GIS-based Analysis for Seismic Vulnerability Assessment of Strengthened Masonry Churches: The Case of Parma (Italy)

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Abstract

Hazard mitigation and risk assessment for built heritage are central to contemporary conservation strategies, particularly in seismic-prone areas like Italy. This study presents preliminary findings of a research project focusing on the seismic vulnerability of historical masonry churches in the Province of Parma, a region with moderate seismic risk and a rich architectural heritage. Churches are among the most seismically vulnerable structures due to their complex construction, undocumented modifications, and sometimes ineffective past interventions. The research integrates GIS-based territorial analysis with archival investigation to evaluate the effectiveness of seismic strengthening measures implemented after the 1983 earthquake, especially in light of subsequent seismic events. A comprehensive database has been developed, cataloguing construction typologies, damage reports, and intervention strategies. Statistical and comparative analysis at both territorial and building scales helps assess the relationship between masonry characteristics, reinforcement techniques and seismic performance. Findings underscore the crucial role of past interventions in influencing current structural behaviour – sometimes positively, but also with unintended consequences. The study highlights the value of a multidisciplinary, data-driven approach combining digital tools and historical knowledge to support risk-informed conservation strategies. Ultimately, it aims to inform prioritization and planning frameworks that enhance the resilience of cultural heritage against future seismic events.

1. Introduction

In recent decades, the implementation of response strategies and mitigation measures to address the growing incidence and increasingly complexity of natural disasters has become a global priority of recent conservation policies for built heritage (UN/ISDR, 2005; UNESCO, 2010; UNDRR, 2015).
Within this framework, seismic risk reduction and structural vulnerability assessment emerged as key components (Sovel, 2005; Tandon, 2013). Seismic risk is indeed one of the most critical threats to historic structures, particularly in seismically active countries such as Italy, where moderate to high seismicity endangers an extraordinarily rich Cultural Heritage (CH) (Binda, 2006; Lagomarsino, 2006; Modena et al., 2011, Carocci et al., 2021).
Masonry churches are among the most vulnerable historical structures to seismic damage (Doglioni et al., 1994). This architectural typology displays intrinsic weaknesses and a recurrence of similar collapse mechanisms related to large masonry walls with limited transverse connections (façade, apse wall and triumphal arch). Furthermore, the absence of rigid, well-connected floor slabs combined with large, thrusting vaults and heavy roofs that are inadequately anchored to the walls significantly increases their vulnerability and encourages local out-of-plane collapse mechanisms (Blasi, 2013; De Matteis et al., 2019).
These vulnerabilities have been addressed through the implementation of seismic reinforcements during the original construction phases and subsequent retrofitting interventions. However, if these interventions are poorly designed or executed, they can introduce new weaknesses.
This issue is particularly relevant in light of the retrofitting practices used throughout the 20th century, when preference was given to steel and reinforced concrete techniques. Although were intended to enhance safety, these modern interventions, supported by structural mechanics (Marano, 2007; Rocchi, 2003) and disjointed from traditional construction principles and proportional design theories (Giannantoni, 2022; Como, et al., 2019), sometimes introduced new vulnerabilities, contributing to structural instability or even collapse (Bartolomucci, 2023a; Cifani et al., 2012).
Therefore, predicting the seismic response of historic buildings is inherently complex as it reflects the cumulative effects of their construction history related to architectural features and past interventions (Roca, 2005). This requires detailed knowledge of the building's current state to effectively reduce seismic vulnerability (Donatelli, 2017; Coïsson, 2019). Moreover, awareness of structural weaknesses previously identified in the same building type is also essential (Fiorani and Cacace, 2020). In light of this, a multi-scale approach that combines territorial assessment and building-specific analyses can support the development of effective, preventive risk mitigation strategies.
This is in line with international policies, which recognize that a comprehensive disaster risk information is essential for better risk-informed decision-making and investment. According to 'Priority for Action 1' of the Sendai Framework (UNDRR, 2015), it is crucial to strengthen the availability and use of data, analytical tools, and methodologies for conducting systemic risk assessments (UNDRR, 2022), at all levels, from global to local, in order to support the development of more accurate, high-quality and effective risk management strategies.
Several studies investigating the influence of architectural features and previous seismic retrofitting on the seismic response of architectural buildings have been carried out in Italy, focusing on central regions where recent seismic activity and architectural fragility intersect (Doglioni, 2000; Saretta et al., 2021; Valluzzi et al., 2021, Bartolomucci, 2023b).

