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Evaluation Methods Based on Stress Resultant for Seismic Performance of Steel Members with Fiber Model

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Abstract

The fiber model which is one kind of frame analysis methods is sometimes used as an effective tool for the nonlinear dynamic response analysis. Recently, some seismic evaluation methods based on the strain for evaluating the seismic performance of stiffened steel box members were proposed. However, it is reported that these previous methods based on the strain cannot adequately estimate the seismic performance. In this study, it is explained that the stress resultant can be little affected by hysteresis patterns and have the ability to be a good parameter in order to evaluate the seismic performance appropriately. In addition, a seismic evaluation method based on the stress resultant with the fiber model is proposed for evaluating the seismic performance of stiffened steel box members. Finally, the validity of the proposed method is confirmed for stiffened steel box members by comparing the calculation results by the proposed method with the experimental results and FEM analysis results.

Keywords: stress resultant; stiffened steel box members; fiber model; seismic design methods.

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1. INTRODUCTION

The Kobe Earthquake that occurred in 1995 had brought severe damage to steel bridge piers. After the earthquake, “Seismic Design Specifications for Highway Bridges” in Japan (Japan Road Association 1996; Japan Road Association 2002) were revised and the nonlinear dynamic response analysis was recommended as the method to evaluate the seismic performance of steel bridge piers against Level 2 earthquake motions like the Kobe Earthquake.
Recently, the fiber model which is one kind of frame analysis methods is sometimes used as an effective tool for the nonlinear dynamic response analysis. As seismic evaluation methods with the fiber model, some methods based on the strain have been proposed for evaluating the seismic performance of stiffened steel box members (JSSC 2006; Ono et al. 2007; Ono et al. 2008). However, the evaluation results by the methods based on the strain are affected by the hysteresis patterns. On the other hand, according to the previous researches, the seismic performance of stiffened steel box members such as hysteresis loops, the maximum horizontal load P_{max} and the horizontal displacement at the maximum load δ_m until the region in which P_{max} is observed tend to be little affected by the loading history (PWRI et al. 1999). Therefore, the seismic performance evaluated by the method based on the strain can be different from the actual seismic performance of stiffened steel box members.

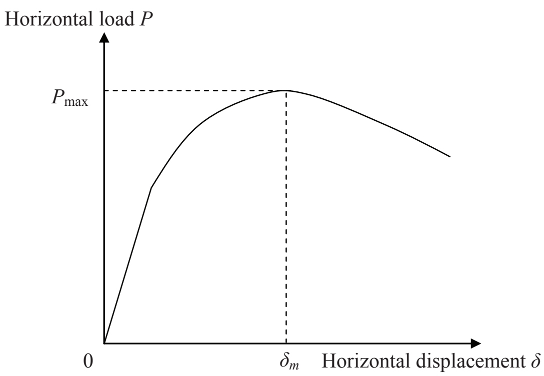


Figure 1: Limit state

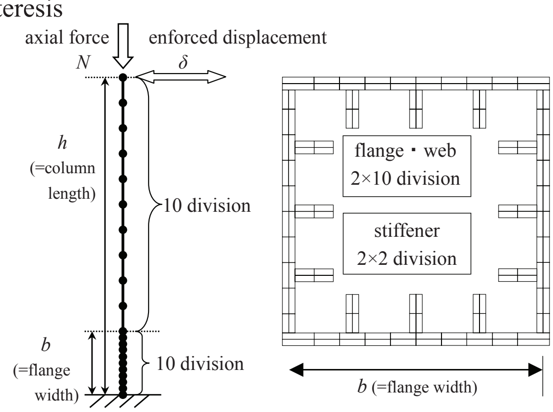


Figure 2: Modeling and Element division

In this study, it is explained that the stress resultant can be little affected by hysteresis patterns and have the ability to be a good parameter in order to evaluate the seismic performance appropriately. In addition, a seismic evaluation method based on the stress resultant with the fiber model is proposed for evaluating the seismic performance of stiffened steel box members. Furthermore, the validity of the proposed method is confirmed for stiffened steel box members by comparing the calculation results by the proposed method with the experimental results and FEM analysis results.

