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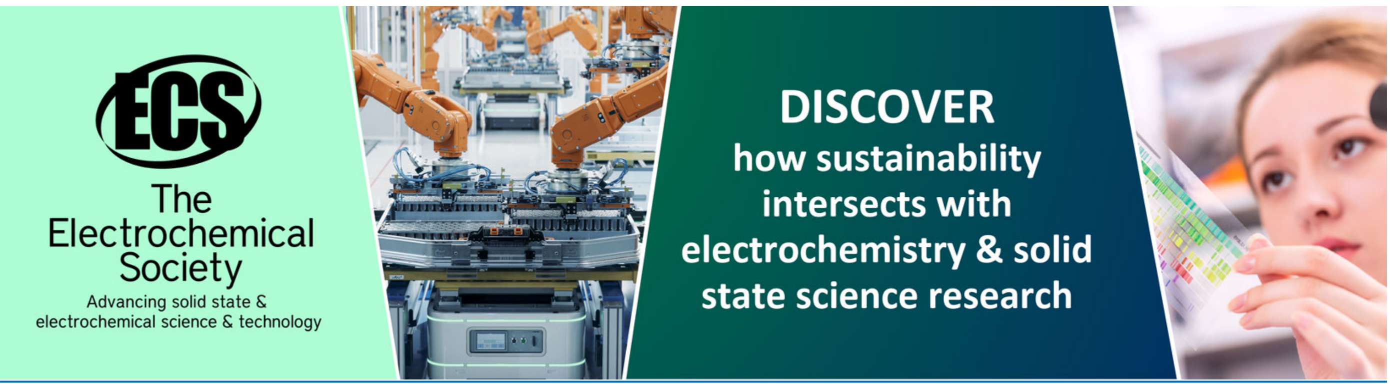

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# Damage Detection Sensitivity of a Vehicle-based Bridge Health Monitoring System

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**Abstract**. As one solution to the problem for condition assessment of existing short and medium span (10-30m) reinforced/prestressed concrete bridges, a new monitoring method using a public bus as part of a public transit system (called "Bus monitoring system") was proposed, along with safety indices, namely, "characteristic deflection", which is relatively free from the influence of dynamic disturbances due to such factors as the roughness of the road surface, and a structural anomaly parameter. In this study, to evaluate the practicality of the newly developed bus monitoring system, it has been field-tested over a period of about four years by using an in-service fixed-route bus operating on a bus route in the city of Ube, Yamaguchi Prefecture, Japan. In here, although there are some useful monitoring methods for short and medium span bridges based on the qualitative or quantitative information, the sensitivity of damage detection was newly discussed for safety assessment based on long term health monitoring data. The verification results thus obtained are also described in this paper, and also evaluates the sensitivity of the "characteristic deflection", which is a bridge (health) condition indicator used by the bus monitoring system, in damage detection. Sensitivity of "characteristic deflection" is verified by introducing artificial damage into a bridge that has ended its service life and is awaiting removal. Furthermore, the sensitivity of "characteristic deflection" is verified by 3D FEM analysis.

## 1. Introduction

In the field of bridge management engineering, a great deal of decision making often depends on the assessment and experience of the domain experts in related fields, such as professional experience, knowledge on bridge management, etc. Then an important parameter in management for existing bridges is the remaining life assessment that is crucial as a kernel of the systematization for bridge maintenance throughout service life including economic analyses referring to initial cost and assessment technologies. In bridge structures there are many different unforeseen conditions because bridges are larger and often need to serve longer more than 100 years, compared with the other products such as electrical, mechanical and systems engineering fields. And they are subjected to diverse types of deterioration mechanism such as corrosion, fatigue, carbonation, alkali aggregate reactions, etc. Therefore it is probable to have some risk for not fulfilling the complete standards of safety so some failure probability is possible. Structural aging, environmental conditions, and reuse are examples of circumstances that could affect the reliability and the life of a bridge structure. Engineers have been visually inspecting, monitoring and proof testing bridges for Centuries. However, presently health and performance are described based on subjective measures that are not universal. In addition, defects, deterioration and damage are not discovered until it is possible to visually observe the signs they exhibit at which time these would have taken their toll on health. These shortcomings impact the timeliness, effectiveness and the reliability in any management decision irrespective of any sophistication in the management process. Moreover, even experienced engineers may find visual signs of defects, deterioration and damage and still not be able to diagnose the causative mechanisms, or their impact on the reliability of the system and global health. The global health of an entire bridge as a system, inclusive of the performance criteria corresponding to every one of the limit-states is actually what is needed for effective management decisions. There are needs of periodic inspections to detect deterioration resulting from normal operation and environmental attack or inspections following extreme events, such as strong-motion earthquakes or hurricanes. To quantify these system performance measures requires some means to monitor and evaluate the integrity of civil structures while in service [1-8]. Then, since the necessity of developing a practical health monitoring system has been point out for detecting deterioration phenomenon as early as possible for bridge maintenance.

