DEVELOPMENT OF AN EARTHQUAKE DAMAGE DETECTION SYSTEM FOR BRIDGE STRUCTURES

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Abstract

After a large scale earthquake, evaluation of damage of highway structures such as bridge structures has great importance to assure the emergency route for rescue and transport of urgent supplies. Currently, the damage evaluation is basically conducted by means of visual inspection by bridge experts, but generally it takes so long time to collect whole damage information in the affected area. Therefore, the authors are developing a new damage evaluation system using advanced sensors, which can detect the damage level of structures more correctly and quickly just after the earthquake. This paper presents the proposed "Seismic Damage Evaluation System for Bridge Structures" and the effectiveness of proposed damage evaluation method is demonstrated through a series of shaking table tests. Also, the integration of proposed system to the SATURN system, which is practically used in Japan as a seismic damage information system, is discussed.

1 Introduction

The importance of the quick disaster response including emergency rescue and recovery immediately after an earthquake was recognized anew in the 1995 Great Kobe Earthquake. Especially, the evaluation of damage of highway networks such as bridge structures has great importance because they play key roles in the disaster rescue operations and transports of emergency materials. Currently, the damage evaluation of highway bridges, which are one of the important highway structures, is made based on visual inspection by bridge experts. If a large scale earthquake occurs and several damages are caused, it takes so long time to gather the reliable damage information of all bridge structures in the affected area. And generally it is difficult to evaluate the damage quantitatively by the visual inspection. Since the visual inspection is based on human observation, it is not effective to inspect the damage during night time and to inspect the damage of the structural parts under the ground or water.

Therefore, more detailed and systematic damage inspection system, which can evaluate the structural damage correctly and rapidly without any seasoned professional engineers, is required. The authors are developing the advanced sensors which can detect the damage of structures using new materials such as fibers and TRIP steel, and new damage evaluation method using data set from the sensors.

Figure 1 shows the illustration of the "Seismic Damage Evaluation System for Bridge Structures."

This paper proposes the damage evaluation method of bridge structures based on the natural period change. The relation between the ductility factor and elongation of the natural period is simply obtained and the effectiveness was demonstrated through the

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shaking table tests for a reinforced concrete column. And the Seismic Assessment Tool for Urgent Response and Notification (SATURN) system, which has been currently used at practical stage, is introduced and the integration plan of the Seismic Damage Evaluation System for Bridge Structures to the SATURN system is introduced.

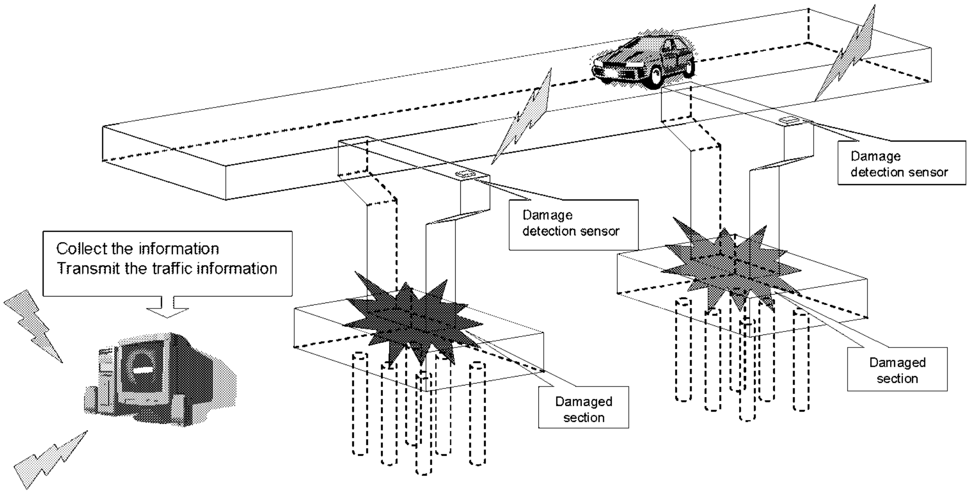


Figure 1. Seismic Damage Evaluation System for Bridge Structures

2 Damage Evaluation Method Using Acceleration Record

2.1 Damage sensing of reinforced concrete columns

To measure the displacement or strain properly, the sensors have to be placed at the most possible damage sections such as the bottom of columns. But the bottom of bridge columns is generally under the ground or water. It is generally hard to put the sensors at the appropriate sections. The authors are proposing a damage evaluation method using acceleration sensors which can be easily put on the existing bridges columns.

