Performance of a school hosted within a historical complex affected by the 2016 seismic sequence

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Keywords: Structural damage, Non-structural damage, Cloister type complex, Teramo

ABSTRACT
Immediately after the August 24th, 2016, earthquake in Central Italy, universities have been asked to inspect schools and assess their usability, under the coordination of ReLUIS (Rete Laboratori Universitari Ingegneria Sismica = Earthquake Engineering University Laboratories Network). Later on, about one hundred schools deemed as unfit to use have been evaluated in order to establish if it was possible to repair them before September 2017 or if it was more appropriate to build a new school. Among investigated buildings there are not only those in the epicentral area, but also some located even 30-45 km from the epicentres of the main events. One of those is the music high school located in Teramo, Abruzzi region, housed within the former monastery of San Giovanni a Scorzone established in 1384. The seismic vulnerability of the building was investigated in 2014 according to the Italian Building Standard. Based on the documentation produced therein, observations made after the August event, and a new inspection carried out in December 2016, the building has been assessed according to the procedure proposed after the Emilia 2012 Earthquakes. Despite ground shaking not being very severe, due to high vulnerability, the performance was that of a damage level 2 (damage between significant and severe), with important distress to non-structural elements. Such performances call into question the suitability of housing critical functions in historical buildings that, however, can suffer an accelerated decay if left unused and, thus, unmaintained.

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ABSTRACT
Immediately after the August 24th, 2016, earthquake in Central Italy, universities have been asked to inspect schools and assess their usability, under the coordination of ReLUIS. Later on, about one hundred schools deemed as unfit to use have been evaluated in order to establish if it was possible to repair them before September 2017 or if it was more appropriate to build a new school. Among investigated buildings there are some located even 30-45 km from the epicentres of the main events, such as the music high school located in Teramo, Abruzzi region. The seismic vulnerability of the building was investigated in 2014. Based on the documentation produced therein, observations made after the August event, and a new inspection carried out in December 2016, the building has been assessed according to the procedure proposed after the Emilia 2012 Earthquakes. Despite ground shaking not being very severe, due to high vulnerability, the performance was that of a damage level 2 (damage between significant and severe), with important distress to non-structural elements. Such performances call into question the suitability of housing critical functions in historical buildings that, however, can suffer an accelerated decay if left unused and, thus, unmaintained.

1 INTRODUCTION

At the occurrence of earthquakes the role of schools is crucial, because both of possible high exposure of human lives and of strategic role that these buildings can play during an emergency as public gathering and shelter places. On August 24th, 2016 a seismic sequence started in central Italy with a 6.0 moment magnitude, M_W, event with epicentre in Accumoli. The sequence produced another eight earthquakes with $5.0 \leq M_W \leq 6.5$ until January 2017. Already following the first event the ReLUIS consortium (Rete Laboratori Universitari Ingegneria Sismica = Earthquake Engineering University Laboratories Network) coordinated for the Department of Civil Protection the inspections in school buildings (DiLudovico et al. 2017). After the completion of all inspections the very large event of October 30th occurred, the most intense in Italy since 1980. This earthquake caused the need to reassess already inspected buildings and to survey a significant number of schools not involved by the August shock. Moreover, the Commissioner appointed for the Reconstruction asked the Department of Civil Protection and ReLUIS to evaluate if about one hundred schools deemed as unfit to use were suitable to repair before September 2017 or if it was more appropriate to build a new construction. Among such schools is also the complex described hereinafter.

2 THE COMPLEX

2.1 Description

At the time of the first earthquake of central Italy sequence, the Istituto Statale Superiore di Studi Musicali e Coreutici “Gaetano Braga” (music high school) of Teramo, Abruzzi region, was housed within the former monastery of San Giovanni a Scorzone. The monastery is located on the east side of the historical centre of the city on piazza Giuseppe Verdi. The block, or structural aggregate, to which the school belongs houses also the Corale Teramana “Giuseppe Verdi” (a local chorus), three shops, the Gruppo Volontariato Vincenziano Teramano (a charity), a pre-school (all at ground floor with access from piazza Verdi, Figure 1), a rectory, a municipality-owned apartment, and the church of San

Giovanni (all with entrance from via Stazio). All these portions are vertically interfering with the high school, with the only exception of the church.

