Method for Investigating the Integrity of Widened Narrow RC Bridges and Evaluating Their Safety

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Citation

Abstract
In this study, we investigated bridges that have been widened so that they can better serve modern-day needs. We paid particular attention to narrow reinforced-concrete (RC) bridges that are at most 4m wide. Such bridges are common in rural areas, and the safety of these bridges is often evaluated under the assumption that the original and widened parts of these bridges are perfectly integrated; this, however, is often not the case because of, for example, the deterioration of the original parts of the bridge owing to age or the poor quality of the work done to widen the bridges. Therefore, we propose a method that can check the integrity of the original and widened parts of a bridge; this method obtains data about the vibration behavior of the bridge via acceleration sensors and impact testing. After describing this method, we show how a finite element analysis can be used to evaluate the influence of the integrity of the two parts of these bridges on their overall safety. To demonstrate the feasibility of our method, we evaluated an actual widened narrow RC bridge in Japan using the proposed method. We found that the two parts of this particular bridge were not perfectly integrated, and the finite element analysis showed that a stress 2.3 times higher than the expected stress can be applied to sections of the bridge. These results suggest that the bridge may be unsafe.

1. Introduction
In many countries around the world, the aging of bridges is becoming a problem. In Japan, for example, many of the bridges that were constructed during the period of strong economic growth in the 1960s and 1970s have been found to have since experienced significant deterioration and damage [1, 2]. This problem has been exacerbated by modern-day volumes of traffic in Japan; currently, compared with the aforementioned period of high economic growth, there are approximately 10 times as many automobiles being driven in the country. As such, many bridges in Japan are unable to adequately allow for the free movement of traffic. This is a particular problem for bridges in rural areas because these are often very narrow. To solve this problem, work has been done to widen such bridges and there exists lots of textbook and guideline to explain the method [3, 4].

This paper focuses on bridges that are less than 4m wide but have been subsequently widened; these types of bridges are commonly found in rural areas. When maintaining such widened narrow bridges, it is important that the stress states of the original and widened parts of the bridge are understood so that its load resistance capacity and safety can be effectively evaluated. When the safety of these widened narrow bridges is evaluated, the general assumption is that the original and widened parts of the bridges are perfectly integrated; however, these parts are often not perfectly integrated owing to both...
the deterioration of the original parts of the bridges and errors made during the work done to widen them. Because widened narrow bridges in rural areas often experience low volumes of traffic and are infrequently used, the safety and performance of these bridges are often overestimated, which is different from the situation that the important bridges are often analyzed structurally to evaluate safety [5, 6]. We believe that if the performance of these bridges is evaluated more appropriately, this will result in greater bridge safety in the world including Japan. For example, a system that determines which bridges need to be repaired sooner than others can be developed.

In this study, we first propose a method to check the integrity of the original and widened parts of bridges; this method uses impact testing and acceleration sensors to elucidate the vibration behavior of bridges. A finite element analysis (FEA) is then used on an actually widened narrow reinforced-concrete (RC) bridge in order to determine what influence the integrity of the connections between the original and widened parts of the bridge has on the bridge’s safety. FEA was conducted under various load patterns for scenarios in which the sections between the bridge were integrated or separated, and the safety of the bridge was examined using the calculated stress.

2. Case Study: Kitahama Bridge

A field test was conducted by this study in the summer of 2016. The bridge that was studied in this field test was located on Kitahama road in Shikoku, which is an island in Japan; hereafter, we will refer to this bridge as Kitahama Bridge. Kitahama Bridge is a RC slab bridge that is 3.4m long; the width at its widest part is 5.1m, and the width at its narrowest part is 2.56m. These details can be seen in Figure 1. Although the bridge was widened at some point, it is unclear as to how much time had elapsed between the bridge being constructed and it being widened. The bridge can be seen in the photograph shown in Figure 2.

![Figure 1. Schematic diagram of Kitahama Bridge, as viewed from above.](image)

We found that there was a big difference between the degree of deterioration of the RC slabs in the original and widened parts of the bridge. Figure 3 shows a photograph of the bridge taken from underneath it; in the figure, the borders between the original and widened parts of the bridge are demarcated by dashed black lines. It can be seen in this figure that the concrete in the original part of the bridge has begun to flake, and the steel rebar has become exposed; furthermore, the cross-sectional area of the rebar has visibly decreased. The widened part of the bridge, meanwhile, is relatively undamaged. A long crack can be seen along the vertical joint between the original and widened parts of the bridge in Figure 4. This suggests that there may be a problem with the connection between the original and widened parts of the bridge.

