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An Evaluation of the Structural Behaviour of Historic Buildings Under Seismic Action: A Multidisciplinary Approach Using Two Case Studies

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Abstract: The evaluation of the structural behaviour of iconic historic buildings represents one of the most current structural engineering research topics. However, despite the various research works carried out during recent decades, several issues still remain open. One of the most important aspects is related to the correct reconstruction of the complex geometries that characterise this type of construction and that influence structural behaviour, especially in the presence of the horizontal loads caused by seismic action. For these reasons, different techniques have been proposed based on the use of laser scanners, Unmanned Aerial Vehicles (UAVs), and terrestrial photogrammetry. At the same time, several analysis methods have been developed that include the use of linear and non-linear approaches. In this present paper, the seismic performance of the Santa Maria Novella basilica and Santa Maria di Collemaggio basilica (before the partial collapse due to the 2009 L'Aquila earthquake) were investigated in detail by means of several numerical analyses. In particular, a series of non-linear time history analyses (NTHAs) were carried out, as reported in the Italian Building Code. To represent the non-linear behaviour of the main structural elements, smeared cracking (CSC) constitutive law was adopted. The geometry of the structures was reconstructed from a complete laser scanner survey of the churches, in order to consider all the intrinsic irregularities that characterise the heritage buildings. Finally, a comparison between the structural behaviour of the two case studies was carried out, highlighting the differences and similar aspects, focusing on possible collapse mechanisms and the identification of the most critical structural elements represented, in both cases analysed, by the main pillars of the transept.

Keywords: cultural heritage; seismic vulnerability; geometry reconstruction; non-linear analyses

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1. Introduction

The importance of rehabilitating and preserving iconic historic structures has led to an ever-growing focus on developing new structural analysis techniques based on a multidisciplinary approach [1–4]. One of the most important aspects that influences the evaluation of the structural performance of historic buildings is represented by the correct geometry reconstruction. In fact, during the last decades, several approaches have been proposed based on the use of laser scanners [5–7], Unmanned Aerial Vehicles [8,9], and terrestrial photogrammetry [10,11], with which it is possible to determine all the intrinsic irregularities characterising the structural elements geometry of historic buildings. Moreover, most of these buildings are in seismic-prone zones and are constructed with ancient unreinforced masonry (URM) using various construction techniques [12–14]. In particular, religious architecture, such as cathedrals, monasteries, and churches, represents a significant portion of heritage buildings, which are characterised by a high level of seismic vulnerability. Focusing attention on Italian historic buildings, many of them have suffered significant damage during recent strong seismic events, such as the 2009 L'Aquila earthquake, when

170 out of 240 monuments showed important damage or partial failure [15]. In fact, this type of building is generally characterised by a complex structural configuration due to the presence of several open spaces and slender walls and the absence of stiffening floors. A further crucial factor influencing the structural behaviour of historic constructions is the quality of the materials used, especially for masonry that has deteriorated over time. This deterioration leads to a reduction in the mechanical properties of the material, which, in turn, leads to a decline in the structural performance of the main elements, both under static and dynamic loads. Furthermore, several useful approaches for evaluating the structural behaviour of URM buildings have been proposed [16]. In fact, considering that masonry is a composite structural material made of blocks (natural or artificial) assembled with layers of mortar or dry joints, the correct modelling of its structural behaviour is challenging, due to several aspects, such as anisotropy, heterogeneity, etc. For these reasons, different methodologies have been presented in the scientific literature [17]. Nevertheless, the use of refined models that are capable of taking into account all these aspects is limited in design practice, where the application of simplified approaches is more common. In general, these approaches are based on the schematization of the main structural elements by means of macroelements, in order to reduce the computational effort. Nowadays, in common practice, pushover analysis is combined with simplified structural models based on the macroelements approach. One of the most used modelling strategies is represented by the Equivalent Frame Method (EFM), which is widely adopted for the evaluation of the seismic performance of URM buildings with regular geometry. In this method, the macroelements are used to discretise walls as an assemblage of piers, spandrels, and rigid nodes. However, the EFM is characterised by strongly simplified hypotheses and several limitations.

During recent years, several approaches have been proposed for the evaluation of the seismic performance of existing URM constructions. Masciotta and Lourenço [18] have analysed the seismic performance of slender masonry structures, considering different methods and highlighting their advantages and related limitations. In Valente et al. [19], an advanced numerical insight for the evaluation of the seismic behaviour of two row housing compounds was carried out by means of the implementation of several finite element models. Among the wide range of analysis methods, numerical approaches stand out for their diffusion. In fact, the finite element method, combined with non-linear techniques, represents one of the most used approaches, in particular to perform the structural analysis of complex structures.

In this paper, the seismic performances of two iconic historic churches—(i) the Santa Maria Novella basilica in Florence and (ii) the Santa Maria di Collemaggio basilica in L'Aquila (before the partial collapse that occurred during the 2009 seismic event)—were analysed. Starting from the geometry models that were reconstructed from complete laser scanner surveys, finite element models were implemented to perform the structural analyses. The findings from the two different churches were compared in order to identify the similarities between them, considering their characteristic structural configurations.

2. Case Studies

2.1. Basilica of Santa Maria Novella

The basilica of Santa Maria Novella is one of the most iconic historic churches in Italy, located in Florence in close proximity to the square bearing the same name (Figure 1). It was the first basilica to be built in Florence characterised by elements of the Gothic style.

As can be observed in Figure 2, the church underwent a series of modifications that affected its main structural elements, resulting in significant alterations to its original configuration. The basilica's current cross-shaped plan is 99.20 m long and 28.20 m wide and has a maximum transversal size of 61.54 m at the transept (Figure 3a). In the longitudinal direction, the church features three aisles with varying spans between columns (Figure 3b).

The nave is characterised by a height of 30.00 m and a width of 12.00 m. The aisles are 6.00 m wide and 20.00 m high. The pointed arches, which support a series of ribbed vaults, stand on columns made of stone with varying cross sections. These columns are used to hold up the vaults of the nave and of the aisles, which are located at a different height. The maximum height of the nave stone columns is equal to 15.00 m, while the columns positioned in correspondence to the aisles have a maximum height of 9.00 m. The transept presents three spans, with a central square apse and lateral minor chapels.

Figure 1. Santa Maria Novella basilica.

