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Damage Assessment of Historical Masonry Churches Subjected to Moderate Intensity Seismic Shaking

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Abstract: An earthquake of magnitude 4.3 MW struck Cosenza (Calabria region, South Italy) and its immediate area on 24 February 2020. Although no damage was reported to ordinary masonry buildings, the ancient masonry churches suffered widespread damage. The herein article presents an analysis of the failures suffered by monumental buildings (e.g., churches) following a moderate seismic action. The contribution is based on the in situ damage observation of 14 churches, with a dating ranging from the 12th to 20th century. The study consists of a first phase, in which the different damage modes are identified, describing their causes and effects, and a second phase that correlates the damage detected to the main parameters that influence the seismic response of the churches (geometric characteristics, boundary condition, masonry and floor organization, past interventions, etc.), regardless of the state of conservation that was discrete for all buildings before the telluric event. From the rapid visual survey, the “weight” of each seismic parameter on the type of damage detected was then established. The past “retrofitting” interventions were decisive in the response of the ancient structure, with particular regard to those that made an aggravation of seismic mass and an increase in stiffness.

Keywords: 24 February 2020 Cosenza earthquake; masonry monumental building; light intensity seismic shaking; seismic damage assessment; rapid visual survey procedure

1. Introduction and State of the Art

On the 24 February 2020, at 16:02:58 Coordinated Universal Time (UTC), (http://cnt.rm.ingv.it, accessed on 5 January 2021), a seismic event was recorded with a moment magnitude MW 4.3, with the epicenter located within the municipality of Rende (Province of Cosenza, Calabria Region, Italy) and an estimated hypocenter location 9 km in depth. The earthquake caused damage in an area of northern Calabria, with a total population of nearly 200,000 inhabitants within a 10 km radius, belonging to 15 municipalities listed in Table 1.

In the days immediately following the seismic event, the crisis unit Coordinamento regionale UCCR-MiBACT per la Regione Calabria, of which the writer is coordinator for the province of Cosenza, took action to survey the damage suffered by monumental buildings. The screening, in collaboration with the fire brigade, began immediately after the quake and continued slowly until May 2020, due to the restrictive measures for the COVID pandemic.

The ancient chronicles limit themselves to describing the effects on buildings deriving from the most catastrophic events without, in general, explicitly mentioning damage due to earthquakes of modest magnitude [1]. The seismic scales—aimed at assessing the intensity of the earthquake—of the late nineteenth century (Rossi–Forel scale, 1873) and above all, the one named Mercalli–Seiberg [2] provide the first evaluations of the consequences deriving from an earthquake of light level. Recent studies, particularly extensive, have turned to the recognition of the damage suffered by churches due to violent earthquakes [3,4], with particular regard to those events that hit the Italian peninsula (i.e., Umbria, 1997; Abruzzo, 2009; Emilia Romagna, 2012; Central Italy, 2016; Isola d’Ischia, 2017) [5–19].
Table 1. List of municipalities within 10 km from the epicenter of the earthquake of 24 February 2020.

| Municipality              | Population | Epicenter Distance from Church (km) | Investigated Church                                      |
|---------------------------|------------|--------------------------------------|----------------------------------------------------------|
| Castiglione Cosentino     | 2.896      | 4                                    | Santi Niccolò e Biagio (16th c.)                         |
|                           |            |                                      | S.S. Rosario (18th c.)                                  |
|                           |            |                                      | Madonna di Costantinopoli (17th c.)                     |
|                           |            |                                      | S.S. Vergine della Pietà (12nd c.)                     |
|                           |            |                                      | Ritiro (17th c.)                                       |
|                           |            |                                      | Santa Maria della Consolazione (20th c.)               |
| Rende                     | 35.338     | 4                                    | San Francesco di Paola (16th c.)                        |
| San Pietro in Guarano     | 3.663      | 6                                    | Cathedral (13rd c.)                                     |
| Rose                      | 4.373      | 7                                    | Sant’Agostino (15th c.)                                 |
| Castrolibero              | 9.894      | 7                                    | Santa Maria della Sanità (15th c.)                     |
| Zumpano                   | 2.570      | 7                                    | Cappella dell’Assunta (18th c.)                        |
|                           |            |                                      | Santa Maria delle vergini (16th c.)                    |
|                           |            |                                      | "Passetto" (17th c.)                                   |
| Cosenza                   | 67.546     | 8                                    | San Francesco di Paola (16th c.)                        |
| Marano Marchesato         | 3.553      | 8                                    |                                                         |
| San Vincenzo la Costa     | 2.195      | 8                                    |                                                         |
| Lappano                   | 941        | 8                                    |                                                         |
| Marano Principato         | 3.180      | 9                                    |                                                         |
| Montalto Uffugo           | 19.669     | 9                                    |                                                         |
| San Fili                  | 2.719      | 9                                    |                                                         |
| Rovito                    | 3.158      | 9                                    |                                                         |
| Celico                    | 2.802      | 10                                   |                                                         |

The structural behavior of churches, in general, subjected to dynamic actions, is discussed in a few of papers [20–28].

On the other hand, the analysis of the effects on religious monumental buildings resulting from earthquakes of light magnitude is little debated in the scientific community. The rare references are related to the failures produced to the non-structural artistic elements (NSEs) of the churches that already occur at a modest level of damage to the structures [29–33].

In order to protect works of art, the legislator has introduced—in the Italian legislation on constructions—the evaluation to the Limit State of Damage to Artistic assets, SLA (NTC 2008; DPCM 9 February 2011, Linee guida per la valutazione e la riduzione del rischio sismico del patrimonio culturale). This outlines the conditions in which the monuments suffer damage of modest entities, such that they can be restored without a significant loss of cultural value. Furthermore, the MiBACT (Italian Ministry of Cultural Heritage and Activities and Tourism) Circular n. 15 of 5 April 2018, recommends providing interventions on non-structural elements capable of reducing the level of damage even in the event of minor intensity earthquakes.

The study herein focuses on the rapid visual analysis of a group of historic masonry churches—not homogeneous from the point of view of the date of construction, geometrical configuration and characteristics of the masonry fabric—which suffered damage due to an earthquake of not high intensity. The purpose is to draw a systematic picture of damage manifestations within the complexity of the key factors that determine the seismic response of the building. The resulting catalogue of characteristic structural behaviors is useful to refine and validate the calculation procedures. Furthermore, the in-depth knowledge of the construction, even in the case of light seismic actions, allows for a correct assessment of the safety level of the church. Such a knowledge is of fundamental importance to implement appropriate repair and reinforcement measures that can, in addition to human life safeguarding, reduce the risk of damage as well as the loss of non-structural elements, frequently of historical and artistic value.
2. The Expeditious Survey According to the Italian “A-DC Scheda chiese”

The total investigated churches, belong territorially to four different municipalities in the province of Cosenza (namely Cosenza, Rende, Castiglione and Montalto Uffugo), was 14 (See Table 1 and Figure 1).

