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A comprehensive multi-level approach for seismic failure analysis of masonry churches in Sorrento (Naples, Italy)

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ABSTRACT

Italy hosts a vast array of ecclesiastical buildings, many constructed well before the establishment of modern seismic design codes. As a result, these structures were built without consideration for seismic forces and frequently lack the box-like structural behavior essential for earthquake resistance. Recent seismic events have exposed their pronounced vulnerability to both local and global failure mechanisms, endangering human lives and threatening the conservation of invaluable architectural heritage. Against this backdrop, the present study evaluates the accuracy and applicability of the simplified mechanical model outlined in the Italian Guidelines for Cultural Heritage (IGCH), with a focus on Evaluation Level 1 (EL1). The investigation centers on a representative sample of masonry churches located in Sorrento, a municipality within the province of Naples. The study commenced with the application of the CarTiS first-level form to delineate sub-municipal sectors and classify the buildings according to their structural typologies. Subsequently, the CarTiS second-level form was employed to perform a detailed typological and structural characterization through comprehensive collection of geometric and construction-related data for each church. From this dataset, six churches were selected for an in-depth seismic vulnerability assessment conducted in multiple stages. Initially, the EL1 screening method was applied to facilitate large-scale preliminary evaluation. This was complemented by a more sophisticated analysis employing a macro-element modeling approach via the 3Muri software, enabling detailed assessment of both global and local structural responses. Two critical comparative analyses were then conducted: one between the EL1 acceleration factor and the αSLV coefficient derived from Evaluation Level 3 (EL3), and another comparing the EL1 damage index with damage indices obtained through local mechanism analyses. Although limited by a small sample size, the findings demonstrate a strong correlation across methodologies, validating the simplified EL1 approach as a reliable and efficient tool for preliminary seismic assessment of historic masonry churches exposed to earthquake risk.

1. Introduction

1.1. Vulnerability of cultural heritage

The assessment of seismic behavior in unreinforced masonry buildings and the subsequent reduction of their vulnerability represent a critical area of interest for both researchers and engineers. However, this task remains highly challenging, as demonstrated by recent severe seismic events across the Mediterranean region—including the L'Aquila earthquake in 2009, the Emilia-Romagna event in 2012, the Central Italy earthquakes in 2016, and the 2023 earthquakes in Morocco, Turkey, and Syria. These events have caused extensive damage manifesting both locally—such as overturning or bending of structural elements—and globally, impacting the integrity of entire buildings [1–7].

Within this vast architectural heritage, the preservation of ecclesiastical buildings holds particular significance, as they constitute a substantial portion of this building stock. This heritage is invaluable, not only for its reflection of historical construction practices but also for its embodiment of cultural values and community identity.

In 1990, it was estimated that approximately 95,000 such buildings

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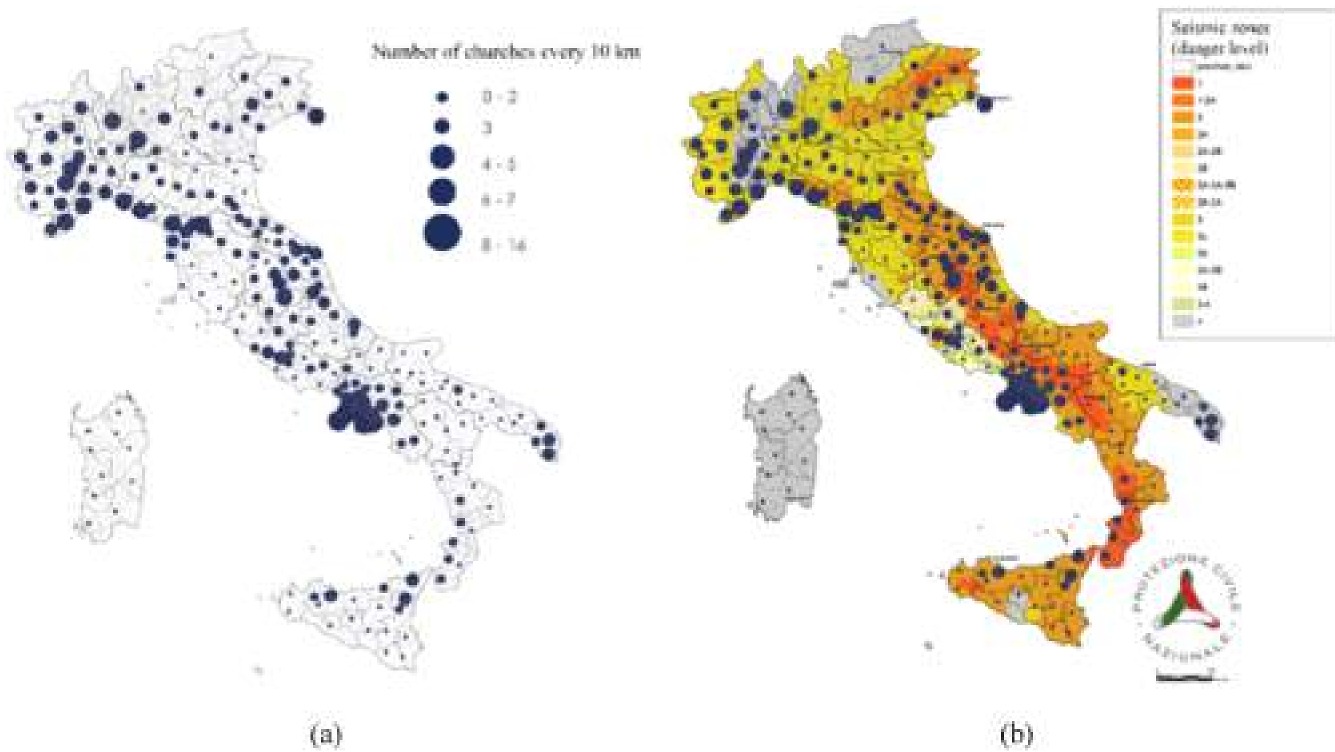

Fig. 1. (a) Distribution of existing churches across Italy; (b) Location of churches in relation to the Italian seismic hazard classification. (*Source: Department of Civil Protection).*

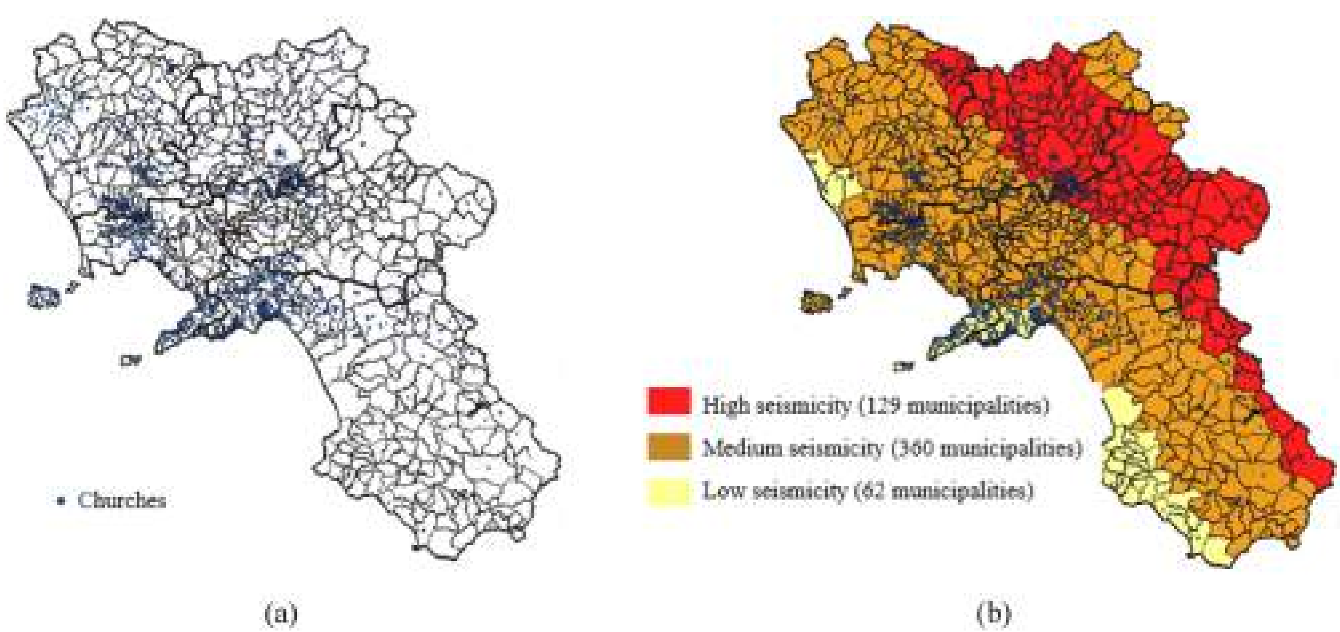

Fig. 2. (a) Distribution of churches in the Campania region; (b) Location of churches in Campania with reference to the seismic hazard classification.

existed in Italy, with about 85,000 (nearly 90 %) constructed before the 20th century. These older structures were built without seismic design considerations and typically lack the essential box-like structural behavior necessary for earthquake resistance [8–10].

Furthermore, as illustrated in Fig. 1, many of these buildings are situated in regions characterized by moderate to high seismic hazard [11–13].

Churches, like many clustered masonry buildings, are typically part of larger architectural complexes composed of multiple adjoining structures with varying degrees of structural integration. Beyond the primary church edifice, it is common to find ancillary buildings such as rectories and bell towers, often constructed adjacent to or physically connected with the main structure. Post-war uncontrolled urban expansion has further complicated the architectural fabric, with some churches in certain villages being absorbed into surrounding residential developments. These complexities, coupled with the frequent lack of reliable information regarding construction dates and materials, considerably increase the challenges involved in their study and

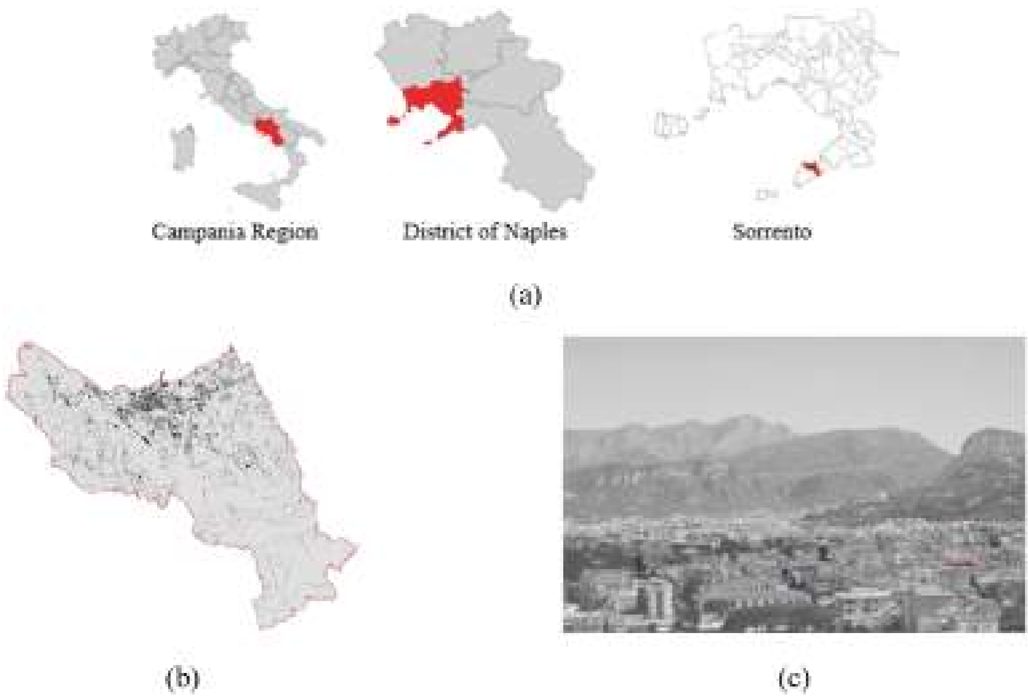

Fig. 3. (a) Location of the municipality of Sorrento within the Campania region; (b) Detailed view of the city of Sorrento; (c) Aerial view.

assessment [14,15].

According to the most recent census undertaken by the Italian Episcopal Conference, approximately 67,000 ecclesiastical buildings have been documented throughout Italy, a feat achieved through the coordinated efforts of 219 dioceses [16]. This extensive database serves as a critical foundation for informed planning, management, and preservation strategies aimed at safeguarding these heritage assets.

Currently, a nationwide initiative is underway to systematically catalogue churches by diocese, with the objective of developing a comprehensive and multidisciplinary framework that addresses the historical-artistic, architectural, archival, and bibliographic dimensions of Italy's ecclesiastical heritage.

Focusing on the Campania region, where this study's analyses target a set of masonry churches in the municipality of Sorrento, data reveal that many of these buildings have undergone significant stylistic modifications over the centuries. Remarkably, several Sorrento churches are built atop the foundations of ancient Roman temples, underscoring the deep historical layering inherent in the region's architectural patrimony.

