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# EFFECTS OF LOADING HISTORY ON THE SEISMIC BEHAVIOR OF REINFORCED CONCRETE COLUMNS

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The response of seven reinforced concrete columns to two different unidirectional cyclic lateral loading types under constant axial load is presented. The tested specimens simulate the seismic behavior of first-story-columns existing in medium to high-rise reinforced concrete buildings. Failure modes and columns' global behavior are discussed. Energy dissipated by different components of each column was estimated. The analysis of experimental results investigated the effect of the type of lateral loading on the performance of the tested columns.

***Key words**: reinforced concrete columns, shear failure, lateral deformability, deformation at collapse, lateral loading type*

## 1. INTRODUCTION

The seismic performance of individual structural elements in medium and high-rise reinforced concrete existing buildings depends not only on the mechanical and geometric characteristics of the loaded elements but also on the type of applied loadings[1, 2, 3, 4]. Different combinations of varied loads and their magnitude levels may lead to different behaviors and consequently reach different conclusions. While the effects of different types of axial loading had been investigated previously[2], this paper presents experimental results of tested columns subjected to a constant axial loading and different unidirectional cyclic lateral loading types. The testing program included sixteen specimens; seven of them are the subject of this paper while the other specimens were oriented to strengthening studies. The obtained results from the presented experiment showed the effect of the selected lateral loading type on the response of the tested columns, affecting, for instance, the deformability, the axial stiffness and the shear strength degradation.

## 2. EXPERIMENTAL PROGRAM

The principal variables of the testing program were, mainly, transverse reinforcement ratio and number of lateral loading cycles, while the axial load was kept constant for all specimens. The specimens were scaled to one third of the actual columns, which considered representative of those occurring in the first story of moderately tall reinforced concrete systems located in seismic regions. The cross section of all columns was square (300x300mm$^2$). The geometric details of the tested specimens and the mechanical properties of the materials are depicted and listed in **Fig.1** and **Table 1**, respectively. It is worth to note here that the planned axial load ratio based on a concrete strength of 24 MPa was 0.25, which corresponds to a constant axial load of 540 kN yet applied on all specimens. The columns were cast at different times and cylinder concrete tests revealed higher strength than the assumed one at 28-day-age.

The columns were tested in a vertical position. Independent axial and lateral forces were applied simultaneously to specimens through a steel beam by mean of jacks. Laterally, columns were subjected to an anti-symmetric double curvature bending where the loading path was controlled by displacement. In order to simulate the action of near and far field earthquakes, two types of lateral loading were selected. Till a certain level, the aimed total maximum deflection for both loading types was the same, while the difference resided in the number of reversals or intermediate cycle peaks as shown in **Fig.2**. After a certain level the loading becomes monotonic for the second type.

Differential transformers and clip gages were used to measure displacements and deformations, while resistance gages were used to measure strains in the reinforcements. Also, in order to insure more details about the deformation of stirrups, clip gages were linked to the stirrups by mean of steel bars welded on the stirrups, as shown in **Fig.3**.

All specimens were designed to fail in shear before or at yield of the longitudinal reinforcement, except specimen No.15, which was expected to fail in flexure (yield before shear failure).

