Discontinuous Dynamics of Santa Maria Annunziata Church Under Seismic Loading: A Non-smooth Contact Dynamics Approach

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Abstract. The dynamics the Santa Maria Annunziata church located in Camerino (Macerata province, Italy), subjected to transversal dynamic loadings has been analysed by using a distinct element code which implements the Non-Smooth Contact dynamics method. Since the contact between blocks is governed by the Signorini's impenetrability condition and the dry-friction Coulomb's law, the church exhibit discontinuous dynamics. The sliding motions of blocks are non-smooth functions of time. Numerical simulations are performed with the aim of investigating the influence of the friction coefficient and of some past retrofitting interventions on the global response**.** The results obtained are compared with the real damage that the Church suffered following the seismic sequence in central Italy in 2016, and for this reason the four main shock that strocked the area were used in the numerical analyses. A good agreement between the numerical and the real damages are finally obtained but it might be interesting to elaborate additional models in which the building presents different degrees of connection with the towers.

Keywords: Masonry · Historical Structure · Discontinuous Approach · Non-Smooth Contact Dynamic Method · Damage Cumulation

1 Introduction

Existing masonry structures are typically distinguished by their exceedingly flexible floors and their perpendicular walls' unclear interlocking [1, 2]. Due to these factors, post-earthquake surveys reveal collapses involving single panels collapsing out-of-plane or macroblocks (parts of structures) forming a partial failure mechanism [3]. These scenarios require targeted and specially designed retrofitting interventions [4, 5].

For structures characterized by a correct distribution of the openings and by the absence of staggered floors, it is possible to use the equivalent frame method [6, 7]. These conditions are not easily identifiable in historic buildings [8, 9], for this reason in recent years two advanced methods have been developed that allow for a numerical response with respect to the real damage, i.e., the continuous and the discontinuous

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models. In the continuous model there is a homogenization of the material without a distinction between mortar and brick. The material is therefore assumed as a continuous deformable body capable of simulating the behaviour under static and dynamic loads through constitutive laws obtained by experimental tests or through values obtained for masonry with similar characteristics [10–13]. In the discontinuous models, on the other hand, in detailed micro-modeling the masonry is represented by considering blocks and mortar [14, 15], otherwise in simplified micro-modeling the thickness of the mortar is incorporated in the blocks [16–18]. These interact with each other through contact surfaces governed by smooth or non-smooth laws [19–22]. The advantage of using this approach lies in the fact that it is possible to consider the separation of the blocks thus reproducing both in-plane and out-of-plane behavior [23–25]. Recently it has been possible to find a combination of the two methods [26, 27].

In this work the dynamic behavior of the Church of the Santa Maria Annunziata located in Camerino, in the province of Macerata (Central Italy) is chosen. The Church was studied through the discontinuous approach using the Non-Smooth Contact Dynamic (NSCD) method implemented in the LMGC90© open-source code.

Following the intense seismic sequence that stroke the central Italy in 2016, the Church was seriously damaged and closed for safety reasons.

2 The Case Study

The case study is the Santa Maria Annunziata Church, located in Camerino, in the province of Macerata, Italy. The Church is in the heart of the city and is the most relevant structure in Camerino (Fig. 1).

The Church dates to the XIII century, the first testimonies speak of a Romanesque church dedicated to San Giuseppe. In 1268 there was the first overhaul of the building, made necessary both because of the devastation suffered in 1259 at the hands of the Swabians headed by Percivalle Doria and because of the needs of the city to expand economically and demographically. Other renovations took place following the earthquake of 1279, when the bell tower collapsed.

In 1748–1749 there was an important revision of the main façade, the thirteenth-century style gave way to the baroque style. Due to the earthquake of 1799, the reconstruction of the structure was necessary. The works involve demolishing the remaining structures and completely rebuilding the Latin cross church with a longer longitudinal axis than the previous one. Other changes concerning the facade were made to this project, for this purpose it was necessary to move the plan of the Church to the North-East. It has built with traditional techniques, it is realized in masonry exception of the North-West façade which is realized in stone. On 8th September 1832, the Church was dedicated to the Santa Maria Annunziata and was consecrated.

