# SHAKING TABLE TESTS OF REINFORCED CONCRETE COLUMNS SUBJECTED TO SIMULATED INPUT MOTIONS WITH DIFFERENT TIME DURATIONS

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## SUMMARY

The purpose of this study is to investigate the differences in the inelastic dynamic behaviour of reinforced concrete columns subjected to simulated input motions with different time duration. The dynamic behaviour of reinforced concrete columns was evaluated by comparing the results of shaking table tests with those of static test. Also presented are evaluations on the differences in the damage potentials of input motions using the concept of energy response. An analytical model considering the bond slippage of anchorage reinforcement was developed to simulate the behaviour of the specimens during the tests. The calculated results could trace well the observed time histories and hysteretic loop. Finally by using this model, responses subjected to simulated input motions with different time duration were discussed.

## INTRODUCTION

In recent years, the experimental approaches have often been applied to investigate the dynamic behaviour of reinforced concrete structures. Most of the experimental works including the peosudo dynamic tests and shaking table tests were concentrated on the behaviour of different types of structures. From the disasters of Off Tokachi Earthquake 1968 and Kobe Earthquake 1995, it is considered that the time duration plays an important role on the damage potential of the earthquake and pointed out that the behaviour of structures is dominated by the characteristics of input motions. The purpose of this study is to investigate the differences on the damage potential of earthquake motions with different time duration. In this study, the dynamic behaviour of reinforced concrete columns is investigated by experimental and analytical methods. Energy responses are also investigated for studying the effects of time duration of the simulated input motions.

## OUTLINE OF THE TESTS

### Specimen and materials

The configuration and arrangement of reinforcement of the specimen are shown in **Fig. 1**. The specimens were designed considering the limitation of the shaking table used and were so designed as to fail in flexure. The size of the column section is B×D=120×100 mm, the longitudinal reinforcement ratio is Pg=0.8%(6-D6), the lateral reinforcement ratio is Pw=0.7%(D4@30) and the shear span ratio is M/QD=3.0. Axial-force ratio is 0.03. Normal portland cement, river sand and river gravel (maximum size 10mm) are used for concrete mix. The mechanical properties of concrete and reinforcements are listed in **Table 1**.

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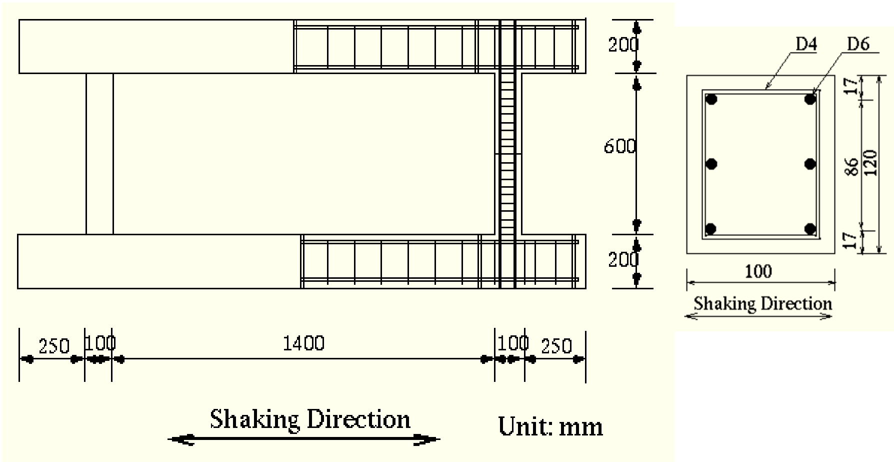



**Figure 1: Details of reinforcement and column section**

**Table 1 Properties of materials**

| | | | | |
|---|---|---|---|---|
| Maximum strength of concrete ($N/mm^2$) | | CASE1 | 30.8 | |
| | | CASE2 | 33.1 | |
| | | CASE3 | 36.0 | |
| Reinforcement | | | D6 | D4 |
| | Yielding strength ($N/mm^2$) | | 419.0 | 214.3 |
| | Young's modulus ($kN/mm^2$) | | 199.3 | 192.1 |

