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Parametric analysis of optimum isolator properties for bridges susceptible to near-fault ground motions

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A B S T R A C T

This paper examines the selection of optimum isolator properties, namely characteristic strength, Q_d, and post-elastic stiffness, k_p, for bridges located in near-fault regions. First, a two-phased sensitivity analysis is conducted to evaluate the influence of bridge, isolator, and near-fault ground motion parameters on optimum levels of Q_d and k_p based on minimizing maximum isolator displacement and force. In the first phase of sensitivity analyses, a screening via design of experiments principles is performed to assess the statistical significance of various parameters on the optimum isolator properties. The second phase includes rigorous sensitivity analyses to assess the trends in optimum Q_d and k_p as a function of the bridge, isolator, and near-fault ground motion parameters. Next, nonlinear time history analyses of typical seismically isolated bridges are conducted for a suite of near-fault ground motions across a range of values of the identified parameters to enable the development of parametric equations for optimum Q_d and k_p to minimize isolator force or displacement. The parametric equations are validated using an alternate suite of near-fault ground motions. Furthermore, the dispersion about the predictive equations are quantified and assessed. It is observed that the developed equations produced reasonable estimates of optimum isolator properties with a relatively consistent dispersion across the modeling parameters. Moreover, it is observed that for near fault ground motions with high intensity and strong directivity, supplemental energy dissipation devices are required to minimize the isolator displacements.

1. Introduction

Seismic isolation is an effective approach for the protection of bridges that has been adopted in bridge design or retrofit for over 35 years [1]. The general concept of isolation is to limit the inertial loads transferred to the substructure by decoupling the superstructure and substructure through the introduction of a laterally flexible element between the deck and pier or deck and abutment (Fig. 1). The introduction of the isolation system is often aimed at shifting the natural period of the structure out of the range of dominant earthquake energy, increasing the damping, and limiting the force transfer, as well as potentially replacing more seismically vulnerable bearings in bridge retrofit cases. A range of potential isolation devices exist, such as the use of elastomeric bearings, lead rubber bearings, and friction pendulum devices, among others. In general, the hysteretic response of these isolators is modeled bilinearly [2,3], as shown in Fig. 1. In this idealization, the force–displacement hysteresis is characterized by the elastic stiffness, k_u; post-elastic stiffness, k_p; characteristic strength, Q_d; yield force and displacement, F_y and u_y, respectively; and design force and displacement, F_i and u_i, respectively.

As a protective device, the maximum isolator force and the maximum isolator displacement often characterize the isolator performance. The peak isolator force is indicative of the effectiveness of the isolation system and level of forces transferred to the substructure, while the isolator displacement is important due to its influence on expansion gap sizing to avoid pounding, as well as sizing of the isolator itself. Ideally, both quantities would be minimized in an optimum isolator design, yielding an effective seismic mitigation strategy and a more cost effective bridge design. Of the isolator parameters previously presented, past studies have concluded that the characteristic strength, Q_d, and post-elastic stiffness, k_p, are the most influential on the isolated bridge response for a given ground motion (the influence of elastic stiffness is not significant) [4]. Hence their careful selection is critical for achieving an optimum and economical isolated bridge system whereby maximum isolator displacements and forces are limited.

While there have been a number of studies that evaluate optimum isolator properties for seismically isolated bridges [5,6], fewer have considered the unique challenges of isolating bridges located in near-fault regions [7–9]. Near-fault regions are often considered to be those where the structure is located within a distance of

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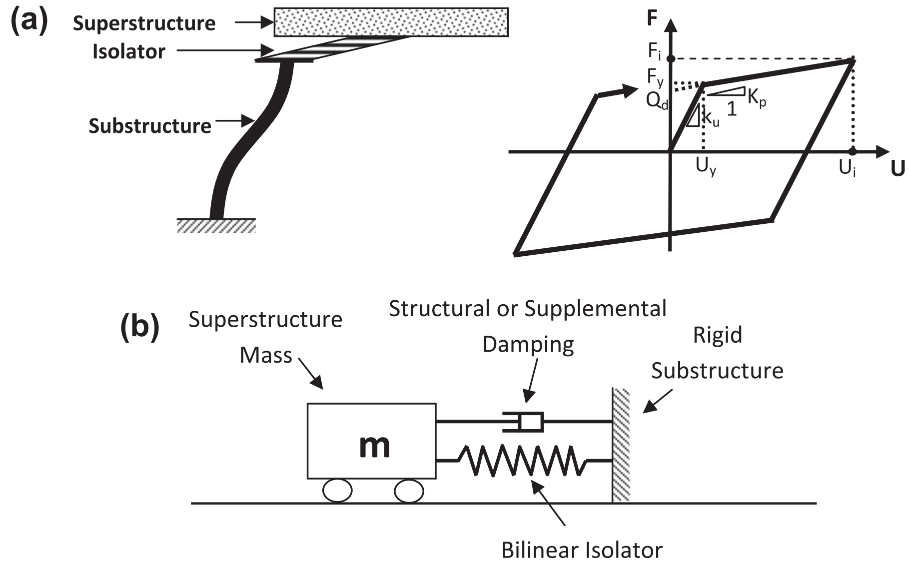

