q \cdot F_{SLV}}{e^{*} \cdot M} \qquad (1)$$

where:

- F_{SLV} is the building shear resistance.
- q is the behaviour factor, taken between 3.0 and 3.6 for buildings regular in elevation with a number of levels equal or greater than two. (Ministerial Decree of Public Works 14/01/2008). In this case, a *q* factor equal to 3 has been used.
- M is the total seismic mass.
- e^{*} is the participating mass fraction on the first vibration mode.

Obtained the ordinate of the spectrum, it is possible to find the acceleration with one of the following equations:

$$a_{SLV}: \begin{Bmatrix} \frac{S_{e,SLV}(T_1)}{S \cdot F_0} \text{ if } T_B \leq T_1 < T_C \\ \frac{S_{e,SLV}(T_1)}{S \cdot F_0} \cdot \frac{T_1}{T_C} \text{ if } T_C \leq T_1 < T_D \end{Bmatrix} \qquad (2)$$

where:

- T_1 is the fundamental period of vibration of the structure calculated with the following relationship:

$$C_1 \cdot H^{3/4} \qquad (3)$$

where H is the maximum height of the building, expressed in meters, and C_1 assumes a value of 0,05 for masonry buildings.

- T_B, T_C, and T_D are the characteristic periods of the response spectrum.
- $S = S_S \cdot T_T$ is a coefficient considering the category of subsoil and the topographical conditions.

The building shear resistance (F_{SLV}) to be used is the lowest value among those evaluated according to the two perpendicular directions. For each direction, the model assumes that collapse occurs when the average shear strength reaches a given shear strength of masonry. Relationships to calculate the base shear strength in the two analysis directions are as follows:

$$F_{SLV,xi} = \frac{\mu_{xi} \cdot \xi_{xi} \cdot \zeta_x \cdot A_{xi} \cdot \tau_{di}}{\beta_{xi} \cdot \kappa_i} \quad F_{SLV,yi} = \frac{\mu_{yi} \cdot \xi_{yi} \cdot \zeta_y \cdot A_{yi} \cdot \tau_{di}}{\beta_{yi} \cdot \kappa_i} \qquad (4)$$

In which:

- A_{xi} and A_{yi} are the shear resistant areas of the i-th floor walls located in x and y directions.
- τ_{di} is the design value of the masonry piers shear strength at the i-th floor, defined with the following expression:

$$\tau_{di} = \tau_{0d} \sqrt{1 + \frac{\sigma_{0i}}{1{,}5\tau_{0d}}} \qquad (5)$$

in which:

- τ_{0d} is the design value of the shear strength of masonry evaluated considering the confidence factor, F_c (herein assumed equal to 1,35).
- σ_{0i} is the average normal stress on the walls resistant area at the i-th floor.
- k_i is the ratio between the resultant of seismic forces on the i-th floor and the total seismic force.
- β_{xi} and β_{yi} are the plan irregularity coefficients to the i-th floor related to the eccentricity value.

- μ_{xi} and μ_{yi} are coefficients considering the stiffness and resistance homogeneity of masonry walls, which can be calculated as:

$$\mu_{xi} = 1 - 0.2\sqrt{\frac{N_{mxi}\cdot \Sigma jA_{xi,j}^{2}}{A_{xi}^{2}}-1} \geq 0.8 \quad \mu_{yi} = 1- 0.2\sqrt{\frac{N_{myi}\cdot \Sigma jA_{yi,j}^{2}}{A_{yi}^{2}}-1} \geq 0.8 \quad (6)$$

where: N_{mxi} and N_{myi} are the number of masonry piers in x and y directions, respectively; $A_{xi,j}$ and $A_{yi,j}$ are the areas of piers in x and y directions, respectively.

- ξ_{xi} and ξ_{yi} are coefficients related to the main type of collapse mechanism expected on the wall masonry at the i-th floor (DPCM 09/02/2011).
- ζ_x and ζ_y are coefficients associated with the wall spandrel resistance in x and y directions, respectively (DPCM 09/02/2011).

