Sensitivity Based Model Updating and Damage Detection of an Artificially Damaged Steel Truss Bridge

Kyoto University Regular Member ○Kai-Chun CHANG
Kyoto University Student Member Richard WANJALA
Kyoto University Regular Member Chul-Woo KIM

1. INTRODUCTION

Deterioration of aging bridges has been a significant issue especially in countries with large inventory nearing or past the design life. One popular method to detect the potential damage utilizes vibrations, based on the intuitive knowledge that damage can change a bridge's mechanical properties and therefore change the dynamic characteristics [1].

A field damage experiment conducted on a real steel truss bridge showed the viability of vibration-based damage detection techniques using modal parameters as damage sensitive features [2]. However, some damage cases were not clearly detected and localized. This study numerically investigates these issues and improves the accuracy of damage detection with a finite element (FE) model updated by a sensitivity-based updating approach.

2. FIELD EXPERIMENT

The target bridge was a simply-supported through-type steel Warren truss bridge, as sketched in Fig. 1. It was 59.2 m long, 8.2 m high, and 3.6 m wide. Five scenarios were considered in this study, as briefly summarized in Table 1. Eight uniaxial accelerometers were installed vertically on the deck of the bridge, five at the damage side (A1–A5) and three at the opposite side (A6–A8), as shown in Fig. 1. From the vehicle induced free vibrations, the bridge's modal frequencies and mode shapes were identified by Stochastic Subspace Identification (SSI) [3]. More details about the field experiment are available in the literature [2].

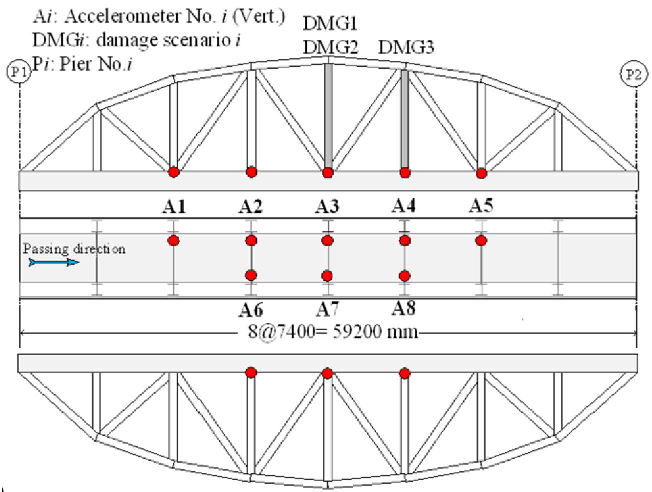

Fig. 1 Sketch of the target bridge and sensor layout.

Table 1 Damage scenarios

INT	Undamaged state
DMG0.5	Half-cut of the vertical mid-span member
DMG1	Full-cut of the vertical mid-span member
RCV	Welded repair of DMG1 by steel plates
DMG2	Full-cut of the vertical 5/8-span member

3. THEORETICAL BACKGROUND

3.1 Model updating

The FE model updating aims to work out a FE model that minimizes the discrepancy between its analytical modal responses and their counterparts experimentally identified from the measurement data.

An initial 2D FE model was developed using ABAQUS® FE analysis software. All the material properties, geometrical properties, joints and boundary conditions were set up according to the original design drawings. By eigenvalue analysis, the analytical modal responses, i.e. modal frequencies and corresponding mode shapes, of the FE model were calculated.

Defining the perturbation in the physical parameters to update as $\delta\boldsymbol{\theta}=\boldsymbol{\theta}-\boldsymbol{\theta}_i$ and the discrepancy in the measured and analytical modal response as $\delta\boldsymbol{z}=\boldsymbol{z}_m-\boldsymbol{z}_i$, where $\boldsymbol{\theta}$ represents the actual parameters that reproduce the measured modal response $\boldsymbol{z}_m$ and $\boldsymbol{\theta}_j$ the parameter estimate after i iterations that yield analytical modal response $\boldsymbol{z}_i$, sensitivity-based model updating is to minimize the following objective function [4]:

$$J(\delta\boldsymbol{\theta}) = \boldsymbol{\varepsilon}^{\mathrm{T}}\, \boldsymbol{W}_{\varepsilon\varepsilon}\, \boldsymbol{\varepsilon} + \{\, \boldsymbol{\theta} - \boldsymbol{\theta}_0 \,\}^T\, \boldsymbol{W}_{\theta\theta}\, \{\, \boldsymbol{\theta} - \boldsymbol{\theta}_0 \,\} \tag{1}$$

where $\boldsymbol{\varepsilon}=\delta\boldsymbol{z}-\boldsymbol{S}\delta\boldsymbol{\theta}$, $\boldsymbol{S}$ is the sensitivity matrix (given below), $\boldsymbol{\theta}_0$ initial parameter estimate, and $\boldsymbol{W}_{\varepsilon\varepsilon}$ and $\boldsymbol{W}_{\theta\theta}$ the response and parameter weighting matrices. Minimizing $\boldsymbol{J}$ with respect to $\delta\boldsymbol{\theta}$ gives an improved parameter estimate as

$$\delta\boldsymbol{\theta} = [\, \boldsymbol{S}^{\mathrm{T}}\, \boldsymbol{W}_{\varepsilon\varepsilon}\, \boldsymbol{S} + \boldsymbol{W}_{\theta\theta} \,]^{-1}\, [\, \boldsymbol{S}^{\mathrm{T}}\, \boldsymbol{W}_{\varepsilon\varepsilon}\, \delta\boldsymbol{z} - \boldsymbol{W}_{\theta\theta}\, (\, \boldsymbol{\theta}_i - \boldsymbol{\theta}_0 \,) \,] \tag{2}$$

3.2 Sensitivity analysis

Sensitivity matrix $\boldsymbol{S}$ was used not only to update the FE model but also to perform sensitivity analysis. It describes how modal response changes with a perturbation in parameter, i.e. how sensitive the modal response is to the parameter. Considering the eigenvalue λ_j of the j-th mode and differencing the eigenvalue equation of a multi-degree-of-freedom undamped dynamic system with respect to the k-th parameter θ_k, the entries of $\boldsymbol{S}$ can be derived as

$$S_{jk} = \partial\lambda_j \,/\, \partial\theta_k = \boldsymbol{\varphi}_j^{T}\, [\, \partial\boldsymbol{K} \,/\, \partial\theta_k - \lambda_j\, (\, \partial\boldsymbol{M} \,/\, \partial\theta_k \,)]\, \boldsymbol{\varphi}_j \tag{3}$$

where $\boldsymbol{M}$ and $\boldsymbol{K}$ are FE mass and stiffness matrices and $\boldsymbol{\varphi}_j$ the eigenvector of the j-th mode.

Keywords: finite element model updating, modal parameters, sensitivity analysis, vibration-based damage detection
Contact address: C1-183, Kyoto Daigaku Katsura, Nishikyo-ku, Kyoto 615-8540, JAPAN; +81-75-383-3421

3.3 Damage detection and localization

The algorithm of damage detection and localization is as follows. First the initial FE model was updated using measured modal characteristics obtained from undamaged state (INT or RCV), and the updated FE model served as the reference. Then the reference model is updated with modal data from damaged state, either DMG0.5, DMG1, or DMG2 to obtain a new model representative of the damaged bridge. Damage detection and localization is conducted by comparing the modal characteristics from the reference model and the updated model.

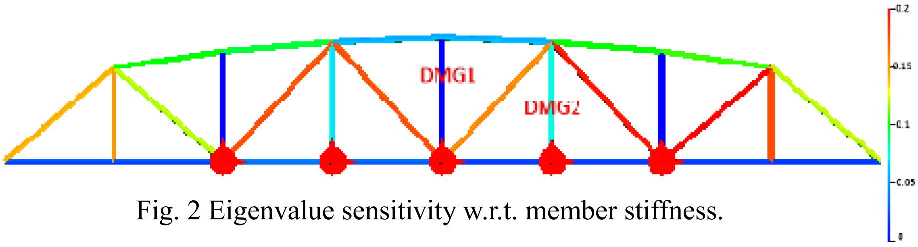

Fig. 2 Eigenvalue sensitivity w.r.t. member stiffness.

