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DYNAMIC PROPERTIES OF BUILDING STRUCTURE CHANGED BY STRONG EARTHQUAKE AND ITS RENEWAL

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SUMMARY

Because of the structural non-linearity, structural properties such as natural period depending on stiffness and behavior corresponding to external excitation etc. are different from those before suffering an earthquake. Through the response analysis, changes of dynamic properties of the university school building pre and post 1995 Hyogoken-Nanbu earthquake are investigated in this paper. Further, renewal of the building was carried out by using an additional external frame after earthquake, change of the dynamic properties due to this renewal and estimation of the seismic performance are described.

It becomes clear that the predominant period of the structure becomes longer due to deterioration of the stiffness and the plastic displacement response becomes larger when the structure suffers similar earthquake again. After the renewal of this building, responses of acceleration and shear force increase with increase of the stiffness and shear resistant strength. However, demand to restrain story deformation angle is satisfied and it can be mentioned that the improvement of seismic performance could be verified.

INTRODUCTION

Concerning the change of natural period of the building which encountered an earthquake in the past, the following knowledge is provided. Natural period found from micro tremor is shorter

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than the natural period for design (natural period calculated with elastic stiffness). Natural period becomes longer as the earthquake input level is large. Natural period found from micro tremor after earthquake gets longer than it before an earthquake. It is the main objective of this paper to make clear the relation between growth of natural period and level of the earthquake motion qualitatively as well as quantitatively.

CHANGE OF NATURAL PERIODS DUE TO EARTHQUAKE

Natural periods obtained from earthquake record and micro tremor observation are shown in table 1. The first building reported is designated as Building A: which is steel encased reinforced concrete office building in Sendai-city with 18 stories and 2 basements subjected to 1978 Miyagiken-Oki earthquake. As the second building, Building B: which is reinforced concrete residential building close to Osaka-Bay with 33 stories and 3 basements subjected to 1995 Hyougoken-Nanbu earthquake. As the notations used in the table, T is the predominant period during earthquake, T_D is the design value of natural period for elastic stiffness, T_{m1}, T_{m2} are the natural period determined by a micro tremor measurement. For the above two buildings A and B, T/T_{m1}=1.6 to 1.7 and T_{m2}/T_{m1} =1.2 to 1.3 are commonly resulted. While the value of T/T_D are found to be T/T_D =1.2 and 1.5 with considerable difference for each building. All periods become a result to be prolonged after an earthquake.

The third one is six storied with one basement building of Kobe University, Building C: which is reinforced concrete school building and suffered 1995 Hyogoken-Nanbu earthquake. T_{m2}/T_{m1}=1.03 and 1.08 for NS and EW directions respectively with relatively small change. Most furniture in the building fell down, but there was no structural damage of the building, and it seems that the earthquake motion was not very big. This building situates on a cliff, but in the down area about 100m apart from here in horizontal distance towards the south sea side, crack of the ground appeared running in east-west direction. In the south side area, the gravestones of a graveyard stumbled over, wooden houses and the reinforced concrete buildings were collapsed or severely damaged.

Table 1 Natural period (Building A, B, C)

	Input wave		T/T_D		T/T_{m1}		T_{m2}/T_{m1}	
Direction	NS	EW	NS	EW	NS	EW	NS	EW
A building (18F)	278gal*1	252gal*1	1.1	1.21	1.58	1.71	1.21	1.26
B building (33F)	222gal*2 (36kine)	267gal*2 (34kine)	1.37	1.49	1.57	1.71	1.29	1.29
C building (6F)							1.08	1.03

*1 Measured at B2F *2 Measured at GL-1m

CHANGE OF VARIOUS CHARACTERISTICS OF THE UNIVERSITY SCHOOL BUILDING DUE TO EARTHQUAKE AND RENEWAL

Outline of a building to be examined

Four storied reinforced concrete building built in the neighbor of the above-mentioned C building is examined experimentally and analytically as follows. This building was built in 1962 and was the existing non-conformed building that did not satisfy a current building standard.

There was not the structural damage by an earthquake, but it was retrofitted in 2003 after the earthquake.

The second floor plan is shown in Fig.1a, which is 8.9m×84m. A short side (NS direction) is 8.9m ×1 spans, and a long side is 4m×21 spans. Bold lines in the figure are the members added by renewal. Strength resistance type of renewal is adopted, and it is a method to reinforce a building by adding PC frames from the outside. For the north side in the longitudinal direction, an additional PC frame is glued to the existing frame. For the south side in the longitudinal direction, a balcony made of PC floor is founded, and a new frame is connected to an existing frame by the PC floor slab and beam. For the transverse direction, carbon fiber sheet is wound up on the columns and beams composing the frame of the seismic wall.

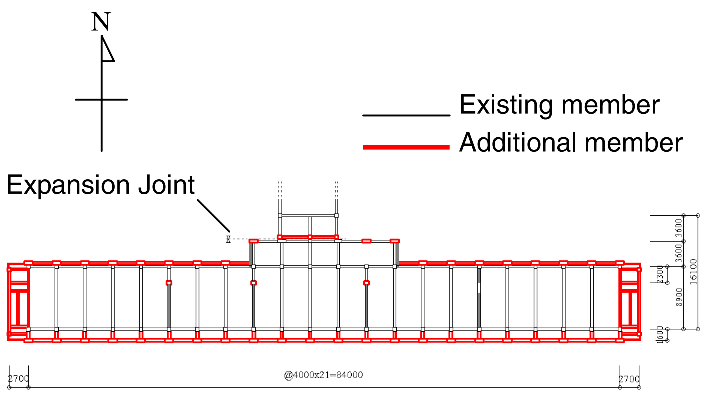


Fig.1a Second floor beam plan before and after renewal

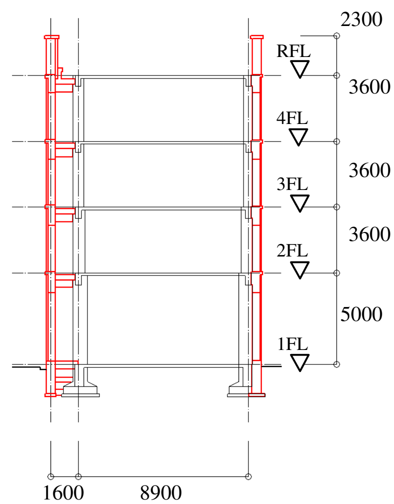


Fig.1b Section of NS direction

A natural period measurement result during the renewal

The following states during the renewal are called phase 1 to 4 , i.e. Phase 1: A state before renewal, Phase 2: Secondary members were completely removed and seismic wall was partially removed, Phase 3: Additional PC frames were built up to the second floor and Phase 4: State that renewal is finished.

