Development of Quick Damage Inspection Method of Jacketed Viaduct Using Microtremor Measurement & Numerical Simulation

by

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ABSTRACT

In this paper, we discuss an evaluation method of vulnerability of retrofitted viaduct with steel jacket using microtremor measurement and a new efficient numerical model for non-linear, large deformation and collapse behaviour of structures.   Railway structures suffered from severe damage by the 1995 Hyogo-Ken Nanbu (Kobe) Earthquake.   Therefore, more than 40,000 columns of railway viaducts of Japan Railways were retrofitted. Although steel jacketing is effective for improving the flexural ductility and shear strength of concrete columns, there are still problems to be solved.   Since we cannot see the condition of concrete columns inside a jacket, we cannot detect the effects of incomplete retrofit construction work and the damage to the concrete column inside a jacket due to strong seismic motions without opening the jacket.   Also, the dynamic characteristics of the jacketed viaducts are little known, we cannot evaluate the vulnerability of jacketed viaduct by the existing method based on the natural frequency of the viaduct.   Therefore, we develop an evaluation method of vulnerability of jacketed viaduct using combination of microtremor measurement and numerical analysis.

Key Words: damage assessment, microtremor measurement, retrofit, jacketed column, dynamic analysis, cyclic loading, Applied Element Method

1. INTRODUCTION

Railway structures suffered from severe damage by the 1995 Kobe Earthquake[1].   Therefore, more than 40,000 columns of railway viaducts of Japan Railways were retrofitted.   The most popular retrofit technique for the columns is a steel jacketing.   Although steel jacketing is effective for improving the flexural ductility and shear strength of concrete columns, problems still exist.   As we cannot see the condition of concrete columns inside the jacket, we cannot detect the effects of incomplete retrofit construction work and damage to the concrete column inside a jacket caused by strong seismic motions without opening the jacket.   Also, as dynamic characteristics of the jacketed viaducts are little known, the vulnerability of jacketed viaduct can hardly be evaluated by the existing

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method that is based on the natural frequency of the viaduct. Therefore, we develop a vulnerability assessment methodology of jacketed viaduct using combination of microtremor measurement and numerical analysis.

2. DETECTION OF NATURAL FREQUENCY OF VIADUCT USING MICROTREMORS

2-1 Outline of the measurement and analysis

Ground and structures in general are always vibrating with small amplitude due to the natural and artificial sources such as wind, tidal wave, traffic noise, industrial vibration, and so on. This vibration is called "Microtremor". Dynamic characteristics of a structure can be obtained if the microtremor can be measured and analyzed. The procedure is introduced below.

1) Setting sensors on a viaduct and on the ground near the viaduct as shown in **Fig. 1**.

2) Measuring microtremors of the viaduct and the ground simultaneously.

3) Calculating spectral ratio between horizontal components recorded on the viaduct and on the ground to obtain the predominant frequency of the viaduct from the peak frequency of the spectral ratio.
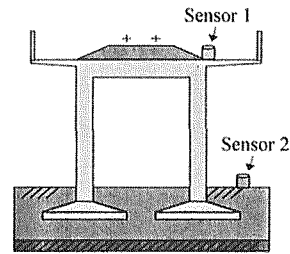

Fig. 1   Railway viaduct and sensors

An instrument developed by the Railway Technical Research Institute (RTRI)[2] was used for measurement. It consists of two sensor units, cables and a main body that contains amplifiers, an A/D converter and a notebook type personal computer. At every observation point, two horizontal components (transverse and lateral components to the railroad) and one vertical component of microtremor are recorded at every 1/100 sec for 40.96 sec. The measurement is repeated three times at each point. In this paper, we discuss transverse component to the railroad. Fourier spectra for the recorded data are calculated and smoothed by using Hanning spectral window. One spectrum of one component of microtremor was estimated by averaging the relevant three Fourier spectra. **Figure 2** illustrates the efficiency of the method using spectral ratio between two components on a viaduct and on a ground. Although the spectrum of the viaduct has three major peaks, a, b and c, the spectral ratio shows the clear peak b'. We can recognize that the peaks, a and c, are affected by the peaks, a' and c', from the ground vibration.
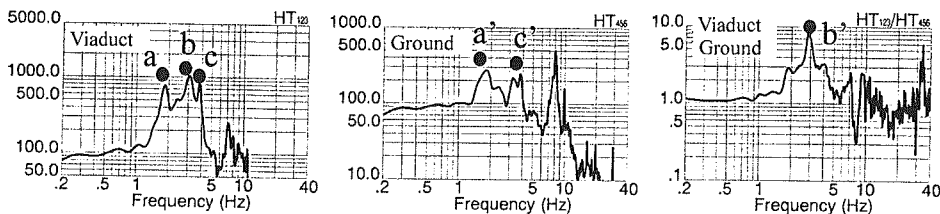