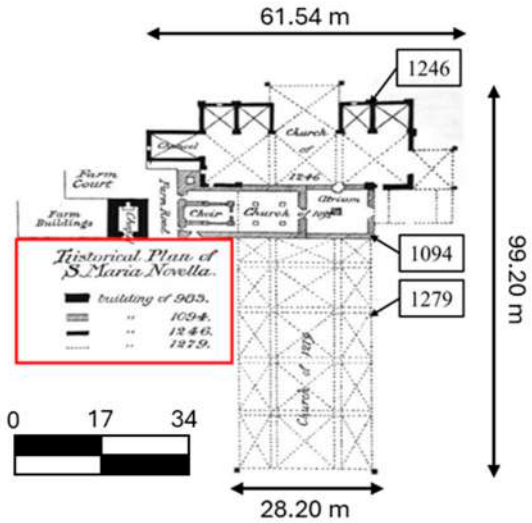
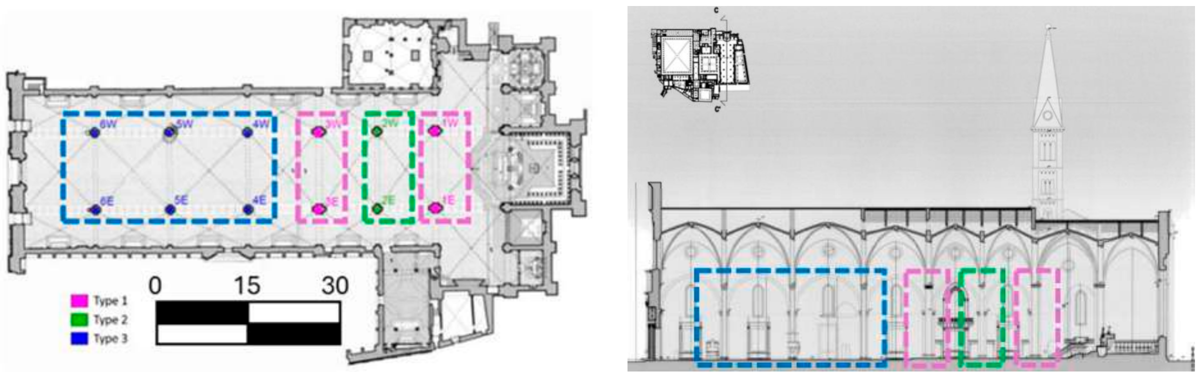


Figure 2. Florence, basilica of Santa Maria Novella. Evolution of its layout [20].



(**a**) (**b**)

Figure 3. Florence, basilica of Santa Maria Novella. (**a**) Plan; and (**b**) longitudinal section [20].

The longitudinal walls along the aisles show a series of lancet windows and but-tresses. Furthermore, the church is characterised by the presence of three different types of stone column. The first has an asymmetric cruciform cross section, with the maximum size orientated along the longitudinal direction of the church (referred to as Type 1 in Figure 3). The second and the third (referred to as Types 2 and 3 in Figure 3, respectively) have a polylobate shape with different sizes.

2.2. Basilica of Santa Maria di Collemaggio

The basilica of Santa Maria di Collemaggio represents one of the most significant Italian historical monuments and, as a result, has been the subject of extensive research in recent years [21,22]. The church was built in the late 13th century by Pope Celestino V and originally exhibited the characteristics of Romanesque architecture. However, over the centuries, the construction process of the basilica has undergone various interventions, primarily due to the consequences of earthquake damage. The church is characterised by the presence of three naves, delineated by two columns of octagonal cross sections (Figure 4a).

(**a**)

(**b**)

Figure 4. Basilica of Santa Maria di Collemaggio. (**a**) Central nave; and (**b**) façade.

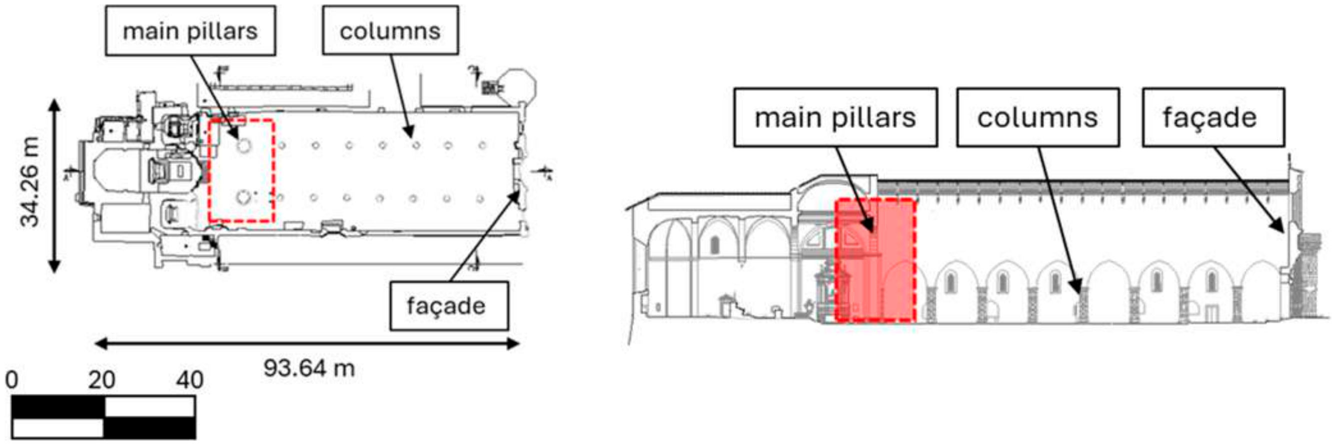
On the opposite side to the façade is the transept, which contains two chapels and a choir. A low dome covered by a wooden roof and entirely rebuilt in the 20th century is situated at the intersection between the transept and the central nave.

The two altars, located on either side of the transept, are characterised by stucco decoration on the walls, vaults, and chapels. These represent the final sections of the building that underwent baroque decoration, which was removed during the 1970s. The remaining parts of the basilica are characterised by bare walls and wooden trusses, which provide structural support for the wooden roof of the central nave and aisles.

One of the most important features of the basilica is its imposing two-tone façade (Figure 4b), as well as the tower, located on the right side of the façade, with an octagonal cross section. The church presents a cross-shaped plan with a length of 93.64 m, having a maximum transversal size equal to 34.26 m in correspondence to the transept (Figure 5).

The original layout of the church dates to the 13th century, but the construction process continued until the 16th century. During the 17th century, the basilica underwent significant alterations in response to the damage caused by the 1639 and 1654 earthquakes. These interventions encompassed not only the embellishment in a baroque style but also the enhancement of the seismic response of the main structural elements [23]. Of particular note are the following interventions: (i) the reduction in height of the aisle walls, and (ii) the enhancement of the interconnections between the various structural components (roof, vaults, walls, etc.).

The 1915 Fucino earthquake caused significant damage to the church, resulting in the partial collapse of the upper-left corner of the façade. Consequently, a new buttress was constructed in the corresponding location on the façade, with robust tie rods to prevent further out-of-plane movements. Moreover, to improve the out-of-plane stiffness, a new frame made of reinforced concrete (R.C.) was incorporated into the reconstruction of the upper-left corner of the façade.



(**a**) (**b**)

Figure 5. Basilica of Santa Maria di Collemaggio. (**a**) Plan; and (**b**) longitudinal section (before the partial collapse that occurred during the 2009 L'Aquila earthquake). The red dashed outline indicates the transept area that collapsed during the 2009 L'Aquila earthquake.