Thus, meticulous data collection and comprehensive census efforts are indispensable to achieve a thorough understanding of the ecclesiastical heritage. Campania ranks among the Italian regions with the highest density of churches. In particular, research by Bartolomei [12] highlights an especially dense concentration of ecclesiastical buildings in the province of Naples, as depicted in Fig. 2.

Campania hosts a total of 4424 churches, with an average density of 0.32 churches per square kilometer. The Province of Naples exhibits the highest concentration, with 1107 churches and a density of 0.94 churches/ km^2, followed by Salerno with 1439 churches at 0.29 churches/ km^2. Caserta and Avellino account for 827 and 691 churches, with densities of 0.31 and 0.24 churches/km^2, respectively, while Benevento registers the lowest figures, with 360 churches and a density of 0.17 churches/ km^2.

1.2. Aim and limitations of the research

Building on this context, the present study evaluates the reliability and effectiveness of Evaluation Level 1 (EL1) as defined by the Italian Guidelines for the Evaluation and Reduction of Seismic Risk of Cultural Heritage (IGCH). EL1 is intended as a rapid, simplified screening tool for assessing the seismic vulnerability of churches [17–19].

Whereas recent scientific research focuses on post-earthquake damage assessments of churches, developing increasingly accurate models with the support of advanced technologies, such as laser scanning and high-resolution survey instruments [20,21], this study proposes an original multi-level approach aimed at comparing seismic performance indicators derived from different procedures.

Initially, twenty-seven churches within the municipality of Sorrento were identified, and extensive data were collected using both levels of the CarTiS form, spanning from territorial to individual building scales. The form enables a detailed collection of information and represents a key resource for the preliminary identification and prioritization of seismic risks. By integrating CarTiS data into a multi-level comparative framework, this study demonstrates its operational value not only for preliminary screening but also as a reliable tool for deeper structural analysis when paired with advanced evaluation methods.

Subsequently, all three IGCH evaluation levels were applied to six case studies, selected based on the availability of comprehensive geometric and structural data. EL1 employed the simplified mechanical method to estimate damage and vulnerability indices alongside acceleration factors.

This analysis was refined by developing macro-element models in the 3Muri software, facilitating the assessment of local collapse mechanisms per EL2, followed by global structural behavior evaluation in EL3. Damage indices at EL2 were derived using approaches similar to EL1, whereas EL3 incorporated nonlinear static analyses to determine seismic coefficients.

The final phase involved two critical comparisons: the first between acceleration factors from EL1 and EL3—expressed as the ratio of capacity to demand peak ground acceleration (PGA) under both rigid and soft soil conditions—and the second between damage indices obtained from EL1 and EL2.

Despite the limited sample size, results revealed a strong correlation between indices, particularly damage parameters, supporting the validity of the EL1 method as a reliable preliminary screening tool for seismic vulnerability of historic churches. To consolidate these findings

Table 1
Churches in the Sorrentine Peninsula.

Municipality	No of Churches	Density (churches/km^2)
Entire territory	137	1.82
Vico Equense	47	1.62
Meta	9	4.00
Piano di Sorrento	16	2.19
Sant'Agnello	14	3.40
Sorrento	**27**	**2.71**
Massa Lubrense	24	1.06

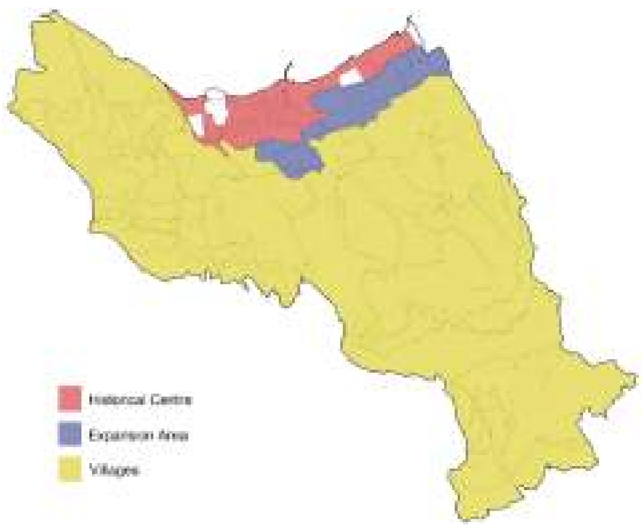

Fig. 4. Identified sectors within the territory of Sorrento.

and incorporate recent updates to acceleration factor calculations, further application of the full assessment procedure across a broader inventory of ecclesiastical buildings is warranted.

Nevertheless, this study has several limitations that must be acknowledged. The numerical model, while widely recognized, faces constraints when applied to irregular heritage buildings with complex geometries, where local discontinuities and construction details may not be fully represented. Moreover, the absence of calibration against experimental data limits the validation of the numerical outcomes, which should therefore be regarded primarily as comparative indicators rather than absolute values. Further limitation arises from the lack of detailed information on the mechanical properties of the construction materials, since in-situ tests were unavailable, reducing the accuracy of the structural characterization. These factors inevitably restrict the generalization of the findings and highlight the need for future research to incorporate refined survey techniques, experimental testing, and calibration procedures to enhance the reliability and applicability of the proposed methodology.

2. Assessment of Sorrento's ecclesiastical buildings using the CarTiS form

2.1. Main characteristic and historical evolution of the territory of Sorrento

The churches analyzed in this study are located within the municipality of Sorrento, part of the province of Naples, as illustrated in Fig. 3a. Covering an area of approximately 9.9 square kilometers (Fig. 3b), Sorrento is home to roughly 16,500 residents.

Renowned as one of the most picturesque cities along the Sorrentine Coast in Campania, Sorrento attracts numerous visitors, celebrated for its stunning landscapes and distinctive local cuisine.

The municipality of Sorrento has a documented history of significant seismic activity dating back to the year 1000, as recorded by the National Institute of Geophysics and Volcanology (INGV). Historical evidence gathered during the investigation of Sorrento's churches identifies two particularly impactful earthquakes that caused substantial damage to local ecclesiastical structures: the 1688 Sannio earthquake and the more recent 1980 Irpinia earthquake [22].

A comprehensive geological assessment conducted by Ugati and Cuccurullo for the municipal civil protection plan [23] offers a detailed characterization of the area. Although the Sorrento Peninsula and the adjoining Lattari Mountains are currently classified as seismically inactive zones, this classification does not negate the inherent seismic risk, as the region remains susceptible to influence from neighboring active fault systems. Seismicity in this area is primarily linked to two major tectonic systems:

- The Campanian–Lucanian Apennines, and
- The Neapolitan volcanic system, encompassing Vesuvius, Campi Flegrei, and Ischia.

The Campanian Apennines represent one of Italy's most seismically active regions, frequently experiencing moderate earthquakes with magnitudes ranging between 4 and 5, occurring at depths of up to 35 kilometers.

In terms of cultural heritage, the Sorrentine Peninsula is distinguished by a notably high density of ecclesiastical buildings, as detailed in Table 1, underscoring the importance of targeted seismic risk assessment and preservation efforts in this historically rich area.

At the time of this study, the CEI database listed 13 churches within the municipality of Sorrento, compared to a total of 27 churches and chapels identified by the researchers. This likely constitutes the first comprehensive survey of all ecclesiastical buildings in the area. Notably, many of the documented churches are currently difficult for the public to access, due either to disuse or poor state of conservation.

2.2. CarTiS Form – first level: identification of urban sectors and types of churches

During the initial phase of analysis and data collection on the surveyed churches, the first level CarTiS form was applied. This form was specifically developed as part of the ReLUIS Project (2019–2021 and 2022–2024), promoted by the Italian Department of Civil Protection under the MARS Project (Risk Mapping and Earthquake Damage Scenarios), within Work Package 4 (WP4), Task 4.6 (Fragility Models and Curves for Churches). It was later integrated into the broader CarTiS initiative, under Work Package 2 (WP2), which focuses on the inventory of existing structural and architectural typologies [23].

The primary objective of the CarTiS Churches survey is to qualitatively classify ecclesiastical building typologies across the national territory. The focus lies on local construction practices and typological-structural features. This information is essential for enhancing the database of typological distributions, which forms the foundation for assessing vulnerability and conducting large-scale seismic risk analyses, regardless of the adopted methodological framework—whether statistical-empirical, mechanical-numerical, or hybrid.

The application of the first-level CARTIS form follows a structured procedure involving several key phases:

- Identification of homogeneous sectors: These are areas within one or more municipalities (or a Union of Municipalities) characterized by churches with similar morphological and structural attributes.
- Mapping of homogeneous sectors: Geographical delineation of the identified sectors.
- Survey and characterization of the building stock within each sector, based on parameters such as construction period, stylistic elements, structural systems, and local construction traditions.

T01 - MUR1 (Tuff Masonry)
HC1: Cathedral of Saints Philip and James
HC6: Basilica of Saint Antonino
T02 - MUR1 (Tuff Masonry)
HC2: Church of San Paolo
HC9: Sanctuary of the Madonna del Carmine
T03 - MUR1 (Tuff Masonry)
HC3: Church of the Annunziata
HC4: Church of Saint Francesco
HC5: Church of Saints Felice and Bacolo
HC7: Church of the Madonna delle Grazie
HC14: Church of Maria SS. Assunta
V2: Church of Santa Maria di Casarlano
T04 - MUR1 (Tuff Masonry)
HC10: Church of Saint Anna
HC11: Church of the Madonna del Soccorso
HC13: Church of Saint Maria della Pietà
EA2: Church of Saint Onofrio
EA3: Church of Saint Lucia
EA4: Church of Saint Pietro a Mele
EA5: Church of Saint Antonino
V1: Church of Saint Maria di Montevergine
V3: Church of Saint Biagio
V5: Church of Saint Maria del Toro
V7: Church of the Madonna di Costantinopoli
T05 - CAR1 (Reinforced Concrete)
EA1: Church of Nostra Signora di Lourdes
V6: Church of the Santissimo Rosario
Churches with unique characteristics:
HC8: Church of the Addolorata
HC12: Church of S. Maria de Restilianis
V4: Church of Saint Atanasio
V8: Church of Saint Maria della Purità

Fig. 5. Spatial distribution and list of the 27 churches surveyed within the municipality of Sorrento, categorized according to the used construction technology.

Each sector comprises buildings that exhibit comparable characteristics, shaped both by their historical construction context and by local architectural and structural influences.

In the case of Sorrento, three homogeneous sectors were identified (see Fig. 4):

- Historical Center (HC, in red): The town's central area, originally enclosed by ancient city walls, now partially demolished.
- City Expansion Area (EA, in purple): Located just beyond the original boundaries of the historic center.
- Villages (V, in yellow): Comprising small historical centers in adjacent towns.

Following a typological-structural analysis, the churches in the Sorrento area were classified into five principal typologies, based on the parameters defined in the CarTiS survey form. The classification took into account various factors, including the vertical structural system, construction period, floor plan layout, surface area, and internal spatial dimensions.

The identified typologies are summarized as follows:

- Typology T01: Characterized by a Latin cross plan with a central nave and three aisles, these churches have a surface area exceeding 1000 m^2 and are constructed with regular masonry composed of grey tuff blocks.
- Typology T02: Defined by a Latin cross plan with a single central nave flanked by side chapels, this group includes buildings with an internal surface area ranging from 300 to 999 m^2, built using regular grey tuff masonry.
- Typology T03: This category features a rectangular hall plan. An exception is the Church of Santa Maria di Casarlano, which includes a side aisle but is grouped here due to its comparable scale. Surface areas fall between 300 and 999 m^2, with the vertical structure constructed in grey tuff masonry.
- Typology T04: The most widespread typology, comprising eleven churches—mainly parish churches or chapels—distributed across all three sectors. These buildings typically have a single rectangular hall, a surface area between 100 and 299 m^2, and are built with grey tuff block masonry.
- Typology T05: This group includes more recent constructions, dating from the second half of the 20th century. These churches are built using reinforced concrete and have internal surface areas between 300 and 999 m^2.

