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Alternative approaches to computational mechanics: Blender for the analysis of earthquake-damaged historical buildings

Martina Di Giosaffatte[a], Mattia Schiavoni[a], Francesca Roscini[b], Francesco Clementi[a,*]

[a] *Department of Construction, Civil Engineering and Architecture (DICEA), Università Politecnica delle Marche, Via Brecce Bianche 12, 60131, Ancona, Italy*
[2] *Department of Engineering, Niccolò Cusano University, Via Don Carlo Gnocchi 3, 00166, Rome, Italy*

Abstract

The Italian historical building stock largely consists of masonry structures built without seismic design criteria, making them particularly vulnerable to earthquakes. This structural fragility, combined with the significant seismic hazard of the territory, highlights the need for analysis tools designed to provide reliable assessments within reasonable timeframes. Conventional numerical methods, such as the Discrete Element Method (DEM), while highly accurate, require extensive input data, complex modeling, and significant computational resources, limiting their effectiveness in the preliminary assessment of historic buildings characterized by irregular geometries and heterogeneous materials. This study explores an alternative approach based on the use of Blender, a 3D modeling environment originally developed for graphical purposes, integrated with the Bullet Constraints Builder (BCB) engine. The ability to import point-based geometries and customize deformation behavior through scripting provides a lightweight and flexible tool for simulating structural response up to collapse. The analysis was conducted by applying the approach to the Civic Tower of Amatrice, damaged during the 2016 Central Italy earthquake sequence. Results show that Blender effectively reproduces the stiffness distribution and main deformation patterns, with significantly reduced computational times compared to traditional methods. Although it does not replace more detailed models for the analysis of complex collapse mechanisms, this methodology represents an effective intermediate tool for rapid preliminary assessments of historic structures.

Keywords: Masonry structures, Seismic vulnerability, Discrete Element Method, Blender, Bullet Constraints Builder, Computational time

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* Corresponding author. Tel.: 3402733978;
E-mail address: francesco.clementi@univpm.it

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1. Introduction

The structural analysis of masonry buildings, particularly those of significant historical and cultural heritage, demands modeling approaches (Ferrante et al. 2021; Giordano et al. 2020; Schiavoni et al. 2023b, 2023a, 2025; Schiavoni, Roscini, and Clementi 2024) that accurately capture their complex mechanical behavior under various loading conditions (Bartoli, Betti, and Vignoli 2016; Cavalagli, Comanducci, and Ubertini 2018; Clementi et al. 2018; Malena et al. 2019; Sorrentino et al. 2019). Traditionally, the Equivalent Frame Model (EFM) (Lagomarsino et al. 2013; Sim\~{o}es et al. 2020; Vanin, Penna, and Beyer 2020) has been widely adopted due to its computational efficiency and simplicity. By idealizing masonry walls as systems of nonlinear macro-elements, such as beams and piers, EFM effectively simulates the in-plane behavior and key structural mechanisms at a global scale. However, this approach inherently relies on predefined failure modes and significantly simplifies out-of-plane effects, limiting its ability to accurately represent localized damage phenomena, complex three-dimensional behaviors, and nonlinear responses in advanced stages of deformation.

In contrast, the Discrete Element Method (DEM) (Cundall and Strack 1979) presents a more refined and physically grounded modeling framework by explicitly representing masonry as an assembly of discrete blocks interconnected through contact laws that govern friction, cohesion, and potential detachment (Luding 2008). This micro-mechanical approach faithfully reproduces the geometric arrangement and mechanical interactions of masonry components, enabling detailed simulation of crack initiation, joint separation, and progressive collapse mechanisms. Despite its high fidelity, DEM is computationally intensive and requires careful calibration of numerous contact parameters, which poses challenges in terms of computational resources and modeling expertise (Schiavoni et al. 2023b, 2024), especially for large-scale or complex structures.

Recently, advancements in geometry-based modeling environments such as Blender (Community 2025), combined with real-time physics engines like Bullet Constraints Builder (Kostack and Walter 2018), have opened new avenues for structural analysis of masonry heritage buildings. Although these platforms were not originally developed for engineering applications, their capacity to handle detailed mesh geometries and implement customizable physical behaviors via scripting offers a flexible and efficient alternative. Blender's rigid body dynamics simulations allow for rapid, intuitive modeling of interaction-driven structural behavior in complex geometries, making it particularly suitable for preliminary assessments and early-stage collapse investigations where input data may be limited. However, current limitations include the inability to model discontinuities such as cracking, fragmentation, or material detachment, restricting their applicability to pre-collapse phases. However, Blender's capacity to simulate stiffness degradation and deformation up to near-peak loading provides valuable insights for rapid evaluation, conservation planning, and emergency decision-making following seismic or other hazardous events.