The values of the above-described parameters used in the current case study are summarized for each storey in Tables 1, 2 and 3.

Table 1. Ground Storey Parameters

τ_{di}	τ_{0d}	σ_0	N	A_{TOT}	μ_x	μ_y	ζ_x	ζ_y	ξ_x	ξ_y	β_x	β_y	k
[kN/m²]	[kN/m²]	[kN/m²]	[kN]	[m²]	-	-	-	-	-	-	-		-
56,9	20,74	202,66	46105,26	227,5	0,827	0,80	1	1	1	1	1,25	1,25	1

Table 2. First Storey Parameters

τ_{di}	τ_{0d}	σ_0	N	A_{TOT}	μ_x	μ_y	ζ_x	ζ_y	ξ_x	ξ_y	β_x	β_y	k
[kN/m²]	[kN/m²]	[kN/m²]	[kN]	[m²]	-	-	-	-	-	-	-		-
56,9	20,74	199,26	30269,56	151,9	0,877	0,81	1	1	1	1	1,25	1,25	0,83

Table 3. Second Storey Parameters

τ_{di}	τ_{0d}	σ_0	N	A_{TOT}	μ_x	μ_y	ζ_x	ζ_y	ξ_x	ξ_y	β_x	β_y	k
[kN/m²]	[kN/m²]	[kN/m²]	[kN]	[m²]	-	-	-	-	-	-	-		-
43,9	20,74	108,57	11645,92	107,27	0,84	0,87	1	1	1	1	1,25	1,25	0,5

After these parameters have been defined, it is possible to calculate the shear strengths (F_{SLV}) in both directions for each level, which in turn allow obtaining the values of the collapse acceleration ($S_{e,SLV}$) using Eq. 1. Results are illustrated in the following Table 4:

Table 4. Results of collapse acceleration $S_{e,SLV}$ for the three floors

Ground Storey		First Storey		Second Storey	
$S_{e,SLV,x}$ [m/s²]	$S_{e,SLV,y}$ [m/s²]	$S_{e,SLV,x}$ [m/s²]	$S_{e,SLV,y}$ [m/s²]	$S_{e,SLV,x}$ [m/s²]	$S_{e,SLV,y}$ [m/s²]
3,40	**2,81**	4,15	3,67	9,85	8,91

To define the demand acceleration (a_{SLV}), it is calculated the vibration period of the structure using the NTC18 indications. The structural period (T_1), which is equal to 0,44 s, is in the range between T_B and T_C of the response spectrum. For this reason, the collapse acceleration on rigid ground can be calculated with the first expression between the two relationships proposed in the Guidelines (See Eq. 2) by using the lowest value of shear strength, which corresponds to the ground level value in y direction:

$$a_{SLV} = \frac{S_{e,SLV}\,(T_1)}{S\cdot F_0} = \frac{2{,}81}{1{,}45\cdot 2{,}37\cdot 9{,}81} = 0{,}08g \quad (7)$$

The last step is the calculation of both the acceleration factor: $f_{a,SLV}$ and the seismic safety index I_{SS}. The first parameter is the ratio between the rigid ground acceleration and the one corresponding to the reference return period (SLV):

$$f_{a,SLV} = \frac{a_{SLV}}{a_{g,SLV}} = \frac{0{,}08g}{0{,}17g} = 0{,}47 \quad (8)$$

Instead, I_{SS} is the ratio between the return period of seismic action leading the structure to the Life Safety Limit State and the corresponding reference return period (SLV):

$$I_{SS} = \frac{T_{SLV}}{T_{R,SLV}} = \frac{69}{475} = 0{,}15 < 1 \qquad (9)$$

Since this safety index is lower than 1, it is asserted that this first evaluation level, even if in a simplified way, shows the high seismic vulnerability of the building which will be deepened in the following paragraphs.