In addition to these five main typologies, a number of churches exhibit unique architectural features that distinguish them from the

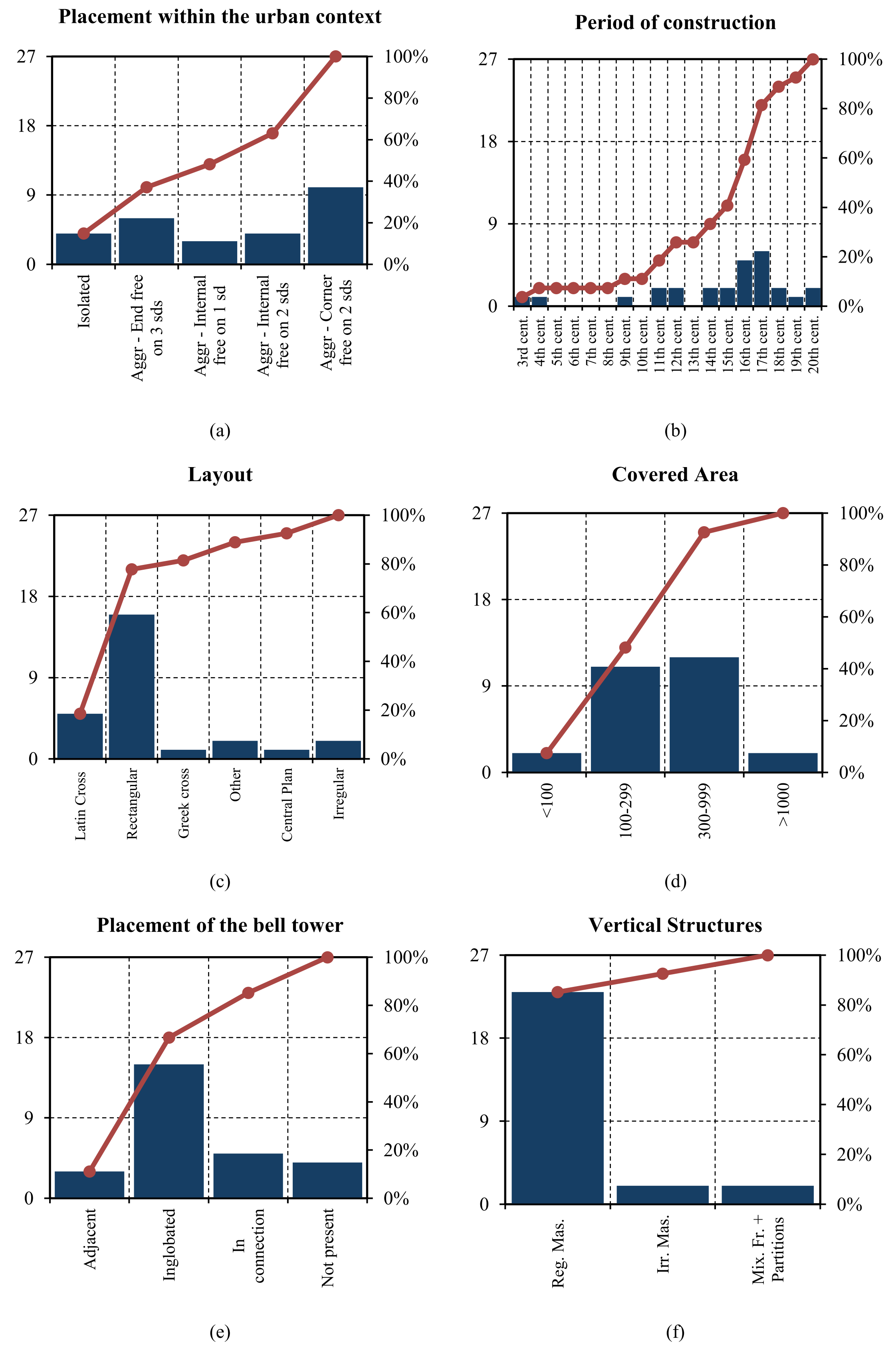

Fig. 6. Data acquired from second-level CarTiS form: a) Placement within the urban context, b) Construction period; c) Plan Layout; d) Covered Area; e) Position of bell tower; f) Vertical Structures.

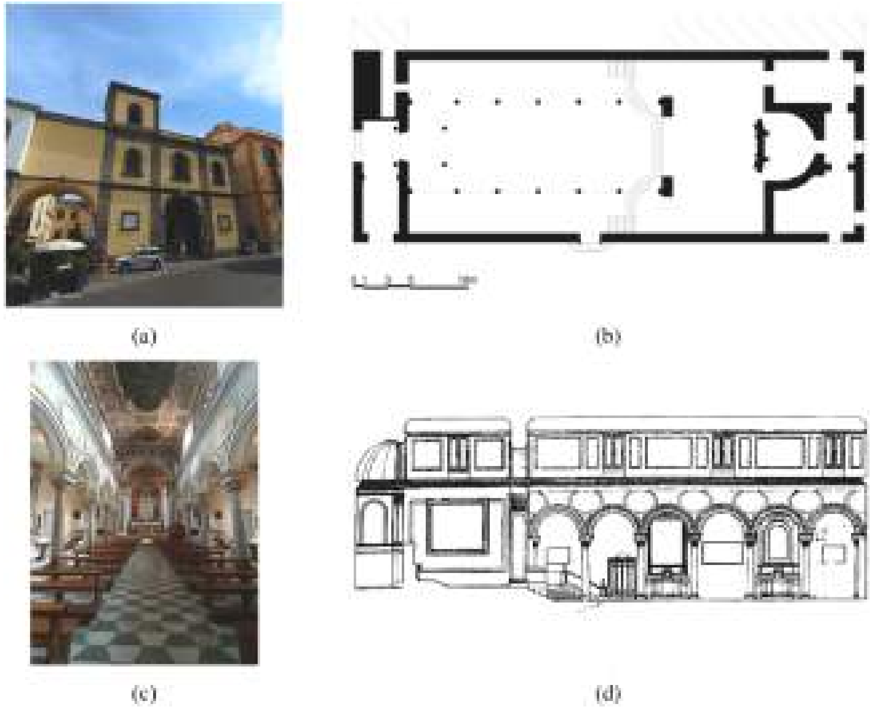

Fig. 7. Photogaphic documentation of the church of *Saint Antonino*: a) Main façade; b) Ground floor layout; c) Nave, d) Cross-Section.

broader classification. Notable examples include:

- The Church of the Addolorata, featuring a Greek cross plan;
- The Church of Santa Maria de Restilianis, with an elliptical central plan;
- The Church of Saint Atanasio and the Church of Santa Maria della Purità, both notable for their masonry composed of tuff and stone.

The spatial distribution and classification of the churches are illustrated in Fig. 5.

2.3. CarTiS Form – Second Level: study of the main characteristics of churches

Following the identification of sectors and construction typologies, the analysis advanced with the application of the second-level CarTiS form, which focuses on the detailed characteristics of individual churches. Key aspects examined included the building's location within the urban context, construction period, plan layout, façade features, and other architectural and structural elements. The analysis of twenty-seven religious buildings within the municipality of Sorrento allowed for a deeper understanding of the local specificities of the ecclesiastical heritage.

A selection of the collected data is presented graphically in Fig. 6.

Data concerning the spatial context reveal that only 4 buildings (15 %) are freestanding, whereas the vast majority are part of an aggregated building fabric (Fig. 6a).

This configuration has important implications for seismic vulnerability assessments, as structural interactions with adjacent buildings can significantly influence a church's seismic performance.

With regard to the construction period, approximately 89 % of the churches were originally built before the 19th century, with the greatest concentration dating to the 16th and 17th centuries (Fig. 6b). This highlights the high historical value of the ecclesiastical heritage and suggests the prevalent use of traditional construction techniques, often lacking seismic-resistant design.

From an architectural perspective, the most common layout is the rectangular floor plan, observed in 59 % of the sample (Fig. 6c), reflecting a typical configuration in historic religious architecture.

In terms of surface area, most churches fall within the 100–299 m^2 (41 %) and 300–999 m^2 (44 %) ranges (Fig. 6d), indicating a notable degree of heterogeneity in the size of these structures.

A further significant element is the presence of a bell tower. In 56 % of cases, the bell tower is structurally integrated into the main body of the church (Fig. 6e), a feature that can critically influence the building's dynamic behavior during seismic events.

Finally, concerning the vertical structural system, 85 % of the buildings are constructed using regular masonry, primarily composed of grey tuff blocks (Fig. 6**f**). While common in the Campania region, this material has distinctive mechanical properties that necessitate careful consideration in seismic vulnerability evaluations.

2.4. The investigated churches within the sample

Based on available geometric and structural surveys, six churches were selected for further analysis, conducted at increasing levels of detail—from the territorial scale to the study of global structural behaviour.

The first three case studies correspond to Typologies T01, T03, and T04, respectively, while the remaining three are buildings with distinctive architectural or structural features. For each church, a brief historical background and an overview of the architectural layout are provided to support the understanding of their principal structural characteristics.

2.4.1. Church of Saint Antonino

The Basilica adopts a Latin cross plan, comprising three naves separated by twelve marble columns (six on each side), many of which are spolia—reused elements from ancient Greco-Roman temples and structures. The columns punctuate a sequence of arches. At the ends of the side aisles, marble staircases descend to the crypt of the Saint, located beneath the transept. The ceilings of the main nave, the transept, and the side aisles feature wooden coffered panels, while the structure concludes with a semicircular apse, covered by a semi-dome. The central

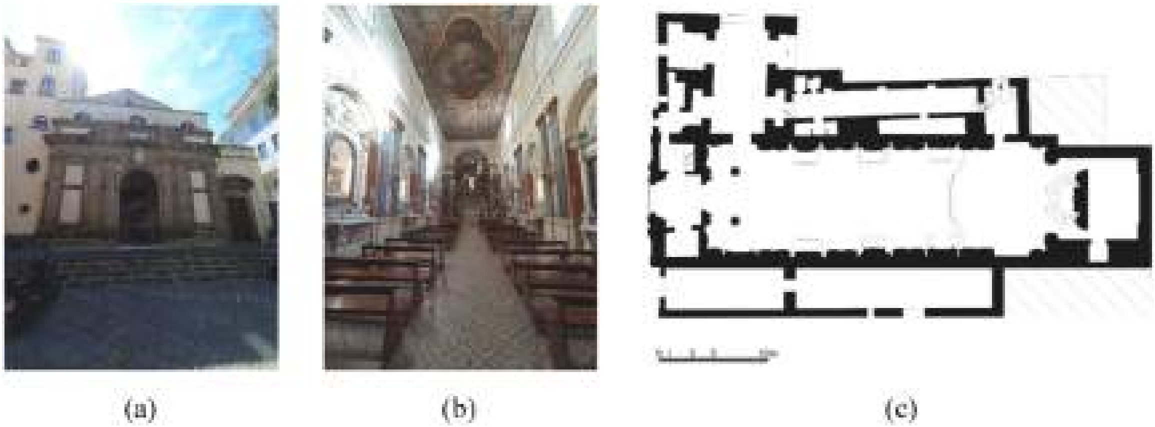

Fig. 8. Photographic documentation of the church of *Annunziata*: a) Main façade; b) Nave; c) Ground floor layout; d) Cross-Section.

nave rises to a maximum height of 12.50 m, while the side naves reach 8.00 m.

Masonry structures consist of tuff blocks having a variable thickness ranging from 70 to 80 cm.

Access is provided through an endonarthex, with the main entrance opening onto the square of Saint Antonino and a secondary entrance on Saint Antonino Street. The open interior is composed of two adjoining spaces, ideally divided by a round arch, both covered by sail vaults.

The quadrangular façade is organized into three levels, delineated by grey tuff cornices, and incorporates the bell tower, which is connected to the former convent via an elevated passage on the left side. Today, the former monastic complex serves as Sorrento's Town Hall. At the center of the façade is the main entrance portal, featuring a round arch constructed from grey tuff stones.

Although the original layout dates to the medieval period, significant restoration and remodeling works between the 17th and early 18th centuries gave the church its current Baroque appearance [24]. Following the 1980 Irpinia earthquake, the church underwent extensive restoration after its roof structures collapsed. The main nave's roof was rebuilt using steel trusses supporting corrugated metal sheeting and a lightweight concrete screed, which was then finished with terracotta tiles.

A view of the main façade and the ground floor layout is shown in Fig. 7.

2.4.2. *Church of the Annunziata*

The Church of the Annunziata is believed to have been built over the remains of a temple dedicated to the goddess Cybele. According to tradition, its foundation dates back to the 12th century, specifically the year 1133. The church originally formed part of a larger religious complex, annexed to an Augustinian monastery. In 1714, the church underwent significant architectural modifications, followed by the construction of the current grey tuff façade in 1768. The monastery was later suppressed in 1809 and repurposed—first as a gendarmerie, then as a civil hospital. During this period, the church was closed. It was only in 1811 that the municipality granted its use to the lay Confraternity of Saint Monica.

The building features a rectangular floor plan with a single nave and is accessed through an endonarthex, with the main entrance opening onto Fuoro Street. The endonarthex, reaching a maximum height of approximately 10.50 m, is topped by a sail vault and accessed through a tall portal with a round arch.

Inside, the nave is articulated by six lateral altars, each housed within a niche framed by round arches carved into the side walls. It is covered by a flat wooden ceiling, above which a painted canvas has been mounted, featuring a large central painting.

The nave leads to the presbytery, where the main altar, faced in polychrome marble, displays a statue of Saint Monica. This area is covered by a barrel vault with six frescoed lunettes, three on each side. The internal space is characterized by a total height of approximately 14.00 m.

The main façade is articulated into three distinct levels:

- The first level presents a tall central portal framed by a round arch in grey tuff, flanked by a series of grey tuff pilaster strips. These architectural elements are topped by a broken pediment, which houses the coat of arms of the Archbishop of Naples, who commissioned the façade in 1768 [25].
- The second level, located above the endonarthex, is characterized by a plastered surface featuring three oval openings.
- The third level consists of a recessed façade crowned by a tympanum, within which is a small central oculus.

The tuff masonry walls exhibit considerable variation in thickness, reflecting the numerous alterations made over the centuries. The main façade has a base thickness of 140 cm, with an additional 30 cm contributed by the pilaster strips. However, the façade is not uniform: the left portion measures only about 60 cm in thickness.

The nave walls also display varying dimensions. At the locations of the side altars, the wall thickness is approximately 1 m, whereas in sections without niches, it increases to around 190 cm.