However, northern Italy, particularly the Emilia-Romagna region, which is characterised by specific construction methods and architectural features (Grifoni, 2014), has also experienced several damaging earthquakes. Notably, even retrofitted masonry churches in this area have suffered significant damage in recent earthquakes (Di Francesco, 2014; Zanazzi and Leoni, 2024).
In this context, the present paper outlines the preliminary findings of ongoing research investigating the seismic vulnerability of historic masonry churches in the Province of Parma. The study focuses on churches affected by the 1983 earthquake, which was one of the most significant seismic events in Parma recent history (Di Pasquale, 1986).
The study assesses the relationship between architectural characteristics and the damage suffered on that occasion by combining GIS-based territorial analysis and archival documentation. Furthermore, the seismic reinforcement measures implemented after the 1983 earthquake are analysed to evaluate their effectiveness in the context of subsequent seismic events. Specifically, this paper focuses on out-of-plane failure mechanisms affecting church façades and perimeter walls. Case studies are presented to offer a critical comparison between observed damage, construction features, retrofitting interventions and contemporary standards.
The ultimate goal is to identify the key qualitative factors influencing the seismic response of previously reinforced religious buildings, thereby informing more effective, targeted seismic risk mitigation strategies. These findings aim to support the development of prioritised intervention frameworks and enhance the broader understanding of vulnerability in different architectural and territorial contexts.

2. Seismic Risk assessment of Historic Churches in Parma integrating Archival Data and GIS analysis

The seismic event on 9 November 1983 highlight the vulnerability of Parma's architectural heritage, particularly in the city centre, where many churches were damaged. The earthquake, estimated to have a magnitude of 5.4 on the Richter scale, occurred at an epicentre between Fornovo, Langhirano and Parma. Nevertheless, Parma experienced severe effects, with a macroseismic intensity of VII on the Mercalli scale (Di Pasquale, 1986).
Of the approximately 100 churches located within Parma's municipal boundaries, 44 lie within the historical city centre. Given the concentration and cultural value of these structures, it is essential to adopt an effective data management strategy. In this context, innovative tools such as Geographic Information Systems (GIS) are effective in collecting, organising, and analysing large volumes of data. GIS systems enable the integration, georeferencing and querying of extensive, heterogeneous datasets, thereby enhancing data interoperability and supporting the formulation of effective conservation and management strategies for more efficient, evidence-based interventions (Bartolomucci, 2023a; Fiorani and Cacace, 2020; Della Torre, S., 2022).
To assess the seismic vulnerability of these religious buildings, archival research and GIS-based spatial analysis were conducted on the 44 churches located in the city centre of Parma (Figure 1), considering aspects such as historical damage, architectural characteristics, and previous seismic reinforcement.

Figure 1. Masonry churches located in the historical centre of Parma and identification of damaged structures (in red) after the 1983 earthquake (Privitera, 2025).

2.1 The Archival research

Archival research conducted at the Soprintendenza per i Beni Architettonici e Paesaggistici di Parma e Piacenza (SABAP-PR) was instrumental in retrieving information about the damage caused by the 1983 earthquake and the subsequent structural reinforcements (Figure 2).
However, interpreting the data was challenging due to the fragmentary nature of the archival records and the use of outdated technical terminology. These limitations were partly overcome by cross-referencing the records with bibliographic sources, historical technical manuals and coeval building codes. Despite these constraints, the archival research successfully identified affected buildings and offered insight into the conservation practices adopted in the decades following the 1983 earthquake. Of the 44 churches examined, 28 were found to have suffered seismic damage. Damage levels were specifically assessed using technical reports and photographic documentation, in accordance with the classification approach outlined in the A-DC Model.

