Non-linear Numerical Simulation of Natural Frequency Change of Damaged RC Structure Reinforced by Steel Jacket

by

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ABSTRACT

After the 1995 Kobe Earthquake, a great number of RC bridges were retrofitted with steel jacket. Therefore, the jacketed RC bridge has become one of the popular civil structures nowadays. Unfortunately, till now, the behavior of jacketed column is little known, and moreover, the damage to the jacketed RC structures cannot be detected because the concrete columns inside the jacket can not be seen from outside. In this paper, a 2-D numerical model of jacketed RC column using Applied Element Method (AEM) is proposed. Numerical simulations of two kinds of experiments for studying the natural frequency change of jacketed structure due to damage are carried out in order to discuss the applicability of the proposed numerical model for quick damage inspection of jacketed RC structures.

***Key Words** : numerical simulation, Applied Element Method, quick damage inspection, steel jacket*

1. INTRODUCTION

In the 1995 Kobe earthquake, the RC bridges of railway facility were seriously damaged. For instance, 32 railway viaducts collapsed and about 3,400 railway viaduct pillars were affected[1)]. After the earthquake, many viaduct columns were reinforced by steel jacketing. About 50,000 columns were reinforced only in the railway viaduct. At present, viaducts reinforced with steel jacketing have become one of the main railway structures and thus it is important to grasp their dynamic behavior. So far structures have been visually inspected by skillful engineers. However, in the case of a structure reinforced by steel jacketing, the damage condition inside the jacket cannot be visually checked, causing troubles to the damage inspection conducted immediately after an earthquake. Therefore, the development of a new inspection method to replace the visual examination of the structures reinforced by steel jacketing is needed. The inspection techniques that may be suitable for the structures reinforced with steel jacket are the impact vibration test[2)] and the microtremor measurements[3)]. These techniques use the dynamic characteristics of the

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structure, which change with the structural degradation. In order to improve the accuracy of these methodologies, it is necessary to understand the change of the dynamic characteristic due to the structural damage. Although some experiments have been conducted for this purpose[4),5),6)], the amount of data related to the dynamic characteristics of damaged jacketed structures is still not enough. In order to analyze the changes of the dynamic characteristics of reinforced structures with various forms and material characteristics, the numerical analysis is an effective tool. A numerical model, which can analyze the damage behavior of a structure with sufficient accuracy, is required and therefore the authors decided to use the Applied Element Method (AEM)[7)], a new nonlinear structural-analysis technique to model the jacketed RC structures. This paper presents the 2-dimensional model of a jacketed RC structure and the simulation of two experiments, which investigate the natural-frequency changes of a steel-jacketed RC bridge pier due to structural degradation. The applicability and accuracy of the proposed model for the damage assessment of jacketed RC structures is examined.

2. TWO-DIMENSIONAL NUMERICAL MODEL OF JACKETED RC COLUMN

2-1 Applied Element Method: AEM[7)]

In the Applied Element Method (AEM), the structure is modeled as an assembly of small rectangular elements made by dividing the structure virtually. Each element is connected by pairs of normal and shear springs located at the contact points, which are distributed around the element edges. In the 2-dimensional analysis, each element has three degree of freedoms. The concrete material model is applied to each distribution spring. At the location of the reinforcing bar, two pairs of springs are used for the concrete and steel bar, respectively. Nonlinear material models of steel and concrete are shown in Figure 3. If the stress of a spring exceeds its

