Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2025) 1070-1077

ECCOMAS
Proceedia

COMPDYN 2025
10th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15-18 June 2025

ON THE DYNAMICS OF MASONRY CHURCH: DISCONTINUOUS AND CONTINUOUS APPROACHES

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Abstract

In a time when ensuring the safety of existing buildings according to modern standards is paramount, evaluating the stability of masonry structures against hazards poses a significant challenge. While masonry is known for its versatility and durability, issues such as insufficient material property data, irregular geometries, and aging complicate structural assessments. To address these challenges, various modeling techniques have been developed through extensive scientific research. This paper critically examines innovative approaches, focusing on a comparison between the Finite Element Method (FEM), a continuous approach, and the Discrete Element Method (DEM), a discontinuous approach, applied to a case study impacted by the 2016 Central Italy earthquake. The FEM is analyzed using Midas FEA NX©, while the DEM is explored with 3DEC© and LMGC90© software, utilizing different contact conditions. The study reveals the strengths and weaknesses of each method: the DEM excels in accurately replicating failure patterns, whereas the FEM offers a quicker setup process, making it suitable for preliminary dynamic analyses of structures..

Keywords: Collapse mechanisms, Finite Element Method, Distinct Element Method, Masonry, Non-linear dynamic analysis.

doi: 10.7712/120125.12472.26080

1 INTRODUCTION

Monumental churches constructed with historical masonry face formidable structural challenges, particularly in seismically active regions. As a non-linear material, masonry exhibits distinct characteristics—such as discontinuities, low tensile strength, and anisotropic strength profiles—that render it particularly vulnerable to earthquake-induced damage. When seismic forces are applied, these structures often manifest failure modes including cracking, crushing, and sliding along joints, potentially leading to catastrophic collapse [1–4].

Assessing the structural integrity of historical masonry churches is further complicated by factors such as irregular geometries, substantial wall masses, and heterogeneous materials that do not behave uniformly. These complexities hinder predictions regarding how these edifices will respond to dynamic loads, especially since masonry construction relies more heavily on compressive strength than lateral stability [5–9].

To navigate these challenges, advanced numerical modeling techniques are essential for accurately capturing potential collapse mechanisms. Contemporary tools, including non-destructive testing and sophisticated numerical models, are vital for understanding the structural behavior of these monumental churches. Notably, both continuous and discontinuous modeling approaches play critical roles in seismic analysis [10–15].

The continuous approach, typically implemented through the Finite Element Method (FEM), assumes a homogeneous material distribution, making it effective for modeling the in-plane behavior of masonry walls while facilitating rapid analysis. Conversely, the discontinuous approach, which includes methods like the Discrete Element Method (DEM) and the Non-Smooth Contact Dynamic (NSCD) Method, provides deeper insights into seismic failure mechanisms by simulating the interactions between masonry blocks and tracking the evolution of cracks and joint sliding [16–19].

A pertinent case study is the Chiesa di San Giacomo in Ascoli Piceno, a historic church that sustained significant damage during the 2016 Central Italy earthquake. By employing both FEM and DEM methodologies, this study evaluates the church's seismic response, particularly in the lateral walls where damage was most pronounced. Despite prior structural interventions, the earthquake revealed vulnerabilities that these modifications could not fully mitigate.

This research emphasizes the necessity of tailored approaches when assessing the seismic vulnerability of historical masonry structures. Each building's unique blend of materials, geometry, and historical context demands a combination of advanced modeling techniques for an accurate structural evaluation. The integration of FEM and DEM offers a comprehensive framework for predicting collapse mechanisms, ultimately aiding in the preservation of these cultural heritage sites for future generations [20–22].

2 THE CASE STUDY

The church is situated in the historic center of Ascoli Piceno, in the southern Marche Region. Currently, no evidence has been found of any pre-existing structures at the church site. However, it is plausible that earlier buildings may have existed, as churches from that era were often erected on sites of prior religious significance. Excavation work conducted between 1935 and 1936 confirmed the absence of ancient structures; at a depth of just 60 cm, no walls or foundations were uncovered. The sole exception was a crypt featuring a stone doorway and a gabled roof, which does not appear to be pre-existing, as it is enclosed by the church's foundation and tower walls. This indicates that the crypt and the church were likely constructed simultaneously, unless the church's dimensions were adjusted to accommodate an older structure potentially linked to an ancient Roman sewer beneath the site. Further excavation is needed to validate this hypothesis.

