A SIMPLIFIED PREDICTION METHOD OF MAXIMUM OUT-OF-PLANE INELASTIC SEISMIC RESPONSE FOR STEEL ARCH BRIDGES

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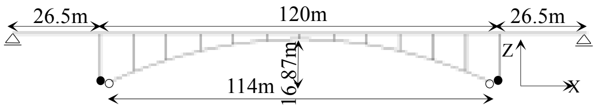
1. Introduction

Japanese seismic design code for highway bridges specifies Ductility Design Method, which is based on static analysis considering the material and geometrical non-linearity, as a simplified seismic design method. The method employs equal energy assumption for the maximum response estimation. However, the application of this method is limited because the applicability of the equal energy assumption is not clear for some structures including the steel arch bridges. Nonlinear dynamic response analysis which is very costly and needs a lot of calculation time is required for the seismic design of steel arch bridges.

In this study the applicability of equal energy assumption to steel arch bridges is examined and a prediction method of inelastic maximum response which doesn't need the dynamic response analysis is proposed to simplify the seismic design of steel arch bridges.

2. Studied Models

Six steel arch bridge models are studied to examine the applicability of equal energy assumption. Model 1, shown in Figure 1 is used as the template model for the generation of Model 2, 3, 4 only by changing the arch rise, and Model 5, 6 only by changing the distance between the two arch ribs. By these models the effect of the arch rise/span length ratio and the distance between the arch ribs to the applicability of the assumption is studied. The structural parameters of the analyzed models are shown in Table 1.



	D_x	D_y	D_z	Θ_x	Θ_y	Θ_z
△	Free	Fixed	Fixed	Free	Free	Free
○	Fixed	Fixed	Fixed	Free	Free	Free
●	Fixed	Fixed	Fixed	Fixed	Free	Fixed

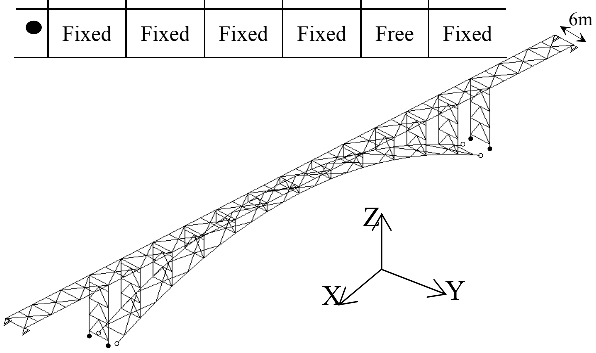


Fig. 1: Model 1

Table 1: Analyzed models.

Model No.	Span Length (m)	Arch Rise (m)	Arch Rise / Span	Width (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

3. Applicability of Equal Energy Assumption

First the applicability of equal energy assumption is studied. Free vibration analysis, pushover analysis, linear and nonlinear dynamic response analysis are conducted for each model. Principal free vibration modes and frequencies are shown in Table 2. The ground motions used in the dynamic response analysis are 6 level-2 type-2 spectral fitted ground motions, 3 for ground condition 1 and 3 for ground condition 2. In order to have sufficient plastic deformation ground motions are amplified by some coefficients like 1.5, 1.7, 2 and 5 respectively. The ground motions are in out-of-plane direction. By using the results of linear dynamic response analysis and pushover analysis maximum nonlinear dynamic response (δ_{SP}) is estimated by equal energy assumption. Then δ_{SP} is compared with the actual maximum dynamic response (δ_{DP}) obtained by nonlinear dynamic response analysis. The applicability of equal energy assumption is studied by the evaluation of the estimation accuracy (δ_{SP}/δ_{DP})-ductility factor μ_E ($=\delta_{SP}/\delta_y$, δ_y: yield displacement) relationship. In