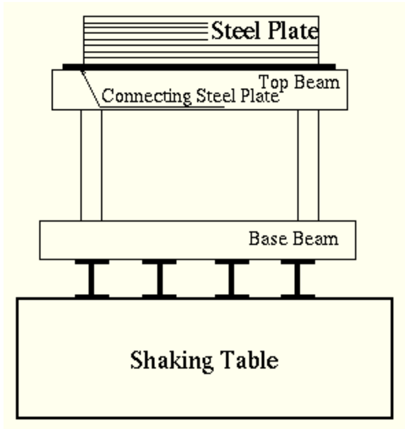



**Figure 2: Set-up of specimen**

**Test set-up and measurement**

The shaking table of Tohoku University, which can move horizontally in 2 directions (x and y directions) simultaneously, was used for dynamic tests. The specimen was fixed on the shaking table by connecting two pieces of frames with a connecting steel plate as shown in **Fig. 2**, and the steel plate's weight of 4.44 ton was attached on the connecting steel plate of the specimen. The measured items are relative displacements of columns, accelerations at top and base beams as well as shaking table [Kumasawa, 1992].

**Test program and input simulated motions**

The variable parameters of the tests are input motions. Three identical specimens, which have the same dimensions and details, were prepared. The input motions used in the dynamic tests were simulated input motions. As shown in **Fig. 3**, CASE2 is the motion with long time duration, and CASE3 is the motion with short time duration. Simulated input motions were generated by using the same acceleration response spectrum as shown in **Fig. 4**. The input excitation levels are shown in **Table 2**. Besides these excitations, several steps were added to obtain the target response level. CASE2 had eight steps and CASE3 had five steps finally. In order to know static behaviour of the specimen, static cyclic loading test named CASE1 was performed before shaking table tests.

## TEST RESULTS AND DISCUSSIONS

### Final failure mode

In the final failure modes, flexural cracks were formed at the top and bottom ends of the columns in three specimens. The concrete crashed at the top and bottom of the columns. There were no significant differences on the crack patterns in the three specimens.

### Maximum response values

As shown in **Fig. 5**, the maximum inertia forces of the dynamic tests are plotted on the lateral load-displacement curve of the static test. It is found that the maximum responses of the dynamic tests are higher than the static one after yielding point. CASE2 is 1.14 times of CASE1 and CASE3 is 1.17 times of CASE1 at the same relative displacement. It is mainly caused by the strain rate effect [Otani, 1986].

**Table2 Input levels**

| Input level | Response target | Target ductility |
|---|---|---|
| 1 | Elastic range | 0.05 |
| 2 | Cracking-yielding | 0.30 |
| 3 | Yielding | 1.00 |
| 4 | Large displacement | 2.00 |

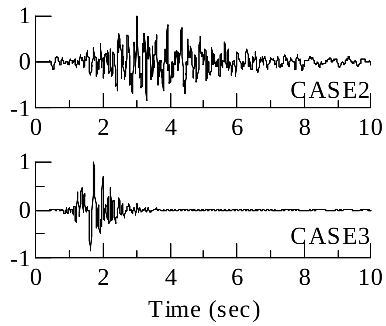



**Figure 3: Target input acceleration of shaking table tests**

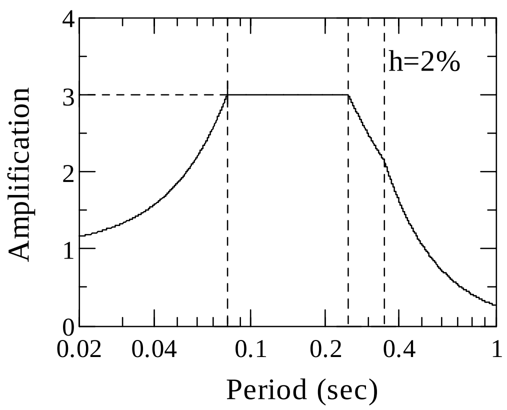



**Figure 4: Target acceleration response spectrum**

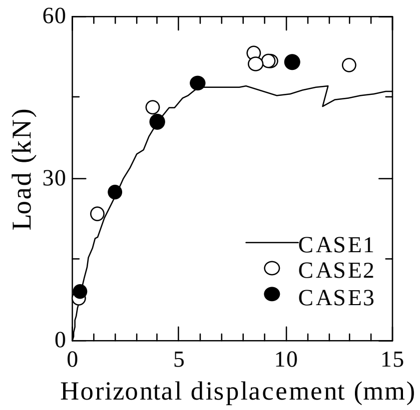



**Figure 5: Comparison of the maximum inertia forces with static load-disp. curve**

### Energy response

For a system of single degree of freedom, energy equation is given as :

$$\begin{array}{ccccccc} \int_0^t D(\dot{x})\dot{x}dt & + & \int_0^t F(x)\dot{x}dt & = & -\int_0^t m\ddot{x}_0\dot{x}dt & - & \int_0^t m\ddot{x}\dot{x}dt \\ E_D & + & E_H & = & E_I & - & E_V \end{array} \tag{1}$$