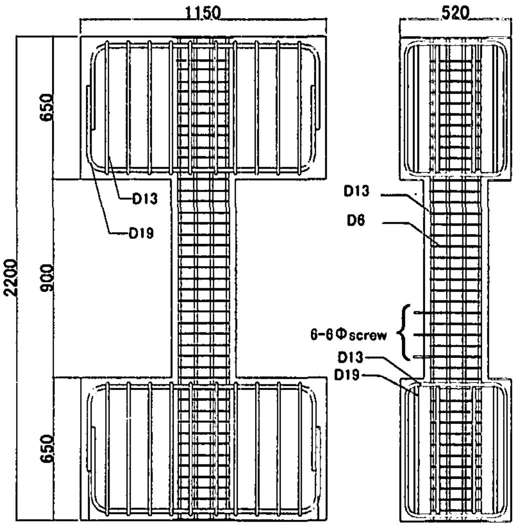


**Fig.1** General geometric details of tested specimens (Unit: mm)

**Table 1** Material and characteristics of specimens

| Spec. | Height (mm) | Concrete strength $\sigma_c$ (MPa) | Axial load ratio $\eta$ | Long. steel (MPa) | Trans. steel (MPa) |
|---|---|---|---|---|---|
| No.1 | 600 | 27.7 | 0.22 | 12-D13<br>$\rho_l$=1.693% | 2-D6@50<br>$\rho_w$=0.43% |
| No.11 | 900 | 28.15 | 0.21 | 16-D13<br>$\rho_l$=2.258%<br>SD390<br>$f_{ly}$=447 | 2-D6@150<br>$\rho_w$=0.14% |
| No.12 | | | | | |
| No.13 | | 26.1 | 0.23 | | 2-D6@50<br>$\rho_w$=0.43%<br>SR295<br>$f_{wy}$=398 |
| No.14 | | | | | |
| No.15 | | | | | 4-D6@50<br>$\rho_w$=0.85% |
| No.16 | 600 | | | 12-D13<br>$\rho_l$=1.693% | 2-D6@50<br>$\rho_w$=0.43% |

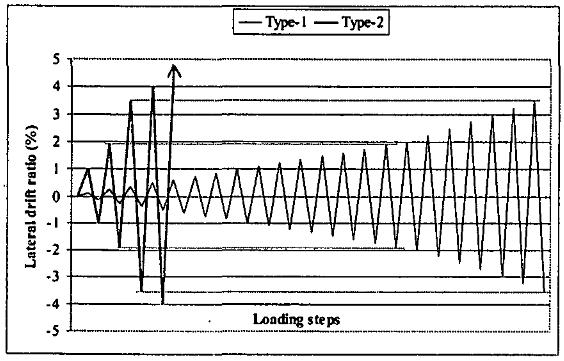
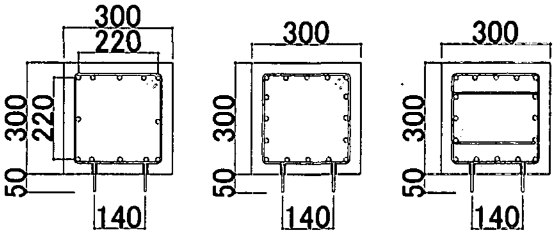


**Fig.2** Lateral loadings



No.1, No.16 No.11~No.14 No.15

**Fig.3** Transverse details

## 3. OBSERVED BEHAVIOR AND FAILURE MODE

Contrary to what it was expected, changing the lateral loading pattern did not exhibit much differences among tested specimens, especially those with low transverse reinforcement ratio or low shear span ratio. Also, it is worth to note that collapse of columns was more brittle under lateral loading Type-2 than under lateral loading Type-1.

Disregarding the type of loading, all specimens failed as predicted, though the actual concrete strength was higher than the assumed one. Except in specimen No.15 and except flexural cracks for other specimens at first loading steps, generally, shear cracks characterized the crack patterns development and conditioned the failure mode of columns. While failure of specimens with low transverse steel ratios or low shear span ratio (No.1, No.16, No.11, No.12) was due to clear diagonal tension cracks, failure for other specimens with higher transverse steel ratios and higher shear span ratio (No.13, No.14) was based on truss mechanism. Specimen No.15 experienced the formation of the truss mechanism after yielding of longitudinal reinforcement. Bond splitting and spalling of concrete cover were observed on specimens during the last loading cycles.

Actually, the evolution of cracks and their widths depended closely on the type of lateral loading. Their number was higher and their width was lower under loading Type-2 than under loading Type-1.

