VULNERABILITY EVALUATION OF JACKETED VIADUCT USING MICROTREMOR MEASUREMENT & NUMERICAL SIMULATION

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SUMMARY

In this paper, we discuss a vulnerability assessment methodology of retrofitted viaduct with steel jacket using microtremor measurement and a new efficient numerical model for non-linear, large displacement 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. The most popular retrofit technique for the columns was a steel jacketing. Although steel jacketing is effective for improving the flexural ductility and shear strength of concrete columns, problems still exist. As we can not see the condition of concrete columns inside a jacket, we can not detect 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 cannot be evaluated by the existing method that is based on the natural frequency of viaduct. Therefore, we develop a vulnerability assessment methodology of jacketed viaduct using combination of microtremor measurement and numerical analysis. We could confirm that microtremor measurement is an efficient tool for detecting the natural frequency of viaduct, and also by the Applied Element Method (AEM), dynamic properties of structures can be simulated accurately. We can detect results of incomplete retrofit construction work by comparing the predominant frequency before and after retrofit operations. If we obtain the relation between change of natural frequency and damage level of jacketed viaducts by using numerical simulation, it becomes possible to grasp the damage levels of jacketed viaducts accurately and quickly by microtremor measurements just after the earthquake.

INTRODUCTION

Railway structures suffered from severe damage by the 1995 Kobe Earthquake [RTRI, 1996]. 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 can not see the condition of concrete columns inside the jacket, we can not detect 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 method that is based on the natural frequency of viaduct. Therefore, we develop a vulnerability assessment methodology of jacketed viaduct using combination of microtremor measurement and numerical analysis.

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DETECTION OF THE NATURAL FREQUENCY OF VIADUCT USING MICROTREMORS

2.1 Outline of the measurement and analysis

The ground is 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 analysed. The techniques are introduced below.

1) Setting sensors on a viaduct and on ground near the viaduct. (**Figure 1**)
2) Measuring microtremors of the viaduct and the ground simultaneously.
3) Calculating a 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.

An instrument developed by the Railway Technical Research Institute [Nakamura, 1996] 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, horizontal components (transverse and lateral components to the railroad) and one vertical component of microtremor were recorded every 1/100 sec for 40.96 sec. The measurement was repeated three times at each point. In this paper, we argue transverse component to the railroad. Fourier spectra for the recorded data were 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 component on the viaduct has three major peaks a, b and c, the spectral ratio shows the clear peak b'. We can recognise that the peaks a and c are affected by the peaks a' and c' from the ground component.

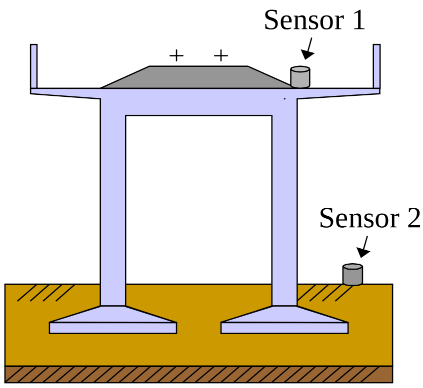


Figure 1: Railroad viaduct and sensors for microtremor measurement

2.2 Measured viaduct and ground condition

Figure 3 shows the measured viaducts. Viaducts from A to C are standing 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 **Figure 4**. The widths of the column of these viaducts range from 0.6 to 0.8 (m), height from ground surface are range from 4.2 to 5.8 (m), and pile length range from 0 to 13.0 (m), respectively.