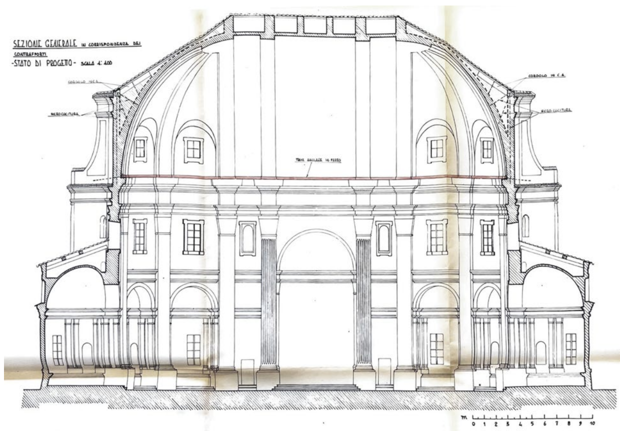

Figure 2. Example of archival documentation detailing the strengthening interventions performed on masonry churches in Parma following the 1983 earthquake (Privitera, 2025; SABAP-PR, PR/M 38).

2.2 The GIS Database

A GIS database was developed using the open-source software QGIS to manage and analyse the collected data.
After defining logical and physical abstraction models, the GIS database was implemented. This included provincial and municipal boundaries (ISTAT, 2025), as well as a shapefile of the 28 damaged churches. Each record in the attribute table was enriched with data on seismic intensity during the 1983 event (INGV, 2025), architectural characteristics, documented damage and post-earthquake interventions. Each church was assigned a unique identification code based on the Emilia-Romagna Region’s WebGIS platform (WEBGIS, 2025), allowing potential future interoperability.
In this initial phase of the research, the architectural characteristics considered included the church’s plan layout (single or multi-nave) and its spatial context (isolated, with at least one free side, or confined between adjacent buildings).
Information on the damage was catalogued by assigning a damage level on a scale from 0 (no visible damage) to 5 (complete collapse of the macro-element), according to EMS1998 (Grünthal, 1998) to each of the 28 mechanisms defined by national guidelines (D.P.C.M. 23/02/2006). These levels were derived from technical documentation and photographic evidence retrieved from the SABAP-PR archives (Figure 3).
Moreover, based on project reports, a systematic inventory of structural interventions implemented after the 1983 earthquake was compiled. These interventions were standardised in terminology according to regulatory and technical references from the period (D.M. 02/07/1981). In the GIS environment, each reinforcement was then associated with the corresponding damage mechanism (e.g. out-of-plane overturning of the main façade was linked to seismic strengthening measures such as tie rods, reinforced ring beams or localised masonry repairs).

Figure 3. Example of GIS analysis investigating the correlation between the constructive features of Parma masonry churches and the level of damage for out-of-plane mechanisms caused by 1983 earthquake (Privitera, 2025).

A preliminary statistical analysis, described in paragraph 3.1, revealed a link between damage mechanisms and the architectural and urban characteristics of religious buildings.
Furthermore, the frequent adoption of similar structural solutions in accordance with contemporary codes and standards was evident, as detailed in paragraph 3.2.
These similarities enabled comparative analyses to be conducted on specific case studies, evaluating the effectiveness of some of the most commonly adopted interventions. In this regard, paragraph 3.3 discusses the effectiveness of tie rods, ring beam systems and masonry repairs against out-of-plane failure mechanisms.

3. GIS-Based Analysis of Damage Patterns and Reinforcement in Parma’s Churches

A preliminary assessment of the influence of qualitative factors and previous reinforcement measures on the structural vulnerability of churches in Parma is described in the following, focusing on the out-of-plane and in-plane mechanisms of the façade and nave walls.