Fig.3 shows the transition of the natural period. In case of Phase 1, values are those obtained by calculation ($=T_D$) and in case of Phase 2 to 4, values obtained from Fourier spectrum of the micro tremor or recorded wave induced by forced vibration of manpower. In phase 1 before renewal, the first natural periods T for NS and EW directions took same values of 0.24 seconds, while the period of Phase 2 after secondary member removal lengthened to 0.34 second and 0.43 second, which are 1.31, 1.75 times of those before renewal respectively. In phase 3, stiffness becomes larger and the natural period for the EW direction becomes shorter than that for the NS direction.

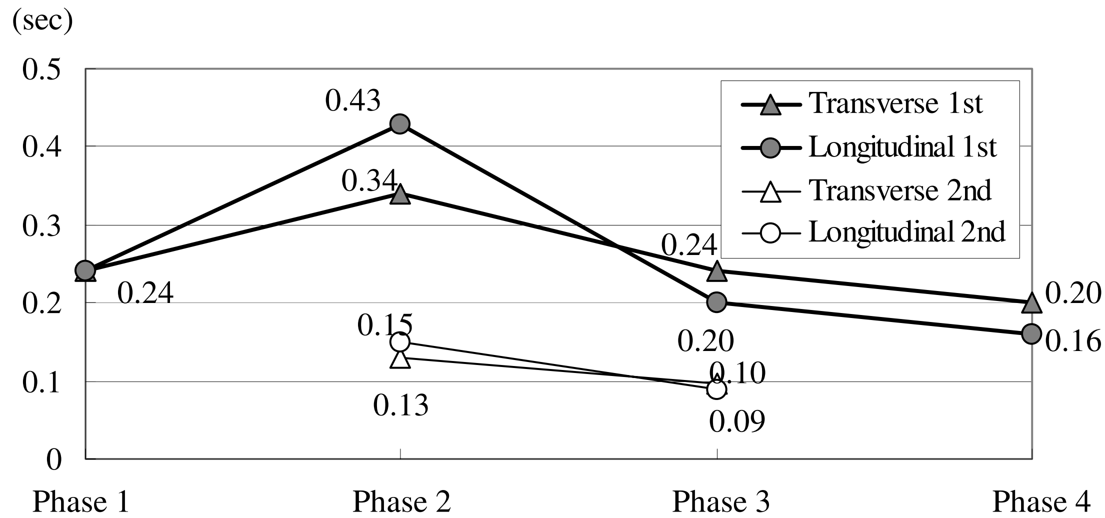


Fig.2 Transition of natural period (Phase 1 to 4 during renewal)

For phase 4 after renewal, natural periods are 0.2 second and 0.16 second for NS and EW directions respectively, which are shortest among these phases.

Assumption and model in the analysis

Four lumped mass shear system is applied and the response limited to the EW direction is examined in the analysis. Damping is assumed to be stiffness proportional type with damping ratio of h=0.03 for the first natural mode. As the hysteresis model, Takeda model is adopted which is used popularly in designing reinforced concrete structure and a correspondent skeleton curve with tri-linear type (in Fig.3b) is applied. In Fig.3-a, the monotonic loading curves determined by the incremental load method are shown. As can be seen, maximum strength after renewal is about 2 times of that before renewal.

The mark expressed by ○ on the curve for each floor shows the point where yielding of one of the structural members begins. Mark□ shows the point that the story deformation angle of 1/250 is developed and the corresponding resistant force is usually defined as the maximum strength for structural design. In the response analysis to input velocity level of V_{max}=50cm/s, response of the story deformation angle exceeded 1/250, so the above maximum strength is assumed to be taken at the point with story deformation angle of 1/100 and 1/200 for pre and post renewal buildings respectively.

In tables 2a and 2b, parameters taken in the analysis for pre and post renewal are shown respectively. In Fig.4, the design value of natural periods and modes determined by the analysis using the initial stiffness ${}_1k$ are shown. As for the stiffness after renewal, stiffness distribution is approximately uniform but the stiffness at the first floor is the smallest and it becomes 2 to 5 times (from the first story to the top) larger than that before renewal. The mass of each floor after renewal increased to approximately 1.5 to 2 times. Before renewal, distribution of the stiffness shows triangular shape which decreases towards the upper story. Reflecting this stiffness distribution, the displacement of the first mode tends to increases towards the upper story as can be seen in Fig.4a.

Input earthquake waves used in the analysis

An input earthquake wave is the following six observed waves:

El Centro 1940NS, Taft 1952EW as standard waves of a severe earthquake,

Tohoku Univ.NS (during 1978 Miyagiken-Oki Earthquake) as Japanese oceanic type earthquake,

Kobe Univ., JMA Kobe NS, NTT Kobe NS (during 1995 Hyogoken-Nanbu Earthquake) as Japanese inland earthquake.

Results obtained for input velocity levels of V_{max}=25, 30, 50 (cm/sec) are described hereafter.

In Fig.5, acceleration response spectrum for four earthquake waves that show large response.

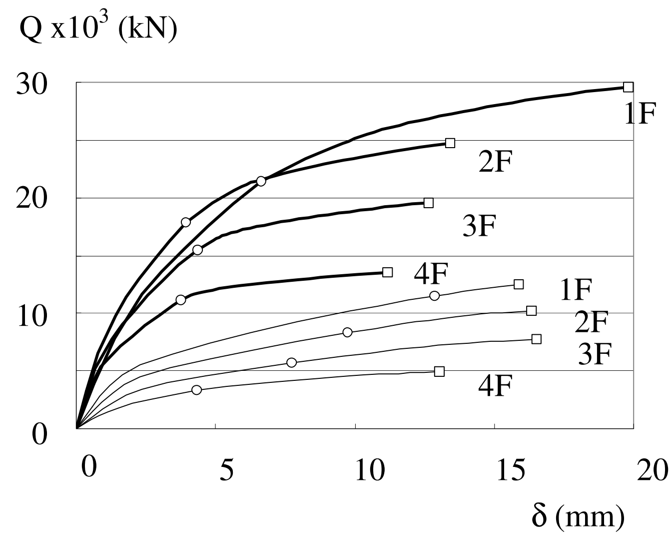


Fig.3a Skeleton curve before and after renewal

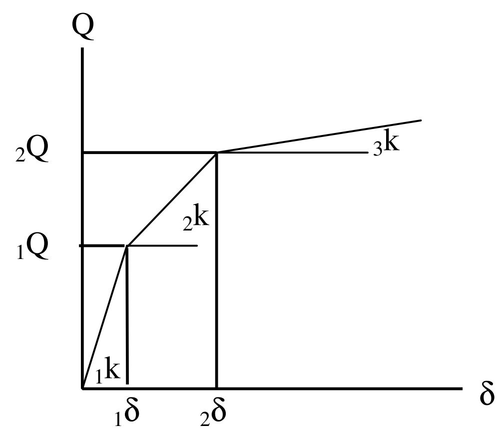


Fig.3b Tri-linear model

Table 2a Parameters of the model for analysis (before renewal: Phase 1)