The authors have been developing a long term health monitoring method using a public bus as part of a public transit system (called "Bus monitoring system") [9-11] to be applied mainly to short and medium span bridges. As a safety index from the system, "characteristic deflection" which is relatively free from the influence of dynamic disturbances due to such factors as the roughness of the road surface, and a structural anomaly parameter was proposed. The advantages of bus monitoring system are as follows: a) If a large vehicle about 10 m long is used for measurement, it is highly likely that when the vehicle crosses a short and medium span bridge, that is the only vehicle in the same lane on the bridge, b) If a short and medium span bridge, which is has relatively high flexural stiffness, is to be vibrated, it is necessary to use a relatively heavy vehicle, c) If a fixed-route bus is used as a source of bridge excitation, it is easy to reproduce measuring conditions such as the time of passage, route, frequency and velocity, d) Since a fixed-route bus equipped with a sensor makes the rounds, it is possible to monitor main short and medium span bridges in a particular area on a regular basis. As a result, substantial cost reduction can be achieved because there is no need to install sensors to all bridges to be monitored, e) The electric power for the measuring instruments used can be supplied by the power supply of the bus.

This paper described not only the validation results obtained from the long-term monitoring and discusses the usefulness of the system but also the problems of the conventional observation method based on the "characteristic deflection", which is a bridge condition indicator that makes possible efficient detection of structural anomalies of the bridge being monitored, are identified, and a new observation method that enhances the damage detection sensitivity of the system is evaluated. This study also examines the influence of artificial damage (guardrail removal) on the characteristic deflection to evaluate the sensitivity of the system in detecting damage given to the field test bridge. The sensitivity of the characteristic deflection is verified by 3D FEM analysis. Finally, various study results as mentioned above are put together to systematically discuss the practical scope of application, damage detection accuracy and remaining problems of the system.

## 2. Basic Concept of the Bus Monitoring System

The bus monitoring system has been developed by the method of monitoring short and medium span bridges by using fixed-route buses operated as part of public transport systems [9-11]. **Fig. 1** illustrates a basic concept and damage detection flow of the bus monitoring system. Main reasons why the use of fixed-route buses, which are large and heavy vehicles, was considered are as follows: (1) If a large vehicle about 10 m in length is used for on-the-move measurement on a short or medium span bridge, that vehicle is likely to be the only vehicle passing over the bridge at point in time, (2) In order to make a short or medium span bridge, whose stiffness is relatively high, it is necessary to use a reasonably heavyweight vehicle, (3) Large vehicles used to vibrate bridges make it easier to reproduce

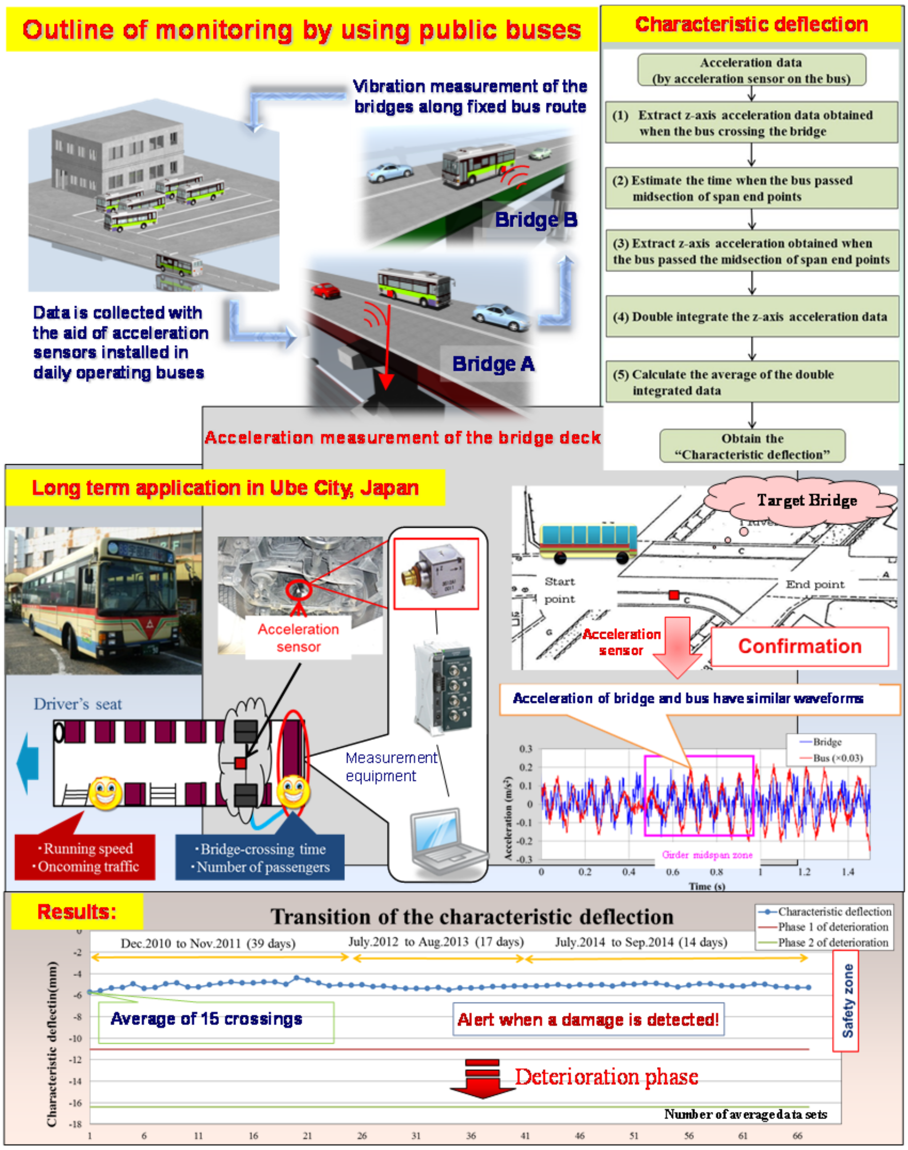


**Figure 1.** Basic concept and damage detection flow of the bus monitoring system

measuring conditions such as travel time, route, frequency of passages and vehicle speed, (4) By using a fixed-route bus equipped with acceleration sensors, main short and medium span bridges in the area of interest can be monitored on a regular basis. By so doing, monitoring cost would be substantially less than in the case where sensors were installed at all bridges, and (5) Power for the measuring devices can be supplied from the power supply available in the bus.