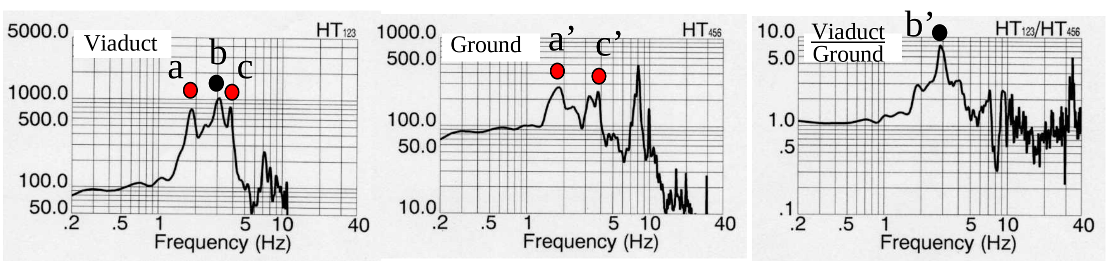
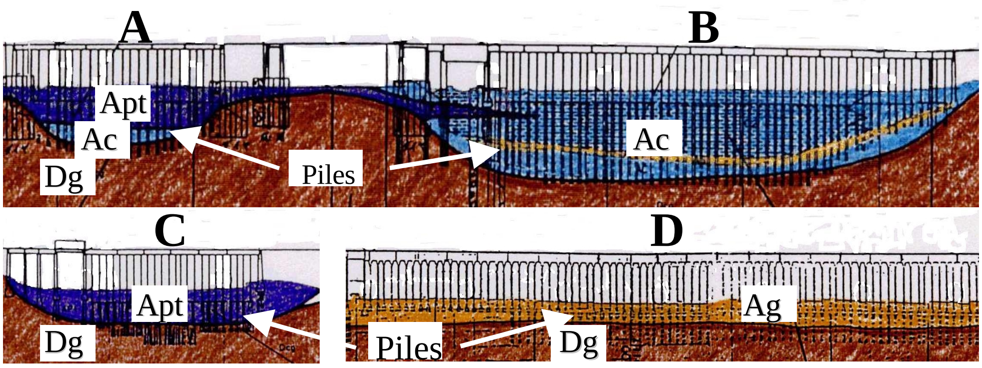


Figure 2: Selection of the predominant peak using spectral ratio



Apt: Alluvial humus, Ac: Alluvial clay,

Ag: Alluvial sandy gravel, Dg: Diluvial sandy gravel

Figure 3: Measured viaducts and ground conditions

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 of 2.4Hz to 4.5Hz. It ascertained that there is 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 becomes lower than before. Because these are the viaducts touched with the abutment, whose natural frequency is high in general, the predominant peak of the viaduct is affected by the abutment and it becomes 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.

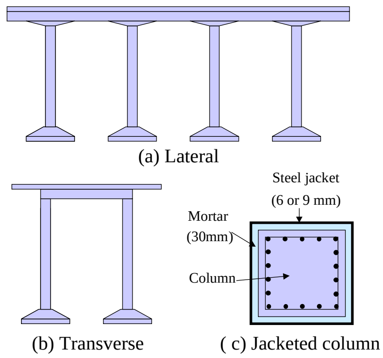


Figure 4: Standard shape of railroad viaduct and cross section of jacketed column

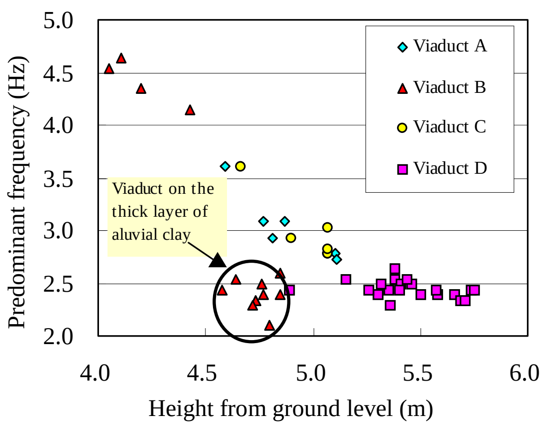


Figure 5: Relation between predominant frequency and height of viaduct

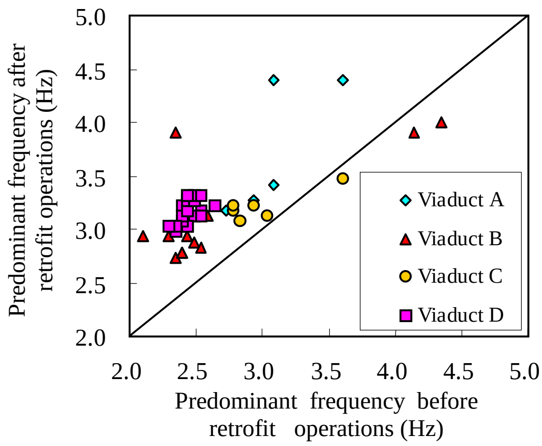


Figure 6: Change of predominant frequencies of viaducts before and after jacketing operations