3.1 Influence of spatial context and architectural typology on seismic damage

With regard to façade damage, a key aspect of the analysis was the relationship between the spatial positioning of the churches and the activation of failure mechanisms.
In the specific, the considered mechanisms were M1 (overturning of the façade), M2 (overturning of the upper part of the façade) and M3 (in-plane mechanisms).
The churches have been categorised as isolated, partially confined (with at least one free side) or fully confined (between adjacent buildings). Of the 28 churches analysed, 15 had at least one free side, with the remaining cases split almost equally between isolated buildings (7) and those embedded within an urban aggregate (6).
Considering out-of-plane mechanisms (Figure 4), the analysis showed that 72% of isolated churches were undamaged, whereas 28% experienced moderate damage (D2–D3) under both M1 and M2.
Of partially confined churches, 67% showed no damage, while 20% experienced serious damage (D3), and 13% suffered severe damage (D4) under M1. The upper part of the façade (M2) appeared to be more resilient: 86% were undamaged, while 14% displayed moderate damage (D1–D3).
Furthermore, 83% and 66% of fully confined churches exhibited no damage for M1 and M2, respectively. Only one church out of six (17%) suffered severe damage (D4) under M1, while two churches (34%) experienced moderate damage (D2–D3) under M2.

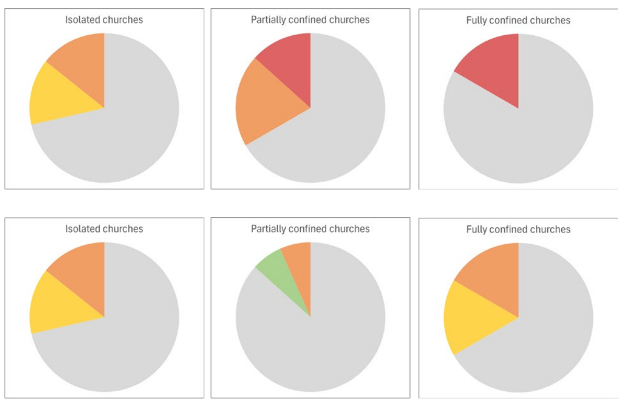

Figure 4. Percentage of M1 (top line), M2 (bottom line) activation for each level of damage (grey for D0; green for D1; yellow for D2; orange for D3; red for D4; brown for D5), for isolated, partially confined, and fully confined churches.

Therefore, partially confined churches exhibited the highest activation rate for M1 (33%) and the highest associated damage levels (D3–D4). This may be due to asymmetric constraints on the façade, resulting in greater stress concentrations. Conversely, M2 was activated less frequently (14%) and with lower damage levels (D1–D2), likely because seismic energy was dissipated through M1 mechanisms.

On the other hand, fully confined churches exhibited the lowest M1 activation rate (17%), although one instance of damage reached level D4. This suggests that connection to not only orthogonal walls, but also adjacent buildings improved the stability of the façade. This highlights the critical importance of connections against overturning: where they are missing, damage is significantly severe.

By contrast, M2 activation was more frequent (34%) in confined churches, indicating that when the façade is well anchored and cannot overturn, the upper portion (the tympanum) becomes more vulnerable. Nevertheless, M2-related damage remained moderate (D2–D3), which is lower than that observed for M1.

Compared to fully and partially confined churches, isolated churches showed a medium activation rate (28%) and damage level (D2–D3), indicating average vulnerability to seismic activity. Furthermore, it is noteworthy that the activation rate and damage levels were the same for M1 and M2 in isolated churches, whereas the frequency and severity of these mechanisms varied in partially and fully confined churches. This highlights the significant influence of spatial context on seismic performance.

With regard to in-plane mechanisms of the façade (Figure 5), isolated churches again exhibit average vulnerability, with the same activation rate (28%) and damage level (D3) as for out-of-plane mechanisms. In contrast, fully confined churches demonstrated a higher activation rate (50%) for M3 than for out-of-plane mechanisms, accompanied by moderate to severe damage levels (D2–D3). This identifies them as the most vulnerable typology to in-plane seismic actions. Partially confined churches, which were more vulnerable to out-of-plane mechanisms, exhibited slightly improved performance against in-plane actions. Although their activation rate increased marginally to 40%, the associated damage levels remained lower (D3).