The structural aggregate shows an irregular plan layout (Figure 1 and Figure 2). It is organized around a cloister but with lateral extensions on via Cameli and via Sant'Antonio. The aggregate presents several floors, not completely aligned across its entire footprint: i) a basement floor with access from via Stazio (Figure 3 and Figure 4); ii) a ground floor with access from piazza Verdi (Figure 1); iii) a first floor accessible from the main staircase (intersection of piazza Verdi with via Sant'Antonio, Figure 1); iiii) attic accessible from a trapdoor in the first floor aisle (Figure 2). The roof structure has a sloping geometry with pitch ends on the church and the wing on piazza Verdi – via Cameli (Figure 5).

The aggregate is made of unreinforced masonry with rubble or approximately dressed natural stone units (Figure 6) or solid clay bricks. The cloister has monolithic natural stone columns and corner brickwork pillars at ground floor, octagonal brickwork pillars at first floor.

Horizontal structures are rather different and comprise: 1) brickwork barrel and cross vaults at ground floor, sometimes presenting iron tie rods; 2) three masonry domes on the lateral aisle of the church; 3) a reed-mat cloister vault with lunes on the lecture hall; 4) jack-arch floors above one of the shops on piazza Verdi; 5) I-beams and hollow clay blocks on via Stazio and at the intersection piazza Verdi – via Sant'Antonio, 6) a gypsum ceiling above the first floor of the school; 7) timber roof with trusses.

Figure 1. Ground floor (piazza Giuseppe Verdi) plan. Crack pattern after the October 30th event on the original survey by Ninni et al. (2014). All measures in m. NI = Not inspected, PD = plaster delamination, Li = acquisition point of ambient velocities

Figure 2. First floor plan. Crack pattern after the October 30th event on the original survey by Ninni et al. (2014). All measures in m. NI = Not inspected, Li = acquisition point of ambient velocities

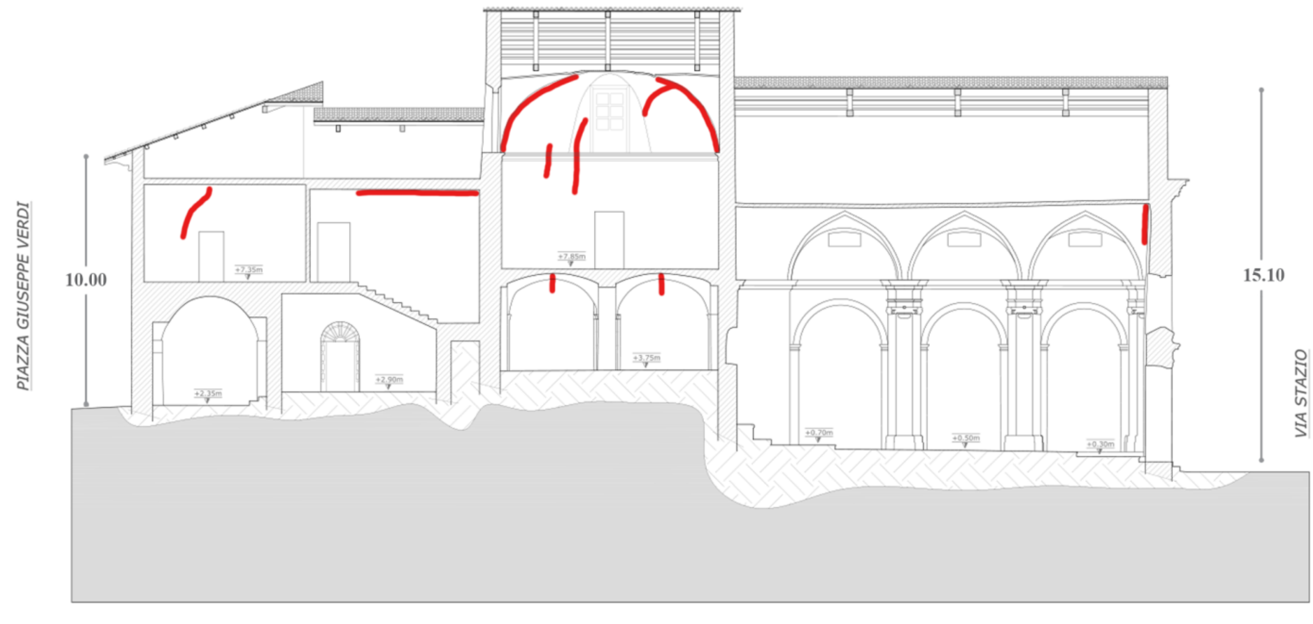

Figure 3. A-A' section across the main staircase, the lecture hall and the church of San Giovanni (refer to Figure 1 and Figure 2). Crack pattern after the October 30th event on the original survey by Ninni et al. (2014). All measures in m