4. RESULTS AND DISCUSSIONS

Herein, the stiffness (Young's modulus) of all the 29 members were taken as parameters to update and the modal frequencies and mode shapes of the first three reliable modes were taken as responses whose discrepancies between analytical and experimental counterparts are to minimize. The sensitivity analysis involving eigen-frequency summation of the first 3 modes w.r.t. the member stiffness (Fig. 2) showed that generally diagonal members are more sensitive than internal ones. For the vertical members artificially damaged in the field experiment, the DMG1 member (at the mid-span) were less sensitive to changes in member stiffness than the DMG2 member (at the 5/8 span) were. The above observations justified the findings in previous studies [2], which concluded that DMG1 was less easily to be identified than DMG2.

Modal frequencies were updated to a higher degree of accuracy, as can be observed in Table 2, where the first five modal frequencies of the initial model and the updated undamaged model are summarized. The modal assurance criteria (MAC) between the modal shapes of the updated FE model and their counterparts from the field experiments are also listed. It is observed that MAC correlations were not generally updated to a high degree due to the lower weighting in mode shapes.

As indicated in Sec. 3.3, the reference model (INT or RCV) was updated again for each damage state (DMG0.5, 1, and 2). Comparing the reference model and the updated damage model, one could detect and locate the damage. The comparison was quantified by the coordinate modal assurance criteria (COMAC) between the two models, as shown in Fig. 3. It can be said that the damage detection and localization was successful for locating the damage at the minimum COMAC value. It should be noted that the previously conducted study [2] failed to locate damage using COMAC of the first five experimentally identified modes. The successful localization in this study implies the contribution of either reliable-mode selection, model updating, or both.

5. CONCLUDING REMARKS

In this study a sensitivity-based model updating was performed on a 2D FE model of a real steel truss bridge, on which artificial damage were applied for damage detection investigations. Member stiffness of all members were taken as parameter to update and the first three modal frequencies and mode shapes as responses, whose deviation from their experimental counterparts were to minimize. The updated FE model presented a good agreement in modal frequencies and slightly poorer agreement in mode shapes, simply caused by the higher weighting in modal frequencies. More importantly, it could successfully locate the damage by presenting a minimum COMAC value. Besides, sensitivity analysis too gave prior insight into damage detectability.

Table 2 Modal parameters of the updated INT model

Mode	f_{EXP}(Hz)	$f_{FE,U}$(Hz)	MAC_U(%)
1	2.98	2.98	97.8
2	6.87	6.87	85.9
3	9.7	9.65	70.8
4	10.49	10.86	90.9
5	13.49	14.51	76.6

Note. f_{EXP}: frequency from experiment; $f_{FE,U}$, MAC_U: frequency and MAC from updated FE model.

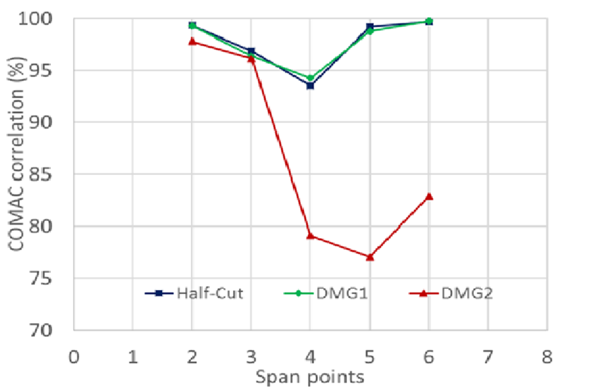

Fig. 3 Damage localization using COMAC correlation from various cases.

REFERENCES

[1] C.R. Farrar, S.W. Doebling, and D.A. Nix. Vibration-based structural damage identification. *Philosophical Transactions of the Royal Society A* 359, pp. 131-49, 2001.

[2] K.C. Chang and C.W. Kim, Modal-parameter identification and vibration-based damage detection of a damaged steel truss bridge, *Engineering Structures* 122(1), pp. 156-173, 2016.

[3] P.V. Overschee and B.D. Moor, *Subspace identification for linear systems*, Dordrecht: Kluwer Academic Publishers, 1996.

[4] M.I. Friswell and J.E. Mottershead, *Finite element model updating in structural dynamics*, Dordrecht: Kluwer Academic Publishers, 1995.