Engineering Structures 119 (2016) 110–121

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Seismic vulnerability of ancient stone arches by using a numerical model based on the Non-Smooth Contact Dynamics method

Giovanni Lancioni *, Davide Gentilucci, Enrico Quagliarini, Stefano Lenci

Department of Civil and Building Engineering, and Architecture, Polytechnic University of Marche, Via Brecce Bianche, 60131 Ancona, Italy

ARTICLE INFO

Article history:
Received 25 November 2015
Revised 22 March 2016
Accepted 5 April 2016
Available online 23 April 2016

Keywords:
Non-Smooth Contact Dynamics
Historical stone structures
Dynamics of arches
Seismic vulnerability

ABSTRACT

The dynamics of two Roman stone arches has been studied by means of the Non-Smooth Contact Dynamics method (NSCD), implementing a discrete element numerical model in the LMGC90 code. Schematized as a system of rigid blocks, undergoing frictional sliding and plastic impacts, the arches have exhibited a complex dynamics, because of the geometrical non-linearity and the non-smooth nature of the contact laws.

First, harmonic oscillations have been applied to the basement of the arches, 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 arches stability against seismic excitations has been addressed, and three-dimensional simulations have been performed. Attention has been payed to the occurrence of out-of-plane overturning mechanisms induced by possible bending of the arches.

The numerical results have suggested some structural retrofitting actions needed to improve the arches seismic safety.

1. Introduction

Preservation of the historical and architectural heritage against natural disasters represents an actual and challenging issue, faced from many different standpoints. From the one side, the development of new performing materials allows to use innovative restoring techniques and strengthening measures, which increase the efficiency and reduce the invasiveness. From the other side, modelling efforts are conducted to develop methods capable of accurately predicting the complex responses of ancient building to extreme natural actions. Indeed, detailed modelling studies constitute valuable tools orienting the best restoring choices.

In the present study, modelling attention is payed to the dynamics of stone arches subject to periodic and seismic excitations. A large amount of models, both theoretical and numerical, has been proposed for the statics of arches. On the contrary, the literature on the dynamics of arches is limited. Since the dynamical response of stone arches is very complex, because of non-linearities and its non-smooth nature, only few simplified analytical models have been proposed, which capture partially the intricate dynamics of arches. In [1], the seismic capacity of masonry arches has been evaluated by means of the limit analysis [2,3], where the seismic loadings have been approximated by a distribution of equivalent horizontal forces. In [4], a four hinges mechanism is assumed, and the resulting one degree-of-freedom dynamical system is studied, and, in [5], the reduced-order model proposed in [4] is enriched by a proper impact law. In [6], the reduced-order problem is determined by identifying the four-hinge mechanism via limit analysis.

Regarding the numerical approaches, distinct element formulations have been applied to the study of stone or masonry structures dynamics. They are based on the assumption that structures are assemblages of rigid blocks with frictional joints. They use *time-stepping* algorithms to integrate the problem equations, which are alternative to the *event-driven* approaches. While the former approaches can manage systems with many degrees-of-freedom and many contacts, like stone buildings, the latter schemes are more accurate, but applicable only to few degree-of-freedom systems, like robotic or mechanical mechanisms [7,8]. There are two main distinct element formulations: the Distinct Element method (DE), first proposed by Cundall and Stack [9] for the study of rocks, which has been implemented in the UDEC code [10], and the Non-Smooth Contact Dynamics method (NSCD) [11], developed by Jean and Moreau [12,13], and implemented in the LMGC90 code [14]. They differ in three basic points:

* Corresponding author. Tel.: +39 071 220 4571.
E-mail address: g.lancioni@univpm.it (G. Lancioni).

http://dx.doi.org/10.1016/j.engstruct.2016.04.001
0141-0296/

i. the contact laws between blocks (the Signorini's law of impenetrability and the Coulomb's friction law) are regularized through a penalty formulation in the DE method, while they are directly implemented, in their non-smooth form, in the NSCD method;
ii. the DE method uses an explicit integration scheme, and the NSCD method applies implicit integration;
iii. the DE method accounts for structural dissipation, by assuming Rayleigh damping, while the NSCD method neglects any structural damping. The only sources of dissipation are the perfectly plastic impacts between blocks, and friction.