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 estimated 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) [Meguro and Tagel-Din, 1997] which will be discussed later is used for simulation. **Figure 7** shows the example of structural system to be analysed, 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 [JCI, 1999]. The results are shown in **Figure 8**. Although there is the minor exception, the error is within only 0.3 Hz range. The simulation results correspond to the measurement values well. These results show that the natural frequency of the viaduct can be estimated accurately by the AEM 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

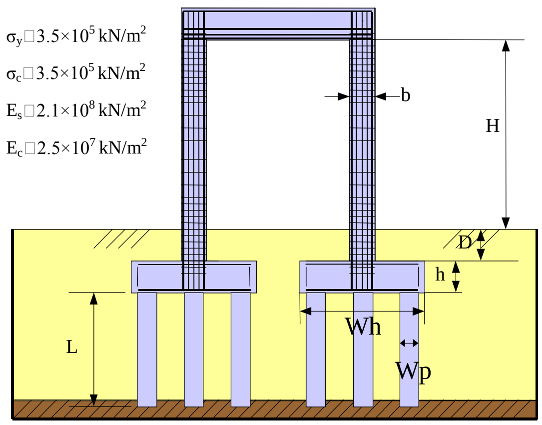


Figure 7: Structural systems for simulation

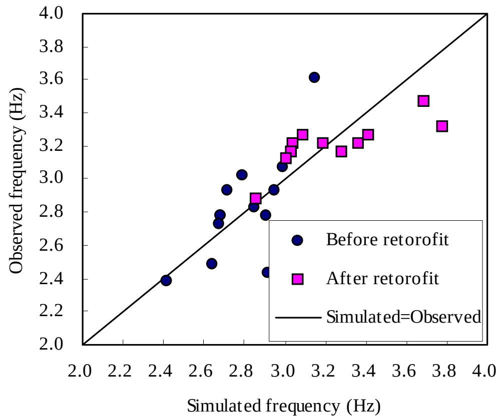


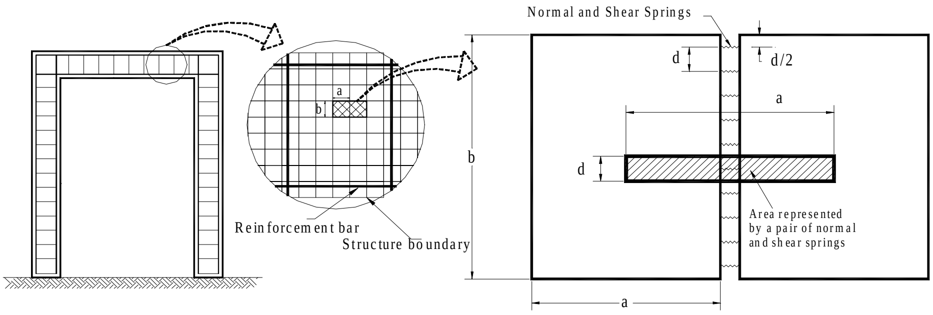
Figure 8: Comparison between the results obtained by simulation and measurement

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 structural behaviour from elastic range, crack initiation and propagation, separation of structural elements to total collapse in reasonable CPU time with reliable accuracy. With the AEM, structure is modelled as an assembly of small elements, which are made by dividing the studied structure virtually, as shown in **Figure 9 (a)**. The two elements shown in **Figure 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 **Figure 9 (b))** of the studied elements. All 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 separation between reinforcement bars and surrounding concrete can not be easily considered within an element. However, when we look at the behaviour of element collection as a unit, due to the stress conditions, separation 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. These degrees of freedom represent the rigid body motion of the element. Although the element motion is as a rigid body, 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 behaviour of assembly of elements is deformable.
The simulation of the railroad viaduct has already been done [Uehan and Meguro, 1999], and we could get good results in the modal analysis and collapse behaviour simulation.