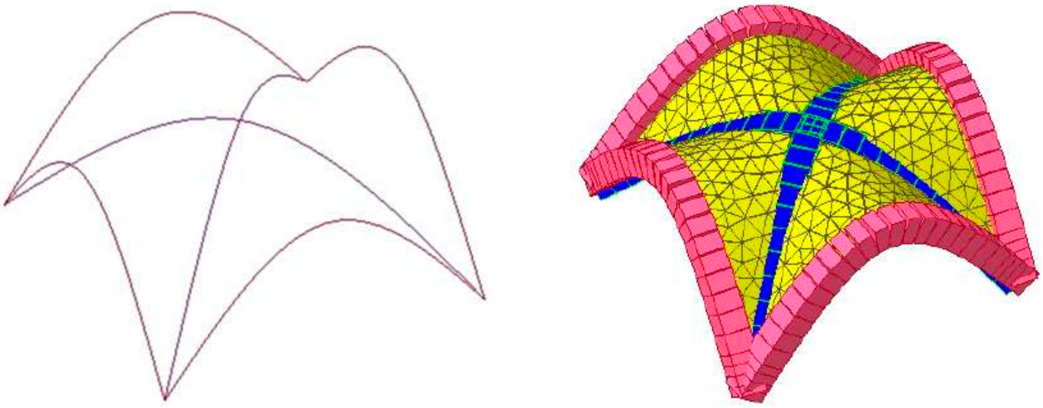
Subsequently, the basilica was subjected to a further seismic event in 1958. During this seismic event, the pre-existing cracks widened, particularly in correspondence to the transept dome, which was demolished and completely rebuilt using reinforced concrete. The remaining restoration interventions were completed during the 1970s. The baroque style decorations were removed. During the course of this operation, some of the principal original structural elements were revealed, while others were significantly altered compared to their original configuration. In particular, the cross section that characterised the main pillars of the transept was entirely modified, and the two last octagonal columns near the transept were rebuilt using reinforced concrete. The remaining masonry columns were modified, removing the 17th-century cruciform cover and revealing the original masonry structure. The longitudinal walls, already subject to the above-mentioned height reduction intervention, were raised through the construction of two new R.C. curbs positioned within the thickness of the walls.

As a consequence of the 1997 Umbria and Marche earthquake, further interventions were carried out to improve the seismic performance of the church: e.g., the reinforcement of the longitudinal walls. Furthermore, a new horizontal dissipation bracing system, composed of steel hysteretic dampers, was realised beneath a wooden roof [24,25]. The junctions between the buttress, the façade, and the longitudinal walls were enhanced. The masonry walls were reinforced through the implementation of drilling reinforced with steel bars and grout injections.

On 6 April 2009, the church was struck by the famous L'Aquila earthquake, which caused serious damage: the collapse of the transept (highlighted by the red dashed outline in Figure 5) involved the failure of the two main pillars, the triumphal arch, the dome, the barrel vaults, and part of the wooden roof structure. The reconstruction interventions were concluded in 2017 and involved the complete reconstruction of the transept area and the repair of the damage suffered by the columns [26–28]. It is important to note that the church configuration considered in this research is the one prior to the partial collapse that occurred during the 2009 L'Aquila earthquake. Consequently, the above-mentioned retrofitting interventions carried out after 2009 were not taken into account in the following structural analyses.

3. Geometry Reconstruction and FEM Implementation

The main structural elements with complex geometries in the two case studies were reconstructed from the 3D point cloud obtained from laser scanner surveys. In particular, the geometry of the basilica of Santa Maria di Collemaggio was reconstructed in line with the approach reported in [29–31]. Moreover, for the reconstruction of the geometry of the basilica of Santa Maria Novella, the laser scanner used was a Leica HDS 7000. Due to the complexity of the case studies, several scans were required to fully reconstruct the structures. The scan quality was set to medium (3×), with a resolution of 1 pt per 12.27 mm at 10 m. The TLS scans were processed using the Reconstructor software, version 4.4.2., with the Iterative Closest Point (ICP) algorithm [32]. Particular attention was devoted to the definition of the vaults, and the domes' correct geometries were reproduced by means of the contour-level curves (Figure 6a) that define the related surfaces (Figure 6b) [33]. The laser scanner's point clouds allowed for the accurate reconstruction of the main structural elements, taking into account the irregularities typical of historic buildings. These irregularities would not have been detectable using a standard geometric survey. This aspect is particularly important for the accurate definition of the seismic behaviour of such a structure.



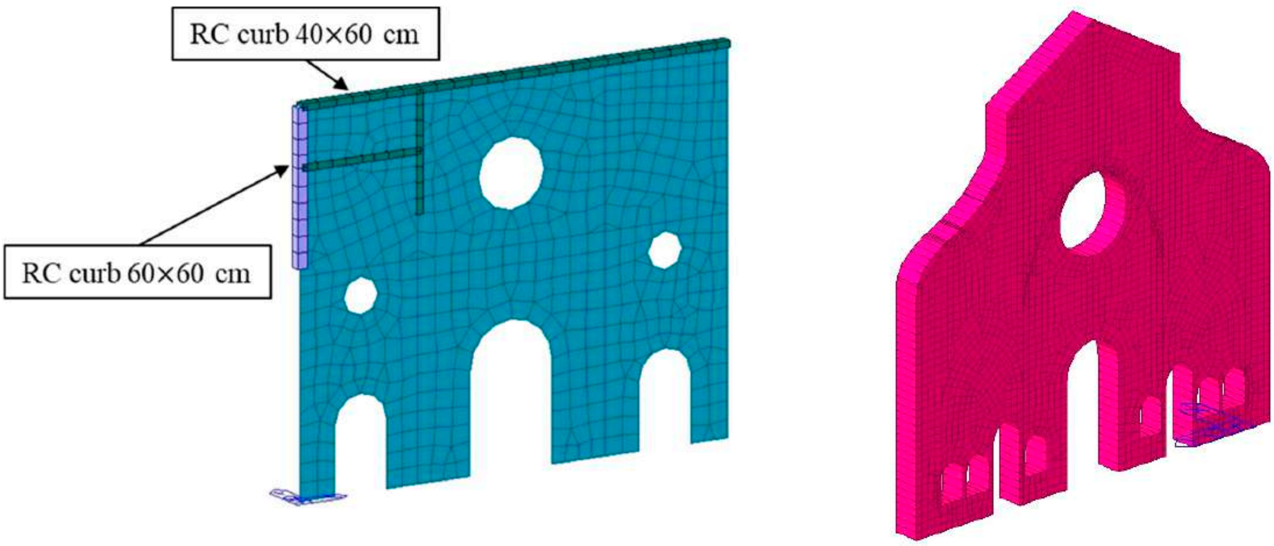
(**a**) (**b**)

Figure 6. Example of vault schematization: (**a**) polylines of sections obtained from the point cloud; and (**b**) surface of the vault.

Moreover, both churches present peculiar façades, not only in terms of their configuration but also due to the presence of multiple openings (Figure 7).