FL	H (m)	Mass $X10^3$(kN)	Stiffness$X10^6$(kN/m)			Relative Displacement $X10^{-3}$(m)	
			$_1k$	$_2k$	$_3k$	$_1\delta$	$_2\delta$
4	3.6	7.7	1.4	0.46	0.17	1.2	5.8
3	3.6	6.6	1.9	0.38	0.18	1.8	10.0
2	3.6	7.4	2.6	0.51	0.24	1.6	10.7
1	5.1	9.1	3.6	0.64	0.39	1.4	8.6

Table 2a Parameters of the model for analysis (after renewal: Phase 4)

FL	H (m)	Mass $X10^3$(kN)	Stiffness$X10^6$(kN/m)			Relative Displacement $X10^{-3}$(m)	
			$_1k$	$_2k$	$_3k$	$_1\delta$	$_2\delta$
4	3.6	15.0	7.8	1.9	1.3	0.7	4.0
3	3.6	10.0	8.1	2.7	1.2	0.8	3.9
2	3.6	10.5	9.4	2.8	1.2	1.0	4.2
1	5.1	13.1	6.1	2.1	1.0	1.7	6.6

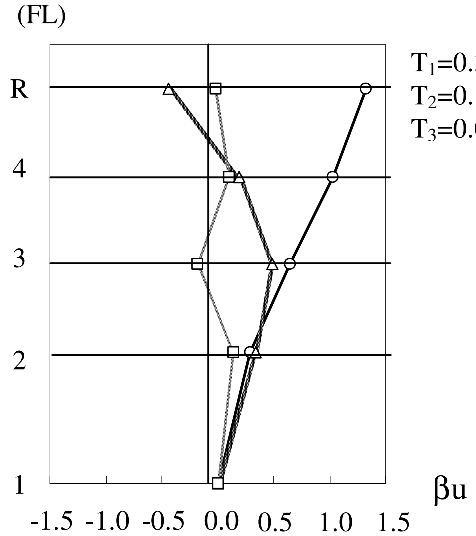


Fig.4a Design value of natural period and modes calculated using the initial stiffness (Phase 1: before renewal)

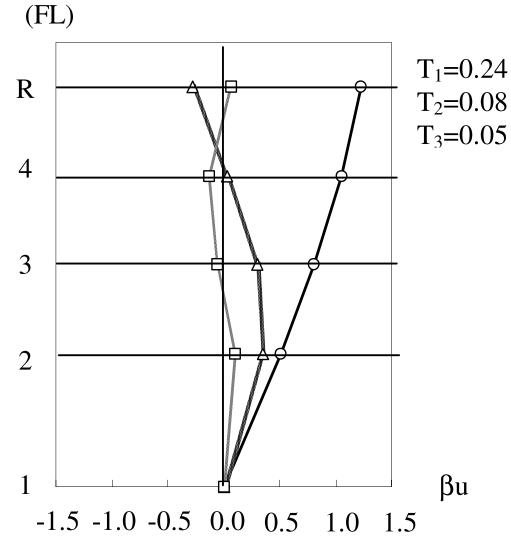


Fig.4b Design value of natural periods and modes calculated using the initial stiffness (Phase 4: after renewal)

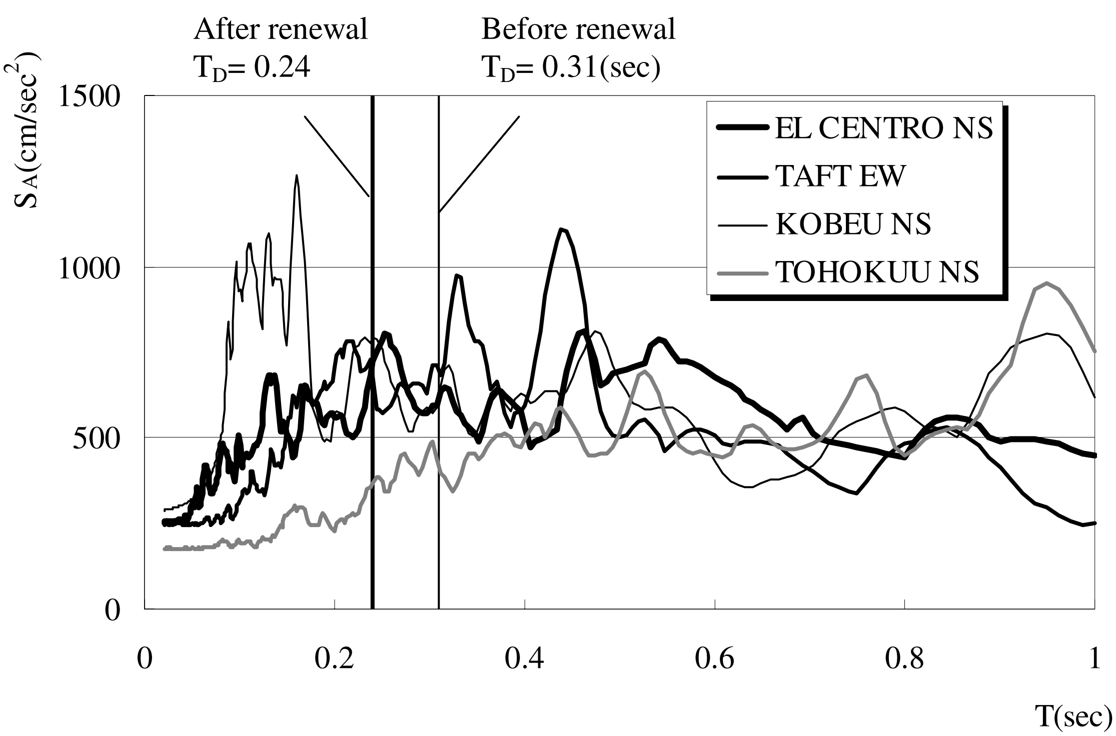


Fig.5 Acceleration response spectra S_A for various input earthquake (input level of V_{max}=25cm/s)

EARTHQUAKE RESPONSE CHARACTERISTICS AND CHANGE OF THE STRUCTURAL PROPERTIES AFTER EARTHQUAKE

As the results of the earthquake response analysis, the natural period, ductility factor and other various responses and properties of the building are investigated. When a building is subjected to an earthquake and experienced the plastic range, stiffness decreases and shows behavior to be different from an initial state. The relation between the earthquake input level and change of dynamic properties of the building are intended to make clear.