(a) Element generation for AEM (b) Spring distribution and area of influence of each pair of spring

Figure 9: Modelling of structure to AEM

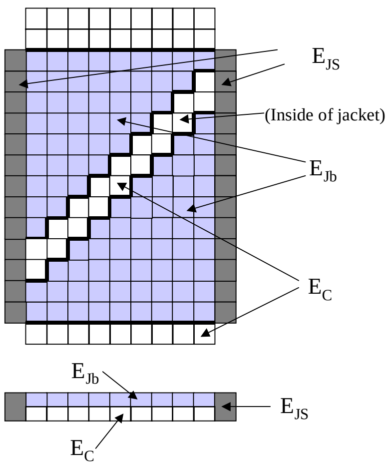


Figure 10: Modelling of Jacketed column

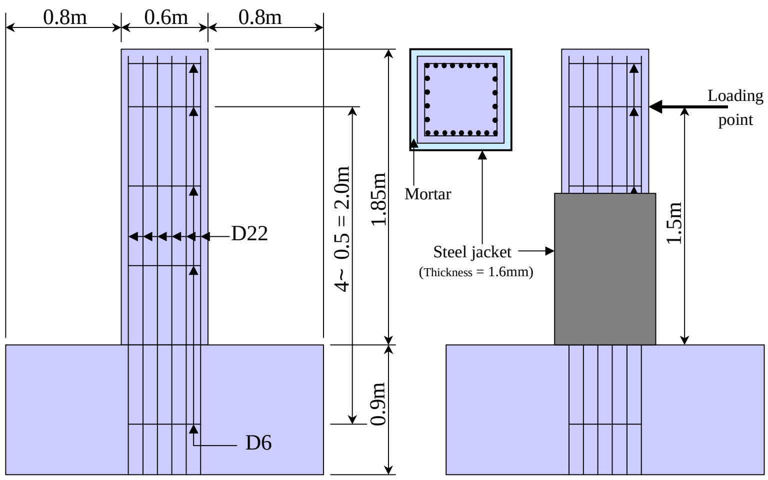


Figure 11: Specimens for cyclic loading

3.1 Two dimensional modelling of jacketed column

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 **Figure 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.

3.2 Effects of jacketing

To verify an accuracy of the 2-D Jacketing model, numerical simulation in case of cyclic loading to the jacketed column is performed. The simulation of the column without jacket is also enforced for the comparison. **Figure 11** shows the reinforcement details of the specimens. The specimen without jacket is modelled using 1,224 elements of 0.05 (m) ×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 [Nagaya, *et al.*, *1999*]. 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.

3.3 Change of frequency of jacketed viaduct due to the damage

As we can not see the condition of concrete columns inside jacket, we can not detect the damage to the concrete column caused by strong

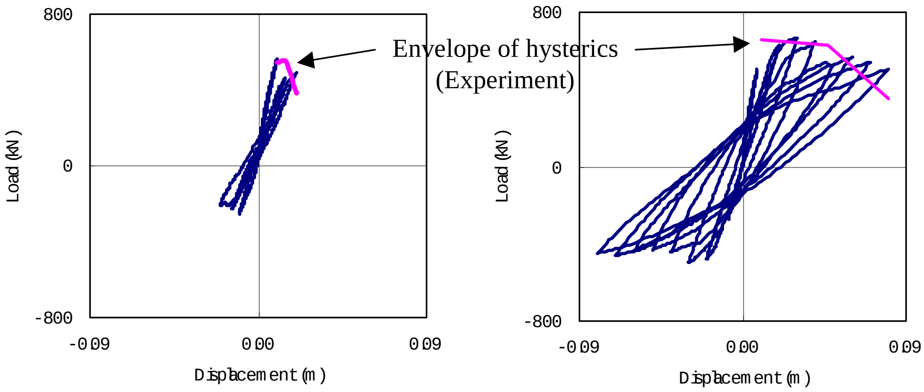


Figure 12: Hysterics curves by AE simulation and envelope of hysterics by experiment