Assuming that the bridge system is supported by a reinforced concrete (RC) column as a single degree of freedom system, and assuming that the column has an elasto-plastic force-displacement relation, the natural period of the system is calculated by the **Eqs. (1) and (2)** as below.

$$T = 2\pi\sqrt{\frac{m}{K}} \tag{1}$$

$$T_0 = 2\pi\sqrt{\frac{m}{K_0}} \tag{2}$$

Where,

T_0: Natural period of elastic system without damage

T: Natural period of system after earthquake with certain damage

m: Mass

K_0: Elastic stiffness of system without damage

K: Equivalent Stiffness of system with some damage

The relationship between the change of natural period and ductility factor is simply obtained as follows:

$$T/T_0 = \sqrt{\frac{K_0}{K}} \tag{3}$$

$$K_0 = P_y/\delta_y \quad , \quad K = P_y/\delta \tag{4}$$

$$T/T_0 = \sqrt{\frac{\delta}{\delta_y}} = \sqrt{\mu} \tag{5}$$

Where,

Py: Yield strength
δy: Yield displacement
δ: Maximum displacement response by earthquake
μ: Ductility factor

In the above equation, the equivalent stiffness after earthquake is assumed to be obtained by maximum displacement response and this assumption is generally acceptable for RC structures.

As shown in **Eqs. (5)**, the change of natural period from the initial period without damage is equal to the square root of ductility factor. This means that the damage (ductility ratio) of columns can be evaluated by the data set from the acceleration sensors on the top of the columns.

2.2 Shaking table test

2.2.1 Test specimen and testing conditions

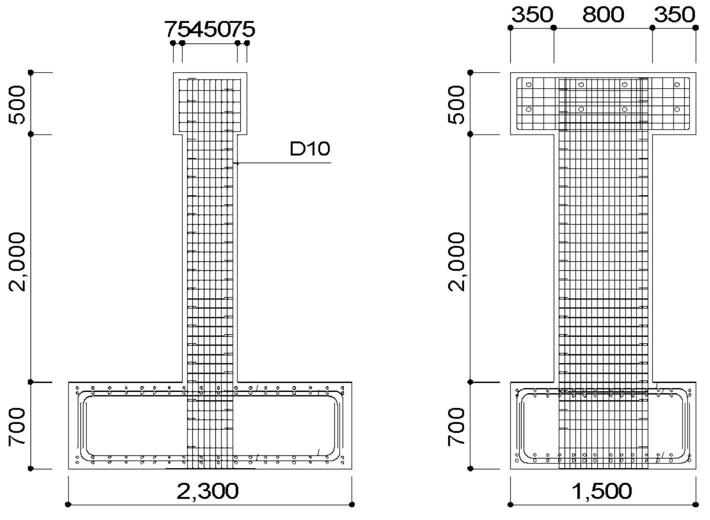


Figure 2. RC column specimen for shaking table test

To verify the proposed damage evaluation method, the shaking table tests were carried out at PWRI. **Figure 2** shows the RC column specimen with rectangular section of 45cm x 80cm. The geometric scale is assumed as about 1/4 of the real one. The reinforcement ratio is designed based on the typical highway bridge columns in the urban area of Japan. Steel weight was fixed at the top of the RC column as an auxiliary mass to apply the axial force and horizontal inertia force. Computed yield displacement and ultimate displacement at the centroid point of the weight were 18.9mm and 62.3mm, respectively.