The two methods are powerful tools to investigate the dynamics of ancient buildings subject to ground oscillations and to determine their failure mechanisms (see [15] for an overview). The UDEC code has been used to model columns [16] and column-architrave structures [Psycharis2003] of classical temples. In [5,17] it has been applied to the study of stone arches, and parametric analyses have been conducted which correlate vulnerability and failure modes to the values of certain problem parameters. The LMGC90 has been recently applied to the study of the seismic vulnerability of stone arches [18], a Roman arena and an aqueduct [19], a Romanesque church [20,21], and a stone bridge in [22]. In these works, the potentialities of the NSCD method have clearly emerged. Indeed, it succeeds in combining simplicity and great predictive capabilities. Simplicity comes from the fact that only two constitutive parameters, i.e., the friction coefficient and the mass density, enter the model. This is an advantage when ancient buildings are considered, since the determination of their mechanical properties (like the material moduli) is always uncertain and variable. Predictive properties comes directly from the numerical results, which, in the above quoted works, have given a deep insight into the seismic vulnerability of the considered structures, pointing out possible failure mechanisms, and, consequently, suggesting appropriate retrofitting works.

In the present study, the NSCD method is used to investigate the dynamical response of some Roman stone arches (see Fig. 1), placed not far from Kistanje, Croatia, and to assess their seismic vulnerability. In the last years, these arches have been the object of intense archaeological investigations [23], and of non-destructive test analyses [24]. Nowadays, only two arches are survived, but having a precarious state of maintenance, both for intrinsic degradation factors due to the materials they are made of, and for the disarrangement phenomena connected to the particular static configuration they have reached during the centuries. As a result, the thrust line of the right arch in Fig. 1 appears to be not well confined. Thus, a careful analysis of the dynamical response of the arches to base excitations is needed in order to determine the effective level of stability of the arches, and, if necessary, to indicate appropriate retrofitting actions for the structural safety recovery.

The study is organised into two parts. In the first one, parametric analyses are conducted, aimed at drawing a global picture of the arches in-plane dynamics. An in-plane harmonic oscillation is applied to the basement of the arches, and maps which correlate the level of vulnerability of the arches to the amplitude and frequency assigned to the basement oscillation are drawn. Furthermore, the mechanisms leading to the arches collapse are thoroughly studied, and the influence of the friction coefficient on the collapse mode is investigated. Even the sensitivity of the dynamical response to the blocks geometry is considered.

In the second part, the excitation of a real earthquake is applied to the arches basement to assess the seismic vulnerability of the structure. Three-dimensional simulations are performed to account for possible out-of-plane overturning mechanisms. Since the actual structure presents geometrical disarrangements of the blocks, which contributes to its precarious state of maintenance, initial configurations that bend in the out-of-plane direction have been also considered. The resulting simulations have revealed that even small initial bent angles drastically reduce the system stability against overturning mechanisms.

Fig. 1. The arches of Burnum (Croatia).

The paper is organised as follows. In Section 2 the case study is briefly summarized, and the actual state of conservation of the arches is described. In Section 3, the numerical model is presented, describing the basic ingredients of the NSCD method, and the modelling assumptions for the numerical simulations. In Section 4, the arches dynamical response to base harmonic oscillations is studied: vulnerability maps are drawn in Section 4.3, and an analysis of the modes of collapse is carried out in Section 4.4. Section 5 is devoted to the assessment of the arches seismic vulnerability. The out-of-plane failure mechanisms resulting from three-dimensional simulations are discussed in Section 5.2. Finally, in Section 6, some concluding remarks are drawn.

2. The case study

The ancient stone arches analysed in this paper, that recent archaeological studies ascribe to the remains of an old forum's basilica [25], are placed into the archaeological site of Burnum, located in the settlement of Ivoševci, not far from Kistanje, Croatia. This site was a pre-Roman military outpost, which became a fortified camp (*castrum*), after the creation of the Roman province of Illyricum (32–27 BC), which was transformed into a fully municipal town (*municipium*) during the second century, keeping important administrative as well as military functions until the Late Roman Age [25].

Nowadays, only two (shown in Fig. 1) of the original five arches still reported in the second half of the 19th century by Theodor Mommsen [26], are standing, while at the end of the 18th century the Venetian abbot Alberto Fortis, in his *Viaggio in Dalmazia*, mentioned three of them. The two arches were the object of an intensive archaeological survey by the Austrian Archaeological Institute of Wien, from 1912 to 1913 and again in 1970–1971 [25]. The geometrical survey used in this work, instead, comes from the most recent archaeological campaign: the Burnum Project (integrated non-intrusive methodologies for archaeology), where the University of Zadar, the University of Bologna, the Polytechnic University of Marche and the Civic Museum of Drnis were involved [24,23,27]. In this project an in-plane photogrammetric survey of the arches was done, by including a direct analysis of their construction techniques. The arches and their pier are made of stone ashlars and no mortar seems to be presented, although some restorations with cement mortars, probably done in the '70, could be misleading [28]. During the survey, the arches were in a precarious state of maintenance, especially close to the crown, due to the weathering