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Comparative evaluation of two simulation approaches of deck-abutment pounding in bridges

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ABSTRACT

The present paper compares two simulation methods of the deck-abutment pounding in bridges: the commonly adopted gap element (or compliance) approach and a nonsmooth dynamics approach. Specifically, the study evaluates these two approaches with respect to their ability to predict the measured response of a straight, large-scale bridge model from an independent experimental study. The paper also investigates the sensitivity of the deck response to critical assumptions of the compliance approach, i.e., the stiffness of the gap element, the presence of friction during contact, the occurrence of sticking during frictional contact, and the constitutive law of the contact elements. The results show that the deck rotation predicted by these two approaches might differ notably, and highlight the dominant role of friction and its modelling on the seismic response of bridges involving pounding at the deck level.

1. Introduction

Numerous bridges suffer damage due to contact (impact/-pounding) during earthquakes [1,2], either between adjacent deck segments or between deck and abutment. Beyond local damage, contact can also alter drastically the effective mechanical system of the bridge, occasionally triggering in-plane deck rotation. Contact might even lead to deck unseating/collapse due to excessive response of the deck or severe damage of the piers [3–6].

The majority of numerical/analytical studies of the pounding phenomenon at the deck level [7,8] simulates the behavior solely in the normal direction of contact adopting a gap element (or 'compliance') approach. This gap element is a stiff spring (with/without a dashpot) working only in compression and activated after the gap-closure. Thus, the deck-abutment interaction is usually modelled with either a single gap element at each corner of the deck (e.g., in [9,10]), or with multiple distributed gap elements aligned perpendicularly to the contact surface (e.g., in [11,12]). To date, a limited number of studies account for the friction along the tangential direction of contact between deck segments or between deck and abutment. An early exception is the study of Jankowski et al. [13] which considered the tangential contact forces between adjacent bridge segments using linear dashpot elements with high damping constant. Zhu et al. [14] proposed a node-to-surface model to treat the frictional contact problem of a 3-span steel bridge. Guo et al. [15] modified this model and evaluated it through shake table tests of scaled bridge models. Bi and Hao [16] proposed a sophisticated three-dimensional finite-element simulation of pounding in segmental straight bridges. More recently, Amjadian et al. [17] examined the response of curved bridges subjected to earthquakes, based on the Karnopp friction model [18].

Adopting the principles of nonsmooth dynamics, Dimitrakopoulos examined the impact between deck and abutment [19], as well as, between successive deck segments [20]. Recently, Shi and Dimitrakopoulos [21] extended that nonsmooth dynamics framework to deal with the multi-support excitation, the inelastic behavior of the reinforced concrete piers, and the continuous (frictional) contact of a multibody configuration. That study verified the experimental results of a large-scale deck-abutment bridge model by Saiidi et al. [22], and illustrated the physical mechanism behind the rotation of straight bridges triggered by the frictional deck-abutment contact.

The motivation for the present study originates from the numerous cases of bridges suffering pounding-induced in-plane deck rotation and the associated need to comprehend the efficiency and the limitations of the different simulation approaches. The [21] study proposed and validated a nonsmooth dynamics framework as an efficient, although unconventional, approach to

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simulate the deck response involving deck-abutment pounding. The objective of this paper is to assess the validity of the compliance method that is more commonly used for modelling deck-abutment pounding in bridges. Specifically, the present paper compares the compliance and the nonsmooth approaches with respect to their ability to predict the measured in [22] deck response. The study also investigates the sensitivity of the deck response to critical aspects of the compliance approach, namely the contact stiffness, the presence of friction during contact, the occurrence of sticking during frictional contact, and the constitutive law of the adopted contact elements.

2. Idealization and methodology of deck-abutment interaction

2.1. Benchmark deck-abutment bridge system

The present study evaluates different simulation methods against the measured response of a 4-span (1/4-scale) reinforced concrete bridge model tested experimentally by Saiidi et al. [22]. The benchmark shake table tests concern a straight continuous post-tensioned deck supported by three 2-column bents and two abutment seats. The three bents are fixed at their base on independent shake tables, that introduce the base motion along the two translational directions. The abutment seats are sliding, under the control of actuators, on guide sliders along the longitudinal direction. Seven sets of input excitations are considered, scaled to different target Peak Ground Accelerations (PGAs) ranging from 0.075 to 1.0 g (along the transverse direction).

Of particular interest to the present study, is the deck-abutment pounding and the subsequent, "unexpected", in-plane rotation of the deck observed during these experimental tests. The study compares two families of simulation methods of pounding: the commonly adopted compliance approach and an alternative nonsmooth approach recently proposed in Shi and Dimitrakopoulos [21]. The former simulation (compliance approach) is realized numerically in OpenSees [23] and analytically in Matlab [24] platform. The latter (nonsmooth approach) is only implemented with the aid of an in-house algorithm [21] in Matlab.