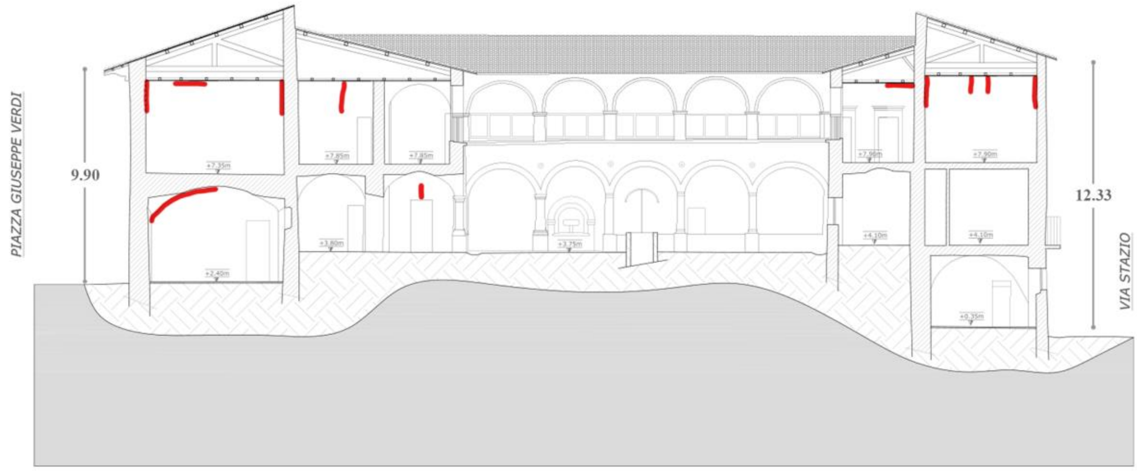

Figure 4. B-B' section across the cloister (refer to Figure 1 and Figure 2). Crack pattern after the October 30th event on the original survey by Ninni et al. (2014). All measures in m

Figure 5. Photomerge of the façade on piazza Verdi (Figure 1) and related roof after the October 30th event

2.2 History

According to Ninni et al. (2014), the current aggregate is housed by the original female monastery of San Giovanni a Scorzone, established in 1384. A conventual community was more or less active in the place until 1916. The monastery, owned by the Crown after the Italian unification of the second half of the 19th century, was devoted to the music high school in 1934, when some renovation works were performed. The church of San Giovanni was originally established on a pre-existing dwelling as a three-nave structure, reduced during the 18th century to a single-nave one. The 1858 date above the main window of the façade is reasonably referred to the last renovation of the church.

2.3 The 2014 assessment

In May 2014 the school has been seismically assessed by Ninni et al. (2014) according to the Italian Building Standard (DMI 2008) and its Commentary (CMIT 2009), within a program envisioned more than a decade before (OPCM 2003). The building has been assessed resorting to a non-linear static procedure performed on a model with a rigid diaphragm constraint. The piers are modelled as part of an equivalent frame with restrained rotation at the base and at the top. Local collapse mechanisms have been analysed according to a strength-based approach.

As part of the present publication, the so called acceleration factor, $f_{a,\,LLS}$, for the life safety limit state has been computed as the ratio of the peak ground acceleration whose response spectrum induces the limit state and the peak ground acceleration from hazard and site studies related to an event with a 712 years return period (OREM 2013). The acceleration factor resulted equal to 0.78 for the global analysis and 0.10 for the local collapse mechanism analysis, which can be rather vulnerable in existing masonry buildings (Casolo and Sanjust 2009). Additionally, Ninni et al. (2014) performed a verification under gravity loads, which resulted unsatisfactory for the cloister columns, despite assuming unity permanent loads partial safety factors.

a) b)

Figure 6. Some masonry samples of the aggregate. a) Ground floor, via Sant'Antonio (Figure 1), b) Basement floor, dwelling, façade on via Stazio