A distinctive feature of the Church of the Annunziata is its entrance level, which lies below the elevation of both Corso Italia and Piazza Veniero. Consequently, the church's left side and apse area are partially underground.

An external view and the ground floor layout of the church are shown in Fig. 8.

2.4.3. *Church of Saint Maria di Montevergine*

The church is located in the hamlet of Cesarano and was constructed in the early 20th century, replacing a previous, more modestly sized structure [26]. The original church, dating back to the 17th century, was converted into a storage facility after a new building was constructed, funded through a community-led initiative in the early 1900s.

Architecturally, the building presents a rustic style, characterized by exposed facades composed of regular grey tuff blocks. The interior, reaching a height of about 15.00 m, is organized according to a rectangular floor plan, articulated by tuff pilaster strips supporting round arches. The nave is roofed with a series of barrel vaults with lunettes, constructed using exposed clay bricks. The presbytery is topped by a dome resting on pendentives, both constructed with exposed brickwork.

The main façade features a tall central portal, elevated above the adjacent square and accessed via a flight of steps. The façade is crowned by a reinforced concrete tympanum.

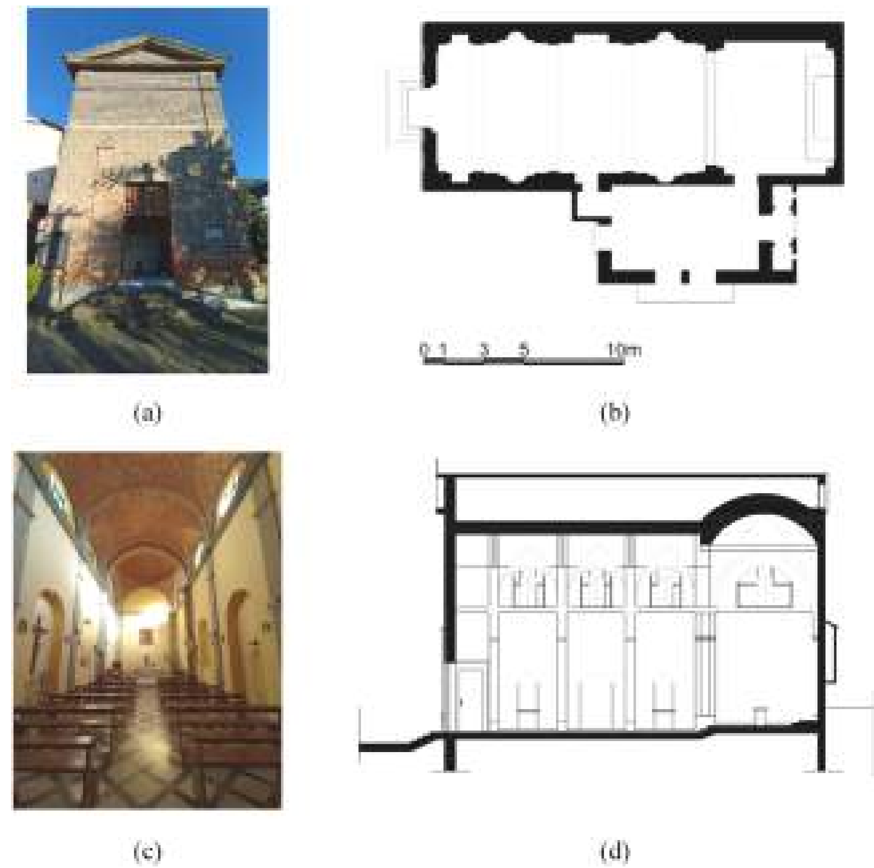

Fig. 9. Photogaphic Documentation of the church of *Saint Maria di Montevergine*: a) Main façade; b) Ground floor layout; c) Nave; d) Cross-Section.

Several structural interventions are visible, including:

- Patchwork masonry repairs (*scuci-cuci*) on the façade;
- A reinforced concrete ring beam located approximately two-thirds of the way up the façade;
- A reinforced concrete roof structure.

The church also contains underlying rooms and lateral spaces housing the sacristy.

The façade wall has an average thickness of approximately 60 cm, with localized increases in thickness at the pilaster strips. The lateral walls have an average thickness of about 90 cm and are punctuated by multiple niches housing votive figures.

The rectangular floor plan is illustrated in Fig. 9.

2.4.4. Church of the Addolorata

The church was built in the first half of the 18th century to commemorate the reconciliation between the Sorrentine patricians of the city's two administrative districts. Following the unification of Italy, the church was deconsecrated and became municipal property. It was not until 1939 that the municipality of Sorrento granted its use to the diocesan curia [24].

Architecturally, the church features a Greek cross plan. The interior walls are adorned with stucco decoration typical of the Baroque style. At the intersection of the main nave and the transept is an elliptical dome, supported by pendentives and four arches that define its base. The major axis of the dome is oriented perpendicular to the longitudinal axis of the nave.

The main nave and transept are covered by barrel vaults with lunettes, reaching a height of approximately 17 m, while the apse is topped by a semi-dome that follows the curvature of the rear wall and rises to an elevation of 9.70 m.

The exterior is characterized by a gable-end façade crowned by a tympanum and decorated with a cornice and a piperno stone portal. The façade includes two windows: the larger is a polylobed window, while the smaller is a simple oculus set within the tympanum. The polylobed motif is echoed in the interior spatial configuration.

The vertical panels are constructed of grey tuff, with thicknesses varying significantly due to the central dome and the building's floor plan. At the base of the elliptical dome—where the thrusts concentrate at the intersection of the main nave and transept—the walls reach approximately 300 cm in thickness. The façade has an average thickness of around 110 cm, with additional reinforcement at the pilaster strips.

The layout and the internal spaces are depicted in Fig. 10.

2.4.5. Church of Saint Maria de Restilianis

The construction of the church dates back to the 14th century [26]. The layout is centralized, featuring an elliptical floor plan covered by a dome with a matching elliptical base, distinguished by a central oculus. The dome arrives at approximately 14 m in height.

The side walls feature two round arches recessed into the wall thickness, each housing a canvas. The apse contains a small marble-clad altar, above which a fresco of Saint Mary of Restilianis adorns the rear wall.

The façade is articulated into three bays, delineated by tall piperno pilaster strips. At the centre, a piperno portal serves as the main entrance. The composition is crowned by a tympanum, defined by moldings made from the same material as the pilasters. The façade exhibits the influence of the giant order, with pilasters extending continuously from base to top, embodying a more restrained character compared to the church's originally more ornate style. In the background, the continuation of the elliptical worship space is clearly visible, surmounted by a wooden truss roof. The thickness of the perimeter masonry walls ranges from 110 to 160 cm, while the façade wall has a

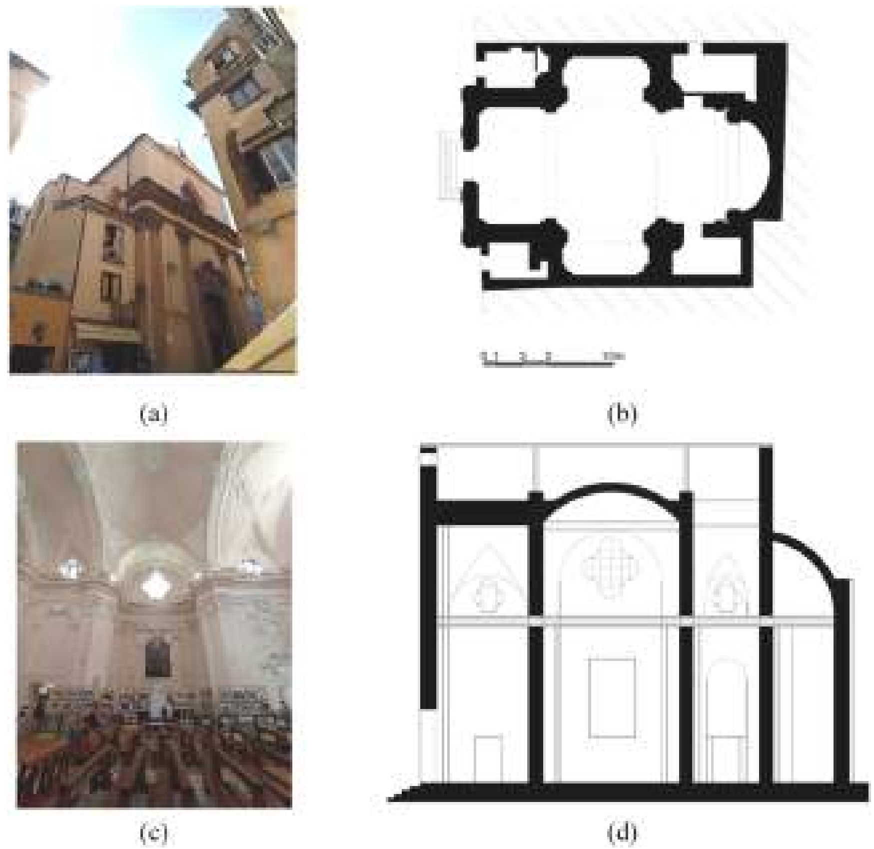

Fig. 10. Photogaphic documentation of the church of the *Addolorata*: a) Main façade; b) Ground floor layout; c) Nave; d) Cross-Section.

base thickness of approximately 130 cm, with localized increases corresponding to the pilasters.

The central plan is presented in Fig. 11.

2.4.6. *Church of Saint Maria della Purità*

This church, due to its modest dimensions, is better classified as a chapel. It is located in the locality of Li Simoni, on the hillside of Capo di Sorrento. Its origins are unknown, but historical records indicate that by the early 19th century it was under private patronage.

The layout is rectangular, covered by a barrel vault with an extrados finished with compacted lapilli and a maximum elevation of about 7.00 m. The façade features a central portal, distinguished by the use of Massa stone, topped by a rectangular window. The composition is concluded by a free-standing tympanum, with a gabled bell tower standing on the left side. The structure is primarily composed of tuff and rubble masonry [26], likely employing irregular tuff blocks. Given the building's small scale, the wall thicknesses are relatively modest, averaging around 60 cm.

The simple rectangular layout is showed in Fig. 12.

3. Main aims and methodology of the work

3.1. *Premises*

As noted in the introduction, this study primarily focuses on evaluating the effectiveness and reliability of the simplified method proposed in Evaluation Level 1 (EL1) of the Italian Guidelines [17]. To this end, several comparative analyses are undertaken between different seismic performance indices.

The first comparison involves the acceleration capacity, specifically examining the capacity-to-demand ratio. This is done by comparing the acceleration factor $f_{a,SLV}$ obtained through EL1 with the coefficient α_{SLV}, derived from a global structural analysis conducted using Evaluation Level 3 (EL3).

The second comparison considers damage indices: the damage index i_d, calculated via the simplified mechanical model, is compared to the index $i_{d,3Muri}$, derived from a more refined analysis involving local collapse mechanisms assessed through kinematic analysis.

Both the α_{SLV} coefficient and the $i_{d,3Muri}$ index were obtained using macroelement models implemented in the 3Muri software developed by STA.DATA (Version 15.0.0.4) [27].

To carry out these comparisons and determine the suitability of the simplified method for rapid post-seismic damage assessments of churches, all three assessment levels outlined in the Guidelines were applied. These levels represent a progression in analytical complexity and detail.

- Level 1 (EL1) provides a simplified method suitable for large-scale, territorial assessments.
- Level 2 (EL2) allows for the evaluation of potential local collapse mechanisms in specific structural portions, typically using both linear and non-linear kinematic analyses, which are particularly effective for this purpose.
- Level 3 (EL3) enables a comprehensive global analysis of the building's seismic response.

The Italian Guidelines were first introduced in 2008 and later revised in 2012 to align with the updated Italian Technical Standards [18,19]. They are now widely adopted in both research and practice, serving as a robust framework for evaluating seismic risk in cultural heritage assets. The guidelines also support prioritization efforts, enabling the identification and classification of the most vulnerable structures, which can inform consolidation strategies and intervention planning [28–30].