Fig. 2   Detection of the predominant peak using spectral ratio

2-2 Measured viaduct and ground condition

Figure 3 shows the measured viaducts. Viaducts from A to C are located on the soft ground composed of humus or alluvial clay. Viaduct D is on the alluvial sandy gravel. The microtremor measurements were conducted before and after retrofit constructions. Standard shape of a railway viaduct and cross-section of jacketed column are shown in the **Fig. 4**. The widths of the column of these viaducts range from 0.6 to 0.8 (m), height from the ground surface ranges from 4.2 to 5.8 (m), and pile length ranges from 0 to 13.0 (m), respectively.

2-3 Frequency change due to retrofit construction

Figure 5 shows the relationship between the predominant frequency before retrofit operation and the height of viaduct. The predominant frequency of the viaduct is distributed within the range from 2.4Hz to 4.5Hz. It is ascertained that there is a good correlation in the frequency and the bridge height. The frequency group of viaducts whose frequency has low correlation with the height was observed in the viaducts which stand on thick layer of alluvial clay with long piles. We must consider the influence from the ground and foundation when we evaluate the dynamic properties of structure using natural frequency. **Figure 6** shows the change of frequencies of viaducts due to jacketing construction. After the steel jacketing operation, rise in the predominant frequency caused by the increase of the stiffness of the columns was confirmed. However, in a few viaducts, the frequency became lower than before. Because these were the viaducts touching with the abutment, the predominant peak of the viaduct is affected by the abutment. Therefore, their natural frequency became high in general and it was difficult to determine the peak of the spectrum of the viaduct. In such a viaduct, we should devise the method of measurement. For example, a spectrum ratio on the viaduct and the abutment should be used.
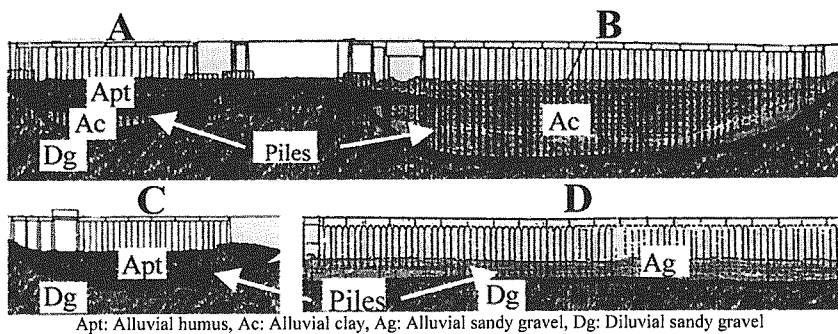

Apt: Alluvial humus, Ac: Alluvial clay, Ag: Alluvial sandy gravel, Dg: Diluvial sandy gravel

Fig. 3 Measured viaducts and ground conditions

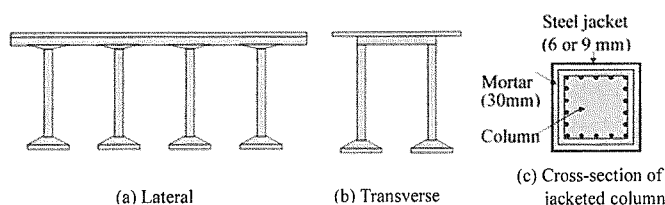(a) Lateral   (b) Transverse   (c) Cross-section of jacketed column

