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New formulation for estimating the damping parameter of the Kelvin-Voigt model for seismic pounding simulation

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A B S T R A C T

Seismic pounding between adjoining buildings frequently causes serious damage; although collision can be avoided with proper separation, can still occur due to code non-fulfillment, loose requirements of old codes, and seismicity underestimation. Inside this context, this work deals with collision between two buildings with aligned slabs. The simulation of this phenomenon is not obvious, involving stress traveling waves, high-frequency behavior, and local effects. Complex distributed continuum mechanics-based models can be used, but are time-consuming; conversely, the concentrated Kelvin-Voigt model can be utilized instead, being simple and inexpensive, yet accurate. Its behavior is characterized by damping and stiffness parameters; the damping influence is particularly important and a number of estimation criteria have been proposed. Among them, the Anagnostopoulos formulation is simple, and provides satisfactory results in most situations. That formulation consists in estimating the damping parameter after a given target value of the coefficient of restitution; the influence, during impact, of the colliding building structures and the seismic excitation is neglected. This paper proposes an alternative approach that releases one of the aforementioned assumptions: the influence of the building structures and their initial separation is taken into consideration. A simplified parametric study oriented to investigate the performance of the proposed strategy is performed; it is found that the accuracy of the Anagnostopoulos formulation is improved in a number of situations. Noticeably, this gain is obtained at a low computational cost. The proposed formulation is satisfactorily utilized to analyze pounding between two multi-story multi-bay RC buildings and to simulate a shaking table pounding experiment.

1. Introduction

Impact between contiguous buildings under strong seismic events is a relevant issue since the huge forces that are generated during the collision significantly affect the dynamic behavior of the pounding buildings. On some occasions, the effect of impact might be beneficial, mainly in terms of inter-story drift; conversely, in many other situations, pounding is detrimental, particularly in terms of absolute acceleration. Collapses and structural and nonstructural damage of buildings due to seismic pounding have been reported [1–9]. Although such collision can be avoided by adequately separating the involved buildings, and this gap is routinely required by the design codes, impact can anyway occur because of several reasons: sometimes code prescriptions are not fulfilled, some past codes did not oblige any such separation, and the seismicity can be underestimated. Therefore, seismic pounding of buildings is something to be taken into consideration.

Collision between adjoining buildings can be classified into two categories: slab-to-slab and slab-to-column (or slab-to-wall) impact; they correspond to aligned and unaligned slabs, respectively. The second type is by far more dangerous, since the impact of a rigid and massive slab on a column (or even on a wall) is most likely to lead to collapse. On the other hand, the first type is not free of danger, and is considerably more frequent, since adjoining buildings with unaligned slabs are regularly avoided. Moreover, the numerical simulation of slab-to-slab impact is highly challenging, as discussed later. Thus, this study is focused on seismic pounding of adjoining buildings with aligned slabs.

As outlined in the previous paragraph, collision between two building slabs is a complex phenomenon, because it involves stress traveling waves, high-frequency behavior, and significant local effects [10,11]. Certainly, sophisticated mechanics-based numerical models are available, but they are highly time-consuming. On the other hand,

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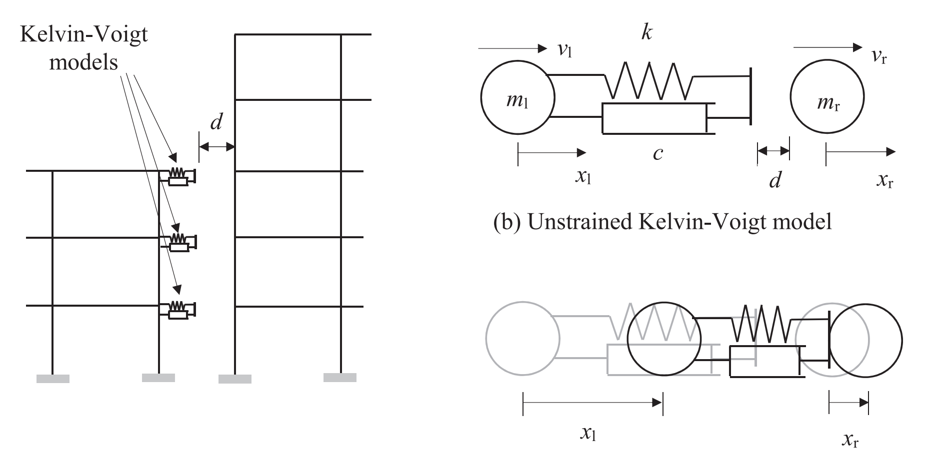
Nomenclature

