Strain-based Evaluation of Bridge Monitoring using Numerical Model Analysis

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Abstract. According to visual inspection on the bridge site, the target bridge has major cracks in RC deck in the center span. This certain type of damage could affect structural performance and should be monitored. The structural health monitoring system was set up on the target bridge and the strain-based evaluation could be used to quantitatively determine bridge condition. The FE model of the bridge was modeled with various types of RC cracking pattern to represent the severity of bridge damage. The relationship between damage level and strain measurement is generated, As a result, Bridge monitoring curve based on strain index has been established.

Keywords: Structural Health Monitoring, RC deck bridge, Finite element model

1. Introduction

In the past three decades, there number of constructed bridges to serve the expansion of civilization. In present, these bridges have aged and deteriorated along with time [1]. The structural performance of these bridges has become lower and could affect the safety of people. The bridge maintenance is required. However, budget and manpower are limited. In order to conduct efficient management, the severity of bridge damage should be evaluated and bridge prioritizing should be performed.

In general, visual inspection is used to determine the severity of damage in bridges. However, the process required an experienced engineer to perform the inspection at the bridge site. Since there are a limited number of engineers, the inspection is usually performed every 2–5 years per bridge [1, 2]. According to the time gap between inspections, the damage could be progressive too far before detection which led to high repairing cost. Hence, early damage detection can improve the efficiency of budget allocation. In addition, there are certain types of damage that couldn’t detect by visual inspection alone (e.g., cracking depth in RC deck, corrosion inside the steel girder). Therefore, an alternative evaluation method can be useful.

Structure health monitoring system is developed [3, 4]. The bridge condition could be remotely assessing via sensor (e.g., strain gauge, accelerometer, displacement transducer). Thus, the unusual behavior indicating bridge damage could be real-time detected. So far, the system is used as an event detector. For example, when the large displacement or strain occurred, the system will alert engineer to perform the inspection at the bridge to ensure the structure safety. Recently, there are studies on
bridge evaluation based on acceleration data [5, 6]. Bridge conditions can be remotely evaluated by
post-processing of acceleration data. The method could save engineer trips to the bridge site for
inspection. Besides acceleration, it is well known that strain and deflection can reflect structural
behavior and might improve the resolution of bridge evaluation from previous studies. Therefore,
there is a possibility that strain gauge and displacement transducer can be used to evaluate the bridge
condition.

In this study, the steel box girder bridge with reinforced concrete deck (RC deck) is chosen as the
target bridge. Visual inspection is performed to identify damage types. Crack patterns in RC deck are
observed and categorized. Then, FE model of the target bridge is modeled with various cracking
patterns to represent the severity of bridge damage. Deflection and strain distribution at the lower
surface of RC deck can be determined. Quantitative evaluation of bridge condition can be performed
by matching the severity of bridge damage and measurement index. As a result, bridge monitoring
curve based on strain index is established.

2. Target Bridge

The steel box girder bridge with the RC deck designed as a non-composited girder has been chosen as
the target bridge as shown in figure 1. The bridge has three continuous spans which side span length is
71.3 meters and the middle span is 88 meters. Visual inspection is performed on the bridge. It is found
that the bridge has major cracks in the center span of the RC floorboard. The influence of the crack
and its progression should be monitored. Thus, sensor measurements (strain gauge and displacement
transducer) are attached at the lower surface of the center span (Figure 2). However, sensor
measurement value also depends on locations of the sensor (e.g., large strain near crack tip, deflection
at the middle of span). Thus, sensitivity analysis to determine an appropriate location for each sensor
should be conducted.