Finally, collapse was reached when columns were unable to sustain any more the applied axial load, which corresponded at the time when shear strength decay consumed the lateral capacity of the columns. In a very good accordance with the conclusions of previous experiments on nearly similar columns$^2$, though the axial load was kept constant during this testing program, columns' collapse occurred along different sliding planes with inclination angle planes ranging from very steep angles (low transverse steel ratio) to moderate ones, besides the type

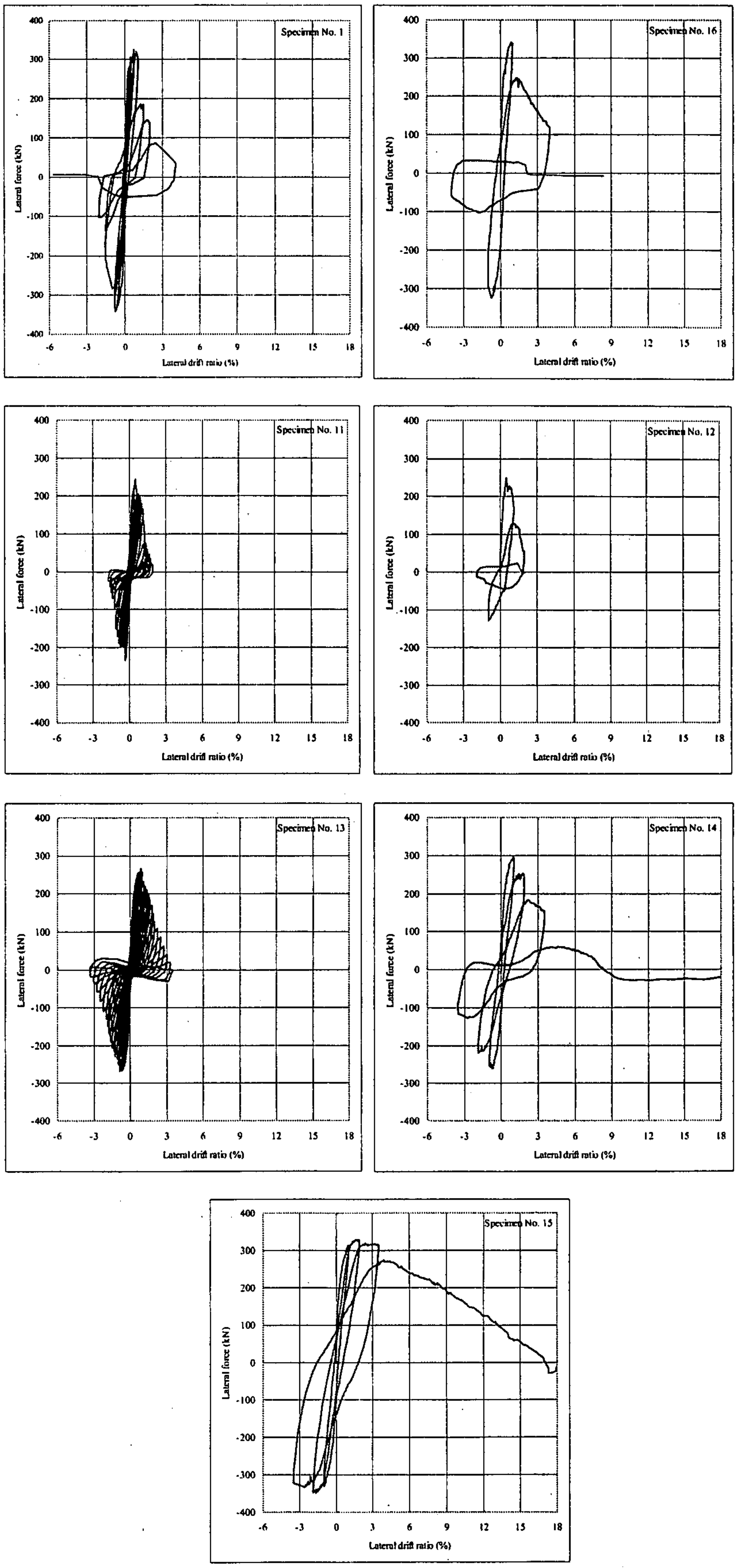


Fig.4 Lateral load-lateral drift responses

of lateral loading.

