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Response spectrum-based method for calculating the reaction force of piers subjected to truck collisions

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ABSTRACT

A previously proposed and validated coupled mass-spring-damper (CMSD) model for simulating truck collisions on bridge piers is used to gain insight into the main parameters affecting the problem. It is shown that the model can be simplified into an equivalent two-degree-of-freedom dynamic system that captures the basic mechanical characteristics of the impact problem. By treating the impact demand caused by the colliding truck's engine and cargo separately, simple and unified response spectra are proposed. The spectra are suitable for use in a design office situation to determine the reaction due to truck collision. A proposed design procedure is validated using the CMSD results and it is shown that it has reasonable accuracy.

1. Introduction

Trucks crashing into bridge piers can generate extreme loading demands on bridge structures. There are many examples from around the world where truck-pier crashes have led to bridge collapse and loss of life [1,2]. The truck-pier crashes has created interest within the structural engineering research community to better understand the parameters that influence such low probability, high consequence events.

Researchers have addressed the problem through experimental methods, detailed computational techniques, and reduced modeling means. Experimental studies, such as those in Popp [3] and Buth et al. [4] are rare because of the high cost of conducting full scale truck-pier crash experiments. To reduce the cost of experimentation, Chen et al. [1] developed simplified truck models and used them to investigate the impact demands generated by dropping them onto reinforced concrete columns using an existing drop-weight setup.

On the computational front, existing studies can be found in El-Tawil et al. [5], Buth et al. [6], Agrawal et al. [7], and Chung et al. [8]. Chen et al. [2] carried out extensive parametric analyses of truck head-on collisions with bridge piers. They investigated the influence of key parameters affecting the truck-pier impact process including pier cross-sectional characteristics, truck mass, vehicular impact speed, impact location, road slope, and cargo (payload) stiffness.

Reduced models of truck-pier crashes are typically formulated in terms of a few high level variables (e.g., force, moment, and displacement) and designed to yield quick, but accurate, estimates of design variables of interest. Reduced models typically make use of simple spring-mass systems to model the impact process. Existing studies in this area include Vrouwenvelder [9], Milner et al. [10], Al-Thairy and Wang [11] and Chen et al. [12]. Chen et al. [2] proposed what they termed coupled-mass-spring-damper (CMSD) model to simulate truck collisions on bridge piers. The model considered the basic mechanical characteristics of the collision truck, and was shown to greatly reduce the difficulty of running crash analyses and drastically shorten the computation time.

At present, extremely simplified equivalent static methods are still widely used in the US, Europe and other countries for the design of bridge piers against vehicle collisions. In existing methods, a constant design value of the impact force or a number of design values that vary by road grade are specified as the structural demand. Such an approach fails to consider the characteristics of the vehicle and impacted structure and also any interaction between them. The equivalent static design values are calibrated

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to only few tests or analyses, the applicability and reliability of which are questionable. For example, based on only two crash tests in Buth et al. [4], the AASHTO Bridge Design Specifications [13] increased the design vehicular force from the original 400 kips (about 1800 kN), which had been in use for nearly 20 years, to 600 kips (about 2700 kN), and increased the impact point height from 1.2 m to 1.5 m above the ground. The Chinese General Code for Design of Highway and Culverts [14] specifies that 1000 kN and 500 kN should be taken as the design vehicular impact forces parallel and perpendicular to the driving direction, respectively; and the impact forces along the two directions should not be considered at the same time. Although Eurocode 1-Accidental Loading [15] specifies the design impact force as a function of the characteristics of the adjacent highway, the theoretical foundations for the provisions are not clearly presented.

The deficiencies of current design methods are well recognized by multiple researchers including El-Tawil et al. [16]. Tsang and Lam [17] showed that using a pseudo-static analysis method would significantly underestimate the resistance of reinforced concrete columns subjected to vehicle impact. Sharma et al. [18–20] proposed various types of models for simplified design against vehicular impact that account for stochastic nature of the problem. However, their impact computations were based on classical Hertz contact theory, and did not consider the inelastic nature of the impacting vehicle.

The key to designing a bridge pier against truck impact is how to accurately specify the design demand. One obvious solution is to use the reduced models to solve the dynamic problem, but that entails the use of specialized software. Borrowing from earthquake engineering concepts, a simpler solution that has not yet been attempted is to use response spectrum analysis. With this as an objective, this paper reports on detailed parametric studies conducted using the CMSD model in Chen et al. [2] to calibrate a response spectrum model. The intent is to propose a analytical method that could someday be useful for determining the design value of the impact force for vehicle-pier crash situations.