Over the years the church has resisted several earthquakes, without significant damages to the structure. Differently, the shocks of 1979 (Valnerina) and 1997 (Umbria-Marche) caused injuries that are still identifiable thanks to the chromatic diversity of the material used in local interventions.

The nave of the Church develops for a total length of 66.60 m and a height of 30.50 m. In the Church, there is a semi-basement floor placed at a depth of 5.30 m. Compared to

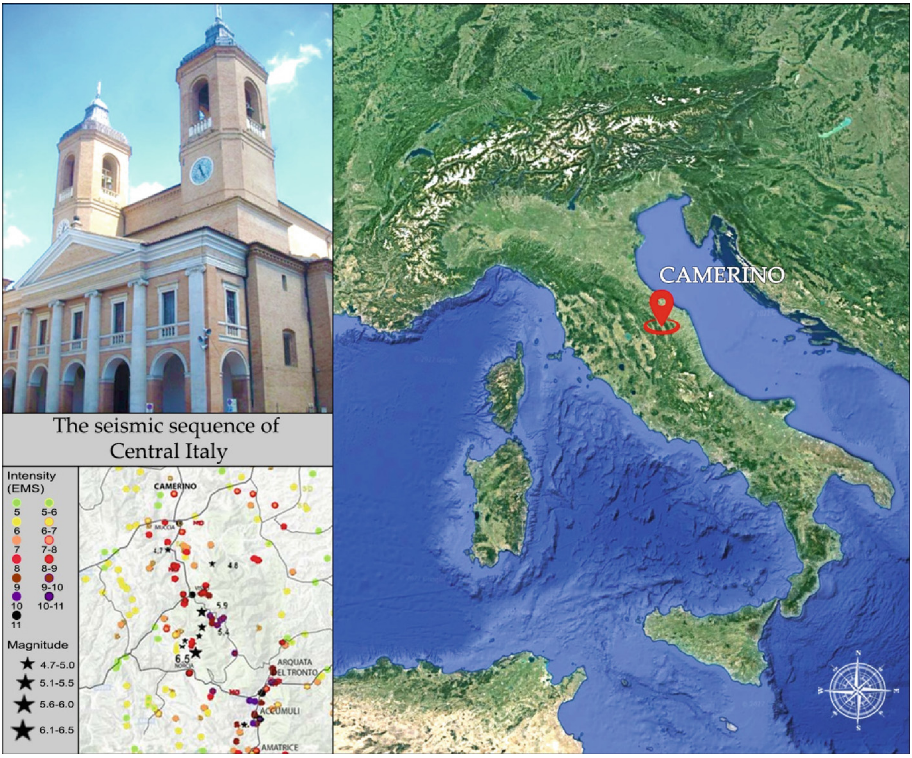

Fig. 1. The Santa Maria Annunziata Church (Camerino, Macerata province, Italy) and the Italian macroseismic intensity map.

the height at the entrance, the gable is at a height of 17,95 m while the towers reach a height of 40.10 m (Fig. 2).

Following the seismic events that hit central Italy in 2016, the Church is in a poor state. The seriously damaged parts are the façade, the towers and the connection towers-church. It is shown how the façade, due to a poor connection with the orthogonal walls was subject to the phenomenon of hammering with the consequent formation of lesions in the upper part. In the towers, on the other hand, vertical cracks can be seen that start from the openings and reach the base.

Further damage has been reported to the historical-artistic heritage present inside the Church, there are shear cracks which have caused damage to the statues inside the niches.