## 4. LOAD AND DISPLACEMENT RESPONSE

As observed on specimens with same shear span ratio, though a small difference in concrete strength, higher transverse reinforcement ratio provided higher shear resistance and allowed larger lateral deformability. Also, shear strength reached higher levels for specimens with lower shear span ratio, however their lateral deformability was lower, **Fig.4**.

The curvature-lateral drift response of all specimens, except in specimen No.15, showed a fast increase in the lateral deformation rather than in the curvature. This fact indicated the dominance of shear deformation during loading as to the flexural one.

As to lateral loading, compared to loading Type-1, application of loading Type-2 resulted in higher shear strength on the first loading direction and in lower shear strength on the opposite direction. Higher values were obtained because of the absence of low amplitude reversals, which would induce some damage. Lower values were obtained in the opposite direction because of the cracks imposed by the large amplitude of the first loading direction. Those cracks induced a drop in the shear strength on the first direction that influenced, consequently, the shear strength in the opposite direction. Also, shear strength degradation is more pronounced for loading Type-1 than for loading Type-2, which can be explained by the development of more cracks in the first loading type than in the second one. As for lateral deformability, except specimens

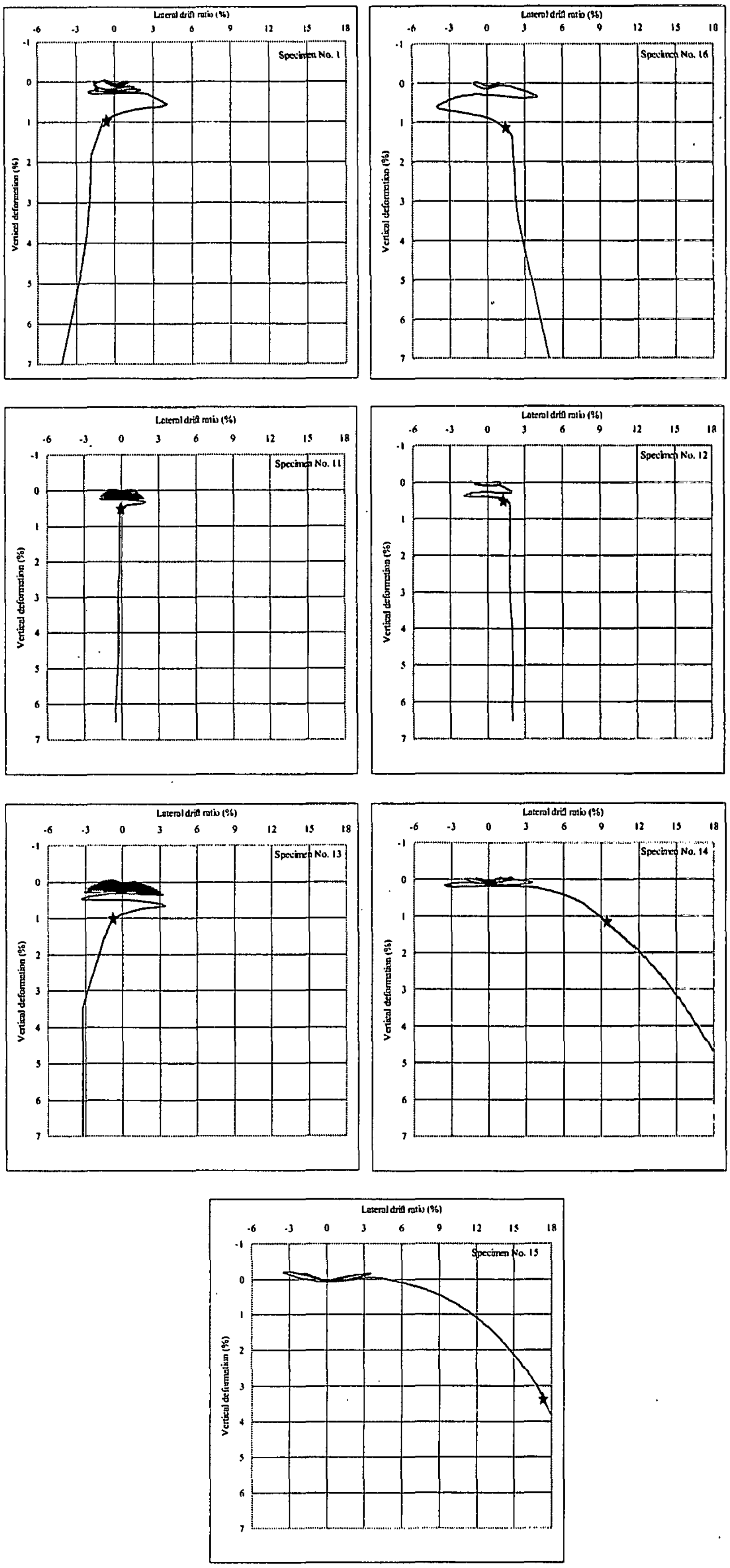


**Fig.5** Vertical deformation-lateral deformation responses

No.13 and No.14 that responded differently relatively to the lateral loading type where loading Type-2 allowed higher lateral deformability, other specimens did not show any difference as to lateral deformability levels, though under different loading types.