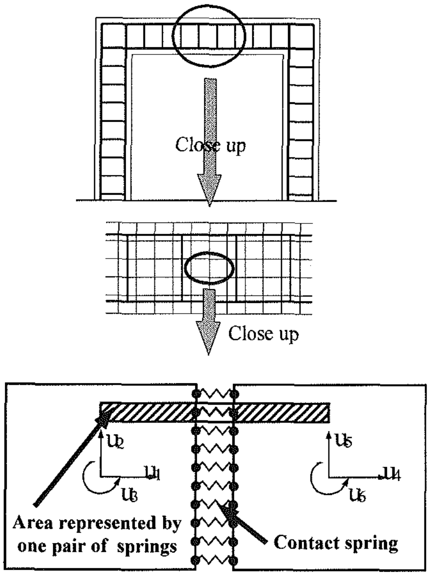
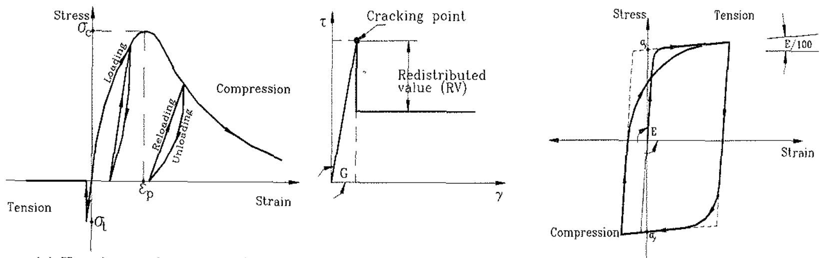


Figure 1 Modeling of structure in AEM



(a) Tension and compression (b) Shear

Concrete Steel

Figure 2 Material modeling of concrete and steel resistance, the spring yields and finally breaks. In this way, AEM can follow the structural behavior accurately from elastic range to total collapse.

2-2 Two-dimensional model of jacketed column

A two-dimensional model for a jacketed column by using AEM is proposed. The structural model 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 the jacket element between two-side jackets (Element type E_{Jb}). Element type E_C has concrete material property whereas elements E_{JS} and E_{Jb} have the material property of steel. There is no connection between the elements of E_{Jb} and E_C as shown in Figure 3. Because the edge elements of the types E_C and E_{Jb} are connected with the elements of the type E_{JS}, the inside concrete is restrained by the steel jacket. Inside concrete is permitted to crack and reinforcements are permitted to yield and break.

2-3 Simulation in order to check the characteristics of the 2-D model of the jacketed column

In order to check the behavior of the numerical model, three models, with different reinforcement levels (see Figure 4) were analyzed:

(1) No Reinforcement.

(2) Reinforced with Steel Jacket (Thickness = 1mm).

(3) Reinforced with Steel Jacket (Thickness = 2mm).

These three models were created using 5cmx5cm AEM elements.

The input acceleration is shown in Figure 5. The three models were analyzed until their total collapse. Material properties were as follows:
Concrete Young's modulus E_C = 22.0 GPa, concrete compressive strength σ_C = 30.0 MPa, steel Young's modulus E_S = 210 GPa, steel yield stress σ_{y1} (for D16)= 390 MPa, steel yield stress σ_{y2} (for Jacket)= 310 MPa. The axial force of the column was 294 kN. No stirrup was included in the model. Although the element of 5x5cm was used for the side jacket element, the influence of the element size was removed by adjusting the Young's modulus and the strength of the element.

The collapse pattern of each numerical model is shown in Figure 6. In order to check the damage condition of the internal RC column, only the elements of the types E_C and E_{JS} are shown in Figure 6. In case (1), no reinforcement, shear failure occurred in the central part of a column. In case (2), reinforced with steel jacket of thickness 1 mm, since thickness of steel jacket was not enough, steel jacket yielded and damage due to shear occurred in the lower part of column. In case (3), reinforced with steel jacket of thickness 2 mm, the damage concentrates on the lower part of column, which is not reinforced by steel jacket. The damage to the reinforced portion is small. In this case, it can be said that the jacketing effect is significant. In conclusion, the complicated damage behavior of the RC column reinforced by steel jacket was successfully analyzed by the proposed model.