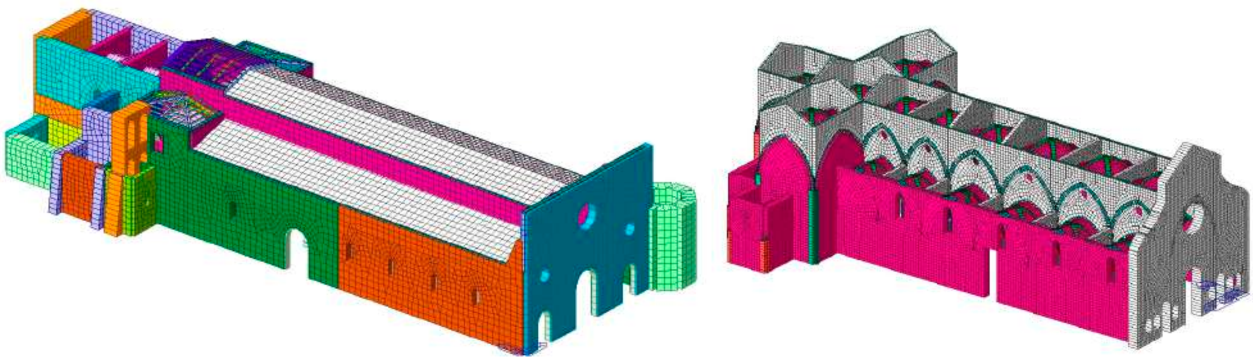
To evaluate the seismic performance of the two churches, finite element models (FEMs) were implemented based on the above-mentioned comprehensive geometry reconstructions [34–37]. In particular, the geometry of both basilicas was schematised by means of the beam elements to represent the main pillars of the transept, the columns, the arches, the R.C. curbs, the structure of the roof, and the plate elements to reproduce the structural behaviour of the façade, the walls, the vaults, and the domes (Figure 8). The mesh size (implemented in Midas GEN 2024 v2.1 software [38]) was adapted to reproduce as accurately as possible the geometric characteristics of the two basilicas, also considering the above-mentioned widespread presence of openings in the walls and in the façade. The FEM of the basilica of Santa Maria di Collemaggio was implemented using 3916 beam elements and 12,652 plate elements. The FEM of the basilica of Santa Maria Novella was schematised by means of 6949 beam elements and 69,330 plate elements.

The main mechanical properties of the materials (determined according to as reported in [39,40]) characterizing the two churches are summarised in Table 1, where E is the Young's modulus, ν is the Poisson's ratio, and γ indicates the weight density. When appropriate, the bending and shear stiffness of the main structural elements were reduced using the appropriate scale factors, calculated according to the method reported in [39], in order to consider the possible presence of cracks.



(a) (b)

Figure 7. Façade representation: (**a**) Santa Maria di Collemaggio; and (**b**) Santa Maria Novella.



(a) (b)

Figure 8. FEM of (**a**) Santa Maria di Collemaggio; and (**b**) Santa Maria Novella.

Table 1. Materials characteristics.

-	Material	E [MPa]	ν [-]	γ [kN/m^3]
Santa Maria di Collemaggio				
Transept pillars	Masonry	1600	0.2	18
Walls	Masonry	800–2000	0.2	18
Octagonal columns	Stone	20,000	0.2	22
Roof structure	Wood	10,000	0.2	5
R.C. curbs	Reinforced concrete	31,475	0.2	25
Steel bracing system	Steel	210,000	0.3	78.5
Santa Maria Novella				
Columns	Stone	4032	0.2	22
Arches	Stone	4032	0.2	22
Walls	Masonry	1230	0.2	20
Vaults	Masonry	1500	0.2	18

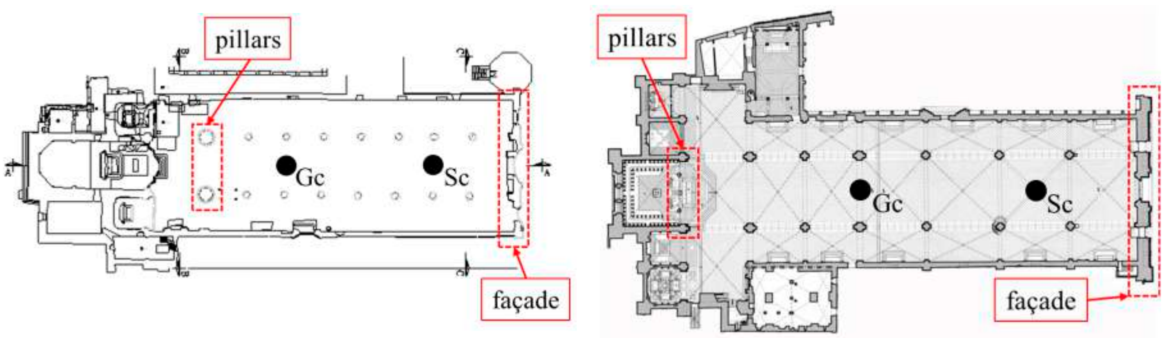
The self-weight of the different elements that characterise the churches and the dead loads, with the related masses, were applied to the FEMs shown in the previous Figure 8. The presence of seismic action was considered by means of seven spectrum-compatible accelerograms, selected from the PEER Ground Motion database [41,42]. Table 2 shows the main characteristics of the seismic records used in this research work.

Table 2. Main characteristics of the seismic signals.

Earthquake Name	Station	Year	Mw [-]
Santa Maria di Collemaggio			
Irpinia_Italy-01	Torre Del Greco	1980	6.90
Irpinia_Italy-02	Rionero In Vulture	1980	6.20
New Zealand-02	Matahina Dam	1987	6.60
Umbria Marche (aftershock 2)_Italy	Norcia	1997	5.60
Umbria Marche (aftershock 2)_Italy	Norcia-Zona Industriale	1997	5.60
L'Aquila_Italy	Celano	2009	6.30
L'Aquila (aftershock 1)_Italy	L'Aquila—Parking	2009	5.60
Santa Maria Novella			
Santa Barbara	Santa Barbara Courthouse	1978	5.92
Coyote Lake	Gilroy Array #6	1979	5.74
Mammoth Lakes-01	Long Valley Dam (Upr L Abut)	1980	6.06
Irpinia_Italy-01	Bagnoli Irpinio	1980	6.90
Irpinia_Italy-01	Brienza	1980	6.90
Irpinia_Italy-02	Rionero In Vulture	1980	6.20
Coalinga-01	Slack Canyon	1983	6.36

Both the FEMs were considered fixed at the base through the application of perfect restraints at the base node of each vertical structural element.

Analysing the structural configuration of the churches, it is possible to notice that both are characterised by the presence of a big eccentricity between the centre of gravity (G_c) and the stiffness centre (S_c) of the nave structures due to the significant difference in stiffness between the façade and the main pillars of the transept area (Figure 9).