The current church is believed to have been built in the latter half of the 13th century by local stonemasons and "magistri de petra" from Ascoli, who were active in the region during the 13th and 14th centuries, as documented in archival records. Constructed from local travertine in the Romanesque style, akin to other churches in Ascoli from that period, the church retains its original orientation, with the main entrance facing west and the apse oriented to the east (Figure 1).

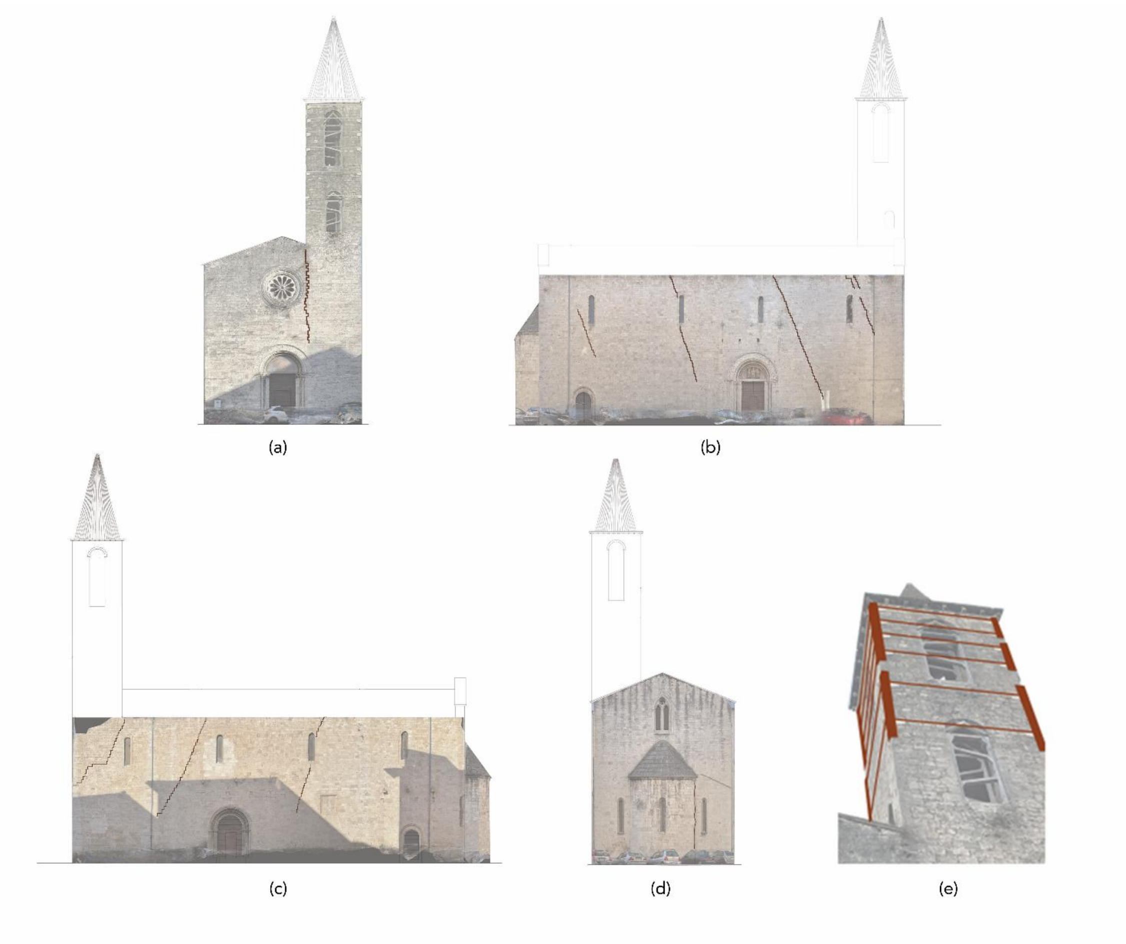

Figure 1: The four façades with the damage after the seismic sequence of 2016.

3 THE NUMERICAL MODELLING

This study explores the seismic response of the Church of San Giacomo through a comparative analysis of two modeling approaches (Figure 2): the Discontinuous Model (DM) and the Continuous Model (CM). The primary distinction between these methodologies lies in their treatment of material nonlinearity.

