Seismic Modelling of a Masonry Monument Including the Interaction of the Vaults, Longitudinal Walls and Soil

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Abstract. The efficient preservation of masonry monuments presents several challenges given that they are characterized by much larger uncertainties than ordinary buildings and conventional analysis tools may fail in providing a reliable characterization of their structural behavior. A complete understanding of the structural behavior of masonry monuments requires integration of historical, topographical, structural, and geotechnical information. From 2010, an interdisciplinary committee has been established to study the Cathedral of Modena, a masterpiece of Romanesque architecture in Italy. Great effort has been devoted to the assessment of the structural health of the Cathedral, revealing that the vaults are the most vulnerable components, and that the dynamic response may be significantly affected by differential soil properties at the supports. The Discrete Element Method provides a useful numerical tool to assess the dynamic behavior of masonry buildings, though previous work has been primarily focused on the structural response with less attention devoted to soil-structure interaction. In this study, a simplified modeling technique is employed to account for soil structure interaction within the DEM framework. More specifically, a specific cross section of the Cathedral, characterized by different soil properties at the supports and the absence of tie-rods, is studied. The results indicate the importance of the soil effects on the structural response.

Keywords: Historical masonry monuments · Masonry vaults
Discrete element methods · Soil interaction

1   Introduction

The evaluation of the structural health of the historical monuments presents one of the greatest challenges due to their inherent complexity, such as the articulated geometry, the variability of materials used and ancient construction techniques employed. Moreover, the natural decay of the materials, the effects of any events that may have caused damage (such as past earthquakes…) and possible past structural interventions increase the uncertainties on the actual state of the structure. Integrated knowledge of a

monument is, thus, the first step to develop consistent structural analyses and to understand correctly its vulnerabilities. A correct and complete analysis of a historical building has to be based on the historical, geometrical, material and structural knowledge of the structure in order to design structural interventions not only to guarantee safety, but also to respect the context, which surrounds them [1, 2]. Moreover, the most widespread construction material used, especially in Italy, for historical monuments is masonry. Masonry is characterized by a complex mechanical behaviour due to its composite nature resulting from the interaction of bricks and mortar (both characterized by significantly different behaviour under tension and compression) thus leading to specific issues when analysing and modelling these constructions. In the FE framework, masonry is often modelled as a homogeneous continuum. While this procedure may give indications on the global structural response, it is not suitable for detailed stress analysis of specific portions or elements, due to the difficulty of capturing all expected failure modes [3]. In the light of these considerations, the Cathedral of Modena has been studied for almost one decade through the mutual exchange of expertise of different disciplines within of a Scientific Research Committee. The information obtained through the integrated knowledge revealed that the vaults are the most vulnerable components, and that the dynamic response may be significantly affected by differential soil properties at the supports. In this work, a specific cross section of the Cathedral of Modena is investigated through Discrete Element (DE) modelling to take into account soil-structure interaction.

2   The Cathedral of Modena

The Cathedral of Modena, whose construction began in 1099 and finished in 1184, was declared "UNESCO Cultural Heritage" site since 1997. The Cathedral is connected to the contiguous Ghirlandina Tower (a tower of about 86 m height) through two masonry arches. The plan configuration is characterized by a wide nave flanked with two aisles along the sides and a semicircular apse at the ends. More details on the history and geometry of the Cathedral are available in a previous work by some of the authors [4] (Fig. 1).
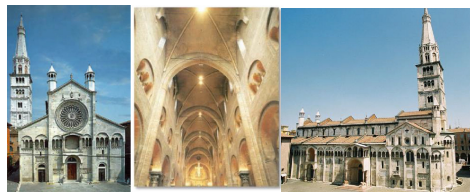
Fig. 1. Cathedral of Modena

2.1   The Actual State of Conservation and the Main Vulnerabilities

The research of the interdisciplinary committee carried out during the last decade led to a deep knowledge of the actual state of conservation of the Cathedral and allowed identification of its main structural vulnerabilities and criticalities. Interventions and transformations during the centuries give rise to the present configuration of the Cathedral. Studies on the history of the Cathedral allow reconstruction of the construction phases. Construction started from the apses and ended with the main façade. Subsequently, repairs due to damage caused by early soil settlements occurred during these initial construction phases [4]. In fact, the actual Cathedral was built on the ruins of previous Cathedrals. However, the ruins only occupy a portion of the actual plan, causing a discontinuity in the soil stiffness beneath the structure (see Fig. 2a).
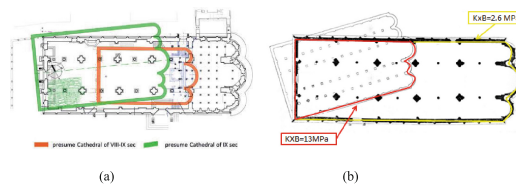

Fig. 2. (a) The pre-existing cathedrals. (b) Non-uniform distribution of Winkler's constant.

