교량의 지진해석에서 단순해석의 효과

Effect of Simplified Methods in Seismic Analysis of Bridges

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요 약 : 본 연구에서는 스틸베어링을 가진 교량의 단순해석의 효과를 상부구조의 충돌의 유무에 따라 점검하였다. 교량의 지진해석에서는 비선형 시간이력해석이 일반적으로 사용되지만, AASHTO 등을 포함해서 많은 시방서는 단순해석법을 제시하고 있다. 그러나 AASHTO에서는 충돌에 대한 언급이 없고, 이로 인하여 단순해석의 결과가 비선형 시간이력해석과 차이가 있을 수 있음을 알 수 있다. 그래서 본 연구에서 다경간 단순지지 교량과 다경간 연속 교량, 두 형태의 교량에 대하여 비선형 모델을 개발하고, 이들을 단순해석에 적합하게 선형 모델로 수정하였다. 그리하여 비선형 시간이력해석과 단순 선형해석들의 결과를 비교·검토하였다. 이를 통해서, 단순 선형해석에 있어서 충돌 또는 접촉을 고려하는 것이 비선형 시간이력해석 결과와 가장 근접함을 알 수 있었다.

ABSTRACT : The effect of several simplified methods of seismic analysis is estimated. The pounding/contacting of superstructures were considered in the multispan simply supported bridge and the multispan continuous bridge. Although nonlinear time history analysis is generally used for seismic analysis of bridges, many codes including AASHTO propose several simplified analysis methods. AASHTO, however, does not mention pounding. Therefore, the simplified methods may produce results that are different from those of nonlinear time history analysis. This study developed nonlinear analytical models of the two types of bridges mentioned. The models were then modified to the simplified linear models for simplified analysis. The results of the simplified methods were compared with those of nonlinear time history analysis. It was found that including of the pounding/contacting element in the simplified methods generated responses similar to those of the nonlinear time history analysis.

핵 심 용 어 : 단순해석법, 충돌.접촉요소, 강교량, 응답비
KEYWORDS : simplified methods of analysis, pounding/contacting elements, steel bridges, response ratios

1. Introduction

AASHTO (1999) defines several simplified seismic analysis methods such as uniform load method, single-mode spectral method, and multimode spectral method instead of time history analysis. Although these simplified analysis methods are developed for the designing of bridges, the methods are generally being used for analyzing existing bridges.

The objectives of this study is to comprehend the effect of several simplified analysis methods on seismic behavior of steel bridges. Nonlinear time history analysis (NTHA) generally requires complicated nonlinear bridge models and a lot of times to perform the analysis. The simplified methods, on the other hand, need simplified linear models and have convenient procedures for analyzing.

This study selects equivalent static load analysis (ESLA), response spectral analysis (RSA), and linear time history analysis (LTHA) as simplified methods. The ESLA is the same as the uniform

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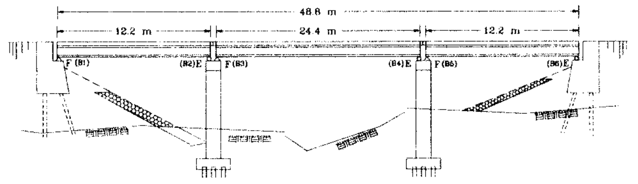
본 논문에 대한 토의를 2003년 6월 30일까지 학회로 보내주시면 토의 회답을 게재하겠습니다.

load method in AASHTO (1999).

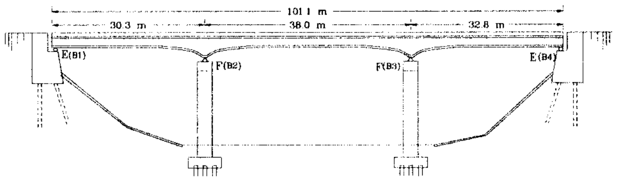
At first, nonlinear models for a multispan simply supported (MSSS) bridge and a multispan continuous (MSC) bridge with steel bearings shown in Fig. 1 are developed for nonlinear time history analysis, and then they are modified to the linear models for the simplified analysis methods. The focus of this study is on the pounding (contact in static analyses) element to describe the impact between decks or decks and abutments in seismic performance of bridges. The nonlinear bridge models of course include the pounding element. However, in the simplified linear models, the two cases of with and without the pounding element will be included. All types of analyses are conducted in the longitudinal direction.