Fig. 4 Standard shape of railway viaduct and cross section of jacketed column
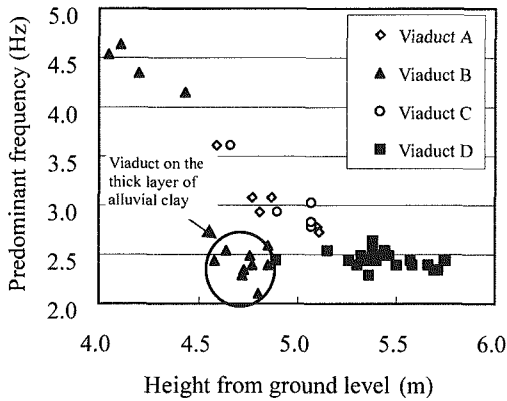
Fig. 5   Relation between predominant
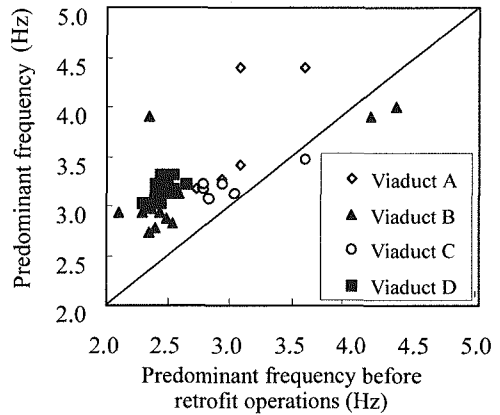frequency and height of viaduct

Fig. 6   Change of predominant frequency of viaducts
before and after jacketing operation

2-4 Comparison of the simulation result and measurement result

In this paper, two tools, microtremor measurement and new technique for numerical simulation, are dealt with.   From the previous result, we can say that the natural frequency can be evaluated by using microtremor measurement.   As the next step, the efficiency of new technique for numerical simulations is verified.   The numerical analyses of the viaducts are enforced and the results are compared with the measurement results.   The Applied Element Method (AEM)[3], which will be discussed later, is used for simulation.   **Figure 7** shows the example of structural system to be analyzed, and the dimension of each part of the simulation model is within the range shown in **Table 1**. Pn in the table shows the number of the piles.   The material properties of the concrete and reinforcing bars used in this study are standard values decided by the actual strength of the materials[4].   The results are shown in **Fig. 8**.   Although there is the minor exception, the error is within only 0.3 Hz range.   The simulation results agree well with the measurement values.   These results show that the natural frequency of the viaduct can be evaluated accurately by the AE simulation.

Table 1   Range of dimensions of each part of the simulation model

H (m)	b (m)	h(m)	D(m)	L(m)	Vs (m/s)	Wh(m)	Wp(m)	Pn
4.6 – 5.4	0.6 –0.8	1.0 – 1.5	0.4 – 1.8	3.0 – 12.0	80 - 200	3.2 – 4.0	0.3– 0.45	0 - 11
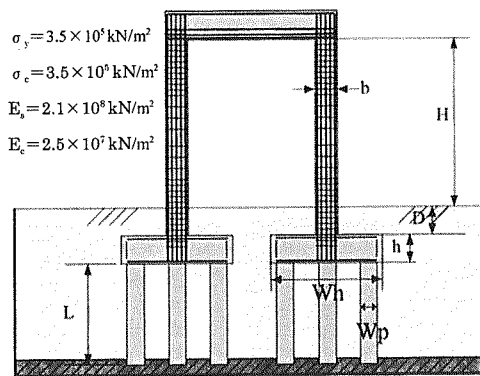
Fig. 7 Structural systems for simulation

$\sigma_y = 3.5 \times 10^5 \, \text{kN/m}^2$

$\sigma_c = 3.5 \times 10^5 \, \text{kN/m}^2$

$E_s = 2.1 \times 10^8 \, \text{kN/m}^2$

$E_c = 2.5 \times 10^7 \, \text{kN/m}^2$
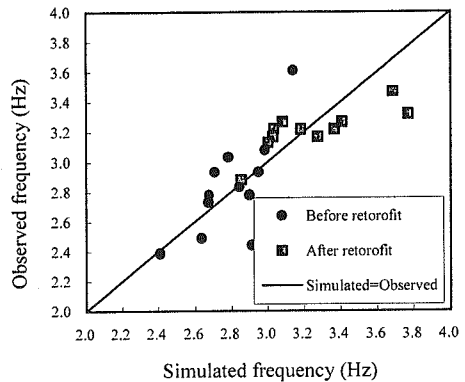

Fig. 8 Comparison between the results obtained by simulation and measurement

3. ESTIMATION OF DAMAGE LEVELS OF THE COLUMN INSIDE JACKET

3-1 Outline of Applied Element Method (AEM)