This study focuses on leveraging the DEM approach for detailed mechanical analysis of masonry structures, while exploring the potential of Blender-based simulations as a complementary tool for efficient, preliminary structural assessments.

Nomenclature

BCB	Bullet Constraints Builder
DEM	Discrete Element Method
EFM	Equivalent Frame Model
$x_i \epsilon \mathbb{R}^3$	Position vector of the center mass of block i
$\omega_i \epsilon \mathbb{R}^3$	Position and angular velocity vectors
I_i	Inertia tensor
f_i^{ext}	External forces
m_i^{ext}	External moment
f_{ij}^{int}	Internal forces
m_{ij}^{int}	Internal moment
N_i	Set of blocks in contact with B_i

2. The case study

The Civic Tower of Amatrice, located in the historic center of the town (Fig. 1), is a masonry structure approximately 25 meters high with a rectangular plan measuring about 4.00 by 5.30 meters.

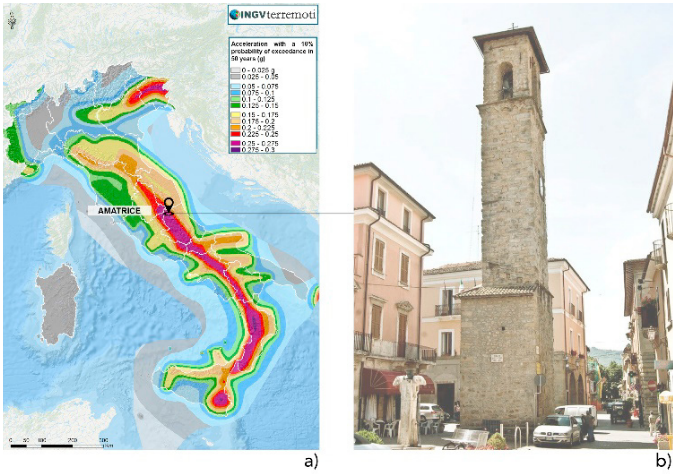

Fig. 1. (a) Geographical context of Amatrice within the Italian seismic zone; (b) view of the Civic Tower of Amatrice

The tower consists of three main vertical sections with walls that progressively thin with height. The lower section, up to about 9 meters, is constructed from roughly squared sandstone blocks arranged regularly, while the upper sections, including the bell chamber above 19 meters, feature more irregular masonry and thinner walls. The bell chamber is formed by four regular pillars with symmetrical openings and was topped by a wooden hipped roof. Adjacent to the tower's base, a small annex houses the staircase and is characterized by less orderly masonry, with squared stones at corners and a rubble core (Fig. 2). During the 2016 seismic sequence, the Civic Tower of Amatrice performed well overall, with its main masonry walls remaining intact. The most severe damage occurred in the bell chamber, which, due to its slender columns and lack of transverse connections, collapsed after the October earthquake, causing the heavy bell to fall onto the tower. Additional in-plane damage was observed at the annex base, where cracks formed due to poor masonry quality and weak connections. The main tower itself showed minimal cracking, likely thanks to prior reinforcements. To prevent further damage, a steel frame with vertical members and horizontal cables was installed to stabilize the structure.

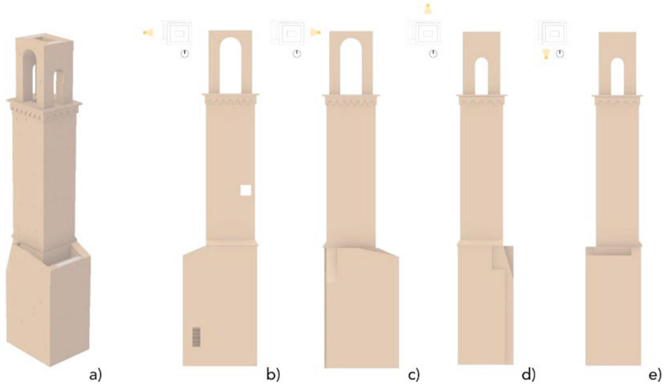

Fig. 2. Civic Tower of Amatrice: (a) Axonometric view, (b) east façade, (c) west façade, (d) north façade, and (e) south façade

3. Computational modelling strategies

A detailed three-dimensional discrete model of the Civic Tower of Amatrice was developed from a CAD-based survey, balancing geometric accuracy and computational efficiency. The external masonry was realistically reproduced with necessary simplifications, while the rubble-core infill was idealized with regular blocks and transverse elements to reflect its weak, disordered nature. The final model consists of about 11,500 blocks with mechanical properties representative of historical masonry, as summarized in Table 2.