Effect of the input earthquake level on the hysteresis curves and vibration periods

Figure 6 is a result of hysteresis curves of the building before renewal, where input wave is El Centro earthquake wave and results of the third floor are shown. As can be seen in the figure, non-linearlity of the hysteresis loop becomes remarkable as the input level is bigger of 50 cm/s^2. Stiffness k_d appearing in Takeda models is expressed in equation (1) in the appendix, and the value of stiffness k_d is evaluated by the maximum value δ_{max} of the displacement response which is experienced during the earthquake. And according to the hysteresis law, this value of k_d determines all the history after the occurrence of the greatest displacement response. Therefore, after vibration stop due to an earthquake, natural period after an earthquake is determined from the free vibration wave form which occurs by the pulse input of slight amplitude. This value is same as the predominant period during an earthquake.

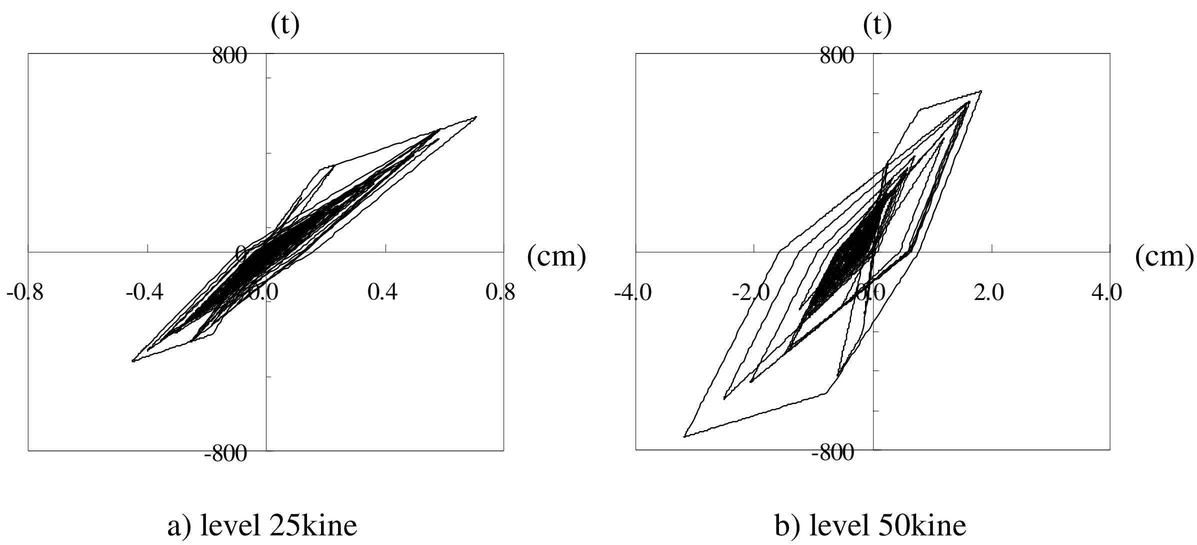


Fig.6 Hysteresis curves for different input wave level (El Centro wave, at 3FL)

Fig. 7a is a result of one example obtained by the input of El Centro and Taft earthquake waves. Natural period of T=0.31 second with input level 0 is design natural period T_D in figure 4a. As shown in Fig.7b, predominant period of about T=0.66 and 0.61 seconds for each earthquake of input level of V_{max}=50cm/s are approximately 2 times of the design value of the natural period. After renewal, these values of design value and predominant period during the earthquake increase with the input level similarly.

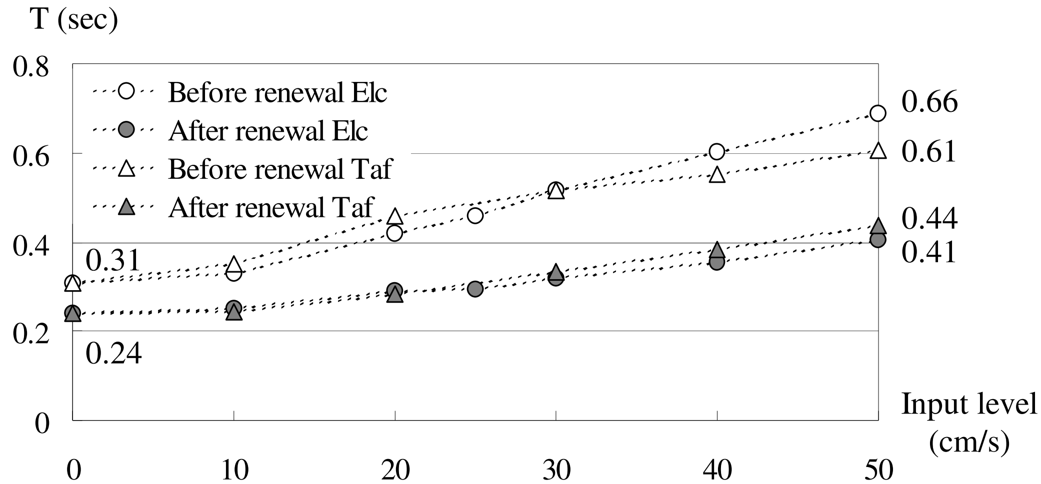


Fig.7a Predominant period T during earthquake varied with input wave level

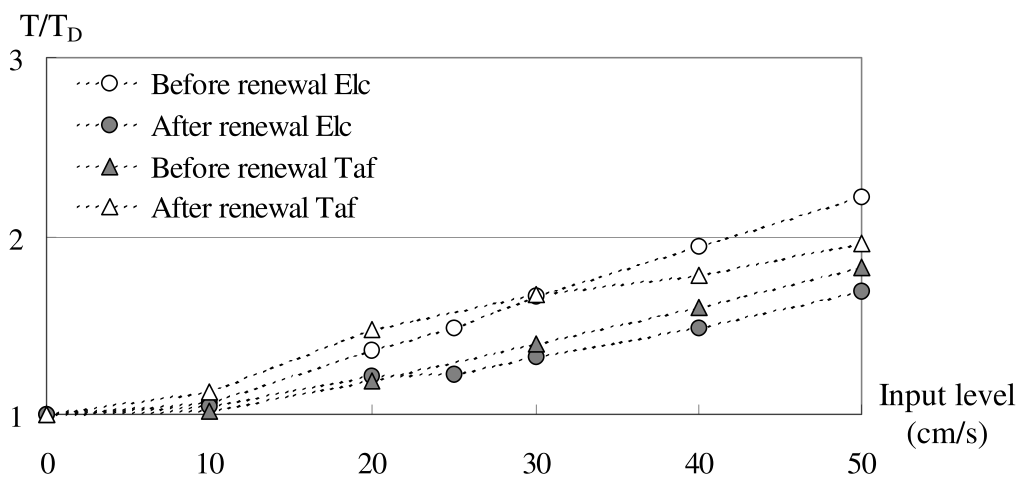


Fig.7b Predominant period ratio T/T_D during earthquake varied with input wave level

Change of dynamic properties after earthquake experience

As in Fig.8, carrying out the response analysis to the earthquake in success twice, change of the dynamic properties are investigated through the comparison of the first and the second response.