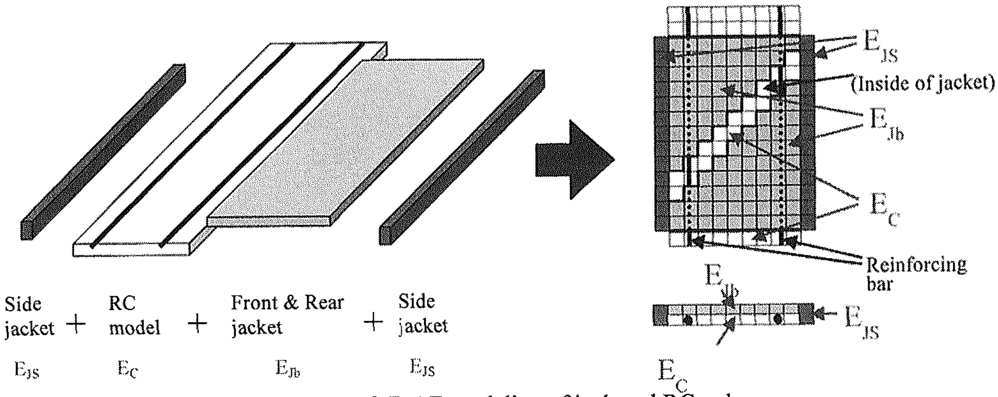


Figure 3 2-D AE modeling of jacketed RC column

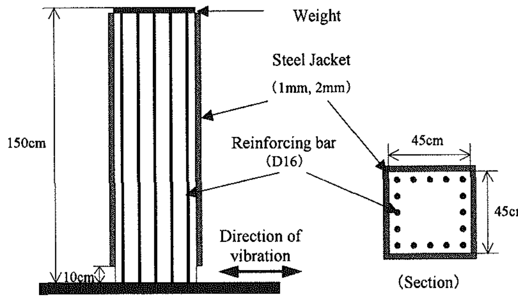


Figure 4 Outline of simulated RC specimen

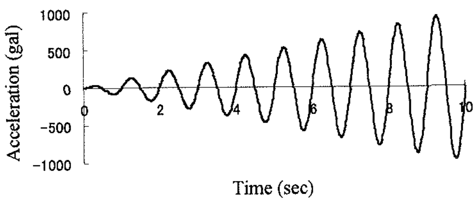


Figure 5 Input acceleration

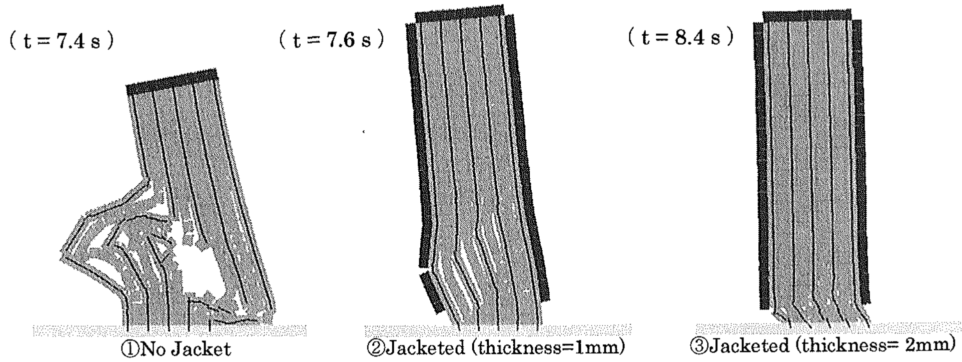


Figure 6 Difference of collapse pattern of numerical models

3. SIMULATION OF THE NATURAL-FRQUENCY CHANGE DUE TO DAMAGE

3-1 Application to the damage inspection

The degree of damage of a jacketed RC structure cannot be fully grasped by visual inspection. In order to assess the degree of damage to a jacketed RC structure using the inspection techniques based on vibration measurements, e.g. impact vibration tests, microtremor measurements, it is necessary to identify the changes of the dynamic characteristics accompanied by damage to the structure in advance. So far the authors have investigated the change of the dynamic characteristics accompanied by damage to RC structure using nonlinear structural analysis[8]. In this section, the accuracy of the proposed model is investigated using experimental results.

3-2 Cyclic loading to real rigid frame viaduct[4),5)]

1) Outline of experiment

Yoshida *et al.*[4)] conducted the loading experiment of a real viaduct reinforced by steel jacket. Daiichi Shinagawa viaduct R13 of the down line, which is removed in connection with Shin-Shinagawa station establishment, was used in the experiment. The structure type of the viaduct is RC rigid frame viaduct supported by 2 columns with 3 spans for single truck. The typical section of the viaduct and the loading equipment are shown in Figure 7. Each column was reinforced by the steel jacket (thickness = 6mm) as shown in Figure 8. The gap between the column and the steel jacket was 30 mm, and it was filled up with shrinkage-compensating mortar. Walls were installed in the frame of R12 and R14, which adjoin R13, to act as reaction walls. The slabs between viaducts were cut and the loading jacks were installed there.

