Improvement on Quick Inspection Method for Damaged RC Structures Using Applied Element Method

by

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ABSTRACT

This paper discusses the quick inspection method for earthquake damaged railway bridges using vibration measurement and a new numerical model for nonlinear analysis of structures. First, the accuracy of the *Applied Element Method* (AEM), used in this study, is verified through the seismic response simulation of two-storied RC rigid frame viaduct which was collapsed due to the 1995 Kobe earthquake. Secondly, the AEM is applied to evaluate the damage level of the structure based on the change of frequency of damaged RC column through the numerical simulation on the frequency change of damaged RC column. Lastly, a procedure to define the damage judgement criteria for structures is proposed.

Key Words: *damage inspection, Applied Element Method, microtremor, collapse simulation*

1. INTRODUCTION

In order to restore immediately the damaged railway system due to a severe earthquake, the quick inspection method of railway structures is indispensable. Presently, eye-judgement by a skilled engineer is regarded as the most credible inspection method. However, from this judgement, the relation between damage levels and appearance of the damaged structure is not very clear. Moreover, the experience level of inspector may affect the accuracy of the eye-inspection.

On the other hand, the impact vibration test and microtremor measurement method, have been used in the field of health monitoring of railway structures [1), 2)]. These methods can detect the vulnerability of structures based on an objective value such as the natural frequency of the structure. Forehand information of these results can fill the shortcomings of the eye-inspection based on the outward appearance of the structure.

We think that the microtremor measurement is one of the most efficient techniques for structural damage inspection because we can get the dynamic characteristics of structure just by setting sensors on it.

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Our attempt is to improve the accuracy of the inspection method, by means of the numelical studies like the change of dynamic characteristics of the structures due to damage. In this paper, we discuss a quick damage inspection technique for the RC rigid frame viaduct by using microtremor measurement and numerical simulation. First, the accuracy of the Applied Element Method (AEM) [3], which is used in our study, is verified through the collapse simulation of railway viaduct which was collapsed due to the 1995 Kobe earthquake. Secondly, the AEM is applied to evaluate the damage level of the structure based on the frequency change. Lastly, a procedure to define the damage judgement criteria for structures is proposed.

2. INSPECTION TECHNIQUE USING DYNAMIC CHARACTERISTICS OF STRUCTURES

In the field of health monitoring of railway structures, the inspection techniques are developed by using dynamic characteristics of structure. These methods make use of the natural frequency of structures as the index of damage and/or deterioration levels. The vibration induced by the sources such as the moving train, impact on the structure and microtremor, is used in order to get the natural frequency of the structure (**Fig. 1**). Microtremor is a very small vibration in usual condition due to the natural and artificial sources, such as tidal wave, traffic noise, industrial vibration, and so on. By using microtremor measurement, dynamic characteristics of structure like the natural frequency can be obtained easily. The microtremor measurement is one of the most efficient and safest methods because no special vibration sources like moving car or impact by hitting structure is necessary.

3. APPLICATION OF NUMERICAL SIMULATION FOR QUICK DAMAGE INSPECTION

3-1 Application of numerical simulation

In order to improve the accuracy of quick damage inspection, the behavior of structure should be understood correctly and the relation between damage levels and change of natural frequency should be clarified. Therefore, in our study, we investigate the damage to structure and the frequency change due to damage. The numerical model suitable for our study should be accurate in small deformation range and also should be able to deal with the damage to structure such as crack of concrete, yield and cut of reinforcing bar. In our study, we use the AEM which can follow the total structural behavior from elastic range, crack initiation and propagation to collapse.

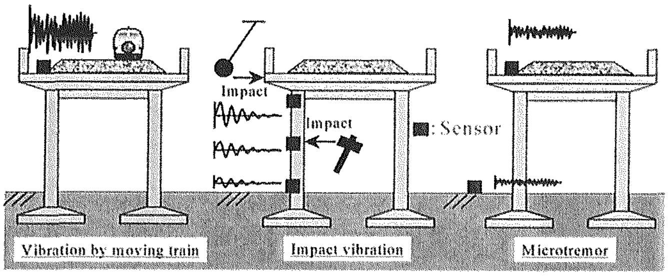


Fig. 1 Damage inspection method using dynamic characteristics of structure

3-2 Applied Element Method

Figure 2 illustrates modeling of RC structure for the AEM. It is assumed that the structure is modeled as an assembly of small rectangular elements made by dividing the structure virtually. The two elements shown in **Fig. 2** are connected by pairs of normal and shear springs located at contact points, which are distributed around the element edges. At the location of reinforcing bar, two pairs of springs are used for concrete and for reinforcing bar. Nonlinear material models of steel and concrete shown in **Fig. 3** are given to the springs, respectively. If the stress of a spring exceeds its resistance, the spring can yield and cut. In this way, AEM can follow the structural behavior from elastic range to total collapse accurately in reasonable CPU time[3)]. By the AEM, even in case of damaged structure, its dynamic characteristics can be easily obtained.