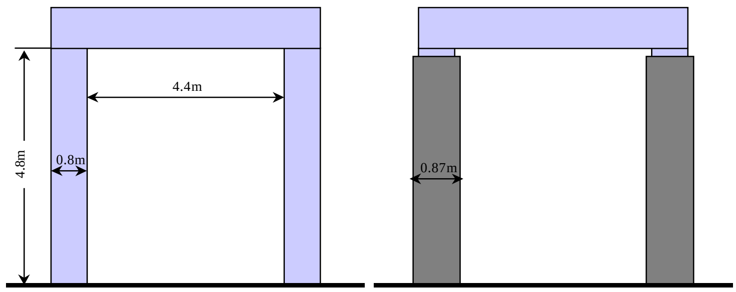


Figure 13: Dimensions of viaduct models with and without jacket for simulation

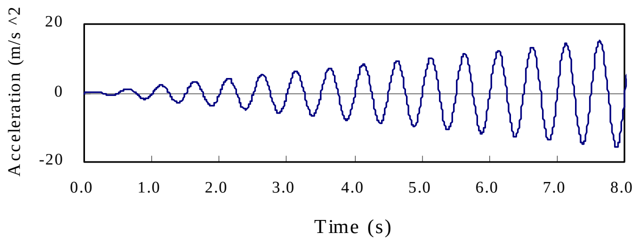


Figure 14: Input ground motion (acceleration)

