DEVELOPMENT OF AN EARTHQUAKE DAMAGE EVALUATION METHOD FOR BRIDGE STRUCTURES USING ACCELERATION SENSORS

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After an extreme earthquake, evaluation of damage and operability of bridge structures is currently done based on visual inspection by bridge experts, and there is a need to develop sensing technology to enable speedy and accurate evaluation of the degree of damage and operability of bridge structures. This paper proposes an evaluation method of the degree of damage of bridge structures. A series of shaking table tests of reinforced concrete single-column models validate the effectiveness and accuracy of the proposed method. A series of dynamic analyses were carried out to evaluate the efficiency of the proposed method for multi-span bridge model. For preventing secondary disasters and securing the traffic network during a disaster, a system, which is designed to collect bridge damage information evaluated with the proposed method, is also developed.

**Key Words:** damage evaluation, reinforced concrete column, shaking table test, natural period, ductility, dynamic analysis

1. INTRODUCTION

When an extreme earthquake occurs, detecting the damage of roadway bridges and other lifelines, and securing transportation networks during the disaster, are extremely important for the immediate post-earthquake deployment (i.e. search and rescue, evacuation of affected people, and transport of emergency supplies). Currently, evaluation of the degree of damage to bridge structures relies on visual inspection by experts; however there are various problems with this approach, such as: the lack of standards for quantitatively evaluating the degree of damage, the difficulty of visual inspection (because the damages are underground or underwater in many cases, or cannot be seen well at night), and the time-consuming process for gathering and understanding the information with a limited number of personnel. Therefore, there is a strong need to develop a technology for accurate and speedy determination of the degree of damage without relying on experts -- in order to prevent secondary disaster, respond after the earthquake promptly, and formulate recovery plans.

For detecting and evaluating damage without visual inspections, practical methods have been developed by measuring the natural period of railway bridges with a shock applied using a plumb bob, and a method has been proposed for estimating the degree of damage from the decrease in the primary natural frequency of an entire reinforced concrete rigid frame elevated bridge system\(^1\). Studies have also been done on methods using microtremors rather than excitation by impact. Uehan and Meguro have proposed a procedure which uses a tremor sensor\(^2\), and a laser Doppler velocimeter\(^3\). However, these methods require the preparation of complicated measurement setup and thus are still problematic for detecting damage in real-time during an earthquake.

Regarding the roadway bridges, on the other hand,
multiple accelerometers and other sensors are installed during construction in some long span bridges and other atypical bridges, to enable direct monitoring of behavior during an earthquake, and in recent years, there have also been proposals for systems that collect and analyze data during earthquake excitation and display the data in real-time. However, it would require enormous costs if such systems are installed in existing bridges, and there are problems such as securing lines for transmitting large volumes of data during a disaster. Thus, the use of this method in the many existing bridges is not realistic. In term of typical bridges, Kondo et al. have also conducted an experimental study regarding the relationship between the natural frequency of an reinforced concrete single column and the degree of damage, but this research has not used a real-time method to evaluate the degree of damage.

In this research, the authors devised a method for capturing changes in the natural period during an earthquake in real-time, evaluating the maximum response ductility from those changes, and then using the result for immediate evaluation of the degree of damage by primary information of operability of the bridge. The efficiency of the method was verified based on the results of a series of reinforced concrete single-column shaking table tests. A system for preventing secondary disasters and securing traffic network during a disaster, which is designed to collect the information of the damage of the bridges evaluated from the proposed method is also developed.

2. SHAKING TABLE TESTS OF REINFORCED CONCRETE SINGLE-COLUMN

(1) Overview of experiment

A series of shaking table tests on reinforced concrete single-column specimens were conducted in order to develop a method that evaluates the degree of damage of bridge piers during an extreme earthquake.

Two reinforced concrete single-column specimens indicated in Fig. 1 and Table 1 were tested on the shaking table of the Public Works Research Institute (PWRI) in this study. A scaling factor of the specimens is approximately four. One specimen was subjected to a unidirectional horizontal earthquake excitation in the X axis (displayed in Fig. 1) and the other was subjected to a thee-directional earthquake excitation.