Table 1. Material parameters used in the discrete model of Civic Tower in Amatrice

	Density [kN/m3]	**Friction** [-]
Irregular stone masonry	19	
Ashlar masonry	22	
Inner rubble masonry	19	
Masonry - Ground		0.90
Masonry - Masonry		0.50
Masonry - Inner rubble masonry		0.30
Parameters used in BCB	**Majority of contact**	
Compressive strength [MPa]	10	
Tensile strength [MPa]	0.10	
Shear strength [MPa]	0.1*(1-z/h)	

Based on this model, the study compares two numerical approaches for assessing the tower's seismic behavior: the Discrete Element Method (DEM), which allows detailed simulation of block interactions and collapse mechanisms but requires high computational effort, and the Bullet Constraints Builder (BCB), which enables faster, simplified analyses suitable for rapid assessments and emergency scenarios.

4. Bullet constraints builder framework

The Bullet Constraints Builder (BCB) is a physics-based tool integrated within Blender to model masonry structures as assemblies of rigid 3D blocks connected by nonlinear breakable constraints. The detailed geometry, typically developed in a CAD environment, is imported as a .obj file to ensure an accurate representation of each masonry unit. Each block is assigned homogeneous mechanical properties and interacts through contact points detected geometrically and handled automatically by BCB.

The dynamic response is governed by rigid-body kinematics and solved through the Newton–Euler equations:

$$m_i \ddot{x}_i = f_i^{ext} + \sum\nolimits_{j \in N_i} f_i^{int}, \qquad I_i \dot{\omega}_i = m_i^{ext} + \sum\nolimits_{j \in N_i} m_i^{int} \tag{1}$$

Contact constraints are organized into clusters within a defined interaction radius, optimizing the contact network and improving computational efficiency. Failure thresholds embedded in the constraint matrix [C] govern the transition from intact to fractured states, allowing for realistic damage propagation under unilateral contact and friction laws. A time-stepping scheme iteratively updates positions, velocities, and constraint forces, providing a robust yet efficient simulation of progressive collapse and complex nonlinear behavior.

5. Numerical analysis

The seismic analysis of the Civic Tower of Amatrice was conducted by first applying gravitational loads, followed by seismic excitations at the tower's base using ground velocity records from the Amatrice (AMT) station during the 2016 Central Italy earthquake sequence. Table 1 summarizes key information for the four analyzed seismic events.

Table 2. Characteristic of main earthquakes recorded in Amatrice (AMT) stations during the Central Italy earthquake in 2016

Seismic Event		**ML**	**Depth**	**Station**	**Channel**	**Channel**	**Channel**
					NS PGA	**EW PGA**	**UD PGA**
[-]		[-]	[km]	[-]	[cm/s^2]	[cm/s2]	[cm/s^2]
1st	24/08/2016	6	8.1	AMT	368.39	-850.8	391.37
2nd	24/08/2016	5.4	8	AMT	-93.28	105.58	63.77
2nd	26/10/2016	5.9	7.5	AMT	-58.55	90.74	-49.11
3rd	30/10/2016	6.1	9.2	AMT	393.63	521.62	317.82

The velocity time histories used for simulations have a total duration of 46 seconds, composed of 10 seconds of strong motion per event, separated by 2 seconds of zero velocity intervals (Fig. 3a). To accurately monitor the seismic response, four control points were identified on the Civic Tower model (Fig. 3b). These points were chosen to provide a representative overview of the global structural behavior during the seismic events and to serve as reference locations for comparing results across different modelling approaches.