![Figure 2. Photograph of Kitahama Bridge.](image)

![Figure 3. Photograph of Kitahama Bridge taken underneath the bridge.](image)

![Figure 4. A long crack can be seen along the vertical joint between the original and widened parts of the bridge; a black dashed rectangle has been drawn around it.](image)
3. Method for Evaluating the Integrity of Widened Bridges

This chapter proposes a method for checking the integrity of widened bridges and describes the results obtained when the method was used for Kitahama Bridge.

3.1. Investigating the Integrity of Widened Bridges Through Impact Testing

This section explains the method used to evaluate the integrity of the connection between the original and widened parts of a bridge.

If these two parts are perfectly integrated, it is relatively easy to evaluate the stress state and safety of a bridge. However, if the connection between these two parts is imperfect due to, for example, the deterioration of the original part of a bridge or the poor quality of the connection made between these two parts, the connection between the two parts may break down and separate when a large load is applied. In bridges with such imperfect connections, the two parts are found to behave differently when the bridge is in a state of near-collapse; as such, the safety of these bridges is lower. Because few details can typically be found regarding the widening work done on small rural bridges such as Kitahama Bridge, and the quality of the work done to widen these bridges is often low, assuming that such bridges behave as if the original and widened parts are perfectly integrated may result in an overestimation of the safety of these bridges. As such, it is important that the integrity of widened bridges is evaluated properly.

In the case of a simple structure such as Kitahama Bridge, if the original and widened parts of the bridge are perfectly integrated, then the natural frequency of the first bending mode of the two parts should be the same. However, if the connection between them is imperfect, the vibration characteristics of the two parts will likely be different. The method proposed in this study makes use of this theory, and the procedure for the method is as follows:

1. Acceleration sensors are installed on both the original and widened parts of a bridge, so that acceleration waveforms can be acquired during impact testing.
2. During impact testing, an impact force is applied to the bridge with a striking implement such as a hammer.
3. A fast Fourier transform (FFT) is performed on the acceleration waveforms in order to calculate the natural frequencies of the two parts of a widened bridge, and an amplitude spectrum is produced for the vibrations at each sensor position.
4. The integrity of the widened bridge is evaluated by comparing the natural frequencies of the two parts of the widened bridge.

The advantage of this method is that it is easy to use and can be utilized to make quantitative evaluations. Though there already exist plenty of research which employs the natural frequency to detect damage in bridges [7-10], no research employs it to check the condition of the connection by comparing that of original and widened parts to author’s knowledge.

3.2. Using This Method on Kitahama Bridge

The method described in the previous sub-section was applied to Kitahama Bridge; Figure 5 shows the locations of where the acceleration sensors were placed and the positions at which the bridge was subjected to an impact force; Figure 6 shows an image of an impact test. Hereafter, as can be seen in Figure 5, the widened part of the bridge on the downstream side is referred to as section A, the original part as section B, and the widened part on the upstream side as section C. Impact forces were applied at three different positions (AH, BH, and CH), as shown in Figure 5; in particular, these positions were chosen to elicit the first bending modes in each section.

![Figure 5](image-url) Locations in which the acceleration sensors were placed (AS, BS1, BS2, BS3, and CS) and the positions where the impact forces were applied to the bridge (AH, BH, and CH).

![Figure 6](image-url) A photograph of an impact test being conducted on Kitahama Bridge.

In order to obtain the acceleration waveforms, five piezoelectric-type acceleration sensors (MODEL 2304A, Showa Instruments Co., Ltd.) were used: one for section A (at AS), three for section B (at BS1, BS2, and BS3), and one for section C (at CS). The charges generated by the acceleration sensors were recorded on a personal computer using the built-in power supply of the amplifier and an analog-to-digital (A/D) converter (A/D conversion speed: 2 µs, maximum sampling frequency: 160 kHz, A/D conversion resolution: 16 bits). The sampling frequency used for the acceleration sensors was 20 kHz, and a finite impulse response filter [11]
was applied. Figure 7 shows the acceleration waveforms for each sensor when impact forces were applied at AH, BH, and CH. As can be seen in Figure 7(b), when an impact force was applied at BH, the amplitude of the vibrations produced at AS and CS were smaller than those obtained at BS1 and BS3, even though these four points were equidistant from BH. It was found that the vibrations barely propagated to CS; this suggests that the widened part of the bridge was not perfectly integrated with the original part, and that the bridge behaved quite differently at section C. Similarly to this measurement, it was found that when impact forces were applied to AH and CH, the vibrations did not propagate to the adjacent parts of the bridge (as can be seen in Figure 7(a) and (c), respectively).