3 Discrete Element Method: Non-smooth Contact Dynamics Method

The masonry is represented as a collection of 3D rigid elements, where the mortar thickness is included. The elements interact each other at points of contact that are regulated by specific constitutive laws. Typically, the iteration between the bodies at the

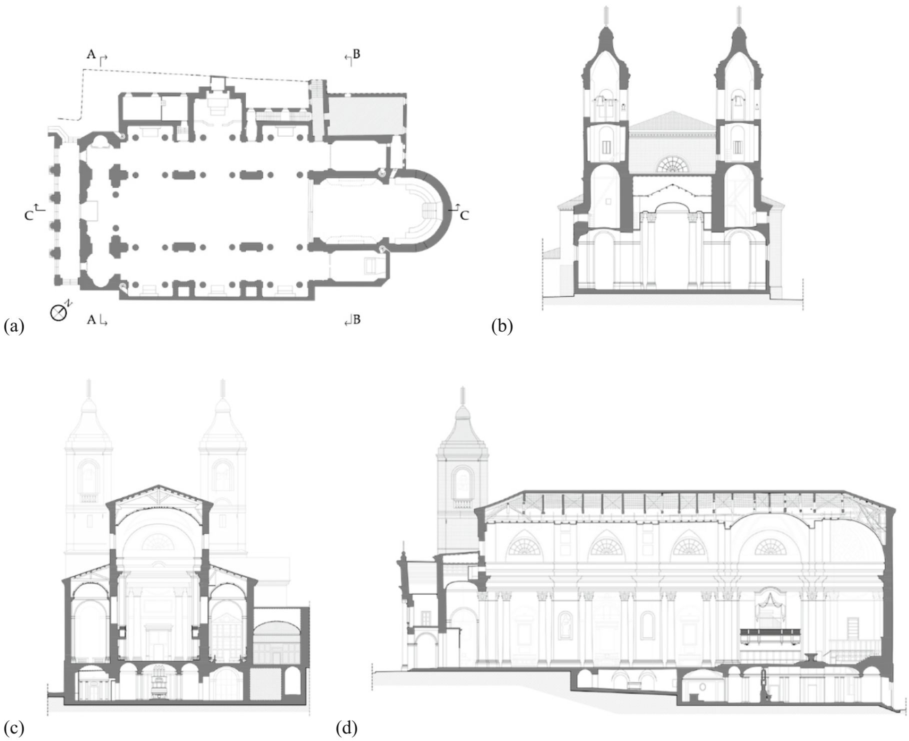

Fig. 2. Horizontal section (a), transversal section A-A (b), transversal section B-B (c) and longitudinal section C-C (d).

contact points is done by normal and shear components, which depend on the speed and relative displacement of the bodies. A realistic overall behaviour may be obtained by considering a good number of contact points.

In particular, the dynamic response of the Church of Santa Maria Annunziata is evaluated using the Non-Smooth Contact Dynamics (NSCD) method. The NSCD method is implemented in LMGC90© code [28]. This method was proposed by [29, 30] distinguishing it from the Distinct Element Method (DEM) because: (i) does not consider structural damping; (ii) integrates the non-smooth contact laws; (iii) it uses an implicit integration scheme.

Considering two bodies B_i and B_j and calling respectively P_i and P_j their possible points of contact (Fig. 3a), if n is the orthogonal unit vector at the point P_i, g is the distance between the two bodies:

$$g = \left(P_j - P_i\right) \cdot n. \tag{1}$$

Calling respectively r_n and r_t the normal and tangential forces of B_i and B_j and $\dot{u}_n$, $\dot{u}_t$ respectively the normal and tangential velocities of P_j respect P_i, we use two contact laws:

1. Signorini's law of impenetrability (Fig. 3b):

$$g \geq 0, r_n \geq 0, gr_n = 0, \tag{2}$$

$$if \;\; g = 0 \rightarrow \dot{u}_n \geq 0, r_n \geq 0, \dot{u}_n r_n = 0. \tag{3}$$

This law indicates a perfect plastic impact, i.e. Newton's law returns a coefficient equal to zero. In this way, due to the impact, there are no bounces, this can be justified by the fact that bricks and stones have a low coefficient of return, which allows to neglect bounces.