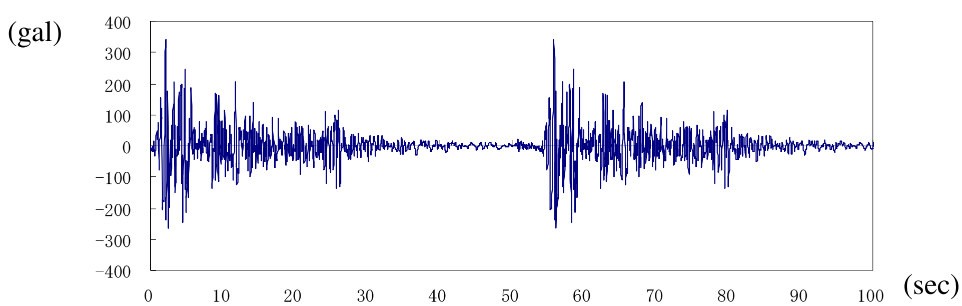
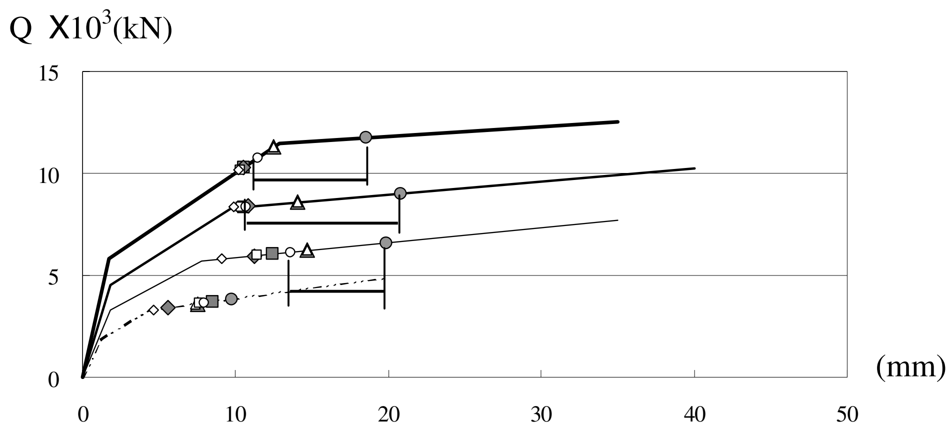
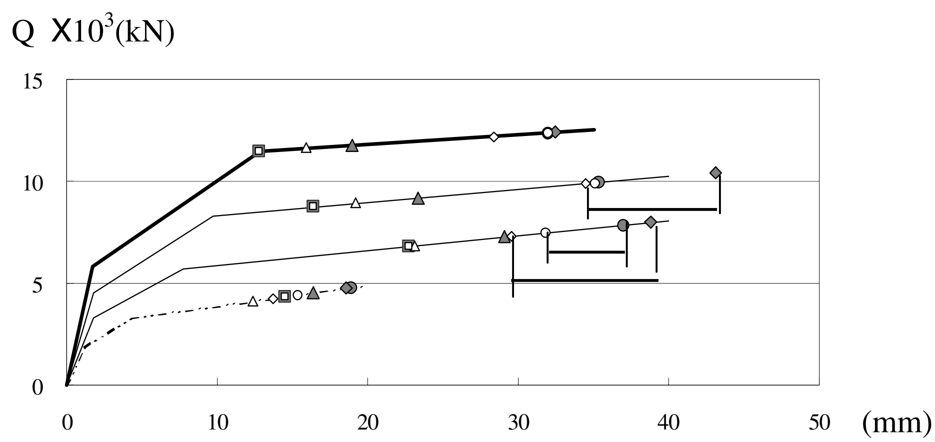


Fig.8 Model of continuous input earthquake (Example of El Centro wave)

Fig.9 and 10 show skeleton curves for pre and post renewal, and the marks for maximum displacement response are plotted on them From these figures the followings are found. The maximum displacement response induced by the second earthquake exceeds that by the first earthquake. In the floor where displacement response becomes large by the first input, the response becomes still larger by the second input. Fig.11 and 12 show the vertical distributions of the ductility factor in the form of ductility factor ratio, μ_2/μ_1 ,where some of the calculated results which have comparatively large value are selected and shown.
The ratio of ductility factor is larger at upper floors in case of before the renewal while it is larger at the first floor in case of after the renewal. The floors where the ductility factor becomes large are upper floors in case of pre renewal, while it becomes large at the first floor in case of post renewal. Irrelevant to input earthquakes and input levels, ductility factor takes value above 1, i.e. in other words the ductility factor due to second earthquake μ_2 is larger than that by the first earthquake μ_1 irrelevant to the input.