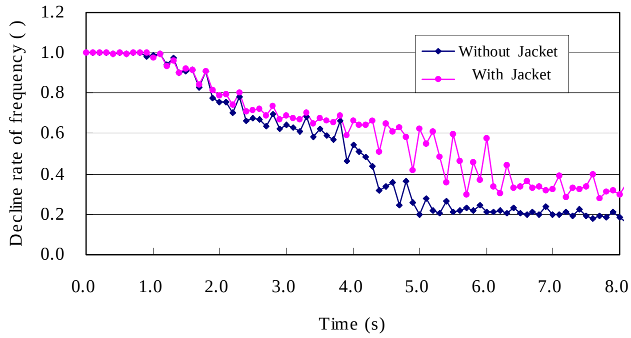


Figure 15: Change of natural frequency of the viaduct models

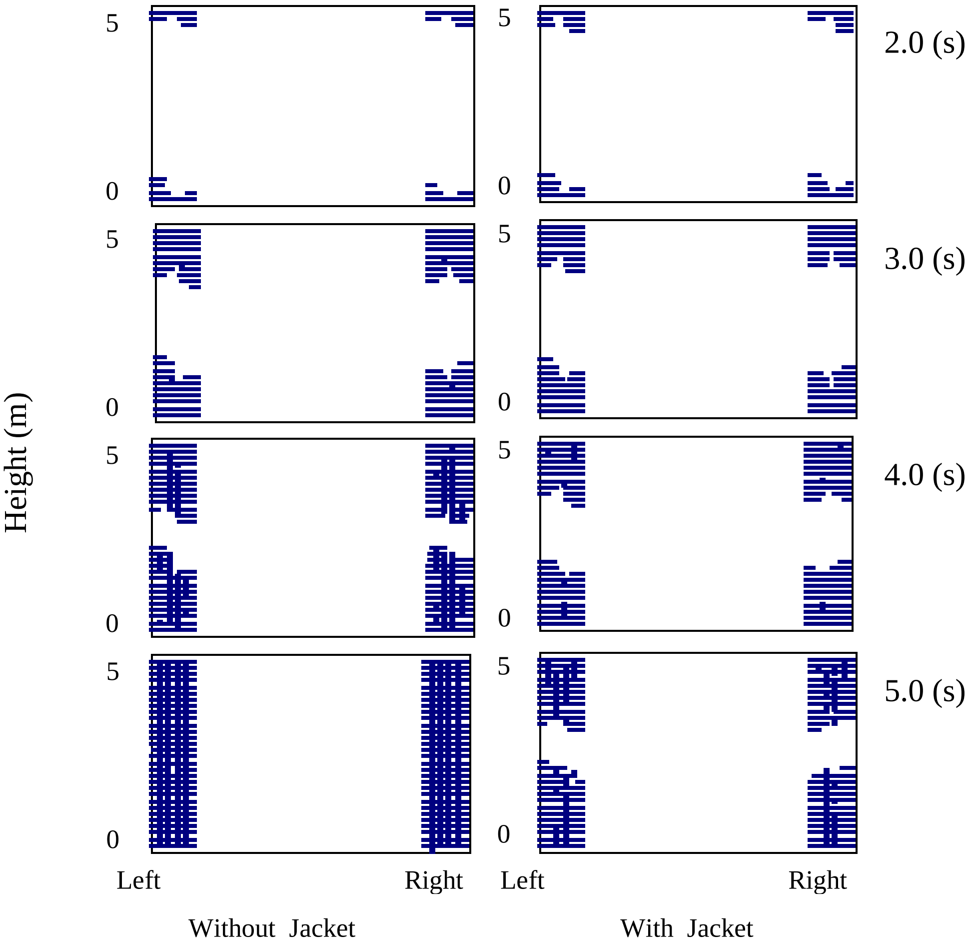


Figure 16: Propagation of cracks in concrete

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 grasped by the microtremor measurement. To make it possible, it is necessary to obtain the relationships between change of natural frequency and damage level before hand 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 calculated.

Here, ground acceleration is applied to two viaduct models, and change of the natural frequency of the viaducts due to the damage of 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 modelled using 448 elements of 0.16 (m) ×0.16 (m). Additional 406 elements are used for the jacket model. Material properties are as follows: $\sigma_y=3.5\times10^5$ kN/m^2 ,$\sigma_c=3.2\times10^4$ kN/m^2, $E_c=2.5\times10^7$ kN/m^2, $E_s=2.1\times10^8$ kN/m^2. Input ground acceleration wave is shown in **Figure 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 sloely. From the results, it ascertained that the ductility of the viaduct is increasing 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 systematised.

4. CONCLUSIONS

Followings are the conclusions summarised based on the results obtained by this study.

1) Using microtremor measurement, the natural frequency of viaducts can be obtained accurately, quickly and safety. 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 the 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 AE simulation, we can assess the seismic damage to the jacketed viaduct without opening the jacket by microtremor measurement.

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REFERENCES

Japan Concrete Institute (JCI). (1999), Report of research committee on countermeasure against earthquake disaster of concrete structure of civil engineering field, Kinki branch of JCI. (In Japanese)

Meguro, K. and Tagel-Din, H. (1997), "A new efficient technique for fracture analysis of structures", *Bulletin of Earthquake Resistant Structure Research Center, Institute Industrial Science (IIS), The Univ. of Tokyo*, No.30, pp.103-116.

Nagaya K., et al. (1999), "Experimental research on shear strength retrofit of beam part of RC ridged flame pier by using steel flame, *Proceeding of 3rd symposium on technique of seismic retrofit, maintenance, and vulnerability assessment*, pp.1-7, Japan Society of Civil Engineers,. (in Japanese)

Nakamura, Y. (1996), "Real-Time Information Systems for Seismic Hazards Mitigation, UrEDAS, HERAS and PIC", *Quarterly Report of RTRI*, Vol.37, No. 3.

Railway Technical Research Institute. (1996), "Reconnaissance report on damage of railway facilities in Hyogo-ken Nanbu (Kobe) Earthquake", *RTRI REPORT*, Special No.4. (in Japanese)

Uehan, F., and Meguro, K. (1999), "Fundamental research on a simple technique of damage assessment of double-decked RC rigid flame viaduct", *Proceedings of the 25th Japan Society of Civil Engineers (JSCE) Earthquake Engineering Symposium*, Vol. 2, pp.845-848. (in Japanese)