The cyclic loading test of the R13 along the direction parallel to the track, was carried out by displacement control. After applying cyclic loadings with maximum displacements of ±15 mm, ±30 mm, ±60 mm, ±90 mm, ±120 mm, ±150 mm, ±180 mm, ±210 mm, and ± 240 mm, a monotonic loading of +350 mm was imposed as the last step. The impact vibration test of the direction parallel to the track was carried out when each loading step was finished in order to investigate the change of the natural frequency due to damage of the viaduct.

2) Numerical Model

The column of the viaduct was modeled using AEM elements of size 8.25(cm) x8.25(cm), as shown in Figure 9. It was assumed that the top of the column was restrained against rotation because the viaduct beam was very rigid. The behavior of the whole viaduct was represented with one column carrying one eighth of the total mass of the slab and beams.

The design compressive strength of the concrete of the viaduct was 23.5 (MPa), and the compression test results, which were obtained at the time of construction gave a compressive strength of 32.9 (MPa). SD49 was used for the longitudinal reinforcing bars and SS41, for the stirrups. At the first stage of the analysis, the properties of the material of the viaduct were not fixed. Six models with different material properties, as shown in Table 2, were created by combining the material properties of the three types of concrete and the two types of longitudinal reinforcing bar shown in Table 1. In addition, by arranging a soil-foundation spring at the bottom of the model, the natural frequency of the column was adjusted so that it became equal to the measured natural frequency of the real viaduct. As a result, the natural frequencies of all the models (1) - (6) were equal in the initial state. The changes of the natural frequency of each model due to the structural damage were analyzed and compared with the experimental results.

3) Results and considerations

The experimental and numerical results are shown in Figure 10. According to the experimental results, the natural frequency reduced to 85% of the original value after the ±30 mm loading. After the ±120 mm loading, the natural frequency reduced to 50% and it remained almost constant after that. In the simulation result by AEM, the natural frequency reduced to 79 - 83% after the ±30 mm loading, to 55 - 61% after the ±120 mm loading, to 50 - 54% after the ±240 mm loading, and to 47 - 51% after the +350 mm loading. In the numerical simulation results, the difference of the material properties of each model did not have much influence on the natural-frequency change.

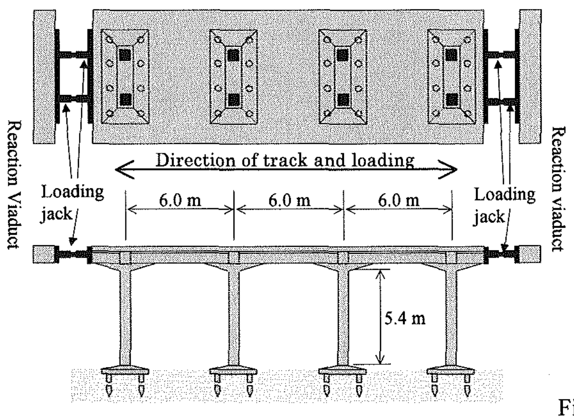


Figure 7 Viaducts and loading equipments

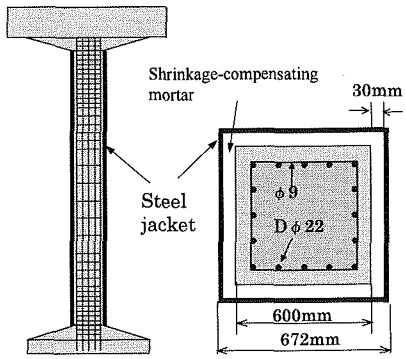


Figure 8 Arrangement of reinforcing bars and cross section of the jacketed column

Table 1 Material properties

	Compressive strength (MPa)	Young's Modulus (GPa)
Concrete C1	23.5	24.5
Concrete C2	35.0	28.0
Concrete C3	17.6	21.6
	Yield stress (MPa)	Young's Modulus (GPa)
Longitudinal bar S1	490	200
Longitudinal bar S2	558	200
Stirrup	400	200