Where $m$ is mass of system, $x$ is displacement, $D(\dot{x})$ is damping force, $F(x)$ is restoring force, and $\ddot{x}_0$ is ground acceleration. In the equation (1), input energy $E_I = -\int_0^t m\ddot{x}_0 \dot{x} dt$ is considered to be an index to indicate the cumulative damaging potential of ground motion [Akiyama, 1985]. In this study, momentary input energy $\Delta E$ is defined by the increment of dissipated energy $(E_D + E_H)$ during $\Delta t$ that is interval time of $E_v = 0$ $(\dot{x} = 0)$ as shown in **Fig. 6**. $\Delta t$ is a half cycle period of hysteresis loop, and changes for each cycle.

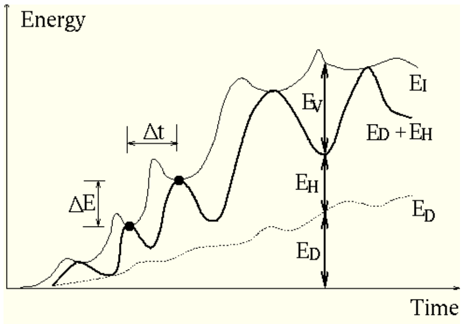
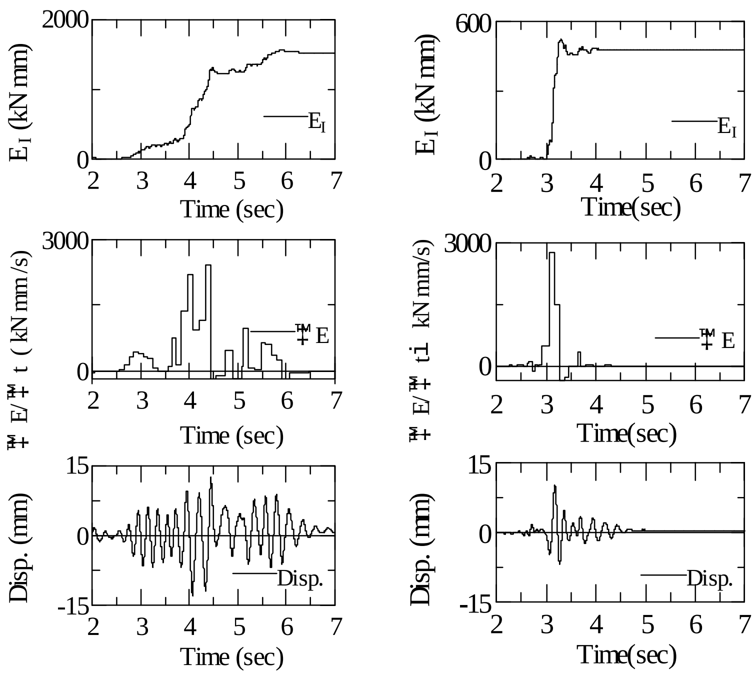


Figure 6 Energy time history

$$\Delta E = \int_t^{t+\Delta t} D(\dot{x})\dot{x}dt + \int_t^{t+\Delta t} F(x)\dot{x}dt = -\int_t^{t+\Delta t} m\ddot{x}_0 \dot{x}dt \quad (2)$$

Based on the definitions above, the time histories of input energies $E_I$, momentary input energies $\Delta E$ and displacement responses of dynamic tests CASE2 and CASE3 are shown in **Fig. 7**. In CASE3, momentary input energy $\Delta E$ is almost concentrated in initial short time range and total input energy $E_I$ is smaller than CASE2. Furthermore, in CASE2 and CASE3, the maximum displacement responses occurred at the times just after the maximum momentary input energies were inputted.



