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Experimental and numerical investigation of the earthquake response of crane bridges

Cyril Feau [a], Ioannis Politopoulos [a,*], George S. Kamaris [a], Charlie Mathey [a], Thierry Chaudat [a], Georges Nahas [b]

[a] CEA, DEN, DM2S, SEMT, EMSI, F-91191 Gif-sur-Yvette, France
[b] IRSN/PSN-EXP/SES/BEGC, 92265 Fontenay aux Roses, France

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ABSTRACT

The experimental and numerical response of crane bridges is studied in this work. To this end, an experimental campaign on a scale model of an overhead crane bridge was carried out on the shaking table of CEA/Saclay in France. A special similarity law has been used which preserves the ratios of seismic forces to friction forces and of seismic forces to gravity forces, without added masses. A numerical model, composed of beam elements, which takes into account non-linear effects, especially impact and friction, and simulates the earthquake response of the crane bridge, is presented. The comparison of experimental and analytical results gives an overall satisfactory agreement. Finally, a simplified model of the crane bridge, with only a few degrees of freedom is proposed.

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1. Introduction

The earthquake response of crane bridges is a very important issue related to safety requirements for industrial facilities and, especially, nuclear plants. Actually, a failure of a component of the crane bridge or of its supports (e.g. supporting steel or concrete runway beams) should be avoided. In addition to the consequences on the handling capacity of the facility after the earthquake, a major problem may occur if a part of or the whole crane bridge falls on sensitive structures or equipment. Surprisingly, to the authors' knowledge, a very few experimental and analytical research work in this field has been done in the past. The dynamics of elastic continua with moving loads has been covered by Fryba [1] and more recent work presents the approximate analytical solutions [2–6] and finite element solutions [7,8] to similar problems. Regarding the earthquake response of these structures, not many publications can be found in the literature. Komori et al. [9] carried out seismic tests under horizontal excitation whereas Otani et al. [10] focused on the vertical earthquake response of a 1/8 scale model. Schukin and Vayandrakh [11] studied the earthquake behavior of a polar crane bridge by means of a comprehensive finite element model. Betbeder et al. [12] and Betbeder and Labbé [13] deal with simplified models accounting for the reduction of the crane bridge forces due to sliding. Sarh et al. [14] analyzed the behavior of a simplified scale model of a crane bridge subjected to random unidirectional excitation and compared it with experimental tests. More recently, Kenichi et al. [15] carried out a shake table experimental campaign on a model of a crane bridge focusing on the uplift response of the trolley.

To have a further insight into the earthquake response of crane bridges an experimental campaign of a 1/5 scale model was carried out on one of the shake tables of the Commissariat à l'Énergie Atomique et aux Énergies Alternatives (CEA) in Saclay, France. In the following we describe the most important features of the model, the experimental set-up and we present the main experimental results. Moreover, we discuss some subtle points related to the numerical modeling of the mock-up and we compare the analytical and experimental results.

2. Experimental tests

The mock-up is a simplified 1/5 scale model of a 22.5 m long overhead crane bridge. Given that the shake table is a 6 m × 6 m table, this scale is the biggest scale that could have been considered. The total mass of the unloaded prototype is of about 100 t. The bridge steel girders that support the crane trolley have a rectangular hollow section 1050 mm × 2100 mm. The width of the section flanges and vertical walls are 21 mm and 12 mm respectively. The runway beams are continuous I type steel beams with a typical span of 10 m. The height of the section is 1500 mm, the flanges width and thickness are 600 mm and 35 mm respectively

* Corresponding author. Tel.: +33 169083665, fax: +33 169088331.
E-mail address: ipolitopoulos@cea.fr (I. Politopoulos).

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and the web thickness is 12 mm. One important issue for the design of the model was the determination of the similarity law which is presented in the following subsection.