3-3 Simulation of collapse behavior[4)]

Numerical simulation of the JR (Japan Railways) Hansui viaduct that was collapsed due to the 1995 Kobe earthquake is performed. The real damage situation is shown in **Fig. 4**[5)]. This viaduct is the double-decked viaduct with 3 spans and its shape is shown in **Fig. 5**[5)]. 1,226 square elements whose side length is 18cm are used to model the viaduct. The number of distributed springs between two adjacent elements is 10. The material properties of concrete and steel bars are defined by considering the actual strength as showing in **Table 1**[6)]. The arrangement of reinforcing bars is the same as the real one shown in **Fig. 5**. The natural frequency of the numerical model (2.65 Hz) with the effect of soil-pail system is almost same as that of the real undamaged JR Hansui viaduct (2.60 Hz). The simulated collapse behavior of the model due to the 1995 Kobe earthquake ground motion recorded at the JR Takatori observatory (NS-component)[7)] is shown in **Fig. 6**. The obtained damage by the numerical model agrees well with the real one.

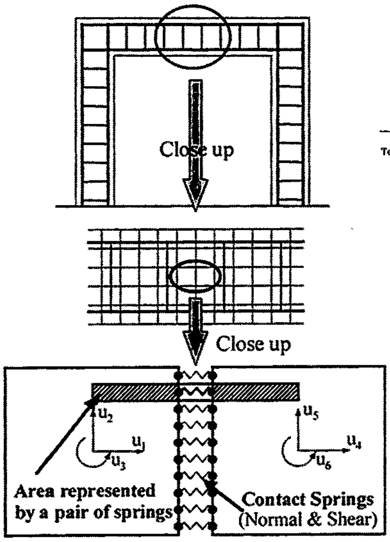
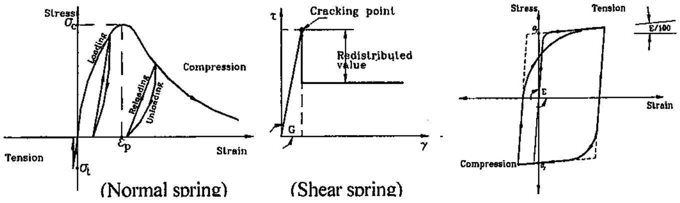


Fig. 2 Modeling of structure for AEM



(Normal spring) (Shear spring)

Concrete Spring Steel Spring

Fig. 3 Material models of concrete and reinforcement

Table 1 Material properties used in numerical model

Concrete	
Young's modulus (kN/m^2)	2.8×10^7
Compressive strength (kN/m^2)	3.2×10^4
Tensile strength (kN/m^2)	2.4×10^3
Reinforcing bar	
Young's modulus (kN/m^2)	2.1×10^8
Yield stress (kN/m^2)	3.5×10^5

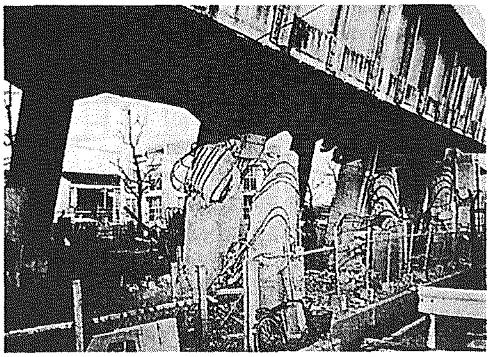


Fig. 4 Damage condition of JR Hansui viaduct

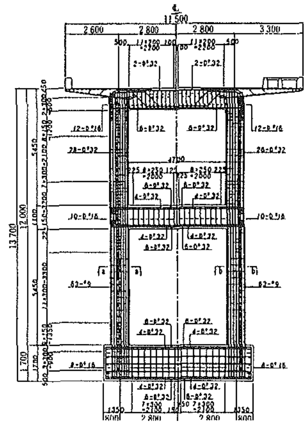


Fig. 5 Reinforcement details of the viaduct

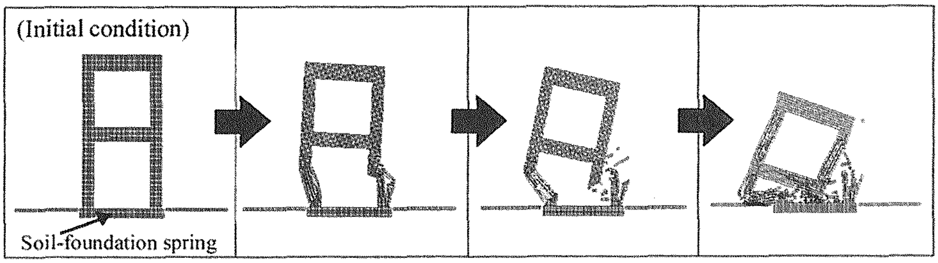


Fig. 6 Collapse behavior of numerical model due to the ground motion recorded at JR Takatori observatory (NS-component)