Final step8 of CASE2

Final step5 of CASE3

**Figure 7: Energy time histories**

## INELASTIC ANALYSIS OF REINFORCED CONCRETE COLUMN

For a reinforced concrete column subjected to lateral loads, total lateral displacement can be attributed to displacements due to flexure, slippage of anchorage reinforcement, and shear. Then the total lateral displacement $\Delta_{top}$ may be described as $\Delta_{top} = \Delta_f + \Delta_{shear} + \Delta_{slip}$. Where $\Delta_f$ is the displacement due to flexure, $\Delta_{shear}$ is the displacement due to shear, and $\Delta_{slip}$ is the displacement due to slippage of anchorage reinforcement. The displacement due to shear is neglected herein. Here a flexure model and a slippage model of anchorage reinforcement are independently formulated and later coupled in the proposed model. The fibre model is used to predict the flexure behaviour, and a slippage model, which is formulated based on the static test results of CASE1, is used to predict the displacement due to slippage of the anchorage reinforcements.

### Flexural displacement

The flexural displacement was obtained by the fibre model, which divided the end section of column into concrete and steel fibres. The strains in these fibres were calculated from stain at the centre of column section and section curvature by assuming that plane section remains plane. Since the bending moment diagram is linear along the column, only one-half of the column and only one end section is considered. The theoretical moment curvature diagrams were obtained assuming stress-strain relationships for steel and concrete, respectively as shown in **Fig. 8**. In order to idealize the curvature distribution, a half of the column is divided into three segments, as shown in **Fig. 9**. The first segment is assumed to be uncracked and the curvature distribution along it is assumed to be linear. The second segment is assumed cracked but unyielded and the curvature distribution along it is assumed linear. The third segment is assumed to have yielded and the curvature distribution is assumed to be constant considering a hinge zone. Here $M_{cr}$ is cracking moment and $M_y$ is yielding moment of column. Displacement due to flexure then can be obtained by integrating the curvature distributed [Kaba, 1984].

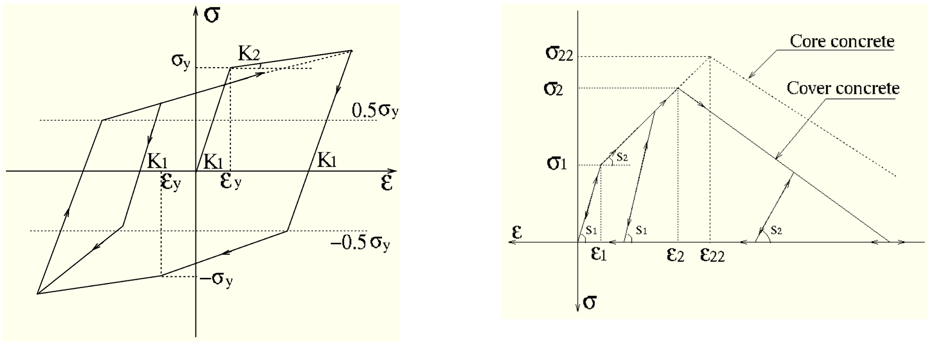



**Figure 8: Stress-strain relationship**

### Displacement due to slippage of anchorage reinforcement

Lateral displacements due to the bond slippage of anchorage reinforcement (defined as the extension of tensile reinforcements along the embedded length in the base beam) were calculated assuming that the bond slip rotation $(\theta)$ occurs around the neutral axis of the cross section of the column bottom as shown in **Fig. 10**. It is based on the assumption that the tensile force P of the reinforcement bar causes the slippage of the anchorage reinforcement. The additional longitudinal bar extension $\Delta L$, due to slippage, at the top of the footing was calculated at the outermost tensile steel layer in the column by integrating the slippage of anchorage reinforcement along the embedded bar length inside the footing. Based on the static test (CASE1) results, the effective embedded length was determined as 200 mm and the bond strength was calculated by referring Japanese design guideline. Thus, the bond slip rotation $(\theta)$ was calculated as $\Delta L$ divided by $L_i$, which is the distance of the centre of the outermost tensile steel layer from the neutral axis. The corresponding lateral displacement at the top of the column $\Delta_{slip}$ was obtained as $\Delta_{slip} = \theta \cdot H$, where H is the column shear span. The neutral axis location, the strain and stress in the tensile steel corresponding to the lateral load were determined from moment-curvature analysis of the critical section. For cyclic loading, the relationship between force of longitudinal reinforcement and slip displacement is defined as shown in **Fig. 11**. Here $P_y$ is defined as the yielding point of reinforcement, and $\delta_A$ is determined from the observed slippage of critical section during static test CASE1 [Filippou, 1983], [Moro, 1977].

