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Experimental and analytical studies of seismic response of highway bridges isolated by rate-dependent rubber bearings

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ABSTRACT

The mechanical behavior of a majority of rubber bearings used for seismic isolation is known to exhibit rate dependence. Although this feature has been known for years, few studies have attempted to quantitatively evaluate the influence of this characteristic on the seismic response of an isolation system at the structural level. In this study, experimental and analytical investigations were conducted to probe the seismic response of highway bridges isolated by rate-dependent rubber bearings. Three types of such bearings were investigated: natural rubber bearings, high damping rubber bearings (HDRBs), and super high damping rubber bearings (SHDRBs). To achieve the study objective, real-time hybrid simulation (RTHS) tests were performed on a typical multi-span continuous girder highway bridge under various earthquake ground motion intensities. In the RTHS tests, a velocity loading method was adopted and the bearings were physically tested in a real-time scale and larger time scales such that the bearings were exerted under different loading rates. The influence of the rate-dependent behavior of bearings on the seismic response of the bridge was investigated by conducting a series of parametric studies. The test results indicated that the seismic response of the bridge was significantly affected by all three types of rate-dependent rubber bearings, especially HDRBs and SHDRBs. Finally, a newly proposed rate-dependent analytical model and the traditional rate-independent bilinear model for rubber bearings were used in the numerical simulation. A comparison of the simulation results indicated that the proposed model performed better than the bilinear model in the seismic response analysis.

1. Introduction

Highway bridges are crucial components of transportation systems used in modern society and are considered to be lifeline structures. Therefore, it is of great importance that these bridges maintain continued functionality during and after catastrophic earthquake disasters. However, because of their potential vulnerability to severe earthquakes, many instances of structural damage and even bridge collapses have been repeatedly experienced in the past decades [1–5]. To enhance the seismic performance of both newly constructed and retrofitted bridge structures, installation of elastomeric bearings as seismic isolation devices has been increased worldwide [6,7], particularly in response to the field performance of bridge structures after the 1995 Kobe earthquake [8]. Compared to traditional non-isolated bridges, isolated bridges aim to decouple the deck from the substructure. In addition, with the horizontal flexibility and high damping features, elastomeric bearings provide desired seismic isolation effects by transmitting reduced earthquake-induced forces and lowering the ductility demands of the bridges.

A variety of elastomeric bearings, including natural rubber bearings (NRBs) [6], high damping rubber bearings (HDRBs) [9], and super high damping rubber bearings (SHDRBs) [10], have been developed and used in practical applications to control the seismic response of bridges. Specifically, NRBs are manufactured by a laminated structure that contains alternating natural rubber and intermediate steel layers, they exhibit low-damping originating from the rubber material. HDRBs and SHDRBs have emerged as a novel technique of such isolation devices, wherein the rubber material possesses both high strength and a higher level of damping by adding specific chemical fillers to the natural rubber during the

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mixing process. Through the addition of these fillers, HDRBs and SHDRBs enhance the energy dissipation capacity and contribute supplemental high damping to the isolation system [11].

The acceptance and applications of seismic isolation technique has prompted extensive studies devoted to the investigation of the seismic performance of highway bridges equipped with different types of rubber bearings. Ghobarah et al. [12] and Turkington et al. [13] analytically studied the effectiveness of lead rubber bearings (LRBs) in mitigating the seismic responses of bridges and developed design procedure for bridges equipped with LRBs. Igarashi and Iemura [14] conducted hybrid simulation test to experimentally validate the seismic performance of a highway bridge with isolation bearings. Hwang and Wang [15] proposed an analytical model to predict the seismic response of HDRBs based on the fractional-derivative Maxwell model, and the proposed model was verified by performing shaking table tests. Abe et al. [16] conducted a comprehensive investigation and comparison on the seismic performance of three bridges isolated by NRBs, LRBs and HDRBs, respectively. Kunde and Jangid [17] also performed similar research to obtain the seismic response of bridges isolated by HDRBs and friction pendulum sliding bearings. The bidirectional rate-independent response of HDRBs was analyzed by Grant et al. [18], they utilized the proposed model in parametric studies of an isolated bridge. With the contribution from the past research efforts, the effectiveness of rubber-bearing-based seismic isolation techniques has been demonstrated and validated through comparative studies on isolated highway bridges, and several analytical models of such bearings have been proposed. Recently, many researchers have found that the HDRBs and SHDRBs exhibit significant rate-dependent behavior [19–21], whereas the NRBs show relatively mild rate dependence [22–23]. It should be also mentioned that although Ref. [24] showed that high damping rubbers possess less rate dependence, this discrepancy can be mainly attributed to the different rubber compound of the HDRBs. Consequently, the aforementioned studies have failed to conduct comprehensive investigations to quantitatively evaluate the effect of this behavior on the seismic response of isolation systems at the structural level.