Concerning the vertical deformation, as shown in **Fig.5**, for each pair of specimens, degradation in the axial stiffness was comparable at the end of testing for both lateral loading types, though the degradation was fast at the beginning of loading for the specimens subjected to loading type-1. Finally, the collapse occurred at the same level of vertical deformation for each pair (No1 and No.16, No11 and No.12, and No.13 and No.14).

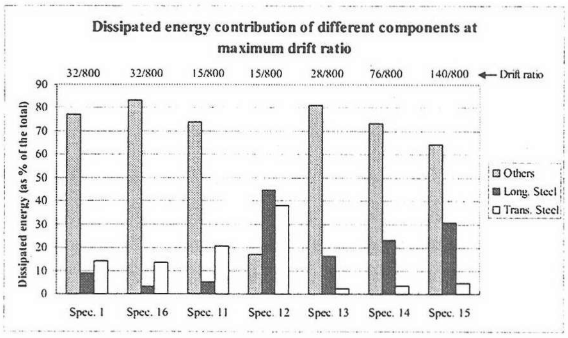
## 5. REINFORCEMENT STRAIN

Longitudinal reinforcement strains were measured on at least four bars for each specimen and at five different sections including those at extreme parts of columns. Except on specimen No.15, no a single bar yielded before shear failure in all specimens. Also, strains generally reached slightly higher maximum values under loading Type-1 than under loading Type-2, except in specimen No.12. Buckling of steel bars during loading was one of the conditions that lead to collapse. This fact, generally, occurred simultaneously when stirrups' hooks opened.

Transverse reinforcement strains were measured on four sides of stirrups and at five different levels on the half bottom of each specimen. Yield was reached for almost all stirrups depending on the position of the stirrups to the major cracks. Strains reached, generally, slightly higher maximum values under loading Type-1 than under loading Type-2, except in specimen No.14. It is worth to note here that collapse of columns was mainly due to the opening of the hooks where no rupture was observed in stirrups except in specimen No.12.

Deformations in the stirrups were also measured by means of some clip gages. Depending on the position of the stirrups, average strains computed from the clip gages, generally, agreed with the results of the strain gages till a certain level of lateral loading, then the strain values became very high due to the rotation of the bars supporting the clip gages.