### Dynamic analysis method

Newmark Algorithm (ß=0) was used for dynamic analysis. Damping which is proportional to the initial stiffness is used with a damping factor of 0.02 at the first natural period of 0.08 sec. As shown in Fig. 5, apparent increases in strength of columns were observed in dynamic tests. For dynamic analysis, strain rate effects for reinforcement and concrete were considered by the equations $\sigma'_y = \sigma_y(1.20 + 0.05\log\dot{\varepsilon})$ and $\sigma'_c = \sigma_c(1.38 + 0.08\log\dot{\varepsilon})$ respectively. Here, $\sigma_y$ is yielding strength of main reinforcement and $\sigma'_y$ is increased yielding strength after considering stain rate effect. $\sigma_c$ is maximum strength of concrete and $\sigma'_c$ is increased maximum strength of concrete after considering strain rate effect. Non-linear analyses were executed successively from the first step to the final step.

## Comparisons between tests and analytical results

The analytical results obtained by the proposed model are compared with the static test results as shown in **Fig. 12**. The monotonic loading analysis is in very good agreement with the observed envelope curve of load-displacement relationship. For cyclic loading analysis, the proposed model traces the static hysteretic loop well. As shown in **Fig. 13**, dynamic analytical results of inertia force-displacement relationships corresponding to the final step 8 of CASE2 and the final step 5 of CASE3 give close results such as maximum strength and hysteretic behaviour by considering the strain rate effect. The larger repeated hysteretic loops of CASE2 compared to CASE3 are well reproduced.