This investigation focuses on six case studies, selected from a broader

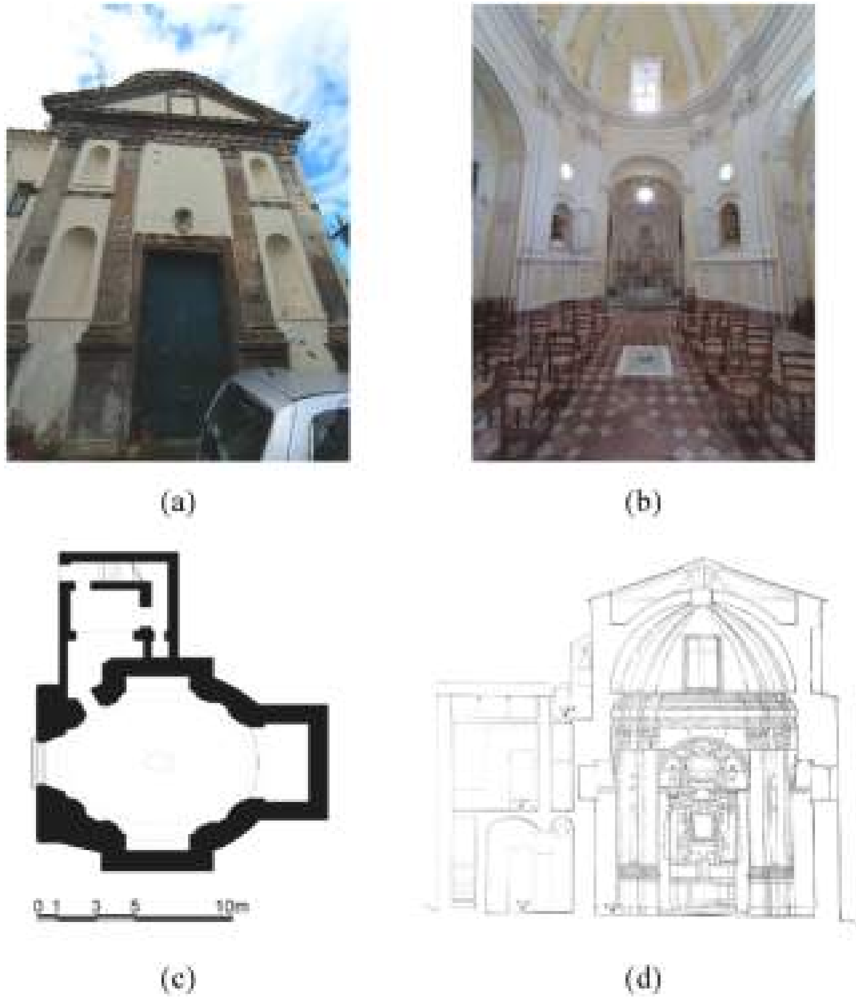

Fig. 11. Photogaphic documentation of the church of *Saint Maria de Restilianis*: a) Main façade; b) Nave; c) Ground floor layout; d) Cross-Section.

set of churches based on the availability of detailed geometric and structural data.

3.2. Assessment of the vulnerability via simplified mechanical model (EL1)

In the initial phase of this study, the procedures prescribed in Evaluation Level 1 (EL1) of IGCH were applied. This level includes three simplified mechanical models, each designed for a specific building typology: palaces and villas, churches and religious buildings, and bell towers. For this investigation, the model designated for "*Churches, places of worship, and other large-hall structures without intermediate floors*" was used. This model outlines twenty-eight potential failure mechanisms involving macroelements commonly found in churches.

It represents an evolution of the earlier post-earthquake assessment form developed after the 1995 Lunigiana and Garfagnana earthquake, which identified eighteen possible collapse mechanisms [31]. This was followed by the 2006 introduction of the *Damage Assessment Form for Cultural Heritage – Churches, Model A-DC*, employed after the 1997 Umbria–Marche earthquake, which expanded the classification to twenty-eight mechanisms [32].

The expansion allowed for a more nuanced identification of structural vulnerabilities, thereby enhancing the planning and prioritization of intervention measures. An overview of these mechanisms is shown in Fig. 13.

Among the most frequently observed mechanisms were Overturning of the main façade (LM1), Overturning of the upper portion of the façade (LM2), Bell tower-related failures (LM27 and LM28), Cracking of the dome, where present (LM14) and Damage to side chapels (LM22).

The objective of the application of this preliminary method is to calculate the vulnerability and damage indices.

The vulnerability index i_v, which ranges from 0 to 1, is calculated as the weighted average of the behaviour of the various structural elements:

$$i_v = \frac{1}{6}\frac{\sum_{k=1}^{28}\rho_k\left(v_{ki} - v_{kp}\right)}{\sum_{k=1}^{28}\rho_k} + \frac{1}{2} \tag{1}$$

where, for the k-th mechanism:

v_{ki} and v_{kp} are the scores assigned to the vulnerability indicators and seismic devices, respectively, as given in Table 5.2 of the Guidelines;

ρ_k corresponds to the weight attributed to each mechanism. This value is equal to 0 if the mechanisms cannot be activated in the church due to the absence of the macroelement. Contrary, it assumes a value of 1 if the mechanisms are active, with the exception of mechanisms No. 4 and 15. In all other cases, ρ_k ranges between 0.5 and 1 (applicable to mechanisms No. 10, 11, 12, 18, 20, 22, 23, 24, 25 and 26).

In addition to the vulnerability index, the same method also enables the calculation of the damage index i_d:

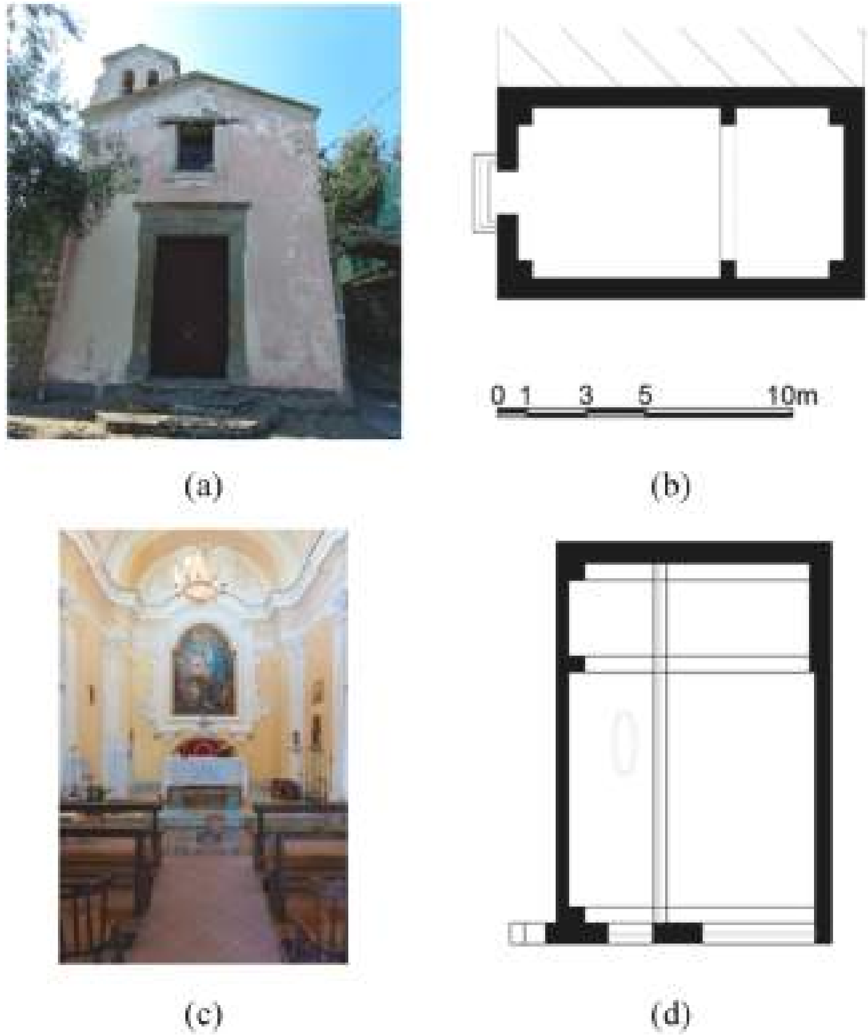

Fig. 12. Photogaphic documentation of the church of *Saint Maria della Purità*: a) Main façade; b) Ground floor layout, c) Nave; d) Cross-Section.

$$i_d = \frac{1}{5}\frac{\sum_{k=1}^{28}\rho_k \quad d_k}{\sum_{k=1}^{28}\rho_k} \tag{2}$$

where d_k is the damage level regarding the k-th mechanism (ranging from 0 to 5).

Once these indices are determined, it becomes possible to calculate for each church the ground acceleration values corresponding to the Life Safety Limit State (SLV) using the following expression:

$$a_{SLV}S = 0.025 \bullet 1.8^{5.1-3.44i_v} \tag{3}$$

where S is the parameter that accounts for the stratigraphic and topographic conditions of the soil.

The calculation of the capacity acceleration is useful for determining the acceleration factor, which is one of the key terms used for the comparison. This factor, defined as the ratio between capacity and demand ground accelerations, assuming rigid soil conditions (Soil Category A), is calculated as follows:

$$f_{a.SLV} = \frac{a_{SLV}}{a_{g,SLV}} \tag{4}$$

Finally, to calculate the seismic safety index, it is necessary to determine the return period T_{SLV} corresponding to the attainment of the Life Safety Limit State (SLV). This is done using the following relationship:

$$T_{SLV} = T_{R1} \bullet 10^{\log\left(\frac{T_{R2}}{T_{R1}}\right) \bullet \log\left(\frac{a_{SLV} \quad S}{F_C a_1 S_1}\right) \Big/ \log(a_2 S_2 \big/ a_1 S_1)} \tag{5}$$

where:

T_{R1} and T_{R2} represent the return periods for which seismic hazard is provided, with T_{SLV} falling within this range;

a_1S_1 and a_2S_2 are the corresponding values of peak ground accelerations on rigid soil, adjusted by coefficients that account for the subsoil category and topographic conditions.

F_C is the Confidence Factor.

The seismic safety index, given by the ratio between the return period T_{SLV} associated with the seismic action reaching the generic limit state and the corresponding reference return period $T_{R,SLV}$, is provided as follows:

$$I_{S.SLV} = \frac{T_{SLV}}{T_{R,SLV}} \tag{6}$$

For both parameters—the acceleration factor and the seismic safety index—values greater than or equal to 1 indicate that the constructions is not vulnerable. Conversely, values below 1 highlight situations that may require further attentions or consolidation interventions.

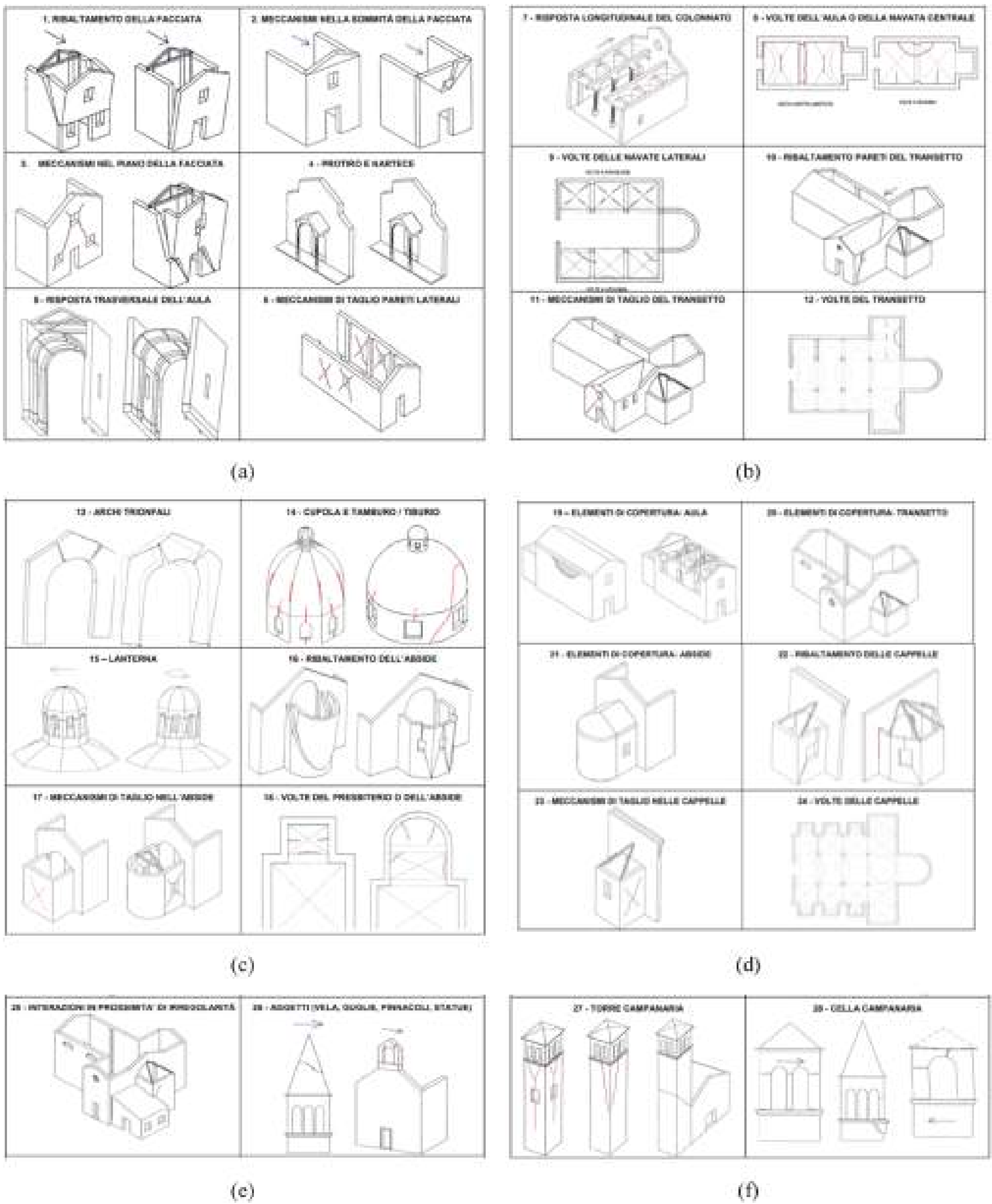

Fig. 13. The twenty – eight mechanisms defined by the IGCH: a) Mechanisms 1 – 6; b) Mechanisms 7 – 12; c) Mechanisms 13 – 18; d) Mechanisms 19 – 24; e) Mechanisms 25 – 26; f) Mechanisms 27–28.