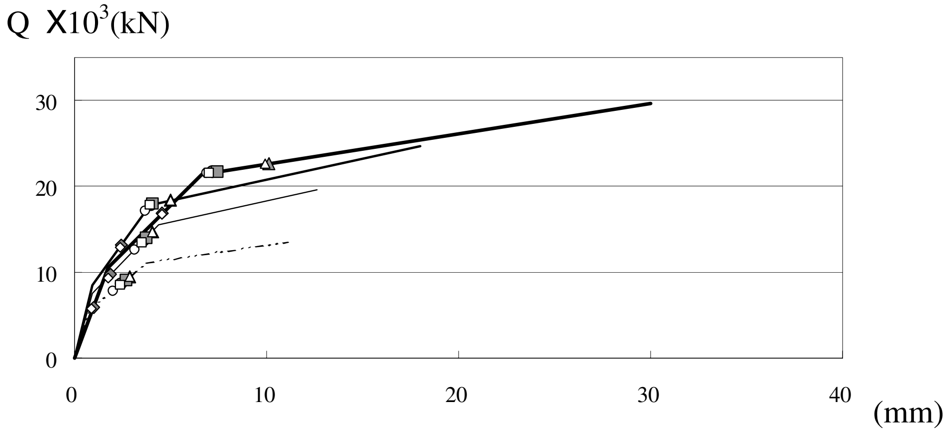


a) for V_{max}=30cm/s

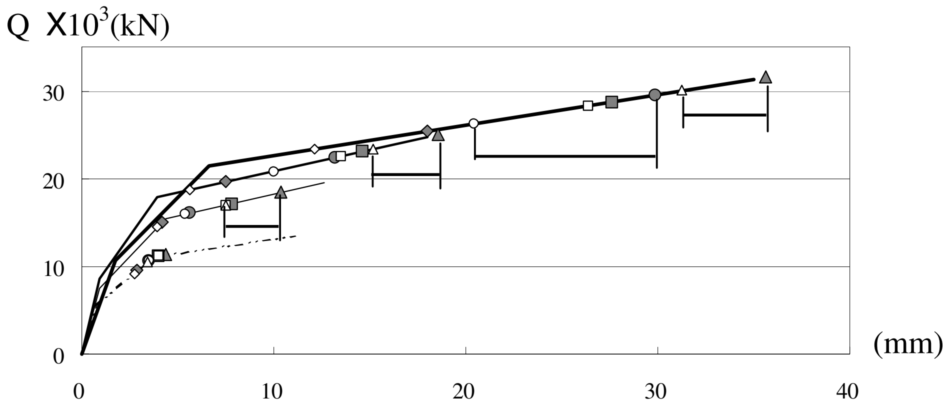


b) for V_{max}=50cm/s

Fig.9 Shear force-displacement response before renewal



a) for V_{max}=30cm/s



b) for V_{max}=50cm/s

Fig.10 Shear force-displacement response after renewal

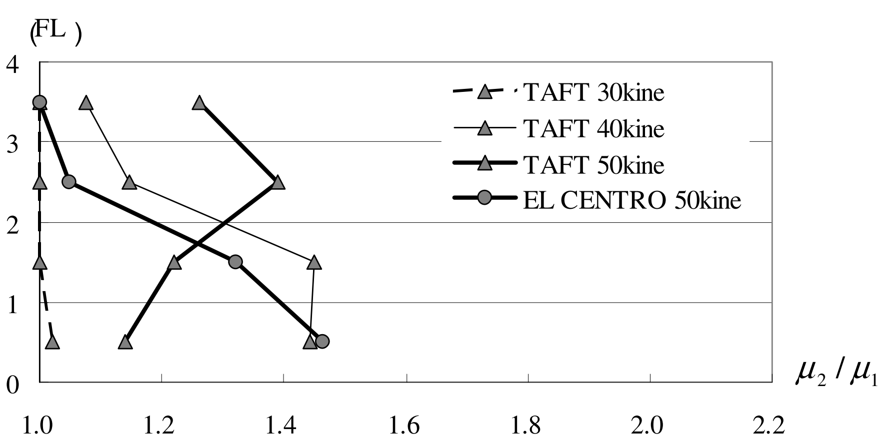


Fig.11 Ratio of ductility factor by first input to that by second input μ_2 / μ_1 (before renewal)

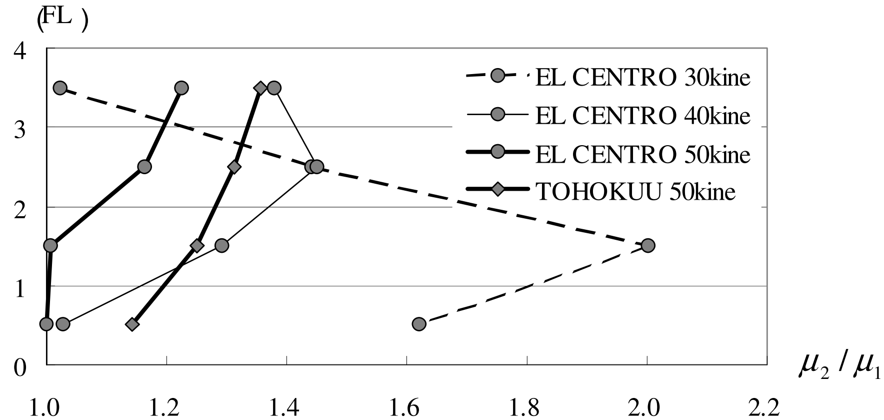


Fig.12 Ratio of ductility factor by first input to that by second input μ_2 / μ_1 (after renewal)

CHANGE OF EARTHQUAKE RESPONSE CHARACTERISTICS BY THE RENEWAL AND ESTIMATION OF SEISMIC PERFORMANCE

Thorough the response analysis of the four storied school building described above, change of the earthquake response characteristics due to renewal and seismic performance of the renewal are investigated. Before renewal, analytical value of the predominant natural period is from T=0.31 second (=T_D) to T=0.66 second (for input level of V_{max}=50cm/s) as before described. While after renewal, it become shorter and T=0.24 to 0.41 second. Numerical results taking the input level as V_{max}=25 and 50cm/s for six earthquake waves are described below. In Figs. 13 and 14, marks on the force-displacement lines of each floor show the maximum earthquake responses. Figs.15 and 16 show the vertical distributions of shear force Q, acceleration Acc, ductility factor μ and story deformation angle R.

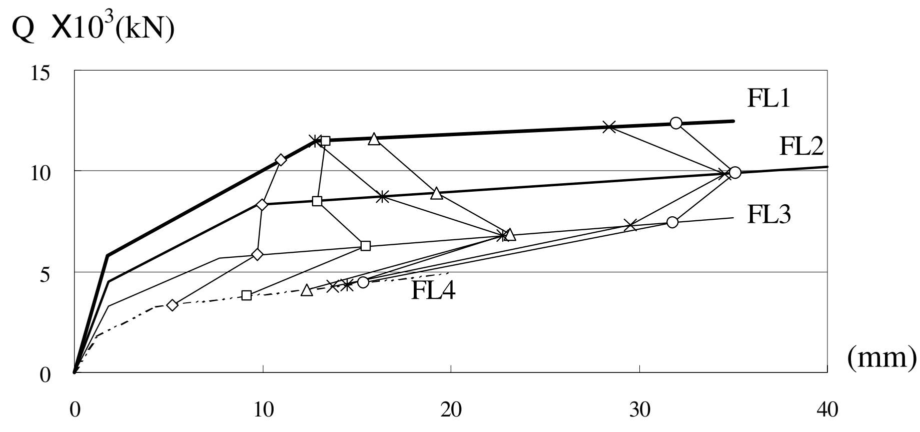


Fig.13 Shear force-displacement response (before renewal, V_{max}=50cm/s)