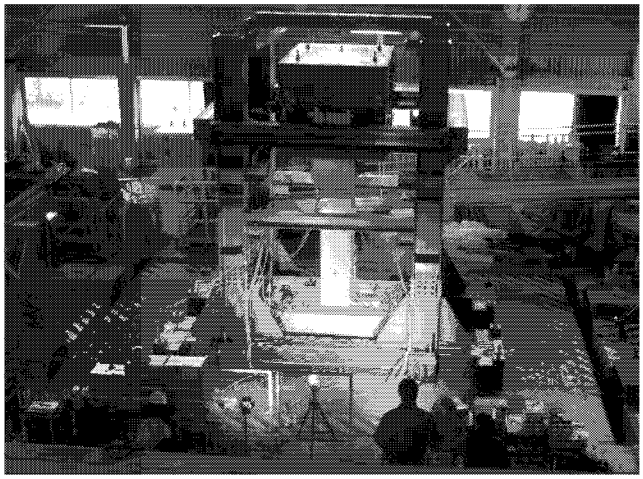
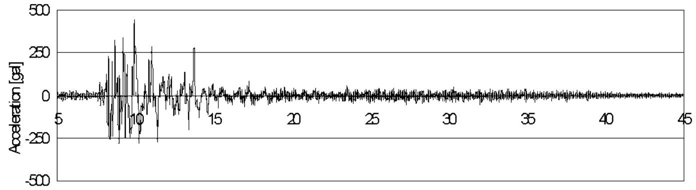


Photo 1. Shaking table test setup

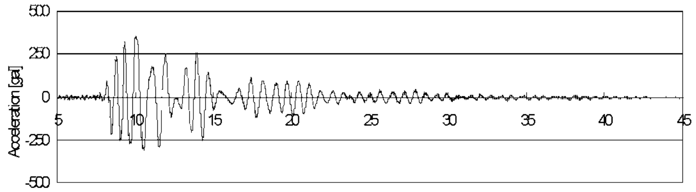
The shaking table was excited in the direction of column weak axis and the north-south component of the records observed at JR Takatori Station in 1995 Kobe earthquake was used as an input earthquake ground motion to the shaking table. Since the geometric scale of the column model is about 1/4 of real one, so the time axis of the input acceleration was compressed to 50%. The amplitude of the input ground motion was increased stepwise from 15% to 80%.

Three axis accelerometers were put on the shake table, the footing of the column specimen and the centroid of the weight at the top of the column. The displacement response was also measured by contactless laser displacement sensor. Strain gauges were put on the re-bars around the bottom of column. **Photo 1** shows the test set up.

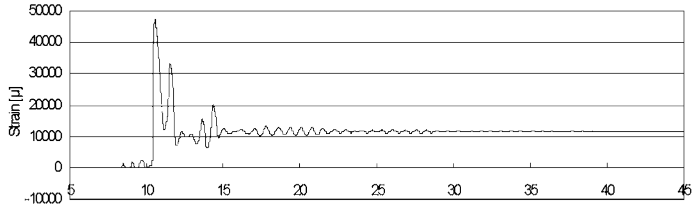
2.2.2 Test results



(a) Acceleration on shaking table [gal]



(b) Acceleration at centroid of weight [gal]



(c) Strain of rebar at the bottom of column [μ]

Figure 3. Time history of accelerations and strain (50% amplitude of Takatori record)

Figure 3 shows the time history data when the column was subjected to the 50% amplitude of JR Takatori record. Time histories of acceleration of the shaking table, response acceleration at the centroid of the weight and response strain of re-bar at the bottom of the column were shown in the figure. The figure shows that the response exceeding the yield point of the column was developed after around 10 seconds of the input motion.

Table 1 summarizes the tested data including the natural period, maximum accelerations, maximum displacement and ductility factors of each shaking step. Natural periods were computed using the Fourier transform of the acceleration data set of 10 seconds after the response became stable. According to the obtained results, the response was in the range of the elastic limit when 15% amplitude of JR Takatori record was input to the shake table. The natural period was increased significantly when 50% amplitude of JR Takatori record was applied.