As the earthquake input signals, the acceleration records observed at the JR Takatori Station during the 1995 Hyogo-Ken-Nambu Earthquake were used, and the amplitude was varied in steps as indicated in Table 1. Because of the scale factor of four, time axis of the signals was compressed by 50%. Accelerations were measured by tri-axial accelerometers on the shaking table, on the footing, at the center of gravity of the weight, and the top of the weight during the excitation. Strains of longitudinal reinforcement were measured from the footing center to near the center of the column, and they were compactly arranged at the bottom of the column. Displacement of the center of the weight was measured using a laser displacement gauge.

(2) Test results

Table 2 shows the maximum acceleration, maximum strain, maximum displacement and response ductility measured during the experiment. For Specimen 1 and X direction of Specimen 2, data at the same measurement points are shown.

This table shows that the response was within the elastic range in all cases for the JR Takatori 15% input. Comparing the results for Specimen 1 and X
direction of Specimen 2, a larger rebar strain was found in Specimen 2, even allowing for response error in the shaking table itself from the input values. Also, in all excitation cases, nonlinear responses were observed for both specimens, exceeding yielding points, during the 2nd excitation (Specimen 1: JR Takatori record 50%, Specimen 2: JR Takatori record 90%). After the end of testing of the Specimen 2, a 1Hz sine wave was input and a large response displacement was produced compared to the input, due to resonance with the natural period of the specimen.

During the experiment, cracks appeared around the entire perimeter of Specimen 1 in response to 50% JR Takatori record input, but no spalling of the cover concrete was observed. When the Specimen 2 was subjected to the 90% JR Takatori record, chipping of the corner concrete and floating of the covering concrete around the entire perimeter were observed as shown in Photo 1.

The Specimen 1, which is subjected to unidirectional excitation, shared less damage comparing with the Specimen 2 with three directional excitation, i.e., chipping and floating of the cover concrete was not observed until the 2nd excitation with 80% JR Takatori record.

Contrasting the results in Table 2, when the response ductility exceeded 4, the observed damage was only cracking around the entire perimeter. However, chipping and peeling off on the covering concrete was observed in the test specimen when the response ductility reached about 10 or higher.

### Table 2 Experiment results.

| Excitation case | Natural period after excitation (sec) | Maximum acceleration of shaking table (m/sec^2) | Maximum acceleration at weight center (m/sec^2) | Maximum strain at column base (%) | Response ductility factor |
|-----------------|--------------------------------------|-----------------------------------------------|-----------------------------------------------|-------------------------------|----------------------------|
| Specimen 1 X axis direction | Natural period before excitation 0.29 | 0.34 1.11 2.15 0.754 6.3 0.4 | 0.64 4.45 3.56 67 62.8 4.5 | 0.88 4.81 3.39 33 95.6 0.3 | 0.79 7.22 3.52 26 136.1 9.3 |
| Specimen 2 X axis direction | Natural period before excitation 0.31 | 0.51 1.36 2.44 1.721 13.4 0.9 | 1.02 4.31 3.37 NA 176.0 11.9 | 0.85 3.35 1.44 NA 104.7 7.1 |
| Specimen 2 Y axis direction | Natural period before excitation 0.21 | 0.24 1.35 2.18 1.119 5.4 0.5 | 0.49 6.86 5.16 57 76.2 7.7 | 0.49 3.99 3.46 51 68.7 6.9 |
| Sine wave 1Hz | 0.86 0.52 1.09 NA NA 47.9 3.5 | 0.54 0.14 0.46 47 5.1 0.1 |

### Fig. 2 Input acceleration and response ductility.

These phenomena that can be visually confirmed might vary depending on factors such as rebar arrangement in the affected region, and the number of repetitions of the input. It is obviously difficult to accurately estimate the displacement response from visual inspection.

### 3. EVALUATION OF RESPONSE DUCTILITY

#### (1) Input acceleration and response ductility

According to Table 2 and indications above, it is considered that the response ductility is a valid index for evaluating the degree of damage.