## 6. DISSIPATED ENERGY



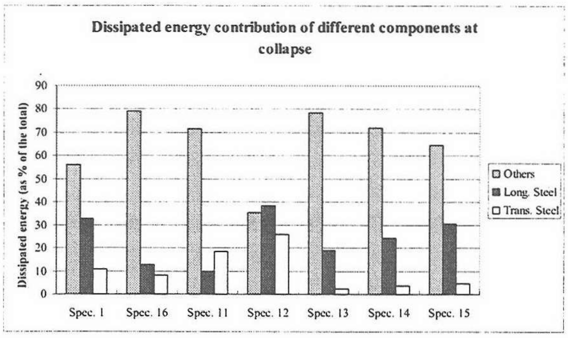


**Fig.6** Dissipated energy

Depending on the loading type and the reinforcement amount, the total dissipated energy varied from one element to another. Higher values were reached for higher confinements, for higher shear span ratios and *also for higher numbers of hysteretic reversals* as mentioned in the values given in **Table 2** which correspond to the dissipated energy at maximum lateral drift ($E_R$) and at collapse ($E_N$). The parts absorbed by the columns' components, longitudinal and transverse reinforcements and concrete, were distributed according to the developing cracks, their widths and the degradation of the core concrete. It was noticed that the energy dissipated by the longitudinal reinforcement increased rapidly while loading from the maximum lateral drift to the drift corresponding to collapse.

Also, during loading, generally, the concrete part dissipated far higher amount of energy in all specimens compared to the reinforcements part, except in specimen No.12. This fact calls attention to the effect of friction and its contribution to dissipate energy. **Fig.6** Illustrates the percentage of the total energy dissipated in different parts for each column.

**Table 2**: Dissipated energy (kN.m)

| Specimen | $E_R$ | $E_N$ |
|---|---|---|
| No.1 | 12.31 | 17.36 |
| No.16 | 7.98 | 15.10 |
| No.11 | 14.02 | 16.01 |
| No.12 | 5.23 | 8.06 |
| No.13 | 30.59 | 35.56 |
| No.14 | 23.17 | 23.83 |
| No.15 | 64.62 | 65.45 |

## 7. REMARKS AND CONCLUSIONS

The experimental work conducted on the previously mentioned specimens and explained in this paper reached the following remarks:

1. Strains measured by strain-gages or clip gages had nearly the same value for both lateral loading types, till a certain level of lateral loading.
2. Expected failure modes (shear or flexure) were reached though the differences between the assumed concrete strength value and the actual ones.
3. Increase rate of lateral deformability was higher than the one of curvature for both loading and in all columns failed in shear.
4. Collapse was more brittle under loading Type-2 (few hysteretic reversals) than under loading Type-1 (many hysteretic reversals).
5. Changing the lateral loading pattern, in this testing program, did not exhibit much differences as expected, to name, specimens with low transverse reinforcement ratio and those with low shear span ratio.
6. Evolution of cracks and their widths depended closely on the type of lateral loading. Their number was higher and their width was lower under loading Type-2 than under loading Type-1.
7. Collapse occurred when shear strength decay consumed the lateral capacity of the columns.
8. Collapse occurred along very steep plane for columns with low transverse reinforcement ratio or low shear span ratio and less steep planes for other columns.

Finally, according to the selected loading type in this experimental program, the following conclusions can be drawn:

1. For columns with same shear span ratio, higher transverse reinforcement ratio provides higher shear strength and larger axial and lateral deformability. For columns with same transverse reinforcement ratio, lower shear span ratio provides higher shear strength and lower lateral deformability.
2. Few-hysteretic-reversal-loading type induces higher shear strength in the first loading direction and lower shear strength in the opposite direction.
3. Shear strength degradation is more pronounced for many-hysteretic-reversal-loading type than for few-hysteretic-reversal-loading type.
4. For low transverse reinforcement ratio or low shear span ratio, lateral loading type has no influence on the attained maximum lateral deformability.
5. For relatively high transverse reinforcement ratio, few-hysteretic-reversal-loading type induces larger lateral deformability.
6. Lateral loading type has no influence on the limit axial deformation.
7. Strain values in longitudinal or transverse reinforcements are slightly higher under many-hysteretic-reversal-loading type than under few-hysteretic-reversal-loading type.
8. Energy dissipated by the reinforcements is almost not influenced by the lateral loading type.
9. Collapse occurs at the same level of vertical deformation despite the lateral loading type difference.

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