2.1. Similarity law

Due to the limitations in the capacities of the experimental facilities, experimental models are, usually, reduced scale models. To be representative of the behavior of the response of the real structure (prototype), tests on reduced scale models should be carried out following similarity laws. A natural way to do this is through dimensional analysis [16–19]. Let us look at a quantity of interest, for instance, the vector of relative displacement with respect to the shake table displacement at any point of the bridge, at coordinate $\underline{x}$, $\underline{d}(\underline{x})$. Assuming a homogeneous, isotropic, rate independent material and a Coulomb dry friction for the sliding interfaces, this quantity may be written as a function of the system's parameters:

$$\underline{d} = \phi_d(E, \nu, \mu, \underline{x}, t, \rho, g, \underline{\Gamma}, L, \ldots, \sigma_y, \ldots L_i \ldots) \tag{1}$$

where E is the Young modulus, ν is the coefficient of Poisson, μ is the friction coefficient, t denotes time, ρ is the mass density, $\underline{\Gamma}$ is the vector of shake table acceleration, L is a characteristic length of the structure (e.g. length of the bridge girders). For the sake of conciseness we limit ourselves only to the above ten variables ($\underline{d}$, E, ν, μ, $\underline{x}$, t, ρ, g, $\underline{\Gamma}$, L). However, one must keep in mind that several other variables (e.g. nonlinear material properties, other geometrical dimensions like the girders' section dimensions, wheel dimensions, etc.), play a role in the system's response. All these are schematically denoted, in the "dot" part into the brackets in Eq. (1) as, for instance, the yield stress σ_y and other geometrical dimensions L_i. In the present case, the rank of the matrix of the dimensions' exponents of the variables governing the system's response is equal to 3 (i.e. equal to the number of fundamental dimensions: mass, time and length). According to the Vachy–Buckingham's Pi theorem, Eq. (1) can be written in dimensionless form with $N-3$ dimensionless variables, N being the number of the initial variables.

$$\frac{\underline{d}}{L} = \Phi_d\left(\nu, \frac{\rho L \underline{\Gamma}}{E}, \frac{E}{\rho L g}, t\frac{\sqrt{E/\rho}}{L}, \frac{\underline{\Gamma}}{\mu g}, \frac{\underline{x}}{L}, \ldots, \frac{\sigma_y}{E}, \ldots, \frac{L_i}{L}, \ldots\right) \tag{2}$$

A similar relation holds if the quantity of interest is the dimensionless stress $\underline{\underline{\sigma}}/E$ instead of the dimensionless displacement. The products $\Pi_1 = \rho L \underline{\Gamma}/E$ and $\Pi_2 = E/\rho L g$ may be seen as the ratios of seismic excitation forces to elastic forces and of elastic forces to gravity forces respectively. The latter is the Froude number. The dimensionless time $\Pi_3 = t\sqrt{E/\rho}/L$ is the ratio of time to the time needed by sound waves to travel over the length L. $\Pi_4 = \underline{\Gamma}/(\mu g)$ accounts for the ratio of the seismic excitation forces to the friction forces.

A complete similitude is achieved if all dimensionless variables have the same values for both the model and the prototype. In the framework of seismic tests of structures two similarity laws are widely used: velocity similarity and, even more frequently, Froude or gravity similarity. Consider a uniform geometrical scaling, that is, the coordinates of the model and of the prototype (scale 1 structure) satisfy the relation $\underline{x} = \lambda \underline{x}_0$, where λ denotes the scaling factor (1/5 in this case) and subscript 0 denotes, throughout this paper, quantities referred to the prototype. According to the velocity similarity law, all dimensionless products in Eq. (2) are the same for the model and the prototype, except the Froude number Π_2. If the same material (E, ν, ρ) is used for both the prototype and the model, the above similarity implies that the time scaling is $t/t_0 = \lambda$ and the ratios of mass, M, stiffness, K and eigenfrequencies, f, of the model to those of the prototype are:

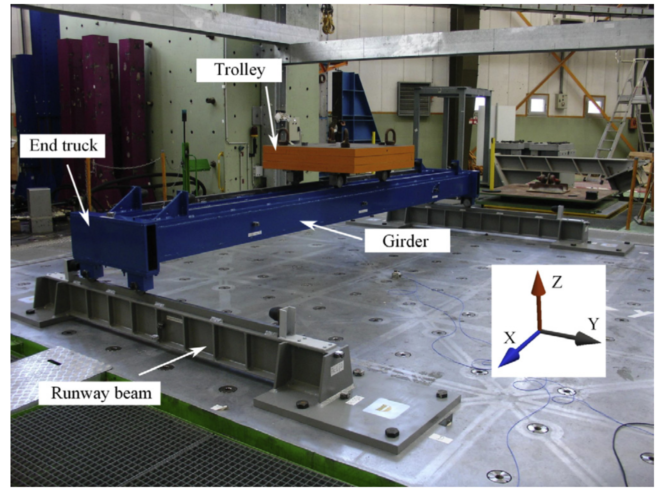

Fig. 1. Model of the crane bridge mounted on the shake table.

$$M/M_0 = \lambda^3, \quad K/K_0 = \lambda, \quad f/f_0 = 1/\lambda \tag{3}$$

Π_3 and Π_1 similitude imply that the time scaling is $t/t_0 = \lambda$ and that the excitation (table) acceleration components, Γ, must be amplified by the reciprocal of the scaling factor i.e. $\Gamma(t)/\Gamma_0(t_0) = 1/\lambda$. The resulting displacement, velocity and acceleration components, respectively d, v and a, vary as:

$$d(t)/d_0(t_0) = \lambda, \quad v(t)/v_0(t_0) = 1, \quad a(t)/a_0(t_0) = 1/\lambda \tag{4}$$

This law is called velocity similarity because there is no velocity scaling. It is well known that the main drawback of this similarity law is that, since the Froude number similitude is not satisfied, the ratio between dynamic and static stresses of the model is not the same as in the prototype. Moreover, in the present case, where the importance of friction phenomena is crucial, if the same coefficient of friction μ, is used for both the prototype and the model, it is not possible to respect Π_4 similarity. Therefore, similarity of the friction forces with respect to the seismic excitation forces cannot be achieved unless specific interface materials are used with a friction coefficient $1/\lambda$ times the friction coefficient of the prototype. Given that steel to steel friction coefficient is of about 0.20 this would imply a model friction coefficient of about 1 which is hardly feasible if not impossible.

The most frequently used similarity law, in experimental earthquake engineering, is the gravity or Froude similarity. In this case, all the dimensionless variables in Eq. (2), including the Froude number, are the same for the model and the prototype. This results in the following similarity relations:

$$\begin{aligned} &\rho/\rho_0 = 1/\lambda, \quad K/K_0 = \lambda, \quad f/f_0 = 1/\sqrt{\lambda}, \; t/t_0 = \sqrt{\lambda}, \\ &\Gamma/\Gamma_0 = 1, \quad d/d_0 = \lambda, \quad v/v_0 = 1/\sqrt{\lambda}, \quad a/a_0 = 1 \end{aligned} \tag{5}$$

This similitude law respects similarity of the ratios of friction and gravity forces to seismic excitation forces. However, the necessary condition to meet this requirement is that the mass density ρ, should be changed leading to $M/M_0 = \lambda^2$ instead of $M/M_0 = \lambda^3$. In many cases, for instance buildings' models, this is achieved, in practice, by adding additional masses on the slabs of the mock-up. However, adding masses, all over the crane bridge beams, would be not only practically complicated, but it would, also, have a considerable impact on the stiffness of the crane bridge. Actually, since $\lambda = 1/5$, the added masses should be four times the mass of the bridge itself. It is obvious that such rigid heavy blocks, put one next to the other to increase the mass of the beams, would have,

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