Table 2
Conversion of a_c/a_d (i_d) ratio into damage index d_k'.

a_C/a_D	1	0,8	0,6	0,4	0,2	0
d'_k	0	1	2	3	4	5

3.3. Analysis of local collapse mechanisms through EL2

Following the completion of the simplified procedures outlined in Evaluation Level 1 (EL1), the investigation proceeded with Evaluation Level 2 (EL2). This level involves a more detailed analysis aimed at assessing local collapse mechanisms. These mechanisms—also referred to as first-mode mechanisms—concern structurally independent portions of the building, defined as macroelements, and typically manifest as overturning or flexural failures.

Such failure modes are commonly observed in buildings that lack the so-called "box effect," often due to insufficient connections between vertical walls and horizontal diaphragms, or between adjacent masonry panels [33–35].

The primary objective of EL2 is to compute a damage index, conceptually similar to that defined in EL1, but refined by considering the activation accelerations specific to each local collapse mechanism. To this end, kinematic analyses were performed for all 28 identified mechanisms to determine their respective capacity (activation) accelerations. These were then compared against the corresponding seismic demand accelerations.

Because the resulting capacity-to-demand ratios lie between 0 and 1,

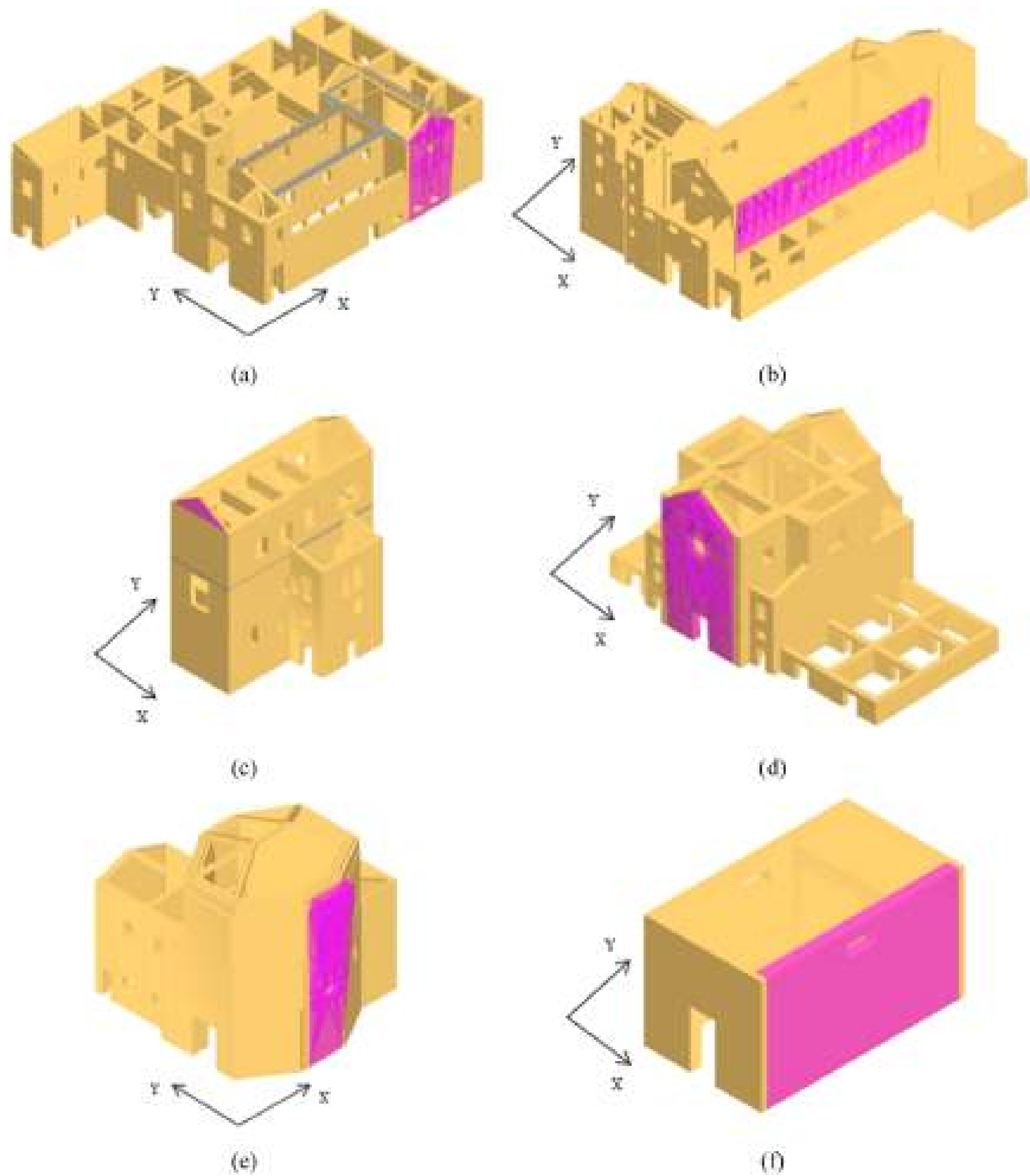

Fig. 14. Some of local collapse mechanisms: a) Overturning of the transept wall (LM10); b) Overturning of the side wall of the main nave (LM6); c) Overturning of the tympanum of the façade (LM2); d) Overturning of the main façade (LM1); e) Overturning of the side wall of the hall (LM6); f) Overturning of the side wall of the nave (LM6).

Table 3
Mechanical properties of the two inspected masonry types.

Regular Tuff Masonry				
Tensile strength f_m	**Young Modulus E**	**Shear Modulus G**	**Specific weigh W**	**Shear strength τ**
[N/mm^2]	[N/mm^2]	[N/mm^2]	[kN/m^3]	[N/mm^2]
2.00	1410	450	16	0.04
Irregular Tuff Masonry				
Tensile strength f_m	**Young Modulus E**	**Shear Modulus G**	**Specific weigh W**	**Shear strength τ**
[N/mm^2]	[N/mm^2]	[N/mm^2]	[kN/m^3]	[N/mm^2]
1.40	1080	360	16	0.028

a conversion was applied—based on the thresholds defined in Table 2—to translate them into a comparable damage index (d_k').

At this point, using (7), it was possible to calculate the damage index ($i_{d,3Muri}$) for the local mechanisms, which was then compared to the analogous index obtained from a more simplified analysis.

$$i_{d,3Muri} = \frac{1}{5} \frac{\sum_{k=1}^{28} \rho_k \quad d_k'}{\sum_{k=1}^{28} \rho_k} \tag{7}$$

For the purpose of assessing local mechanisms, macroelement models were built using the 3Muri software ver. 15.0.0.2 (see Fig. 15).

To evaluate these failure mechanisms, the current technical standards recommend the use of *limit analysis*, a method based on the equilibrium of masonry structures idealized as assemblies of rigid macro-elements. These elements are assumed to possess infinite compressive strength and no tensile capacity—an assumption consistent with the inherently low tensile strength of masonry materials. As a result, structural collapse is typically governed by loss of equilibrium, which depends on the geometry of the wall, its boundary conditions, and support configuration.

In the analysis of each failure mechanism, the affected portion of the structure is modeled as a *kinematic chain*, composed of rigid blocks that may undergo relative rotation or sliding. This idealization allows for the identification of potential instability paths leading to collapse.

To verify the activation of these mechanisms, a simplified analytical approach is employed, utilizing the formulas prescribed by the current Italian Technical Standards [18,19].

For Life Safety Limit State (SLV) the verification is satisfied if the spectral seismic acceleration activating the kinematics a_0^* is greater than the peak ground seismic acceleration $a_{0,\min}$, as displayed in Eq. 8:

$$a_0^* \quad \geq \quad a_{0,\min} \tag{8}$$

in which:

$$a_0^* = \frac{\alpha_0 \cdot g}{e^* \cdot F_C} \quad q \tag{9}$$

where:

α_0 represents the seismic action multiplier causing the collapse. It is obtained by applying the Principle of Virtual Works, in terms of displacements, by equating the work done by external forces and the one of internal forces produced by a virtual displacement.

g is the gravity acceleration;

e^* is the participating mass fraction related to the first vibration mode;

F_c is the confidence factor.

For what concerns the expression of $a_{0,\min}$, two different equations

Table 4
Seismic parameters for analysis of churches.

Nominal Life	50 years
Use Class	Class III – Large crowds
Subsoil Category	C
Topographic Category	T1

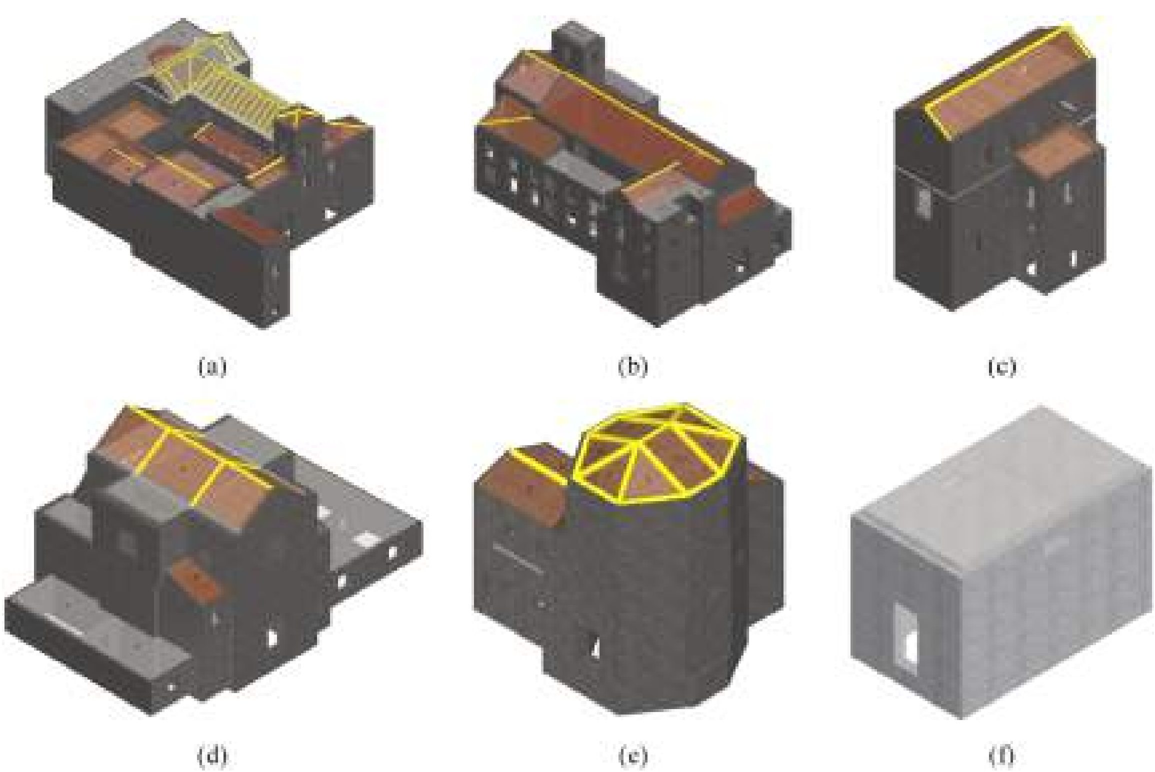

Fig. 15. Three-dimensional models of the selected churches: a) Basilica of SaintAntonino; b) Church of the Annunziata; c) Church of Saint Maria di Montevergine; d) Church of Addolorata; e) Church of Saint Maria de Restilianis; f) Church of Saint Maria della Purità.