2. Seismic evaluation method based on stress resultant

2.1. Limit state

In “Seismic Design Specifications for Highway Bridges” in Japan, the limit state for the seismic design of steel bridge piers is stipulated as the point in which the maximum horizontal load P_{max} is observed as shown in Figure 1 (Japan Road Association 2002). Thus, in this study, the limit state for the seismic design is defined as the same point as the Japanese seismic design code.

2.2. Analysis model and element division

In all analyses with the fiber model of this study, EERC/Fiber (Earthquake Engineering Research Center Inc. 2007) of the same analysis program as previous study was used (Ono et al. 2008). In EERC/Fiber, the deformation was calculated by considering not only the bending deformation but also the shear deformation. Figure 2 shows an example of the analysis model with the fiber model.

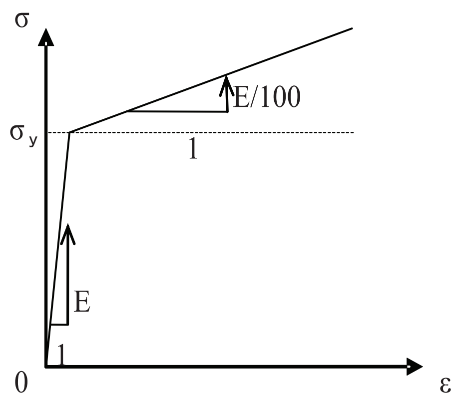


Figure 3: Bi-linear model

Regarding the division of elements in the height direction, the region from the base to height b (b = flange width) which was the flange width was divided into 10 elements and other region was also divided into 10 elements. As for the cross sectional division, flanges and webs were divided into 2×10 cells and longitudinal stiffeners were divided into 2×2 cells.

2.3. Constitutive equation

As for the constitutive equation, the bi-linear model with E/100 of the secondary slope shown in Figure 3 was utilized in the fiber model analysis. The kinematic hardening rule was adapted as the hardening rule in the cyclic loading analysis.

2.4. Experimental results and FEM analysis results

In order to propose the seismic evaluation method based on the stress resultant, the test specimens (PWRI et al. 1999; Goto et al. 2007) and FEM analysis models (Goto et al. 2007; Usami et al. 2000) which approximately satisfy the range of application of M-Φ model specified in "Seismic Design Specifications for Highway Bridges" (Japan Road Association 2002) were chosen.

2.5. Proposition of seismic evaluation method based on stress resultant

In this section, the pushover analysis was conducted under the analysis condition as shown in 2.2 and 2.3 As for the experimental results and FEM analysis results as shown in 2.4, the values of the stress resultant, (N_m, M_m), were extracted when the horizontal displacement of the pushover analysis reached δ_m of the experimental results and FEM analysis results. And using the extracted values of the stress resultant, (N_m, M_m), the seismic evaluation method based on the stress resultant was proposed.

The formula such as equation (1) has frequently been used for estimating the ultimate strength of steel members under the axial force and the bending moment in previous studies. Therefore, the investigations also in this study were also conducted on the basis of equation (1).

$$\left(\frac{N}{N_u}\right)^{\xi_1}+\left(\frac{M}{M_u}\right)^{\xi_2}=1.0 \tag{1}$$

Where N is the axial force, M is the bending moment, N_u is the ultimate strength of columns, M_u is the ultimate bending strength and ξ_1, ξ_2 are constants.
As for the setting of N_u, Q-factor measurement which can evaluate the ultimate strength of columns is applied as shown in equation (2).

$$N_u = Q\times f\left(\sqrt{Q}*\bar{\lambda}\right)N_y \tag{2}$$

$$Q=\frac{\sigma_{cl}}{\sigma_y}=\begin{cases}1.0 & (R_R\le 0.571)\\ 0.986/R_R-0.286/R_R{}^2+0.0338/R_R{}^3 & (R_R>0.571)\end{cases} \tag{3}$$

$$f\left(\bar{\lambda}\right)=\frac{\sigma_{cg}}{\sigma_y}=\begin{cases}1.0 & (\bar{\lambda}\le 0.2)\\ \frac{1}{2\bar{\lambda}^2}\left[1+0.089\left(\bar{\lambda}-0.2\right)+\bar{\lambda}^2-\sqrt{\left\{1+0.089\left(\bar{\lambda}-0.2\right)+\bar{\lambda}^2\right\}^2-4\bar{\lambda}^2}\right] & (\bar{\lambda}>0.2)\end{cases} \tag{4}$$