The adjacent 88-m high Ghirlandina Tower was constructed almost in parallel with the Cathedral itself, up to 60 m of height, corresponding to the fourth level, whereas the remaining has been realized in a subsequent period (between 1261 and 1319). [5]. The presence of the Tower caused significant differential soil settlements. These differential settlements, together with the discontinuity in the soil stiffness due to the presence of the ruins, caused significant out-of-plane deformations of the external walls (as revealed by a 3D laser scan) [6]. Geotechnical investigations were conducted to obtain the soil mechanical properties in order to properly account for the vertical and lateral soil stiffness in the structural analyses.

In order to take into account the different consolidation of the soil, two values of the Winkler constant have been considered (Fig. 2b). All the details on the information obtained through the integrated knowledge of the actual state of the Cathedral are available in [7].

The evaluation of the degradation state of the main structural elements has been carried out by means of cracking pattern survey performed in 2010. The results show vertical cracks along the arches and the main transversal walls, which separate the central nave from the aisles. The main cracks (visible in the gray portions of Fig. 3a) are mainly located in the portions coincident with the transition area between different soil properties, due to the presence of ruins beneath part of the Cathedral. After the 2012 Emilia earthquakes, a second survey revealed the presence of new cracks, mainly localized in the vaults (Fig. 3b).
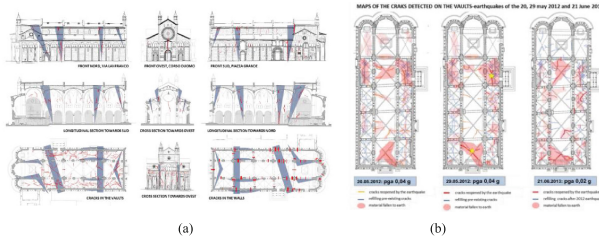
Fig. 3. (a) Cathedral's crack pattern after the 2010 survey (b) Localization of the cracks detected on the vaults after the 2012 earthquakes (May 20 and 29, 2012, and June 21, 2013)

3 The Global Structural Behaviour

The structural behavior of the Cathedral has been investigated through 3D FE models of increasing complexity. The results obtained in term of static behavior and the details of the FE models are presented in a previous work [7]. Moreover, time-history analyses have been conducted by imposing at the base of the Cathedral (along the y and x-direction) the acceleration as recorded during the 20th May 2012 Emilia Earthquake at the station of Modena (MDN) [8]. The record is characterized by a peak ground acceleration PGA of around 0.04 g and by the pseudo-acceleration response spectrum (with 5% damping ratio) as shown in Fig. 4a. The soil has been modelled through linear springs (active in both horizontal and vertical directions) with stiffness values based on the results of the geotechnical investigations. The aims of the simulations was to quantify the maximum longitudinal (along y-direction) and transversal displacement responses (along x-direction) at the springings of each vault and then to compute the opening/closing displacement component (e.g. relative displacement along the y-direction indicated by the dashed lines in Fig. 4b, vault VNC4) and the shear defor-mation component (see dashed lines in Fig. 4b, vault VNC2). The maximum values of widening/closing displacements obtained are of the order of 0.1 cm (almost negligible), whereas maximum shear displacements are around 0.5 cm.
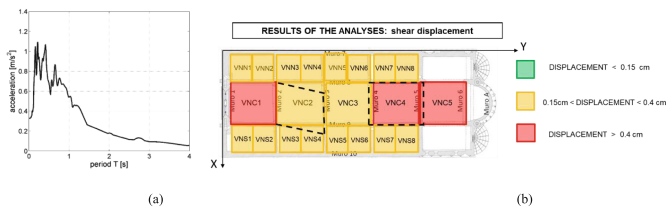
Fig. 4. (a) Pseudo-acceleration response spectrum (5% damping ratio) of the 20 may 2012 Emilia Earthquake, Modena MDN record. (b) Nomenclature of the vaults of the Cathedral and shear displacement at the springings of the vaults as obtained from the time history analyses