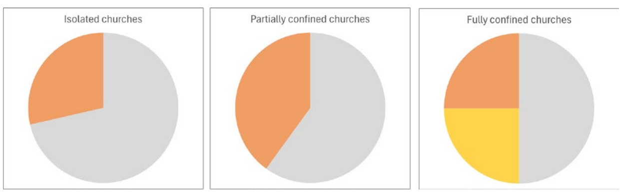

Figure 5. Percentage of M3 activation for each level of damage (grey for D0; green for D1; yellow for D2; orange for D3; red for D4; brown for D5), for isolated, partially confined, and fully confined churches.

Further analyses examined the relationship between plan configuration (single or multiple naves) and the activation of transverse (M5) and shear (M6) response mechanisms. Of the 28 churches analysed, 22 have a single nave and six have a three-nave configuration.

The analysis (Figure 6) suggested that churches with a single nave generally demonstrate greater seismic resilience against overturning mechanisms: 64% showed no damage, 32% experienced moderate damage (D2–D3) and only 4% suffered severe damage (D4). By contrast, only 33% of three-nave churches remained undamaged, while 67% experienced moderate damage (D2–D3). This increased vulnerability is likely due to their larger dimensions and more complex structural systems, which often include additional architectural components such as lower side chapels and larger, thrusting vaults and roofs. Furthermore, it is worth noting that 75% of the damaged three-nave churches are partially confined, which reinforces the correlation between partial confinement and increased vulnerability to overturning mechanisms.

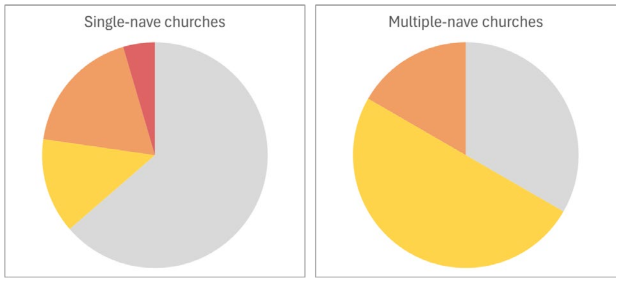

Figure 6. Percentage of M5 activation for each level of damage (grey for D0; green for D1; yellow for D2; orange for D3; red for D4; brown for D5), for single-nave churches and multiple-nave churches.

In terms of in-plane mechanisms (Figure 7), around half of the churches showed M6 activation (54% of single-nave churches and 50% of multi-nave churches), with damage levels typically moderate (D2–D3). These results point to a greater susceptibility of single-nave churches to in-plane mechanisms than to out-of-plane mechanisms. In contrast, multi-nave churches appear to be more resilient to in-plane actions than to overturning behaviour.

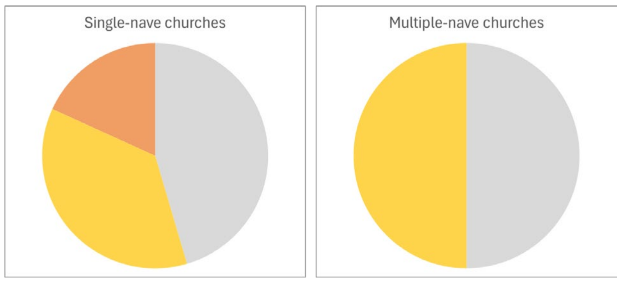

Figure 7. Percentage of M6 activation for each level of damage (grey for D0; green for D1; yellow for D2; orange for D3; red for D4; brown for D5), for single-nave churches and multiple-nave churches.

In any case, no collapses were recorded for the overturning and shear mechanisms of the façade and the nave, suggesting that Parma’s churches generally exhibited a relatively average degree of seismic resilience in the 1983 earthquake.