The screening was carried out by means of a codified Italian survey form “A-DC Scheda chiese”, (PCM-DPC-MiBAC, 2006; MiBACT, 2015), drafted in agreement between the Italian Civil Protection Department and MiBACT. The form allows the assessment of the damage index (id with values between 0 and 1), which quantifies the average level of damage suffered by the church. The index is obtained through a normalized average of the damage level (dk) detected for each mechanism—of the 28 possible identified by the form—based on the number of mechanisms detected in the church. That is according to the relation:

\[
id = \frac{d}{5n}
\]  

where \(n\) = number of detected mechanisms (\(n \leq 28\))

\[
d = \sum_{k=1}^{n} dk
\]

\(dk\) is the level of damage associated with each detected mechanism and can assume integer values between 0 and 5 (0 = zero damage; 1 = slight damage; 2 = moderate damage; 3 = serious damage; 4 = very serious damage; 5 = collapse).

The analyzed churches show a damage index (id) ranging from a maximum of 0.56, relative to the church of San Niccolò e Biagio, to values of about 0.13 for the church of Santa Maria della Sanitā, with an average value of about 0.3 relative to all examined buildings.

Furthermore, the safety condition of the churches was established from the rapid survey. In particular, the evaluation provided the following assessment:
- Temporarily unsafe, until the completion of a detailed structural investigation to allow appropriate measures for minimizing seismic risk and re-establishing building safety, in regard the church in Castiglione Cosentino;
- Partially safe; this evaluation is referred to the church of Ritiro in Rende, where, in a portion of the building—the first bay of the lateral aisles—access was prevented. However, the unsafe part does not compromise the structural stability of the safe parts;
- Safe with precautions, namely only after provisional measures have been carried out, such as propping, can be considered safe; this is an evaluation related to the church of Santa Maria della Sanità in Cosenza.

The remaining churches were evaluated as safe. The crack and deformation pattern detected in churches—from an exclusively visual analysis (expert screening) and without the aid of any instrumental test—was, therefore, related to the geometry, quality of the masonry, constraints and undergone interventions, from which it was deduced the “weight” of each parameter in the response of historic masonry churches to seismic stresses of light intensity.

3. Materials and Methods for the Seismic Response Assessment

The church, built in conformity with a celestial archetype according to the Christian tradition, embodies various symbols which, together with liturgical need, led to the choice of impressive organisms with precise proportional relationships.

The churches, therefore, assume grandiose dimensions with slender walls without horizontal and vertical intermediate diaphragms. Furthermore, the presence of heavy thrust structures such as arches, vaults and domes as well as of large openings in the walls are recurrent. A configuration that involves large voids and concentrated masses in the structural model makes churches extremely more vulnerable to seismic events than ordinary masonry buildings, even for moderate magnitude.

Additional strategic elements in the response to the actions deriving from earthquakes are the materials and organization of the masonry fabric, which vary depending on the chronological scope of execution.

The state of conservation of the examined churches is discreet. These constructions, in fact, were recently subjected to maintenances which stemmed problems related to the age of the materials as well as any failures deriving from stresses in a static regime. However, significant interventions that varied the original masses and altered the distribution of stiffness and stress are also to be highlighted.

The behavior manifested by the church on the occasion of modest horizontal actions was interpreted by dividing the building into macro-elements. Therefore, the observations on the suffered damage, detailed below, refer to portions of the church (i.e., facade, nave, triumphal arches, vaults, etc.) substantially characterized by autonomous seismic performance.

3.1. Main Buildings Seismical Parameters

The described methodology based on the existing literature concerning rapid survey methods [13,34–36] analyzes the main factors that influence the seismic response of the masonry monument. In this regard, the main novelty element in the proposed rapid seismic assessment is a parameter that attempts to describe the “weight” of the geometry on the response to seismic excitations.

Furthermore, the procedure took the typological and the masonry characteristics into account, as well as the inter-floor and roof slabs features. In addition, the wall density in each main direction, the interventions undergone by the construction, the seismicity of the area as well as the local geologic and morphologic factors that can affect the level of shaking experienced in earthquakes, have been considered.
3.1.1. Typological and Geometrical Features

The analyzed churches, isolated or with the annexed convent, are generally located on a flat or gently sloping site of the urban center or its first suburbs. In one case only (the church of Santi Niccolò e Biagio in Castiglione), the church stands on a relief. The planimetric layout that is found is in most cases a single hall-like room on which side chapels open.

A further typology is organized according to three naves marked by colonnades that culminate in the transept (i.e., Cosenza Cathedral) or terminate in the apse, as for the church of Santi Niccolò e Biagio in Castiglione and the church of the Ritiro in Rende. The latter is the only one that has a Greek cross plan with the lantern tower as fulcrum that encloses a dome, bordered by arches and mirror vaults in masonry.

In summary, the majority of the examined churches, with a rectangular plan, have symmetry only in the longitudinal direction and a concentration of resistant elements in the apse area. Similar configuration has to be ascribed to the churches built on a Latin cross plan (i.e., Santa Maria della Sanità). Furthermore, the chapels and service buildings built only on one side that frequently characterize the group of churches under study, make the plan outline not exactly compact. The only church with a central plan is that of the Ritiro in Rende, in which the pseudo-biaxial symmetry allows a distribution of the lateral stiffness and of the mass symmetrical with respect to two orthogonal axes [37]. The “Passetto”, a long corridor that changes direction along its development, shows a high irregularity in plan.

On the other hand, in elevation, although the buildings are characterized by more marked differences in the sample under study, symmetry and regularity, general speaking, have been observed.

The façade of the Cathedral, of the church of Santi Niccolò e Biagio as well as of the Ritiro in Rende has a salient shape with a tripartition that follows the planimetric subdivision into naves. Such a division is marked, in the first two buildings, by robust buttresses useful to counteract the thrust coming from the internal arches. The other analyzed churches, vice versa, adopt a hut shaped main façade, which follows the two slopes of the roof. The facades have a rose window or a mixtilinear window, however in general they are sober, in stark contrast to the interior, whose decorative stucco—if we exclude the Cathedral of Cosenza—is rich and exuberant.