4.2. *Evaluation Level 2*

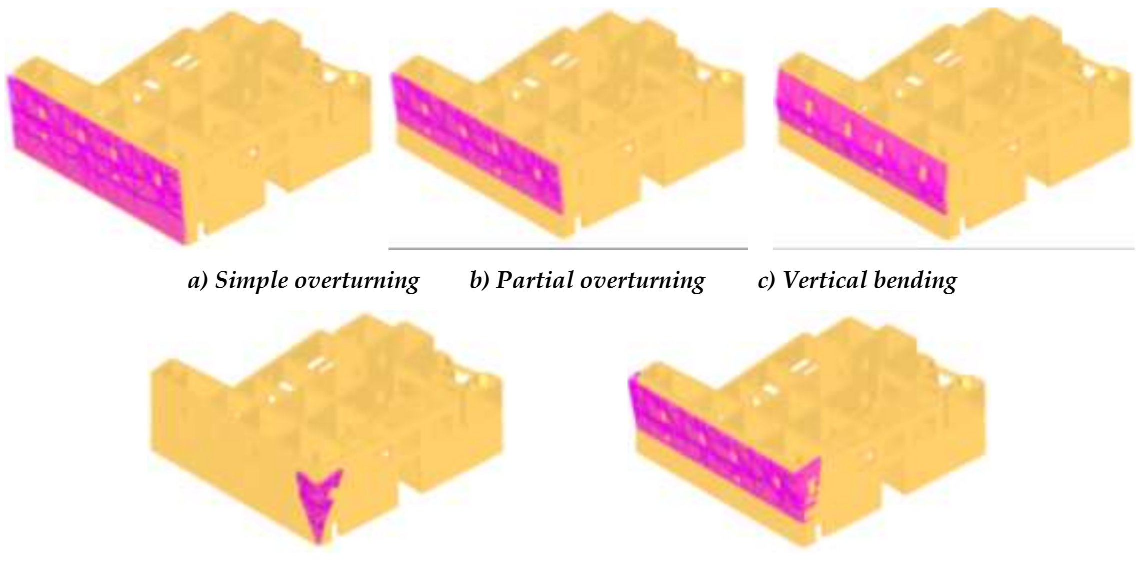
The Evaluation Level 2 (EL2) assesses, through kinematic analysis, the activation of local collapse mechanisms, also known as first mode mechanisms. They correspond to out-of-plane behavioural mechanisms of macro-elements, which are structurally independent parts exhibiting failure modes under seismic actions orthogonal to their own plane.

In the present case, simple and partial overturning, vertical bending, corner overturning, and diagonal wedge overturning have been considered as local mechanisms (Fig. 9) (Milano et alia, 2009; D'Ayala et alia, 2003; Faccio, A.A. 2012-2013). They have been evaluated by modelling the structure with the TreMuri computer software (Lagomarsino et al., 2004; Penna et al., 2013).

It is a calculation program based on FME (Frame by Macro Elements), that schematizes the structure with an equivalent frame made up of horizontal (spandrels) and vertical (piers) macro-elements. The intersection between them generates rigid nodes. The nonlinear behaviour of masonry piers is assumed as elastic-perfectly plastic with initial cracked elastic stiffness (Formisano et alia, 2016). However, while the non-linear behaviour of macro-elements has been considered in the Evaluation Level 3, in this phase linear kinematic analysis only has been applied.

For each mechanism to be analysed, the portion of masonry is transformed into a kinematic chain (unstable system), with the identification of rigid bodies capable of rotating or sliding among them (Ministerial Circular M. C., 02/02/2009).

Each mechanism has been verified for the perimeter walls of the building and the results are in most of the cases not satisfied, as depicted in Table 5, where, for each considered mechanism, it is reported the number of analyses performed on walls with positive and negative check results.



a) Simple overturning ***b) Partial overturning*** ***c) Vertical bending***

d) Corner overturning ***e) Diagonal wedge***

Figure 9. Local mechanisms studied with the TreMuri software

Table 5. EL2 analysis results

	EL2		
Local Mechanism	**Analysed walls**	**N. Positive checks**	**N. Negative checks**
Simple overturning	12	3	9
Partial overturning	8	3	5
Vertical bending	12	5	7
Corner overturning	6	2	4
Diagonal wedge overturning	5	2	3

The local analysis results carried out on the farm have shown that the structure exhibits a high degree of vulnerability towards first mode mechanisms. Among the various mechanisms studied, simple overturning represents the most dangerous phenomenon affecting the seismic behaviour of perimeter walls. This result could be due to the lack of connection between two adjacent tuff masonry walls and between them and the horizontal structures. Thus, the wooden floors do not show good connections to vertical panels and the thrusts of masonry vaults increase the exposition to overturning phenomena.