As shown in **Fig. 1**, the vertical displacement of the bridge and the bus under its rear wheel springs is an estimated deflection obtainable by integrating the vertical acceleration waveform twice. The displacement can be expressed, as the sum of (1) the static displacement dependent on bridge stiffness and bus weight, (2) a non-steady-state vibration component having a stochastic nature characterized as a Gaussian process attributable to a rough road surface and having a mean value of 0, (3) vibration components governed by the equation of motion such as the bridge and the vehicle, and (4) external disturbance factors due to differences in the operating conditions of the bus and differences in data extraction and processing methods. For the purpose of this study, the characteristic deflection [9],[10] which is relatively free from the influence of dynamic disturbances due to the roughness of road surface, etc., is defined as an indicator that may be useful in efficiently detecting a structural anomaly of existing bridges [11].

## 3. Examination and Discussion of Damage Detection Sensitivity

*3.1 Examination by an Existing Bridge with Artificial Damage*
To evaluate the sensitivity of the characteristic deflection used by the bus monitoring system as a serious damage indicator, the influence of artificial damage (bridge guardrail removal) on the characteristic deflection was evaluated by using a decommissioned bridge (a real old bridge to be removed shortly). This chapter deals with the field test results thus obtained. A simulation analysis using an analysis model allowing for the coupling between the bus and the bridge is also performed to calculate changes in the characteristic deflection of the artificially damaged bridge, and damage detection sensitivity is compared and evaluated from the analytical point of view.

*3.1.1 Overview of the test*
The field test was carried out by using a 72-year-old (as of the time of the study) reinforced concrete bridge to be dismantled and removed shortly ("Sakae(SK) Bridge" [12]; see **Fig. 2**). In view of factors such as seasonal (temperature) changes and the presence or absence of bridge guardrails, it was decided to conduct measurement using the bus monitoring system a total of four times, namely, in September 2012 and in January, February and March 2013. As in the case of the long-term field test mentioned earlier, the vertical (z-axis) acceleration response and "characteristic deflection" occurring when the municipal bus (vehicle) running at a constant speed crosses the bridge in the in-bound and out-bound lanes (15 in-bound runs and 15 out-bound runs) are calculated. Taking advantage of the absence of other road traffic (ideal condition) because the bridge was already in the process of demotion and removal, the measurements were conducted under various conditions by varying such conditions as vehicle weight and vehicle speed (constant speed).

*3.1.2 Types and characteristics of vehicles used for measurement*
The vehicles used for the measurement purpose are Ube-city's sightseeing bus having a gross weight of about 15 tf and a mini vehicle having a gross weight of about 1.3 tf. As in the long-term field test mentioned earlier, an acceleration sensor was installed at a similar position (under the rear wheel spring) of each vehicle for continuous measurement. Besides this sensor, three other acceleration sensors of comparable performance were also installed [on the right side, at the center (normal location) and on the left side under the rear wheel spring] to evaluate the influence of sensor locations. **Fig. 3(a)** and **(b)** show the general views of the two types of vehicles used and the acceleration sensor locations. **Table 1(a)** and **(b)** show the specifications of the vehicles used and data on the performance and other details of the sensors.

**Figure 2.** General view of SK-Bridge in service

*3.1.3 Outline of the bridge*

The SK-Bridge used for the field measurement is a 168.3-meter-long, 11.0-meter-wide eight-span simple cantilever reinforced-concrete T-girder bridge completed in 1941 (managed by the Ministry of Land, Infrastructure, Transport and Tourism). For reconstruction, the bridge was demolished and removed by stages over a period of two years from fiscal year 2012. **Table 2** and **Fig. 4** show the structural specifications and pre-removal configuration and dimensions of the SK-Bridge and the bridge section where the field test was conducted. Since there was no other road traffic on the bridge at the time of measurement, only seasonal (temperature) changes were taken into consideration as an external disturbance factor affecting characteristic deflection in evaluating the influence of the presence or absence of bridge guardrails (regarded as artificial damage). For the purpose of that evaluation, a field test was carried out on four occasions (once in autumn, twice in winter and once in

