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Finite element model updating considering boundary conditions using neural networks

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ABSTRACT

A novel technique to evaluate the bridge boundary condition using neural networks is proposed. It can be used to establish a more accurate finite element (FE) model considering the behaviors of boundary conditions. In the proposed method, the aging and constraining effect of the boundary condition is represented by an artificial rotational spring at each support. A relationship between the responses of the bridge and the rotational spring constant is analytically investigated. This relationship can be used to estimate the rotational spring constant of the bridge using neural networks. The proposed method was verified through laboratory tests and field tests on a steel girder bridge. The proposed method can estimate the bridge boundary conditions directly from the actual behaviors of bridge supports, and this can effectively reduce the uncertainty of boundary conditions in FE model updating.

1. Introduction

As bridges become deteriorated, bridge health monitoring is becoming increasingly important. In order to quantitatively analyze the state of bridges, it is necessary to construct a precise bridge analysis model. To this end, finite element (hereafter FE) model updating techniques have been widely used. A variety of studies has been conducted to update a bridge model using various physical quantities such as acceleration [1–4], static displacement and strain response [5–7], and combination of static and dynamic responses [8–10]. Various optimization algorithms such as particle swarm algorithm [11], genetic algorithm [12], hybrid genetic algorithm [9], and neural networks [13], have been also studied.

Uncertainty of the boundary conditions is one of the key issues in FE model updating method. In FE model updating, sensitivity of boundary conditions is an important variable to represent bridge responses. There are several studies however that considers the effect of the boundary conditions in the model updating method. Aktan et al. (1998) considered the boundary conditions for numerical models of an operating highway bridge by implementing rotational and vertical springs at the supports. A manual calibration strategy was suggested by global and local calibration in sequence. The boundary condition is a critical variable in global calibration [14]. Dilena et al. (2011) considered boundary condition improvement to obtain the damage evaluation of reinforced concrete bridge in FE model. In order to represent sliding and fixed constraints, supports were modeled by adding a linear elastic spring acting along the longitudinal direction, and then a sensitivity analysis was performed to identify the relationship between natural frequencies and spring stiffness [15]. Brownjohn et al. (2003) evaluated a bridge refurbishing and strengthening by dynamic testing and model updating. To reflect the structural change of the bridge, the abutment was modeled as rotational springs [16]. The FE model of the Kap Shui Mun Cable-stayed Bridge was also updated based on measured frequencies. The parameters of decks, towers and the connection/boundary conditions between the deck and piers were selected as updating variables in the model updating. Changes of up to 200% from the initial values were recorded for the connection/boundary condition parameters, since there were no upper and lower bounds for them. This is because there is no rational guideline to select the initial values of connection/boundary springs [17]. Catbas et al. (2007) manually calibrated boundary conditions of the Commodore Barry Bridge before the iterative FE model updating process. Due to the best agreement of two lower natural frequencies, all bearings in their example were assumed fixed. The appropriateness of this assumption, however, was not fully investigated [18]. Hence, there is no guideline for selecting a proper element and updating the selected element to reflect the current state of a target bridge in FE model updating. In

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addition, there is no alternative technique to directly measure the current behavior of bridge support nevertheless the dynamic testing is an indirect method to identify the support behavior.

Translation and rotational springs are typically incorporated to model a bridge support. However, rotational spring has greater impact on the bridge responses, rather than the translational spring, since the main load carrying mechanism for a bridge structure is bending behavior. As an example, the increment in the first natural frequency is not significant for the hinge-hinge case which represent the infinite translation spring at one end. However, the rotational spring can represent up-to fixed boundary condition [19].

Moreover, there is no physically-measurable data which is directly related to translational springs, since the longitudinal and vertical displacements at the actual bridge support are very small. The existing model updating researches were performed using indirect physical quantities to the boundary condition, e.g. dynamic characteristics [1–3]. However, rotational angle is a directly related physical quantity to rotational spring. Park et al. (2016) has developed a system that greatly improves the accuracy of the rotational angle of bridges based on a laser and vision based system [20]. Thus, it is possible to use direct physical quantities of bridge supports in FE model updating.

In this study, an advanced FE model updating method to establish a more accurate FE model considering boundary conditions using neural networks is proposed. The proposed method represents the bridge boundary condition with an artificial rotational spring, and a formula was derived to investigate the relationship between the spring constant and bridge responses. By using this relationship, the spring constant of the bridge can be determined using neural networks. The verification of the proposed method was carried out through numerical analysis, a series of laboratory and field tests.