2. Dry-friction Coulomb's law (Fig. 3c):

$$|r_t| \leq \mu r_n : \begin{cases} r_t < \mu r_n \rightarrow \dot{u}_t = 0 \\ |r_t| = \mu r_n \rightarrow \dot{u}_t = -\lambda \frac{r_t}{|r_t|} \end{cases} \tag{4}$$

where the friction coefficient is μ and λ is a positive real arbitrary number. The motion equation can be expressed as:

$$M\ddot{q} = f(q, \dot{q}, t) + l, \tag{5}$$

where M is the matrix of masses, $\ddot{q}$ the acceleration, $f(q, \dot{q}, t)$ the vector of internal and external forces operating discretely on the system and l the contact's resultant. The characteristic pairs of each contact $(\dot{u}_n, \dot{u}_t)$ and (r_n, r_t) are connected to the global vectors $\dot{q}$ and l by linear mappings that depend on q, respectively.

Reactions l and velocity $\dot{q}$ are discontinuous functions of time due to the non-smooth nature of the contact Eq. (2)–(4).

When the velocities are discontinuous, Eq. (5) is integrated into time t.

The equation of motion is integrated into the interval $[t_i, t_{i+1}]$:

$$M(\dot{q}_{i+1} - \dot{q}_i) = \int_{t_i}^{t_{i+1}} f(q, \dot{q}, t)dt + \bar{l}_{i+1}, \tag{6.2}$$

$$q_{i+1} = q_i + \int_{t_i}^{t_{i+1}} \dot{q}(t)dt, \tag{6.2}$$

where $\bar{l}_{i+1}$ is the pulse in the interval $[t_i, t_{i+1}]$, $\dot{q}_{i+1}$ is the variable that approximated the speed in the time $[t_{i+1}]$. In (6) and in the local contact Eqs. (2) and (3), reactions are approximated by the average of the pulse where the contact is concentrated at the local level.

In this work the deformability of the blocks is neglected, in this way, there are no internal deformations but only the sliding and oscillation of the blocks that composed the Church.

The main purpose of the model is to reproduce as faithfully as possible the geometry and structural elements that make up the Church of the Santa Maria Annunziata. To reduce computational burdens, it was considered appropriate to use a large block modelling, the 3D model was made with the Midas FEA NX© software, reproducing the

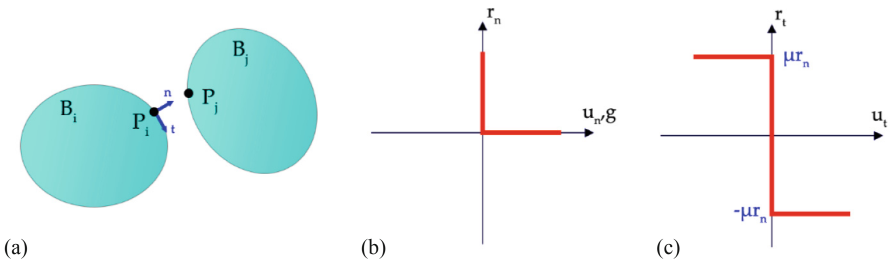

Fig. 3. Contact between bodies (a), Signorini's law (b) and dry-friction Coulomb's law (c).

blocks one by one, avoiding complex shapes, and simplifying the shape when deemed necessary.

The masonry is represented by rigid non-convex three-dimensional blocks reproducing a good interlocking between them. The openings, vaults and arches were discretized with regular blocks, and the foundation was represented with a rigid block.

It was decided to model only the vaulted floors inside the towers, for the others it was chosen to consider their contribution in terms of loads. This simplification was possible thanks to the accurate survey, which made it possible to identify the various floors. In this way, the model counts 27850 blocks (Fig. 4).