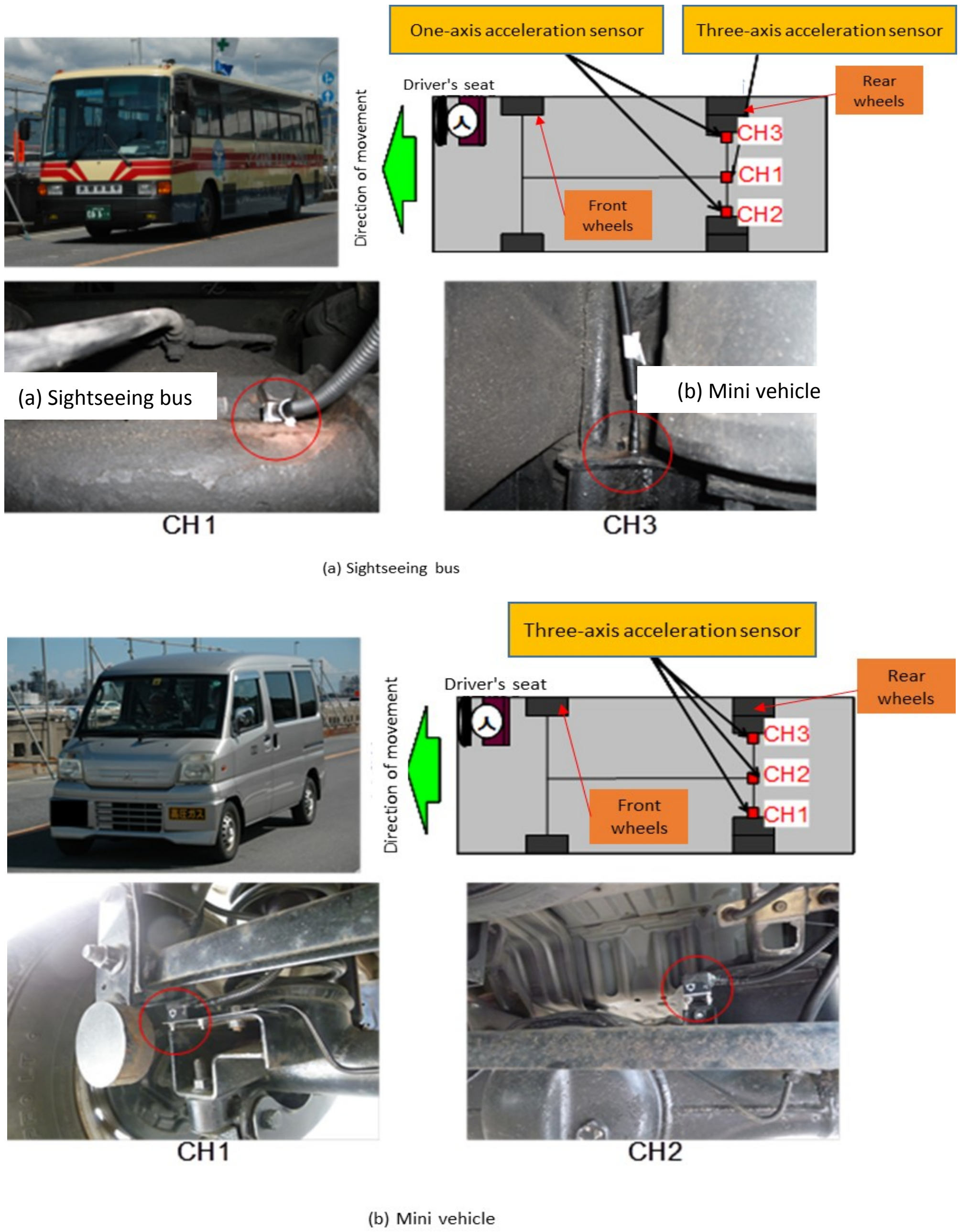


**Figure 3.** Measurement vehicles and acceleration sensor locations(Sightseeing bus & Mini-van)

**Table 1.** Specifications of measurement vehicles and acceleration sensors

(a) Measurement vehicles

| Items | Bus | Mini vehicle |
|---|---|---|
| Riding capacity | 57 persons | 2(4) |
| Length | 1,194 cm | 339 cm |
| Width | 249 cm | 147 cm |
| Height | 330 cm | 189 cm |
| Vehicle weight | 11,810 kg | 860 kg |
| Gross weight | 14,945 kg | 1,320 kg |
| Front axle weight | 4,030 kg | 440 kg |
| Rear axle weight | 7,780 kg | 420 kg |

(b) Acceleration sensors

| Items | Model No. | Serial No. | Channel | Axis | Sensitivity | Unit | Location |
|---|---|---|---|---|---|---|---|
| Bus | SA11ZSC-TI | 5692 | CH1 | Z | 0.99 | $mV/ms^{-2}$ | Center |
| | M353B16 | 106161 | CH2 | Z | 1.058 | $mV/ms^{-2}$ | Right |
| | M353B12 | 106410 | CH3 | Z | 0.483 | $mV/ms^{-2}$ | Left |
| Mini vehicle | 2422 | 1236 | CH1 | Z | 794.0 | mV/G | Center |
| | | 1237 | CH2 | Z | 795.1 | mV/G | Right |
| | | 1238 | CH3 | Z | 797.3 | mV/G | Left |

