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Structural integrity assessment of bridges using ambient vibration data

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ABSTRACT

Bridges are the natural assets to be properly managed for the safe operation and efficient maintenance. Conventionally, the structural integrity of a bridge has been assessed by load carrying capacity evaluated from loading tests with test trucks by measuring static and dynamic responses, such as deflections or strains under known loading conditions. However, it is very hard to carry out loading tests on in-service bridges with a large amount of traffics, since full or partial block of traffic during the tests may cause not only inconvenience to drivers but also increase of the logistic cost and time. To overcome these difficulties, an alternative method is proposed using model updating based on ambient vibration data without traffic control. The proposed method consists of ambient vibration measurement of a bridge, experimental modal analysis, correction of the initial finite element (FE) model based on the identified modal properties, and the structural integrity assessment of the bridge based on the updated FE model. Field tests were carried out on several bridges in Korea and U.S. The structural integrity assessments of bridges were carried out using the proposed method and the results and rational discussions are addressed.

1. Introduction

The load carrying capacity is one of the widely used structural integrity index for bridge rating and maintenance. Many studies have been performed to improve the

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evaluation procedures of load carrying capacities of bridges (Faulkner et al. 1996, Wolek et al. 1996, Catbas et al. 2003). Conventionally, static and quasi-static load tests with weight-controlled heavy trucks have been widely used to evaluate the load carrying capacity of a bridge. However, the traffic should be controlled fully or partially for the conventional load tests, which may result in the inconvenience to the public and increases logistics cost and time. Moreover, the sensor instrumentation may be very difficult or impossible when the tested bridge is placed across a river, a sea, or traffic lanes. To overcome these shortcomings, an alternative method is proposed for evaluation of the load carrying capacity under the ordinary traffic conditions with a simpler measurement system using ambient vibration tests in this study. The procedure is composed of measurement of ambient accelerations, extraction of the modal properties, correction of the initial FE model, and estimation of the deflection correction factor by load test simulation on the initial and updated FE models. Field tests were carried out on a pre-stressed concrete I- girder bridge and steel box girder bridge.

2. Load Carrying Capacity of a Bridge

2.1 Load Carrying Capacity

The load carrying capacity of a bridge (P) is commonly evaluated by combining design live load (P_r), rating factor (RF), deflection (or stress) correction factor (K_δ (or K_ε)), impact correction factor (K_i), and correction factors for traffic volume and pavement roughness (K_t, K_r) as

$$P = P_r \times RF \times K_\delta (or\ K_\varepsilon) \times K_i \times K_t \times K_r \qquad (1)$$

Where P_r is a given design value; RF is determined by structural analysis using the initial FE model of a bridge; and K_t and K_r are empirically estimated by structural engineers. On the other hand, two correction factors, K_δ (or K_ε) and K_i, are generally evaluated by load tests on a bridge. Static load tests and vehicle running tests have been traditionally carried out to obtain K_δ (or K_ε) and K_i.

In Korea, bridges are classified into three classes considering their location, surroundings, and importance. The design live load (DB-24) of bridges in the first class is specified as 432kN by the Korean bridge design specification, which is approximately 20% larger than the design live load (HS-20) in the ASSHTO design specification (AASHTO 1997). And RF, which is the ratio of live load resistance to design live load including the dynamic effect expressed as impact factor i, can be evaluated by either allowable stress design (ASD) or ultimate strength design (USD) concept as

$$RF^{ASD} = \frac{\sigma_a - \sigma_d}{\sigma_l (1 + i_{code})}, \qquad RF^{USD} = \frac{\phi M_n - \gamma_d M_d}{\gamma_l M_l (1 + i_{code})} \qquad (2)$$

Where σ_a is an allowable stress; σ_d and σ_l are stresses under design dead and live loads; φ is a strength reduction factor; M_n is a nominal moment strength; M_d and M_l are moments under design dead and live loads; γ_l and γ_d are live load and dead load factors; i_{code} is an impact factor determined by Korean design specification as

$$i_{code} = \frac{15}{40+L} \le 0.3 \qquad (3)$$

Where L is an effective length of a bridge in meter. The ASD concept may be used for steel members, while the USD concept may be used for concrete members.

The basic load carrying capacity can be obtained by combining the design live load and the rating factor. However, this value cannot represent the current state of a deteriorated bridge; therefore correction factors become necessary to reflect this issue.