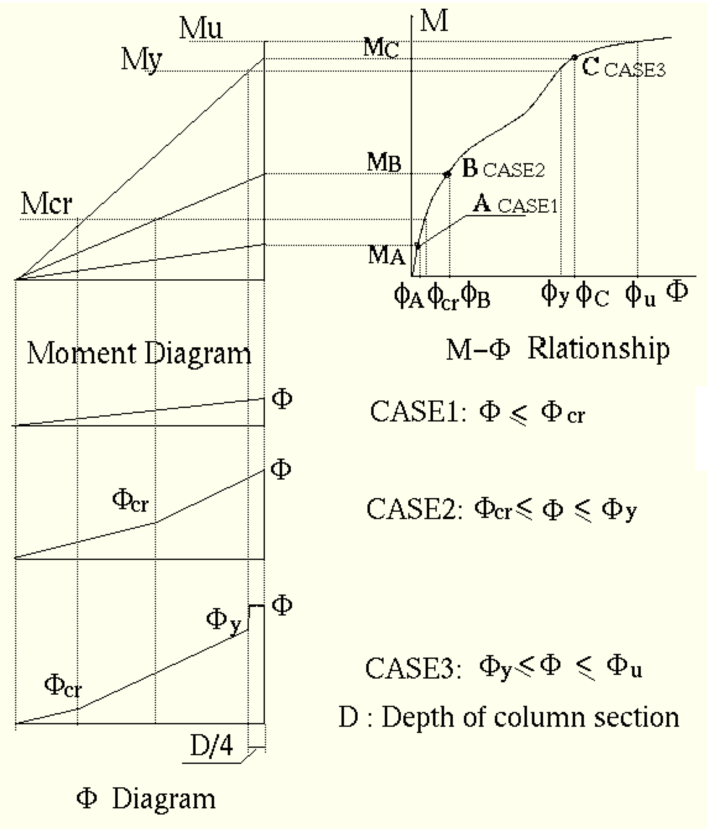



Figure 9 Curvature distribution along the half of column

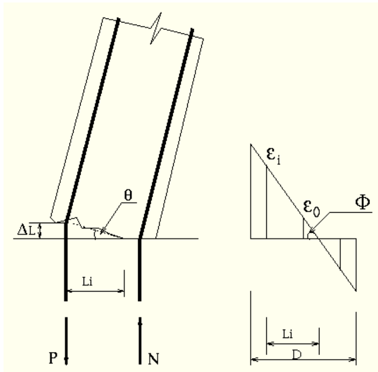



**Figure 10: Slippage model of anchorage bar**

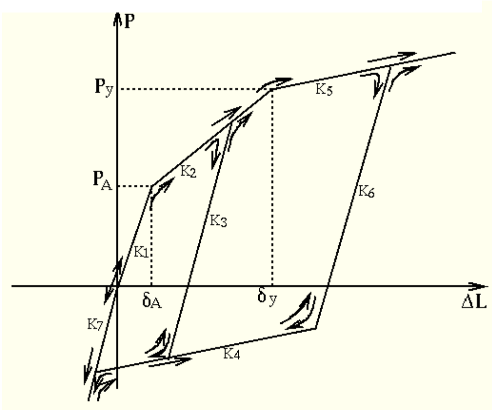



Figure 11 Force−slip displacement relationship

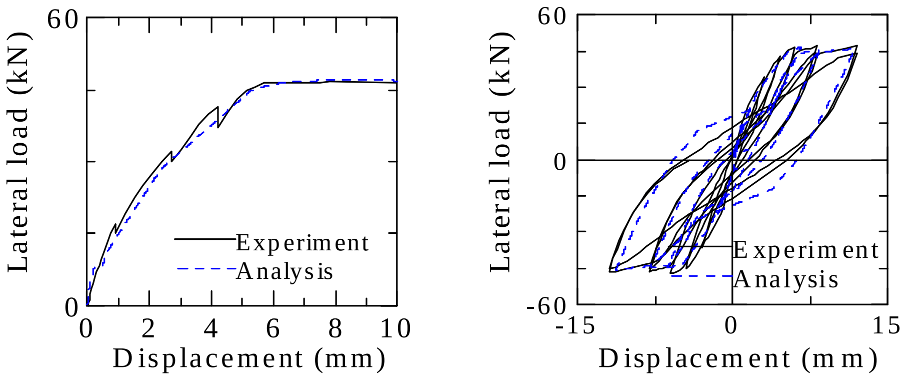
# DYNAMIC RESPONSE ANALYSES OF REINFORCED CONCRETE COLUMNS SUBJECTED TO SIMULATED INPUT MOTIONS WITH DIFFERENT TIME DURATION

## Earthquake motions

Input motions should be compensated before shaking table tests considering the interaction between shaking table and specimen. In this study before dynamic tests CASE2 and CASE3, input motions were compensated by using the specimen, which had been used for static test CASE1. But compensations were insufficiently performed because the total weight of specimen was larger than the weight of shaking table. Then the recorded response acceleration spectra of input motions in the dynamic tests were different from the target acceleration response spectrum as shown in **Fig. 4**. For investigating the effect of time duration on the damage potential of different input motions, reproduced motions should reflect real characteristics of target input motions. From these circumstances the effect of time duration was investigated by analyses using the proposed model. The target input motions used for shaking table tests CASE2 and CASE3 were applied to these analyses and named as CASE-L and CASE-S respectively. The maximum input accelerations of CASE-L and CASE-S were determined by the target acceleration response spectrum as shown in **Fig. 4**. The elastic target response of acceleration is the same and decided to be 950 cm/s$^2$.

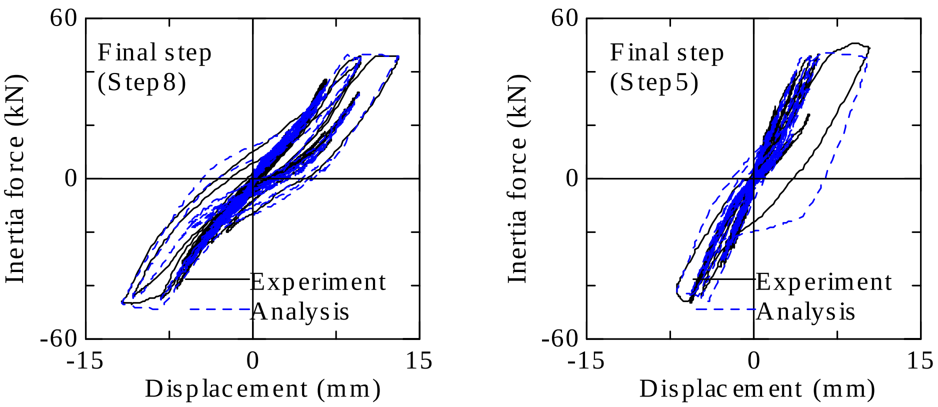
### Results and discussions

Inertia force-displacement relationships of CASE-L and CASE-S are shown in **Fig. 14**. From the effect of repeated cyclic loading, the stiffness of CASE-L reduced more severely compared to CASE-S. **Fig. 15** shows input energy $E_I$ as well as momentary input energy $\Delta E$ and displacement responses. In CASE-L, the momentary input energy was inputted in several times and it was inputted in almost 2 times in CASE-S. In CASE-L and CASE-S, there was no significant difference in the maximum values of momentary input energy and maximum displacement. Furthermore, the maximum displacements occurred just after the momentary input energies were inputted in both cases.