As shown in **Figure 3**, maximum strain of re-bar at the bottom of column exceeded far beyond the yield point and maximum displacement of the weight also reached to the computed ultimate displacement. After the shaking, the cracks were recognized at the bottom of column by visual observation but no peeling off of the cover concrete was found. Afterward, 60% amplitude and 80% amplitude of the JR Takatori record were applied for input excitation but no significant damage progress was found. The cover concrete was peeled-off when the second excitation of 80% amplitude of JR Takatori record was input.

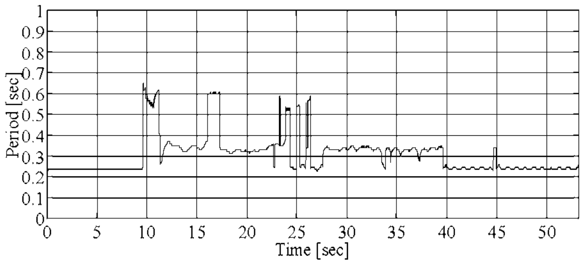
Table 1. Results of the shaking table test

Stages of the test	Natural period (s)	Maximum acceleration on shaking table (gal)	Maximum acceleration on centroid of weight (gal)	Maximum strain of rebar at the bottom of column (micro)	Maximum displacement of weight (mm)	Yield displacement (mm)	Ductility factor calculated from displacement	Ductility factor calculated from natural period
Background shaking befor the test	0.29							
15% of Takatori record	0.34	111	213	795	6	18.9	0.33	1.36
50% of Takatori record	0.64	443	356	47,481	63	18.9	3.32	4.79
60% of Takatori record	0.68	481	339	32,619	96	18.9	5.07	5.44
80% of Takatori record (1)	0.79	722	352	25,716	136	18.9	7.2	7.25
80% of Takatori record (2)	0.93	707	346	17,378	148	18.9	7.84	10.12
80% of Takatori record (3)	0.93	693	308	20,912	137	18.9	7.27	10.12

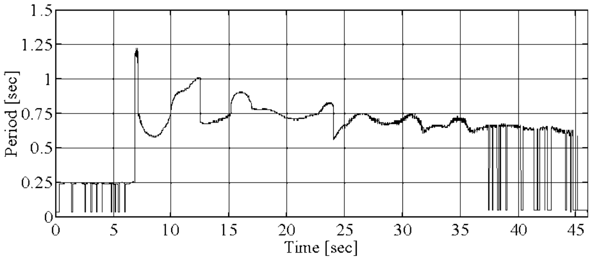
2.2.3 Evaluation of damage based on natural period change

Figure 4 shows the Wavelet transforms of the acceleration response recorded at the centroid of weight at the top of the column. They show the change of the natural period of the column during the shaking. **Figure 4(a)** shows the case when 15% amplitude of JR Takatori record was input and no damage was found.

Figure 4(b) shows the case when 50% amplitude record was input and the nonlinear response exceeding yield displacement was developed. From **Figure 4(b)**, it is found that the natural period was significantly elongated due to the damage occurrence in the column.



(a) Input: 15% of JR Takatori record



(b) Input: 50% of JR Takatori record

Figure 4. Shift of natural period

2.2.4 Evaluation of damage using ductility factor

Figure 5 shows the comparison between the ductility factors computed from the natural period by **Eqs. (5)** and calculated from the observed response displacement. The natural period, yield displacement and displacement response are summarized in **Table 1**. As shown in **Figure 5**, the good agreement was found between them. Therefore, it is possible to easily evaluate the maximum ductility response based on the natural period change using the acceleration data observed at the top of column. Then the damage degree can be evaluated from the ductility response.

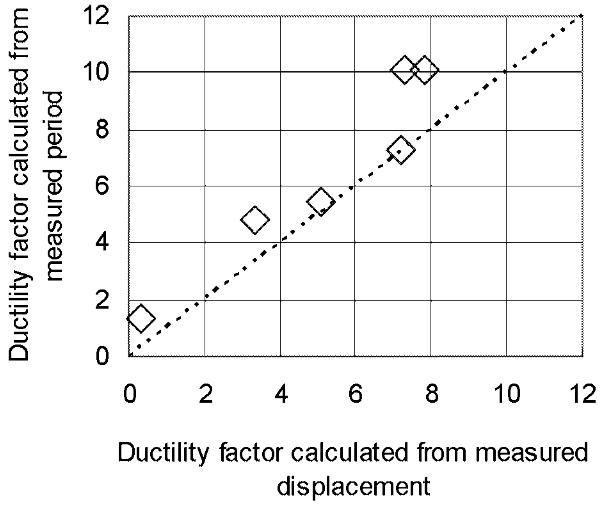


Figure5. Comparison of ductility factor estimated by natural period change and observed displacement

