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Seismic response analysis of skew bridges with pounding deck–abutment joints

Elias G. Dimitrakopoulos

Department of Engineering, University of Cambridge, CB2 1PZ, United Kingdom

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ABSTRACT

In this paper the seismic response of short skew bridges with deck–abutment pounding joints is revisited. The permanent deck rotations and transverse displacements of such bridges after the recent earthquake in Chile created an incentive to revisit their non-conventional behaviour. A novel non-smooth rigid body approach is proposed to analyze the seismic response of pounding skew bridges which involves oblique frictional multi-contact phenomena. The coupling of the response, due to contact, is analysed in depth. It is shown that the tendency of skew bridges to exhibit transverse displacements and/or rotate (and hence unseat) after deck–abutment collisions is not a factor of the skew angle alone, but rather of the plan geometry plus friction. This is expressed with proposed dimensionless criteria. The study also unveils that the coupling is more pronounced in the low range of the frequency spectrum (short-period excitations/flexible structures) and presents novel dimensionless response spectra for the transverse displacements and rotations, triggered by oblique contact in a skew bridge subsystem. Despite the complexity of the response, the proposed spectra highlight a clear pattern. The dimensionless rotations, arising from contact, decline as the ratio of the structural versus excitation frequency increases and become practically negligible in the upper range of the frequency spectrum. Finally, a pilot application to a typical skew bridge is presented.

1. Introduction

This paper focuses on the seismic response of short skew bridges with deck–abutment joints, while it derives from a broader study [1–4] on the problem of earthquake-induced pounding in bridges. The recent earthquake in Chile [5,6] has created an incentive to revisit the non-conventional behaviour of skew bridges. As earthquake reconnaissance reports [7] indicate, skew bridges often rotate in the horizontal plane, thus tending to drop off the supports at the acute corners [8]. This behaviour is triggered by oblique contact and results in coupling of longitudinal and transverse response, binding in one of the obtuse corners and subsequently rotation in the direction of increasing the skew angle [8] (see also Fig. 1). Despite the recorded evidence from previous earthquakes which underline the importance of this mechanism, as well as the empirical vulnerability methodologies that acknowledge skew as a primary vulnerability factor of bridges [9], there are only a few analytical attempts to comprehend this mechanism.

One of the first contributions was made by Maragakis et al. [10], motivated by extensive damage during the 1971 San Fernando [7] earthquake. Maragakis et al. [10] focused on the interaction of short skew bridges with the abutments and the resulting rigid body rotational vibrations. In that study, the bridge deck was simulated with a rigid stick model and pounding with the abutments was taken into account with a spring activated after the gap closure. The analysis performed therein showed significant transverse displacements at the end supports due to rotations. Planar rigid body deck rotations were found to be primarily produced by impact of the skew deck with the abutment and not by non-symmetric (e.g. eccentricity in plan with respect to the centre of mass) restoring characteristics of the substructure, or impact between deck and wing walls. More than 20 years later, Abdel-Mohti and Pekcan [11] compared detailed 3D finite element modelling with simplified beam stick models of skew bridges and argued that the beam stick model is capable of capturing the coupling of the response and the main modes of the bridge, at least for moderate skew angles.

In their recent study, Saadeghvaziri and Yardani-Motlagh [12] examined the seismic vulnerability of Multi-Span Simply-Supported (MSSS) bridges. They marked that impact can impose high shear demands on the bearings of MSSS skew bridges, raising their failure probability. The coupling of the response displacements as well as rotations, caused by skew deck–abutment contact, was also underlined by Bignell et al. [13]. Bignell et al. conducted a series of push-over analyses with structural configurations representative of typical Illinois bridges. The ultimate load capacity of a bridge was reduced, due to the skew angle, up to nearly two thirds compared to the corresponding non-skew bridge. In addition, the presence of a skew angle introduced failure mechanisms unseen in the non-skew case, e.g. abutment bearing failure. Maleki [14] studied single span skew bridges using a SDOF model in an attempt to

E-mail address: ilias.dimitrakopoulos@gmail.com.

