Engineering Structures 62–63 (2014) 1–10

Contents lists available at ScienceDirect

Engineering Structures

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

On the use of base isolation for the protection of rigid bodies placed on a multi-storey frame under seismic excitation

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ARTICLE INFO

Article history:
Received 12 June 2013
Revised 3 December 2013
Accepted 13 January 2014
Available online 6 February 2014

Keywords:
2D rigid block
Eccentricity
Multi-storey frame
Sliding
Rocking
Overturning

ABSTRACT

The use of base isolation applied to rigid bodies placed on a multi-storey frame is considered with the aim of understanding whether or not seismic isolation is beneficial in preventing their collapse during an earthquake. The rigid body is placed on either a fixed or an isolated oscillating base. It may be subjected to sliding, rocking and sliding–rocking motions. When base isolation is considered, security stops capable of preventing the isolation system from breaking are always assumed to be present. The frame, modelled as a four-storey, shear-type system, is always considered to work in the elastic regime. The geometrical characteristics of the body are chosen so that a collapse event, such as overturning or falling out from the support, is obtained for an excitation for which the behaviour of the frame remains in the elastic regime. Overturning and falling-out curves are plotted against PGA (Peak Ground Acceleration) to demonstrate the role of the geometrical parameters characterising the body, of the spectral characteristics of the earthquake and of the level of the frame at which the object is placed. The analyses performed reveal that base isolation applied to a rigid body placed on a frame is not always appropriate in cases where the same body is placed on a fixed base.

1. Introduction

There is extensive literature concerning rigid bodies. Starting from Shenton and Jones [1], many works present models of rigid body behaviour addressing problems related to works of art or, more generally, to non-anchored substructures. Usually two kinds of excitations are taken into account: either one-sine pulse and harmonic excitations [2–4] or earthquake excitations [5–7]. Differently, in Spanos and Koh [8] a random shacking of the structure, with an excitation of the form of modulated white noise, is considered. Most papers concern two-dimensional models of symmetric rigid bodies placed on the ground while only a small number deal with non-symmetric rigid bodies [9–11]. Some papers highlight specific features of the dynamics of rigid bodies, such as the definition of maps describing the criteria for the different phases of motion [12,13], the existence of survival regions which lie above PGA (Peak Ground Acceleration) associated with the first occurrence of overturning [3,14] or the correct definition of the impact occurrence [15]. In Spanos et al. [16] the behaviour of two stacked rigid blocks is considered, while in Spanos et al. [17], Spanos and Koh [8] the focus is on blocks on flexible foundations. In some models with a more specific focus on works of art such as Vestroni and Di Cintio [18], Di Egidio and Contento [19], base isolation is considered. Specifically, in Di Egidio and Contento [20] the possibility of the rigid body sliding and rocking with its base partially outside the base isolation is taken into account. Only a small number of papers make use of three-dimensional models to describe the behaviour of rigid bodies, for example to study the motion of a disk of finite thickness [21,22], the wobbling of a frustum [23] or sloshing in a tank [24] or to analyse the behaviour of slender bodies such as statues and obelisks [25].

In this paper the use of base isolation applied to rigid objects placed on various floors of a multi-storey frame is analysed in detail in order to understand whether or not seismic isolation is beneficial in preventing collapse during an earthquake. In this field various methods exist to analyse the interaction between the primary and secondary structure (Oropeza et al. [26], Villaverde [27]), considering both linear and nonlinear behaviours of the primary structure. Although the Authors of this paper in Zulli et al. [25] demonstrate that a three-dimensional model of a rigid block should be used to correctly evaluate the collapse event of a near-square-based rigid block, here a simpler 2D model is used. This is justifiable since the rigid block considered here is always assumed to possess a rectangular base with one side considerably longer than the other. In this case the only possible rocking motion is the one around the longer side of the rectangle. Hence, to describe this motion, a classical 2D model of the rigid block is sufficient.

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0141-0296/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.engstruct.2014.01.019

The body may undergo sliding, rocking and sliding–rocking motions; when considered, the base isolation system is modelled as an oscillating support, connected to the ith floor of the frame through a linear visco-elastic device. Security stops capable of preventing the base isolation system from breaking by limiting the maximum displacement are always assumed to be in place. The equations of motion of the rigid block, the conditions of impact between the body and base isolation and between the base isolation and security stops, and the triggering conditions for the rocking and the sliding motions and collapse conditions, such as overturning or falling out from the support, have been obtained by following previous papers by the authors Di Egidio and Contento [19] and Contento and Di Egidio [28].

The frame is modelled as a four-storey, shear-type system. Its spectral characteristics are similar to those of a four-storey, concrete-frame building. It is always assumed that the frame works in the elastic regime. The geometrical characteristics of the block are chosen to make it possible to reach a collapse event, such as overturning or falling off the base isolation, for the PGA associated with the excitation at which the behaviour of the frame remains within the elastic field.

Only two seismic records of an Italian earthquake with different spectral characteristics are used in the analyses (Brienza and Calitri), since it is not the aim of this paper to provide an exhaustive characterisation of the seismic behaviour of the system, but rather to understand whether or not seismic isolation is useful in protecting the body during an earthquake. If there is a sole seismic input to which special attention must be devoted in the use of base isolation of rigid blocks on a frame, this aim can be considered to have been achieved.