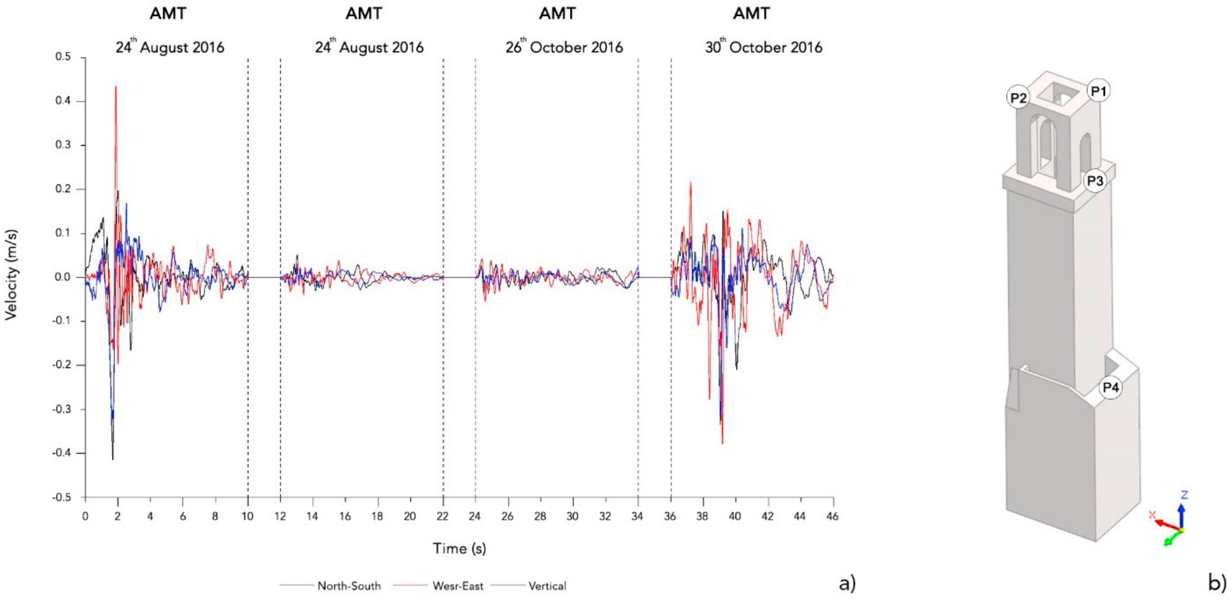

Fig. 3. (a) Velocity of strong motion recorded by the Amatrice (AMT) station and (b) location for the control points used for the nonlinear dynamic analyses of the Amatrice Civic Tower

6. Comparison between DEM and BCB Modelling Approaches

The comparative analysis between the Discrete Element Method (DEM) and the Bullet Constraints Builder (BCB) focuses on displacement trends at the predefined control points on the Civic Tower of Amatrice.

The DEM model effectively captures localized displacements and the progressive development of collapse mechanisms. In the X direction, it clearly identifies early opening and separation within the bell chamber, with deformation evolving consistently throughout the seismic sequence. This reflects a realistic disaggregation of vertical supports and failure patterns, due to DEM's detailed representation of masonry discontinuities and dynamic interactions.

Conversely, the BCB model reproduces similar overall deformation trends but tends to overestimate displacements at some control points. These amplified displacements are not accompanied by actual failure mechanisms, resulting in increasing modelling errors and less accurate damage representation.

At the tower base, point P3 experiences minimal out-of-plane displacements in both models due to geometric confinement. However, while DEM captures slight flexural behavior, the BCB model appears overly rigid, potentially limiting its ability to simulate nuanced structural responses.

Point P4 reveals significant differences: DEM predicts large displacements associated with shear deformation and out-of-plane movement typical of irregular masonry, which the BCB model fails to reproduce. This is mainly due to BCB's simplified load distribution and contact assumptions that lead to a more homogenized response.

In the Y direction, displacement trends initially align between both models. However, only the DEM captures the transition to structural instability and collapse during stronger seismic shocks. The BCB shows diverging displacement trajectories at several points but does not simulate realistic detachment or loss of contact, highlighting its limitations in dynamic failure modelling.

Overall, the DEM provides a more precise and reliable simulation of damage progression and discontinuous behavior, making it suitable for advanced collapse analysis. The BCB, while faster and easier to implement, is more appropriate for preliminary evaluations where detailed failure mechanisms are not the primary focus. The Fig. 4 shows an overview of the primary results.