3. Numerical Model

3.1. Bridge details

Based on the drawing of components (i.e., main girders, transverse girders, RC deck, and rubber
bearing), the finite element model (FE Model) of the target bridge has been created by using
ABAQUS 6.14 [7] as shown in figure 3. The RC deck and rubber bearing were modeled by using solid
element while steel girder was modeled by using shell element. The material properties of concrete
and steel were assigned based on the value indicated in the specification and the rubber bearing
stiffness was calculated by using the estimate equation. Moreover, abutment and pier bearing have
difference dimensions. Therefore, the rubber bearing stiffness calculated individually at each location.
The material properties used in the model are shown in table 1.
Figure 2. Cross sectional of Target Bridge

Table 1. Material properties

| Index | Material                     | Young Modulus |
|-------|------------------------------|---------------|
| 1     | Concrete                     | 28 GPa        |
| 2     | Steel                        | 205 GPa       |
| 3     | Abutment bearing rubber      | 54.14 MPa     |
| 4     | Pier bearing rubber          | 60.14 MPa     |

3.2. Crack modelling

Based on the visual inspection, crack patterns found in the bridge are transverse crack (T-crack), longitudinal crack (L-crack), and combined crack (TL-crack). In order to observe the influence of damage, crack patterns were modeled with a series of transverse crack and combined crack direction. Moreover, various crack intervals are considered for representing the severity of bridge damage. For example, short crack interval represents that there are a number of cracks which means the bridge condition is severely damaged.

In order to introduce the RC deck cracking into the FE model, the stiffness reduction by using orthotropic elasticity properties [7] was assigned on elements along the crack to represent the damage. The orthotropic property in terms of stress ($\sigma$), nominal strain ($\varepsilon$), shear strain ($\gamma$), young modulus (E), shear modulus (G), and Poisson’s ratio ($\nu$) can be expressed as shown in equation (1) and equation (2).

Three types of an element were defined as T-element, L-element, and TL-element. The crack patterns are shown in figure 4. The orthotropic properties of each type of element are shown in table 2.

$$\begin{align*}
\varepsilon_{11} &= \frac{1}{E_1} \begin{bmatrix} 
-1 & -v_{12} & -v_{13} \\
-v_{12} & 1/E_2 & -v_{23} \\
-v_{13} & -v_{23} & 1/E_3 
\end{bmatrix} \begin{bmatrix} 
\sigma_{11} \\
\sigma_{22} \\
\sigma_{33} 
\end{bmatrix} \\
\varepsilon_{22} &= \frac{1}{E_2} \begin{bmatrix} 
-1 & -v_{12} & -v_{13} \\
-v_{12} & 1/E_2 & -v_{23} \\
-v_{13} & -v_{23} & 1/E_3 
\end{bmatrix} \begin{bmatrix} 
\sigma_{11} \\
\sigma_{22} \\
\sigma_{33} 
\end{bmatrix} \\
\varepsilon_{33} &= \frac{1}{E_3} \begin{bmatrix} 
-1 & -v_{12} & -v_{13} \\
-v_{12} & 1/E_2 & -v_{23} \\
-v_{13} & -v_{23} & 1/E_3 
\end{bmatrix} \begin{bmatrix} 
\sigma_{11} \\
\sigma_{22} \\
\sigma_{33} 
\end{bmatrix} \\
\gamma_{12} &= \begin{bmatrix} 
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 
\end{bmatrix} \begin{bmatrix} 
\sigma_{12} \\
\sigma_{23} \\
\sigma_{32} 
\end{bmatrix} \\
\gamma_{13} &= \begin{bmatrix} 
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 
\end{bmatrix} \begin{bmatrix} 
\sigma_{12} \\
\sigma_{23} \\
\sigma_{32} 
\end{bmatrix} \\
\gamma_{23} &= \begin{bmatrix} 
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 
\end{bmatrix} \begin{bmatrix} 
\sigma_{12} \\
\sigma_{23} \\
\sigma_{32} 
\end{bmatrix} 
\end{align*}$$

$$\begin{align*}
G_y &= \frac{\sqrt{E_1 E_3}}{2(1+\nu)} 
\end{align*}$$

Figure 3. FE model of Target Bridge
3.3. Loading conditions

The FE model is subjected to load at the center span of the bridge. The axle load was represented by two nodal load with 50 kilonewtons (kN) at the wheel location. In addition, two loading cases which are load on center and load on lane is used as shown in figure 5.