4.3. *Evaluation Level 3*

The Evaluation Level 3 (EL3) analysis is used to evaluate the global behaviour of the building, modelled through a macro-element approach with the TreMuri software (Fig. 10), using non-linear static analyses. Pushover analyses have been carried out considering the two distributions of horizontal forces considered by current standards, which lead to consider 24 different load combinations considering the variation of the seismic direction and the eccentricity of the seismic mass.

In Table 6, the worst results in two directions have been reported. The software provides not only D_u and D_{max}, which are the capacity and demand displacements of structure, respectively, but also the factor q^* (q^*<3), which is the ratio between the elastic response force and the yield strength of the equivalent non-linear system. Finally, the parameter α_{SLV} is provided. It has the same meaning of f_{aSLV} and it is expressed as the ratio between capacity and demand in relation to Peak Ground Acceleration.

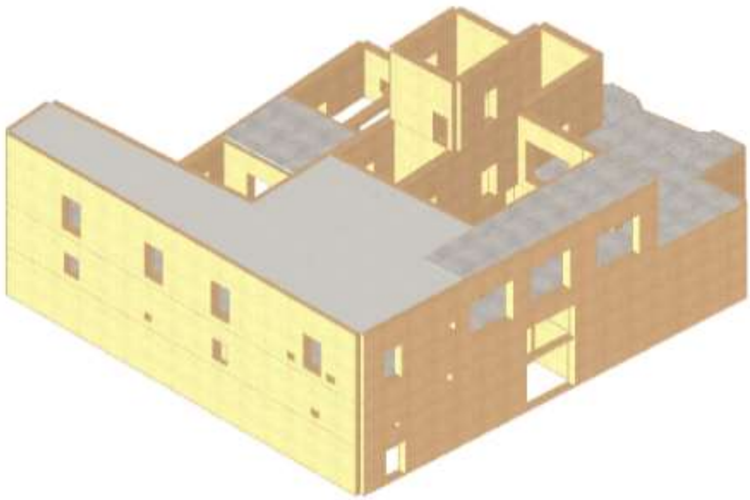


Figure 10. 3D Model of the Rossi farm

Table 6. Worst analysis results from EL3

Direction	Eccentricity [cm]	D_u [cm]	D_{max} [cm]	q^*	α_{SLV}
-X	175,78	1,12	3,57	3,67	0,343
+Y	161,49	1,26	3,74	4,96	0,351

With regards to the analyses, the software provides the results of principal damages on the 3D Model of which we report the results related to analysis Nr. 19 (in the y-direction) (Fig. 11). It shows that the main damages are the compression–bending (in pink) and tensile plastic phenomena (in blue) for the spandrels.

Instead, except masonry piers that remain intact, the governing mechanisms for them are the compression – bending (in red) and shear (in yellow).