Applied Element Method (AEM) is a newly developed method for structural analysis. The main advantage of the method is that it can follow the total structural behavior from elastic range, crack initiation and propagation, separation of structural elements till the collapse accurately in reasonable CPU time[3]. With the AEM, structure is modeled as an assembly of small elements, which are made by dividing the studied structure virtually, as shown in **Fig. 9 (a)**. The two elements shown in **Fig. 9 (b)** are assumed to be connected by pairs of normal and shear springs located at contact points, which are distributed around the element edges. Each pair of springs totally represent stresses and deformations of a certain area (hatched area in **Fig. 9 (b)**) of the studied elements. At the location of reinforcement, two pairs of springs are used, for concrete and for reinforcement bar. This means that the reinforcement spring and concrete spring have the same strain and the effects of relative displacement between reinforcement bars and surrounding concrete is not considered within an element. However, when we look at the behavior of element collection as a unit, relative displacement between elements occurs because of failure of concrete springs before the failure of reinforcement springs, and hence, relative displacement between reinforcement bars and surrounding concrete can be taken into account automatically. In the AEM, reinforcement springs can be set at the exact location of the reinforcement bars in the structural model. Each of the elements has three degrees of freedom in two-dimensional model. Therefore, the element motion is as a rigid body. However, its internal deformations are represented by the spring deformation around each element. This means that although the element shape doesn't change during analysis, the behavior of assembly of elements is deformable.

The simulation of the railroad viaduct has already been done[5], and we could get good results in the modal analysis and collapse behavior simulation.
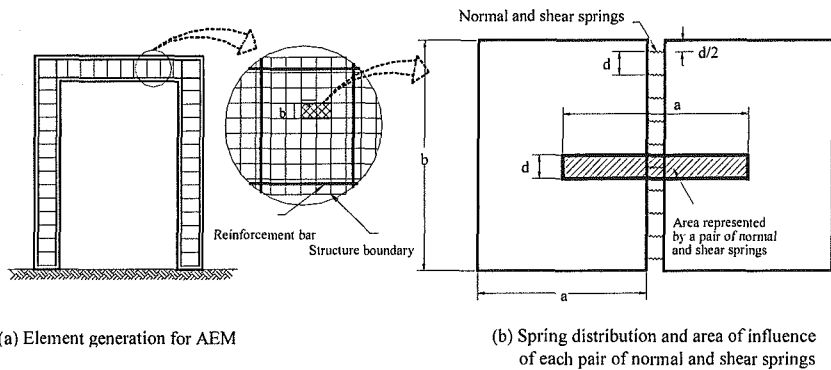
(a) Element generation for AEM

(b) Spring distribution and area of influence of each pair of normal and shear springs

Fig. 9 Modeling of structure in AEM

3-2 Two dimensional modelling of jacketed column[6]

Two-dimensional model of a jacketed column by using AEM is proposed. The model of the structure is composed of three different types of elements. The first one is the concrete element inside jacket (Element type E_C), the second one is the element for side jacket (Element type E_{JS}) and the third one is jacket element between two-side jackets (Element type E_{Jb}). First one has a concrete material property and the other two types of elements have the material property of steel. There is no connection between the elements of E_{Jb} and Ec in the bottom figure of **Fig. 10**. Because the edge elements of both E_C and E_{Jb} are connected with E_{JS}, the inside concrete is restrained by the steel jacket. Inside concrete is permitted to crack and reinforcements are permitted to yield and cut.
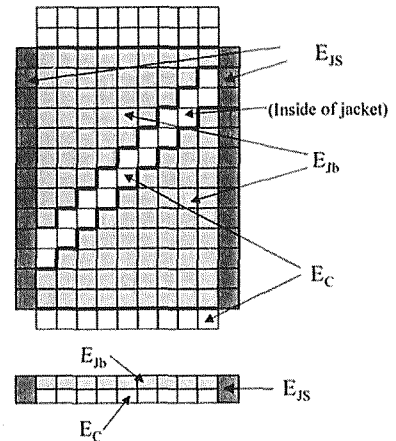

Fig. 10 Modeling of jacketed column

3-3 Effects of jacketing

To verify an accuracy of the 2-D Jacketing model using in the study, numerical simulation in case of cyclic loading to the jacketed column is performed. The simulation of the column without jacket is also carried out for the comparison. **Figure 11** shows the reinforcement details of the specimens. The specimen without jacket is modeled using 1,224 elements of 0.05 (m)$\times$0.05 (m). Additional 266 elements are used for the jacket model.

