The NSCD method for dynamic analyses of ancient masonry tower under transversal dynamic loadings

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Summary. The dynamics of a medieval tower, inside the Metropolitan Cathedral-Basilica of Saint Cyriacus in Ancona (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 tower exhibits 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.

Introduction

The conservation and the restoration of ancient buildings belonging to the cultural heritage, and preserving their main architectural features, are becoming a very important issue in Europe. This is especially true in Italy, which hosts the largest amount of monumental churches, monasteries, and towers in the world, and where some earthquakes, occurred in the last few decades (Umbria-Marche 1997–1998, Abruzzo 2009, Emilia-Romagna 2012, Marche-Lazio-Umbria-Abruzzo 2016), severely damaged a number of unique pieces of the architectural heritage [1].

Masonry towers are quite widespread in Italy, especially in high-seismicity regions. Very often, such buildings exhibit unique peculiar morphologic and typological characteristics, which might affect their different structural behaviours under horizontal loads.

Traditionally, masonry towers were conceived to withstand vertical loads only, but in recent years national and international standards have imposed the evaluation of their structural performance under dynamic excitations and they encourage the use of sophisticated nonlinear methods of analysis [2]. A main issue in the dynamic behaviour of masonry towers is the influence of the axial stresses induced by gravity loads, whose values are often very high. Considering that historical masonry is typically characterized by a complex geometry, irregularities and a high degree of inhomogeneity, stress concentrations can occur, thus promoting local collapses. Hence, the structural failure can be driven even by a moderate increase in the stress level, which can occur during dynamic (e.g., earthquake) events or in the presence of long-term loads.

At present, a number of studies are available in the literature dealing with the numerical/experimental analysis of masonry towers. Actually, to the best of the authors' knowledge, the non-smooth nature of the dynamic response of tower and belfry is not analyzed. For this reason, in the present paper, the dynamics of a medieval masonry tower is investigated numerically by means of a distinct element code which implements the Non-Smooth Contact Dynamics method (NSCD) [3]. The main aim of the study is to determine the weakness zones of this type of structure during seismic events and the efficacy of past interventions.

Basilica of Saint Cyriacus in Ancona: a brief history

Ancona Cathedral is a Roman Catholic cathedral in Ancona, central Italy, dedicated to Saint Cyriacus of Ancona (Fig. 1a). It is the seat of the Archbishop of Ancona. The building is an example of mixed Romanesque-Byzantine and Gothic elements, and stands on the site of the former acropolis of the Greek city, the Guasco hill which overlooks Ancona and its gulf.

Italic temple, perhaps dedicated to Aphrodite, existed on the site as early as the 3rd century BC. On top of it, in the 6th century AD, a Palaeo-Christian church was built: this had a nave and three aisles with the entrance facing southeast. Some remains of it still surviving include a mosaic pavement and perimeter walls. In 995–1015 AD a new church was built, which kept the original walls. In 1017 the renovated basilica received the relics of Saint Marcellinus of Ancona and Saint Cyriacus. Further enlargement works occurred between the late 12th and the early 13th centuries, with the addition of a transept to obtain a Greek cross plan, and an entrance towards the southwest, resulting in the church now facing the port and the new road entering the city. The transepts were at a higher level than the previous nave, and had apses. The church, previously dedicated to Saint Lawrence, was re-dedicated to Saint Cyriacus the Martyr, the patron saint and (possibly) bishop of Ancona.

An initial restoration took place in 1883. During World War I, the basilica was damaged by a bombardment of the Austro-Hungarian fleet. The damage was restored in 1920, but in World War II Anglo-American aerial bombings destroyed the south transept and the Crypt of Tears under it, along with the art treasures housed there. Once the transept was rebuilt, the church was officially reopened in 1951. Further damage was caused by an earthquake in 1972, followed by a new restoration and another official opening in 1977.

The edifice is built of white stone from Mount Conero, with apses protruding from the transept's ends and an elevated body, with a dome at the crossing, in correspondence to the nave. All the external surfaces feature a decoration of

Lombard bands. The bell tower is in an isolated position. It is mentioned from 1314 and was built above a pre-existing late 13th-century military tower (Fig. 1a).

a) b)

Figure 1. The general view of the Metropolitan Cathedral-Basilica of Saint Cyriacus.

Modelling and analysis of masonry tower

The behavior of Saint Cyriacus tower is investigated in a real 3D model. For this purpose, the LMGC90© code [3] is used, due to its ability to compute the interaction of a large number of bodies, based on the NSCD method. The NSCD method has been applied to assess the seismic vulnerability of historical buildings in [4,5].
The geometry of the models corresponds to the geometry of the real structure, based on in situ measurements, and are reported in Fig. 1b. Very detailed models have been created to better understand the influence of a seism mechanism within the structures, in presence or in absence of some past retrofitting interventions done in the tower. The chosen procedure for simulating the seismic vibration is assumed to be comparable to a real earthquake, producing vibrations in three dimensions.
The NSCD method belongs to the family of discrete element methods, distinguishing from the classical Distinct Element method for three differences: (i) it integrates directly the non-smooth contact laws, (ii) it uses an implicit integration scheme, and (iii) it does not account for any structural damping [3]. It is important to stress the fact that the NSCD method is based on some modelling simplifications. The main assumption is that bodies are rigid. Since the contact between blocks is governed by the Signorini's impenetrability condition and the dry-friction Coulomb's law, the tower exhibits discontinuous dynamics. Regarding the contacts between bodies, the above-mentioned relations imply perfectly plastic impact, i.e., the Newton law with restitution coefficient equal to zero [3], which does not account for bounces after impact. This presents two main advantages: (i) the contribution of impacts to the computational complexity is modest since they are modelled in a very basic and simple way; (ii) since the impact is perfectly plastic, it dissipates energy, and, from a mechanical viewpoint, this is a way to account for material damages and micro-cracks, which form in the stones at impact, and, from a computational point of view, dissipation contributes to the stability of the numerical integration. We notice that also friction contributes to dissipation, but damping, a fundamental ingredient of continuum models, is not considered here.
First, harmonic oscillations have been applied to the basement of the tower, and a systematic parametric study has been conducted, aimed at correlating the system vulnerability to the values of amplitude and frequency of the assigned excitation. In addition, numerical analyses have been done to highlight the effects of the friction coefficient and of the blocks geometry on the dynamics, and, in particular, on the collapse modes. Then, the study of the tower stability against seismic excitations has been addressed. Attention has been paid to the occurrence of out-of-plane torsional overturning mechanisms as observed in the last Italian earthquakes, and some damage comparisons with different numerical models, like continuous finite element approach, are also done.

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