2. Nonlinear and Simplified Analytical Models of Bridges

Since the multispan simply supported bridge and the multispan continuous steel bridge consist of elements that may exhibit highly nonlinear behavior (steel bearings, columns, abutments, impacts), a two-dimensional nonlinear analytical model of the bridges is developed using DRAIN-2DX (Prakash et al. 1992).



(a) Multispan Simply Supported Bridge



(b) Multispan Continuous Bridge

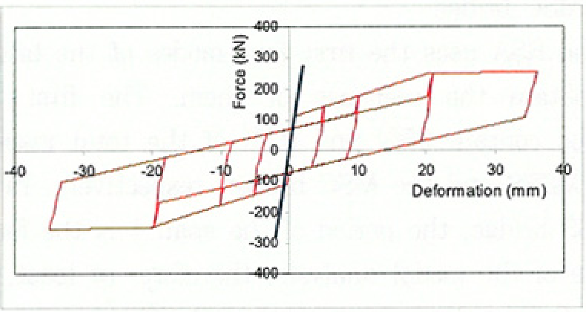
Fig.1. General Shapes of Steel Bridges

Since the superstructure is expected to remain linear under longitudinal earthquake motion, it is modeled using a linear element that represents the stiffness and mass properties of the composite steel girder reinforced concrete deck. The columns are modeled using the DRAIN-2DX fiber element. Each fiber has a stress-strain relationship, which can be specified to represent unconfined concrete, confined concrete, and longitudinal steel reinforcement. The distribution of inelastic deformation and forces is sampled by specifying cross section slices along the length of the element. Degradation and softening after yielding, pinching and bond slip are not included in the present model, and shear is represented elastically.

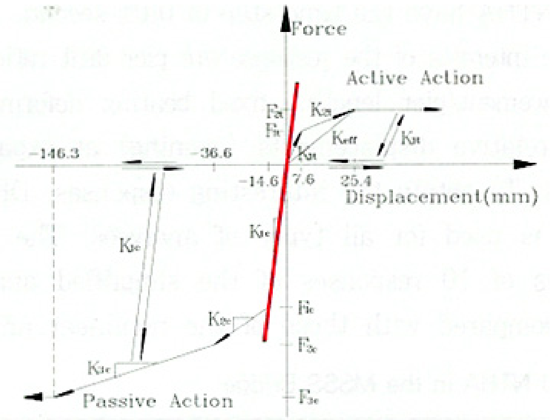
Both the MSSS and MSC steel bridge have steel rocker bearings and steel fixed bearings. Experimental tests of steel bearings similar to those of the MSSS and the MSC bridge in this study were conducted by Mander et al. (1996) and Barker et al. (1997). The results from these tests were used to develop analytical steel bearing elements. The abutment properties used in the models are based on recommendations by Caltrans (1990) and results from previous experimental studies (Maroney et al., 1994; Goel and Chopra, 1997). The model represents the multi-linear inelastic behavior of the abutments in both active action (tension) and passive action (compression).

The contact element approach is utilized to represent impact between decks and at the abutments (Maison and Kasai, 1992). Previous studies have shown that when a linear element with very high stiffness is used for impact, it can produce unrealistically high impact forces and accelerations (DesRoches and Fenves, 1997). Therefore, a trilinear element with elastic loading/unloading with a gap is used to represent impact between decks or decks and abutments. The pile foundation is modeled using a combination of linear springs in horizontal and rotational direction. The pile foundation stiffnesses for both direction are based on the type and number of piles, as well as the soil properties.

The nonlinear behavior of several components (steel bearings, columns, and abutments) is linearized in the simplified models as shown in Fig. 2. The stiffness of the linear models for fixed steel bearings is 136 kN/mm based on the Mander's test (Mander et al., 1996), and the stiffness of abutments is 670 kN/mm based on Choi's study (Choi, 2002). The fiber elements of columns are replaced by elastic beam-column elements. Expansion bearings and foundations are replaced by ideal rollers and fixed conditions, respectively, in the simplified analytical models. Fig. 3 shows the general view of the simplified model of the MSSS steel bridge.



