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Effect of steel collars on the seismic behaviour of axially-cracked historical stone columns

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ABSTRACT

Granite and heavy stone circular columns could often be found in the cultural heritage among ancient churches and historical buildings in all the Mediterranean area. Their good strength properties allow them to carry big load values, while their bright colours and aesthetical characteristics were used by a lot of architects in the past to achieve structural solutions with great visual impact.

Though such materials have great compressive strength values, environmental effects, especially long term effects, can damage the structural members, by cracking them. In this way the slenderness of the column increases, and the presence of an imposed ground motion can be very dangerous, since the column will be more vulnerable to rocking motion, which in critical cases could lead to overturning or material crushing due to stress concentration.

This paper focuses on the behaviour of cracked granite and heavy stone columns subjected to rocking motion due to pulse type ground shaking. In this field, the effect of the presence of circular collars is analysed and discussed. The overturning spectra are determined, including the presence of the collars, showing their effectiveness in reducing the overturning risk. Comparisons are shown with numerical analyses and a simplified analytical procedure is proposed.

1. Introduction

Granite and heavy stone columns are diffused among the entire architectural heritage in all the Mediterranean area. Since the ancient Roman age a very large amount of historical buildings, churches and monuments have been characterised by slender and massive columns, made with the local available stone. Due to their use since ancient times, a large variety of kinds of columns can be observed. Most of these exhibit different aspects characterising the structural members, such as material and geometry. Even if a great deal of these aspects exist, one feature that can be considered as common in almost all granite and heavy-stone columns is geometrical slenderness. The concepts of brightness, stateliness and bigness together with the good mechanical properties of granites and heavy stones have been used by architects in all historical ages taking advantage of tall and slender columns.

The fact is that granites and heavy stones are characterised by good strength properties, which can be considered as a function of their porosity. Ludovico-Marques et al. [1] carried out different uniaxial compressive tests on granite and sandstone cylindrical specimens and demonstrated with a statistical correlation that the compressive strength and elastic modulus increased when the porosity decreased. This consideration is based on the marked heterogeneity and on the frequent presence of inclusions, vacuums and micro-cracking in materials with high porosity. For porosity values between 0.42% and 1.11% the strength value determined experimentally was over 110 MPa, while the elastic modulus was always over 30,000 MPa.

On the basis of such values, it is clear that a monolithic stone column can be considered as a slender rigid member, which in most of cases is simply supported at its base.

The case of a column with a base equal to $2b$ and height $2h$, subjected to a ground motion, including both the horizontal acceleration $\ddot{u}_g$ and the vertical acceleration $\ddot{v}_g$ will now be considered (Fig. 1a). It is well-known from the literature and already written in text-books that a slender block subjected to a ground motion rocks if the overturning moment of the horizontal inertia force about one edge exceeds the restoring moment due to the weight of the block and vertical inertia force:

$$m\ddot{u}_g h = m(g + \ddot{v}_g)b \tag{1}$$

The minimum acceleration inducing the rocking motion of the block can be determined by means of Eq. (1):

$$\ddot{u}_g > g\left(1 + \frac{\ddot{v}_g}{g}\right) \cdot \frac{b}{h} \tag{2}$$

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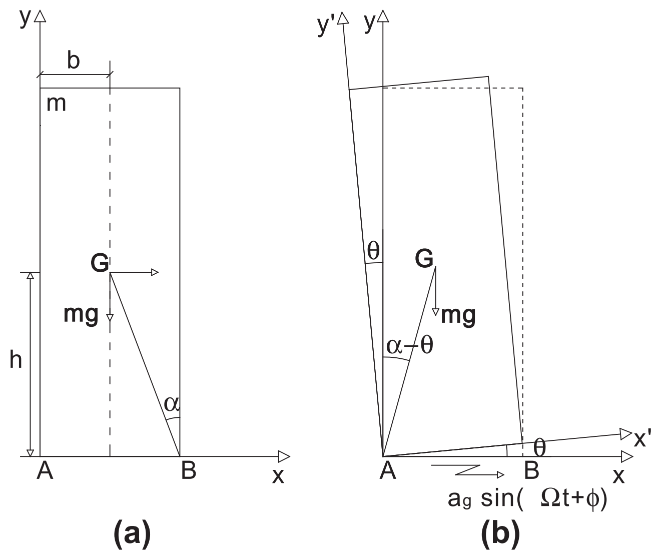

Fig. 1. Patch of a free-standing block subjected to a sine pulse. (a) Free-standing block; (b) rotated block under ground motion.

If the vertical ground acceleration is neglected for the sake of simplicity and in a conservative way, and also considering that $\tan\alpha = \frac{b}{h}$ and that for slender blocks $\tan\alpha \simeq \alpha$, the minimum rocking acceleration proves to be:

$$\ddot{u}_{g,\min} = g \cdot \frac{b}{h} = \alpha \cdot g \tag{3}$$

Eq. (3) means that the activation of the rocking motion on a column strictly depends on its geometric characteristics, and the value of the minimum rocking ground acceleration decreases as the slenderness increases.

