Expansion of a Static Analysis-Based out-of-plane Maximum Inelastic Seismic Response Estimation Method for Steel Arch Bridges to in-plane Response Estimation

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ABSTRACT

We have previously proposed a static analysis-based method for estimating the maximum out-of-plane inelastic seismic response of upper-deck steel arch bridges. The method is developed on the basis of the numerical examinations of 6 upper-deck steel arch bridge models. It employs free vibration analysis, response spectrum method and equal energy assumption for the estimation of maximum out-of-plane response. Correction functions are proposed to modify the estimates by the equal energy assumption. In the current study, applicability of the same procedure to the estimation of maximum in-plane response is discussed. It is found that the method can be used also for the maximum in-plane response estimation by only modifying the pushover analysis procedure. The validity of the method is demonstrated for the same parametric models through further numerical evaluations.

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

1. Introduction

Japanese seismic design code for highway bridges [1] was revised after the Hyogo-ken Nanbu earthquake and a new design ground motion type called the Level 2 ground motion was introduced. The inelastic response demand of all structures is specified to be obtained for the verification of the design against this new ground motion. Steel arch bridges are no exceptions. Nonlinear dynamic response analysis became compulsory to obtain the inelastic seismic demand for them. This greatly complicates the design process for steel arch bridges, which are conventionally treated as structures for which earthquake loading is not predominant. A method that does not rely on dynamic response analysis will significantly simplify the seismic design.

In the previous research [2] we have developed a method for the estimation of maximum inelastic out-of-plane response of upper-deck steel arch bridges that does not require dynamic response analysis. The method combines pushover analysis, which is simpler than the conventional dynamic time-history analysis [3-9], with the response spectrum method by using the equal energy assumption [10] with some correction functions to improve the estimation accuracy. The correction functions are generated through the numerical evaluations of 6 parametric upper-deck steel arch bridge models.

Although seismic deficiencies under longitudinal excitations in steel arch bridges are minor [11], a simplified approach for the in-plane response, which can be an additional tool for the evaluation of the overall seismic performance, is also necessary. For this purpose, in the present paper the applicability of our method to the maximum in-plane response estimation is studied by carrying out numerical examinations on the same bridge models studied previously. It is found that the method can be applied to the estimation of maximum inelastic in-plane response with a reasonable accuracy by only changing the pushover analysis procedure.

2. Proposed method

The basic application steps of the method to the in-plane response estimation are listed below. All of the steps are the same with the original out-of-plane estimation [2] except the modification of the load pattern for the pushover analysis.

Step 1. Establish a finite element (FE) model for the upper-deck steel arch bridge under investigation.

Step 2. Perform eigenvalue analysis to acquire the predominant vibration modes.

Step 3. Obtain the force-displacement relationship of the structure as well as the yield displacement(δ_y) by performing elasto-plastic pushover analysis by using an incremental displacement load pattern placed at the mid point of the stiffening girder in the longitudinal direction (See 3.2).

Step 4. Obtain the maximum response from the response spectrum specified in the JRA code [1] for Level 2 ground motion depending on the corresponding ground condition and modal damping ratio. Calculate the corresponding elastic strain energy.

Step 5. Estimate the maximum inelastic response displacement (δ_{SP}) by applying the equal energy assumption to the force-displacement curve obtained in step 3 and the maximum strain energy obtained in Step 4. Calculate the estimated ductility factor μ_{E}, ($\mu_{\mathrm{E}}=\delta_{SP}/\delta_y$).

Step 6. Calculate the value of the correction function $f(\mu_{\mathrm{E}})$ either for the average estimation (equation (1)) or the lower bound estimation (equation (2)).

$$f(\mu_E) = 1/(0.1843\mu_E + 0.8159),\ (0 < f(\mu_E) \le 1) \quad (1)$$

$$f(\mu_E) = 1/(0.1700\mu_E + 0.7050),\ (0 < f(\mu_E) \le 1) \quad (2)$$

$$\delta'_{SP} = f(\mu_E) \times \delta_{SP} \quad (3)$$

The average estimation correction function is for the optimum estimation whereas the lower bound estimation correction function guarantees that the estimated maximum response is greater than or equal to the actual inelastic response. Correction is only necessary when the value of the correction function is less than 1. Correction is carried out by simply multiplying the estimated maximum inelastic response by the correction function of the desired type as shown in equation (3).