Material properties are as follows:

σ_y(for D22)=3.8×10^5 kN/m^2, σ_y(for D6)=3.7×10^5 kN/m^2, σ_y(for Jacket)=1.8×10^5 kN/m^2, σ_c=2.6×10^4 kN/m^2, E_c=2.5×10^7 kN/m^2, E_s=2.1×10^8 kN/m^2.

Figure 12 shows the simulation results and envelope lines obtained by the experiment[7]. As for the jacketed column, the improvement of the ductility is obvious. The envelopes of the simulation results agree well with the experimental results. These results show the validity of our method.
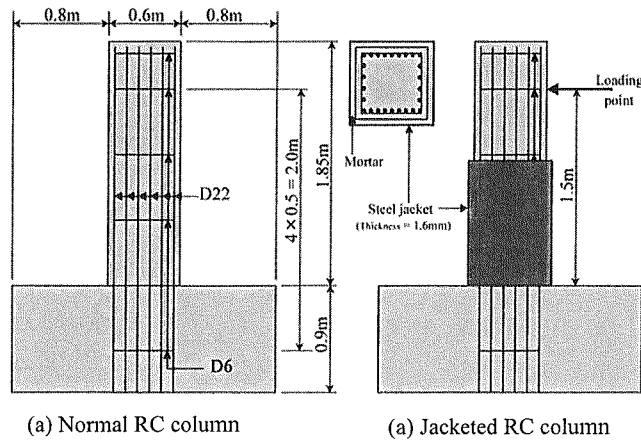

(a) Normal RC column   (a) Jacketed RC column

Fig. 11 Reinforcement details of the columns with and without steel jacket

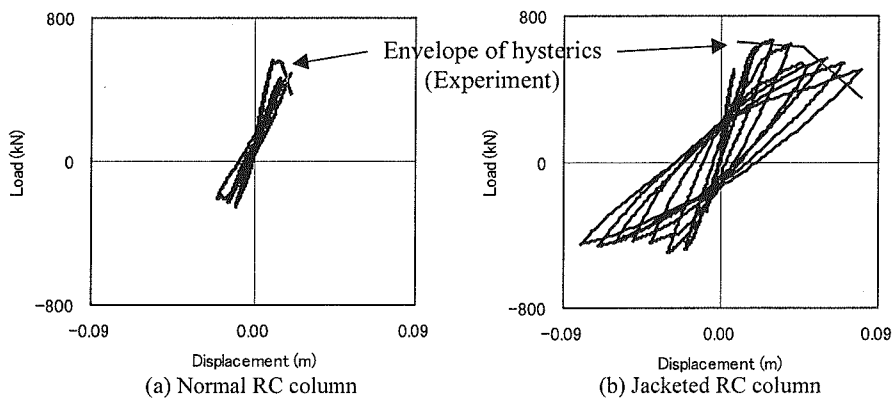(a) Normal RC column   (b) Jacketed RC column

Fig. 12 Hysterics curves by numerical simulation and envelope of hysterics by experiment

3-4 Change of frequency of jacketed viaduct due to the damage

As we cannot see the condition of concrete columns inside jacket, we cannot detect the damage to the concrete column caused by strong seismic motions without opening the jacket. It is very useful from the view point of damage assessment if a degree of damage to the viaduct can be evaluated by the microtremor measurement. To make it possible, it is necessary to obtain before hand the relationships between change of natural frequency and damage level which are not known well yet. Using our proposed method, the damage to the jacketed column can be simulated easily and furthermore, the relation between the frequency changes of structure and damage levels can be evaluated.

Here, ground acceleration is applied to two viaduct models, and change of the natural frequency of the viaducts due to the damage to the columns is examined. **Figure 13** shows the viaduct models. The model in the left is viaduct without jacket, while the other is the model with jacket reinforcement. The viaduct without jacket was modeled using 448 elements of 0.16 (m) × 0.16 (m). Additional 406 elements are used for the jacket model. Material properties are as follows: $\sigma_y = 3.5 \times 10^5$ kN/m², $\sigma_c = 3.2 \times 10^4$ kN/m², $E_c = 2.5 \times 10^7$ kN/m², $E_s = 2.1 \times 10^8$ kN/m². Input ground acceleration is shown in **Fig. 14**.