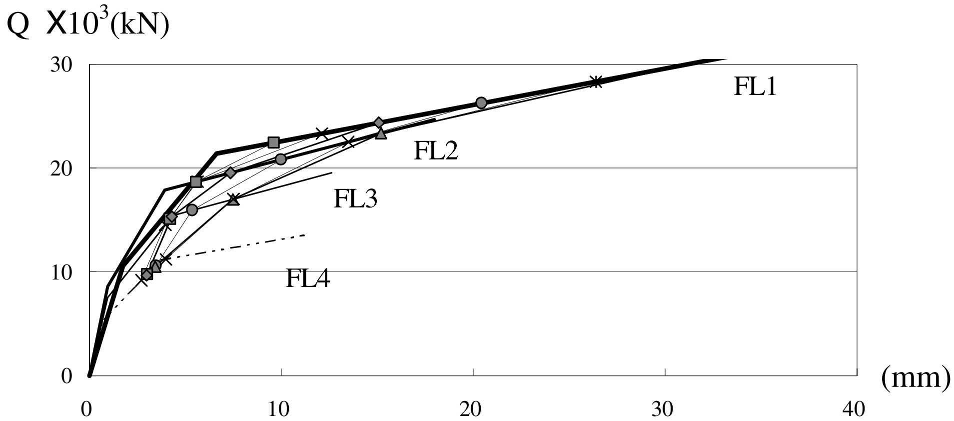
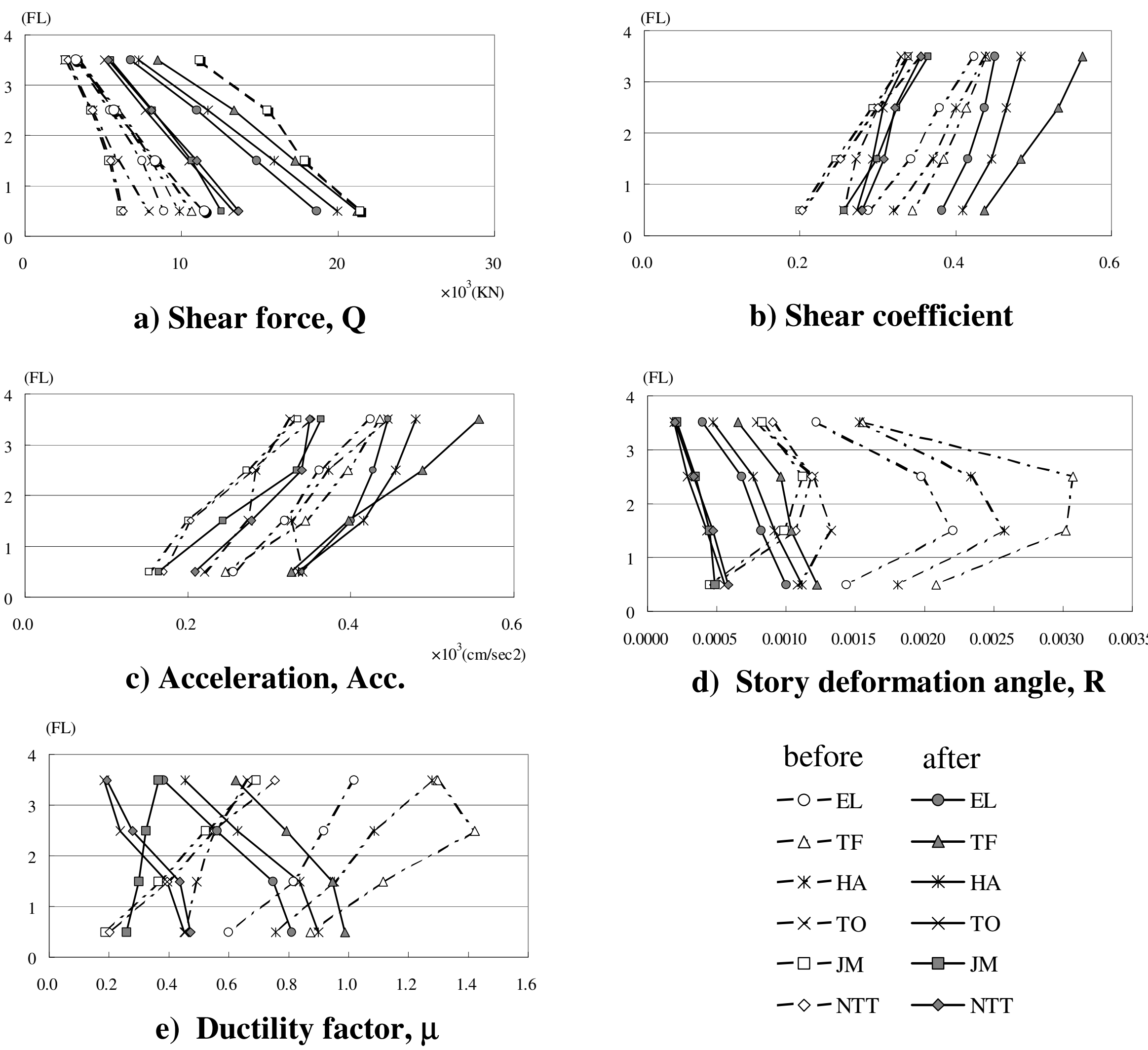


Fig.14 Shear force-displacement response (after renewal, V_{max}=50cm/s)



a) Shear force, Q

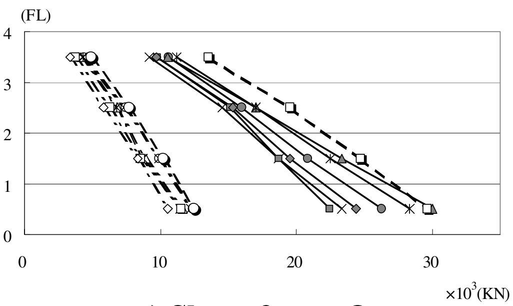
b) Shear coefficient

c) Acceleration, Acc.