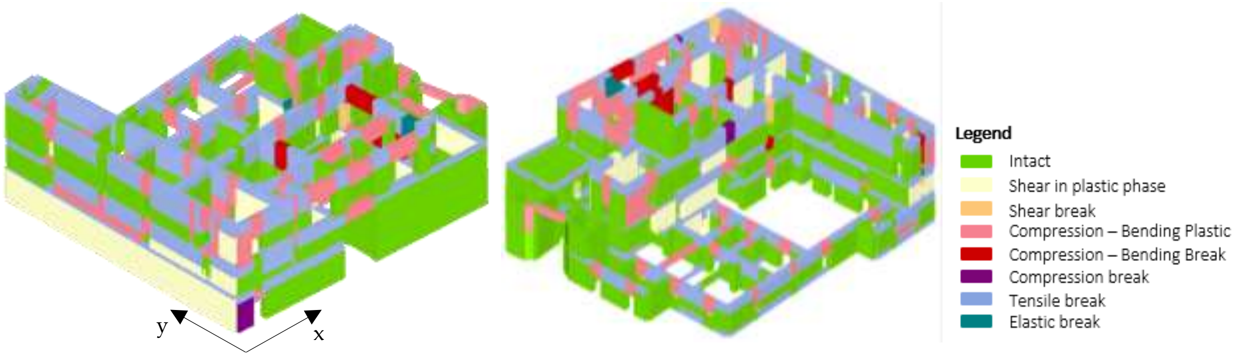


Figure 11. Results of analysis Nr. 19 (Y Direction) on 3D Model

The results of EL3 analysis have shown that, as in the case of EL1, y is the weakest direction. Herein, the q^* factor is greater than three, which is considered as the maximum value allowed by the standard. In the x direction, checks are not satisfied and also in this case, the q^* factor is greater than the limit value.

Finally, from the Evaluation Level 1 analysis, it has been noted that the acceleration factor ($f_{a,SLV}$) is greater than that obtained from the Evaluation Level 3 (α_{SLV}). This highlights that the EL1 is less conservative than the EL3. This unexpected result could be due to the simplifications made in performing analysis with the easiest method.

5. CONSOLIDATION PLAN

Because of the high vulnerability degree highlighted in all the three evaluation levels analyses carried out on the structure, a hypothesis of consolidation operations will be now provided. All the operations are compatible with the Italian Guidelines indications, with the restoration criteria (https://www.istitutorestauroroma.it, last accessed 2021) and with pre-existing structures to preserve its cultural and artistic value. This plan is aimed to guarantee a total safe reuse of the farm by changing its use.

- *Interventions to reduce detachment between vertical masonry walls and floors:* their aim is to ensure a good overall behaviour of the construction by making clamps between the walls and between them and the intermediate floors.
- *Intervention to increase the resistance of masonry piers:* their purpose is the increase of mechanical properties of damaged walls using compatible materials with existing ones. In this category are included the "*scuci e cuci*" technique, the consolidating injections, and re–styling of joints.
- *Interventions to consolidate masonry vaults and arches:* they could be made using innovative materials (as Fibre – Reinforced Polymers) or traditional techniques. (Borri, 2003)
- *Interventions for the consolidation of openings in masonry*: steel hoops.
- *Interventions for wooden floors:* they are proposed to limit their deformability and to ensure a better connection with the perimeter walls. In this typology, there are many possible operations such as the reconstruction of collapsed floors, the replacing of the beam heads, the insertion of dry connectors, or the installation of a second plank.

6. CONCLUDING REMARKS

The paper dealt with the seismic vulnerability of a masonry building located in Volla, a small town in the district of Naples. From the Evaluation Level 1 (EL1) assessment analysis, an acceleration risk factor ($f_{a,SLV}$) equals to 0,47, indicating a medium seismic risk, was achieved. The Evaluation Level 2 (EL2) analysis was also conducted, providing almost all unsatisfied checks. The overall seismic vulnerability study was concluded with the Evaluation Level 3 (EL3) analysis, which led towards results more conservative than those of the EL1. Finally, a consolidation plan was hypothesized with the aim of restoring the farm, which could be reused with a new function. The results of these interventions will guide the future step of the research, oriented to investigate how much the structure behaviour could be improved after performing consolidating operations.

AUTHORS CONTRIBUTIONS

Conceptualization, G.L. and A.F.; methodology, G.L. and A.F.; software, G.L. and A.F.; validation, A.F; formal analysis, G.L. and A.F; investigation, G.L.; resources, G.L. and A.F.; data curation, G.L. and A.F; writing—original draft preparation, G.L.; writing—review and editing, A.F; visualization, G.L. and A.F; supervision, A.F.; project administration, A.F.

All authors have read and agreed to the published version of the manuscript.

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