Moreover, the practitioners have evaluated the vulnerability of non-structural elements (CSLP 2009). Several rooms of the first floor, display partition walls made of horizontally perforated clay blocks, inadequately connected to structural walls and floors and rather slender. In several places plaster delamination has been observed and this has occurred also during the 2016 earthquakes. Most of the first floor is covered by a gypsum ceiling, reinforced by a small diameter mesh, anchored to timber elements of small cross section hanged to the timber roof structure. A significant amount of debris (stone units, clay brick and clay tiles fragments) are present on the extrados of the ceiling. On the roof several slender unreinforced masonry chimneys are present and they are not restrained at all. The same comment applies to the roof tiles.

Finally, Ninni et al. (2014) reported that the lecture hall and the pre-school rooms were tagged as unusable after the 2009 L'Aquila Earthquake, due to evidence of out-of-plane rotation of the façades. Occasionally, in plane damage of piers and spandrels has been observed. Cracks have been observed in ground floor columns of the cloister, one of which has been previously repaired through stitching and external steel collars.

2.4 The 2016 ambient vibration tests

Although without a direct influence on the visual assessment performed, during the survey ambient velocities have been measured in five points, one external on piazza Verdi (Figure 1) and in four points of the first floor, approximately located at the four corners of the complex (Figure 2). A Micromed Tromino device has been used, adopting a 128 Hz frequency of acquisition, and performing 16 min long acquisitions.

a) b)

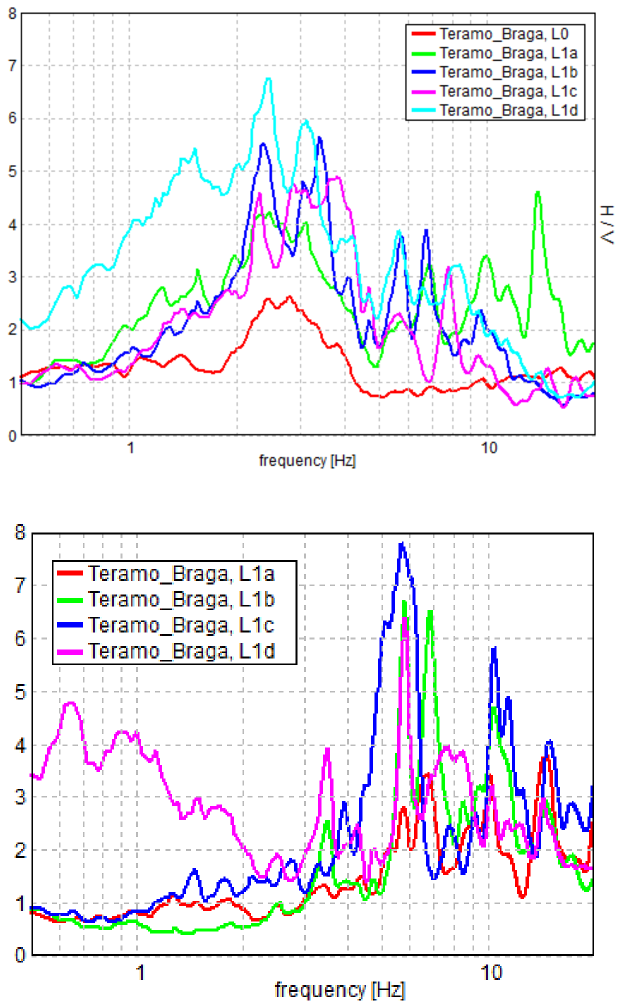

Figure 7. a) Average Horizontal to Vertical Spectral Ratios of the five acquisition locations (Figure 1-Figure 2). b) Standard spectral ratio of first floor locations with respect to ground floor location (direction parallel to via Stazio)

Eigen-frequencies have been identified according to a peak-picking procedure, performed on spectral ratios plots, either the Standard Spectral Ratio (Fäcke et al. 2006) or the Horizontal-to-Vertical Spectral Ratio (Nakamura 1989) are commonly used. In Figure 7a the ratio of average horizontal spectral values to vertical spectral value are presented. The largest amplifications are observed around 2.5 Hz, with slight variations possibly related to the articulated shape of the aggregate and the large cloister. In the same region maximum amplification of the ground is observed. In order to remove this effect the standard spectral ratio, horizontal component of elevated acquisition point with reference to corresponding component of ground acquisition point, is performed in Figure 7b. Maximum amplifications are observed about 5.5 Hz, a value where however a minimum of ground spectrum is observed. Additional records at ground floor, especially below acquisition points L1b-d would help investigate further this controversy.