Where σ_y is the yield stress, Q is the local buckling strength gained from equation (3), $f(\sqrt{Q}*\bar{\lambda})$ is the overall buckling strength of columns gained from equation (4), N_y is the yield axial force, R_R is the width-thickness ratio parameter gained from equation (5) and $\bar{\lambda}$ is the slenderness ratio parameter gained from equation (6).

$$R_R=\frac{b}{t}\sqrt{\frac{\sigma_y}{E}\frac{12\left(1-\mu^2\right)}{4\pi^2 n^2}} \tag{5}$$

$$\bar{\lambda}=\frac{1}{\pi}\sqrt{\frac{\sigma_y}{E}}\frac{2h}{r} \tag{6}$$

Where h is the column length, r is the radius of gyration of cross section, E is the Young's modulus, t is the plate thickness, μ is the Poisson's ratio and n is the number of panels.
As for the setting of M_u, the formula with the parameters which affect the seismic performance of stiffened steel box members like steel bridge piers has been established on the basis of equation (7).

$$M_u=\frac{c_1\alpha^{c_2}\left(\gamma_l/\gamma_l^*\right)^{c_3}}{\left(h/b\right)^{c_4}R_R{}^{c_5}R_F{}^{c_6}}M_p \tag{7}$$

Where M_p is the fully plastic bending moment, R_F is the width-thickness ratio parameter gained from equation (8), γ_l/γ_l^* is the stiffness ratio of a longitudinal stiffener gained from equation (9) and equation (10), α is the aspect ratio of flange plate between two diaphragms (= a/b, a is the diaphragm spacing) and c_1~c_6 are constants.

$$R_F=\frac{b}{t}\sqrt{\frac{\sigma_y}{E}\frac{12\left(1-\mu^2\right)}{\pi^2 k_F}} \tag{8}$$

$$\gamma_l = \frac{I_l}{\frac{bt^3}{11}} \tag{9}$$

$$\gamma_l^* = \begin{cases} 4\alpha^2 n(1+n\delta_l) - \dfrac{(1+\alpha^2)^2}{n} & \left(\alpha < \sqrt[4]{1+n\gamma_l}\right) \\ \dfrac{1}{n}\left[\left\{2n^2(1+n\delta_l)-1\right\}^2 - 1\right] & \left(\alpha \geq \sqrt[4]{1+n\gamma_l}\right) \end{cases} \tag{10}$$

Where I_l is the geometrical moment of inertia of the T-section consisting of a longitudinal stiffener and the effective with of the plate to which it connects, δ_l is the cross-section ratio of one longitudinal stiffener and k_R is the bucking coefficient.

And the constants of equation (1) and equation (7) were decided by the following procedure.

(a) As for each of the test specimens and FEM analysis models, the values of stress resultant, (N_m, M_m), were extracted when the horizontal displacement gained by the pushover analysis reached δ_m of the experimental results and FEM analysis results.

(b) The extracted values of stress resultant, (N_m, M_m), were substituted into (N, M) of equation (1). Then, the constants of equation (1) and equation (7) were decided by the minimization of the standard deviation of left-hand value of equation (1).

From what has been discussed above, the following equation (11) and equation (12) were proposed for the seismic evaluation method based on the stress resultant.

$$\left(\frac{N}{N_u}\right)^{1.6} + \left(\frac{M}{M_u}\right)^{0.82} = 1.0 \tag{11}$$

$$M_u = \frac{1.07\alpha^{0.03}\left(\gamma_l/\gamma_l^*\right)^{0.03}}{(h/b)^{0.07} R_R^{\ 0.14} R_F^{\ 0.03}} M_p \tag{12}$$

The range of application of equation (11) is as follows in consideration of the structural parameters of the test specimens and FEM analysis models.