The DM conceptualizes the church as a collection of discrete masonry blocks, emphasizing nonlinearity primarily within the mortar joints. This approach allows for a detailed examination of how individual blocks interact under seismic forces. For this model, the Discrete Element Method (DEM) and Non-Smooth Contact Dynamics (NSCD) are employed, utilizing 3DEC© and LMGC90© software, respectively. These tools are adept at capturing the discrete geometry of the masonry and the complex interactions at the mortar interfaces.

In contrast, the CM assumes a uniform distribution of material properties throughout the structure, treating it as a continuous medium. Developed using Midas FEA NX©, this model employs the Concrete Damage Plasticity (CDP) framework, which simplifies the analysis but risks neglecting the nuanced behaviors of joints during seismic events.

To ensure accuracy, the mechanical properties were calibrated according to Italian standards (2018), drawing on data for "Random Rubble Masonry" (low-quality masonry) and "Solid Bricks and Lime Mortar" (high-quality masonry). In this calibration, the tensile strength was set at one-tenth of the compressive strength, adjusted by a confidence factor of 1.35, reflecting the variability inherent in historical masonry structures.

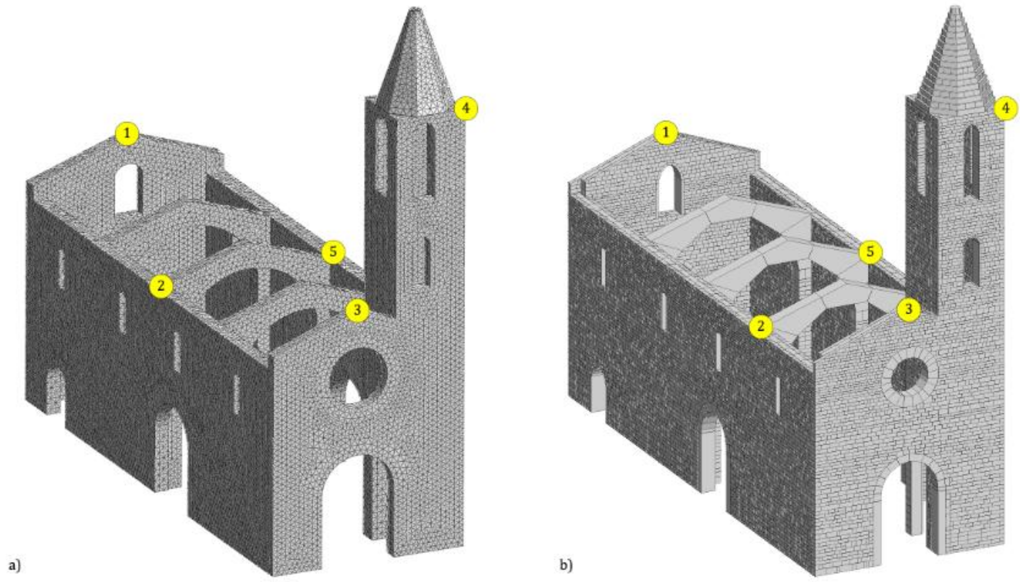

Figure 2: Finite element (a) and Distinct element (b) models with control points used in subsequent nonlinear dynamic analyses.

4 THE NONLINEAR DYNAMIC ANALYSIS

The dynamic structural response of this historic church was assessed through nonlinear dynamic analysis utilizing detailed numerical models. The analysis commenced with the application of gravitational loads alone, followed by the sequential introduction of the 2016 Central Italy earthquake series, which encompassed four significant events recorded between August 24 and October 30. This seismic sequence was selected due to its observed damage patterns, which reflect the cumulative effects of prolonged seismic activity, complicating the identification of the initial onset of damage.

This methodology facilitated a more realistic simulation, providing valuable insights into both the strengths and limitations of the approach, as well as the progression of damage over time. Seismic data were sourced from the Ascoli Piceno (ASP) reference station within the Italian Accelerometric Archive (ITACA) (see Figure 3). To model cumulative damage effects, the earthquakes were applied sequentially. For efficiency, only the 10-second intervals surrounding the largest peaks and a 2-second interval of zero acceleration between shocks were utilized, culminating in a total simulation duration of 46 seconds. A time step increment of 0.005 seconds was implemented, incorporating accelerations in three spatial directions—north-south, east-west, and vertical. Table 1 summarizes key information regarding the four analyzed seismic events.