2.5 *Simplified vulnerability assessment*

Following the instructions given by the Commissioner appointed for the Reconstruction after the 2016 seismic events, the school vulnerability has been qualitatively assessed according to the check list in Table 1. The aggregate displays rather thin structural walls (first floor, especially the wing on via Cameli) and poor quality masonry. Additional, less severe, deficiencies are related to walls resting on horizontal structures, façades rather slender in the horizontal direction (again the wing on via Cameli), poor connections between structural elements (tie rods are rather limited in number) and of non-structural elements to main structure. According to Table 2.4 in OREM (2013), whose background as well that of the previously mentioned one is unreferenced, the degree of deficiencies can be considered high.

Table 1. Identification of deficiencies (Table 2.1 in OREM (2013))in the structural aggregate

	DEFICIENCY	Severe	Light
1	Single leaf structural walls (thickness < 150 mm) for more than 30% of internal walls or 30% of a perimeter wall	Yes	
2	Single leaf structural walls (thickness < 150 mm) for more than 15% (and less than 30%) of internal walls or 15% (and less of 30%) of a perimeter wall		-
3	Double-leaf structural walls (inadequately interlocked – absence of units through the wall thickness), each leaf thickness < 150 mm for more than 30% of internal walls or 30% of a perimeter wall		NA
4	Poor quality masonry (rubble, approximately dressed units without dressed unit horizontal courses, absence of units through the wall thickness, ...), for more than 40 % of total surface	Yes	
5	Poor quality masonry (rubble, approximately dressed units without dressed unit horizontal courses, absence of units through the wall thickness, ...), for less than 40 % of total surface		-
6	Masonry with very poor mortar (easily removable without tools, for at least 1/3 of wall thickness) for more than 40% of total surface	-	
7	Masonry with poor mortar (easily removable with hand tools but no percussion, for at least 1/3 of wall thickness) for less than 40% of total surface		NA
8	Structural masonry with highly perforated hollow clay unit (volume of all holes < 55% of gross volume) for more than 50% of structural area at the same floor		-
9	No or inadequate interlocking at wall intersections		NA
10	Structural masonry supported by a floor only, for more than 25% at a single storey	-	
11	Structural masonry supported by a floor only, for less than or 25% at a single storey		Yes
12	Wall spacing / wall thickness ratio ≥ 14		Yes
13	No or inadequate connection between vertical and horizontal structures		Yes
14	No or inadequate connection between vertical and roof structures		Yes
15	Vertical distance between horizontally adjacent floors larger than 1/3 of storey height		-
16	No or inadequate connection between non-structural and structural elements		Yes
17	Severe and extensive poor maintenance of structural elements		-
18	Severe vertical irregularity, with stiffness and/or strength increasing more than 100% from one storey to the next	-	
19	Marked vertical irregularity, with stiffness and/or strength increasing more than 50% from one storey to the next		-

- = applicable but not present; Yes = present; NA = not assessable for lack of information or instrumentation

3 2016 SEISMIC PERFORMANCE

3.1 *Damage after the August 24th, 2016 event*

Following the August 24th event a team from Eucentre (European Centre for Training and Research in Earthquake Engineering) performed a survey of the music high school, of the pre-school and of the local chorus in order to assess its usability. The building was tagged as unusable, letter E according to the Italian procedure (Zucconi et al. 2017). On vertical structures, horizontal structures and partitions a medium-severe (D2-D3 according to Grünthal (1998)) damage level was present on 1/3-2/3 of the elements. A slight damage, D1, extended 1/3-2/3 of the elements was considered as pre-existent. Plaster, encasement and ceiling delamination, as well as fall of internal and external objects, were reported in the usability form.

It is worth mentioning that according to data released by the Italian National Institute of Geophysics and Volcanology (http://shakemap.rm.ingv.it/shake/7073641/pga.html) the recorded acceleration in TER station, located some 33 km from the epicentre and about 1.3 km from the complex, horizontal peak ground acceleration was equal to 0.066 g. Such limited demand was able to make the school unusable.