Fig. 1. (a) Schematic of isolation system in a bridge with idealized bilinear force–deformation response of a typical isolator. (b) Simplified SDOF bridge model.

approximately 15–20 km [10] from the fault rupture. The pulse-type ground motions produced in these regions are characterized by large amplitude velocities that can pose significant demands on structures. In particular, forward-directivity motions, which have been found to pose the most severe conditions for structural performance, are characterized by intense, long-period velocity pulses [11,12]. Hence, while isolation can be a critical strategy for limiting the transfer of large forces to bridge substructures in near-fault regions, it may also be more challenging to implement due to the higher potential for large isolator displacements.

Previous studies have evaluated the effect of pulse-type excitations [13] or simulated near-fault ground motions [14] on generic yielding structural systems, though do not specifically address parameters of interest in evaluation or practical design of seismically isolated bridges. However, the unique considerations of isolating bridges in near-fault regions have been recognized in recent years. For example, experimental studies have evaluated the response of seismic-isolated bridges to near-fault earthquakes emphasizing the viability of coupled use of new supplemental devices to minimize force transfer and isolator displacements [15]. Analytical evaluations of isolated bridges subjected to near-fault earthquakes have primarily targeted the performance of specific case study bridges with isolation systems (e.g., a prestressed concrete box girder bridge with lead rubber bearings) [16,17]. Therefore the findings on critical near-fault ground motion parameters governing isolated bridge response are generally bridge-specific. While previous studies have evaluated the effect of isolator, structure, and near-fault earthquake characteristics on bridge response [7], optimum parameterized design characteristics have yet to be identified. Thus, there remains a need to evaluate the sensitivity of optimum isolator parameters, Q_d, and k_p, that produce minimum levels of isolator force and displacement, to near-fault ground motions and bridge parameters. Moreover, simplified predictive equations for optimum isolator characteristics are needed to aid in isolation design or selection in near-fault regions. The study presented herein directly targets these gaps, first through a screening study via hypothesis testing to identify critical parameters most significantly affecting optimum isolator properties. A detailed sensitivity analysis complements this screening to more fully characterize the influence of typical ranges of these parameters on optimum isolator properties. Finally, the most critical ground motion and structural parameters are incorporated in the development of predictive equations to obtain optimum yet practical characteristic strength and post-elastic stiffness of the isolators to minimize isolator displacements or forces. The development of predictive equations for optimum isolator properties under near-fault motions provides a foundation for selecting isolator properties for bridges in these regions, as illustrated through several case study examples in the paper.

The randomness of the effect of earthquake ground motions is well known. Thus, the main intent of the equations proposed in this research study is to catch the general trend in the optimum characteristic strength and post elastic stiffness for preliminary design purposes as a function of the isolated bridge and ground motion properties rather than pinpointing the exact optimum values.

2. Near-fault isolation study parameters and optimization scheme

Through the course of the study, a potential range in parameters of the near-fault ground motions and isolated bridge are considered. The influence of these parameters on optimum isolator characteristic strength and post-elastic stiffness is evaluated. The sections below detail the range of parameters considered within the scope of this study, dynamic analysis method, and optimization approach.

2.1. Near-fault ground motions

In this study near-fault ground motions with forward rupture directivity effect (component of ground motion perpendicular to the fault) are considered due to their distinct, destructive velocity pulse characteristics. The near-fault ground motions used in this study are classified into two sets. The first set is used in the sensitivity studies and development of predictive equations for optimum isolator properties, while the second set is used independently for the verification of these equations. Table 1 lists the near-fault ground motions used in this study; the 19 ground motions used in Set 1 and five ground motions used in Set 2. This suite of earthquake records used in the analyses cover a wide range of near-fault ground motion parameters. The amplitude of the velocity pulse (V_p) and the velocity pulse period (T_p) are generally used to characterize the near