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Dynamic seismic response of controlled rocking bridge steel-truss piers

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Abstract

The dynamic seismic response of steel braced bridge piers allowed to uplift and rock on their foundation is investigated analytically. Allowing piers to rock provides a retrofit solution with increased seismic performance by limiting demands to existing non-ductile elements while damage can be avoided or forced into replaceable structural elements. Also, an inherent restoring mechanism exists that can provide self-centering following an earthquake. However, during the rocking response, as the pier transfers its axis of rotation from the base of one leg to another, the impact and uplift from the foundation excites vertical modes of vibration, increasing the lateral base shear and the axial force demands on the pier legs. Methods are developed to characterize and quantify the increased dynamic demands in order to capacity protect the existing elements. These simplified methods are then compared with the results of nonlinear time history analysis for a set of frames representative of highway bridge piers with aspect ratios of 4, 3 and 2, and shown to be reasonably accurate in most cases. An example set of calculations and analysis results are also presented.

Keywords: Steel braced frames; Seismic response; Rocking; Retrofit; Bridges

1. Introduction

The reliance on stable rocking to provide satisfactory seismic performance has recently received a renewed interest: more research is being conducted on this topic and various levels of rocking response have been considered in the retrofit of large bridges. This is in part due to a growing appreciation for the ability of such systems to efficiently withstand seismic demands elastically with little to no damage while providing a self-centering ability. As part of the ongoing research on the topic, Pollino and Bruneau [1] have proposed a controlled rocking system for bridge steel-truss piers where passive energy dissipation devices are added at the base of the structure to control the response of a rocking system otherwise free to uplift. The devices are designed to limit demands to the structure such that it can remain elastic and all damage is forced into these easily replaceable structural "fuses". However, in order to ensure that such rocking structures remain elastic, the maximum forces expected to develop must account for all dynamic effects in the system during the rocking response. Once the designer is able to reliably predict the maximum forces expected to develop within the structure during the rocking response, all members and connections can be designed to remain elastic.

A methodology to quantify the dynamic force effects is presented for a simple steel bridge braced frame. However, the concepts presented are general and could be extended to include different materials and structural systems. The steel braced frame considered is illustrated in Fig. 1 and has a number of square panels (n) with a height (h) and a width ($d = h/n$) with the bracing members in a concentric X-configuration. For this bridge application, all system mass is lumped at the top of the frame legs, as shown in Fig. 1. The predicted response of the proposed controlled rocking concept is then compared with the results of nonlinear dynamic time history analysis for a set of frames representative of bridge steel truss piers having aspect ratios (h/d) of 4, 3, 2 and for a range of energy dissipating device properties. A more detailed example is also shown to illustrate the process of predicting maximum forces and to provide a sample set of results.

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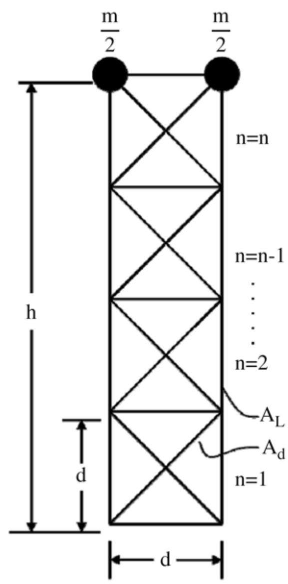

Fig. 1. Simplified steel-braced frame.