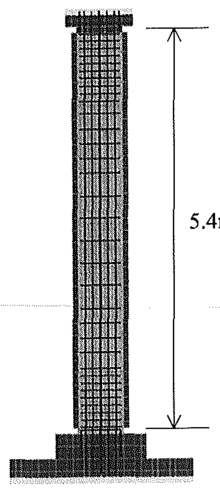


Figure 9 Numerical model of the jacketed column of the viaduct

Table 2 Combination of material properties

Case	①	②	③	④	⑤	⑥
Concrete	C1	C1	C2	C2	C3	C3
Longitudinal bars	S1	S2	S1	S2	S1	S2

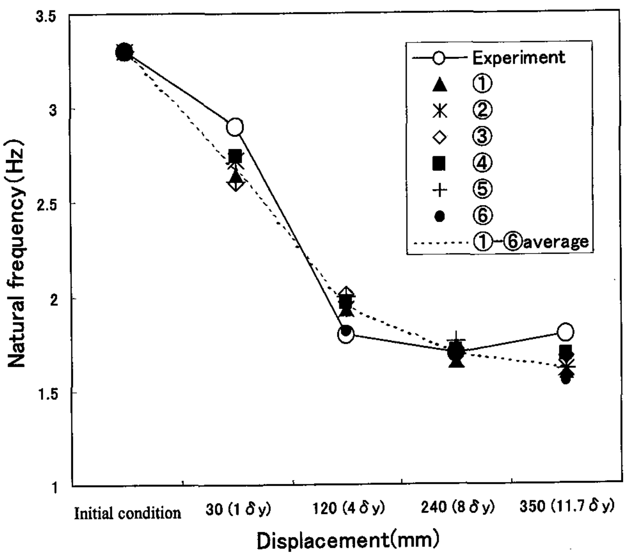


Figure 10 Change of natural frequency of the real viaduct and the numerical models

3-3 Shaking table test of jacketed RC bridge pier[6)]

1) Outline of Experiment

In this experiment, an specimen of a jacketed RC bridge pier was tested on the shaking table. Natural frequency after the shaking was examined using micro vibration (about 5 gal) of the shaking table. Figure 11 shows the RC bridge pier model that was used in this experiment. The section of a bridge pier was 60cmx60cm and its height was 280 cm (height of the acting load was 300 cm). SD295 (D10) and (D6) were arranged as longitudinal reinforcement and stirrups at intervals of 30 cm, respectively. The specimen was reinforced using steel jacket (SS400) with a thickness of 2.3mm. The bottom of the steel jacket was 10 cm above the column bottom. The gap between the column and the steel jacket was 20 mm, and it was filled up with shrinkage-compensating mortar. Twenty anchor bars (M12), which connect the footing and the steel jacket, were arranged at the bottom of the jacket. The material properties are shown in Table 3.

In the experiment, two simple beams, as shown in Figure 12 were connected to the bridge pier model through a pin bearing. The weight of the beams (395kN) was applied to the pier. The opposite sides of the simple beams were supported by steel piers with roller bearings. In the experiment, the JMA Kobe record whose time scale was changed to 65% was used as input motion. The NS component (PGA = 818gal) and the UD component (PGA = 332gal) were applied 3 times by the shaking table.

2) Numerical model

The jacketed bridge pier specimen was modeled using 5cmx5cm AEM element (Figure 14). The material properties and the arrangement of reinforcing bar are the same as that of the specimen. The wave shown in Figure 13 was inputted 3 times, and the change of the natural frequency of the specimen was calculated.

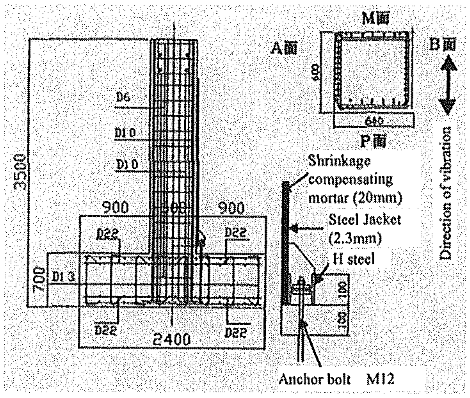


Figure 11 Specimen of jacketed RC bridge pier [6]