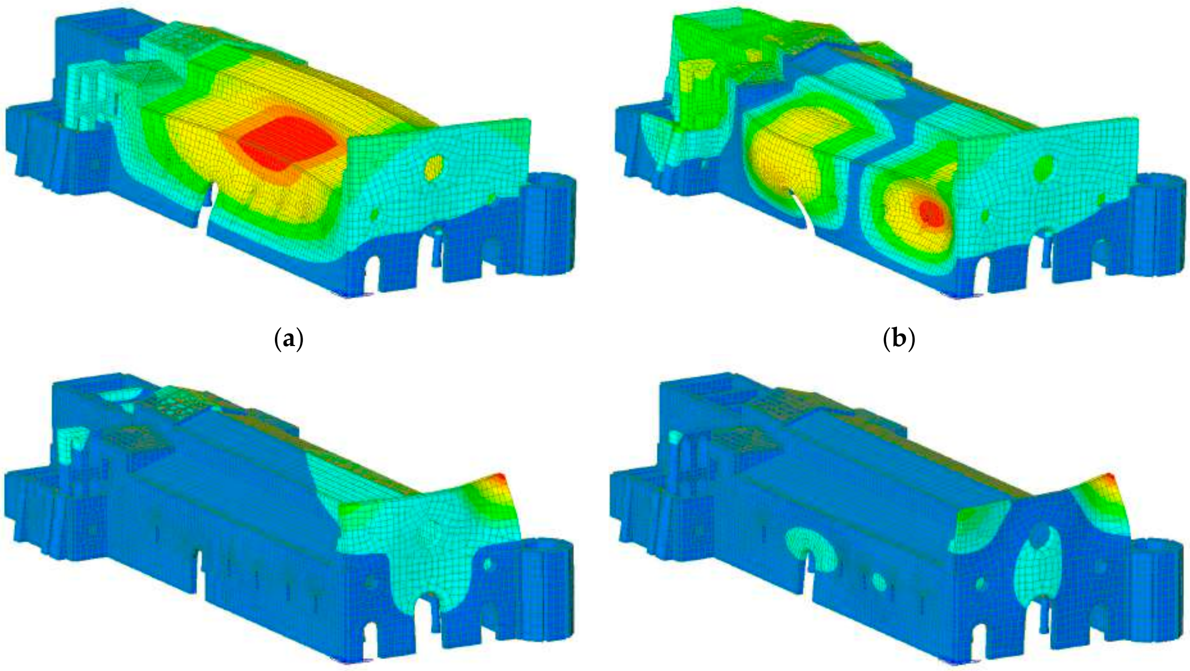
(**a**) (**b**)

Figure 9. Eccentricity between the gravity centre (G_c) and the stiffness centre (S_c): (**a**) Santa Maria di Collemaggio; and (**b**) Santa Maria Novella.

This condition leads to strong torsional effects resulting in a significant increase in the shear forces acting on the transept main pillars when the structure is subjected to seismic action. In fact, this aspect was the main cause of the collapse mechanism that involved the transept area of the Santa Maria di Collemaggio during the 2009 L'Aquila earthquake [43].

4. Numerical Analysis

To evaluate the dynamic behaviour of the two churches, an Eigenvalue analysis was carried out in order to obtain the fundamental natural periods and the related vibration mode shapes. Figures 10 and 11 report the four main vibration mode shapes that characterise the dynamic behaviour of Santa Maria di Collemaggio and Santa Maria Novella, respectively, where MT indicates the participating mass in the transverse direction and ML is the participating mass in the longitudinal direction.



(**a**) (**b**) (**c**) (**d**)

Figure 10. Main fundamental vibration periods for Santa Maria di Collemaggio: (**a**) mode 1, period: 0.674 s, MT = 37.49%, and ML = 0.00%; (**b**) mode 4, period: 0.400 s, MT = 14.43%, and ML = 0.04%; (**c**) mode 10, period: 0.318 s, MT = 0.19%, and ML = 32.79%; and (**d**) mode 13, period: 0.290 s, MT = 0.53%, and ML = 10.68%.

The results obtained from the Eigenvalue analysis show a complex dynamic behaviour that affects both churches, with the total participating mass being divided into several modes. In fact, considering what is shown in Figures 10 and 11, it is possible to notice that only mode 4, which characterises the dynamic behaviour of Santa Maria Novella, presents a participating mass greater than 50%, while mode 1 for Santa Maria di Collemaggio involves about 34% of the total mass of the church. However, it is important to highlight that mode 1 for both basilicas exhibits a vibration mode shape that involves the nave structures.

To evaluate the seismic performance of the two churches, a series of non-linear time history analyses (NTHAs) were carried out using the seismic records reported in Table 2 and considering the approach proposed in [39]. The non-linear behaviour of the masonry materials used in the walls, domes, vaults, and triumphal arches (implemented in the FEMs as plate elements) was introduced by means of the concrete smeared cracking (CSC) constitutive law [44,45]. The adopted parameters, calculated according to the method reported in [46], are outlined in Table 3, where f_c is the compressive strength; G_c is the compressive fracture energy; h is the average size of the elements; f_t is the tensile strength; and G_f^t is the fracture energy, which regulates the tensile behaviour.

Figure 12 reports the compressive and tensile non-linear behaviours adopted for the CSC approach. To take into account the shear behaviour, a linear model was considered using a shear reduction factor β = 1. For the columns and the main pillars (introduced in the FEMs using beam elements), appropriate concentrated plastic hinges located at the base and at the top of the elements were used [47].

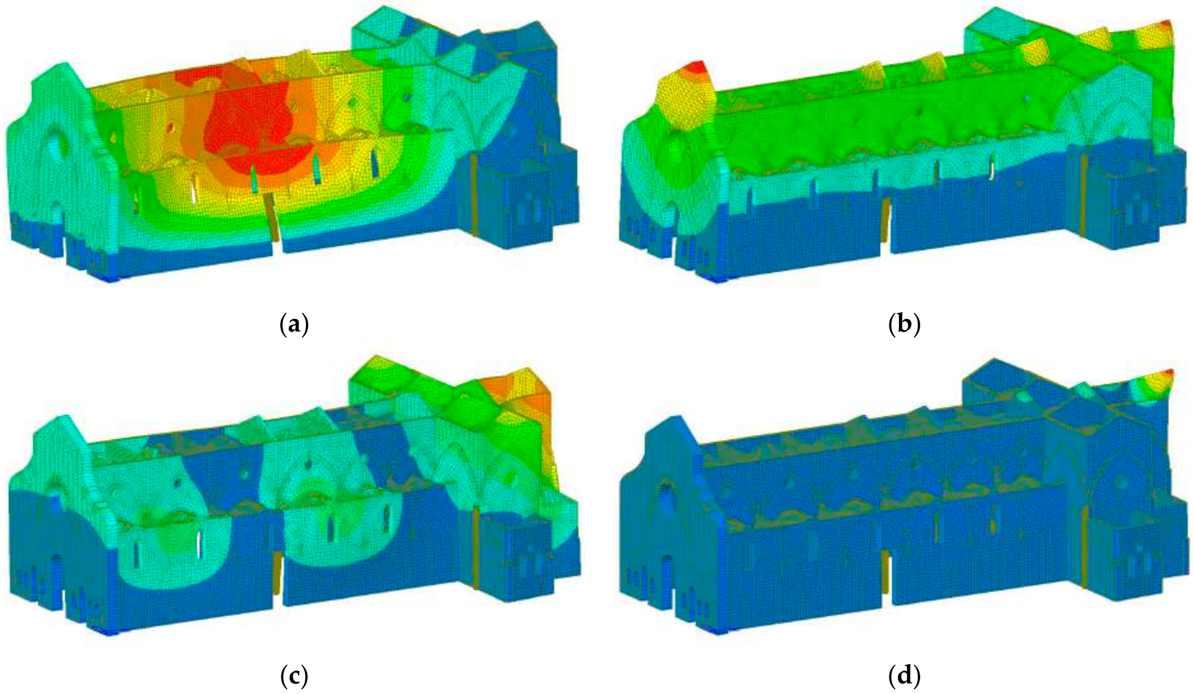


Figure 11. Main fundamental vibration periods for Santa Maria Novella: (**a**) mode 1, period: 0.896 s, MT = 44.14%, and ML = 0.00%; (**b**) mode 4, period: 0.525 s, MT = 0.00%, and ML = 58.64%; (**c**) mode 5, period: 0.475 s, MT = 21.77%, and ML = 0.00%; and (**d**) mode 11, period: 0.341 s, MT = 0.00%, and ML = 1.58%.