3.2 Seismic Strengthening Practices after the 1983 Earthquake: Comparison with Contemporary Technical Codes

A preliminary comparative analysis was conducted between the reinforcement interventions carried out on churches damaged by the 1983 earthquake, and the seismic strengthening techniques prescribed by contemporary technical codes. Specifically, seismic strengthening practices at the time were regulated by two Ministerial Decrees (D.M. 03/03/1975; D.M. 02/07/1981) and the related supplementary application code (Circolare 30/07/1981).

Regarding interventions on masonry walls, it is worth noting that these regulations emphasised the importance of taking a comprehensive approach to the structural reinforcement of masonry buildings and discouraged localised interventions unless they were part of a broader structural reconfiguration project. Even in cases involving overturning mechanisms exclusively, the regulations recommended a global approach (i.e. repairing cracks, enhancing masonry strength and improving the structure's overall ductility), rather than improving the box-like behaviour of masonry structures.

Following the 1983 seismic event, the injection of binder mixtures was the most commonly adopted technique, used in 85% of cases, even in instances of severe damage. According to the regulations, the aim of this technique is to improve the mechanical properties of the masonry. Expansive plastic cement was widely used, whereas epoxy resin was confined to a few cases only. Nowadays, concerns have been raised about its reversibility and compatibility with historic materials.

A more compatible intervention for restoring masonry continuity is repairing cracks by reinserting bricks similar to the originals and controlled-shrinkage mortar (*'cuci e scuci'* technique in Italian). This technique was only recommended by regulatory codes in cases involving limited cracked areas and was often used in combination with injections. Nevertheless, this method was adopted in only 25% of cases for reinforcing damaged masonry.

Otherwise, when the crack is isolated or near weak points such as openings or corners, the regulation promotes the use of reinforced concrete (r.c.) jacketing to provide masonry elements with adequate tensile strength and improve ductility. This technique is also recommended for improving connections between orthogonal walls. However, it was not observed in any of the interventions on the analysed churches (0%).

To create effective connections between masonry walls, if such technologies cannot be used, regulations recommended for reinforced injection technique. This intervention consists of inserting metal bars into the masonry and sealing them with cement mixtures. In Parma churches, after the 1983 earthquake, reinforced injections were used only to a very limited extent (10%).

An even more invasive technique, also recommended by the regulations, involves the creation of reinforced concrete frames consisting of vertical pillars and horizontal ring beams, which are inserted into the masonry and connected to it by metal bars. According to the code, the efficiency of this technique is only ensured if the r.c. elements are organised and connected to each other conveniently. However, post-1983 interventions do not fully adhere to this guideline, instead favouring the use of crowning r.c. ring beams, without creating a coherent and integrated structural system. This approach has been adopted in 20% of damaged churches.

Finally, the regulations stated that, where the connection system does not include an RC ring beam, metal tie rods must be provided to effectively encircle the building. This common technique was observed to enhance the structural stability of 45% of damaged churches, sometimes in combination with the need to reduce the lateral thrust of vaults.

The collected data show that there is a slight divergence between the regulatory prescriptions and the practices of 1983, with the most innovative – and invasive – technologies (e.g. R.C. jacketing and frames) not used, despite being encouraged by the regulations. Traditional techniques such as tie rods were favoured over more complex innovative ones such as R.C. ring beams of reinforced injection, to prevent overturning. Conversely, simple and quick-to-implement innovative techniques such as binder injection were favoured to restore masonry continuity and strengthen walls against in-plane mechanisms. In some cases, however, no specific solution was implemented despite overturning mechanisms being evident, and the intervention was limited to repairing cracks, highlighting a lack of awareness regarding seismic reinforcement for historical masonry structures.

Such an approach is likely due to that the area was not considered seismic at the time and local practitioners did not have much experience with this type of intervention.

