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

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1. Introduction

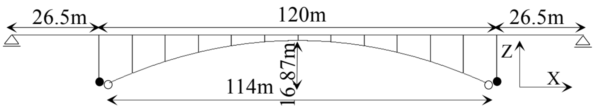
Japanese seismic design code for highway bridges specifies Ductility Design Method, which is based on static analysis considering the material and geometrical non-linearity, as a simplified seismic design method. The method employs equal energy assumption for the maximum response estimation. However, 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 order to simplify the seismic design of steel arch bridges, this study proposes a prediction method of inelastic maximum response which doesn't need the dynamic response analysis on the basis of the applicability examination of equal energy assumption, and verify its validity.

2. Applicability of Equal Energy Assumption

Applicability of equal energy assumption is examined numerically on six steel arch bridge models generated from the template Model 1, shown in Figure 1. The structural parameters of the models are shown in Table 1. The parameters are selected in order to have models representing a general deck-type steel arch bridge behavior and to investigate the effect of these structural parameters on the applicability of the assumption.

Applicability of equal energy assumption is studied by performing free vibration analysis, pushover analysis, linear and nonlinear dynamic response analysis of each model. The natural frequency of the first symmetric out-of-plane free vibration mode which has the greatest contribution to the structural response ranges between 0.647 Hz and 1.363 Hz for the analyzed models. 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 applied 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



	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

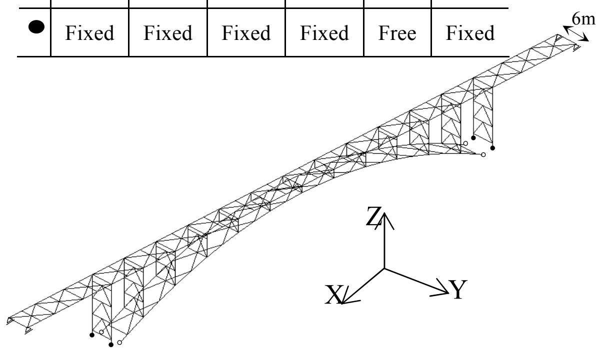


Fig. 1: Model 1

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

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response (δ_{DP}) obtained by nonlinear dynamic response analysis. The applicability of equal energy assumption is evaluated by 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 for all of the models with 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

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

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

The poor estimation results are corrected by equation (3).

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

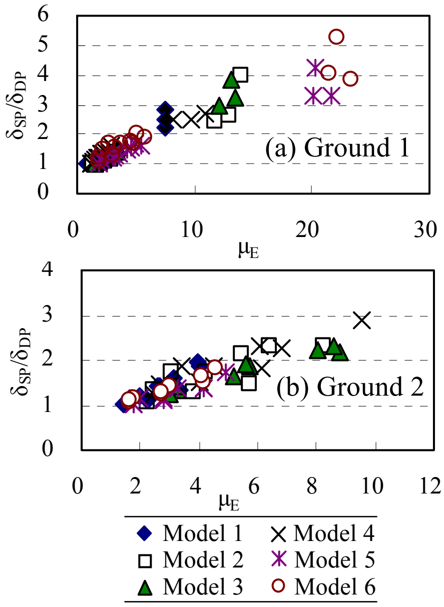

Fig. 2: δ_{SP}/δ_{DP}-μ_E relationship

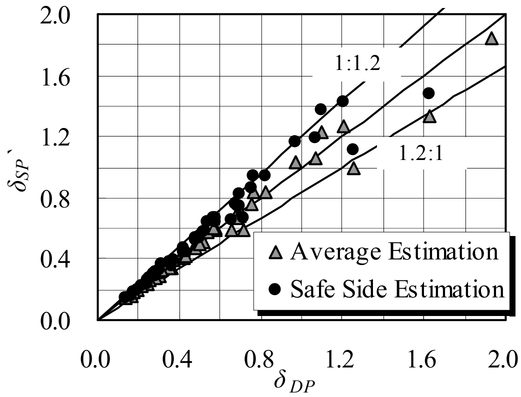

Fig. 3: Verification of the method for type 1 ground motions

3. Proposed Simplified Method and Its Verification

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) Obtain the force-displacement relationship by pushover analysis, c) Calculate 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 estimation by the proposed method resulted in ±15% error for the average estimation and +20% for the safe side estimation for the input ground motions used in the development of the method. 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 for the level-2 type-2 ground motions.

For the confirmation of the applicability of the method to different ground motions, the proposed method is applied to the same models by using the type 1 ground motions for ground conditions 1 and 2 with the amplification factors of 1.5, 2 and 5. In Figure 3 the estimation results δ_{SP}’ are compared with the actual dynamic response δ_{DP}. The applicability of the method is verified as the accuracy of the results is within the error range of ±20%. Although the safe side estimation result is found to be less than the actual response in a few cases, this is not considered as a negative aspect for the applicability of the method as the method is proposed for preliminary design,

4. Conclusions

Main findings of this study can be summarized as: i) Although equal energy assumption results in conservative side estimation for the maximum inelastic response, 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 for preliminary seismic design of steel arch bridges. The future work contains the development of similar prediction method of maximum in-plane inelastic response.