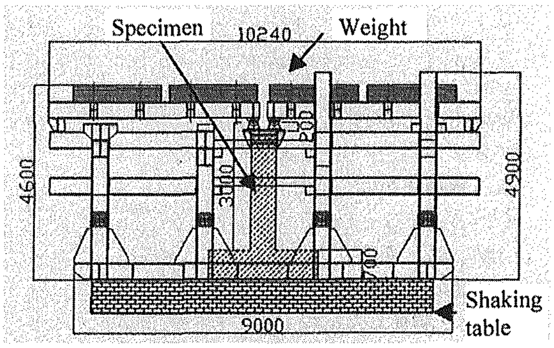


Figure 12 Shaking table and loading equipments [6]

Table 3 Material properties

Concrete	Compressive strength (MPa)	Young's modulus (GPa)
	29.9	21.5
Steel	Yield stress (MPa)	Tensile strength (MPa)
D6	No obvious yield point	524
D10	391	557
M12 (Anchor bar)	355	477
Steel jacket (Longitudinal)	274	369
Steel jacket (Transverse)	307	364

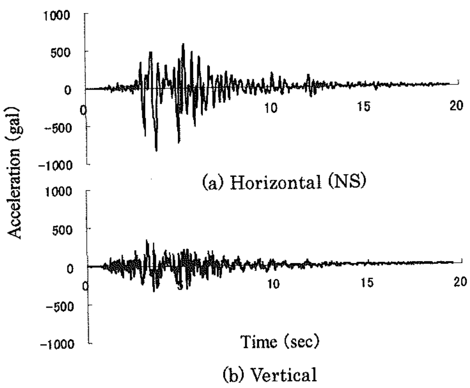


Figure 13 Input Acceleration (JMA Kobe, Time scale 65%)

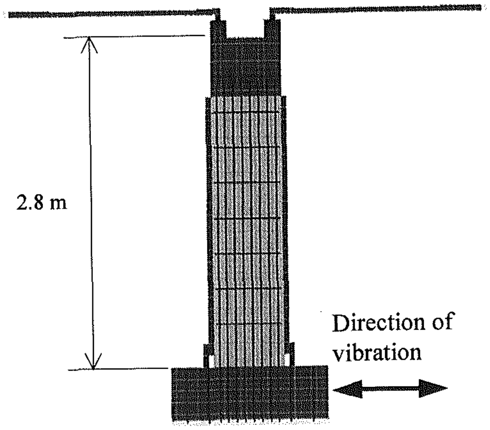


Figure 14 Numerical model of jacketed bridge pier

3) Result and consideration

In the experiment, the natural frequency of the specimen at the initial state was 4.40Hz. The natural frequency of the specimen changed to 2.64 Hz after the first shaking, 2.12Hz after the 2nd shaking, and 1.86Hz after the 3rd shaking.

Before the experiment, Kondo *et al.*[6)] assumed the damage condition and estimated the natural frequency of the specimen as shown in Table 4. Although the calculated natural frequency at the initial state (a) is 5.59 Hz, the natural frequency obtained from the experiment was 4.40Hz, closer to case (a') with 4.51 Hz, in which the influence of the anchors is not taken into consideration. Kondo *et al.* considered that this was because the fixed situation of the anchor bars was inadequate. The unification of a footing and a steel jacket was inadequate and therefore, the effect of anchor bars did not appear in the small amplitude domain. Based on such assumption, they concluded that the degree of damage after the first vibration was (b') on Table 4, after the 2nd vibration was (e), and after the 3rd vibration was (f).

According to our simulation result, the natural frequency of a numerical model was 5.68Hz at the initial state, 3.26Hz after the first vibration, 2.64Hz after the 2nd vibration and 1.78Hz after the 3rd vibration. The damage condition at the bottom of the bridge pier model after the 3rd vibration is shown in Figure 15. In our model, the special effect of the anchor bars, which was mentioned above, was not reflected. When the natural frequency was calculated, the effect of the anchor bars was included. By the analysis result, it is thought that the natural frequency of a numerical model corresponds to (a) of Table 4 in the state of the first stage, to (b) after the 1st vibration, to (c) after the 2nd vibration and to (f) after the 3rd vibration. This result is equal to the sequence (a') → (b') →(c') → (f) if the influence of the anchor bars is removed. That is, our simulation result correspond in general with the experiment result (a') →(b') → (e) → (f) by Kondo *et al.*