Considering the most common values of slenderness of existing columns and also considering that a great deal of the historical architectural heritage is built in seismic areas, it emerges that these vertical structural members are particularly vulnerable to rocking motion. The latter, in critical cases, could lead either to overturning of the column or to local material crushing due to the stress concentration in the bottom zones near the edges. An example of a damaged column due to its rocking motion under a seismic motion is shown in Fig. 2. It refers to a column of the City Hall building in Mirandola (Italy), which was subjected to the severe earthquake (6.1 Mw) that occurred in northern Italy during the month of May 2012. As can be noted, the slender column rocked and was damaged in the corner near one edge due to stress concentration, which exceeded the compressive strength of the pink marble making up the member.

On this basis, it is clear that the effect of ground shaking could be more critical and dangerous in columns which are already cracked due to different environmental or external effects, the latter proving to be different from seismic or dead loads. Such effects could be related to thermal actions, or initial imperfections. The nature of stones and their tensile strength around one-tenth of their compressive strength lead to quick propagation of microcracks, which can seriously damage the structural member. As a consequence the geometric slenderness increases and considering Eq. (3) the minimum overturning acceleration decreases drastically.

One of the most common techniques adopted to retrofit damaged cracked columns, especially during the post-earthquake phase and for cases of wide cracks, is application of steel collars. Though this technique is very commonly used in engineering practice, its effects are not theoretically specified, leaving evaluation of its efficiency to practical experience. The number, dimensions and mechanical properties of the strengthening devices often arise from professional insight, without the perception of the inner physical phenomena. For example, the theoretical motivation for the application of steel collars in granite and heavy stone columns is often linked to confinement action applied by the steel collars, as occurs in reinforced concrete columns. It has to be noted that granites and heavy stones are materials having a low Poisson's coefficient (0.1–0.2), and consequently passive confinement is difficult to apply, being based on material lateral expansion.

As a result, the repairs adopted often do not respect the basic principles of the Chart of Venice [2], which provides guidelines for modern restoration: respect for the original materials; integration of the replacement with the whole; additions are accepted if their influence on the other parts of the monuments and/or its surroundings is negligible.

In this paper the effect of steel collars on the dynamic behaviour of cracked granite and heavy stone columns subjected to a sine pulse is analysed and treated with the classical tools of the theory of rocking of rigid blocks [3]. The equation of motion is adapted to the case study, and the effect of the steel collars is determined in terms of overturning spectra, the results obtained being compared with numerical analyses carried out with the Working Model 2D software [4]. It has to be noted that a lot of algorithms and theories are actually available to study the rocking behaviour of rigid blocks; however, in this work the classical theory of Housner (1960) [3] is used and adapted to the case analysed for the sake of simplicity, and because the aim of the study is to provide useful indications to design the retrofitting technique simply.

2. Theoretical background

The theory of Housner [3] represents the first significant study on the dynamic response of a rigid block supported on a base undergoing horizontal accelerations. The author examined the response for free and forced oscillations, with rectangular and sine pulse forcing functions, describing the motion of rocking blocks with the solution of the motion equation.

The case study refers to a single block with an initial rotation angle $\theta(0) = \theta_0$ and angular velocity $\dot{\theta}(0) = \dot{\theta}_0$ (both to be considered only theoretically). Under the effect of positive horizontal acceleration and assuming that the friction coefficient is large enough to prevent sliding, the block rotates with a negative rotation θ when the ground acceleration amplitude reaches the value of $\ddot{u}_{g,\min}$. The equations that govern this motion are:

$$J_0\ddot{\theta}(t) + mgR \cdot \sin[-\alpha - \theta(t)] = -m\ddot{u}_g(t)R\cos[-\alpha - \theta(t)], \quad \theta(t) < 0 \tag{4}$$

$$J_0\ddot{\theta}(t) + mgR \cdot \sin[\alpha - \theta(t)] = -m\ddot{u}_g(t)R\cos[\alpha - \theta(t)], \quad \theta(t) > 0 \tag{5}$$

where J_0 is the moment of inertia of the block around A and equal to $\frac{4}{3}mR^2$ for rectangular blocks.

Eqs. (4) and (5) are well known in the literature and have been analysed by many authors [5–9] in order to determine the response of rigid blocks under different ground excitations.

It has to be noted that among the different kinds of ground motions, the sine pulse type is one of the most studied in the literature [3,5–11]. This type of ground motion was studied in the present work because, as shown by Makris and Zhang [7], it is able to approximate the kinematic characteristics of several recorded ground motions during real earthquakes. Fig. 3 shows the comparison between the time histories of the ground motion characteris-