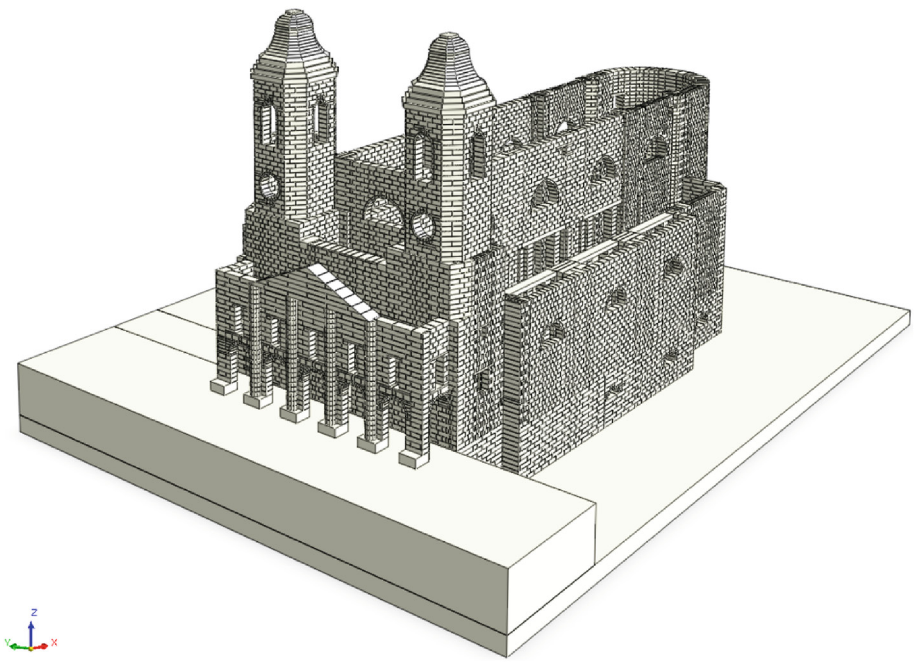

Fig. 4. View of the numerical model of the Church of Santa Maria Annunziata (Camerino, Macerata province, Italy).

The material survey shows the presence of two different materials: solid brick masonry with lime mortar (1800 kg/m^3) and cut stone with good bonding (2100 kg/m^3) in the North-West façade.

The energy dissipation in the LMGC90© is regulated by the restitution coefficient, and in this case it is imposed equal to zero (no bouncing). A friction coefficient equal to $\mu = 0.50$ was used in the interface between the blocks and equal to $\mu = 0.90$ in the interface between the blocks and the base.

4 Numerical Results

The Church is subjected to the seismic sequence of central Italy of 2016. Initially, the structure was subjected only to the gravitational force, then the seismic sequence was applied, using Matelica (MTL) as a reference seismic station. In order to reproduce the cumulative damage the four main events of the seismic sequence were considered (Table 1). For each event, the velocities in the three main directions are taken, considering 10 s of peak and 2 s of null velocities between the different shocks. In this way, the total duration of the analysis is equal to 46 s.

Table 1. The main characteristics of the four quakes considered.

Seismic Event	M_L	Depth [km]	Station	Class EC8[a]	R_{jb} [km]	R_{rup} [km]	R_{epi} [km]	NS PGA [cm/s^2]	EW PGA [cm/s^2]	U PGA [cm/s^2]
24/08/2016 (01:36:32)	6.00	63.90	MTL	B	44.49	44.49	63.90	−66.71	69.95	31.02
26/10/2016 (17:10:36)	5.40	42.70	MTL	B	39.64	40.08	42.70	−44.58	−30.00	17.63
26/10/2016 (19:18:06)	5.90	39.10	MTL	B	28.18	28.19	39.10	−240.47	−122.18	−77.86
30/10/2016 (06:40:18)	6.10	47.10	MTL	B	35.33	35.32	47.10	−122.44	75.96	−44.08

[a]Classification of site not based on direct measure of $V_{s,30}$

In Table 1 are reported the main data of the forum shocks considered where R_{jb} is the Joyner-Boore distance, or rather the smallest spacing between the rupture site and the rupture surface projection; R_{rup} is the shortest distance between the rupture site and the rupture surface and R_{epi} is the distance calculated by the geometric swap.