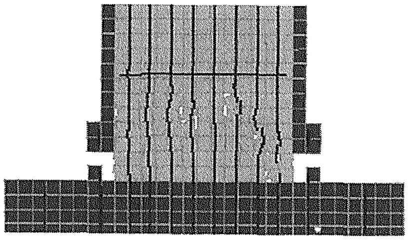


Figure15. Damage to the bottom part of jacketed RC bridge pier

Table 4 Assumed damage level and estimated natural frequency (Kondo et. al.) [6] and results

Damage conditions	Concrete	Longitudinal reinforcing bars	Anchor bars	Young's Modulus of reinforcing bars	Calculated natural frequency (Hz)	Experiment result (Hz)	Numerical simulation (Hz)
(a)	Fully elastic	Valid (linear)	Valid (linear)	1/1	5.59		5.68
(a')	Fully elastic	Valid (linear)	Disregard	1/1	4.51	4.40	
(b)	Yield	Yield point	Yield point	1/1	3.10		3.26
(b')	Yield	Yield point	Disregard	1/1	2.69	2.64	
(c)	Decrease of section	Over yield stress	Over yield stress	2/3	2.63		2.64
(c')	Decrease of section	Over yield stress	Disregard	2/3	2.34		
(d)	Decrease of section	Over yield stress	Disregard	1/2	2.08		
(e)	Disregard concrete cover	After yield	Disregard	2/3	2.08	2.12	
(f)	Disregard concrete cover	After yield	Disregard	1/2	1.84	1.86	1.78

4. CONCLUSION

A Two-dimensional numerical model, which can deal with the complicated damage behavior of a jacketed RC column, was proposed. Moreover, the simulation of the change of the natural frequency due to structural damage of a Jacketed RC bridge pier was carried out in order to verify the applicability of this numerical model for the quick damage inspection of this type of structure. A perfect coincidence of the experimental and numerical results was not obtained due to the complexity of the subject to analyze. Nevertheless, the change of the natural frequency due to damage to a jacketed structure was analyzable with sufficient accuracy using the proposed model. As a future subject, we want to improve the accuracy of the quick damage inspection technique of a jacketed structure using the proposed numerical model.

REFERENCES

1) JSCE: "Report on the Hanshin-Awaji earthquake disaster, Damage to civil engineering structures, Bridge structure," Maruzen, 1996 (in Japanese).
2) Nishimura, A. and Tanamura, S.: "A study on integrity assessment of railway bridge foundation," *Railway Technical Research Institute (RTRI) REPORT*, Vol. 3, No. 8, pp. 41-49, 1998 (in Japanese).
3) Nakamura, Y.: "Real-time information systems for seismic hazards mitigation UrEDAS, HERAS and PIC," *Quarterly Report of RTRI*, Vol. 37, No. 3, pp. 112-127, 1996.
4) Yoshida, K. *et al.*: Experimental study on real RC frame viaduct reinforced by steel (Vol. 1) –Earthquake resisting performance evaluation by cyclic loading test of real RC frame viaduct-, *Proceedings of 55th annual conference of JSCE*, V-500, 2000.
5) Naganawa, T. *et al.*: Experimental study on real RC frame viaduct reinforced by steel (Vol. 2) –Study on soundness diagnosis of RC frame viaduct reinforced by steel after earthquake-, *Proceedings of 55th annual conference of JSCE*, V-501, 2000.
6) Kondo, M., Unjo, S., Adachi, Y.: Damage evaluation of RC bridge pier using natural frequency, *Proceedings of the 2nd Symposium on Ductility Design Method for Bridges*, pp.287-290, 1998.
7) Meguro, K. and Tagel-Din, H.: "A new efficient technique for fracture analysis of structures," *Bulletin of Earthquake Resistant Structure Research Center*, IIS, Univ. of Tokyo, No.30, pp.103-116, 1997.
8) Uehan, F. and Meguro, K. :" Quick Inspection Method for Earthquake Damaged RC Structures by Non-linear Numerical Simulation", *Journal of Applied Mechanics of JSCE*, Vol. 3, pp.621-628, 2000.