The summit tympanum slightly exceeds the height of the nave (i.e., Cosenza Cathedral) or, in almost all of the examined cases, it aligns with the roof slopes. The bell towers, always of limited height, are incorporated into the structure—e.g., a bell gable—or, in limited cases, independent.

The geometrical data collected in the rapid visual survey are related to the main dimensions such as the height of the facade, the average size of the masonry as well as the surface of the church.

In order to quickly compare the vulnerability depending on the geometrical characteristics, a “geometrical quality index” (IQG) was ideated and used. It is defined as the root of the church surface—that is the fictitious average length of the wall—multiplied by the height of the façade measured at the ridge and divided by the average wall thickness.

Based on these data, three homogeneous classes of churches were identified (see Table 2):

- class 1—IQG \( \leq 2 \times 10^2 \)
- class 2—\( 2 \times 10^2 \leq \text{IQG} \leq 5 \times 10^2 \)
- class 3—IQG \( > 5 \times 10^2 \)

The comparison between the investigated churches shows a certain homogeneity in regard to the values of the height of the façade, varying between 11.5 m and 16.5 m. Exceptions are represented by the church delle Vergini and the S.S. Pietà (9 mt) and by the Cathedral of Cosenza, which reaches 22 mt.

A high variability characterizes the extension of the surface, with some churches—equal to 35% of the total examined—reaching a size between 350 and 600 square meters, a second group whose surface is between about 200 and 300 square meters (5 cases, equal to
35% of the total) and a third consisting of buildings of approximately 150 square meters (28% of the total). This is a classification from which the Cathedral of Cosenza is excluded due to the large size of the surface that exceeds 1700 square meters.

The average thickness of the masonry is variable between 0.65 and 1.5 m; a value generally correlated to the surface of the church.

From the analysis of the geometrical characteristics, a certain uniformity is found for the IQG parameter, from which one can assume proportional relationships at the basis of the sizing of the churches. In fact, from the data obtained, the majority of churches—9 in number, equal to 64% of the total—appear to belong to the second class of geometrical quality. The Cathedral of Cosenza also in this case represents an exception with respect to the recorded IQG values, with an index of $6.67 \times 10^2$.

Conversely, the lowest IQG values are recorded in the church of S. Maria della Consolazione, equal to $1.44 \times 10^2$, and in the church of Vergini ($1.06 \times 10^2$). In the first case, the dimensional relationships found are justified by the area in which the building is located, originally rural and sparsely populated, whereas the modest size of the church of Vergini is to be linked to its function: a chapel serving the contiguous convent.

**Table 2. Churches geometrical features.**

| Church                      | H Façade (mt) | Surface (mq) | Average Wall Thickness (mt) | IQG      |
|-----------------------------|---------------|--------------|----------------------------|----------|
| Santi Niccolò e Biagio      | 16.5          | 653          | 0.8                        | $5.27 \times 10^2$ |
| S.S. Rosario                | 13.5          | 313          | 0.9                        | $2.65 \times 10^2$ |
| Madonna di Costantinopoli    | 14            | 565          | 1                          | $3.32 \times 10^2$ |
| S.S. Vergine della Pietà     | 9             | 150          | 0.7                        | $1.57 \times 10^2$ |
| Ritiro                      | 16.5          | 562.5        | 1.5                        | $2.60 \times 10^2$ |
| Santa Maria della Consolazione | 11.5        | 192          | 1.1                        | $1.44 \times 10^2$ |
| San Francesco di Paola (Rende) | 13.5      | 560          | 1.1                        | $2.90 \times 10^2$ |
| Cathedral                   | 22            | 1709         | 1.3                        | $6.67 \times 10^2$ |
| San Giovanni Battista       | 13.5          | 162          | 0.8                        | $2.14 \times 10^2$ |
| Sant’Agostino               | 15            | 330          | 0.8                        | $3.40 \times 10^2$ |
| Santa Maria della Sanità     | 15.5          | 371          | 0.8                        | $3.75 \times 10^2$ |
| Chapel of Assunta           | 15.5          | 150          | 0.65                       | $2.92 \times 10^2$ |
| Santa Maria delle Vergini    | 9             | 170          | 1.1                        | $1.06 \times 10^2$ |
| San Francesco di Paola (Montalto Uffugo) | 20     | 588          | 1.5                        | $3.23 \times 10^2$ |

The seismic performance of masonry buildings largely depends on the shear resistance of masonry walls. Therefore, the wall density (Wd) factor was taken into consideration. It is determined as the ratio of masonry load-bearing walls in each of the orthogonal directions—longitudinal and transverse direction—to plan area (see Table 3).

The spatial relationships, to guarantee the liturgical functions and symbolic and compositional needs, leads in the examined churches, in general, to a predominance of the “quantity” of masonry arranged in the longitudinal direction, with an approximate ratio of 2 to 1 with respect to the wall density in the transverse direction. The church of the Ritiro in Rende is excluded from such a grouping, as it has a central plan. Considering the significant height that characterizes the churches, which leads to a significant wall thickness, the masonry density assumes a considerable consistency compared to the area covered by the church, with average values for Wdx equal to 8.5% and for Wdy of 15.8%. The highest value is recorded in the church of Santa Maria della Consolazione where the total masonry resistant area is more than a third of the floor area. The lowest value of the wall density was identified in the Church of San Francesco di Paola in Rende (Wdx = 7%; Wdy = 11%).
The lowest values of $W_{dy}$ have been identified for the walls of the church of S.S. Rosario and Sant’Agostino (5.6% and 6.3%, respectively). In the churches of S.S. Rosario and Santa Maria della Consolazione, there is a considerable prevalence of the wall area arranged in the longitudinal direction that, compared to the transversal one, has a ratio of almost 1 to 3.

The $W_{dy}$ and $W_{dx}$ values are homogeneous (average value of COV $W_{dx} = 2.5\%$, $W_{dy} = 2.07\%$) and do not seem to have a clear direct correlation with the detected damage, linked in most cases to the structural equilibrium and not to the exceeding of the shear strength of the masonry. In the case of the church of Sant’Agostino, the cracks in the plan recorded in the façade further explain the modest wall masonry density in the transversal direction, compared to other churches, where the identified value $W_{dx}$ is 6.3% (average value of $W_{dx} = 8.3\%$).