Fig. 2 shows the relationship between the response ductility and the input acceleration. A good correlation implies that the response ductility can be estimated with a certain degree of accuracy from the input acceleration. However attention should be paid since there is a possibility to underestimate the
response in cases where resonance is caused by the input period characteristics. Also, in the case of an actual bridge, it is necessary to set up equipment on the footing of the bridge pier in order to obtain an accurate input acceleration. This may cause significant difficulties, for example when equipment must be installed underground or underwater.

(2) Response acceleration and response ductility
    As mentioned above, input acceleration is not a useful parameter to evaluate the response ductility. Thus, response acceleration is considered.
    
    Fig. 3 shows the relationship between the response acceleration and response ductility measured at the center of gravity. Since no linear relationship can be seen between those values, response acceleration cannot be used to evaluate the response ductility.

(3) Natural period of the column and response ductility
    This section considers the evaluation of response ductility based on the natural period of the columns measured on the top of the bridge pier.
    
    If modeling can be done with a simple single degree of freedom system, the natural period $T$ can be expressed as follows using lumped mass ($m$) and the stiffness of the column $K$.

    $$ T = \frac{2\pi m}{\sqrt{K}} $$

    Here $T_0$, $T_{eq}$ are assumed to be the natural period of the column with no damage prior to excitation and with damaged after excitation, respectively. Similarly $K_0$, $K_{eq}$ are assumed to be the stiffness of the column prior to and after excitation. Then the rate of change in the natural period before and after excitation can be expressed as follows:

    $$ \frac{T_{eq}}{T_0} = \frac{K_0}{K_{eq}} $$

    Assumption that the skeleton curve of the reinforced concrete column in this study is an elasto-plastic model, with a yield force $P_y$, and the yield displacement $\delta_y$ and the response displacement $\delta_r$, then:

    $$ K_0 = \frac{P_y}{\delta_y} $$

    $$ K_{eq} = \frac{P_y}{\delta_r} $$

    Therefore, the rate of change in the natural period before and after excitation is:

    $$ \frac{T_{eq}}{T_0} = \sqrt{\frac{\delta_r}{\delta_y}} = \sqrt{\mu} $$

    Thus the rate of change can be expressed as the function of the response ductility $\mu$.

    With this relationship, it is possible to evaluate the response ductility using the rate of change in the natural period of the column before and after excitation. In calculating the natural period, the value of $T_0$ is calculated from the Fourier spectrum of response acceleration for about 10 seconds immediately prior to receiving the principal motion of the 1st excitation, and the value of $T_{eq}$ is calculated from the Fourier spectrum of response acceleration for about 10 seconds at the free vibration after the excitation.

    Table 3 summarizes the calculated natural periods before and after excitation, and the response ductility evaluated from the change of natural periods. Here, the yield displacement in the table was computed based on the Specifications for Highway Bridges, V. Earthquake Resistant Design.

    Fig. 4 shows the relationship between the re-
Table 3 Natural period and response ductility factor.

| Specimen 1 | X axis direction | Natural period before excitation | Excitation case | Natural period after excitation (sec) | Response displacement at weight center (mm) | Yield displacement (mm) | Response ductility calculated from displacement | Response ductility calculated from natural period |
|------------|------------------|----------------------------------|-----------------|--------------------------------------|---------------------------------------------|------------------------|----------------------------------------------|-----------------------------------------------|
|            |                  | 0.26                             | Natural period  | 0.35                                 | 6.3                                         | 0.4                    | 1.4                                          | 1.4                                           |
|            |                  |                                  | JR Takatori     | 0.34                                 | 6.3                                         | 0.4                    | 1.4                                          | 1.4                                           |
|            |                  |                                  | record 15%      | 0.64                                 | 62.8                                        | 4.3                    | 4.8                                          | 4.8                                           |
|            |                  |                                  | record 50%      | 0.59                                 | 95.6                                        | 8.5                    | 5.4                                          | 5.4                                           |
|            |                  |                                  | record 60%      | 0.79                                 | 136.1                                       | 9.3                    | 7.2                                          | 7.2                                           |
|            |                  |                                  | record 80% 1st time | 0.93                              | 148.2                                       | 10.1                   | 10.1                                         | 10.1                                          |
|            |                  |                                  | record 80% 2nd time | 0.93                              | 137.5                                       | 9.4                    | 10.1                                         | 10.1                                          |
|            |                  |                                  | record 80% 3rd time | 0.93                              | 137.5                                       | 9.4                    | 10.1                                         | 10.1                                          |