Figure 2 this relationship is shown together for all of the models for ground 1 and ground 2 input ground motions. Although the results are conservative, the accuracy is very low in many cases. It is also seen that δ_{SP}/δ_{DP}-μ_E relationship follows a similar tendency for different models suggesting that the considered structural parameters have no significant effect on the applicability of the assumption. This could make it possible to approximate the δ_{SP}/δ_{DP}-μ_E relationship with a single linear function valid for different models and different ground motions. Correction functions are developed by using this approximation to improve the estimation accuracy. Correction functions for average estimation and safe side estimation are shown in equation (1) and (2), respectively

$$f(\mu_E) = 1/(0.1958\mu_E + 0.7063),\ \left(0 < f(\mu_E) \leq 1\right) \quad (1)$$

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

Finally the poor estimation results are corrected by equation (3).

$$\delta_{SP}^{`} = \mu_E \times f(\mu_E) \times \delta_y \quad (3)$$

4. Simplified Method

By estimating the maximum elastic response with response spectrum method, prediction of maximum plastic response without dynamic response analysis becomes possible. The proposed method contains the following steps; a) Perform free vibration analysis, b) Get the force-displacement relationship by pushover analysis, c) Get the maximum linear response from the response spectrum, d) Estimate the maximum plastic response by using equal energy assumption together with the proposed correction functions.

The estimated maximum nonlinear response δ_{SP}' by the proposed simplified method is compared with the actual maximum dynamic response calculated by nonlinear dynamic response analysis in Figure 3. The estimation resulted in ±15% error for the average estimation and +20% for the safe side estimation. Therefore it is considered that the proposed method can be applied in preliminary design of steel arch bridges as a simple prediction method of their maximum inelastic response.

Table 2: Principal free vibration mode frequencies (sec^{-1})

Mode Shape	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
	1.041	0.995	0.824	0.647	1.315	1.363
	1.696	1.502	1.328	1.127	1.905	1.739
	2.590	2.204	2.014	1.839	2.723	2.323

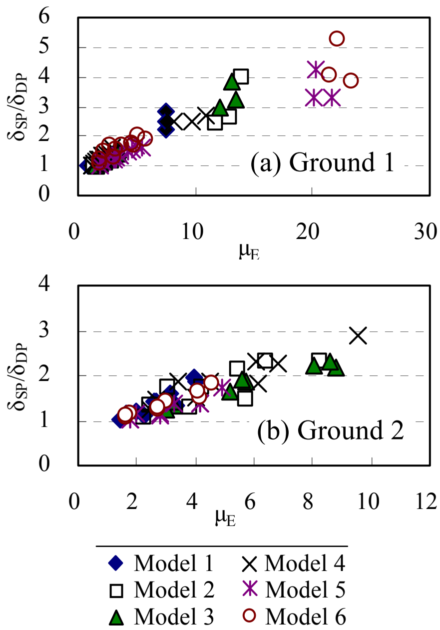


Fig. 2: δ_{SP}/δ_{DP}-μ_E relationship

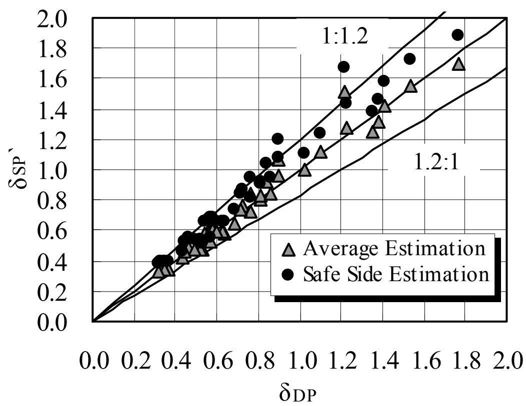


Fig. 3: Estimation Results

5. Conclusions

Main findings of this study can be summarized as: i) Equal energy assumption results in conservative side estimation for the maximum inelastic response. But the results are too conservative for many cases. ii) Prediction accuracy can be improved by the proposed correction functions iii) The proposed prediction method can be used as preliminary design method for steel arch bridges. The future work contains the development of similar prediction method of maximum in-plane inelastic response.