Figure 15 shows the change of natural frequency of the viaduct models. Both decline conditions are the same in the beginning stage. However, the change after about three seconds becomes different. Though natural frequency of the viaduct without jacket decreases rapidly, the frequency of jacketed viaduct decreases slowly. From the results, it can be said that the ductility of the viaduct is increased by the jacketing. **Figure 16** shows the region of cracks of both viaducts in different time. Until three second, there is no big difference between the regions of cracks in two cases. The bending tension cracks (the crack only horizontal direction) are observed in the joint corners between the columns and slabs and also columns and foundations of both viaducts. After four seconds, the crack propagation of the viaduct without jacket becomes obviously faster than that of the jacketed viaduct. In the viaduct without jacket, the diagonal cracks (cracks composed of the horizontal and vertical cracks) which may cause shear destruction are observed. At five seconds, cracks are distributed in the whole surface of the columns, and the condition of the viaduct without jacket becomes very dangerous. In the Jacketed viaduct, crack does not reach the center of the column. The effect of the reinforcement is obvious. If the results introduced in **Figs. 15** and **16** are used effectively, the damage levels of the viaduct and the change of natural frequency can be systematized as shown in **Fig. 17**.
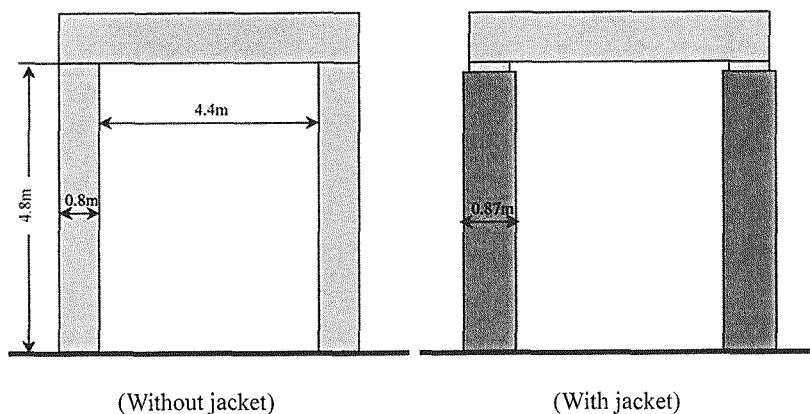

(Without jacket)   (With jacket)

Fig. 13   Dimensions of viaduct models with and without jacket for numerical simulation
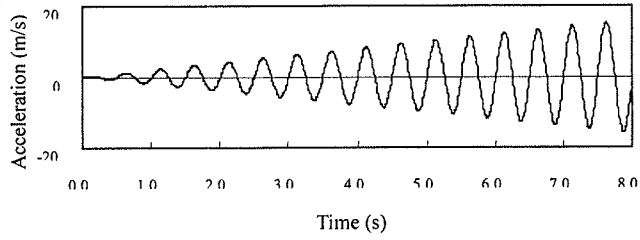
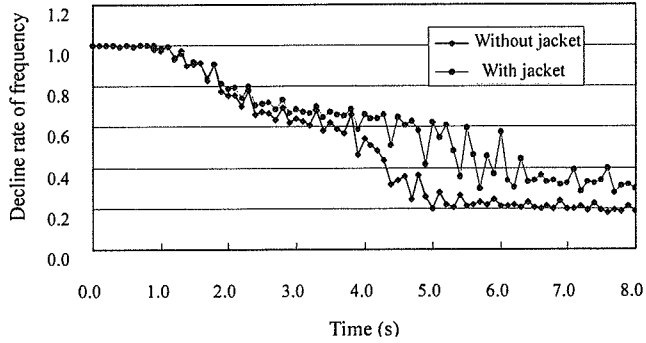**Fig. 14** Input ground motion (Acceleration)