Moreover, such seismic codes were intended for ordinary buildings; therefore, their application to monumental architecture quickly proved problematic due to the lack of a clear methodology for integrating modern materials into historical structures (Circolare 18/07/1986). Early interventions were often excessive and ineffective, proposing the use of reinforced concrete and metal elements unrelated to the actual damage patterns.

In this context, an assessment of the effectiveness of the seismic reinforcement implemented under 1981 codes (D.M. 02/07/1981; Circolare 30/07/1981), was carried out. To this aim, the damage occurred in Parma’s churches during subsequent earthquakes – particularly the event of 15 October 1996 – was investigated.

This analysis shows that most churches that were reinforced after the 1983 earthquake remained largely unaffected. Only the church of San Benedetto exhibited significant cracking due to overturning mechanisms. While this result may suggest some success, it should be noted that the 1996 earthquake, centred in the province of Reggio Emilia and measuring 5 in magnitude, was considerably less intense than the 1983 event (magnitude 7). Furthermore, the lack of comprehensive archival data limits the ability to draw definitive conclusions.

In the following, a selection of cases is presented to further explore the approaches adopted within such a evolving regulatory framework.

3.3 Case Studies of Seismic Reinforcement: Evaluating Structural and Conservation issues in Parma Churches

An in-depth analysis of three churches in the Parma area – San Benedetto, Santa Croce and Santissima Trinità – enabled an in-depth assessment of seismic reinforcements carried out in 1983, considering structural effectiveness and conservation issues.

3.3.1 The Church of San Benedetto is the only one – among the sample analysed – in which the intervention, although minimally invasive and respectful of the original masonry, was structurally insufficient (SABAP-PR, PR/M 37).

The medieval church, which has a single nave and is partially confined within the urban context, took on its current plan configuration following modifications between the 15th and 18th centuries.

During the 1983 earthquake (Figure 8), overturning mechanisms were activated, especially in the upper part of the façade. The same mechanism was also activated in the longitudinal wall on the west side, which was not confined, and considerable cracks was observed in the vaults of the nave.

Consolidation work involved repairing of the cracks by “*cuci-scuci*” technique in the masonry walls and injecting binding mixtures into the vaults. Additionally, the detached decorative elements of the façade were anchored with metal bars.

During the 1996 earthquake (Figure 9), the façade was damaged again, though to a lesser extent, while the side walls remained undamaged.

This is likely because no specific interventions had been previously realized to prevent the façade from overturning, whereas the longitudinal masonry benefited from the work carried out on the roof in 1983, where the main wooden beams were connected to the perimeter masonry using metal anchorages.
This highlights the importance of effective connections and emphasises that repairing cracks using both traditional or innovative techniques, if applied alone, is insufficient to improve the box-like behaviour of the structure, as reiterated by the regulation itself (D.M. 02/07/1981).

Figure 8. Seismic damages occurred on the façade (top image) and the not-confined nave wall (bottom image) during the 1983 earthquake (Privitera, 2025; SABAP-PR, PR/M 37)

Figure 9. Seismic damages occurred on the façade during the 1996 earthquake (Privitera, 2025; SABAP-PR, PR/M 37)

