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A static analysis-based method for estimating the maximum out-of-plane inelastic seismic response of steel arch bridges

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Abstract

This paper presents a method for estimating the maximum inelastic out-of-plane seismic response of upper-deck steel arch bridges. The method employs the equal-energy assumption to predict the maximum response without the need for dynamic response analysis. Firstly, applicability of the equal-energy assumption to upper-deck steel arch bridges is examined numerically by performing free vibration analysis, pushover analysis, and elastic and inelastic dynamic response analyses. Models with different arch-rise to span ratio and arch rib spacing are generated and the influence of these parameters on the applicability of the assumption is studied. Although the assumption resulted in conservative side estimation, in many cases the results were too conservative to be practical for design practice. On the other hand, some tendencies that make it possible to develop some correction functions to improve the estimation accuracy of the equal-energy assumption were found regardless of any parameters. Finally, by using the proposed correction functions and the response spectra a method that does not require dynamic response analysis for the estimation of maximum inelastic seismic demand is developed and its validity is evidenced by numerical analyses.

Keywords: Seismic design; Equal energy assumption; Steel arch bridges; Pushover analysis; Dynamic response analysis

1. Introduction

The Hyogo-ken Nanbu earthquake of 17 January 1995, which was a more severe earthquake than that considered in the design code for structures, caused destructive damage to many structures [1]. Steel bridges were no exception. The range of damage included the collapse of steel bridge piers, as well as local buckling of stiffened box and pipe sections. Since this devastating earthquake, many efforts to improve the seismic performance of steel structures have been made in Japan. These efforts began with the simplest and most common structures such as cantilevered steel piers and portal frame piers. The strength and ductility of these structures under cyclic loading have been examined experimentally or numerically [2–5]. With time the trend has shifted to clarifying the inelastic seismic behavior of more rare but complex structures, such as the steel truss [6], arch [7–14] and elevated bridges [15,16]. Recently, also, more interest is being given in the development and application of vibration control devices to structures [17]. Some findings have been introduced into the revised version of the Japanese seismic design code for highway bridges (JRA code) [18,19]. The design ground motion was also revised and a two-level seismic design method is now specified for, respectively, moderate (called Level-I) and extreme (called Level-II) ground motions [18,19].

Steel arch bridges were conventionally treated as structures for which earthquake loading is not predominant, as they are normally built in mountainous areas with little chance of major earthquakes, since ocean-type earthquakes are common in Japan. Moreover, even if experienced, earthquake excitation was not thought to be crucial, because arches are structures of relatively long natural period and are generally built on rock foundations. For this reason, conventional design took into consideration only moderate earthquakes, during which the structure should remain in the elastic range. However, the new provision for design based on Level-II ground motions for all bridges in Japan has made it necessary also to understand the

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inelastic behavior of steel arch bridges, since severe earthquake loading could put them in a critical situation. There are some earlier papers on the seismic response of steel arch bridges [7–14]. Usami et al. [12] investigated the inelastic seismic performance of a typical upper-deck steel arch bridge subjected to major earthquakes. They found that seismic responses are small under longitudinal ground motion input but severe plasticization and performance deficiencies are observed under transverse excitation. This study proves that Level-II ground motion can be critical for upper-deck steel arch bridges.