(a) Linear Model of Fixed Steel Bearings



(b) Linear Model of Abutments

Fig. 2. Linear Models of Bridge Components

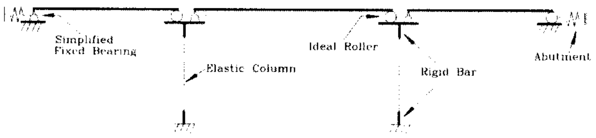


Fig. 3. Simplified Model of the MSSS Bridge

3. Ground Motions

A recent study by Wen and Wu (2001) resulted in the development of simulated earthquake records for three cities in the central and southeastern United states: Memphis, TN, Carbondale, IL, and St. Louis, MO, based on a New Madrid seismic event. The ground motion is developed for two hazard levels: 2% and 10% probability of exceedance (PE) in 50 years. For each city and hazard level, a suite of 10 ground motion records is developed. In this study, the suite of 10 ground motions of 2% PE in 50 years for Carbondale, IL, is used for the analyses. The mean response spectral accelerations (MRS) and mean ± one standard deviation for 5% damping for the suite of ground motions is shown in Fig. 4.

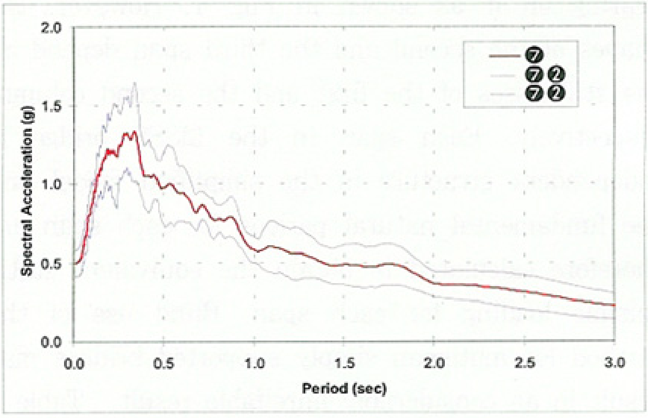


Fig. 4. Mean Response Spectra of Carbondale Ground Motions

4. Analyses and Discussion of Results

In the equivalent static load analysis (uniform load analysis in AASHTO), the fundamental natural period of a bridge is required to calculate Cs described like below:

$$C_s = \frac{1.2AS}{T^{2/3}} \tag{1}$$

where Cs is the dimensionless elastic seismic response coefficient, A is acceleration coefficient, S is the site coefficient for a given soil profile, and T is the fundamental natural period. S is assumed to be 1.0 in this study. Using Cs, p_e can be estimated:

$$p_e = \frac{C_s W}{L} \qquad (2)$$

where p_e is the equivalent static seismic loading per unit length of a bridge applied to represent the primary model of vibration, W is the total weight of a bridge, and L is total length of a bridge.

For the continuous bridge, the procedure can be applied directly using the fundamental natural period of the bridge. However, the application of the method for a multispan simply supported bridge in the longitudinal direction demands some caution. In the MSSS bridge, the fundamental deformation shape of the first span is governed by the stiffness of the right abutment and the fixed bearing on it as shown in Fig. 1. However, the shapes of the second and the third span depend on the stiffnesses of the first and the second column, respectively. Each span in the MSSS bridge is independent structure in the simplified model and the fundamental natural periods for each span are therefore calculated to obtain the equivalent static seismic loading for each span. Blind use of the method for mutispan simply supported bridges may result in an considerably unreliable result. Table 1 shows the weights, the lengths, and the periods for the spans in the MSSS bridge and the MSC bridge. Frames 2 and 3 in the MSSS bridge include the weight of cap-beams and columns in the weight.

Table 1. Structural Properties for Simplified Methods of Analysis

	MSSS			MSC
	Frame 1	Frame 2	Frame 3	
Weight (kN)	1317	3492	1997	11752
Length (m)	12.2	24.4	12.2	101
Period (sec)	0.108	0.980	0.741	1.441

The periods calculated by the uniform load method in Table 1 are very similar to the values calculated by modal analysis for the simplified models; 0.108, 0.984, and 0.746 sec for each span of the MSSS bridge, respectively, and 1.413 sec for the MSC bridge.

The RSA uses the first four modes of the bridges to obtain the response of them. The first four modes contain 95% and 97% of the total mass in the MSSS and the MSC bridge, respectively. In the MSSS bridge, the period of the span 1 is the fourth mode of the modal analysis, therefore, at least, the first four modes are required in the RSA to compare the results with those form the ESLA. The LTHA and NTHA have the time step of 0.01 second.