2.2. Correction Factors by Conventional load Tests

Two correction factors, the deflection (or strain) correction factor (K_δ (or K_ε)) and the impact correction factor (K_i), are introduced to describe the current state of a bridge. The deflection (or strain) correction factor can be evaluated by the conventional load test as

$$K_\delta = \frac{\delta_{calculated}^{initial\ FEM}}{\delta_{measured}} \quad \text{(or} \quad K_\varepsilon = \frac{\varepsilon_{calculated}^{initial\ FEM}}{\varepsilon_{measured}} \text{)} \qquad (4)$$

Where $\delta_{calculated}^{initial\ FEM}$ (or $\varepsilon_{calculated}^{inital\ FEM}$) is a static deflection (or strain) calculated using the initial FE model of a bridge, and $\delta_{measured}$ (or $\varepsilon_{measured}$) is a measured static deflection (or strain) from static or quasi-static load tests using loaded trucks. The correction factors for impact, traffic volume and pavement roughness (K_i, K_t , K_r) are taken as 1.0 in this study.

2.3 Proposed Method

An ambient vibration test (AVT) approach is proposed for evaluating the load carrying capacity of a bridge without correction factors. Fig. 1 shows procedures of the proposed method via ambient vibration tests. This AVT approach can be carried out under ordinary-passing traffic conditions, and requires simpler equipment for measuring acceleration. The stochastic subspace identification method (Peeters and De Roeck 1999, Yi and Yun 2004) is utilized to extract the modal parameters, such as natural frequencies and mode shapes, from the measured ambient acceleration data. Based on the extracted modal parameters, updating of the initial FE model is performed using the genetic algorithm.

Since the proposed method uses dynamic response of a bridge for the model correction, it can be interpreted as a dynamic model correction, while the conventional method is as a static model correction.

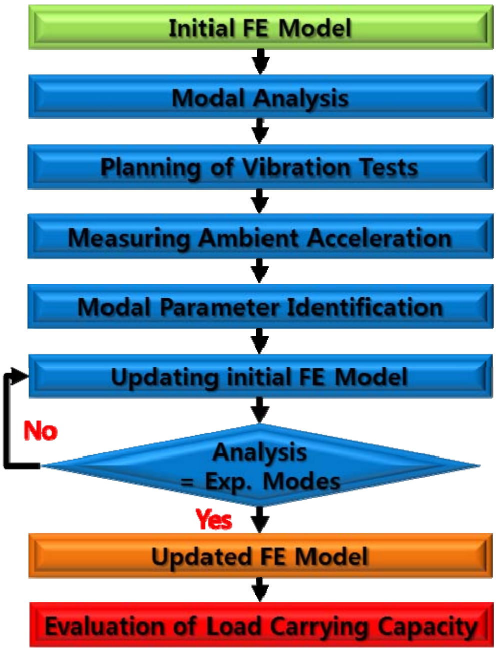


Figure 1. Flow chart of the proposed method

3. Field Test

3.1 On a PCI Girder Bridge

For validation of the proposed method, a series of tests were carried out on a pre-stressed concrete I-girder bridge. (Fig.2) For ambient vibration tests, 21 accelerometers were installed on the bridge. (Fig.3)

Figure 2. PCI Girder Bridge

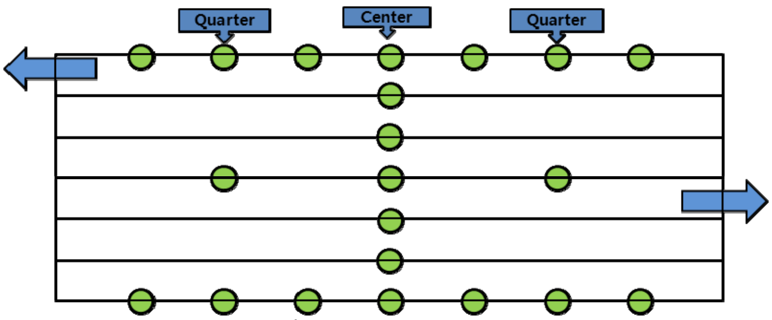


Figure 3. Sensor Array

The dynamic characteristic of PCI Girder Bridge is extracted using the acceleration measured on the field test. Fig. 4 and Fig. 5 show the measured acceleration signal and extracted dynamic characteristic, respectively.