Table 3. Wall density ($W_d$) in each main direction (COV: coefficient of variation; $A_{wy}$: total horizontal cross-sectional area of the wall in the longitudinal direction; $A_{wx}$: total horizontal cross-sectional area of the wall in the transverse direction; $A_c$: area of the church).

| Church                        | $W_{dx}$ (%) | $W_{dy}$ (%) | COV $W_{dx}$ | COV $W_{dy}$ | $A_c$ (mq) | $A_{wx}$ (mq) | $A_{wy}$ (mq) |
|-------------------------------|-------------|-------------|--------------|--------------|-----------|--------------|--------------|
| Santi Niccolò e Biagio        | 7.9%        | 14.3%       | 0.7%         | 0.9%         | 653       | 52           | 94           |
| S.S. Rosario                  | 5.6%        | 17.2%       | 3.4%         | 0.8%         | 313       | 18           | 54           |
| S.S. Vergine della Pietà      | 7.4%        | 16.8%       | 1.2%         | 0.6%         | 150       | 11.2         | 25.2         |
| Ritiro                        | 15.4%       | 18.5%       | 8.1%         | 1.7%         | 562.5     | 87           | 104          |
| Santa Maria della Consolazione| 10.2%       | 26%         | 2%           | 6.4%         | 192       | 18.8         | 50.6         |
| San Francesco di Paola (Ronde)| 7%          | 11%         | 1.7%         | 3%           | 560       | 39.6         | 60.6         |
| Cathedral                     | 9.6%        | 13.6%       | 1.2%         | 1.3%         | 1709      | 62.4         | 137.8        |
| Sant’Agostino                 | 6.3%        | 11.8%       | 2.5%         | 2.5%         | 330       | 21           | 39           |
| Santa Maria della Sanità      | 7%          | 13.4%       | 2%           | 1.5%         | 371       | 26           | 50           |
| **Average Value**             | **8.5%**    | **15.8%**   | **2.5%**     | **2.07%**    |           |              |              |

3.1.2. Masonry and Floors Features

The masonry of religious buildings is, in general, an expression of the most advanced rule of the art of the time thanks to an enlightened and rich client, capable of entrusting the execution to trained workers and supplying carefully selected materials. However, a geographical area such as the Calabrian one—peripheral to the centers of radiation of the architecture of the Italian peninsula—leads, for some of the religious buildings affected by the earthquake of 24 February 2020, to a wall quality that is not adequate to appropriately respond to the induced stress from the seismic excitation (see Table 4).

Several different construction techniques is a constant feature in the analyzed churches. It is the result of more or less extensive repairs and reconstructions following earthquakes. Moreover, the notable presence of non-structural elements (NSEs) should be noted in a generalized manner; a condition whose reasons are to be found in the transformation process undergone between the 16th and 18th centuries. In fact, the new communication exigencies dictated by the Counter-Reformation and the taste variation of the Baroque age led—especially in southern Italy—to a revision of the spatiality of the church, obtained through an overabundant decorative stucco as well as with paintings.

It is possible to assume that the Cathedral of Cosenza received huge donations for the construction with the probable use of non-local workers, at least in regard to the higher-level technical figures. The prefabrication, brought to perfection during the Norman domination (11th–13th century) [38], led to a pseudo-isodomic masonry with a precise alternation of the bed and head joints between the blocks. Furthermore, in the Cathedral there is the presence of walls dating back to the sixteenth century (adjacent to the sacristy) with pseudo-regular limestone ashlars alternated with brick wedges. More disordered with stones of varying size—even rounded, perhaps taken from the nearby river—are the walls relating to the apse rebuilt during an intervention dating back to the nineteenth
century. Upon visual analysis, the mortar is tough and therefore ensures a certain cohesive resistance to the masonry.

A random rubble masonry was used for the construction of the passaggio seu tragitto o passetto, the connecting corridor between the Cathedral of Cosenza and the Episcopio. This one-level building was built by the will of Archbishop Giuseppe Maria Sanfelice in the mid-17th century. It underwent an important restoration in the 19th century which shaped its current facies. In fact, in 1821, the original wooden structure on which the corridor rested was replaced with a masonry barrel vaults system [39]. There are variations in stiffness due to the presence of an increase in the size of the wall section along the corridor and to the greater height that the “Passetto” manifests in the terminal part. The roof consists of a single sloping pitch with timber beams, in some cases just debarked round wood.

Table 4. Main masonry typologies and mechanical properties found in the investigated churches (from “Circolare 2 febbraio 2009, n. 617—Istruzioni per l’applicazione delle “Nuove norme tecniche per le costruzioni” di cui al D.M. 14 gennaio 2008”).

| Masonry Typology          | Church                                      | $f_m$ (N/cm²) min-max | $\tau_0$ (N/cm²) min-max | $E$ (N/mm²) min-max | $G$ (N/mm²) min-max | W (kN/mc) |
|---------------------------|---------------------------------------------|------------------------|---------------------------|---------------------|---------------------|-----------|
| Calcarenite ashlar masonry| Cathedral, Cosenza; Sant’Agostino, Cosenza; | 140                    | 2.8                       | 900                 | 300                 | 16        |
|                           | S.S. Rosario, Rende                         | 240                    | 4.2                       | 1260                | 420                 |           |
| Coursed rubble masonry    | Santa Maria della Sanità, Cosenza           | 200                    | 3.5                       | 1020                | 340                 | 20        |
| Random rubble masonry     | Santa Maria della Consolazione, Rende;      | 100                    | 2                         | 690                 | 230                 | 19        |
|                           | Santi Niccolo e Biagio, Castiglione         | 180                    | 3.2                       | 1050                | 350                 |           |

The church of Sant’Agostino has a late medieval foundation, which corresponds to a wall organization, visible on the main facade, consisting of resistant square-shaped elements with regularly staggered joints. Particular attention is paid to the quoins that denote an effective connection between the perimeter walls.

A similar organization of the wall fabric is found in the late eighteenth-century church of the S.S. Rosario in Rende.

The masonry panels of the church of Santa Maria della Sanità, founded in 1481, are characterized by an orderly distribution of pseudo-regular ashlars, with widespread brick wedges that make the course planar.

A further construction technique found in churches damaged by the earthquake of 24 February 2020, is the one that distinguishes the church of Santi Niccolo e Biagio, of sixteenth-century foundation. In this case, the random rubble masonry, at least for the perimeter walls, is composed of two leaves and an inner cavity free of headers, with stones of modest size and prismatic shape and an intensive use of spolia elements. In addition, there are quoins with blocks of inadequate length and they are not continuous along the entire height of the corner, which suggests an original bond between the perpendicular walls that is not very effective.