4   DEM Analyses of a Transversal Cross Section

In the light of the results obtained by the surveys, the cross section located in the fourth span from the west, characterized by different soil stiffness and the absence of tie-rods, appears to be the most vulnerable portion of the Cathedral. This cross section is here analyzed by means of the Discrete Element Method (DEM) in order to evaluate the interactions between the vaults and the longitudinal walls and the influence of the different soil stiffness at the base, under both static and seismic loads. DEM models were developed with uniform depth of 1 m, but the density of the blocks and the stiffness at the interfaces were modified to take into account the depth of 10 m of the walls and of the vaults and the weight of the overlying non-structural elements, in order to evaluate the dynamic response of one bay of the structure (see Fig. 5a). Two-limit schematizations were considered in the analyses:
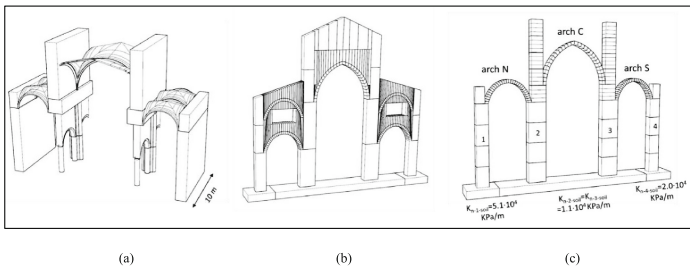
Fig. 5. (a) The investigated cross-section of the Cathedral of Modena: representation of the structural elements. (b) the "Complete DEM" rendering, (c) the "Simplified DEM" rendering and the name of the element used in the calculation

- 2D cross section model including the longitudinal walls, the vaults and also the transversal walls (hereinafter called "Complete DEM" and represented in Fig. 5b) and
- 2D cross section model including only the longitudinal walls and the vaults (hereinafter called "Simplified DEM" and represented in Fig. 5c). The transversal walls are here considered only in terms of weight (vertical loads).

The Complete DEM model is analysed under static loads only with the main objective being to evaluate locations where blocks detach (corresponding to crack openings) and compare these locations with the crack patterns observed before the 2012 Emilia Earthquake, mainly induced by the self-weight and differential soil properties. The Simplified DEM model was then analysed under seismic loads, with the main purpose of evaluating the potential effects due to the 2012 Emilia Earthquake on the Cathedral. It has to be noted that the complete model is able to account for the lateral thrust exerted by the lower arches, which is not considered in the simplified model. Such a discrepancy may affect the lateral displacement induced by both vertical and horizontal loads. In the case of dynamic analyses, after the application of the

gravity loads, the ground motion recorded in Modena during the 2012 Emilia Earthquake is applied to the base.

4.1   Defining Modelling Parameters

The masonry structure is modelled as assemblages of rigid blocks with the elasticity of all material concentrate in the joints [9]. No tensile strength is considered. In addition, a stiffness-proportional damping is determined according to the natural frequencies of individual blocks [10]. The joint stiffness, k_n and k_s are defined using the material property of the blocks as follows:

$$k_n = \frac{EA}{L}; k_s = \frac{GA}{L} \tag{1}$$

Where $\underline{E}$ and G are the elastic and shear modulus of the masonry blocks, respectively, A is the area of the contact between the blocks; L is the length of the rigid material represented in the direction perpendicular the joint. As highlighted in the previous section the differential soil-to-foundation stiffness (in both the vertical and horizontal direction) has probably influenced the actual cracked condition of the monument. As such, in order to account, in a simplified way, for the soil flexibility, equivalent springs at the interfaces between the base of the walls and the soil have to be properly calibrated (Fig. 6). The values of the soil springs for the piers, that not considering differential soil-to-foundation stiffness, (deducted from the geotechnical investigations) are reported in Fig. 5c. Note that considering the equivalent soil springs the piers 1, 2, 3 and 4 have a stiffness of $K_{N\ 1\text{-soil}} = 2.7 \cdot 10^6$ kPa/m, $K_{N\ 2\text{-soil}} = K_{N\ 3\text{-soil}} = 6.0 \cdot 10^6$ kPa/m and $K_{N\ 4\text{-soil}} = 2.6 \cdot 10^6$ kPa/respectively. For the sake of conciseness, all the other modelling parameters can be found in [11].
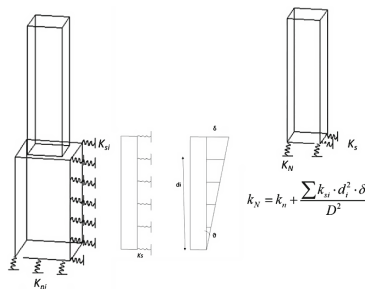

Fig. 6. Interaction between foundation and soil

4.2   Analyses Results

First, the crack openings due to vertical loads only, as obtained from the Complete DEM model is investigated and compared to the crack patterns observed before the 2012 Emilia Earthquake. Figure 7a displays the contour plot of the interface, relative block-to-block, displacements (units are meters). Each colored surface represents an interface between two adjacent blocks. Blue colors indicate no detachment between the blocks (no opening) while the red colors indicate an opening of the interface. The contour plot is qualitatively compared with the crack patterns as observed before the 2012 Emilia Earthquake. It can be noted that the block openings agree with the location of the main cracks. Note that the model takes into account of the different soil stiffness at the base of the walls that are probably the first cause of the crack patterns detected before the 2012. Subsequently, the cracks openings due to the effect of the ground motion as recorded at the Mirandola station during the 2012 Emilia Earthquake are evaluated using the Simplified model. Figure 7b displays the contour