(a) Monotonic loading analysis (b) Cyclic loading analysis

**Figure 12: Lateral load-displacement relationship (CASE1)**




(a) CASE2 (b) CASE3

**Figure 13: Inertia force-displacement relationship**

## CONCLUSIONS

In this study, dynamic behaviour of reinforced concrete columns subjected to simulated input motions with different time duration was studied by experimental and analytical methods. From dynamic tests by the shaking table and a static test, it is found that the strength of dynamic tests is 1.1-1.2 times higher than the static test. The proposed fibre model considering slippage of anchorage reinforcement can simulate well load-displacement relationships and time histories of displacement for the dynamic tests as well as static test. Energy responses were investigated for evaluating the effect of time duration of simulated input motions and it is found that the maximum displacements occurred just after the maximum momentary input energy were inputted to the specimens in both cases with different time duration of input motions.

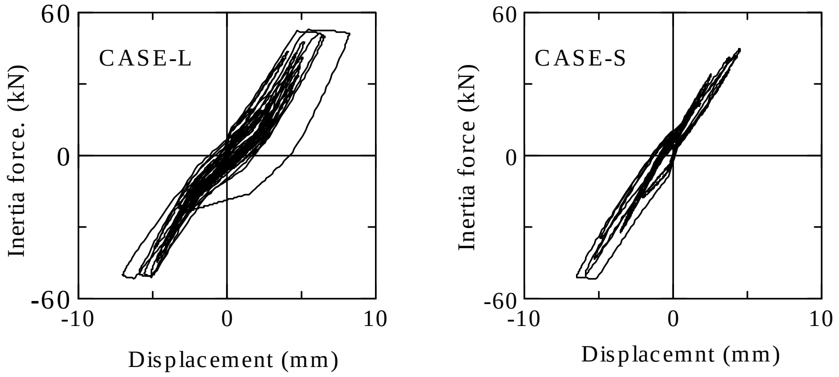



**Figure 14: Inertia force-displacement relationship**

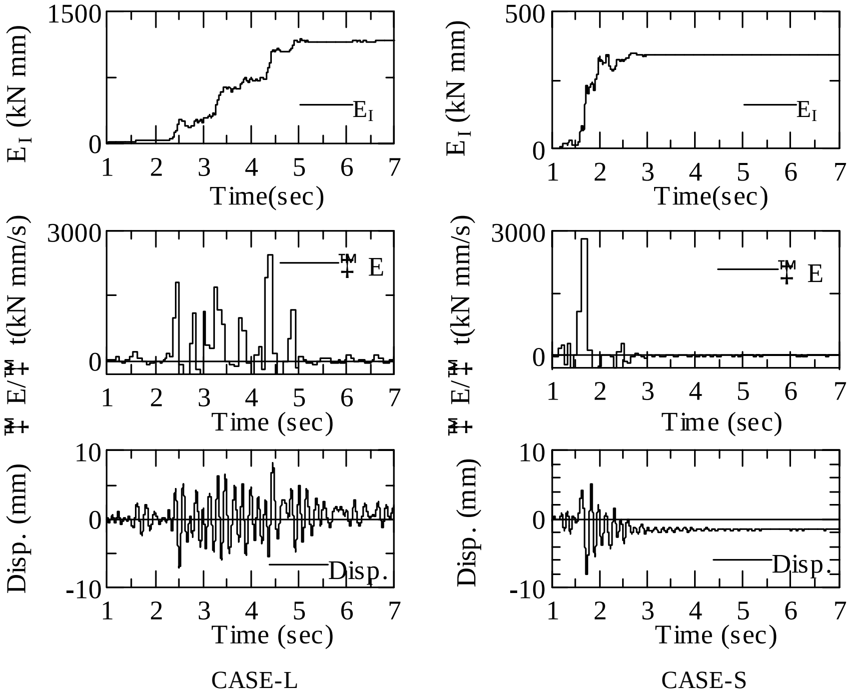



**Figure 15: Energy Response**

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