$0.0 \leq N/N_y \leq 0.2$, $0.5 \leq \alpha \leq 1.5$, $1.0 \leq \gamma_l/\gamma_l^*$, $0.2 \leq \bar{\lambda} \leq 0.5$, $6 \leq h/b \leq 15$, $0.3 \leq R_F \leq 0.5$, $0.3 \leq R_R \leq 0.5$

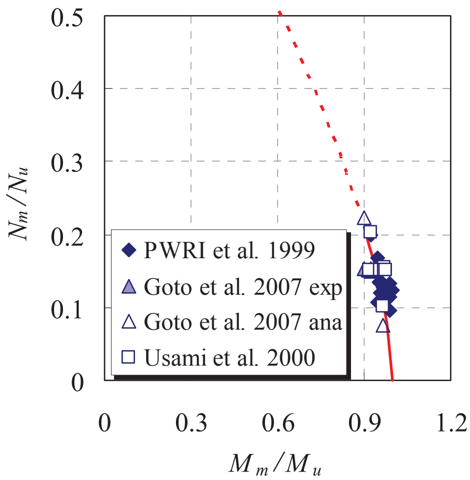


Figure 4: Comparison equation (11) and (N_m, M_m)

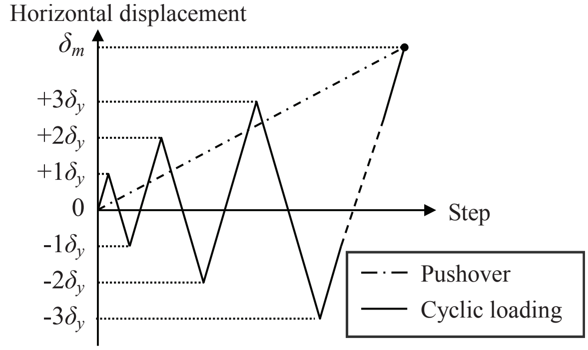
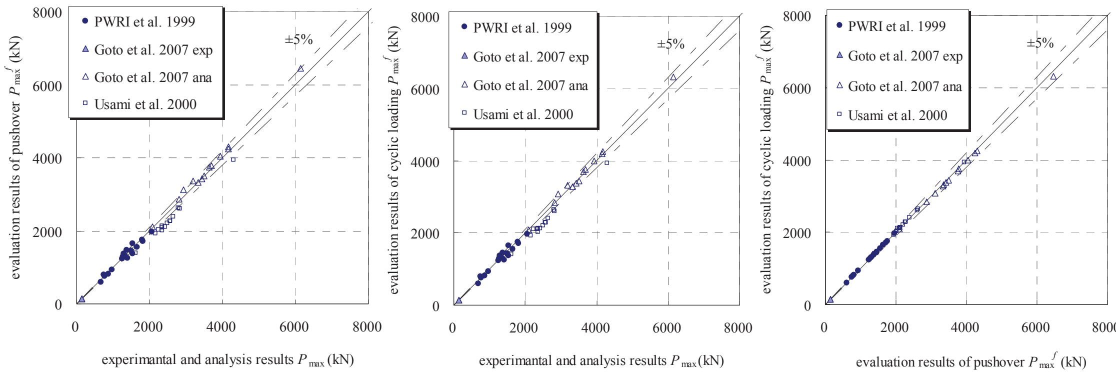


Figure 5: Loading pattern

Figure 4 is the comparison between the evaluation results by equation (11) and the values of stress resultant, (N_m, M_m), of the experimental results and FEM analysis results. In Figure 4, y-axis indicates N_m/N_u and x-axis indicates M_m/M_u. Figure 4 shows a good accuracy of the evaluation method based on the stress resultant in the case of the limit state for the seismic design.