Curves representing the PGA (Peak Ground Acceleration) at which sliding or rocking motions take place starting from the full-contact state, together with curves representing the PGA at which the falling-out from the base or the overturning of the block occur, are obtained. The role of the geometrical parameters characterising the body, of the spectral characteristics of the earthquake and of the level of the frame at which the block is placed are highlighted.

By comparing the results obtained for isolated and non-isolated rigid bodies and those obtained for objects placed on the ground and on a floor of the frame, it is possible to identify in which cases and under which conditions the adoption of base isolation is useful in preventing collapse.

2. Mechanical system

The mechanical system selected for analysis is composed of a primary structure supporting a subsystem consisting of a rigid body placed either directly on a floor or on the base isolation. In the different analyses the floor on which the secondary structure is positioned has been varied.

2.1. Primary structure: the frame

As is common in the literature, the primary structure is modelled as a shear-type frame, as shown in Fig. 1, which can develop only elastic deformations. For computational convenience it has been limited to four floors, this choice entails that the frame is described by a 4 degrees of freedom linear system in which the unknowns $\mathbf{u} = \{u_1, u_2, u_3, u_4\}^T$ are the absolute floor displacements. Quantities k_i and $m_i, (i = 1, \ldots 4)$ represent floor stiffnesses and floor masses, respectively. Equations of motion of the four-storey frame in matrix form read:

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = -\mathbf{M}\mathbf{I}\ddot{u}_g \tag{1}$$

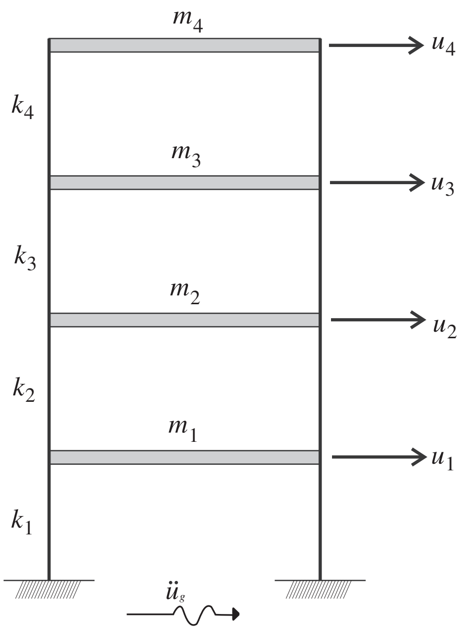

Fig. 1. The four-floor frame: floor stiffness, mass and displacement.

where $\ddot{u}_g$ is seismic acceleration, $\mathbf{I}$ is the identity matrix and

$$\mathbf{M} = \begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & m_3 & 0 \\ 0 & 0 & 0 & m_4 \end{bmatrix}, \quad \mathbf{K} = \begin{bmatrix} k_1+k_2 & -k_2 & 0 & 0 \\ -k_1 & k_2+k_3 & -k_3 & 0 \\ 0 & -k_2 & k_3+k_4 & -k_4 \\ 0 & 0 & -k_3 & k_4 \end{bmatrix}. \tag{2}$$

For the damping matrix $\mathbf{C}$ a Rayleigh model, proportional both to the mass and to the stiffness matrixes, has been adopted, thus:

$$\mathbf{C} = \alpha\mathbf{M} + \beta\mathbf{K}. \tag{3}$$

The two parameters α and β have been chosen so that an equivalent modal damping of the first mode $\xi_1 = 0.02$ is found:

$$\alpha = 2\xi_1 \frac{2\omega_1\omega_2}{\omega_1 + \omega_2}, \quad \beta = 2\xi_1 \frac{1}{\omega_1 + \omega_2}, \tag{4}$$

where ω_1 and ω_2 are the frequencies of the first two modes.

In the following analyses the floor stiffness k_f and the floor mass m_f have been assumed to be equal for all floors ($k_1 = k_2 = k_3 = k_4 = k_f, m_1 = m_2 = m_3 = m_4 = m_f$) and set in order to obtain the period of the first mode of vibration of the primary structure $T_1 = 0.48$ s (the periods of the other modes are $T_2 = 0.17$ s, $T_3 = 0.11$ s,$T_4 = 0.09$ s). Under this assumption the damping matrix C reads as follows:

$$\begin{bmatrix} 2c_1 & -c_2 & 0 & 0 \\ -c_2 & 2c_1 & -c_2 & 0 \\ 0 & -c_2 & 2c_1 & -c_2 \\ 0 & 0 & -c_2 & c_1 - c_2 \end{bmatrix} \tag{5}$$

where $c_1 = \alpha m_f + \beta k_f$ and $c_2 = \beta k_f$. The quantities m_f and k_f have been chosen to represent a four-storey, concrete-frame building ($m_f = 59.53 * 10^3$ kg,$k_f = 8.33 * 10^4$ KN/m).

2.2. Secondary structure: the sliding–rocking rigid body

The secondary structure considered is the system analysed in [19]. It is made up of the eccentric rigid body of Fig. 2a and b placed on a base isolation which is connected to the floor by a linear visco-elastic device shown in Fig. 2c, where $\hat{c}$ and $\hat{k}$ are its damping and