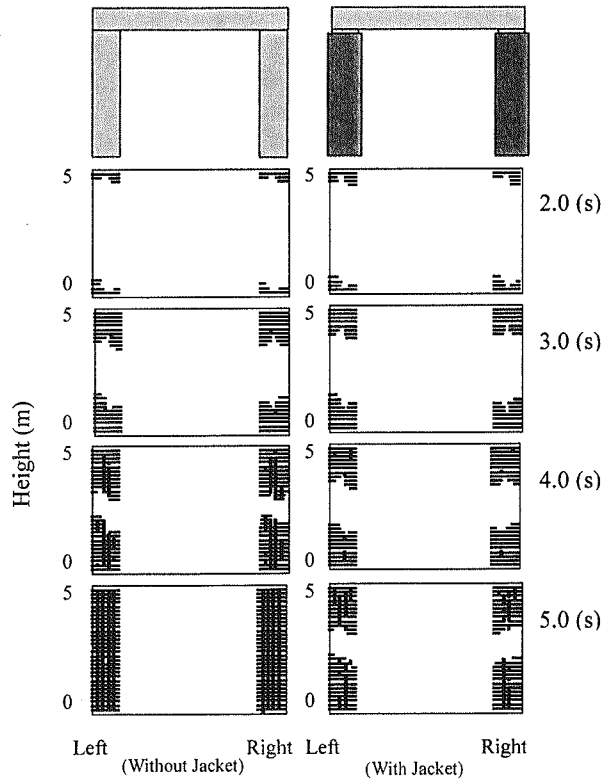**Fig. 15** Changes of natural frequency of the viaduct models

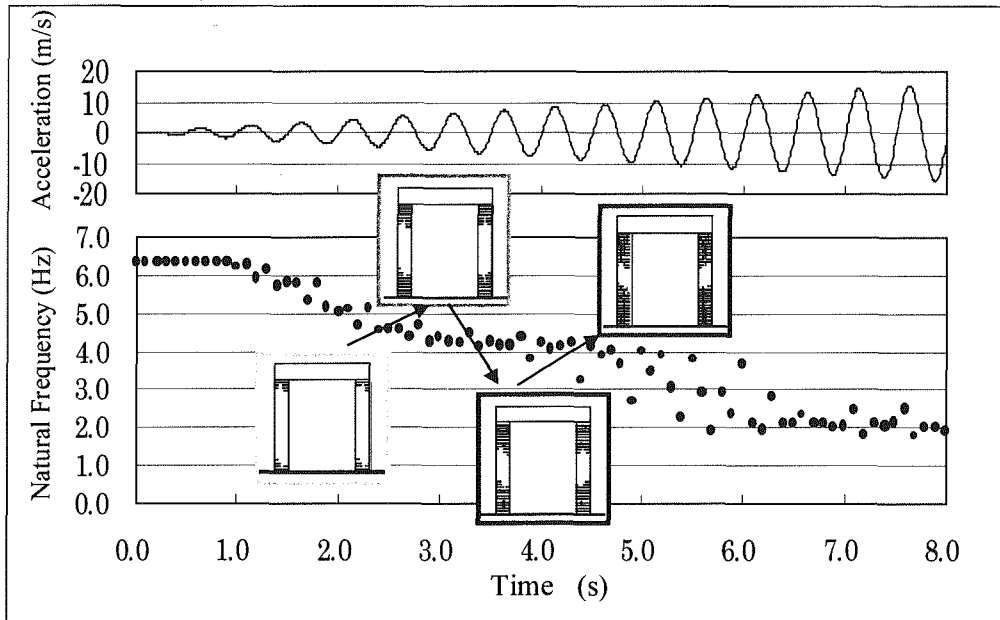**Fig. 16** Propagation of cracks in concrete

Fig. 17 Relation between damage level inside jacket and change of natural frequency of the viaduct

4. CONCLUSIONS

Following are the conclusions based on the results obtained from this study.

1) Using microtremor measurement, the natural frequency of viaducts can be obtained accurately, quickly and safely. Change of natural frequency of viaducts due to retrofit operations can also be detected.

2) By comparing the natural frequency of the viaduct before and after retrofit operations, we can detect the effect of incomplete retrofit construction work.

3) AEM has sufficient accuracy to obtain the natural frequency of viaducts.

4) Simulation results using the proposed model of jacketed column agree well with the experimental results.

5) Using the AEM, we can obtain the relation between the damage level of jacketed viaduct and change of the natural frequency easily.

6) If we prepare a database of the frequency change of viaduct by numerical simulation, we can assess the seismic damage to the jacketed viaduct by microtremor measurement without opening the jacket.

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