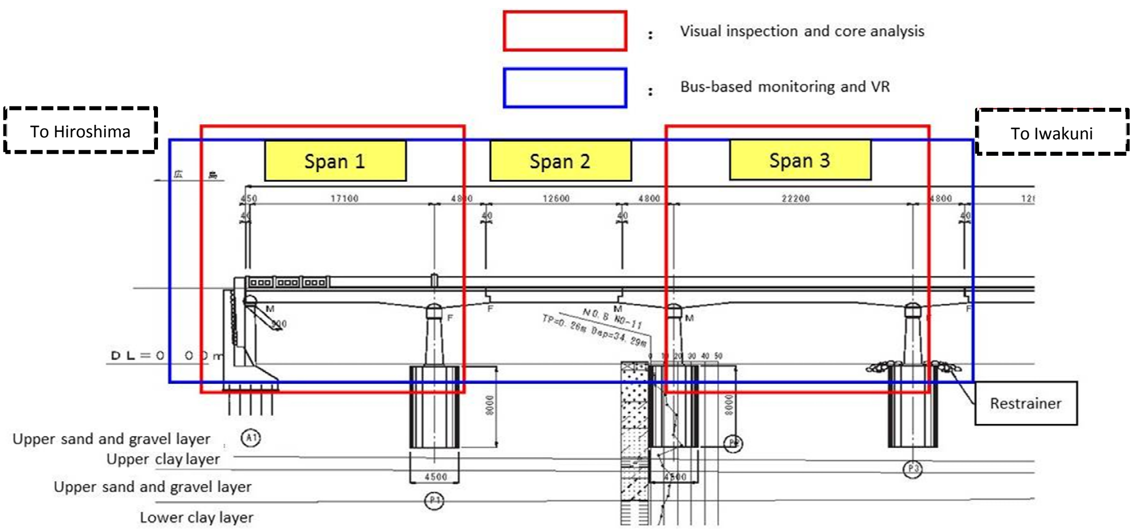


**Figure 4.** Configuration and dimensions of SK-Bridge and spans used for field testing

spring). For the evaluation of changes in the characteristic deflection before and after bridge guardrail removal, the data obtained in January and February 2013 were compared. **Fig. 5** shows the bridge before and after the guardrail removal.

*3.1.4 Test results and discussion*

This section puts together and discusses the results obtained from the field test conducted by using the decommissioned bridge as mentioned above.

**Table 2.** Structural specifications of field test bridge (SK-Bridge)

| | |
|---|---|
| Length | L＝168.29 m |
| Width | W＝11.0m(two lanes＋sidewalks) |
| | W＝2.5 m(sidewalks) |
| Span | Eight spans |
| Super structure | Cantilever reinforced concrete(RC) T-girder bridge |

*1) Differences in sensor location*

Changes in characteristic deflection depending on the location of the acceleration sensor installed under the rear wheel spring were examined. **Fig. 6** compares the acceleration response waveforms obtained from the different sensor locations under the rear wheel spring of the sightseeing bus(see **Table 1(a)**). As shown in **Fig. 6**, acceleration response can be measured at any sensor location with accuracy good enough to make characteristic deflection calculation possible. From this, it can be said that an acceleration sensor needed by the bus monitoring system to calculate the characteristic deflection as a serious damage indicator may be installed at any location under the rear wheel spring.

*2) Differences in axle weight due to vehicle type*

To evaluate the effects of vehicle axle weight on the characteristic deflection, the characteristic deflection was calculated from the acceleration responses of the sightseeing bus and the mini vehicle, which have a gross weight difference of more than 10 tf, measured while they were moving. As examples, **Figs. 7(a)** to **(d)** show an under-rear-wheel-spring (center) acceleration response waveform of the sightseeing bus and an under-rear-wheel-spring (right) acceleration response waveform of the mini vehicle, along with acceleration response waveforms of the sightseeing bus and the mini vehicle obtained from the acceleration sensor installed to the bridge when they crossed the bridge. Comparison of **Figs. 7(a)** and **(b)** reveals that the response waveform obtained from the acceleration sensor installed to the mini vehicle tends to be larger, in both the noise portion and the signal portion, than the waveform obtained from the sightseeing bus. The reason for this is thought to be that since the mini vehicle is lighter than the sightseeing bus (smaller axle weight), the former is more easily affected by the roughness of the road surface when in motion so that vertical vibration of the mini vehicle becomes greater. Comparison of **Figs. 7(c)** and **(d)** reveals that the response waveform obtained from the bridge acceleration sensor when the mini vehicle cross the bridge is significantly smaller than the response waveform recorded when the sightseeing bus crossed the bridge. From this, it is presumed that the mini vehicle, whose gross weight is small, is not heavy enough to cause the bridge to vibrate and that external disturbance factors such as road surface roughness prevent the under-spring structure of the vehicle and the bridge from vibrating together (i.e. the similarity between the vehicle and the bridge does not hold). As a result, it is presumed, the requirements of the bus monitoring system are not met (i.e. not suitable for the calculation of the characteristic deflection).

*3) Comparison of characteristic deflections before and after guardrail removal*

In this section, 15 calculated values of the characteristic deflection derived from the measurement results obtained at four different times of year by using the sightseeing bus having a gross weight of about 15 tf are used to examine the effects of the artificial damage (guardrail removal) introduced into the bridge ("SK-Bridge"). As an example, **Fig. 8** shows the characteristic deflection calculation results for Span 2(cantilever part) and Span 3 (see **Fig. 4**) of the bridge obtained by using the sightseeing bus (moving at 40 km/h). The concrete guardrail removal was carried out between the second measurement (January 2013) and the third measurement (February 2013). The characteristic deflection

(a) Before guardrail removal (b) After guardrail removal

**Figure 5.** Bridge before and after guardrail removal

values obtained before and after the guardrail removal are compared below.