The extracted dynamic characteristic is used as a reference for initial FE model updating. The variables updated are decided through sensitivity analysis. The selected updating variables are shown in Table1. Genetic Algorithm is utilized for model updating.

Table 2 shows the comparison between the updated FE model and ambient vibration test modal analysis results.

An updated model has the same dead load and allowable stress with the initial FE model. However, live load is changed as reflected by the deterioration. Thus, load carrying capacity of an updated model is evaluated using changed live load calculation.

Load carrying capacity is evaluated using the updated FE model and compared with the conventional method (Table 3).

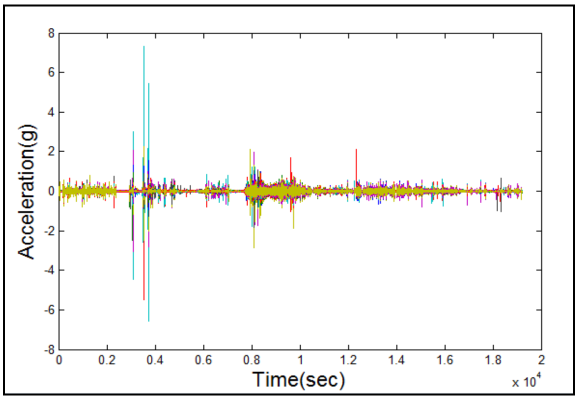


Figure 4. Ambient vibration data

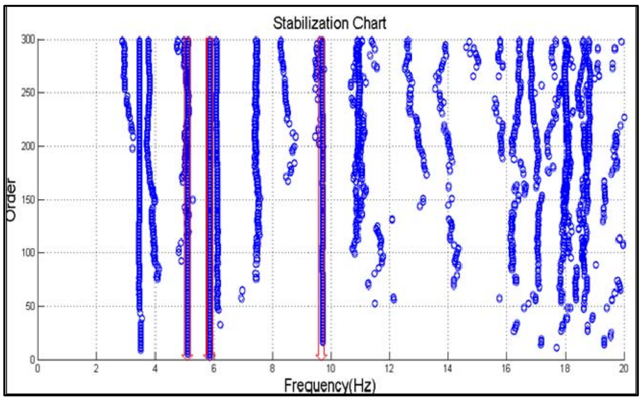


Figure 5. Stabilization chart (SSI)

Table 1. Variables for model updating

Variable	Location	Quantity	Variation	Initial Value	Range
Spring	Each support	2	Tangent	0	-x ~ x
Stiffness of Girder	Inner / External	2	Linear	1	0.5 ~ 1.5
Stiffness of Cross Beam	All member	1	Linear	1	0 ~ 1.5
Sum		5			

Table 2. Comparison of natural frequency and mode shape

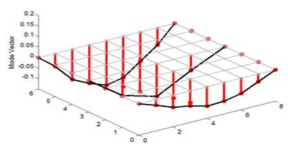
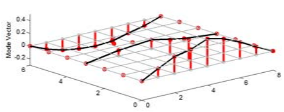
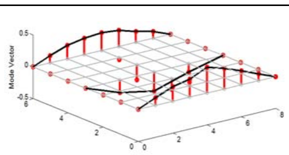
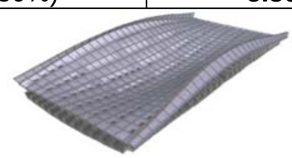
Ambient Vibration Test	Initial FE Model (error)	Updated FE Model (error)
		
5.1135 Hz	3.9534 Hz (-22.69%)	**5.1142 Hz (0.01%)**
		
5.8634 Hz	5.0251 Hz (-14.30%)	**5.8648 Hz (0.02%)**
		
9.7305 Hz	12.002 Hz (23.34%)	**9.7312 Hz (0.01%)**

Table 3. Result of Evaluation (unit : MPa)

Evaluation Method	Allowable Stress	Dead Load	Prestress	Live Load	R.F.	Response Ratio	P
Conventional Method	2.96	11.85	-14.16	2.71	1.95	2.45	4.77
Proposed Method	2.96	11.85	-14.16	2.31	2.29	-	2.29

3.2 On a Steel Box Girder Bridge

For validation of the proposed method, a series of tests were carried out on a steel box girder bridge. (Fig.6) For ambient vibration tests, 21 accelerometers were installed on the bridge. (Fig.7)