2. Overview of CMSD model

The CMSD reduced model was calibrated by Chen et al. [2] to the response of a prototype Ford F800 truck as shown in Fig. 1. The model accounts for the impact demands generated by the engine (including some other stiff components, such as the transmission) and cargo. The CMSD model is illustrated in Fig. 2, where m_1 and m_2 represent the engine and the rest of the truck (including cargo), respectively. Springs 1 and 2 are arranged in parallel to represent the behavior of the truck-pier collision process as observed from simulations conducted using the model shown in Fig. 1. The plateau part of Spring 1 represents the effect of the front part of the truck crumpling during the impact process, while the steep rising part represents the engine's collision with the pier. Similarly, the plateau of Spring 2 represents the effect of the body of the truck interacting with the pier during the crash process, while the steep rising part represents the cargo colliding with the pier. The friction damper c_s is included to account for the energy consumed by friction during collision. The majority of this energy is associated with the truck's body, hence its association with m_2. The characteristics of the springs and damper are determined by matching the response of the CMSD model to the finite element simulation results.

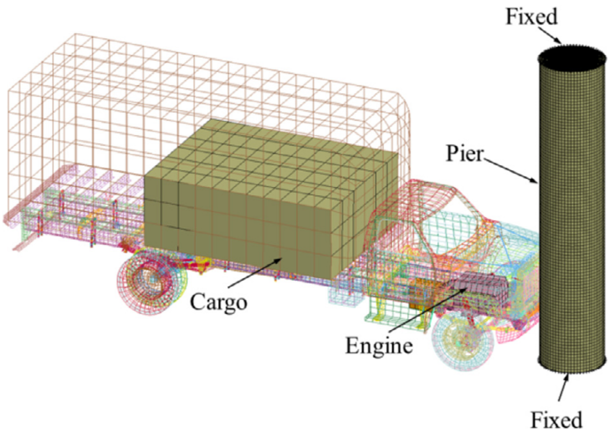

Fig. 1. FE model of truck and bridge pier.

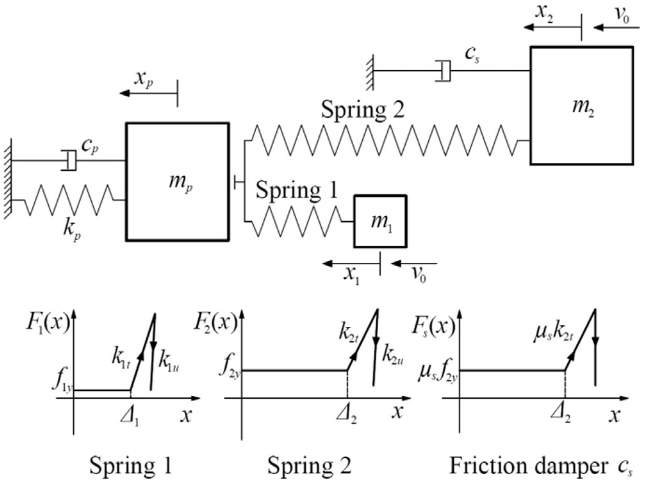

Fig. 2. CMSD model details.

The pier is modeled as a linear SDOF mass-spring-damper system. m_p and k_p are the equivalent mass of the pier and static transverse stiffness at the nominal impact height, respectively, taking into account shear and flexural deformation, which are defined as follows,

$$m_p = \bar{m}\int_0^l \varphi(z)^2 dz \tag{1}$$

$$\varphi(z) = x(z)/x(z_n) \tag{2}$$

$$k_p = 1/x(z_n) \tag{3}$$

where $x(z)$ is the lateral deflection of the piers along the height z under unit concentrated force at the nominal impact height z_n; and $x(z)$ can be calculated based on the classical beam theory [21]; $x(z_n)$ is the deflection when $z = z_n$; $\varphi(z)$ is the dimensionless shape function defined as the ratio of the pier deflection $x(z)$ to the reference deflection $x(z_n)$; $\bar{m}$ is the mass per unit length.

As discussed in Chen et al. [2], if the impact energy of the trucks is not large enough to generate a second spike (the cargo does not reach the pier) or if the second spike is much smaller than the first one, 1050 mm is a reasonable nominal impact height. Otherwise, 1350 mm should be used. In this study, a medium value 1200 mm is used as the nominal impact height for simplicity. A viscous damper, c_p, is introduced in the pier model to account for energy attenuation. Additional details of the CMSD model can be found in Chen et al. [2].

Table 1 lists and defines all the parameters of the CMSD model. As soon as the characteristics of the pier, truck mass, and impact speed are determined, the impact demand on the piers can be calculated by running the reduced model.