First, turning attention to Span 3 (see **Fig. 4**), we notice that the two characteristic deflection values (−2.97, −2.89) obtained after the guardrail removal are about 10% larger than the values (−2.67, −2.61) obtained before the guardrail removal. This is thought to be because the decrease in the flexural stiffness of the bridge resulted in an increase in the characteristic deflection. In Span 2, which includes a cantilever structure, however, the characteristic deflection value (−2.24) obtained after the fourth measurement is slightly smaller than the value obtained before the guardrail removal. Since Span 2 includes a cantilever structure, it is thought likely that the cantilever structure somehow influenced the

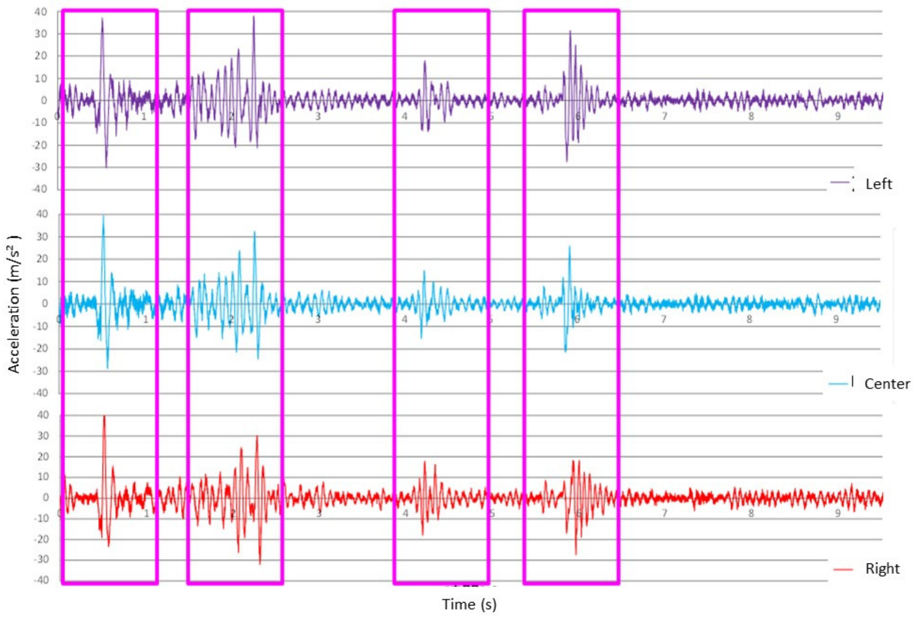


**Figure 6.** Comparison of acceleration response waveforms obtained from sensors installed at different under-rear-wheel-spring locations of the sightseeing bus

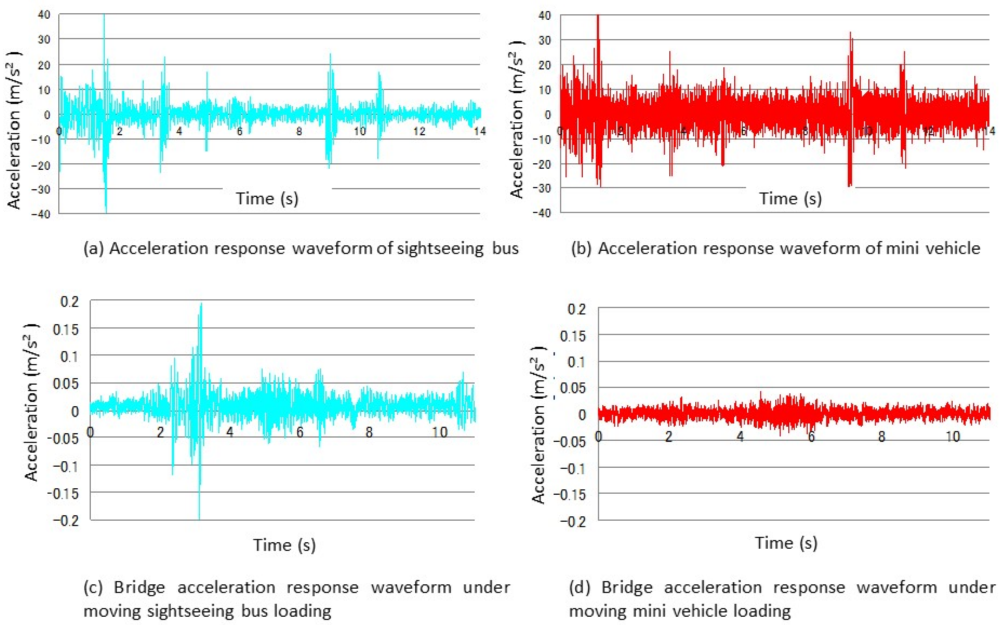


**Figure 7.** Effects of vehicle type on vehicle and bridge acceleration response waveforms

characteristic deflection. When calculating characteristic deflection of a bridge with a cantilever structure, therefore, it is necessary to perform a simulation analysis and compare the calculated values with the analytical results.

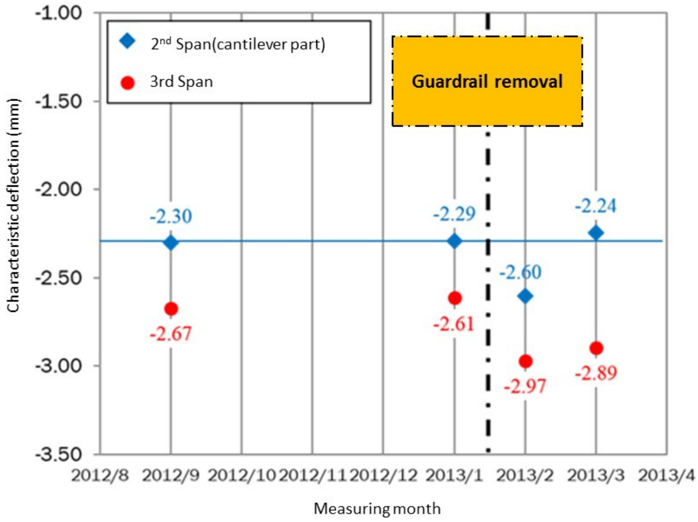


**Figure 8.** Changes in characteristic deflection due to railing removal

### *3.2 Examination by Model-based Simulation Analysis*

This section deals with a model-based simulation analysis of the bridge measurement results obtained from the bus monitoring system performed to analytically identify the bridge behavior before and after the guardrail removal.