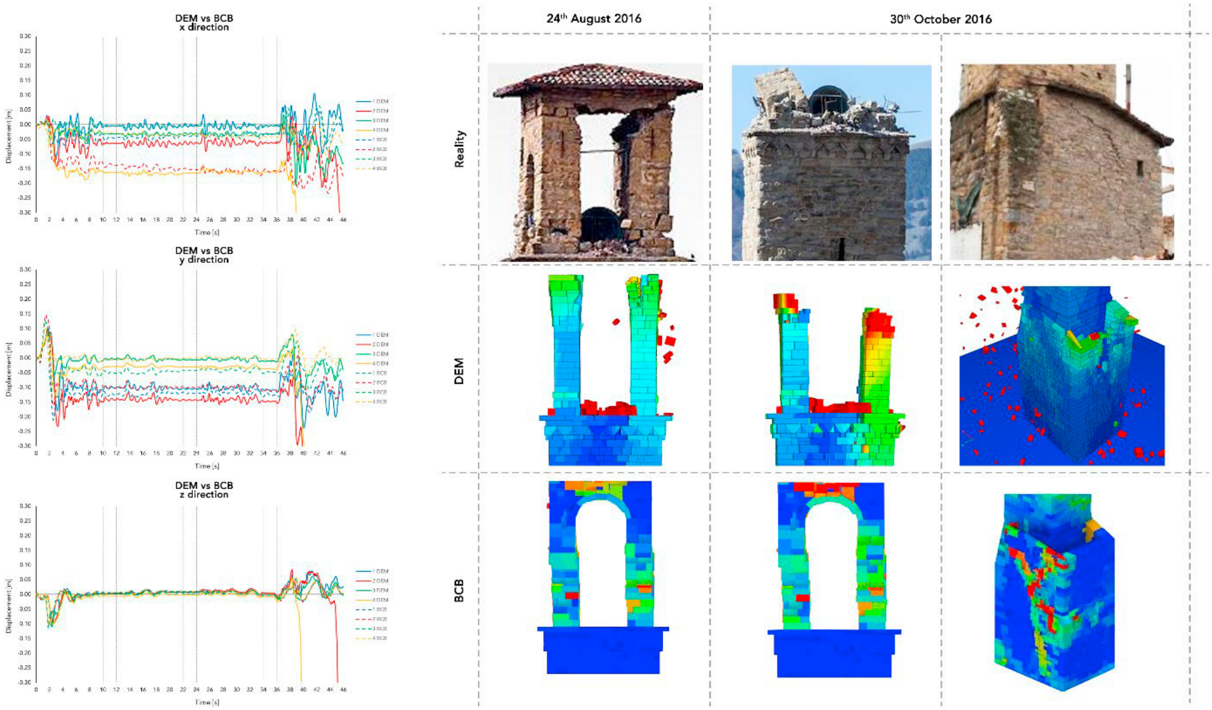

Fig. 4. Displacements and comparison of failure pattern with numerical damage in the two models

7. Conclusion

The application of the Blender-based BCB model to the Civic Tower of Amatrice demonstrated clear advantages in computational efficiency compared to the Discrete Element Method (DEM). While the DEM required nearly 960 hours for the nonlinear seismic analysis of this complex structure, the BCB completed the calculations in about 30 hours, highlighting its suitability for large-scale, detailed models with significantly reduced computational demands.

Mechanically, the BCB accurately reproduced the main displacement patterns and the onset of structural instability during the early phases of seismic excitation, simulating global kinematics comparable to those observed with DEM. This confirms BCB's potential to identify key structural triggers and collapse mechanisms at the macro scale, especially in cases dominated by rigid-body motion and geometric incompatibility.

However, some limitations were noted. The current BCB implementation does not support discrete contact evolution or element separation, limiting its ability to accurately simulate critical local phenomena such as joint opening, detachment, or masonry fragmentation. Additionally, Blender's parent–child hierarchy introduces kinematic constraints that can artificially couple elements, producing overly homogenized responses and masking local deformations, particularly evident in tower elements where outer walls move rigidly with the inner core.

Further sensitivity was found in the modeling of vertical loads, where the use of load distributions inversely proportional to wall height can induce artificial thrust or moment effects, affecting slender or unconstrained wall segments. This underscores the importance of careful load assumptions in geometrically heterogeneous masonry structures.

In summary, despite these challenges, BCB modeling offers a promising, low-cost, and accessible alternative for seismic assessment of complex historic structures like the Civic Tower of Amatrice, especially in preliminary or large-scale analyses. Future developments should focus on improving contact interaction representation and damage modeling to enhance local behavior accuracy while maintaining computational efficiency.

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