Table 3. CSC parameters.

-	f_c [MPa]	G_c [N/mm]	h [mm]	f_t [MPa]	G_f^t [N/mm]
			Santa Maria di Collemaggio		
Walls	1.25	0.1	300	0.15	0.1
Vaults	1.67	0.1	300	0.15	0.1
			Santa Maria Novella		
Columns	3.86	0.1	300	0.30	0.1
Arches	3.86	0.1	300	0.30	0.1
Walls	1.07	0.1	300	0.10	0.1
Vaults	1.07	0.1	300	0.10	0.1

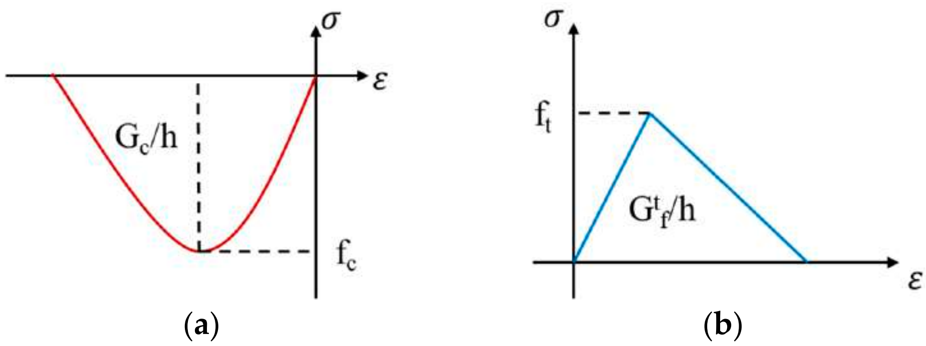


Figure 12. (**a**) Compressive and (**b**) tensile non-linear behaviour function of CSC constitutive law.

The seismic vulnerability was quantified through risk indices defined as the ratio between the value of the peak ground acceleration that leads to the collapse of the first structural elements (PGA_C) and the design peak ground acceleration (PGA_D) calculated as reported in [39] considering the life safety limit state:

$$RI = \frac{PGA_C}{PGA_D} \tag{1}$$

The failure mechanism in both churches involves the two main pillars of the transept as the first elements reaching collapse. This is due to the presence of a high eccentricity between the gravity centre and stiffness centre, shown in detail in Figure 9, which causes a torsional effect and a consequent increase in the shear force acting at the base of the main pillars of the transept. It is important to highlight that the above-described collapse mechanism is what affected the Santa Maria di Collemaggio during the 2009 L'Aquila earthquake, which caused the failure of the transept area. Table 4 reports the value of the risk indices obtained from the execution of the non-linear time history analyses.

Table 4. Risk indices obtained from the execution of the non-linear time history analyses.

PGA_C [g]	PGA_D [g]	RI [-]
	Santa Maria di Collemaggio	
0.075	0.261	0.287
	Santa Maria Novella	
0.059	0.221	0.267

The risk indices obtained from the non-linear dynamic analyses are characterised by values less than 1, which demonstrates how such structures are not adequate to resist the design of seismic action defined by the Italian Building Code [39]. Furthermore, it is possible to notice that both the risk indices obtained are characterised by values less than 0.3, indicating the high seismic vulnerability of the transept main pillars of both churches, due to the mechanical characteristics of the quasi-brittle masonry material.

As reported in the previous Section 3, the obtained results have demonstrated the high seismic vulnerability of the analysed case studies. Moreover, several aspects that define the seismic performance of the two churches appear similar. In fact, it is possible to notice that the vibration mode shape of mode 1, which characterised the dynamic behaviour of both churches, shown in Figures 10a and 11a, is in the transverse direction and mainly involves the nave structure with participating masses equal to 37.49% and 44.14% for Santa Maria di Collemaggio and Santa Maria Novella, respectively. Furthermore, both the case studies are characterised by first fundamental natural periods less than 1 s due to their structural configuration and the presence of stiff vertical elements, such as the walls and the façade. These aspects significantly influence the formation of the collapse mechanism under seismic action, described in detail in the previous Sections 3 and 4, which characterises both Santa Maria di Collemaggio and Santa Maria Novella. In particular, the results of the non-linear time history analysis have highlighted that the most critical elements are the main pillars of the transept, as also demonstrated by the partial collapse that affected Santa Maria di Collemaggio during the 2009 L'Aquila earthquake. Furthermore, it is possible to notice that the observed collapse mechanism, which is strictly related to the load-bearing capacity of the vertical structural elements, such as the nave columns and the main pillars of the transept, could potentially occur in any church with a similar structural configuration to the two analysed case studies. Indeed, the significant eccentricity value between the gravity centre and the stiffness centre, combined with the greater stiffness of the transept pillars in comparison to the nave columns, leads to a significant increase in the shear forces acting at the base of the pillars when the structure is subjected to seismic action.

Moreover, the low values of the risk indices, obtained by considering the peak ground acceleration, which could potentially lead to the collapse of the main pillars of the transept, are in part due to the poor mechanical properties of the masonry.

5. Conclusions

In this paper, a multidisciplinary approach useful for the evaluation of the seismic performance of historic constructions characterised by complex geometries is discussed. In particular, two iconic case studies located in different areas of Italy were analysed: (i) the basilica of Santa Maria di Collemaggio; and (ii) the basilica of Santa Maria Novella in Florence. The starting point of the project involved the reconstruction of their geometry based on the data obtained from a series of complete laser scanner surveys. Subsequently, finite element models of the two churches were developed using plate elements to represent the walls, the façades, the vaults, the dome, and the beam elements to schematise the main pillars of both the transept area and the nave columns. An Eigenvalue analysis was performed to define the dynamic behaviour of the basilicas. This analysis has revealed that the vibration mode shapes of the main fundamental natural periods are analogous between the two case studies. This phenomenon can be attributed to their structural configurations: both exhibit a significant eccentricity between the gravity centre and the stiffness centre, resulting in the presence of torsional effects.