In the analysis, a static FEM analysis [13] was conducted of the simple girder structure excluding Span 2 on the Hiroshima side to calculate the maximum deflection ratio and evaluate the influence of the bridge guardrails on girder stiffness. The analysis, by using the three-dimensional finite analysis method, calculates and compares the midspan deformation in the cases where a midspan vertical downward unit concentrated load (1 kN) is applied. Static analyses were conducted of the four cases listed below:

Case 1: With guardrails, no damage
Case 2: Without guardrails, no damage
Case 3: With guardrails, damaged
Case 4: Without guardrails, damaged

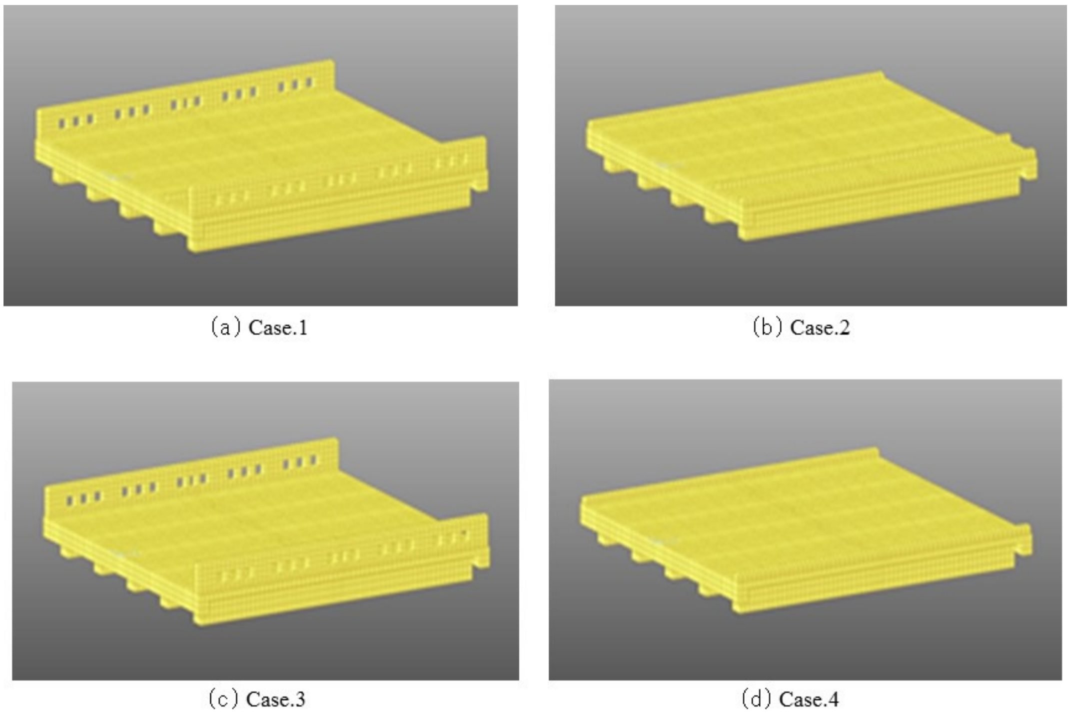


**Figure 9.** Model used for analysis

The analysis used MIDAS-GEN (MIDAS-IT Co.).

*3.2.1 Analysis model and analysis conditions*
**Fig. 9** shows how the analysis model used looks. **Fig. 10** shows an enlarged view of an assumed damage region in the "damaged" case shown in **Fig. 9**. The static analysis conditions are shown in **Table 3**. An eigenvalue analysis showed that the first mode natural frequency is 16 Hz. The first mode frequency determined from theoretical solutions and other study findings [14],[15] is also 16 Hz. It is therefore thought that the model mentioned above is suitable for use in this study.

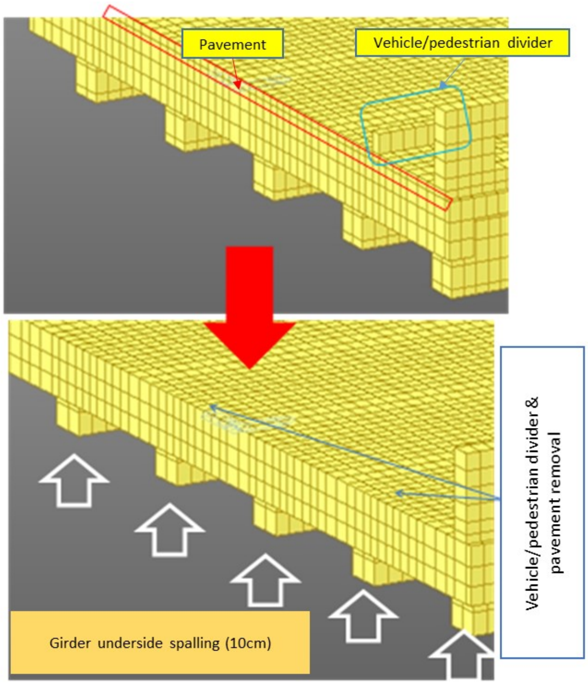

**Figure 10.** Assumed damage

*3.2.2 Comparison between analytical results and characteristic deflection values*
**Table 4** shows the obtained analytical results. The change ratio in the "with guardrails and no damage" case under the assumed conditions is 1.04, indicating that the change amounts only to about 4%. The change ratio in the case where general delamination of the underside of the girder is assumed is about 1.05, indicating a change of about 5%. The geometrical moment of inertia was also calculated in both the "with guardrails" and "without guardrails" cases. The second moments of area thus obtained are shown in **Table 5**. As shown in **Table 5**, the geometrical moment of inertia shows a decrease of about 40% as a result of the guardrail removal. This translates to a deflection ratio of 1.64.