Meanwhile, the compulsory evaluation of inelastic behavior greatly complicates the design process compared to conventional practice. The powerful method of nonlinear dynamic response (time-history) analysis is the most rigorous way to carry out seismic response estimation. However, implementation is time consuming, which hampers its wide application to everyday design. There is a desire for a method of seismic design that does not rely on dynamic response analysis. The JRA code specifies a simplified method called the Ductility Design Method, which is based on static analysis. This is a force-based design procedure utilizing elastic analysis in which a force reduction factor is adopted to account for inelastic behavior. The force reduction factor is calculated using the equal-energy assumption [20], which assumes the elastic energy stored in the elastic and inelastic systems is identical. However, the application of this method is limited only to simple structures, because the applicability of the equal-energy assumption is not clear in the case of structures with complex dynamic response characteristics. In the JRA code, simple dynamic behavior implies that the structure is a system with a predominant first vibration mode and the possible location of the primary plastic hinge can be easily foreseen. This confines use of the method to reinforced concrete piers and steel piers in-filled with concrete. For other structures, referred to as ‘complicated structures’ by the JRA code (including steel arch bridges), dynamic response analysis should be conducted for seismic performance verification. Lu et al. [13,14] proposed a simplified seismic design verification procedure based on pushover analysis and dynamic response analysis of an equivalent single-degree-of-freedom system for upper-deck steel arch bridges. Although the method is very reliable, it is still necessary to carry out dynamic response analysis.

A displacement-based inelastic seismic response prediction procedure for upper-deck steel arch bridges that requires no dynamic response analysis is proposed in this paper. The equal-energy assumption is adopted for the maximum response estimation. The applicability of the equal-energy assumption is investigated as a first step toward prediction of maximum inelastic out-of-plane response. The examination is conducted numerically on six upper-deck steel arch bridge models by comparing estimation results with the results of dynamic response analysis.

There have been some previous reports on the applicability of the equal-energy assumption to steel bridges. Usami et al. [21] examined the applicability of both equal-energy and equal-displacement assumptions through pseudo-dynamic tests of cantilevered columns in steel bridge piers. They found that a fairly good estimation of nonlinear response was achieved

Table 1
Structural parameters of the analyzed models

Model No.	Span length (m)	Arch rise (m)	$\frac{\text{Arch rise}}{\text{Span length}}$	Arch rib spacing (m)
Model 1	114	16.87	0.15	6.0
Model 2	114	22.80	0.20	6.0
Model 3	114	34.20	0.30	6.0
Model 4	114	45.60	0.40	6.0
Model 5	114	16.87	0.15	9.5
Model 6	114	16.87	0.15	13

by using the equal-energy assumption, while the response predicted by the equal-displacement assumption was much smaller than in the actual tests. Nakajima et al. [22] investigated the applicability of the equal-energy assumption to the seismic design of steel portal frames. The paper concludes that it gives a conservative estimation of the maximum nonlinear response, but the estimated maximum displacement can be much larger than that given by elasto-plastic dynamic response analysis. Nakamura et al. [23] also investigated the applicability of the equal-energy assumption to steel portal frames. Their study showed that the equal-energy assumption results in a conservative prediction of maximum response, with the results being too conservative in many cases. They also suggested some correction functions that improve estimation accuracy.

The upper-deck steel arch bridges studied in this paper also yield conservative estimates when the equal-energy assumption is applied, as explained in the text that follows. In fact, estimated response is much larger than the actual response in many cases, making the accuracy of the assumption quite low. However some solid tendencies regarding estimation accuracy are found, and this makes it possible to develop certain correction functions that improve the accuracy. Having improved the estimates obtained with the equal-energy assumption, the correction functions are combined with the elastic response spectrum to predict the maximum inelastic seismic response without the need for dynamic response analysis.

2. Applicability of equal-energy assumption

2.1. Analyzed models

The applicability of the equal-energy assumption is examined numerically by studying six upper-deck steel arch bridge models. The models differ in their arch-rise to span ratio and arch rib spacing, as shown in Table 1. These two structural parameters are given variations over a wide coherent range in order to obtain a pattern representing the behavior of general upper-deck steel arch bridges and also to examine their influence on the applicability of the equal-energy assumption.

Model 1 shown in Fig. 1 is used as the template from which the other five parametric models are generated. This bridge was adopted by the JSSC committee as a representative model for investigations of nonlinear behavior during major earthquakes [24]. The parametric models are generated by using the JSP-15 W preliminary design software for steel arch bridges [25]. Models 2–4 are generated from Model 1 by changing only