Figure 8 shows the natural frequencies that were obtained at sections A, B, and C when FFT was applied to their respective acceleration waveforms. For the sake of simplicity, only the result for BS2 is shown for section B; however similar findings were observed for BS1 and BS3. As can be seen from this figure, the respective predominant frequencies, which were considered to be the natural frequencies of the first bending modes of each of the section, were different (frequency at AS = 25.6 Hz, BS2 = 40.3 Hz, and CS = 31.7 Hz). This result suggests that the original and widened parts of Kitahama Bridge were not perfectly integrated. Additionally, as can be seen from Figure 8(c), when the section of the bridge being hit is different from the section in which the measurement is made, the vibration spectrum attenuates at the area where two sections connect and the amplitude spectrum in the section being measured becomes very small.

**Figure 7.** Acceleration waveforms obtained by each acceleration sensor for different positions at which an impact force was applied. The force was applied at (a) AH, (b) BH, and (c) CH in the above figures.

**Figure 8.** Natural frequency of each section by loading position for different positions at which an impact force was applied. The force was applied at (a) AH, (b) BH, and (c) CH in the above figures.

4. Evaluating the Safety of Widened Bridges Using a Finite Element Model

In this section, we use FEA to compare how the connection between the original and widened parts of Kitahama Bridge affected its structural behavior. Using this analysis, we determined how safe the bridge is.

4.1. Finite Element Model

In this study, the compression strength is measured by applying an impact force to the back of the deck of Kitahama Bridge with a concrete tester, CTS-02V4 (Nitto Construction Inc.); a photograph of this device is shown in Figure 9. The device measures compressive strength using the waveform of the impact force generated by the non-destructive contact between the hammer it contains and the concrete of the bridge. The points at which the compressive strength was measured are shown in Figure 10, and the results of these measurements are shown in Table 1. It was found that the compression strength was relatively small in the original parts of the bridge in which significant deterioration had already occurred. In this study, the Young's modulus, $E_c$, was estimated using Eq. (1) [12]:

$$E_c = 3.35 \times 10^4 \times (\gamma/24)^{2/3} \times (F_c/60)^{1/3}$$

$E_c$ was used for the finite element model (FEM), which also utilized the compressive strength, $F_c$, the values of which can
be found in Table 1. The unit volume weight $\gamma$ used in this study was 24 kN/m$^3$; this particular value was used, as it is Japan’s standard value for this particular parameter of RC. The Young’s modulus values calculated using Eq. (1) are also shown in Table 1. In the FEA, Kitahama Bridge is divided into 16 parts, as shown in Figure 10 with reference to the degree of deterioration. The Young's modulus of a delimited part is assumed to be the same as the value of the measuring point in the same delimited part.

![Figure 9. Photograph of the concrete tester, CTS-02V4 (Nitto Construction Inc.), used in this study.](image)

### Table 1. Compressive strength and Young's modulus values obtained at each measuring point.

<table>
<thead>
<tr>
<th>Measuring points</th>
<th>A1</th>
<th>A2</th>
<th>A3</th>
<th>A4</th>
<th>A5</th>
<th>B3</th>
<th>B4</th>
<th>B5</th>
<th>B6</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
<th>B7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength (MPa)</td>
<td>42.90</td>
<td>45.88</td>
<td>48.25</td>
<td>40.45</td>
<td>38.12</td>
<td>20.80</td>
<td>45.51</td>
<td>22.68</td>
<td>27.43</td>
<td>36.64</td>
<td>30.51</td>
<td>49.42</td>
<td>59.99</td>
<td>45.18</td>
<td></td>
</tr>
<tr>
<td>Young's modulus ($\times 10^3$MPa)</td>
<td>29.96</td>
<td>30.63</td>
<td>31.15</td>
<td>29.37</td>
<td>28.80</td>
<td>23.53</td>
<td>30.55</td>
<td>24.22</td>
<td>25.81</td>
<td>28.42</td>
<td>26.74</td>
<td>49.42</td>
<td>59.99</td>
<td>45.18</td>
<td></td>
</tr>
</tbody>
</table>

4. None of the three sections (A, B, and C) are integrated.

In the present study, a commercial FEM program, Abaqus/Standard 6.14 (Dassault Systèmes), was used to model and analyze Kitahama Bridge; Figure 11 shows an isometric view of the FEM. In the model, we used the eight-node isoparametric brick element C3D8R for the concrete deck of the bridge. The number of nodes and elements used in the FEM were 25,676 and 17,427, respectively.

![Figure 11. FEM of Kitahama Bridge.](image)

### 4.2. Safety Evaluation Conducted Using FEM

#### 4.2.1. The FEM Model

In order to evaluate how the connection between the original and widened parts of Kitahama Bridge impacted its safety, we analyzed the following four integration patterns using FEM:

1. All three sections (A, B, and C) are integrated;
2. Only section B and section A are integrated;
3. Only section B and section C are integrated;
4. None of the three sections (A, B, and C) are integrated.