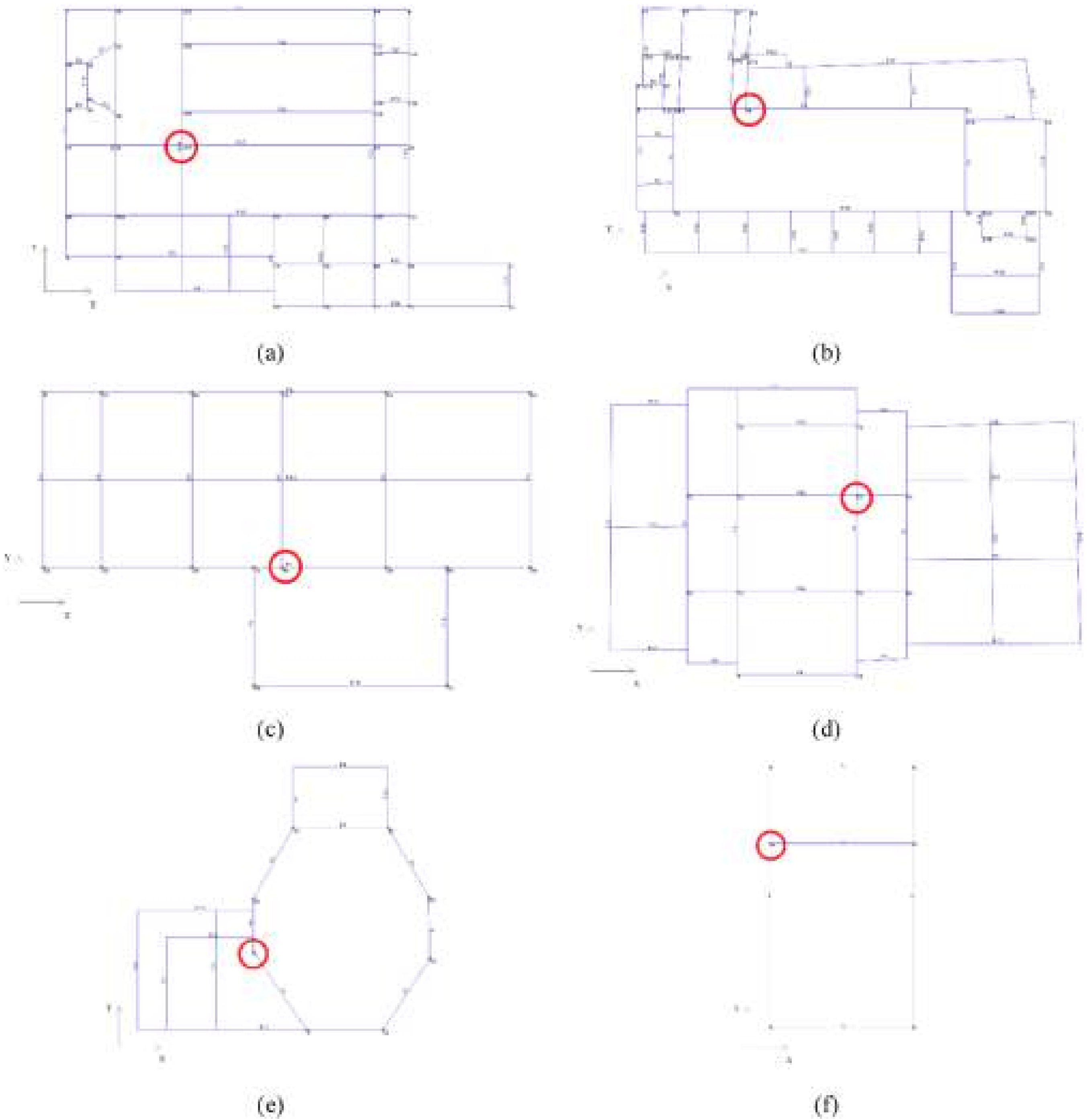

Fig. 16. Placement of the control node of the selected churches: a) Basilica of SaintAntonino; b) Church of the Annunziata; c) Church of Saint Maria di Montevergine; d) Church of Addolorata; e) Church of Saint Maria de Restilianis; f) Church of Saint Maria della Purità.

could be employed based on the position of the constraint. If the constraint is on the ground, the following equation, which corresponds to the Equation C8A.4.9 of the Italian Code, is used:

$$a_{0,\min} = \frac{a_g \bullet S}{q} \tag{10}$$

where:

a_g is the peak ground acceleration, function of the probability of exceeding the chosen limit state;

S is the coefficient which accounts for the foundation soil considering both stratigraphic and topographic conditions.

q is the behaviour factor.

Conversely, when the local mechanism involves a portion of the structure located at a certain height, the following expression (corresponding to the Equation C8A.4.10 of the Italian Code) must be adopted:

$$a_{0,\min} = \frac{S_e(T_1)\cdot\psi(Z)\cdot\Upsilon}{q} \tag{11}$$

in which:

$S_e(T_1)$ is the ordinate of the elastic spectrum depending on the first vibration period T_1;

ψ is the first vibration mode in the considered direction;

γ is the modal participation coefficient. In the absence of more accurate assessments, this parameter may be calculated as 3 N/(2 N + 1),

Table 5
Comparison of indices from EL1 and EL3 - Soil A.

Church	Evaluation Level 1	Evaluation Level 3	
	Acceleration Factor f_a [-]	α_{SLV}	
		X	Y
1 – Church of Saint Antonino	1.083	0.578	0.648
2 - Church of the Annunziata	1.125	1.543	1.916
3 – Church of Saint Maria di Montevergine	**1.451**	**1.415**	0.438
4 – Church of the Addolorata	1.172	1.730	1.277
5 – Church of Saint Maria de Restilianis	**1.137**	0.986	**1.046**
6 – Church of Saint Maria della Purità	1.045	1.214	2.376

Table 6
Comparison of indices from EL1 and EL3 - Soil C.

Church	Evaluation Level 1	Evaluation Level 3	
	Acceleration Factor f_a [-]	α_{SLV}	
1 – Church of Saint Antonino	0.722	0.358	0.391
2 - Church of the Annunziata	**0.750**	**0.675**	**0.863**
3 – Church of Saint Maria di Montevergine	**0.967**	**0.832**	0.245
4 – Church of the Addolorata	**0.781**	1.041	**0.678**
5 – Church of Saint Maria de Restilianis	**0.758**	0.582	**0.636**
6 – Church of Saint Maria della Purità	**0.696**	**0.780**	1.319

where N stands for the number of floors of the building.

q is the behaviour factor.

Some of the local collapse mechanisms of the investigated churches are illustrated in Fig. 14. These include the overturning of the main façade or its tympanum, as well as the overturning of the nave's side wall or the apse.

3.4. Investigation of the global behaviour by means of non-linear analyses

Finally, the EL3 was applied to the six case studies in order to investigate their global behaviour through static non-linear analyses.

This analysis was performed using a macroelement approach implemented in the 3Muri software. The method subdivides each masonry wall panel into three components: piers (located adjacent to openings), spandrels (situated above and/or below the openings), and rigid nodes. Deformations and damage are concentrated in the piers and spandrels, while the rigid nodes—representing the intersections of these elements—are assumed to behave as infinitely stiff, transferring forces without deforming.

All models were developed using the lowest level of knowledge (KL1), associated with a confidence factor (F_C) of 1.35. This level reflects limited knowledge conditions, requiring at minimum a historical-critical analysis, a complete geometric survey, and a limited number of material tests.

Two types of masonry were identified across the case studies. All churches were constructed using regular tuff masonry, with the exception of the Church of *Saint Maria della Purità*, which was built using irregular tuff stones.

The mechanical properties corresponding to both masonry types are summarized in Table 3. Their values were determined according to Table C8.5.I from the Ministerial Circular [19], based on the confidence factor.

The three-dimensional models of the six religious buildings are depicted in Fig. 15.

Following the development of the structural models—including the accurate placement of openings and the insertion of internal floors and roof elements—the seismic action was defined in accordance with current standards.

Vertical loads include dead loads from the self-weight of structural components, which vary significantly between 4 and 6 kN/m^2 due to the diverse geometry and thickness of the masonry vaults. A variable load of 0.5 kN/m^2 was assigned to the roof structures. For spaces intended for residential use, such as the rectory, a variable load of 2 kN/m^2 was applied. These spaces typically have timber floors, whose self-weight ranges between 1 and 1.8 kN/m^2.

Special attention was given to the presence of adjacent aggregates, common in historic urban contexts. Since these aggregates often comprise historic complexes, such as convents, monasteries, or churches combined with priests' residences, the structural elements are frequently interconnected. Consequently, the masonry walls of adjoining buildings were modeled as continuous elements to capture their mutual interaction and load sharing. This approach reflects typical construction practices where physically connected walls influence the overall seismic response of the complex.

A nominal life of 50 years was assumed, consistent with typical design scenarios, and the structures were classified under Use Class III, reflecting their potential to accommodate large gatherings, as is common in churches.

In the absence of detailed in-situ geotechnical investigations, Soil Class C was conservatively adopted to ensure a higher margin of safety in the seismic assessment. In any case, this conservative assumption is supported by the geological report from the Municipality of Sorrento, which indicates that Soil Class C is the most common.

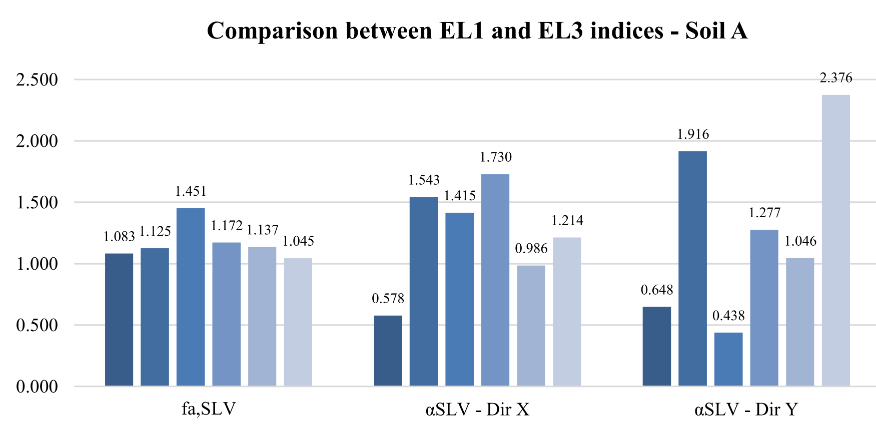

Fig. 17. Graphical comparison of factors - Soil A. (*Legend:* C1: Church of Saint Antonino; C2: Church of the Annunziata; C3: Church of Saint Maria di Montevergine; C4: Church of the Addolorata; C5: Church of Saint Maria de Restilianis; C6: Church of Saint Maria della Purità).

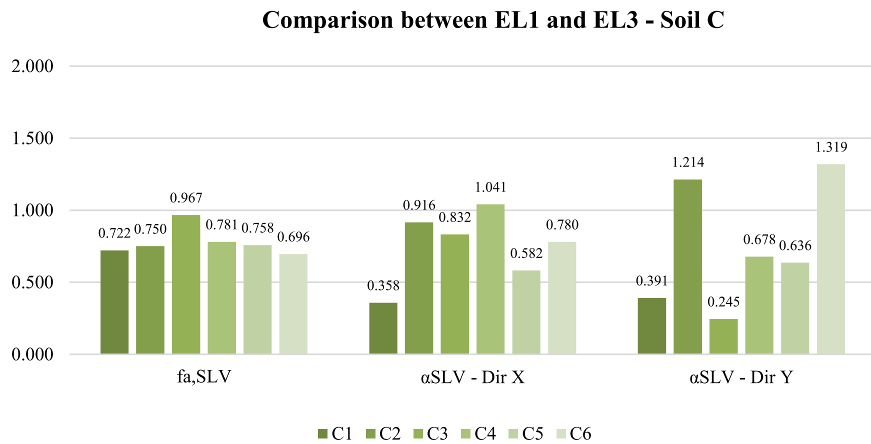

Fig. 18. Graphical comparison of factors - Soil C. (*Legend:* C1: Church of Saint Antonino; C2: Church of the Annunziata; C3: Church of Saint Maria di Montevergine; C4: Church of the Addolorata; C5: Church of Saint Maria de Restilianis; C6: Church of Saint Maria della Purità).