Seismic Event	Station	M_L	Depth [km]	PGA [cm/s^2]	PGV [cm/s^2]	PGD [cm]
24/08/2016 (03:36:32)	ASP	6.00	37.8	86.77	3.518	0.986253
26/10/2016 (17:10:36)	ASP	5.40	42.9	34.010	1.193	0.191321
26/10/2016 (19:18:06)	ASP	5.90	42.9	67.171	2.598	0.783108
30/10/2016 (06:40:18)	ASP	6.10	44.0	117.643	7.532	5.930450

Table 1: The main characteristics of the four quakes employed in the analysis.

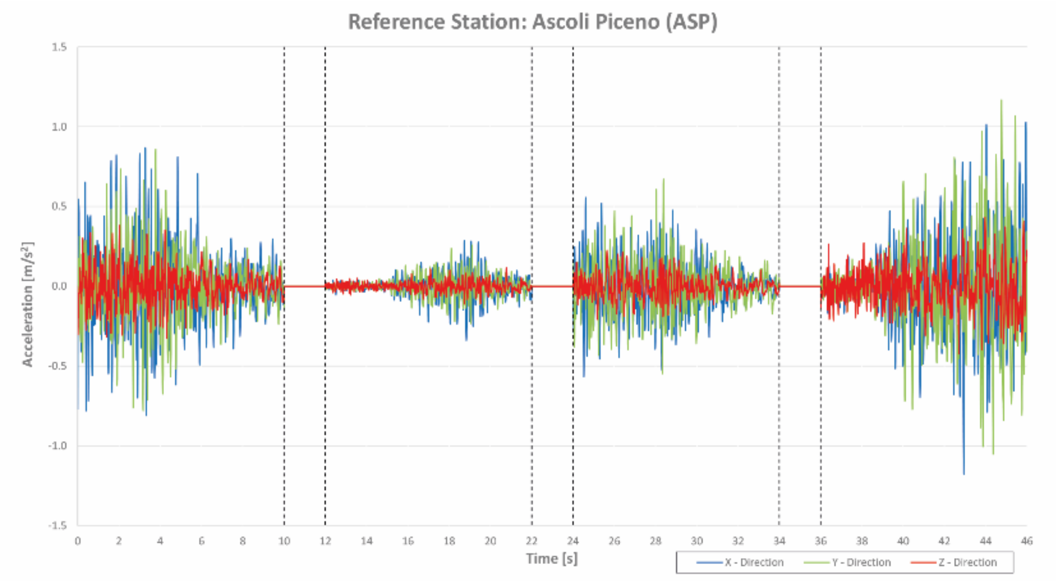

Figure 3: Seismic sequence applied for the nonlinear dynamic analysis (ASP- Station).

5 NUMERICAL RESULTS

This section presents the findings from the nonlinear dynamic analysis of the Church of San Giacomo Apostolo in Ascoli Piceno, employing both continuous and discontinuous numerical models. Five control points (P_1 to P_5) were established to monitor structural displacements in the x, y, and z directions (refer to Figure 2), strategically positioned on the east and west façades, lateral walls, and the bell tower.

The time history analysis results for these points are detailed, alongside data on block sliding and masonry tensile damage at four elevation levels for each modeling approach (DEM, NSCD, CDP) (see Figures 4). The findings reveal that displacements remained minimal until the final seismic event, with peak displacements reaching approximately 1 cm by the third event. In the x-direction, transverse wall points (P_2 and P_5) exhibited consistent displacements across all models, while greater variations in the y-direction were observed in the DEM and CDP models, indicating structural variability in wall connectivity.

In the orthogonal orientation, the front and rear façades demonstrated similar displacement patterns in the x-direction, suggesting coupled behavior, whereas z-direction displacements generally stayed below 10 mm. By the last seismic event, x-direction displacements surpassed 40 mm at several control points (P_1, P_2, P_3, and P_5) in the DEM and CDP models, while the NSCD model showed divergence due to convergence issues. Notably, the tower exhibited detachment from the main structure, particularly along the west-facing façade, resulting in significant tensile damage around structural openings and at the tower connection.

A comparison of numerical and observed crack patterns indicates that each model effectively reproduces the existing damage configuration. The continuous model adeptly captures diagonal failures and shear in internal arches and vaults, while the discontinuous models offer detailed insights into localized damage mechanisms, especially around critical areas such as the bell tower and main façade.

Importantly, displacement responses began to diverge after 34 seconds, marking the onset of localized failure mechanisms in the discontinuous model, attributed to its capacity to simulate interactions and joint sliding between masonry blocks. This divergence underscores the unique strengths of each modeling approach in accurately reflecting complex structural behaviors during seismic events.