Integration patterns 2 to 4 assume that the connection between the original and widened parts of Kitahama Bridge were destroyed and/or completely separated due to the bridge reaching its ultimate failure state. In order to produce a more detailed analysis, it may be necessary for the intermediate states between the combining and separation to be produced; however, evaluating such states greatly increases the complexity of the analysis. Therefore, because of this and because the purpose of this present study is to evaluate the safety of widened bridges, we are only interested in analyzing scenarios in which complete separation is considered.

The loads applied to the bridge model are design dead loads and live loads; these loads are used to maximize the bending moment. These loads were determined using the specifications provided for highway bridges in Japan. For the live load, T loads were used that assumed that there was a rear wheel load of 2.5 t, as can be seen in Figure 12. For the dead load, the weight was calculated using the unit volume weight of 24 kN/m$^3$. The loading position of the T load was on the center line (i.e., the red line in Figure 11) in the direction of the bridge axis; this was chosen, as it produces stress that is most unfavorable to the bridge. A total of 15 loading patterns were
placed over a distance of 100 mm in this study, and they were situated from the left-hand side of Kitahama Bridge (section A) in the direction perpendicular to the bridge axis to the right-hand side of the bridge (section C).

![Figure 12. T load.](image)

FEA was conducted for a total of 60 models (i.e., the 15 loading patterns used for each of the 4 integration patterns). Figure 13 shows the deflection distribution derived from the FEM when the live load was applied at the rightmost end of integration pattern 1 and integration pattern 4. As can be seen from the figure, when there is no connection between the original and widened parts of the bridge, the moment of inertia decreases; this confirmed that the widened areas of the bridge were particularly dangerous.

In order to more clearly and quantitatively evaluate the degree of safety with respect to each integration pattern, we calculated and compared the maximum principal stress of section B ($\sigma_B$) with that of sections A and C ($\sigma_A$ and $\sigma_C$, respectively) for the loading positions of the T load [13] (left tire position: $\sigma_{TL}$, right tire position: $\sigma_{TR}$) are compared in the following sub-section.

![Figure 13. Results of the FEA for integration patterns 1 and 4. The units used for the deflections in these images are expressed in mm.](image)

### 4.2.2. FEM Results and Safety Examination

Figure 14 shows the transition of the maximum principal stress for each connection pattern at each stress point of interest due to the movement of the load. We were able to determine that the most disadvantageous stress state position in most cases was $\sigma_{TL}$ and $\sigma_{TR}$. Additionally, we found that the transition of the maximum principal stress of integration pattern 1 was gentler than that of the other integration patterns. This was believed to be because the stresses were distributed throughout the bridge due to the integration of all the sections. However, in the cases where all or some of the sections had separated from the others, the maximum principal stress of the separated section greatly increased when a live load was applied onto it. We also confirmed that the stress on a separated section was very small when the live load was not applied onto it. In other words, if there was no connection between the original and widened parts of the bridge, then the stress was not dispersed over the entire bridge; this resulted in the safety of the section in which was applied severely deteriorating, which decreased the safety of the bridge as a whole.
Using integration pattern 1, we quantitatively derived the influence of the integrity of the bridge on its safety. These results are shown in Table 2, which shows the maximum principal stress under the most unfavorable loading scenarios for each of the integration patterns. As shown in Table 2, the maximum principal stress of integration pattern 2 is 1.2 times that of integration pattern 1; meanwhile, this value for integration patterns 3 and 4 are both 2.3 times that of that of integration pattern 1. From these FEM results, we can see that because the width of section A of the Kitahama Bridge is narrow, the bridge will become very unsafe if the connection between sections A and B is destroyed and the wheels of an automobile subsequently traverse section A.

5. Summary

This study proposes a method that evaluates the safety of widened narrow RC bridges in which the widened parts are not connected properly to the original parts. The method proposed uses impact testing to investigate the connection between the original and widened parts of these bridges, and it uses FEA to evaluate their safety. This manuscript applies this method to an actually widened narrow RC bridge called Kitahama Bridge. This analysis showed us that the method was effective, and the FEA revealed that 2.3 times greater stress can be applied to a section of the bridge if its integrity is impaired and sections of the bridge are separated from one another. Although this result is specific to Kitahama Bridge and cannot be generalized, this study shows that poor connections between the sections of widened bridges significantly hamper the safety of these bridges.

Appropriately evaluating the safety of widened narrow bridges with the proposed method is expected to contribute to the development of a bridge maintenance strategy with which one can determine which bridges need to be repaired with priority. In our next paper, we intend to develop a safety evaluation method that does not use FEM.

References