List of symbols

a_l/a_r	initial displacement of the left/right colliding frames (Fig. 4)
A	cross-section area
$\mathbf{b}$	constant vector given by $\mathbf{b} = (-k\,d, k\,d)^T$ (Eq. (5))
c	damping. damping of Kelvin-Voigt model according to the Ref. [14]
c_A/c_p	damping of the Kelvin-Voigt model according to the Anagnostopoulos/proposed formulation
c_l/c_r	equivalent damping, during the impact, of the left/right models of the buildings (Fig. 2)
d	gap between two adjoining colliding buildings
E	equivalent concrete elastic deformation modulus
k	stiffness of the Kelvin-Voigt model
k_l/k_r	equivalent stiffness, during the impact, of the left/right models of the buildings (Fig. 2)
l/r	subindexes of the left/right buildings
L	length of the colliding slabs
$\mathbf{M}/\mathbf{C}/\mathbf{K}$	mass/damping/stiffness matrices (Eq. (5))
m	mass of a building or frame
m_l/m_r	equivalent mass of the colliding of slabs of the left/right buildings (Fig. 2)
r, r_T	coefficient of restitution, target coefficient of restitution
r_A/r_p	coefficient of restitution obtained after the Anagnostopoulos/proposed formulations
$t/t_{imp}/t_{max}$	time/impact duration/maximum impact duration
T_i	natural period of the i-th mode
m_i^*	equivalent modal mass of the i-th mode
v_l/v_r	traveling (absolute) velocities of left/right slabs in the beginning of the collision
v_l'/v_r'	traveling (absolute) velocities of left/right slabs in the end of the collision
$\mathbf{x}$	displacement vector given by $\mathbf{x} = (x_l, x_r)^T$ (Eq. (5))
x_l/x_r	coordinates of the colliding of slabs of the left/right buildings
x_0	initial coordinate of both colliding slabs at the onset of impact
β	parameter of the Newmark algorithm
$\varepsilon_0/\varepsilon_r/\varepsilon_\eta$	tolerance ratio/tolerances for the outer/inner loops
$\mathbf{\Phi}$	modal matrix
γ	ratio k_r/k; parameter of the Newmark algorithm
η_1/η_2	modal coordinates of the first/second modes. $\boldsymbol{\eta} = (\eta_1, \eta_2)^T$
λ	ratio c_r/c
μ	ratio m_l/m_r
$\omega/\omega_1/\omega_2$	natural frequency according to [14]/natural frequency of the first/second modes according to the proposed formulation
ω_l/ω_r	equivalent natural frequency, during the impact, of the left/right models of the buildings (Fig. 2)
$\zeta/\zeta_1/\zeta_2$	damping ratio according to [14]/damping ratio of the first/second modes according to the proposed formulation
ζ_l/ζ_r	equivalent damping ratio, during the impact, of the left/right models of the buildings (Fig. 2)
ζ_A/ζ_p	damping ratio of the Kelvin-Voigt model according to the Anagnostopoulos/proposed formulation

the 3-D continuum partial derivative equations of motion (distributed-parameter models) can be solved exactly in some geometrically simple cases, but the ensuing closed-form solutions can be useful only when the required simplifying assumptions are reasonable. Given these circumstances, the description of the analyzed type of impact with concentrated models has been suggested [12]. The most simple and spread one is the linear viscoelastic Kelvin-Voigt model [13], consisting in the parallel combination of a spring and a dash-pot, together with the consideration of the gap between the colliding slabs, as described later in Fig. 1.

The Kelvin-Voigt model is simple, robust and computationally inexpensive, providing reasonable accuracy; moreover, it is implemented in the most common software codes (ETABS, SeismoStruct, OpenSees, among others). On the other hand, sound criteria for selecting the damping parameter are available [14]; with regard to the stiffness parameter, it has proven to be less relevant. Conversely to these positive issues, some studies [15,16] have pointed out that the Kelvin-Voigt model exhibits some degree of inconsistency, since the contact force can take negative values, despite this model being compression-only. With the aim of fixing this conflict, the works [17–19] depict modifications of the Kelvin-Voigt model; however, the study [16] demonstrates that their results are similar to those of the normal Kelvin-Voigt model. In addition, other models such as Hertzdamp [15], nonlinear viscoelastic [20], and Hunt-Crossley [21] have been proposed. These models are computationally more expensive and less robust, are not implemented in the major software codes, and no comprehensive studies providing criteria for selecting the values of the parameters have been reported. Also, the aforementioned inconsistency in the Kelvin-Voigt model does



(a) Distribution of Kelvin-Voigt models (c) Strained Kelvin-Voigt model during impact

Fig. 1. Lumped Kelvin-Voigt models for simulation of pounding between adjoining buildings with aligned slabs.