| Specimen 2 | X axis direction | Natural period before excitation | Excitation case | Natural period after excitation (sec) | Response displacement at weight center (mm) | Yield displacement (mm) | Response ductility calculated from displacement | Response ductility calculated from natural period |
|------------|------------------|----------------------------------|-----------------|--------------------------------------|---------------------------------------------|------------------------|----------------------------------------------|-----------------------------------------------|
|            |                  | 0.31                             | Natural period  | 0.51                                 | 13.4                                        | 0.9                    | 2.7                                          | 2.7                                           |
|            |                  |                                  | JR Takatori     | 0.72                                 | 176.0                                       | 11.9                   | 10.9                                         | 10.9                                          |
|            |                  |                                  | record 50%      | 0.85                                 | 104.7                                       | 7.1                    | 7.8                                          | 7.8                                           |
|            |                  |                                  | Sine wave 1Hz   | 0.69                                 | 47.9                                        | 3.2                    | 4.8                                          | 4.8                                           |

| Specimen 2 | Y axis direction | Natural period before excitation | Excitation case | Natural period after excitation (sec) | Response displacement at weight center (mm) | Yield displacement (mm) | Response ductility calculated from displacement | Response ductility calculated from natural period |
|------------|------------------|----------------------------------|-----------------|--------------------------------------|---------------------------------------------|------------------------|----------------------------------------------|-----------------------------------------------|
|            |                  | 0.21                             | Natural period  | 0.24                                 | 5.4                                         | 0.5                    | 1.3                                          | 1.3                                           |
|            |                  |                                  | JR Takatori     | 0.45                                 | 76.2                                        | 7.7                    | 5.2                                          | 5.2                                           |
|            |                  |                                  | record 50%      | 0.49                                 | 68.7                                        | 6.9                    | 5.2                                          | 5.2                                           |
|            |                  |                                  | Sine wave 1Hz   | 0.34                                 | 5.0                                         | 0.5                    | 2.6                                          | 2.6                                           |

Fig. 5 Dynamic analysis model.

Fig. 6 Comparison of analysis and experiment with a single-column model (Specimen 1).

4. ANALYTICAL APPROACH

(1) Dynamic analysis for test specimens

The proposed method that evaluates the degree of damage, by calculating the response ductility from changes in the natural period of the bridge pier, was verified in a series of the shaking table tests of reinforced concrete single-columns. To validate the method for actual bridges that have various structural conditions, a series of dynamic analyses were conducted.

Before proceeding to the actual bridge, the test specimen shown in Fig. 1 was modeled as shown in Fig. 5. An attempt was made to reproduce the test results. An elasto-plastic model was used for a skeleton curve as used in evaluation of the test results, so that Eqs. (3) and (4) can be used, and an origin-oriented hysteretic model was used to idealize the hysteretic behavior of the columns.

Fig. 6 shows the comparison of the response ductility evaluated from the rate of change in the natural period of experimental results with analytical results of dynamic analysis.

The analytical results and experimental results exhibit the same trend. It was verified that the response ductility can be reproduced well by using the

response ductility calculated from the rate of change in the natural period and that calculated from the measured maximum response displacement. This figure shows that the response ductility calculated from the change in the natural period agrees well with the actual measured value, regardless of differences in the input direction and differences in the input wave, which implies that the response ductility of the bridge pier can be evaluated with sufficient accuracy by the change of natural period.
origin-oriented hysteretic model.

(2) Dynamic analysis of actual bridge models

Four conditions shown in Table 4 were considered, using the two-dimensional discrete model shown in Fig. 7. Here, ground spring and bearing conditions are considered as parameters. The same analytical conditions including hysteretic model are used.

Fig. 8 compares the results of evaluating the response ductility for Cases 1, 2 and 3. The natural period after excitation \( T_0 \), used for the evaluation of the response ductility, is calculated from the Fourier spectrum of the 10 seconds of free vibration of the node at the top of the pier P2. The natural period prior to the excitation \( T_0 \), is decided based on the predominant vibration mode of the bridge pier P2 obtained from the eigenvalue analysis. This was compared with the response ductility evaluated from the displacement of the node on the top of P2.