On the contrary, despite hall buildings frequently displaying a higher vulnerability compared to ordinary buildings (Marotta et al. 2017a; b; Sorrentino et al. 2014; Spence and D'Ayala 1999), the church of San Giovanni suffered a minor crack at the intersection between vault and façade and was tagged as usable by a different inspection team.

3.2 *Damage after the October 30th, 2016 event*

The October 30th event, whose epicentre was located some 41 km from TER station, induced a horizontal PGA of about 0.082 g, hence higher than in August. As one can expect, damage was worsened by cumulative effect of the sequence, but nor partial collapses (Sorrentino et al. 2017) neither masonry disintegration due to poor mortar quality (Liberatore et al. 2016) took place.

Structural damage has been interpreted based on a new survey (Figure 1-Figure 2) and according to damage classification in Table 1.1 of OREM (2013). Widespread cracks having width smaller than 3 mm, sometimes crossing the entire transversal section, were observed on more than 30% of the structural walls surfaces of the first floor (Figure 8). Evident separation between vertical and horizontal structures, as well as at wall intersections, were surveyed at same floor (Figure 9). According to OREM (2013) such damages qualify as significant but less than severe. Consequently, the damage level of the building is classified as 2 (Table 1.4 in OREM 2013). Additionally, widespread cracks having width smaller than 3 mm were observed on some structural walls of the ground floor and in some vaults between ground floor and first floor (Figure 10).

Figure 8. Widespread cracks having width smaller than 3 mm. First floor, wing on piazza Verdi

Figure 9. Evident separation between vertical and horizontal structures, as well as at wall intersections. First floor, wing on via Stazio

Figure 10. Widespread cracks having width smaller than 3 mm on a cross vault between ground floor and first floor. Shop on piazza Verdi

a)

b)

Figure 11. Inclined cracks crossing the whole thickness of a partition between two rooms on via Cameli garden

Figure 12. Separation between partition (left) and structural wall (right). First floor, room on piazza Verdi

Figure 13. Plaster delamination from intrados of I-beams and hollow clay blocks floor. Ground floor, room on via Stazio

As observed also in other earthquakes (Penna et al. 2014), a number of significant damages to non-structural elements were visible in the aggregate. Inclined cracks crossed the whole thickness of some partitions of the first floor (Figure 11). Clear separations between partitions and structural walls were evident at first floor (Figure 12). Large plaster surfaces delaminated from the intrados of I-beams and hollow clay blocks floors (Figure 13).

Figure 14. Cracks and local failure of the gypsum and timber ceiling. First floor, room on piazza Verdi

a)

b)

Figure 15. a) After August 24th; b) After October 30th. Cumulative damage is evident in the lune and in the right adjacent web

Widespread cracks, having width smaller than 3 mm, and local failures affected the gypsum and timber ceiling above the first floor (Figure 14). Widespread cracks, having width smaller than 3 mm, damaged also the reed mat vault of the reading hall, with an distinct increase of the damage level between the end of August and the end of October events (Figure 15). On the contrary, no damage to chimneys and tiles was observed, at least on the roof of the piazza Verdi wing (Figure 5).

4 CONCLUSIONS

The music high school of Teramo, Abruzzi region, has been inspected after the first event of the 2016 Central Italy seismic sequence. Moreover, the complex housed in a former monastery established in the 14th century, was assessed with more detail as part of a program to determine which schools were suitable for a fast repair and which needed a new construction. Despite being located about 33 (41) km from the main August (October) event, and expiring a peak ground acceleration of about 0.066 (0.082) g, the school was marked as unusable, because of damage to structural and non-structural elements. Widespread cracks having width smaller than 3 mm, sometimes crossing the entire transversal section, were observed on more than 30% of the structural walls surfaces of the first floor, where evident separation between vertical and horizontal structures, as well as at wall intersections, were surveyed. Even more severe was the non-structural damage state, with inclined cracks across the thickness of partitions, separation between partitions and structural walls, large plaster delamination, widespread cracks and local failures of traditional ceiling.

Such performances call into question the suitability of housing critical functions, due to large exposure of human lives and need of being operational during an emergency, in historical buildings. At the same time, such heritage constructions can suffer an accelerated decay if left unused and, thus, unmaintained for a prolonged period of time.

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