Figure 6. PCI Girder Bridge

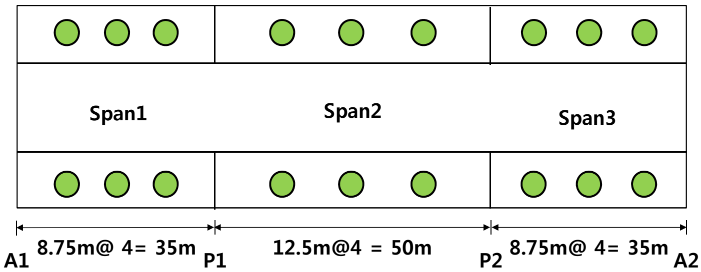


Figure 7. Sensor Array

The evaluation of Steel Box Girder Bridge was performed with the same procedure used in PCI Bridge. Fig. 4 shows the measured acceleration signal and Fig. 5 shows the extracted dynamic characteristic of Steel Box Girder Bridge.

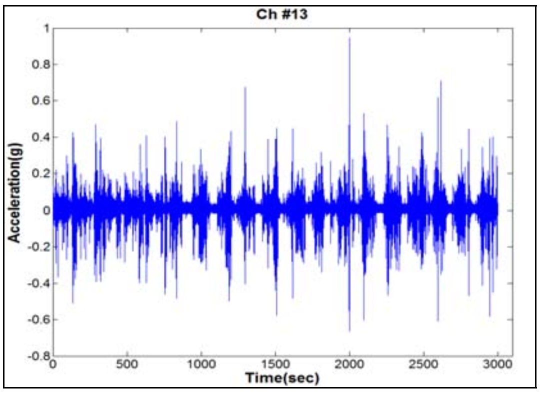


Figure 2. Ambient vibration data

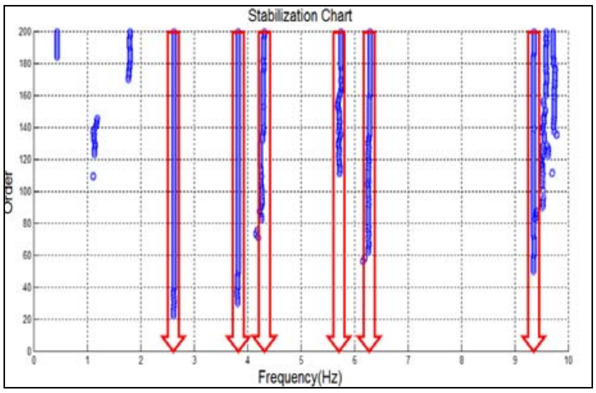


Figure 3. Stabilization chart (SSI)

Similarly, the extracted dynamic characteristic is used as a reference for initial FE model updating. The variables updated are decided through sensitivity analysis. The selected updating variables are shown in table 4. Genetic Algorithm is utilized for model updating. Table 5 shows the comparison between the updated FE model and ambient vibration test modal analysis results.

An updated model has the same dead load and allowable stress with the initial FE model. However, live load is changed as reflected by the deterioration. Thus, load carrying capacity of an updated model is evaluated using changed live load calculation.

Load carrying capacity comparison is shown in Table 6.

Table 4. Variables for model updating

Variable	Location	Quantity	Variation	Initial Value	Range
Spring	Each support	1	Tangent	0	-x ~ x
Stiffness of Girder	All member	1	Linear	1	0.7 ~ 1.3
Stiffness of Cross Beam	All member	1	Linear	1	0 ~ 1.3
Sum		3			