2. FE model updating considering boundary conditions using neural networks

2.1. Relationship between rotational spring and bridge responses

Aging of a bridge structure causes deterioration in its supports, constraining bridge movement. This constraint in bridge movement conveys a state where the bridge support is neither simple nor fixed, but in between (Fig. 1(a)). The restraining effect of the boundary condition is generated by the aging of the expansion joint, the lateral flow, the failure of the support, and so on. Thus, the moment is generated at the bridge ends by the restraint effect. By applying an artificial rotational spring at each support in a FE model, the constraining effect can be simulated. The relationship between the spring constants of the artificial springs and the bridge's responses is derived in this section. It is noted that an artificial spring introduces an end moment load in each support. Assuming that an arbitrary point load w is applied on a simple beam with unknown deteriorated support conditions as shown in Fig. 1(b), the loading conditions can be simplified and decomposed into three loads acting separately as in Fig. 1(c).

Deflection and rotational angles of a simple beam can be computed by the principle of superposition. The rotational angles at both ends and deflection at arbitrary location can be measured and these can be decomposed as Eqs. (1)–(3). The superscript and subscript denote the decomposed subsystem and location, respectively.

$$\theta_A = \theta_A^1 - \theta_A^2 - \theta_A^3 \tag{1}$$

$$\theta_B = \theta_B^1 - \theta_B^2 - \theta_B^3 \tag{2}$$

$$\delta_x = \delta_x^1 - \delta_x^2 - \delta_x^3 \tag{3}$$

Eq. (3) can be rearranged as Eq. (4) using $\alpha(=\delta_x^1/\theta_A^1)$ and $\beta(=\delta_x^1/\theta_B^1)$. It is notable that α and β are not dependent on the magnitude of external loads but only on the loading location. Thus, these values can be regarded as constant values for a specific loading condition.

$$\delta_x = \alpha\theta_A^1 - \delta_x^2 - \delta_x^3 \tag{4-a}$$

$$\delta_x = \beta\theta_B^1 - \delta_x^2 - \delta_x^3 \tag{4-b}$$

Eqs. (4) can be rearranged as Eq. (5) by inserting Eqs. (1) and (2) to Eq. (4) and using analytical solutions for subsystems (2) and (3).

$$\delta_x = \alpha\theta_A + \frac{K_A\theta_A}{6LEI}A + \frac{K_B\theta_B}{6LEI}B \tag{5-a}$$

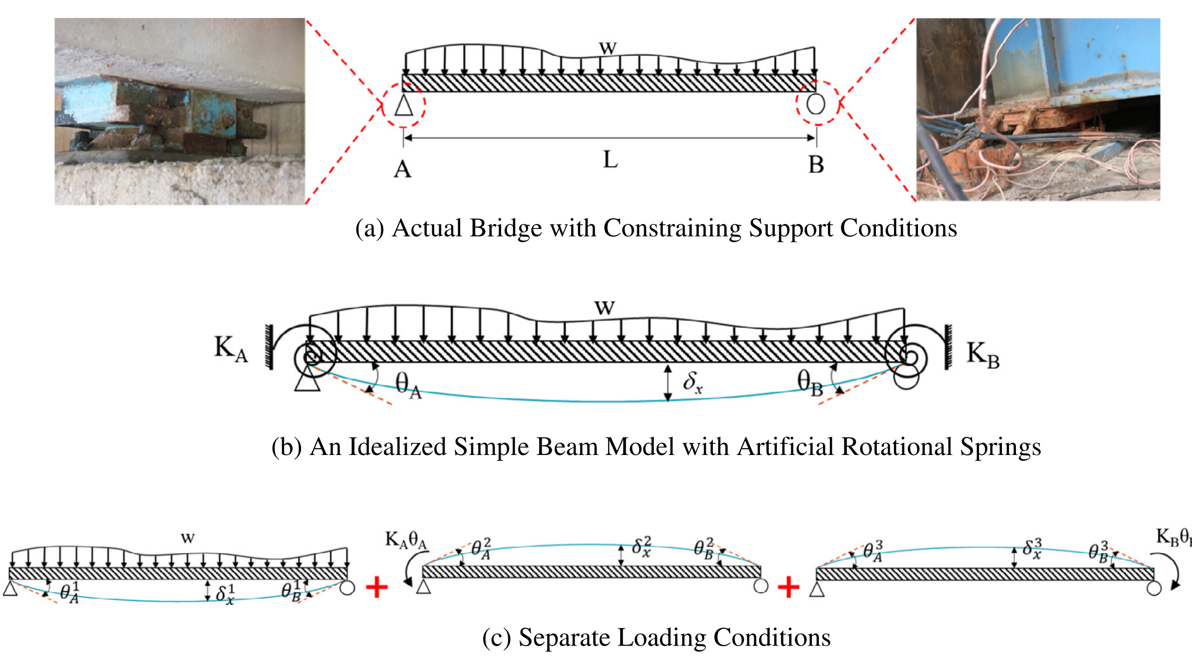

Fig. 1. Simple beam model with unknown support conditions.