The interests of the response are pier drift ratio (top displacement/pier length), fixed bearing deformation, and relative displacements (opening) at expansion joints. To obtain the interesting responses, DRAIN-2DX is used for all types of analyses. The mean values of 10 responses of the simplified analyses are compared with those of the nonlinear analysis

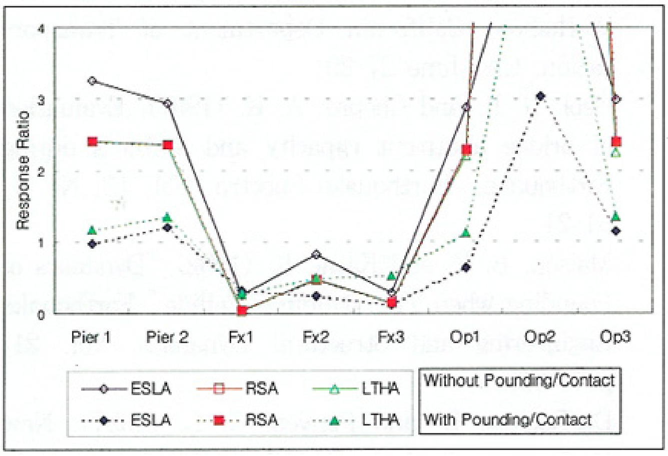
Table 2. Responses of Simplified Methods and NTHA in the MSSS Bridge

		Pier Drift Ratio (%)		Fixed Bearing Deformation (mm)			Relative Displacement (mm)		
		Pier 1	Pier 2	δfx1	δfx2	δfx3	△op1	△op2	△op3
As Built	NTHA	0.91	0.74	16.5	2.34	4.80	62.7	8.40	48.5
Without Pounding/Contact Elements									
Simplified Methods	ESLA	2.96	2.17	4.19	1.93	1.42	181	53.6	144
	RSA	2.18	1.75	0.79	1.12	0.74	143	185	116
	LTHA	2.18	1.75	0.56	1.14	0.74	138	171	110
With Pounding/Contact Elements									
Simplified Methods	ESLA	0.89	0.89	5.26	0.56	0.56	40.1	25.4	55.6
	RSA	2.18	1.75	0.79	1.12	0.74	143	185	116
	LTHA	1.07	1.00	4.55	1.19	2.57	70.1	55.6	65.3

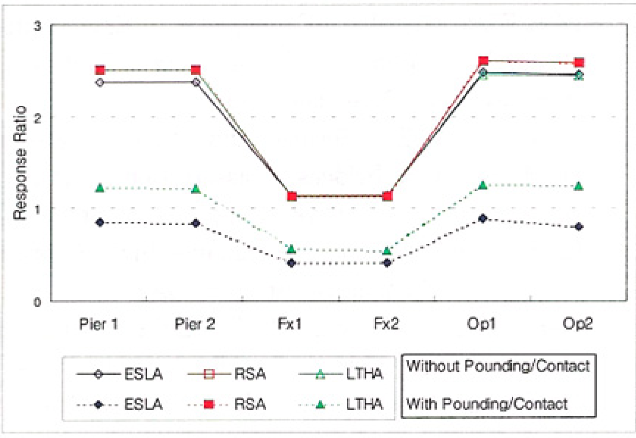
Table 3. Responses of Simplified Methods and NTHA in the MSC Bridge

		Pier Drift Ratio (%)		Fixed Bearing Deformation (mm)		Relative Displacement (mm)	
		Pier 1	Pier 2	δfx1	δfx2	Δop1	Δop2
As Built	NTHA	1.36	1.36	2.50	2.50	94.7	95.5
Without Pounding/Contact Elements							
Simplified Methods	ESLA	3.23	3.23	2.86	2.86	234	234
	RSA	3.41	3.41	2.83	2.83	246	246
	LTHA	3.41	3.41	2.84	2.84	233	233
With Pounding/Contact Elements							
Simplified Methods	ESLA	1.16	1.15	1.03	1.02	83.9	76.6
	RSA	3.41	3.41	2.83	2.83	246	246
	LTHA	1.67	1.66	1.42	1.38	119	119

as shown in Tables 2 and 3 for the MSSS and the MSC steel bridge, respectively. The numbering of piers, fixed bearings, and openings is arranged from left to right in Fig. 1. Fig. 5 shows the ratios of the responses of the simplified models to those of the nonlinear models.



(a) Response Ratio in the MSSS Bridge



(b) Response Ratio in the MSC Bridge

Fig. 5. Response Ratio of Simplified Methods

All simplified analyses without pounding/contact elements for the MSC bridge produce the similar results of the responses. The response ratios of the simplified methods are approximately 2.5, 1.1, and 2.5 for pier drift, fixed bearing deformations, and relative displacements, respectively.