3-4 Simulation of natural frequency of damaged RC column

The experiment on the change of natural frequency of RC specimen due to damage was carried out [8]. The specimen used in the experiment is the 1/2 model of the column of real railway viaduct as shown in **Fig. 7**. The specimen was damaged step by step due to the cyclic loading. The impact vibration test was performed in order to get the natural frequency of the specimen at each damage level. The material properties of specimen obtained by experiment are shown in **Table 2**. The specimen is modeled by 940 square elements whose size is 5×5cm. The number of distributed springs between two adjacent sides is 10. In case of the experiment, one step of cyclic loading is composed 3 cycles, and the impact vibration test was carried out after each steps. The upper section of **Fig. 8** shows the input displacement, and lower section is the comparison between the experimental and simulated results on frequency change. In case of the numerical simulation, the results in case of one cycle/step are shown in **Fig. 8** because the difference of the results between the case of three cycles/step and in case of one cycle/step is not big. The simulated natural frequencies of 1/4, 1/2 and 3/4 cycles are also shown in **Fig. 8**. The simulated results can follow the experimental results well.

After $4\delta_y$, the experimental results become lower than simulated values as the stiffness of the specimen becomes lower when the crack opens widely because no vertical load is applied on the specimen. After $7\delta_y$, the difference between experimental and simulated results becomes more because the sapling off of concrete cover which was not considered in numerical model.

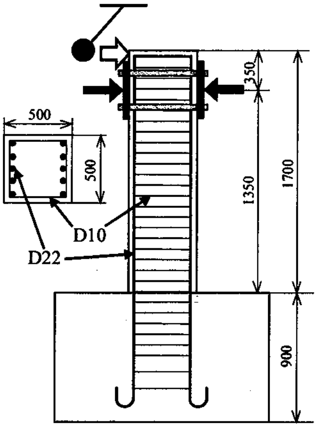


Fig. 7 Specimen used in the study

Table 2 Material properties of specimen

Concrete	Column	Footing
Young's modulus (kN/m^2)	2.19×10^7	2.21×10^7
Compressive strength (kN/m^2)	2.85×10^4	2.87×10^4
Tensile strength (kN/m^2)	2.25×10^3	2.77×10^3
Reinforcing bar	**D22**	**D10**
Young's modulus (kN/m^2)	1.93×10^8	1.81×10^8
Yield stress (kN/m^2)	4.21×10^5	3.85×10^5

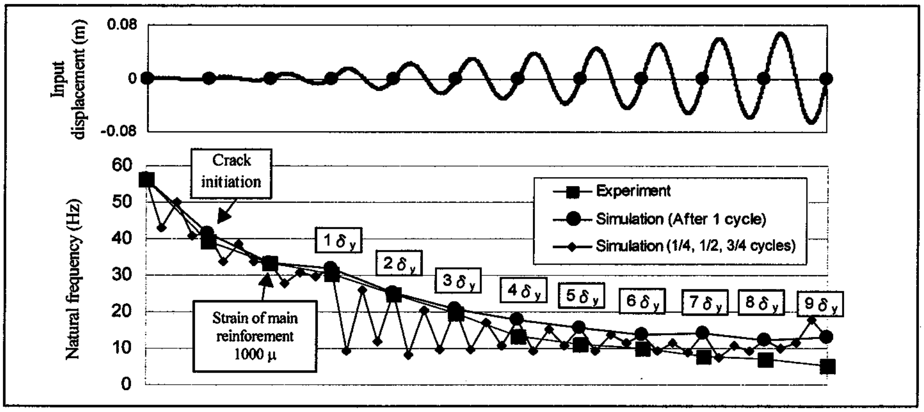


Fig. 8 Input displacement (upper) and changes of natural frequency due to damage (lower)

4. STEPS TO DEFINE THE DAMAGE JUDGEMENT CRITERIA OF REAL STRUCTURE

For the inspection method by using change of natural frequency, the criteria to judge the damage level of structure is necessary. The following is the fundamental process in order to define the damage judgement criteria of real structure.

(1) Modeling of objective structure.