3. Numerical Evaluation

3.1 Analyzed Models

Applicability of the method to the in-plane response estimation is studied numerically on the six upper-deck steel arch bridge models originally generated to establish the method for the out-of-plane direction [2]. Some members of the models are enlarged in order to improve their strength against in-plane excitations. The models are again analyzed by using MARC nonlinear finite element (FE) analysis software [12].

The natural frequencies and modal participations of predominant eigen modes in the longitudinal direction are listed in Table 1 (The whole eigenvalue analysis results can be seen in the previous paper [2]). The first and the third in-plane modes have the greatest contribution to the overall in-plane response as they have larger effective mass ratios. However, it should be noted that the contribution of these two modes is quite small compared to that of the predominant modes in the out-of-plane direction [2] because of the significant participation coming from the higher modes. The shapes of these two modes are illustrated in Figure 1 showing that they are asymmetric.

3.2 Pushover Analysis

The applicability of the method greatly depends on selecting a appropriate load pattern for the pushover analysis that will deform the structure similar to maximum dynamic response. In the out-of-plane response estimation, the load pattern proportional to the product of the eigenvector of the dominant single mode and the distribution of the concentrated mass was adopted [2]. The same approach was applied to the in-plane pushover analysis by adopting a modal force distribution from the single dominant mode in the longitudinal direction (1st in-plane mode). Vertical component of this mode was also taken into account since vertical displacement is significant in the longitudinal excitations. However, analysis revealed that the deformed shape of the pushover analysis is significantly different from the displacement distribution of the dynamic response when such a load pattern is employed. The reason for this is basically that the participation of this mode in the overall in-plane response is small compared to the case of the out-of-plane response.

Although there are some improvements for pushover analysis proposed for better predictions such as considering more than one mode [7-9], they will result in more complicated procedures. Therefore, an alternative load pattern shown in Figure 2 is adopted for the pushover analysis due to its simplicity which is likely to simulate dynamic response at its ultimate stage. This is an incremental displacement load (P_δ) applied at the mid point of the stiffening girder from the both sides, as shown in the figure. To check the validity of this loading pattern, the displacement distribution obtained by pushover analysis is compared with that obtained from the dynamic response analysis. The comparisons are given in Figure 3 only for the stiffening girder in each model since similar shapes are also observed for the arch ribs. The displacement distributions are obtained at the time increment representing the maximum value of the vertical displacement at the reference point in the dynamic response analysis and at the static force increment corresponding to the same value at the reference point in the pushover analysis. A Level 2 Type-II earthquake ground motion magnified with a factor of 5 is utilized in order to acquire enough plasticity in the members. The reference point is selected as the node at the 1/4 span on the stiffening girder since the maximum vertical displacement is observed at this node during dynamic response analysis. These comparisons demonstrate that the displacement distributions agree well each other suggesting that the employed load pattern is sufficiently accurate to account for the in-plane dynamic behavior.

3.3 Estimation Accuracy

The validity of the method for the in-plane response is illustrated through the numerical examples by comparing the maximum nonlinear response δ_{SP}' estimated by the method with the actual dynamic response δ_{DP} calculated directly by nonlinear dynamic response analysis. This comparison is shown for average and lower bound estimations in Figure 4(a) and (b), respectively. The average estimation leads to an error around ±20% for the individual ground motions and ±15% for the average response displacements. The lower bound estimation is studied only for average response displacements since it is meaningful only for a design procedure in which the average of three response displacements should be taken according to JRA code [1]. The error in this case is found to be less than 20% as shown in Figure 4(b). When these results are compared with the yields of out-of-plane direction [2], it can be recognized that the estimation accuracies of the method for in-plane and out-of-plane responses are almost on a level. Within this error range, it is considered that proposed method can be used for the preliminary design of upper-deck steel arch bridges as a simple way of predicting the maximum in-plane response as well.

For further confirmation, the proposed method is applied to the same models by using different set of ground motions. Type I ground motions for ground conditions I and II, amplified by factors of 1.5, 2 and 5 are employed like it was done for the out-of-plane direction evaluations. The estimation obtained, δ_{SP}', are compared with the actual dynamic response, δ_{DP}, in Figure 5. Fairly good estimation results are obtained for average estimations with the estimation error less than ±20%. Lower bound estimation also leads to an error of less than 20%. However, it should be noted that some of the estimation results are less than the actual results, although the safe side estimation should be achieved with the lower bound estimation.