The plots shows that there is a good correlation and that the response ductility can be easily evaluated by numerical analysis from changes in the bridge natural period if it has a conventional fix-move bearing system.

However, in Case 4, in which the bridge has elastomeric bearings that are used for distributing horizontal seismic force to each piers, response ductilities obtained from the natural period were equal to 45 to 95 which are about 10 times larger than the actual response ductility. Because the response of the pier P2 is affected by the vibration of the superstructure (via the bearings), as described in details in the next section, it was impossible to estimate the response ductility using the same method as used for conventional bearings.

(3) Evaluation of the response ductility for bridge piers with elastomeric bearings

Fig. 9 shows the Fourier spectrum of the response acceleration at the top of the bridge pier and at the top of the bearing, during free vibration at the end of the excitation with input of 50% JR Takatori record for Case 4. The Fourier spectrum for the acceleration recorded at the top of the pier shows two peaks, around 0.23 sec and 1.08 sec. Because the peak at 1.08 sec has a larger value, the predominant period of the pier, which is used in the method to determine the response ductility, is evaluated to be 1.08 sec, which results in response ductilities of 45-90 as mentioned above. However, if the spectrum is compared to that of the acceleration at the top of the bearing, it is
obvious that the peak around 1.08 sec is the predominant period of the bearing, but not of the pier, and thus, a natural period of 0.23 sec can be determined as the predominant period of the pier. In order to evaluate the predominant natural period of the pier, the spectral ratio was calculated for response acceleration at the top of the bearing and at the top of the bridge pier, as shown in Fig. 10. The predominant period can be evaluated near 0.23 seconds using such spectral ratio. The response ductility of Case 4, which has elastomeric bearings, was evaluated with Eq. (5).

As shown in Fig. 11, it becomes possible to evaluate the response ductility of the bridge pier, even in bridges with elastomeric bearings, by using spectral ratios to eliminate the effects of the super structure response via the bearings.

5. SYSTEM FOR EVALUATING THE DEGREE OF BRIDGE DAMAGE AFTER AN EARTHQUAKE

The sections above have described a method that evaluates the degree of damage to bridge piers from acceleration response measured at the top of the bridge pier. This section will describe a system for evaluating damage for traffic control under disaster condition using this method. Fig. 12 shows the system concept.

The purposes of this system are the prevention of secondary disasters, the collection and provision of traffic network information during a disaster, and the formulation of rational rehabilitation plans for damaged bridges immediately after an earthquake. The system is designed to enable collecting and provision of the information necessary for such purposes.

An integrated sensor unit with an acceleration sensor, microcomputer board and memory is mounted on top of each bridge pier. During an earthquake, the response ductility of each bridge pier is immediately calculated to enable evaluation of its degree of damage. If the response ductility of the bridge exceeds a threshold value, which is set for each bridge, during an earthquake, it is determined that the bridge has been damaged in some way. Subsequently, the bridge is closed to traffic, and the information spread (using information boards etc.). At the same time, the information is provided to road administrators, nearby running vehicles and other
concerned parties as primary correspondence. Furthermore, if a bridge is preliminary determined to have suffered damage, the acceleration time history record stored in the memory is loaded, and used for a more detailed determination of the degree of damage as a secondary determination. This is then used as a basis for decisions relating to recovery plan and repairing methods.

Consolidating a system like this over a wide-area will make it easy to secure road networks during a disaster, even if there is a large scale earthquake, and will smooth support activities inside and outside the affected region.

6. CONCLUSIONS

A series of shaking table tests and dynamic analyses were conducted for developing methods for evaluating the degree of damage to roadway bridges during an earthquake. This research clarified the followings:

- Although a good correlation is found between input acceleration and response ductility, the response may be underestimated due to the period characteristics of the input wave, and thus caution is necessary.
- The response ductility can be evaluated with sufficient accuracy by changes in the natural period before and after excitation, and this is not affected by the input.
- By using the spectral ratio for response at the top of the bridge pier and the super structure, it is possible to estimate the response ductility from changes in the natural period of bridge piers, even in a bridge having elastomeric bearings.

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