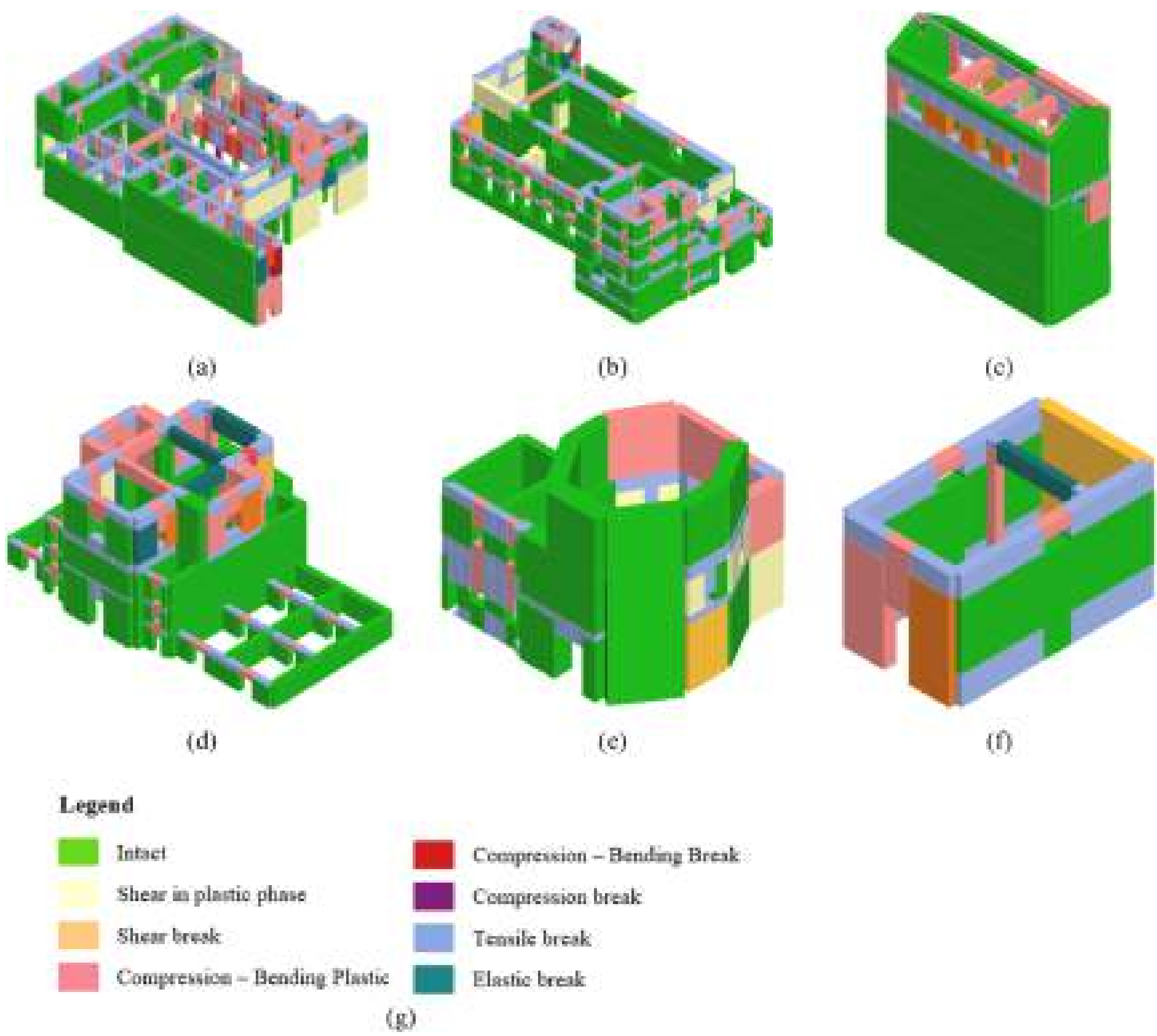

Fig. 19. Damage pattern on the three-dimensional models of the selected churches considering the Soil Type C: a) Basilica of SaintAntonino; b) Church of the Annunziata; c) Church of Saint Maria di Montevergine; d) Church of Addolorata; e) Church of Saint Maria de Restilianis; f) Church of Saint Maria della Purità; g) Legend of the mechanisms.

A summary of the adopted seismic parameters is presented in Table 4.

Once the seismic actions were selected, static non-linear analyses were conducted by monitoring the displacements of a top control node having a barycentric position. The control node was consistently selected following the Standard's recommendations, choosing a point as close as possible to the barycentric position of the building complex and at the level where the majority of the participating mass is concentrated.

Table 7
Comparison between damage indices EL1 and EL2.

Church	Evaluation Level 1 i_d	Evaluation Level 2 $i_{d,3Muri}$
1 – Basilica of S. Antonino	0.67	0.55
2 - Church of the Annunziata	0.60	0.53
3 – Church of S. Maria di Montevergine	0.53	0.64
4 – Church of the Addolorata	0.51	0.64
5 – Church of S. Maria de Restilianis	0.54	0.55
6 – Church of S. Maria della Purità	0.53	0.59

However, in the case of isolated churches lacking internal walls, the control node was positioned near the building's external perimeter.

The placement of the control node for each church is displayed in Fig. 16, where it is indicated on the plan layout generated within the 3Muri environment.

These analyses considered two distributions of inertial forces:

Proportional to static forces (Group 1): Forces were distributed according to the static mass of the structure.

Uniform distribution (Group 2): Forces were derived from a homogeneous distribution of accelerations along the structure height.

The analyses gave rise to capacity curves (Base shear vs. Top displacement) and safety coefficients $\alpha_{SLV,}$ the latter being compared with the corresponding value derived from EL1 (f_a).

4. Comparison of the indices and critical discussion of the results

Following the completion of the knowledge phase for the ecclesiastical structures and the application of the procedures outlined in the three evaluation levels of the Italian Guidelines, this section presents a comparative analysis of the indices obtained, accompanied by a critical evaluation of the results.

The first comparison focuses on the acceleration factor and the α_{SLV} safety coefficient. The acceleration factor is derived from the simplified mechanical model used in EL1, while the α_{SLV} coefficient is obtained from pushover analyses performed in EL3. Both indices represent the ratio between the capacity and demand peak ground acceleration.

In accordance with the IGCH recommendations, the acceleration factor should be calculated assuming Soil Type A, corresponding to stiff or rock-like ground conditions. However, to more accurately reflect the actual geotechnical context of each church, a dual comparison was conducted: one under the assumption of Soil Type A, and another considering the actual conditions as Soil Type C.

The results of the comparison under the assumption of stiff soil are presented in Table 5, while those incorporating the real soil conditions are shown in Table 6.

In the first scenario, assuming rigid Soil Type A, the correlation between the acceleration factor (from EL1) and the safety coefficient α_{SLV} (from EL3) appears limited. A close match—defined as a deviation within ±0.10 between the two indices—was observed in only three cases, regardless of the direction of analysis.

Another notable observation is that the α_{SLV} coefficients derived from EL3 are generally significantly higher than the corresponding acceleration factors. This discrepancy is likely due to the simplified assumptions inherent in the EL1 method, which does not account for many structural complexities. In contrast, the EL3 macroelement model provides a more accurate representation of the building's behavior, incorporating the contribution of floor diaphragms and their interaction with the masonry walls.

In the second scenario, where actual soil conditions (Soil Type C) are considered, the agreement between the two indices improves, with a higher number of cases showing a closer correspondence.

For a more comprehensive evaluation, it would be beneficial to extend this comparison to the entire set of churches. Nonetheless, the current analysis suggests that incorporating real geotechnical conditions results in better alignment between EL1 and EL3 outputs. This indicates that the acceleration factor should ideally be calculated using the actual soil conditions beneath each building, rather than defaulting to a rigid soil assumption.

The graphical representation of this comparison, for both soil types, is shown in Fig. 16 and Fig. 17.

To enable a consistent comparison between the simplified EL1 procedure and the more advanced EL3 analyses, the damage patterns from the nonlinear static analyses are illustrated on the three-dimensional models in Fig. 19.

In most cases, pushover simulations revealed widespread shear failure mechanisms (elements shown in yellow and orange), particularly affecting masonry piers along the lateral naves, the main façade, or near the apse. These failures are typically linked to large openings and the horizontal thrusts exerted by masonry arches and vaults. This behavior aligns with the low damage index values obtained during the rapid assessment. These shear failure modes correspond to several local

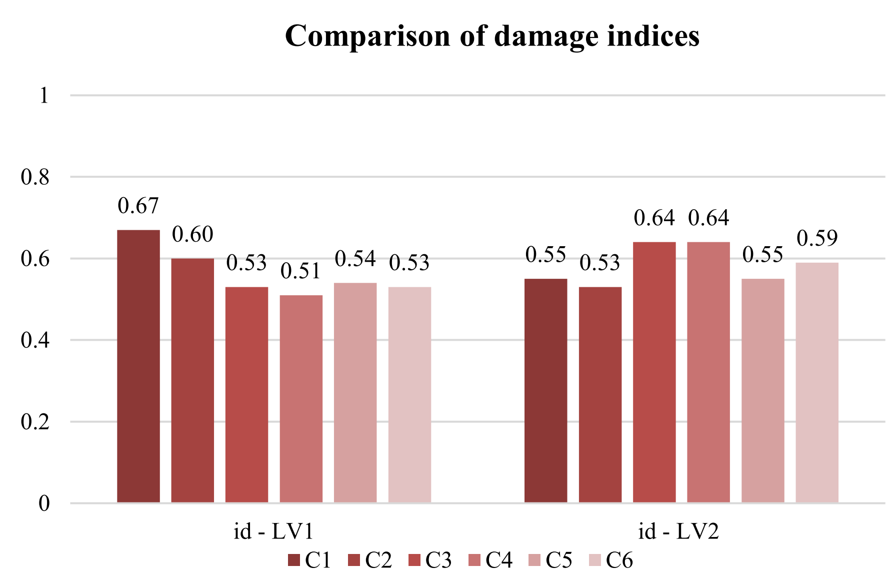

Fig. 20. Graphical comparison between damage indices from EL1 and EL2. (*Legend:* C1: Church of Saint Antonino; C2: Church of the Annunziata; C3: Church of Saint Maria di Montevergine; C4: Church of the Addolorata; C5: Church of Saint Maria de Restilianis; C6: Church of Saint Maria della Purità.).

mechanisms considered in EL1, including mechanisms Nos. 3, 5, 6, 17, 23, and 27.

Another common failure mode is compression-bending damage (elements in pink), primarily observed in the upper portions of slender wall panels, likely induced by thrust from the roof structures.Fine modulo

The second comparison focuses on the damage index obtained through the simplified mechanical model (EL1) and that derived from the evaluation of local collapse mechanisms (EL2). As illustrated in Fig. 18, a strong correlation is evident between the two sets of values. This finding is particularly significant, as it underscores the reliability of the simplified method—which evaluates 28 predefined mechanisms—for performing rapid damage assessments in churches affected by seismic events.

Notably, as provided by Table 7, the results obtained from the simplified model closely align with those produced by the more detailed EL2 analysis, in which each collapse mechanism is explicitly assessed using a mechanical model. As with the acceleration comparison, this procedure would benefit from being extended to the full dataset to confirm the general applicability of the findings.

A graphical representation of the second comparison is provided in Fig. 20.

5. Conclusions

This study set out to assess the reliability and effectiveness of Evaluation Level 1 (EL1), as proposed by the *Italian Guidelines for the Evaluation of the Seismic Vulnerability and the Reduction of Seismic Risk of Cultural Heritage (IGCH)*, in performing rapid assessments of the seismic vulnerability of historic masonry churches affected by seismic events. The central objective was to determine whether the simplified procedures outlined in EL1 yield results consistent with those obtained through more advanced analytical methods.

To this end, a series of comparisons were conducted using the main indices provided by the IGCH methodology. The analyses were carried out on a sample of twenty-seven churches in the municipality of Sorrento (Naples), following a structured multi-level approach:

- The first-level CarTiS form facilitated the identification of homogeneous sectors;
- The second-level CarTiS form enabled a detailed architectural and constructional survey;
- Based on the availability of sufficient geometric and structural data, six churches were selected for comprehensive analysis across all three evaluation levels:

a) EL1 – A simplified mechanical model was used to compute indices such as the acceleration factor, seismic safety index, damage index, and vulnerability index;

b) EL2 – Local collapse mechanisms were assessed via kinematic analysis, leading to a damage index that considers individual failure modes;

c) EL3 – Non-linear static analyses were performed using macroelement modeling in 3Muri software, providing a global understanding of seismic behavior and yielding the α_{SLV} safety coefficient.

Two key comparisons were carried out:

- EL1 vs. EL3 – Acceleration Factor vs. α_{SLV} Coefficient: When assuming rigid soil conditions (Type A)—as prescribed by the Guidelines—the correlation between the two indices was limited. However, incorporating actual soil conditions (Type C) resulted in a significantly improved correspondence. This finding highlighted the importance of site-specific geotechnical data, suggesting that reliance on default soil classifications may compromise the accuracy of EL1 assessments.
- EL1 vs. EL2 – Damage Indices: A strong consistency was observed between the damage index derived from the simplified EL1 method and that obtained through the more detailed EL2 analysis of local collapse mechanisms. This result validated the robustness of the EL1 approach, demonstrating its reliability in predicting potential damage, particularly valuable for rapid post-earthquake assessments.

While the number of in-depth case studies was limited, the findings suggest that EL1 offered a sound and effective basis for preliminary seismic evaluation of ecclesiastical structures, especially in emergency contexts where time and resources are constrained. To further substantiate these conclusions, it is recommended that the full evaluation process will be extended to the entire dataset of surveyed churches. Additionally, to confirm the method's generalizability, it is essential to explore diverse architectural typologies and geotechnical settings.

Furthermore, the study emphasized the critical role of accurate site characterization, especially regarding seismic acceleration parameters. Incorporating real stratigraphic conditions significantly enhanced the reliability of results and should be considered an integral part of the EL1 procedure.

From a practical standpoint, this research provides a reliable strategy to assist local authorities, heritage preservation bodies, and civil protection agencies in prioritizing interventions. The simplified EL1 method could be integrated into decision-support systems for post-seismic reconstruction and planning, enabling consistent assessments that safeguard both the safety and cultural value of ecclesiastical heritage.

Importantly, unlike studies that focus solely on buildings already damaged by earthquakes and rely primarily on specific nonlinear procedures, this research offers a comparative evaluation across different assessment levels. This approach enhances the understanding of how vulnerability and damage indices vary between methodologies and under different analytical assumptions.

In conclusion, the research supported the use of EL1 as a valuable and efficient tool within broader strategies aimed at the seismic protection and conservation of cultural heritage, especially in scenarios where rapid assessment is essential.

CRediT authorship contribution statement

Giovanna Longobardi: Writing – original draft, Software, Resources, Investigation, Formal analysis, Data curation. **Antonio Formisano:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Luigi Amitrano:** Writing – original draft, Software, Investigation, Formal analysis.

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Declaration of Competing Interest

The Authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data supporting the reported results can be obtained from the authors upon request.

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