Another type of masonry organization that characterizes the top part of the façade and a portion of the side elevations belongs to the church of Castiglione. It is the result of a probable reconstruction in the early twentieth century—perhaps after the 1905 earthquake—following an overturning mechanism. It is a random rubble stone masonry with inserted horizontal bricks with periodic spacing in order to regularize the masonry apparatus. The horizontal setting given by the bricks allows a potential cyclic oscillation around cylindrical horizontal hinges, avoiding the disintegration of the masonry, with the possibility in the case of an earthquake – with a high magnitude—to activate a kinematic mechanism [40].
A similar arrangement can be found in the church of Santa Maria della Consolazione, although the stones of variable size are mainly rounded, presumably taken from the river. The terminal part of the bell tower of the church of Santi Niccolò e Biagio is made of bricks.

The remaining churches are characterized by a masonry constituted by pebbles and irregular and not well staggered stone blocks; albeit a recurring element is regular quoins at the corner of the walls.

The interior of many of the examined churches is covered by wattle barrel vaults with, in most cases, lunettes that improve the stiffness in the transverse plane.

The wattle vault is made up of wooden ribs consisting of one or a double row of boards on which bear intertwined canes which constitute, at the intrados, the support for the stucco decoration. The latter, based on gypsum, is characterized by a modest ductility and therefore manifests a fragile response even in the case of small displacements. The vaults are self-supporting or, more frequently, supported with the cooperation of trusses tie beam or timber members independent of the roofing carpentry.

The structure of the roof, for the majority of the studied churches, is made of wood, organized according to a truss configuration or constituted by reticular steel beams, the result of recent replacement interventions of the original wooden carpentry.

An exception is represented by the Cathedral of Cosenza, where the aisles are mostly without false ceiling, showing exposed wooden trusses. Conversely, the last span of the east side aisle has the original, medieval, cross vault consisting of calcarenite small stone blocks laid edge on and ribs. The same type of floor, but of nineteenth-century construction, characterizes the transept, while a masonry half-dome identifies the apsidal basin.

3.1.3. Historical Seismicity and Past Interventions

The area affected by the earthquake of 24 February 2020 is characterized by a high seismic hazard with expected ground accelerations, which have a 10% probability of being exceeded in 50 years, exceeding 0.225 g. In fact, from the analysis of historical earthquakes in a chronological scope between the seventeenth and twentieth centuries, it is clear that the area under study has continuously undergone macro-earthquakes (see Scheme 1).

![Scheme 1. Historical seismicity of the analyzed area.](image)

The earthquake of 1638, with its epicenter in central Calabria and the destruction of numerous towns near Cosenza, was catastrophic. The territory under study was hit with an intensity, evaluated on the effects produced on people and buildings, between 8 and 9 degrees of MCS. For more than a century, the chronicles did not record any significant
telluric events, until 1767. In this case, the epicenter was near Cosenza and the estimated magnitude was 7 MCS. The year of 1783 was the year of yet another terrible earthquake that had more than 30,000 victims [41], consistent changes in the morphology of the territory and the destruction of numerous towns in southern Calabria. In Cosenza, the intensity was assessed as 7 degrees of MCS [1].

After about 50 years, on 12 October 1835, with an intensity on the MCS estimated at 8.0, an earthquake vehemently hit Cosenza and its surroundings. Thus began a series of frequent earthquakes (1836, between 6 and 7 MCS; 1854, 8 MCS; 1870, between 7 and 8 MCS; 1887, 5 MCS), continued until the beginning of the 20th century: 1905 (intensity evaluated in 7 of the MCS), 1908 and 1913 (both of an intensity of 6 MCS according to [1]). A temporal continuity of seismic events—if we exclude the hiatus between the earthquake of 1638 and that of 1767, which does not go beyond the “space” of a generation—instills, between the 1600s and up to the present day, a widespread perception in the Cosenza community of the seismic risk. The “memory” of the earthquake leads to the application of measures aimed at mitigating the seismic vulnerability in buildings subject to repairs and reinforcement, albeit with exceptions.

The observation of the damages suffered as a result of the earthquake of 1783 and the knowledge about the seismic behavior of a structure led the Borbone government to the promulgation of Istruzioni per gli Ingegnieri commissionati nella Calabria Ulteriore, a series of rules aimed at building safer constructions against earthquakes [42]. This code, in addition to including an extensive part on ordinary buildings which recommends the adoption, as a vertical structure, of a masonry reinforced by wooden frames, dedicates article 18 of chapter 1 to churches. Such a provision prohibited the execution of thrust organisms such as vaults and “orders” catene di ferro, che attraversino le larghezze dei vanni (the installation of tie-rod, which cross the widths of the rooms). These anti-seismic measures can be found in the analyzed churches built or repaired after the end of the eighteenth century and throughout the nineteenth century and beyond.

The spread and the trust placed in reinforced concrete for new constructions since the early twentieth century has led to the use of such technology in the monuments of Cosenza. In the 1930s, the retrofitting operation to the west elevation of the Cathedral of Cosenza involved r.c. pillars executed in breach of the masonry walls as well as reinforced concrete jacketing. Furthermore, half trusses in reinforced concrete, pertinent only to the right aisle, were built in the same intervention.

The primacy of reinforced concrete, among materials and techniques for construction—even for ancient ones—was consolidated in Italy in the second half of the twentieth century. The use of r.c. tie beam placed at the roof level is recommended by the Law of 25 November 1962, n. 1684 (art.4 g) and reiterated in subsequent legislation (Ministerial Decree 2 July 1981, Normativa per le riparazioni ed il rafforzamento degli edifici danneggiati dal sisma nelle regioni Basilicata, Campania e Puglia; DM 24 gennaio 1986, Norme tecniche relative alle costruzioni antismistiche). In the church of Santa Maria della Santità in Cosenza, of Santi Niccolò and Biagio in Castiglione Cosentino (Figure 2), in the Sanctuary di Constantinopoli, in the church of Santa Maria della Consolazione in Rende (Cs) and in San Francesco di Paola in Montalto Uffugo (in this case it reaches 70 cm high), there are perimeter reinforced concrete beams at the top of the walls aiming at connecting the walls and obtaining a box-like behavior of the structural system in case of seismic shaking.
The retrofitting intervention that involved the church of Santi Niccolò e Biagio di Castiglione Cosentino dates back to the end of the twentieth century. It included the construction of a concrete screed reinforced with a steel welded lattice on the extrados of the ribbed vault of the main nave, bound by metal hangers to the steel trusses of the roof. A reinforcement of glass fibers embedded in a cementitious matrix was performed for the mirror vaults of the side aisles. Furthermore, the technology of r.c. was used to stem the considerable crack pattern generated in the pillar due to considerable values of combined axial and flexural loads. In fact, the inner of the pillars with a regular tufa ashlar of the nave were emptied to insert a core in reinforced concrete, connected with a r.c. strip foundation. The new r.c. pillars reach, approximately, the impost of the arches. The use of steel strapping in the corner areas is also worthy of mention.