3.3.2 The Churches of Santa Croce and Santissima Trinità are significant examples of the extensive use of strengthening techniques recommended by the 1981 regulation (D.M. 02/07/1981).
The Romanic Church of Santa Croce (SABAP-PR, PR/M 50) is a partially confined building with three naves. It underwent substantial transformations in the 17th century, including the partial reconstruction of the façade.
The Medieval Church of Santissima Trinità (SABAP-PR, PR/M 42) is a single-nave, partially confined building. Several modifications were made during the 18th and 19th centuries, including raising the façade and the vaults of the nave and choir.
The 1983 earthquake caused severe damage to masonry walls of these churches. Santa Croce exhibited vertical cracks in the front wall (especially in the upper part) and in the unconfined longitudinal wall. Santissima Trinità exhibited vertical cracks in the corners that highlight the detachment of the façade. Significant damage also occurred to the vaults in both churches.
The reinforcement intervention included repairing the cracks with reinforced injections: steel bars injected whit expansive cement mixture and epoxy resins were used for masonry walls, while micro-injections with stainless steel bars were employed to repair frescoed vaults.
In the case of Santissima Trinità, a tie-rod system was created using external tie rods with pole anchorage, while in the case of Santa Croce, harmonic steel cables were inserted into horizontal perforations in the thickness of the façade and side walls. Furthermore, a r.c. ring beam was constructed at the top of the masonry walls and connected to them with reinforced injections. At Santa Croce, a r.c. ring beam was also inserted at the base of the dome and an r.c. load-bearing shell was constructed on the extrados of the vaults.
These interventions fully comply with the regulatory guidelines of the time and have proven effective, as the churches have not been damaged in subsequent seismic events.
However, since this technique has previously been shown to damage the structure (Bartolomucci, 2023a), a more in-depth analysis is needed. Moreover, the use of reinforced concrete in contact with ancient masonry and decorated surfaces raises questions of compatibility and reversibility with historical materials (Coïsson & Ottoni, 22015).
Overall, these cases confirm the ongoing tension between structural effectiveness and conservation issues. While less invasive interventions did not guarantee adequate protection, more structurally effective ones often involved significant alterations to masonry heritage (Ferrari, 2020).
At least, a turning point came with the 1986 Ministerial Decree (D.M. 24/01/1986), which introduced a distinction between *'adjustment'* and *'improvement'* interventions; the latter being more appropriate for heritage buildings. This marked a shift towards more respectful, conservation-oriented seismic strategies that emphasised preliminary structural understanding and material compatibility over invasive modifications.
The awareness that, over time, such buildings have developed their own structural "equilibrium schemes" and that can be severely compromised by incompatible alterations or invasive reinforcements (Giovannoni, 1945) led to the current approaches (D.P.C.M. 09/02/2011, D.M. 17/01/2018; ICOMOS, 2003) that recommend minimal and non-invasive strengthening interventions to improve seismic response by reducing structural vulnerability.

4. Conclusions

This study highlights the complex interplay between structural safety and conservation in the seismic retrofitting of historic churches in Parma following the 1983 earthquake. By integrating archival research with GIS-based spatial analysis, it was possible to identify recurring damage patterns and correlate them with architectural typologies, spatial configurations, and reinforcement strategies, with specific reference to out-of-plane and in-plane mechanisms.

The findings reveal that partially confined churches are particularly vulnerable to overturning mechanisms, while fully confined churches exhibit higher weakness to in-plane seismic actions. On the other hand, single-nave churches display a lower vulnerability to out-of-plane mechanisms, while multi-nave churches appear to be more resilient to in-plane actions.

Moreover, the comparative analysis of post-1983 reinforcement interventions and their performance during subsequent seismic events suggests that measures aligned with the 1981 technical codes were generally effective in mitigating vulnerability to lower-magnitude earthquakes. However, these interventions often raised compatibility concerns with historic materials and forms. Conversely, less invasive approaches, although more respectful of the original fabric, frequently failed to deliver adequate structural protection. These observations underline the need for a balanced, context-sensitive approach that reconciles structural performance with the principles of heritage conservation.

The research also points to several paths for future development. First, a geographical extension of the study to the hilly areas of the Parma province is essential, as these regions differ in materials and construction techniques and may provide a broader and more diverse dataset for assessing seismic vulnerability. Second, a temporal extension is needed to analyse traditional anti-seismic features already present in churches prior to 1983, in order to evaluate their contribution in protecting undamaged buildings. Third, targeted in situ investigations and structural modelling analysis are recommended to verify construction details of past interventions and quantitative assessment of their effectiveness.

Nevertheless, this paper demonstrates the value of GIS as an accessible and powerful tool for assessing the seismic vulnerability of historic buildings, particularly when previous strengthening interventions are considered both from a structural and conservation perspective. The synergy between digital spatial documentation and a thorough understanding of historical interventions enhances predictive capabilities and supports the development of resilient, sustainable strategies for heritage preservation.

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