Table 5. Comparison of natural frequency and mode shape

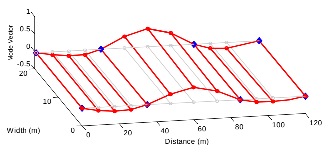
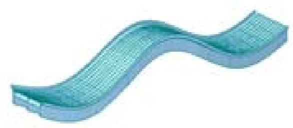
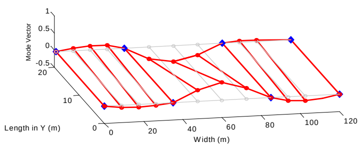
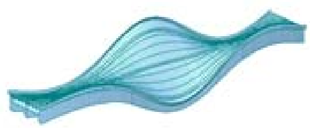
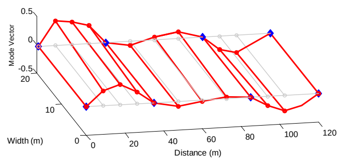
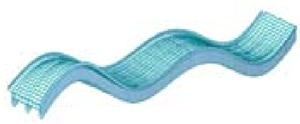
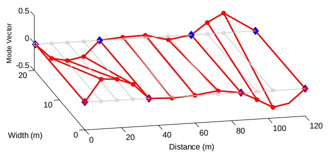
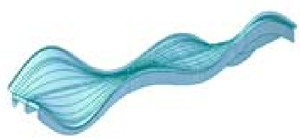
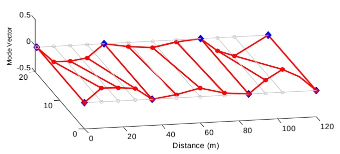
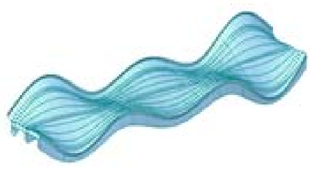
Ambient Vibration Test	Initial FE Model (error)	Updated FE Model (error)
		
2.63 Hz	2.64 Hz (0.38%)	**2.60 Hz (-1.14%)**
		
3.83 Hz	4.18 Hz (9.14%)	**3.88 Hz (1.31%)**
		
4.29 Hz	4.58 Hz (6.76%)	**4.42 Hz (3.03%)**
		
5.75 Hz	6.12 Hz (6.43%)	**5.58 Hz (-2.96%)**
		
6.29 Hz	6.69 Hz (6.36%)	**6.20 Hz (-1.43%)**

Table 6. Result of Evaluation

Evaluation Method	Allowable Stress	Dead Load	Live Load	R.F.	Response Ratio	P
Conventional Method	190	104.20	48.51	1.77	1.19	2.10
Proposed Method	190	104.20	45.52	1.88	-	1.88

4. CONCLUSION

In this study, feasibility was verified Evaluation of Load Carrying Capacity of a PCI Girder Bridge and Steel Box Girder Bridge using Model Updating Techniques. The method for evaluation of the load carrying capacity of a bridge is proposed using ambient vibration tests, which does not require traffic control during the tests and needs simpler installation of sensors than that of the conventional method. First, modal properties, such as natural frequencies and mode shapes, were extracted using SSI from the ambient acceleration data, and the Load Carrying Capacity were evaluated using the updated FE model based on the modal properties. Using the proposed method, the evaluation of load carrying capacities of bridges have been carried out on test bridges. From the test results, it have been found that the suggested method can effectively calculated the load carrying capacities of bridges.

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REFERENCES

Faulkner, B.C., Barton, F., Baber, T.T., & McKeel, W.T. (1996), Determination of bridge using acceleration data. Virgina Transportation Research Council. VA, USA.

Peeters, B. & De Roeck, G. (1999), Reference-based stochastic subspace identification for output-only modal analysis. Mechanical Systems and Signal Processing. 13(6): 855-878.

Yi, J.H. & Yun, C.B. (2004), Comparative study on modal identification methods using output-only information. Structural Engineering Mechanics. 17(3-4): 445-466.

Nelder, J.A. and Mead, R. (1965), A simplex method for function minimization. The computer Journal. 7(4): 308-313

Juang, J.N, and Pappa, R.S.(1985), An Eigensystem Realization Algorithm for Modal Parameter Identification and Model Reduction, Journal of Guidance, Control and Dynamics, AIAA, Vol.8, No.5, pp.620-627.

Ibrahim, S.R. and Mikulcik, E.C.(1977) A Method for the Direct Identification of Vibration Parameters from the Free Response, Shock and Vibration Bulletin, No.47, Part 4, pp. 183-198.

Feng, M.Q. and Kim, J.M. (1998). Identification of a Dynamic System Using Ambient Vibration Measurements. Journal of Applied Mechanics, ASME, Vol. 65, No. 2, pp. 1010-1023.

Brinker, R., Zhang, L. and Andersen, P.(2000) Modal Identification from Ambient Response Using Frequency Domain Decomposition, Proceedings of 16th International Modal Analysis Conference, San Antonio, Texas, USA, pp. 625-630.

Ren, W.X., Zatar, W., Harik, I.E. (2004), Ambient vibration-based seismic evaluation of a continuous girder bridge. Engineering Structures, Vol.26, No.5, pp.631-640.