Coeval is the retrofitting, following a land subsidence, carried out in the church of the Ritiro in Rende through the installation of a micropiles foundation (Scheme 2).
The soil properties can considerably affect the damage suffered by buildings during the seismic event. However, it should be noted that the analysis carried out did not find significant differences in the level of damage among the churches—with exception to the Church of Santi Niccolò e Biagio—leading to the presumption that high level of local amplification did not occur. It worth also noting that site effects become significant, in particular for high energy earthquakes [43]. It is precisely the homogeneity of the detected damage level, instead, that leads to assuming correlations between the response of the constructions and near-field effects due to the proximity of the shaking source.

Data for computing dominant frequencies of the ground motion record as well as of the examined churches are not available.

However, recent seismic microzonation studies have provided the main information on the potential response of the soil layers under earthquake for the municipality of Rende and for that of Cosenza, in which 12 of the analyzed churches are located.

A microzonation map is not available, instead, for the other analyzed areas. Related to the latter, therefore, it has been assumed that the geotechnical and the geomorphological properties are factors that provide the propensity for the variation of earthquake characteristics on the ground surface.
The churches examined in the municipality of Rende are located in the historic center. From a geological point of view, such a portion of the territory is characterized by white clays occasionally intercalated with sands, with poor resistance to erosion and low permeability. With regard to the morphological aspect, it can be classified as a narrow ridge. Based on this information, it is clear from the documents attached to the PSC (Piano Strutturale Comunale, https://www.comune.rende.cs.it/, accessed on 12 March 2021) that in the historic center of Rende, a widespread amplification of the ground motion is possible. It is linked to the focus of seismic waves along oblique slopes and to the potential overturning and/or detachment of rock blocks with a retreat of the escarpment edge. A similar scenario can be assumed for the church of Santi Niccolò and Biagio in the municipality of Castiglione Cosentino sited on a ridge area and from which a geological point of view is characterized by the presence of sands with arenaceous and clayey intercalations.

Analogues’ propensity to generate site effects is conceivable for the historic center of Cosenza, where most of the investigated churches are located. In fact, it can be defined as a stable area but susceptible to seismic motions amplification (Comune di Cosenza, Microzonazione sismica, 2015). The soil stratigraphy of the historic center of Cosenza can be classified in two macro-groups. The church of the Vergini, of San Giovanni Battista and of Santa Maria Sanitá lay the foundations on a soil layer composed by loose silty sands or slightly compacted silts. On the other hand, a soil characterized by moderately cemented, compacted and cohesive sands and silty sands distinguishes the Cathedral, the “Passetto” and the chapel of the Assumption.

3.2. Damage Survey

Following the earthquake of 24 February 2020, there was no evident damage to unreinforced ordinary masonry buildings, nor to people. The church buildings, on the other hand, suffered similar damage—for each structural element involved—in morphology, extension and severity, with, however, some exceptions.

The failures that affected the Cathedral of Cosenza were widespread. The pier to the left of the triumphal arch underwent an increase in the existing crushing mechanism, caused by excessive values of combined axial compression and bending stresses (Figure 3). There is a condition that is a consequence of the recent installation of a heavy reinforced concrete lattice, at the level of the bell tower. The lattice transfers its dead load precisely on such a structural element, to which the compressive stresses deriving from the vertical component of the triumphal arch is added. The activation of a similar local mechanism, with the concentration of stresses as a result of the shake action, occurred near the impost of the arches of the naves. This resulted in localized crushing with the expulsion of material from the top of the pillar into soft limestone blocks and variously inclined cracks with a predominantly sub-vertical trend. Such a phenomenon occurred only on one side of the pillar. The motivation was found in the existing deformation—i.e., a rotation in the direction transversal to the cathedral—probably impressed by previous earthquakes on the pillars of the nave, which produced a load eccentricity, aggravated by the seismic stresses.
In the last span of the east nave, the new conformation induced to the vault by the rocking of the walls led to the appearance of the Sabouret fissures near the springer [44,45]. Cracks located in the key, on the other hand, were generated in the vaults of the transept. These discontinuities, which correspond to plastic hinges on the extrados, derive from the out-of-plane displacement of one or both side walls, which caused the highest deflection in the key area.

The cracks with longitudinal trend—with the consequent fall of stucco and plaster—detected in the middle of the ribbed vaults that characterize the ceilings of the churches of Santa Maria della Sanità (Figure 4), Sant’Agostino, San Francesco di Paola in Montalto Uffugo and Santa Maria della Consolazione, are to be attributed to the same cause. Furthermore, in these constructions, the transverse response of the hall has led to a further phenomenon: the partial detachment of the vault from the walls and the generation of transverse cracks in the lunettes.

Typical is the failure mechanism, mobilized by in plane seismic action, which has characterized the triumphal arches of the Chapel of the Assumption, the Cathedral of Cosenza and the Sanctuary of the Madonna di Constantinopoli. The rotation of one or both piers caused shear ruptures and the generation of more than one hinge. Emblematic are the fractures highlighted in the triumphal arch of the church of San Francesco di Paola in Montalto Uffugo and of Santi Niccolò and Biagio. In fact, the earthquake caused springer cracks with a maximum distance between the tips recorded on the extrados. Vice versa, the crack—of greater entity—that distinguishes the key is characterized by a cusp in the upper part of the arch, a phenomenon that can be traced back to the generation of at least three plastic hinges due to the reciprocal distancing of the piers.
Figure 4. The church of Santa Maria della Sanità in Cosenza. Drawing of the plan (on the left) and details of the analyzed failures (on the right).

The church of the Ritiro in Rende emphasizes cracks at the intersection between the mirror vaults pitches (Figure 5).

Figure 5. The Church of Ritiro in Rende. Drawing of the plan (on the left) and details of the analyzed failures (on the right).
The church of Sant’Agostino shows a recent crack pattern relative to the façade, consisting of variously inclined fractures (Figure 6). The activation of a shear mechanism was also recorded in the “passetto”—connecting the Cathedral of Cosenza to the Episcopio. In fact, the in-plane action of the earthquake caused widespread cracks along both walls of the corridor with a sub-vertical trend that denounce a poor quality of the meshing between the component stones. Furthermore, larger cracks are recorded near the change in stiffness, towards the end, due to a change in the shape of the corridor. The presence of concentrated stresses near the support of the beam led, in some cases, to the generation of the fracture. There are further solutions of continuity at the intersection between the orthogonal walls, attributable to the disconnection of the perpendicular wall, namely an indication of an incipient motion of rotation.