4. Concluding Remarks

The applicability of the previously proposed method for estimating the maximum inelastic out-of-plane response of upper-deck steel arch bridges to the maximum in-plane response estimation is examined. Examinations are carried out numerically on six parametric upper-deck steel arch bridge models. The suitable load pattern for the pushover analysis is evaluated. It is found that the method can be applied to the estimation of maximum in-plane response by only changing the pushover analysis procedure. The main findings are summarized below;

(1) The load pattern introduced in this study, which is an incremental displacement load applied at the mid point of the stiffening girder from the both sides, can be used in the pushover analysis to approximate the in-plane dynamic response of upper-deck steel arch bridges.

(2) The proposed method can be applied to the maximum inelastic response estimation for in-plane ground motion inputs as well as for the out-of-plane ones in the preliminary seismic design considerations.

References

[1]. Japan Road Association (JRA). Specifications for highway bridges, Part V. Seismic design, Tokyo, Japan; 2002.

[2]. Cetinkaya OT, Nakamura S, Takahashi K. A static analysis-based method for estimating the maximum out-of-plane inelastic seismic response of steel arch bridges. Engineering Structures 2006; 28(5), 635-647.

[3]. Krawinkler H, Seneviratna GDPK. Pros and cons of a pushover analysis of seismic performance evaluation. Engineering Structures 1998; 20(4-6): 452-464.

[4]. Lu Z, Ge H., Usami T. Applicability of pushover analysis-based seismic performance evaluation procedure for steel arch bridges. Engineering Structures 2004(13); 26: 1957-1977.

[5]. Kim SP, Kurama YC. An alternative pushover analysis procedure to estimate seismic displacement demands. Engineering Structures 2008; 30(12): 3793-3807

[6]. Borzi B, Pinho R, Crowley H. Simplified pushover-based vulnerability analysis for large-scale assessment of RC buildings. Engineering Structures 2008; 30(3) : 804-820

[7]. Chopra AK, Goel RK. A modal pushover analysis procedure for estimating seismic demands for buildings. Earthquake Engineering and Structural Dynamics 2002; 31(3): 561-582.

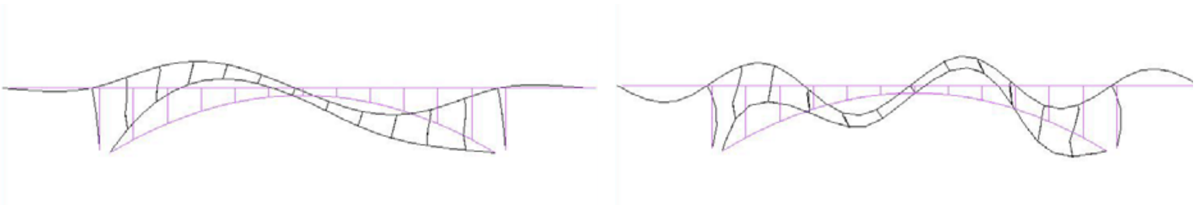
[8]. Jan TS, Liu MW, Ying CK. An upper-bound pushover analysis procedure for estimating the seismic demands of high-rise buildings. Engineering Structures 2004; 26(1):117-128

[9]. Han SW, Wen YK. Method of reliability-based seismic design. I: equivalent non-linear system. Journal of Structural Engineering (ASCE) 1997; 123(3): 256-265.

[10]. Veletsos AS, Newmark, N M: Effect of inelastic behavior on the response of simple systems to earthquake motions. In: Proceedings of the Second World Conference on Earthquake Engineering, 1960, p. 895-912.

[11]. Usami T, Lu Z, Ge H, Kono T. Seismic performance evaluation of steel arch bridges against major earthquakes. Part 1: Dynamic analysis approach. Earthquake engineering and Structural Dynamics 2004; 33:1337-1354.

[12]. MARC User Manual Volume A-Volume E, version K7. MARC Analysis Research Corporation; 1997.