Finally, in Fig. 5 the damages obtained from the numerical model are compared with those that occurred following the seismic sequence in 2016.

The results obtained from the numerical model are in good agreement with the real ones. The approximation of the blocks does not faithfully trace the lesions but still identifies the most vulnerable parts. On the South-West façade (Fig. 5) the parts that have been most affected by the seismic sequence of central Italy are the two bell-towers.

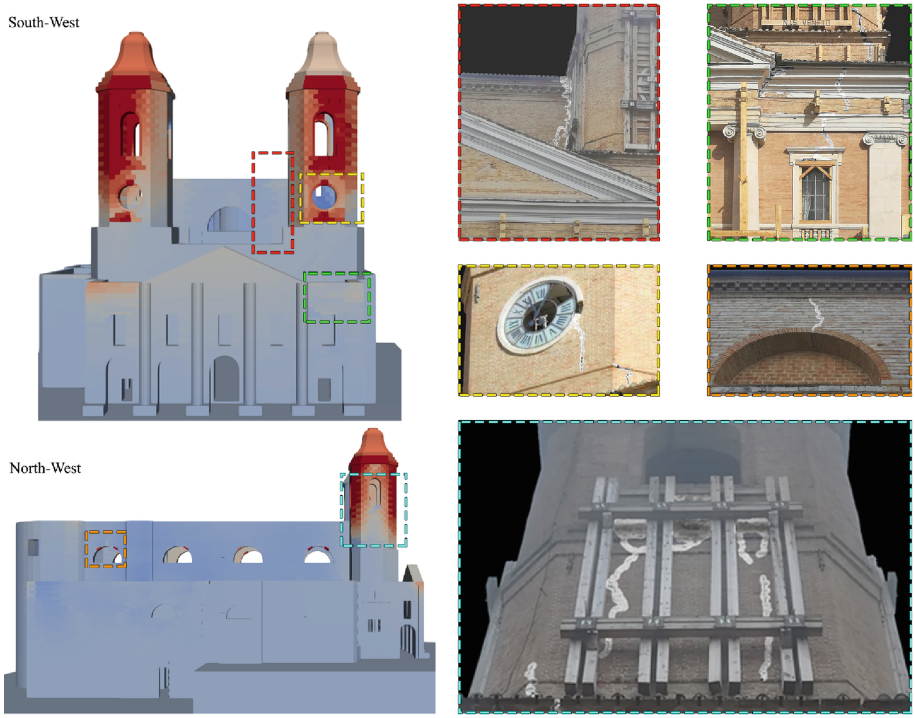

Fig. 5. Comparison between the numerical and real damages after the seismic sequence of central Italy in 2016.

Lesions can be seen in correspondence with the clock and in correspondence with the tower-to-church connection caused by hammering between the walls. On the North-West façade (Fig. 5), on the other hand, the most evident cracks concern the whole part of the bell tower and the openings placed on the nave of the Church.

5 Conclusions

The Church of Santa Maria Annunziata placed in Camerino (Macerata province, central Italy) was analysed with the seismic sequence of central Italy in 2016. To reproduce the cumulative damage, the four main shocks are applied in sequence. To investigate the dynamic behaviour of historical masonry structure the discrete approach is used, specifically trougth the NSCD method developed in the LMGC90© code. Thanks to the approximations used in the NSCD method, i.e., (i) does not consider structural damping; (ii) integrates the non-smooth contact laws; (iii) it uses an implicit integration scheme, it was possible to obtain great predictive capabilities.

In agreement with the real damage, it is possible to notice how the numerical model identifies the most vulnerable parts, i.e., the bell cells and the tower-to-church connection. Therefore, to obtain extremely more accurate results it is necessary to use a more accurate discretization (with extremely high computational costs).

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