2.3 Development of intelligent sensor

In the above, the damage evaluation method using the natural period change was proposed, and the effectiveness was demonstrated through the shaking table test of an RC column. Based on these results, the authors are developing the following advanced intelligent sensor system which can be easily put on the existing bridges columns.

- ☐ MEMS (Micro Electro Mechanical System) sensor to be applied as an accelerometer. MEMS sensor is mass-produced at low cost recently.
- ☐ The computer program in order to evaluate the damage and estimate the functionality of the bridge structures are being developed and installed in the microcomputer system.
- ☐ Information transmission function is being installed using wireless LAN or ditto technology for notifying the evaluation results and accumulation of evaluation data.
- ☐ Semi permanent power source system which consists of electric generating unit and storage unit is to be installed. The most promising system is the use of solar, wind and vibration generator units and double layer capacitor storage units.

Applying these developed systems, the evaluation of the damage and the judgment of functionality of the bridge structures can be made more reliably and quickly.

3 SATURN System

3.1 Outline of SATURN

SATURN (Seismic Assessment Tool for Urgent Response and Notification) is a tool which gives urgent information to the sectors who are in charge of managing public infrastructures and supports their decision making immediately after an earthquake. This system provides rough estimation of damage on public infrastructures in the early stage when the sectors have insufficient information. This system is already being used in some regional development bureaus of MLIT (Ministry of Land, Infrastructure and Transportation).

MLIT has the seismograph network system to get earthquake ground motion characteristics such as maximum acceleration, spectrum intensity value and JMA (Japan Meteorological Agency) seismic intensity immediately after an earthquake. From the data collected in the network, SATURN provides ground motion distribution monitored at some 100 sites of each regional development bureau in a short time. SATURN also provides rough estimation of liquefaction risk and damage on river embankments as well as highway bridges in about 15 minutes. System functions of SATURN are display of the earthquake information and simulation of contingent earthquake.

Immediately after an earthquake, SATURN will display the information from seismograph and the estimated damage of public infrastructures on the screen. It also displays detailed damages and geological information and manages the damage investigation data.

3.2 Integration of intelligent sensor system into the SATURN system

Current SATURN system estimates damage of bridges empirically based on calculated ground vibration intensity levels, soil conditions and structural conditions. Accordingly the accuracy of the estimation results can be significantly improved while the information is obtained from the intelligent sensors.

4 Conclusions

☐ New damage evaluation method for bridge structures based on natural period change is proposed. The effectiveness of the method was demonstrated by shaking table test.

☐ It is shown that the response ductility factor can be estimated from the natural period change with reasonable accuracy by the shaking table test.

☐ The concept of the new advanced intelligent sensor which contains of a sensor, a microcomputer, a self-generator and a wireless LAN or similar system was introduced.

☐ The new damage evaluation system using advanced intelligent sensors will be integrated to the SATURN system and it will be able to give urgent information more properly and promptly with the purpose of the time after an earthquake.

References

1. Adachi Y, and Unjoh S. "Development of Shape Memory Alloy Damper for Intelligent Bridge Systems", Proc. of the 6th smart structures and materials, Newport beach, CA, March 1999
2. Adachi Y, Unjoh S. "Seismic damage sensing of bridge structures with TRIP reinforcement steel bars", Proc. of the 7th smart structures and materials, Newport beach, CA, March 2000
3. Kusakabe T, Sugita H, Ohtani Y,Kaneko M, Hamada T. "SATURN –Seismic Assessment Tool for Urgent Response and Notification", Technical note of NILIM No.71, Jan 2003 (In Japanese)