(2) Studying the damage behavior of structure by numerical simulation.

(3) Calculation of natural frequency at each damage level.

(4) Definition of the damage judgement criteria based on the change of natural frequency.

The above mentioned procedure can be used for making the damage judgement criteria of a specific structure only. For making the judgement criteria in general for great numbers of those having various soil-pile conditions, it is very inefficient to carry out the parametric study on the various combinations of soil, foundation and structure. Therefore, first we should estimate the damage type of each structure mainly from the soil condition around the structure, and we should carry out the procedures for each damage type, respectively (**Fig. 9**).

(i) In case that the damage to foundation is negligible.

First, the parametric study on the change of natural frequency due to damage to superstructure is carried out numerically. Then, the frequency change of soil-foundation-superstructure system (total system) is obtained by taking into account the effect of stiffness of soil-foundation spring. The criteria of damage level are defined by using the relation between frequency change of the total system and damage level obtained from numerical model.

(ii) In case that the damage is concentrated on foundation.

First, the parametric study on the change of the stiffness of soil-foundation spring is carried out numerically. Next, the frequency change of total system is obtained by taking into account both the obtained stiffness change due to damage to foundation and the natural frequency of undamaged super structure. The criteria of damage level are defined by using the relation between frequency change of the total system and damage levels of numerical model. This method is applied in case of soft ground that may cause liquefaction and lateral flow.

(iii) In case both superstructure and foundation are damaged.

The frequency change of total system is obtained by numerical simulation of total system. The criteria of damage level are defined based on the relation between frequency change of the total system and damage levels obtained from numerical model.

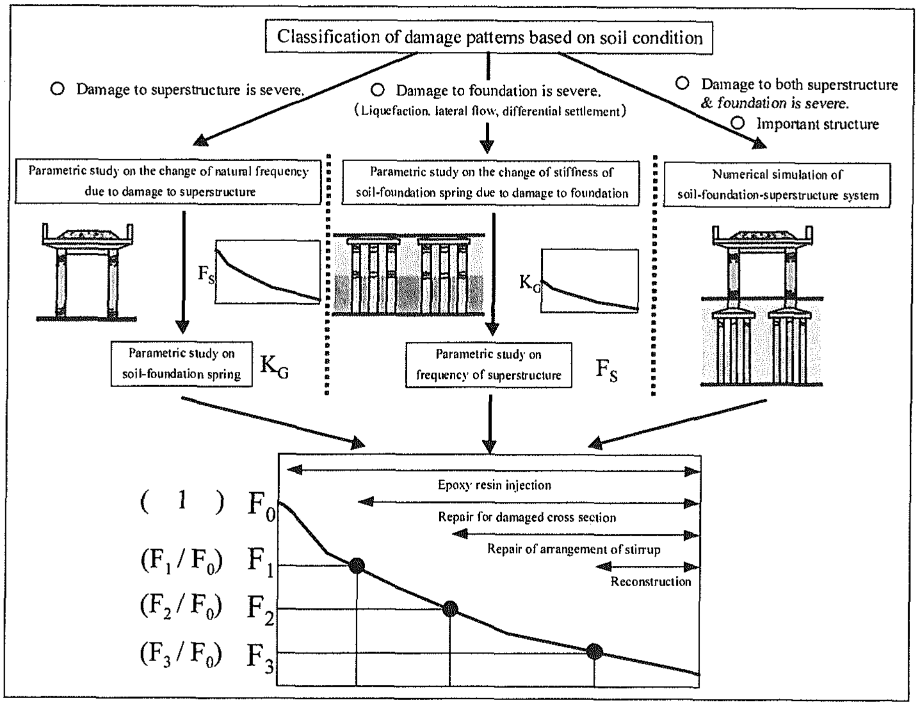


Fig. 9 Procedure for defining the damage judgement criteria of real structure

By Applied Element Simulation, the change of natural frequency of RC structure due to damage, such as crack propagation of concrete, yield and cut of reinforcing bar, is easily evaluated. On the other hand, the experimental research on the suitable restoration construction method for each damage level is proceeded [9]. Therefore, if the proper damage judgement criteria are defined by the above-mentioned methods, we can select the proper restoration construction method simply based on microtremor measurement.

5. CONCLUDING REMARKS

In this paper, we discuss the quick damage inspection method using vibration measurement and Applied Element Method (AEM). First, the accuracy of the AEM is verified, and then, the methodology to define the damage judgement criteria is proposed. In future, we will try to make the damage judgement criteria of real structures in order to develop the expert system for damage inspection. This system can be used to implement the unmanned damage observation system for the quick grasp of damage distribution after severe earthquake by Geographic Information System.

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