2.2. Conventional numerical simulation

Fig. 1(a) illustrates a conventional finite element model, established in OpenSees [23], for the seismic response analysis of the examined bridge-abutment-seats system. The deck ($\Sigma m_{di} = M_d = 140.5$ t and $\Sigma I_{di} = I_d = 13{,}090$ t·m^2) and the abutment seats ($\Sigma m_{ai} = M_a = 0.65$ t and $\Sigma I_{ai} = I_a = 0.31$ t·m^2) are modelled as stick elements with lumped masses and relatively large Young's modulus ($E = 3 \times 10^6$ MPa) to resemble a rigid body. The nonlinear behavior of the RC columns is modeled with zero-length Takeda hysteretic elements [25] in both (horizontal) translational directions. The initial stiffness of the columns (i.e. of the Takeda elements) is estimated from the measured in [22] post-crack stiffness of the bents, and is updated before each of the successive analyses according to the peak displacement recorded experimentally in the previous shake-table test, to capture the stiffness degradation during the testing [21]. The two abutment seats are supported on (stiff) springs ($k_x = 17{,}513$ kN/m and $k_\theta = 49{,}934$ kN·m/rad as estimated from the measured force-displacement loops of the actuator) and dashpots ($c_x = 213$ kN·s/m and $c_\theta = 248$ kN·m·s). The analysis adopts a Rayleigh damping matrix with 8% damping coefficient validated previously [21]. The recorded during the experimental tests motion (displacement and velocity) of the three shake tables and of the two abutment seats, is the multi-support excitation at the bottom of the piers (i.e. the Takeda models) and at the abutment seats, respectively, during the analyses.

The deck-abutment pounding is firstly simulated with the compliance approach, in accordance with the common practice in earthquake engineering. Specifically, at the 4 corners, pertinent node-to-node gap elements are used. These gap elements are stiff linear elastic springs which ignore friction ('zeroLengthSection' element with 'ElasticPPGap' material in OpenSees). The initial gap between deck and abutment is 0.0127 m in the experimental test, but the gap size changes during the successive shake-table tests [22] due to the residual displacements/deformations of the RC columns. The initial gap before each analysis is updated accordingly to match the recorded (in [22]) gap size at the beginning of each excitation.

2.3. Analytical modelling

To further investigate the compliance approach, a similar multibody-model of the bridge-abutment-seats system is established in Matlab. The multibody model (Fig. 1b and c) is comprised of three rigid bodies, the deck ($M_d = 140.5$ t and $I_d = 13{,}090$ t·m^2) and the two abutment seats ($M_a = 0.65$ t and $I_a = 0.31$ t·m^2). Seven degrees of freedom (DOFs) capture the planar motion of the abutment seat '1' $\boldsymbol{u}_1^a = [x_1, \theta_1]^{\mathrm{T}}$, the abutment seat '2' $\boldsymbol{u}_2^a = [x_2, \theta_2]^{\mathrm{T}}$, and the deck $\boldsymbol{u}_d^a = [x_d, y_d, \theta_d]^{\mathrm{T}}$.

The equation of motion of the deck-abutment system of Fig. 1(b and c) when subjected to multiple-support excitation at the 3 bent supports $\left(\boldsymbol{u}_g^a\right)$ and the 2 abutment seats $(\boldsymbol{u}_a^a)$ [22], can be written as [21,26]:

$$\boldsymbol{M}\ddot{\boldsymbol{u}}^a - \boldsymbol{h} - \boldsymbol{W}_N\boldsymbol{\lambda}_N - \boldsymbol{W}_T\boldsymbol{\lambda}_T = \boldsymbol{0} \tag{1}$$

where $\boldsymbol{M}$ is the mass matrix, $\boldsymbol{u}^a$ is the displacement vector of the deck and the abutment seats with respect to an absolute system of reference (superscript a), and $\boldsymbol{h}$ is the vector of the non-impulsive forces, equal with:

$$\boldsymbol{h} = \boldsymbol{C}\dot{\boldsymbol{u}}^r + \boldsymbol{F}_S(\boldsymbol{u}^r) \tag{2}$$

$\boldsymbol{C}$ is the damping matrix, $\boldsymbol{F}_S$ is the vector of the restoring forces as determined by Takeda hysteretic models [25], and the upper dot denotes time differentiation. The relative displacement $\boldsymbol{u}^r$ (superscript r) vector, is equal to the difference between the absolute displacement vector $\boldsymbol{u}^a$ and the (multi-support) input displacement $\boldsymbol{u}_g^a$ vector:

$$\boldsymbol{u}^r = \boldsymbol{u}^a - \boldsymbol{u}_g^a \tag{3}$$

The definition of the velocity vector $\dot{\boldsymbol{u}}^r$ follows similarly. Finally, $\boldsymbol{W}_N$ and $\boldsymbol{W}_T$ are the direction matrices of the contact forces in the normal (subscript N) and the tangential (subscript T) direction, respectively. Subscripts "N" and "T" are used throughout this study in the same way. Vectors $\boldsymbol{\lambda}_N$ and $\boldsymbol{\lambda}_T$ contain the contact forces along the two directions of contact. The calculation of the unknown contact force vectors $\boldsymbol{\lambda}_N$ and $\boldsymbol{\lambda}_T$ and direction matrices $\boldsymbol{W}_N$ and $\boldsymbol{W}_T$ (Eq. (1)) depends on the simulation assumptions of the deck-abutment contact/impact interaction.

Regardless, contact occurs when the relative contact distance (gap functions g_{N1} to g_{N4}) between the corners of the deck and the adjacent abutments vanishes. In general, the problem is geometrically nonlinear as the direction of the contact axes, as well as, the location of the contact points at the abutments seats, is not fixed but response dependent. Fig. 2(b) shows the change of the normal/tangential directions of the contact (vectors $\boldsymbol{n}$ and $\boldsymbol{t}$ respectively), in a geometrically linear and a nonlinear analysis, respectively. As the results demonstrate later (Section 3.2) though, for the particular case examined herein the difference between a