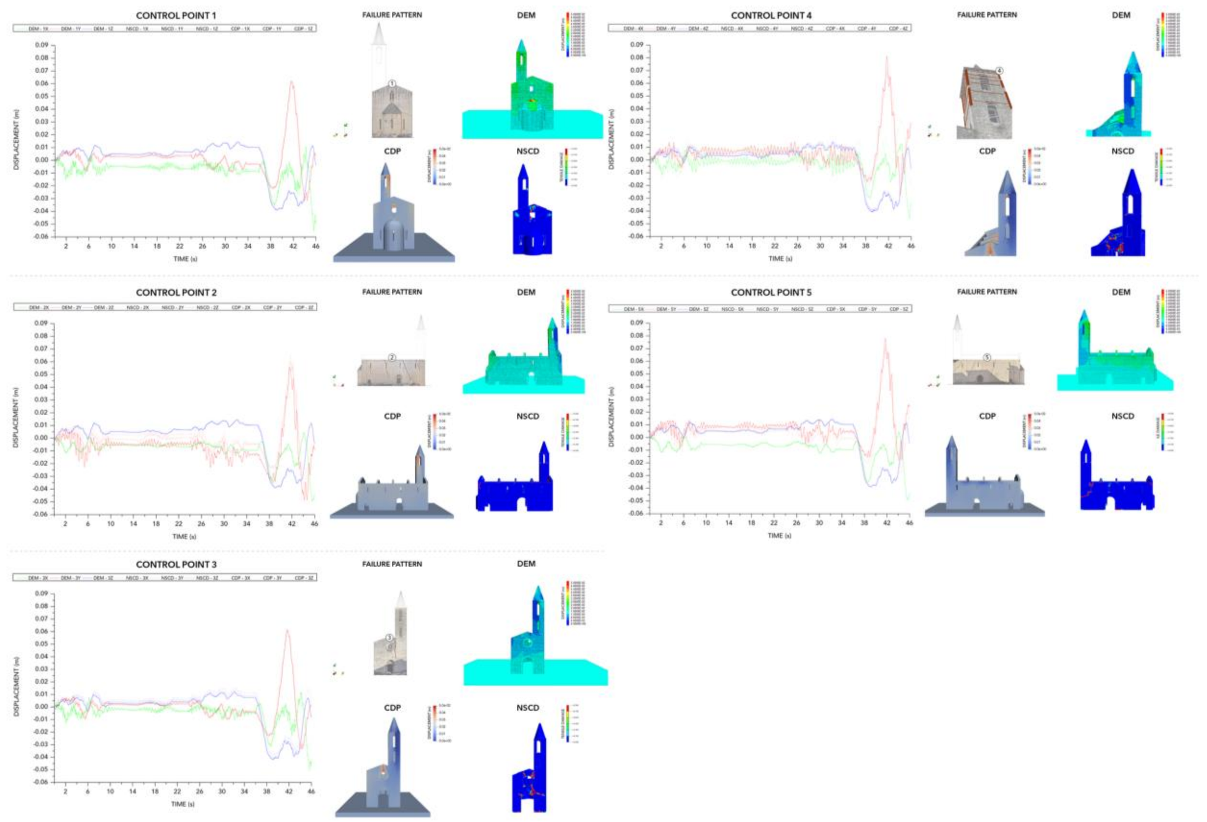

Figure 4: Displacements and comparison of failure pattern with numerical damage in the three models for each control point.

6 CONCLUSIONS

This study investigates the structural integrity of San Giacomo Church in Ascoli Piceno, Italy, following damage from the 2016-2017 Central Italy earthquakes. Utilizing nonlinear dynamic analyses, both continuous and discontinuous modeling approaches were employed.

The continuous model treated the masonry as isotropic and homogeneous, while the discontinuous model represented it as a collection of three-dimensional blocks, accounting for mortar properties and inter-block interactions. Both models analyzed structural response across four major seismic events, yielding comparable displacement data.

Although both models replicated observed damage patterns, their precision varied. The continuous model was effective in regions where masonry texture had minimal impact, whereas the discontinuous model excelled in areas with irregular masonry, highlighting critical block interactions.

Ground motions recorded near the site were applied to the models, focusing on the peak 10 seconds of each event to optimize computational efficiency. Accelerograms in the discontinuous model and CDP method were used to evaluate the church's vulnerability across three spatial directions.

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