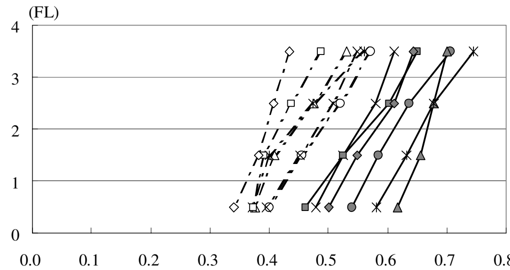
d) Story deformation angle, R

e) Ductility factor, μ

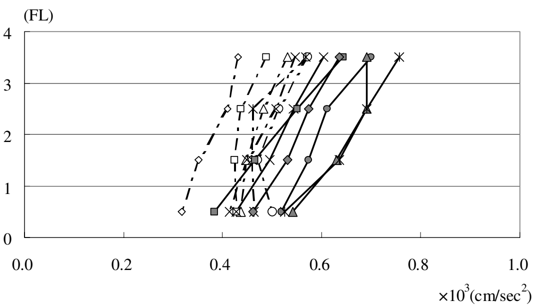
Fig.15 Comparison of responses before and after renewal (V_{max}=25cm/s)



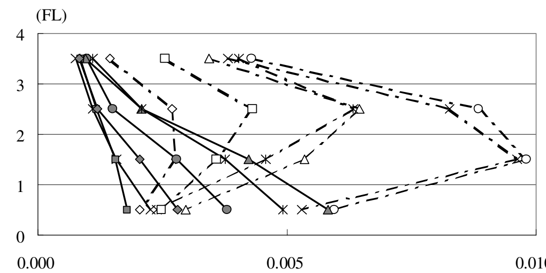
a) Shear force, Q



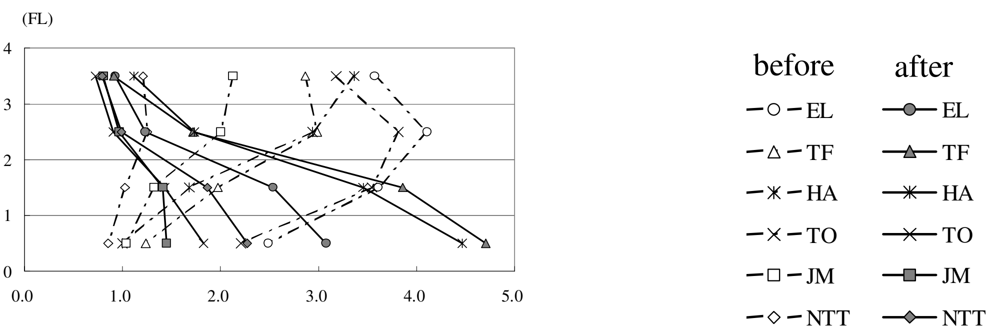
b) Shear coefficient



c) Acceleration, Acc.



d) Story deformation angle, R



e) Ductility factor, μ

Fig.16 Comparison of responses before and after renewal (V_{max}=50cm/s)

Result for input level of V_{max}=25cm/s: Analytical results of acceleration response for pre and post renewal are resulted in Acc=400 and 500cm/s^2 respectively. Ductility factor before renewal exceeds 1 at the second and the third floors and it becomes smaller remaining in the elastic range.

Result for input level of V_{max}=50cm/s: Acceleration responses of pre and post renewal become as Acc=500 and 800cm/s^2 respectively. Vertical distribution forms of ductility factor and story deformation angle resemble each other. After the renewal, shear force becomes three times of that of after renewal and shear coefficients increased about 1.5 times. The ductility factor before renewal shows maximum value at the third floor with $\mu = 4$. After renewal, plasticity starts from the first and the second floors which have relatively small shear resistant force in comparison with the shear response developed. The maximum value of the ductility factor takes place at the first floor of $\mu = 4.5$. This value is larger than the maximum value before renewal.

Since the collapse mode may differ before and after renewal, each response value may not equally become the decisive factor for seismic performance. However, except a story displacement angle, shear force, acceleration and ductility factor responses become larger after the renewal. In the case of an input level of 50cm/s, story displacement angle R decreases approximately to R=1/200 at the first floor, which is half times of that of before renewal, whereas it was about R=1/100 around the second and the third floors before renewal.

This building is a school building and the community use is made a point of. Therefore the reduction of the earthquake responses of displacement and story displacement angle is evaluated greatly. Adding the PC members and unifying with the existing members, provision of the Building Standard is satisfied and the intention to improve the existing non-conformed building can be achieved.

CONCLUSION

The followings are concluded:

1. Qualitative study has been done on the relation between input earthquake level and decrease of the stiffness i.e. increase of natural period of the building.
2. Since the structure responses in the elastic and plastic range under severe earthquake, the difference of the past history effects on the behavior for an earthquake to come in afterward. The decrease of the stiffness causes increase of the displacement response and through the analytical investigation it becomes clear that the dynamic property or seismic performance of a building is changed after earthquake.
3. In case of four storied school building of Kobe University, for the large earthquake input velocity level of V_{max}=50cm/s after renewal, responses of shear force and the ductility factor becomes large, displacement response becomes small due to the increase of the stiffness by additional PC frames and the displacement angle is restrained to within 1/200. Since this building is a school building, displacement restraint of a non-structure member is made much of and this renewal satisfies this point.

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APPENDIX I, HYSTERESIS LAW IN TAKEDA MODEL

Histeresis law concerning to the reduction of the stiffness in a plastic displacement range (d_{max}> d_2) is quoted for reference.
When displacement d exceeded d_2, the segments①,②,③ so on in a figure are traced sequentially. Where P1(Q1,d_1), P2(Q2,d_2) and P_3(Q_3,d_3) are the first point, yield point and maximum resistant point, respectively. P_{max}(Q_{max}, d_{max})is the maximum response experienced in the past.
Stiffness K_d and K_0 in the figure are expressed by the following equations. Where m is the coefficient to determine the inclination K_d and it is taken as m=0.5 in this study.

$$K_d=K_o \cdot \left| d_{\max} / d_2 \right|^m \qquad (1)$$

$$K_0=(Q_1+Q_2)/(d_1+d_2) \qquad (2)$$

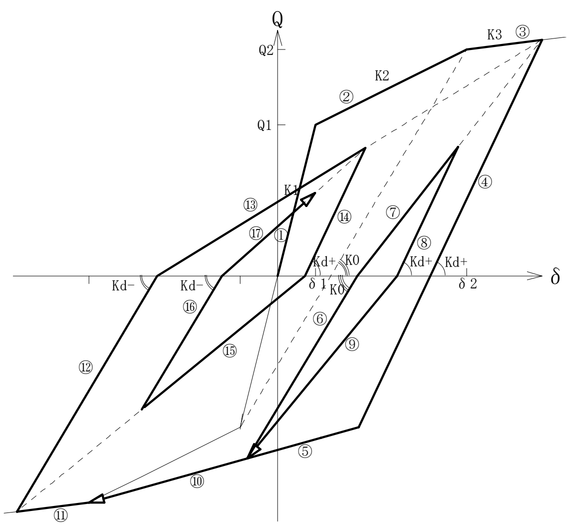

Fig.I Hysteresis law (Takeda Model, for plastic region $\delta_{\max} \geq \delta_2$)