To evaluate the seismic vulnerability of the two churches, a series of non-linear time history analyses were carried out using seven spectrum-compatible accelerograms obtained from the PEER database and considering the approach reported in [39]. The obtained results were quantified by means of risk indices defined by the ratio between the value of the peak ground acceleration that leads to the collapse of the first monitored structural elements and the design peak ground acceleration calculated as reported in [33] for the life safety limit state. Both the case studies were characterised by risk index values less than 1 (0.287 for Santa Maria di Collemaggio and 0.267 for Santa Maria Novella), which highlights the high seismic vulnerability of the two buildings.

According to the considerations on the basilicas' structural configurations, the first elements to collapse are the main pillars of the transept area. This hypothesis is supported by the partial collapse observed at Santa Maria di Collemaggio during the 2009 L'Aquila earthquake.

Finally, it is important to highlight that the collapse mechanism observed in the two case studies can apply to all historic churches with a similar structural layout. This is due to the presence of a significant eccentricity between the gravity centre and the stiffness centre. This aspect can be useful for planning the correct structural interventions to improve the seismic performance of historic churches while taking care not to develop collapse mechanisms in other structural elements, such as the façade or the nave columns.

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References

1. Milani, G. Lesson learned after the Emilia-Romagna, Italy, 20–29 May 2012 earthquakes: A limit analysis insight on three masonry churches. *Eng. Fail. Anal.* **2013**, *34*, 761–778. [CrossRef]
2. Jain, A.; Acito, M.; Chesi, C. Seismic sequence of 2016–17: Linear and non-linear interpretation models for evolution of damage in San Francesco church, Amatrice. *Eng. Struct.* **2020**, *211*, 110418. [CrossRef]

3. Cianchino, G.; Masciotta, M.G.; Verazzo, C.; Brando, G. An Overview of the Historical Retrofitting Interventions on Churches in Central Italy. *Appl. Sci.* **2023**, *13*, 40. [CrossRef]
4. Barazzetti, L.; Banfi, F.; Brumana, R.; Gusmeroli, G.; Previtali, M.; Schiantarelli, G. Cloud-to-BIM-to-FEM: Structural simulation with accurate historic BIM from laser scans. *Simul. Model. Pract. Theory* **2015**, *57*, 71–87. [CrossRef]
5. Jafaar, H.A.; Meng, X.; Sowter, A.; Bryan, P. New approach for monitoring historic and heritage buildings: Using terrestrial laser scanning and generalised Procrustes analysis. *Struct. Control Health Monit.* **2017**, *24*, e1987. [CrossRef]
6. Balado, J.; Frias, E.; Gonzalez-Collazo, S.M.; Diaz-Vilarino, L. New Trends in Laser Scanning for Cultural Heritage. *Lect. Notes Civ. Eng.* **2022**, *258*, 167–186.
7. Moyano, J.; Justo-Estebaranz, A.; Nieto-Julián, J.E.; Ojeda Barrera, A.; Fernández-Alconchel, M. Evaluation of records using terrestrial laser scanner in architectural heritage for information modeling in HBIM construction: The case study of the La Anunciación church (Seville). *J. Build. Eng.* **2022**, *62*, 105190. [CrossRef]
8. Stek, T.D. Drones over Mediterranean landscapes. The potential of small UAV's (drones) for site detection and heritage management in archaeological survey projects: A case study from Le Pianelle in the Tappino Valley, Molise (Italy). *J. Cult. Herit.* **2016**, *22*, 1066–1071. [CrossRef]
9. Khelifi, A.; Ciccone, G.; Altaweel, M.; Basmaji, T.; Ghazal, M. Autonomous Service Drones for Multimodal Detection and Monitoring of Archaeological Sites. *Appl. Sci.* **2021**, *11*, 10424. [CrossRef]
10. Kinglsland, K. Comparative analysis of digital photogrammetry software for cultural heritage. *Digit. Appl. Archaeol. Cult. Herit.* **2020**, *18*, e00157.
11. Arias, P.; Herraez, J.; Lorenzo, H.; Ordonez, C. Control of structural problems in cultural heritage monuments using close-range photogrammetry and computer methods. *Comput. Struct.* **2005**, *83*, 1754–1766. [CrossRef]
12. Binda, L.; Saisi, A. Research on historic structures in seismic areas in Italy. *Prog. Struct. Eng. Mater.* **2005**, *7*, 71–85. [CrossRef]
13. Formisano, A.; Milani, G. Seismic vulnerability analysis and retrofitting of the SS. Rosario church bell tower in Finale Emilia (Modena, Italy). *Front. Built Environ.* **2019**, *28*. [CrossRef]
14. Lagomarsino, S.; Cattari, S. Perpetuate guidelines for seismic performance-based assessment of cultural heritage masonry structures. *Bull. Earthq. Eng.* **2015**, *13*, 13–47. [CrossRef]
15. Brandonisio, G.; Lucibello, G.; Mele, E.; De Luca, A. Damage and performance evaluation of masonry churches in the 2009 L'Aquila earthquake. *Eng. Fail. Anal.* **2013**, *34*, 693–714. [CrossRef]
16. D'Altri, A.M.; Sarhosis, V.; Milani, G.; Rots, J.; Cattari, S.; Lagomarsino, S.; Sacco, E.; Tralli, A.; Castellazzi, G.; de Miranda, S. Modeling strategies for the computational analysis of unreinforced masonry structures: Review and classification. *Arch. Comput. Methods Eng.* **2020**, *27*, 1153–1185. [CrossRef]
17. Sacco, E.; Addessi, D.; Sab, K. New trends in mechanics of masonry. *Meccanica* **2018**, *53*, 1565–1569. [CrossRef]
18. Masciotta, M.G.; Lourenço, P. Seismic analysis of slender monumental structures: Current strategies and challenges. *Appl. Sci.* **2022**, *12*, 7340. [CrossRef]
19. Valente, M.; Milani, G.; Grande, E.; Formisano, A.A. Historical masonry building aggregates: Advanced numerical insight for an effective seismic assessment on two row housing compounds. *Eng. Struct.* **2019**, *190*, 360–379. [CrossRef]
20. Meschieri, M. Indagini Strutturali Sullo Stato Tenso-Deformativo e Sulle Cause dei Dissesti Della Basilica di Santa Maria Novella in Firenze Mediante un Modello ad Elementi Finiti 3D. Master's Thesis, Politecnico di Milano, Milan, Italy, 2016.
21. Antonacci, E.; Beolchini, G.C.; Di Fabio, F.; Gattulli, V. Retrofitting effects on the dynamic behaviour of S.Maria di Collemaggio. *Comput. Eng.* **2001**, *30*, 479–488.
22. Ranalli, D.; Scozzafava, M.; Tallini, M. Ground penetrating radar investigations for the restoration of historic buildings: The case study of the Collemaggio Basilica (L'Aquila, Italy). *J. Cult. Herit.* **2004**, *5*, 91–99. [CrossRef]
23. Arcidiacono, V.; Gimellaro, G.P.; Ochsendorf, J.A. Analysis of the failure mechanisms of the basilica of Santa Maria di Collemaggio during 2009 L'Aquila earthquake. *Eng. Struct.* **2015**, *99*, 502–516. [CrossRef]
24. Cartapati, E. Discussion 2 on "Introspection on improper seismic retrofit of Basilica Santa Maria di Collemaggio after 2009 Italian earthquake" by G.P. Cimellaro, A.M. Reinhorn and A. De Stefano. *Earthq. Eng. Eng. Vib.* **2012**, *11*, 291–292. [CrossRef]
25. Ciampi, V. Discussion 1 on "Introspection on improper seismic retrofit of Basilica Santa Maria di Collemaggio after 2009 Italian earthquake" by G.P. Cimellaro, A.M.Reinhorn and A. De Stefano. *Earthq. Eng. Eng. Vib.* **2012**, *11*, 281–282. [CrossRef]
26. Crespi, P.; Franchi, A.; Giordano, N.; Scamardo, M.; Ronca, P. Structural analysis of stone masonry columns of the Basilica S. Maria di Collemaggio. *Eng. Struct.* **2016**, *129*, 81–90. [CrossRef]
27. Zucca, M.; Franchi, A.; Crespi, P.; Longarini, N.; Ronca, P. The new foundation system for the transept reconstruction of the basilica di collemaggio. In Proceedings of International Masonry Societies Conferences, Proceedings of the 10th International Masonry Conference 2018, Milan, Italy, 9–11 July 2018; IMC: Milan, Italy, 2018; pp. 2441–2450.
28. Franchi, A.; Napoli, P.; Crespi, P.; Giordano, N.; Zucca, M. Unloading and reloading process for the earthquake damage repair of ancient masonry columns: The case of the Basilica di Collemaggio. *Int. J. Archit. Herit.* **2022**, *16*, 1683–1698. [CrossRef]
29. Brumana, R.; Della Torre, S.; Oreni, D.; Previtali, M.; Cantini, L.; Barazzetti, L.; Franchi, A.; Banfi, F. HBIM challange among the paradigm of complexity, tools and preservation: The basilica Di collemaggio 8 years after the earthquake (L'Aquila). In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, ISPRS Archives, Proceedings of the 26th International CIPA Symposium on Digital Workflows for Heritage Conservation 2017, Ottawa, ON, Canada, 28 August–1 September 2017*; CIPA: Ottawa, ON, Canada, 2017; Volume 42, pp. 97–104.