Furthermore, nonlinear dynamic analysis has been served as a preferred seismic performance assessment method in current design guidelines [25,26], and accurate analytical models that represent the nonlinear mechanical properties of the rubber bearings are greatly required to verify the seismic performance goals of isolated bridges in a performance-based design framework [27,28]. Since a rubber bearing exhibits rate dependence, different loading rates on the bearing generally induce a remarkable variation in its hysteresis loops. This behavior is difficult to describe but is considered to be important in certain circumstances. In particular, the performance of bearings under near-fault ground motions should be properly investigated because such ground motions usually contain significant high-intensity velocity pulses that would significantly influence the rate-dependent behavior of rubber bearings [29]. The assumption of a simplified and robust bilinear force–displacement model is not valid to appropriately capture the rate-dependent behavior of rubber bearings [30]. Hence, the rate-dependent behavior of rubber bearings has been well described in literature, e.g., by the present authors [9], Tsai et al. [19], Bhuiyan et al. [20] and Dall'Asta et al. [21]. Some sophisticated high-fidelity models have also been proposed to overcome the aforementioned limitations [9,10,19–21]. Unfortunately, although the problem of modeling the rate-dependent behavior of rubber bearings has been widely studied, the problem of quantitatively evaluating the influence of this characteristic on the seismic response of the isolation system has been inadequately investigated in the existing literature. In short, previous studies have mainly characterized the rate-dependent rubber bearings at the component level (e.g., in terms of the hysteretic loop of the bearing).

The present study extends the previous work [9] by the authors on modeling the rate-dependent behavior of HDRBs at the component level to the seismic performance level of three types of isolation systems (i.e., NRB, HDRB, and SHDRB). The primary goal of this study is to gain further insight into the influence of the rate-dependent behavior of rubber bearings on the seismic response of an isolated highway bridge at the structural level (e.g., in terms of the comprehensive response of the global isolation system), thus revealing the interaction between the bridge and the rubber bearings. In this study, detailed real-time hybrid simulation (RTHS) tests were first performed on a typical multi-span continuous girder highway bridge under two levels of seismic excitations. As an extension of conventional pseudodynamic test, RTHS is executed in real time and suitable for effectively evaluating the behavior of rate-dependent devices when this effect seems to play an important role in the seismic performance of structures [31]. A key advantage of this technique is that only the critical nonlinear part of the structure (whose behavior is unknown) is experimentally tested. Hence, it serves as a viable and economic approach to access the dynamic performance of structures in a full-scale physical model [32]. An RTHS system based on the velocity loading method was adopted in the study with the consideration of the strong rate-dependent behavior of rubber bearings. The test results showed that the rate-dependent bearings had a significant influence on the seismic response of an isolated bridge and indicated the demand for a proper analytical model of the rubber bearings to consider this characteristic. Then, in order to consider the actual state of bearings in typical isolated bridges in service, a generalized analytical model of three types of rubber bearings newly proposed by the authors was introduced in the study. The proposed model allows to describe the rate-dependent rubber bearings based on the virgin rubber material, and to overcome the limitations of previous studies that generally focused on the scragged condition of rubber [21,22]. Finally, the accuracy of the proposed model in the seismic analysis of an isolated highway bridge was verified by comparing the RTHS test and numerical simulation results, and the superior performance of the proposed model over the rate-independent bilinear model was also demonstrated.

2. Experimental studies

2.1. Real-time hybrid simulation test method

The RTHS test, which is a novel hybrid method to evaluate the seismic response of large structures, employs a combination of a dynamic loading test technique and computer-based numerical simulation. Unlike the shaking table test, the entire thrust of the RTHS test is to divide the structure into numerical and experimental parts, and only the critical structural components are physically tested. The RTHS test allows the testing of specimens under realistic earthquake excitation and is performed in a real-time basis [33]; therefore, this test is advantageous for the purpose of this study, i.e., to evaluate the seismic response of highway bridges equipped with rate-dependent rubber bearings.

Fig. 1 presents the schematic of the RTHS test system used to execute the test program. This system consisted of a loading system, a host PC, a controller for the dynamic actuator, and a loading system control PC. The rubber bearing specimen was mounted in a frame of the vertical loading system and subjected to displacements imposed by the dynamic servo hydraulic actuator with a loading capacity of 1000 kN. The vertical force, horizontal force, and displacement were recorded during the tests by a PC-based instrumentation system.