In the MSSS bridge, the response ratios without considering pounding/contacting vary from 2.4 to 3.3 for pier drift and reach 22 for relative displacement.

However, for the fixed bearing deformation, the response ratios are lower than 1.0.

In the NTHA, the fixed bearings have large deformations due to impacts between decks or decks and abutments. In reviewing Tables 2 and 3 and Fig. 5, it is found that the simplified methods without considering pounding/contacting overestimate the demand of piers.

The RSA produces the same results in the both cases of with and without pounding/contacting. The method uses the modal characteristics of a structure to calculate the response. Modal analysis, however, can not consider the pounding elements having gap because the initial stiffness of the gap element is zero.

The response ratios of the ESLA and LTHA with pounding/contacting are close to 1.0 for pier drift and relative displacement in the both types of bridges. However, the response ratios for the fixed bearings are less than 1.0 for the ESLA and LTHA with pounding/contacting. In the MSSS bridge, the response ratio of the opening 2 is much large since the friction of expansion bearings in the NTHA prohibit the large opening 2 and the simplified models do not have any friction on the expansion joint.

5. Conclusions

This study showed that the equivalent static load analysis and linear time history analysis with considering pounding/contacting produced the responses similar to those of the nonlinear time history analysis in the two types of steel bridges. In other words, the simplified methods of analysis without considering pounding/contacting may produce sever errors in the assessment of the seismic performance of bridges.

The response spectra analysis does not reflect the effect of the pounding/contacting. The method produces the similar results to the equivalent static load analysis and linear time history analysis in the cases of "without pounding/contact". Therefore, it is recommended that the response spectra analysis is used only for the analysis not necessary considering pounding/contacting between structures.

The deformation of fixed bearings were underestimated by the simplified methods of analysis even with pounding/contacting. The pounding forces govern the deformation of the bearings in the MSSS bridge, however in the MSC bridge, the inertia forces of the deck control the deformation more. In addition, the stiffness of the bearings in the simplified models higher than the original model after yielding point. Therefore, it is not easy to find a general trend of the fixed bearing deformation.

References

1. AASHTO (1999). "Standard Specification for Highway Bridges," American Association of State Highway and Transportation Officials, 16th Ed., Washington, D.C.
2. Prakash, V., Powell, G.H., Campbell, S.D. and Filippou, F.C. (1992) DRAIN-2DX User Guide, Department of Civil Engineering, University of California at Berkeley.
3. Mander, J. B., Kim, D. K., Chen, S. S., and Premus, G. J. (1996). Response of Steel Bridge Bearings to the Reversed Cyclic Loading , Technical Report NCEER 96-0014, Buffalo, NY.
4. Barker, M.G. and Hartnagel, B.A. (1997). "Longitudinal Restraint Response of Existing Bridge Bearings," MISSOURI COOPERATIVE HIGHWAY RESEARCH PROGRAM, REPORT 97-4, MISSOURI DEPARTMENT OF TRANSPORTATION.
5. Caltrans (1990). "Bridge Design Specifications Manual, California Department of Transportation.
6. Maroney, B., Kutter, B., Romstad, K., Cahi, Y. H., and Vanderbilt, E. (1994). Interpretation of Large Scale Bridge Abutment Test Results, Proceedings of 3rd Annual Seismic Research Workshop, California Department of Transportation, CA, June 27-29.
7. Geol, R. K. and Chopra, A. K. (1997). Evaluation of bridge abutment capacity and stiffness during earthquake, Earthquake Spectra, Vol. 13, No. 1, p1-21.
8. Maison, B. F. and Kasai, K. (1992). "Dynamics of Pounding when Two Buildings Collide," Earthquake Engineering and Structural Dynamics, Vol. 21: p771-786.
9. DesRoches, R. and Fenves, G. L. (1997). New Design and Analysis Procedures for Intermediate Hinges in Multiple-Frames Bridges, Report No. UCB/EERC-97/12, Earthquake Engineering Research Center, University of California, Berkeley, CA., December, 1997.
10. Choi, E. (2002). "Seismic Analysis and Retrofit of Mid-America Bridges," Dissertation of Ph.D., Department of Civil and Environmental Engineering, School of Engineering, Georgia Institute of Technology, Atlanta, GA.
11. Wen, Y. K., and Wu, C. L. (2001). "Uniform Hazard Ground Motions for Mid-America Cities," Earthquake Spectra, Vol. 17, No.2, p359-384.

(접수일자 : 2002년 8월 16일)