30. Oreni, D.; Brumana, R.; Della Torre, S.; Banfi, F. Survey, HBIM and conservation plan of a monumental building damaged by earthquake. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, ISPRS Archives, Proceedings of the 1st international Conference on Geomatics and Restoration: Conservation of Cultural Heritage in Digital Era, Florence, Italy, 22–24 May 2017*; GeoRes: Florence, Italy, 2017; Volume 42, pp. 337–342.
31. Brumana, R.; Della Torre, S.; Previtali, M.; Barazzetti, L.; Cantini, L.; Oreni, D.; Banfi, F. Generative HBIM modelling to embody complexity (LOD, LOG, LOA, LOI): Surveying, preservation, site intervention—The Basilica di Collemaggio (L'Aquila). *Appl. Geomat.* **2018**, *10*, 545–567. [CrossRef]
32. He, Y.; Liang, B.; Yang, J.; Li, S.; He, J. An iterative closest points algorithm for registration of 3D laser scanner point clouds with geometric features. *Sensors* **2017**, *17*, 1862. [CrossRef]
33. Brumana, R.; Condoleo, P.; Grimaldi, A.; Banfi, F.; Landi, A.G.; Previtali, M. HR LOD based HBIM to detect the influences on geometry and shape by stereotomic construction techniques of brick vaults. *Appl. Geomat.* **2018**, *10*, 529–543. [CrossRef]
34. Valente, M. Earthquake response and damage patterns assessment of two historical masonry churches with bell tower. *Eng. Fail. Anal.* **2023**, *151*, 107418. [CrossRef]
35. Page, A.W. Finite Element Model for Masonry. *ASCE J. Struct. Div.* **1978**, *104*, 1267–1285. [CrossRef]
36. Valente, M.; Milani, G. Seismic assessment of historical masonry towers by means of simplified approaches and standard FEM. *Constr. Build. Mater.* **2016**, *108*, 74–104. [CrossRef]
37. Zucca, M.; Reccia, E.; Longarini, N.; Cazzani, A. Seismic Assessment and Retrofitting of an Historical Masonry Building Damaged during the 2016 Centro Italia Seismic Event. *Appl. Sci.* **2022**, *12*, 11789. [CrossRef]
38. Midas GEN Analysis Reference, 2024. Available online: https://support.midasuser.com (accessed on 27 September 2024).
39. Decreto Ministeriale 17/01/2018, Ministero delle Infrastrutture e dei Trasporti, G.U. Serie Generale n.42 del 20/02/2018–S.O.8. Available online: https://www.gazzettaufficiale.it/eli/id/2024/07/05/24G00110/sg (accessed on 27 September 2024).
40. Circolare 21 Gennaio 2019, n. 7, Istruzioni per l'applicazione delle "Nuove Norme Tecniche per le Costruzioni". Available online: https://www.gazzettaufficiale.it/eli/id/2019/02/11/19A00855/sg (accessed on 27 September 2024).
41. Tropeano, G.; Soccodato, F.M.; Silvestri, F. Re-evaluation of code-specified stratigraphic amplification factors based on Italian experimental records and numerical seismic response analyses. *Soil Dyn. Earthq. Eng.* **2018**, *110*, 262–275. [CrossRef]
42. Goulet, C.A.; Kishida, T.; Ancheta, T.; Cramer, C.H.; Darragh, R.B.; Silva, W.J.; Hashash, Y.M.A.; Harmon, J.; Parker, G.A.; Stewart, J.P.; et al. PEER NGA-East database. *Earthq. Spectra* **2021**, *37*, 1331–1353. [CrossRef]
43. Gattulli, V.; Antonacci, E.; Vestroni, F. Field observation and failure analysis of the Basilica S. Maria di Collemaggio after the 2009 L'Aquila earthquake. *Eng. Fail. Anal.* **2013**, *34*, 715–734. [CrossRef]
44. Petrangeli, M.; Ožbolt, J. Smeared Crack Approaches—Material Modeling. *ASCE J. Eng. Mech.* **1996**, *122*, 545. [CrossRef]
45. Scamardo, M.; Zucca, M.; Crespi, P.; Longarini, N.; Cattaneo, S. Seismic vulnerability evaluation of a historical masonry tower: Comparison between different approaches. *Appl. Sci.* **2022**, *12*, 11254. [CrossRef]
46. Milosevic, J.; Lopes, M.; Gago, A.S.; Bento, R. Testing and modeling the diagonal tension strength of rubble stone masonry panels. *Eng. Struct.* **2013**, *52*, 581–591. [CrossRef]
47. Giordano, N.; Crespi, P.; Franchi, A. Flexural strength-ductility assessment of unreinforced masonry cross-sections: Analytical expressions. *Eng. Struct.* **2017**, *148*, 399–409. [CrossRef]