**Table 3.** Analysis conditions

| Items | Conditions |
|---|---|
| Analysis method | Static elasticity analysis using 3D solid elements |
| Material constants | JIS (RC) Fc24 or equivalent |
| | Modulus of elasticity : 2.2668E7 |
| | Poisson's ratio : 0.2 |
| | Unit weight : 24.0 |
| Load | Midspan vertical downward unit concentrated load (1 kN) |
| Boundary conditions | Simple beam; restrained at bottom of girder end |

The results of the 3D FEM analysis mentioned earlier show that the change ratio ranges from 1.04 to 1.05(see **Table 4**), and the effects of the guardrail removal are very small compared with the values obtained from the geometrical moment of inertia. This is thought to indicate that stress transmission paths extend two-dimensionally under the midspan loading due to the moving bus. This does not agree with the result of stiffness evaluation based on the assumption, for cross-sectional calculation, of Navier's hypothesis (of plane sections remaining plane) and bending in the bridge axis direction.

Comparison with the characteristic deflection reveals that the calculated values of the characteristic deflection for Span 2 show decreases after the guardrail removal.

**Table 4.** Analysis results (midspan deflection)

| Case | Deflection (≠ characteristic deflection) | Ratio to "with guardrail" case |
|---|---|---|
| 1 | $-2.89 \times 10^{-6}$ m | |
| 2 | $-3.00 \times 10^{-6}$ m | 1.04 (4% increase) |
| 3 | $-3.29 \times 10^{-6}$ m | |
| 4 | $-3.47 \times 10^{-6}$ m | 1.05 (5% increase) |

*3.2.3 Discussions*
According to the characteristic deflection calculation

results for Span 3, the characteristic deflection values obtained after the guardrail removal (average: 2.93 mm) indicate a decrease of about 10% compared with the characteristic deflection values (average: 2.64 mm) obtained before the guardrail removal. In view of the fact that the change ratio obtained through the static analysis in the case assuming general delamination of the underside of the girder was about 5%, it can be said that the characteristic deflection is reasonably sensitive to the guardrail removal. For Span 2, which includes a cantilever structure, however, the characteristic deflection after the guardrail removal showed a slight increase from the value obtained before the guardrail removal. This result is not consistent with the results of 3D FEM analysis, either. One likely reason for this is that the model used for the analysis consists of a simple span without a cantilever structure, while the calculated values of the characteristic deflection have been influenced by the cantilever structure. Changes in measurement results due to seasonal factors are possible, but that seems unlikely in view of the results for Span 3. Span 2 requires further study, and it is also necessary to examine other factors such as the possible influence of the type of bridge structure on the characteristic deflection.

These results have shown, at least at this stage of study in which the usefulness and validity of the characteristic deflection as an evaluation indicator for use by the bus monitoring system is being verified, that the method of using a three-dimensional model for comparison and evaluation is useful when measuring a bridge in which stress transmission paths extend two-dimensionally.

**Table 5.** Geometrical moment of inertia calculation results

| Items | With guardrails | Without guardrails | Decrease ratio |
|---|---|---|---|
| Cross-sectional area ($m^2$) | 6,650 | 5,948 | 10.5 % |
| Neutral axis location (m) | 0.974 | 0.877 | |
| Geometrical moment of inertia ($m^4$) | 1.612 | 0.980 | 39.2 % |

## 4. Concluding remarks

This paper has discussed the results of damage detection sensitivity of the bus monitoring system for short and medium span bridges, that is the characteristic deflection used as an evaluation indicator. Damage detection performance of the characteristic deflection has been verified systematically by introducing artificial damage (guardrail removal) into a decommissioned bridge that was in the process of demolition. Main results of this study are summarized as follows:

1) In the field test conducted by using a bridge that was decommissioned and was undergoing demolition, the influence (sensitivity) of artificial damage (guardrail removal) on the characteristic deflection was evaluated. The results obtained for Span 3 of the bridge confirmed that the characteristic deflection is reasonably sensitive to a decrease in the flexural stiffness of the entire bridge. In the case of Span 2, which includes a cantilever structure, however, the characteristic deflection before the guardrail removal was greater than the characteristic deflection after the guardrail removal. This result is not consistent with the 3D FEM analysis results, either. It is likely that the calculated values of the characteristic deflection have been influenced by the cantilever structure. Further study is needed, therefore, particularly on the influence of the type of bridge structure on the characteristic deflection.
2) At present, the usefulness and validity of the characteristic deflection as an evaluation indicator are being evaluated and verified. It can be concluded, at least at this stage, that the method of using a three-dimensional model for comparison and evaluation is useful when measuring a bridge in which stress transmission paths extend two-dimensionally.

Finally, the long-term field test of the bus monitoring system has produced useful results associated with the practical application of the system although a number of problems still remain to be solved. Important challenges for the bus monitoring system include the automation and rationalization of measurement. The structural health evaluation of bridges can be made simpler and more efficient by analyzing and solving the problems identified as a result of this study.

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