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Notations

α skew angle (as defined in Fig. 2)
a_g, ω_g a length and a time scale of the excitation appropriately selected as in [3]
$\ddot{u}_g$ ground acceleration, upper dots stand for differentiation with respect to time.
W, L Width, Length of a bridge deck in plan (as defined in Fig. 2)
δ gap size at rest
η_0, η_1 dimensionless skew ratio for frictionless and frictional contact respectively, defined in Eq. (1)
$\Lambda_{Ni}, \Lambda_{Ti}$ impulse in the normal and the tangential direction of contact i respectively
$\mathbf{\Lambda}_N, \mathbf{\Lambda}_T$ the column vector of impulses Λ_{Ni} and Λ_{Ti} respectively
$\boldsymbol{\lambda}, \boldsymbol{\lambda}_N, \boldsymbol{\lambda}_T, \boldsymbol{\lambda}_H$ vector of the contact force, in the normal direction (subscript 'N') and the tangential direction for sliding (subscript 'T') and sticking (subscript 'H') contacts.
r_i lever arms in the normal direction of contact i (Eqs. (8))
r_T lever arms in the tangential direction of contact i, $r_T = Lc\alpha/2$
$\omega_0, \omega_{0x}, \omega_{0y}$ translational angular frequency, subscripts 'x' and 'y' indicate the translational direction when is needed
Ω_0 rotational angular frequency
ξ viscous damping ratio
x, x_m translational displacement in x–x direction, subscript 'm' stands for maximum
y, y_m translational displacement in y–y direction, subscript 'm' stands for maximum
θ, θ_m planar rotation around the vertical axis, subscript 'm' stands for maximum
$\mathbf{q}$ vector of the relative to the ground displacements, $\mathbf{q}^T = (x\ y\ \theta)$
$\mathbf{u}$ vector of the relative to the ground velocities ($\dot{\mathbf{q}} = \mathbf{u}$ holds almost everywhere)
T_m mean period. $T_m = \sum_i \left(C_i^2/f_i\right) / \sum_i C_i^2$ where C_i are the Fourier amplitudes of the accelerogram and f_i the discrete Fourier transform frequencies between 0.25 and 20 Hz.
$\mathbf{h}$ vector of the non-impulsive forces
$m, I_m, \mathbf{M}$ mass, rotational moment of inertia and mass matrix respectively
ρ radius of gyration
$\mathbf{E}$ identity matrix
$\varepsilon_{Ni}, \bar{\bar{\varepsilon}}_N$ coefficient of restitution in the normal direction of contact i and diagonal matrix: $\bar{\bar{\varepsilon}}_N = \text{diag}\{\varepsilon_{Ni}\}$
$\mu_i, \bar{\bar{\boldsymbol{\mu}}}$ coefficient of friction of contact point i and diagonal matrix: $\bar{\bar{\boldsymbol{\mu}}} = \text{diag}\{\mu_i\}$
$\bar{\bar{\boldsymbol{\mu}}}_G, \bar{\bar{\boldsymbol{\mu}}}_H$ the $\bar{\bar{\boldsymbol{\mu}}}$ matrices for sliding (subscript 'T') and sticking contacts (subscript 'H')
g_{Ni} relative distance of the potential contact i
γ_{Ni}, γ_{Ti} the velocities of contact i in the normal and the tangential direction of respectively
$\boldsymbol{\gamma}_N, \boldsymbol{\gamma}_T$ vector of contact velocities γ_{Ni} and γ_{Ti}
$\boldsymbol{\gamma}_{NA}, \boldsymbol{\gamma}_{NE}$ the contact velocities vector before (subscript 'A') and after (subscript 'E') contact in the normal direction
$\boldsymbol{\gamma}_{TA}$ the tangential contact velocity vector before
$\boldsymbol{\gamma}_{TE} = \boldsymbol{\gamma}_{TR} - \boldsymbol{\gamma}_{TL}$ the tangential post-contact velocity vector, which is decomposed into the positive (subscript 'R') and negative (subscript 'L') part
$\dot{\boldsymbol{\gamma}}_H = \dot{\boldsymbol{\gamma}}_{HR} - \dot{\boldsymbol{\gamma}}_{HL}$ the tangential contact acceleration vector of the sticking contacts, which is decomposed into the positive (subscript 'R') and negative (subscript 'L') part
$\mathbf{W}_N, \mathbf{W}_T$ direction matrices in the normal (subscript 'N') and the tangential (subscript 'T') direction of contacts
$\mathbf{W}_H, \mathbf{W}_G$ direction matrices of the potentially sticking contacts (subscript 'H') and sliding contacts (subscript 'G')
$\mathbf{W}_Q$ the abbreviation $\mathbf{W}_Q = \mathbf{W}_N + \mathbf{W}_G\bar{\bar{\boldsymbol{\mu}}}_G + \mathbf{W}_T\bar{\bar{\boldsymbol{\mu}}}_T$
$()^T$ denotes the transpose matrix
3D Three Dimensional
C.M. Centre of Mass
MSSS Multi-Span Simply-Supported
PGA Peak Ground Acceleration
SDOF Single Degree of Freedom
MDOF Multi Degree of Freedom
LCP Linear Complementarity Problem

Fig. 1. Typical damage of overcrossings after the Chile earthquake of February 27, 2010.
Source: Taken from [5].

estimate the forces developed during collision. Lou and Zerva [15] emphasized the need for more realistic spatially variable ground motions when analysing the seismic response of a skew bridge with deck–abutment joints.

Meng et al. [16,17] examined the torsional effects introduced in short skew bridges by (accidental or other) eccentricity but did not consider deck–abutment contact. The most relevant conclusion of these studies [18,16], to the present work, is that the rotation of skew bridges with high rotational Ω_0 to translational ω_0 frequency ratios (Ω_0/ω_0) may be less sensitive to the deck-aspect ratio Width/Length $= W/L$ and the skew angle α (Fig. 2).

Some of the salient features of the rotational mechanism associated with the deck–abutment collisions of skew bridges were brought forward in [2]. Studying the oblique impact of a planar skew rigid body against an inelastic half-space (Fig. 2), that study revealed that what matters during full-edge impact is the total geometry of the (skew) deck in plan. In particular the dimensionless skew ratio η_0 and η_1 for frictionless and frictional impact respectively are important:

$$\eta_0 = \frac{\sin 2\alpha}{2\,(W/L)}, \qquad \eta_1 = \eta_0\left(1 + \frac{\mu}{\tan\alpha}\right) \tag{1}$$

When $\eta_0 < 1$ (Fig. 2-top) the angular momentums $r_1\Lambda_{N1}$ and $r_2\Lambda_{N2}$ of the two impulses Λ_{N1} and Λ_{N2} are in different directions