![Figure 6. In-plane shear cracks. Church of Sant’Agostino (on the right), “Passetto” (on the left) in Cosenza.](image)

Failures, arising as a result of the longitudinal response of the nave, are recorded in the church of San Giovanni Battista in Cosenza (Figure 7). The effect is the disconnection of the vault from the triumphal arch. The cause is to be found in the rotational motion transmitted by the earthquake to the façade which generated strains along the transverse profile of the vault. Similar damage morphology, even if characterized by a different entity and based on a different kinematics, is that observed in the church of Santi Niccolò e Biagio. In this case, a portion of plaster near the façade collapsed. The mechanism was favored by the presence of a reinforced concrete screed on the extrados which, in addition to having significantly increased the seismic mass, made it lose the original deformability of the ribbed vault. The façade characterized by buttresses, and whose constraint with the orthogonal walls was stiffened by steel strapping, created boundary conditions which, although they prevented overturning, did not support the outward displacement of the vault. In other words, the façade rigidly confined the floor from which a concentration of stresses near the end of the vault arose. In the church of Santi Niccolò e Biagio (Figure 8), diagonal cracking phenomena were also found—at the intersection between the pitches—in the mirror vaults of the left aisle and cracks on the east pier on which the triumphal arch is placed. For such a structural element, the crack pattern and the masonry bulging are caused by excessive values of the combined flexural and axial loads, increased by the seismic excitation.
The interaction with the adjoining building, built after the original structure, is the basis of the damage mechanism found in the church of Santa Maria della Consolazione.

**Figure 7.** The church of San Giovanni Battista in Cosenza.

**Figure 8.** The church of Santi Niccolò e Biagio in Castiglione Cosentino (Cs). Drawing of the plan (on the left) and details of the analyzed failures (on the right).

**Figure 8.** The church of Santi Niccolò e Biagio in Castiglione Cosentino (Cs). Drawing of the plan (on the left) and details of the analyzed failures (on the right).
The interaction with the adjoining building, built after the original structure, is the basis of the damage mechanism found in the church of Santa Maria della Consolazione. The sacristy located south of the hall is on two levels above ground, with an inter-story floor in metal beams and structural clay tile, whose pocket beam enters for some centimeters in the side masonry of the church. A configuration from which, during the earthquake of 24 February 2020, a church wall hammering resulted. The consequent effect was a continuous hairline crack with a sub-horizontal trend for almost the entire nave, placed at a height of about two meters from the ground level, approximately correspondent to the sacristy floor.

All the investigated churches showed more or less extensive damage to the decorative apparatus with falling parts of stucco and layers of plaster, other portions remained in unstable equilibrium. The churches located in the municipality of Rende have oil lamps—reminiscent of an ancient Orthodox rite—generally suspended from tie-rods. The vibrations induced to the structure by the earthquake caused the detachment from the constraint and some of these lamps crashed to the ground (e.g., Sanctuary of the Madonna di Costantinopoli).

4. Results and Discussion

The damage detected for each macro-element showed a certain homogeneity of the response of the churches in relation to the quality of the seismic parameters considered (i.e., geometrical configuration, masonry organization, suffered interventions, boundary conditions: constraints and loads), regardless of the state of conservation, which was discreet for all buildings before the telluric event. However, some peculiar behaviors of the structures have been recorded. In fact, some monuments highlighted an anomalous response that can be mainly relate to “retrofitting” interventions carried out in recent years by means of technologies that are not very compatible, from a mechanical point of view, with the masonry.

From the discussion of the results, based on the evidence found in situ, a seismic parameter weight, SPW, is provided. A qualitative value—high, medium, low, according to the degree of influence on the examined damage mechanism—is attributed to that parameter. The results of such analysis are summarized in Table 5.

The dynamic actions with a direction transversal to the hall, induced by the earthquake of 24 February 2020, caused deformations in the wattle vault’s curvature as a result of the oscillations in the walls of the aisles on which they rest. This is a condition that resulted in the triggering of a fracture that crosses the vault in the longitudinal direction, in general almost in its entirety, near the key area (Figure 9). However, it should be noted that there was no damage to the wooden structure, which remained in the elastic field while the cracks only affected the intrados plaster. From the investigations carried out, the recurrence of such a crack pattern in five of the churches studied is due to the absence of tie-rods, an element that weighs heavily. In fact, the masonry apparatus is extremely heterogeneous for those five buildings investigated, which leads to the evaluation of low SPW. Moreover, such a mode of damage seems to disregard the geometrical configuration, as the IQG values associated with each church are inhomogeneous and variable from $1.44 \times 10^2$ (church of Santa Maria della Consolazione) to $3.75 \times 10^2$ (for the church of Santa Maria della Sanità). In support of the latter hypothesis are the observations made on the churches with barrel vaulted ceilings in the nave that did not suffer evident failures (church of S.S. Rosario, Sanctuary of Constantinopoli and S.S. Pietà) whose common character, in addition to the presence of the tie-rods, is the considerable variability of the IQG values.

The tie-rod was an effective defense to limit damage to other thrust elements such as the triumphal arch of the Sanctuary of the Madonna of Constantinopoli and the Rosario in Rende. An exception, in this case, is represented by the triumphal arch of the church of Santi Niccolò e Biagio which has developed, despite the presence of two tie-rods and at least four plastic hinges, due to the stretching lack of the metal bar. Such a damage mechanism developed in a similar way for the churches under investigation, regardless of
the characteristics of the masonry and the extent of the span covered, from which follow an estimate SPW value low for both parameters.

Figure 9. The church of San Francesco di Paola in Montalto (on the right) and of Sant’Agostino in Cosenza (on the left). The cracks involved the key of the nave vault and the lunettes.

In the church of S. Maria della Consolazione in Rende, the seismic response was peculiar. The resulting crack pattern, also in this case, depended on the metal slab to the wall of the church hall bound.