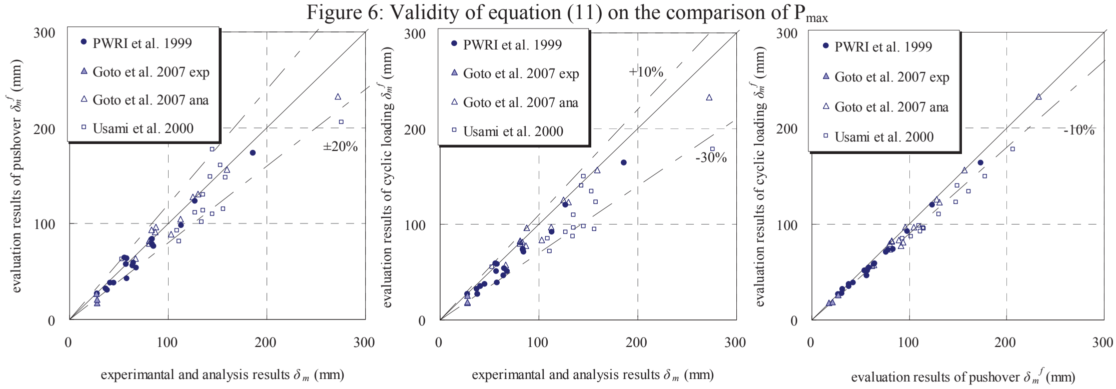
2.6. Validity of proposed method

In order to confirm the validity of the proposed method based on the stress resultant, the evaluation results with equation (11) by the fiber model analysis were compared with the experimental results and FEM analysis results described in 2.4. In the fiber model analyses, the enforced displacement and the specified compressive axial force were applied to each analysis model as shown in Figure 2. As shown in Figure 5, two types of loading patterns were conducted about the loading pattern of the horizontal displacement. One of the loading patterns was the pushover analysis and the other was the cyclic loading analysis shown in Figure 5. In the cyclic loading analysis, the models were subjected to the oscillating displacement to which the incremental values of the yield displacement were added until δ_m was reached. Figure 6(a) and Figure 7(a) indicate the comparison in the case of the pushover analysis. Figure 6(b) and Figure 7(b) indicate the comparison in the case of the cyclic loading analysis. Figure 6(c) and Figure 7(c) indicate the comparison of evaluation results between the pushover analysis and the cyclic loading analysis. P_{max}^f is P_{max} of the evaluation results with equation (11) by the fiber model analysis. δ_m^f is δ_m of the evaluation results with equation (11) by the fiber model analysis.



(a) Pushover analysis (b) Cyclic loading analysis (c) Effects of loading history

Figure 6: Validity of equation (11) on the comparison of P_{max}



(a) Pushover analysis (b) Cyclic loading analysis (c) Effects of loading history

Figure 7: Validity of equation (11) on the comparison of δ_m

As for the comparison of Pmax, Figure 6(a) shows that the difference between the evaluation results P_{max}^f by the pushover analysis and the experimental results or FEM analysis results of Pmax is around ±5% margin. Figure 6(b) also shows that the difference between the evaluation results of P_{max}^f by the cyclic loading analysis and the experimental results or FEM analysis results of Pmax is around ±5% margin. Besides, Figure 6(c) implies that there exists only a slight difference between P_{max}^f by the pushover analysis and P_{max}^f by the cyclic loading analysis.

As for the comparison of δm, Figure 7(a) shows that the difference between the evaluation results of δ_m^f by the pushover analysis and the experimental results or FEM analysis results of δm is around ±20% margin. Figure 7(b) shows that the difference between the evaluation results of δ_m^f by the cyclic loading analysis and the experimental results or FEM analysis results of δ_m^f is around -30% ~ +10% margin. Additionally, Figure 7(c) suggests that there be the differences of around -10% ~ 0% between δ_m^f by the pushover analysis and δ_m^f by the cyclic loading analysis.

3. Conclusion

In this study, it is explained that the stress resultant can be little affected by hysteresis patterns and have the ability to be a good parameter in order to evaluate the seismic performance appropriately. In addition, some investigations were carried out to propose the seismic evaluation method based on the stress

resultant with the fiber model for evaluating the seismic performance of the stiffened steel box members. The results of investigations are as follows.
(1) The bending moment, one of the stress resultant, can be little affected in the cyclic loading analysis. This tendency is as same as the property of the seismic performance of steel members such as the maximum load $P_{\max}$ and the horizontal displacement δ_m.
(2) The evaluation method based on the stress resultant is proposed and the validity of the proposed method is confirmed by the comparison between the evaluation results by the proposed method and the experimental results or FEM analysis results. Furthermore, it is shown that the evaluation results by the proposed method can be little affected by the loading pattern and the proposed method enables the proper seismic evaluation of the stiffened steel box members in the case of the cyclic loading.

4. ACKNOWLEDGMENTS

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