For each analytical configuration, analysis cases were named according to crack patterns, crack intervals, and loading locations. The analytical configuration can be list as shown in table 3.

![Crack patterns](image1)
![Loading conditions](image2)

**Figure 4.** Crack patterns  
**Figure 5.** Loading conditions

| Index | Name      | Crack patterns | Crack interval (m) | Loading location |
|-------|-----------|----------------|--------------------|------------------|
| 1     | No-crack-C| No crack       | -                  | Center           |
| 2     | No-crack-OL| No crack     | -                  | On lane          |
| 3     | 1.0T-C    | Transverse crack | 1                | Center           |
| 4     | 1.0T-OL   | Transverse crack | 1                | On lane          |
| 5     | 0.5T-C    | Transverse crack | 0.5              | Center           |
| 6     | 0.5T-OL   | Transverse crack | 0.5              | On lane          |
| 7     | 0.25T-C   | Transverse crack | 0.25             | Center           |
| 8     | 0.25T-OL  | Transverse crack | 0.25             | On lane          |
| 9     | 1.0TL-C   | Combined direction | 1              | Center           |
| 10    | 1.0TL-OL  | Combined direction | 1              | On lane          |
| 11    | 0.5TL-C   | Combined direction | 0.5             | Center           |
| 12    | 0.5TL-OL  | Combined direction | 0.5             | On lane          |
| 13    | 0.25TL-C  | Combined direction | 0.25             | Center           |

**Table 2.** Orthotropic properties for cracks  
**Table 3.** Analytical configurations

![Table images](image3)
4. Bridge monitoring curve

The analysis results were obtained from the lower surface of the deck (X-axis) as indicated in figure 3.

4.1. Deflection

Deflection is calculated from vertical displacement along the lower deck and shown in figure 5. The influence of cracking in the RC deck on deflection can be observed. The bridge with more severe damage will have larger deflection. The deterioration level of the bridge can be distinguished. Especially, in the case of load at center, the difference of each damage level can be clearly observed. To represent the severity of damage using deflection consider as a straightforward index for evaluating the bridge condition.

However, deflection measurement is not so convenience in practical monitoring because displacement transducer is required to set an initial position before start measurement. There is a possibility that the transducer slips out from the original position (e.g., strong wind, earthquake, animal). On the other hand, a strain gauge can be attached with a protector that can withstand the environment circumstance. Therefore, the bridge assessment based on strain index is considered to be more practical.

4.2. Transverse strain

Transverse strain along the lower deck surface is shown in figure 4. As in agreement with deflection index, it is found that transverse crack has an influence on strain along the lower deck surface. The severity of damage can be evaluated using strain measurement at lower deck surface. For example, 0.25T-C, 0.25TL-C which considered as severe damage can be observed. Hence, the bridge monitoring curve based on strain index has been established.

Figure 5a and Figure 5b, the loading condition has a significant influence on the order of measured strain. Loading at the center of the deck caused a larger strain level than loading on lane. However, the severity of damage also can be observed in a smaller range of strain (figure 5c). Therefore, there should be noted that the strain measurement range is required to have enough resolution to capture the damage.

![Figure 5. Deflection at lower deck](image-url)
5. Conclusions
In this study, visual inspection was performed on the steel box girder bridge with the reinforced concrete deck (RC deck). Major cracks were found in the center span of the RC deck. Then, FE model of the target bridge is modeled with crack based on the inspection. Various cracking patterns were introduced into FE model to represent the severity of bridge damage. The relationship between bridge damage level and measurement index (deflection and strain) is generated and can be used to evaluate bridge condition. As a result, bridge monitoring curve based on strain index has been established.

Acknowledgement
The research work shown in this paper was supported by Council for Science, Technology and Innovation, Cross-ministerial Strategic Innovation Promotion Program (SIP), Infrastructure Maintenance, Renovation, and Management” (funding agency: MLIT) and it has been conducted under the collaborative study with Omron Social Solutions, Co., Ltd.
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