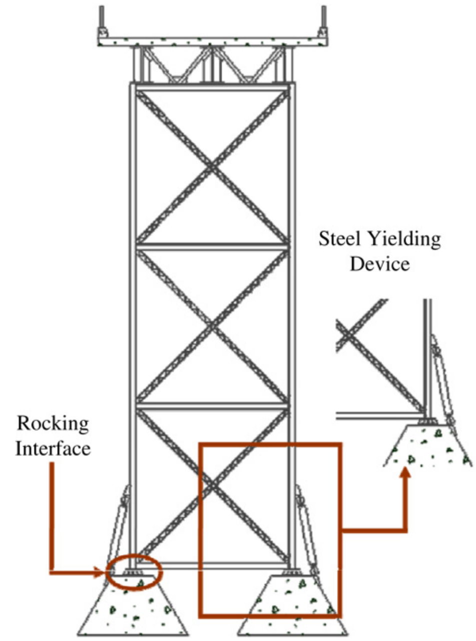

Fig. 2. Retrofitted bridge steel-truss pier using controlled rocking approach.

2. Prior relevant research

The study of rocking structures is not new and Housner [2] first investigated the free and forced vibration response of rigid rocking blocks. Assuming an inelastic impact to occur during each half-cycle, Housner developed equations for the reduction in energy resulting from each impact by equating the moment of momentum and determining the reduction in velocity following the impact. Meek [3] introduced aspects of structural flexibility to the seismic response of single-degree-of-freedom (SDOF) rocking structures and Psycharis [4] followed with an analytical study of the dynamic behaviour of simplified multi-degree-of-freedom (MDOF) structures supported on flexible foundations free to uplift. It was noted in the latter study that vertical oscillations were introduced to this uplifting system even when subjected solely to horizontal excitation.

A number of experimental studies have also been conducted on rocking structural systems. Priestley et al. [5] tested a simple SDOF model investigating its response in free vibration, to sinusoidal input, and to the horizontal component of the 1940 El Centro earthquake. Results showed a significant fluctuation in horizontal acceleration during rocking and large vertical accelerations were induced during impact. Midorikawa et al. [6] experimentally examined the response of a steel-braced frame that allowed uplifting at the base of columns and yielding of specially designed base plates. The shaking table tests solely used horizontal seismic base excitation and it was observed that “the maximum axial forces of columns may be affected by the impact with landing of base plate”.

Thus, past analytical and experimental studies investigating systems that allow a rocking response have observed the increased demands placed on structural systems due to dynamic effects. However, they have not provided significant insight into the possible mechanisms causing these additional demands and on design methods to reliably account for their magnitude for steel-braced frames. As part of a capacity-based design philosophy, to capacity protect the primary structural elements of the system during seismic excitation, these demands must be accounted for.

Some of the earliest structures designed and constructed to allow a rocking response during seismic excitation include the South Rangitikei Rail Bridge and an industrial chimney at the Christchurch Airport, both in New Zealand [7]. The north approach of the Lions’ Gate Bridge in Vancouver, British Columbia was upgraded in the 1990s with a seismic resistance strategy allowing the steel bridge piers (braced frame) to uplift and rock on their foundations [8]. Some concerns arose due to the effects of dynamic impacting of the pier legs with the foundation and coupling of horizontal and vertical modes during rocking. Dynamic, nonlinear 3-dimensional time history analysis was used to assess the dynamic effects. Some major bridges in California have also allowed at least partial uplift of pier legs as a means of providing satisfactory seismic performance, including the Carquinez [9], San Mateo-Hayward [10], and Golden Gate Bridges [11].

Studies on the controlled rocking approach, presented in [1], included development of the static hysteretic behaviour using step-by-step plastic analysis concepts, simplified methods of analysis for design, a design method for calibration of the passive energy dissipation devices and results of time history analyses. The design procedure includes a set of design constraints that provides limits on response such as preventing excessive displacements and overturning. It was demonstrated that preventing overturning of a frame of significant size, such as a bridge pier, can be easily achieved. A sketch of a bridge pier retrofitted using such an approach is shown in Fig. 2. The passive energy dissipation device considered is a steel yielding device that is assumed to exhibit elastic–perfectly plastic hysteretic behaviour with a yield force, P_{yd}, an elastic stiffness, k_{yd} and a yield displacement, Δ_{yd}. The strength of the steel-yielding device is expressed as a fraction of the frame