The moderate horizontal action in the plane of the wall damaged the façade of the church of Sant’Agostino with variously inclined cracks, while a sub-vertical trend characterizes the fractures that were generated in the “Passetto” of the Cathedral. These different behaviors were probably originated by the quality of the masonry: in regular ashlars such as that of Sant’Agostino, rubble masonry with rounded stones and of very small size for the walls of the “Passetto”. These wall typologies are characterized by not high shear strength (see Table 4) and, above all, by a modest value of wall density (Wdx) (see Table 3). Such factors appear to have direct correlation with the recorded crack pattern.

Moreover, for the damage of “Passetto” and of the church of Sant’Agostino, the stiffness variation probably played a leading role. In fact, the first one is characterized by a lack of structural regularity both in plan and elevation, while for the church of Sant’Agostino, the variable thickness of the facade and a large window provided a decisive contribution to triggering the cracks.

Furthermore, regarding the “Passetto”, it was found that some portions of the masonry, due to the concentrated load of the roof beam, constituted a preferential route for the detected crack. A similar effect, with local overcoming of the resistance to combined compression and bending stresses values, occurred at the impost area of the arches of the Cathedral of Cosenza and in the piers of the triumphal arch of the church of Santi Niccolò e Biagio. The masonry apparatus, which varies for the three listed cases, played a role in modifying the morphology of the fracture.
No evidence of façade overturning—due to out of plane seismic action—have been recorded. The reason has to be attributed to the limited value of the stress as well as to the generalized presence of the effective constraint between the perpendicular walls, with regular quoins in many of the analyzed churches.

The data contained in Table 5 lead one to note that a decisive influence in the response of the examined churches is given by the “strengthening” interventions (Figure 10), with particular regard to those that have made an aggravation of seismic mass. This condition occurs in three of the analyzed monuments and is equal to 33% of the total SPW rated high. Geometrical characteristics played a secondary role in about 94% (SPW equal to low or medium) of the examined damage. An exception is represented by the walls of the “Passetto”, whose developed crack pattern due to the in-plane shear stresses was significantly influenced by the in-shape irregularity. On the other hand, the “weight” of the masonry organization in the analyzed failures was rated low for the majority of cases—14 occurrences equal to about 87% of the total (16).

Table 5. SPW with respect to the macro-element and the detected damage mode.

| Church                                         | Damage               | Macro-Element | Geometrical Features | Boundary Condition                | Masonry Features |
|-----------------------------------------------|----------------------|---------------|----------------------|-----------------------------------|-----------------|
| Santi Niccolò e Biagio Cathedral;             | Keystone cracks      | Nave vault    | MEDIUM               | HIGH (due to past interventions)  | LOW             |
| Santi Niccolò e Biagio Cathedral              | Crushing mechanism   | Pier triumphal arch | MEDIUM               | HIGH (due to past interventions)  | LOW             |
| Cappella dell’Assunta; San Francesco di Paola | Keystone cracks      | Nave vault    | LOW                  | LOW                               | LOW             |
| Madonna di Costantinopoli                     | In plane Shear cracks| Triumphal arch| LOW                  | LOW                               | LOW             |
| S. Maria della Consolazione “Passetto”        | Hammering            | Nave wall     | LOW                  | MEDIUM                           | LOW             |
| Sant’Agostino                                 | In plane Shear cracks| Walls        | HIGH                 | HIGH                             | HIGH            |
|                                               | In plane Shear cracks| Façade       | MEDIUM               | HIGH                             | HIGH            |
5. Conclusions

The presented rapid visual screening of masonry monuments has permitted one to analyze the seismic performance of historical buildings.

The study herein has provided an extensive review of damage originated by the earthquake of 24 February 2020, which caused light accelerations to buildings. However, it is appropriate to take into account the possibility that near-field effects occurred, which gave the churches high horizontal and vertical accelerations.

The damage has been described in its cause and effects, correlating them to the main factors that influence the seismic response of the building (masonry organization, geometrical configuration; boundary conditions; seismicity of the location, etc.). For this purpose, a parameter defined SPW (seismic parameter weight) has been ideated. It summarizes, in a rapid evaluation, the degree of influence of each analyzed factor on the recorded damage mechanism.

The study, despite neglecting an important key factor—i.e., in-depth analysis on any site effects—has the merit of producing reliable results in a much simpler and faster way than the time-consuming dynamic analysis.

Such a hermeneutic of the monument’s failures represents a source of learning of the behavior of the walls under earthquake excitations, which is extremely useful in planning correct and appropriate seismic improvement interventions.

The analysis performed, which finds evident limits in the qualitative character, highlighted deformations and widespread cracks in the investigated churches. These are deformation and cracking patterns, however, that are, in general, not alarming as they have not triggered kinematics that can lead in a short time to the collapse of the structures. In any case, stucco falls and partial detachments of various layers of the plaster have occurred and it cannot be excluded that other portions of the decorative apparatus are in unstable equilibrium and therefore close to collapse. In this regard, checks are in progress at the date of writing of the article.

The data deriving from the rapid visual screening led one to evaluate that the geometric characteristics had a “medium” influence degree on the detected damage. From the conducted analysis, it seems evident that the quality of the masonry is a prevalent factor for the shear mechanisms (e.g., in plane cracks in the Sant’Agostino’s facade and in the...
walls of the Passetto) as well as for the crushing phenomena in the pillars of the Cathedral and in the Santi Niccolò e Biagio church.

The reading and interpretation of the damage presented in the study reiterated, beyond all reasonable doubt, show that the grafting of “heavy” technologies into the ancient organism, alien to the masonry technique—for mechanical response and chemical compatibility—involves a detriment, in general, of the structural performance, even in the event of light seismic excitation. In fact, some “strengthening” solutions, belonging in some cases to modern serialized construction, have contributed significantly to the observed crack pattern. From this, unfortunately, we must note that the bitter affirmation of Franco Braga [46] of the end of the 1980s is very topical: “I terremoti sono perniciosi per il patrimonio monumentale italiano, non tanto per l’eccezionalità dei danni prodotti, quanto per il numero ed il tipo di interventi di riparazione e adeguamento antisismico che ad essi hanno fatto seguito” (“Earthquakes are pernicious for the Italian monumental heritage, not so much for the exceptionality of the damage produced, as for the number and type of repairs and anti-seismic interventions that followed them”).

Strengthening devices, on the other hand, such as ties, have limited—for the wattle vaults—the deformability of the perimeter support, preventing the failure.

Furthermore, it is worth underlining the fact that an ancient structure represents an invention product, identifying a precise construction culture, unrepeatable and connoting the monument [47]. Some of the recent interventions, far from the fundamental principle of minimal intervention, in addition to the loss of the original material, have tampered with the load-bearing organism as it was conceived ab initio, hence the irreversible loss of value of the monument.

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