1st In-plane mode 3rd In-plane mode

Figure 1. Predominant in-plane eigenmodes (Model 1)

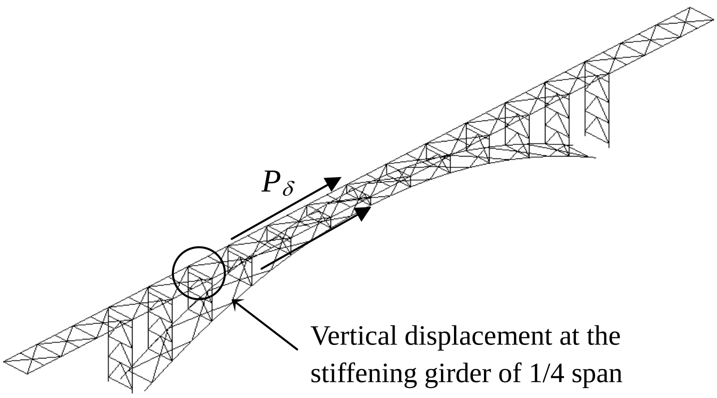


Figure 2. Reference point and the load pattern for the pushover analysis

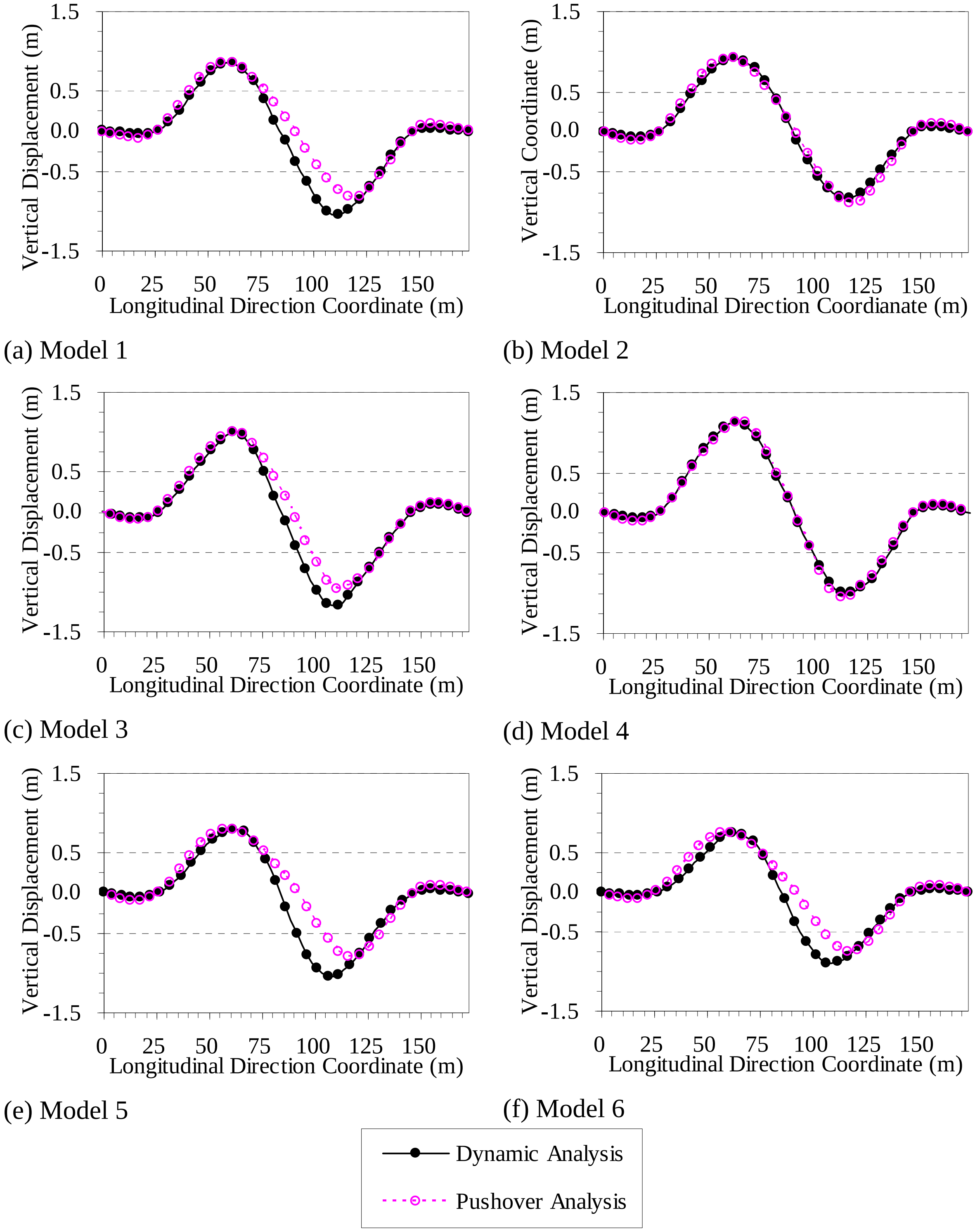


Figure 3. Displacement distributions for pushover and dynamic response analysis

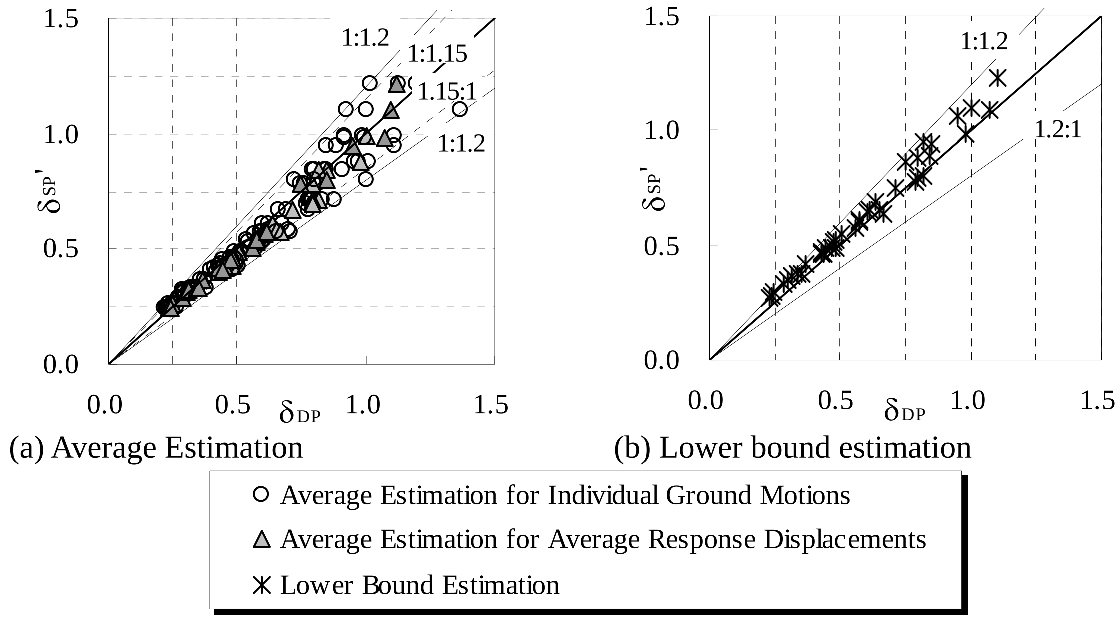


Figure 4. Estimation results with the proposed method

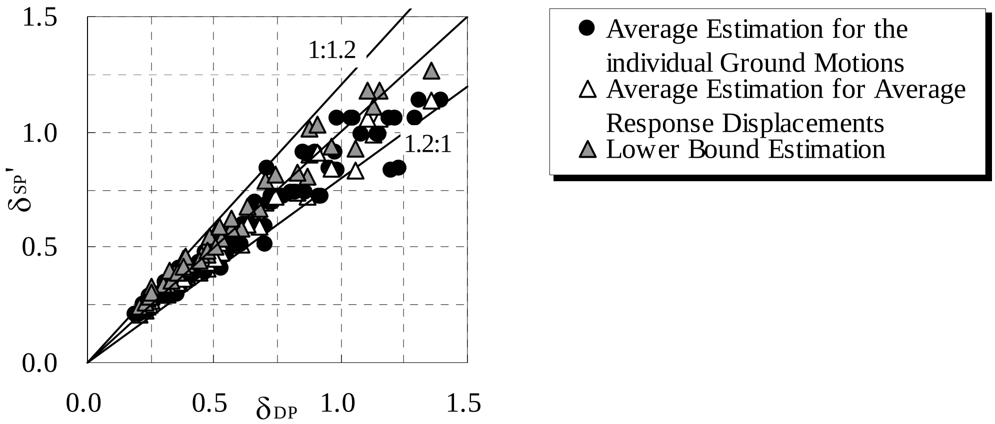


Figure 5. Estimation accuracy for the type-I ground motions.

Table 1: Principle mode frequencies and contributions

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
1st In-plane Mode Frequency (Hz)	0.788	0.751	0.785	0.580	0.822	0.788
Longitudinal direction Effective Mass Ratio (%)	20.03	33.15	55.94	67.68	19.47	19.51
3rd In-plane Mode Frequency (Hz)	2.960	2.844	2.690	1.952	2.721	2.575
Longitudinal direction Effective Mass Ratio (%)	6.96	7.92	1.14	2.26	19.97	24.15