(a)   (b)
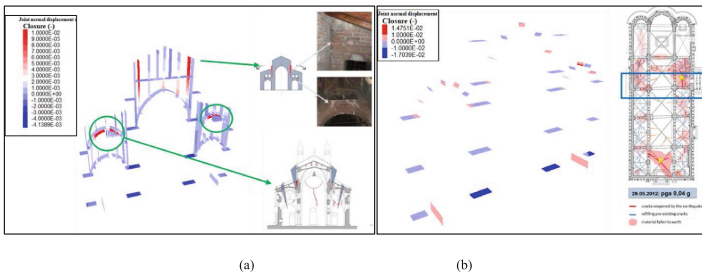
Fig. 7. (a) Interface cracks predicted by the Complete DEM model (in red) and the crack pattern detected in the 2010 survey. (b) Contour plot of the interface opening displacements of the Simplified DEM model and the crack pattern detected after the 2012 Emilia earthquake

plot of the interface, relative block-to-block, displacements along with the crack pattern detected after the earthquake. The DEM analysis displays several new openings mainly concentrated on the arches (that schematized the vaults). These openings are in good agreement with the cracks observed after the Emilia Earthquake (also concentrated predominantly in the vaults).

Figure 8 compares the time-history of the lateral displacements as obtained from the Simplified DEM at the springings of the arches (top of the piers 0 and 1 in Fig. 5c). The record of the displacements at each instant of the time history allows identification of magnitude of the closing/opening of the springings of the arches, but also whether the supporting pillars are moving in the same direction (in phase) or not (out of phase). The analysis of x-displacements recorded during the seismic load in the four control points at the springings of the arches N and S displays (see Fig. 8):

– the displacements recorded at the springers N_e, N_i and S_e are in phase,
– the displacements recorded at location S_i signify significantly different behavior of this pier, and are certainly out of phase with S_e,
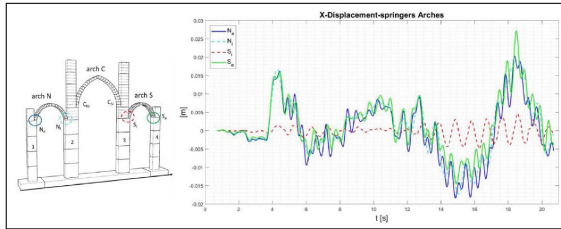
Fig. 8. Plot of the time history of the displacements recorded during the dynamic analyses at the springers of Arches N and S

- the maximum displacements occurred at location S_e; the foundation of the adjacent pier is characterized by a lower stiffness.

For sake of clarity, the displacements recorded at the springers of the arch C are not plotted but it is interesting to note that the displacements recorded at C_{Si} are in phase with Si and those recorded at C_{Ni} with Ni, as expected. Moreover, the maximum values of opening/closing displacements at the springing of the arches recorded by means of DEM model are significantly different to those obtained through the FEM models. In fact with the FEM models the widening/closing displacements recorded at the springers of each vault are all of the same order of magnitude (less than 0.1 cm). The DEM model displays instead a maximum opening/closing relative displacement of the order of 2 cm at the springers of Arch S (characterized by soft soil), but the same order of magnitude obtained by the FEM model for the other arches. The considerably smaller relative displacements predicted by the FEM model for Arch S are potentially due to overestimation of the connectivity of the model caused by not incorporating joint openings. However, further research is necessary to confirm this due to the simplicity of the 2D DEM models.

5   Conclusions

In the present paper, a simplified modelling technique to account for the soil-foundation interaction within the DEM framework has been introduced. The simplified modelling technique was used to model a cross section of the Cathedral of Modena, which in past studies was determined to be particularly susceptible to the effect of differential soil settlement due to the presence of soils with different properties. The results of the DEM analyses indicate that the crack patterns, including both the pre-existing cracks detected in 2010 and the new ones caused by the 2012 Emilia earthquake, are approximately captured by the simplified 2D models. Further, the dynamic analyses indicate the potential importance of differing soil properties beneath the structure, and how these soil properties could increase out-of-phase pier rotations, which could increase damage to vaults. The preliminary comparison between the structural response simulated by the DEM and FEM models indicate that the FEM models predict considerably less differential movement at the vault springing level.

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