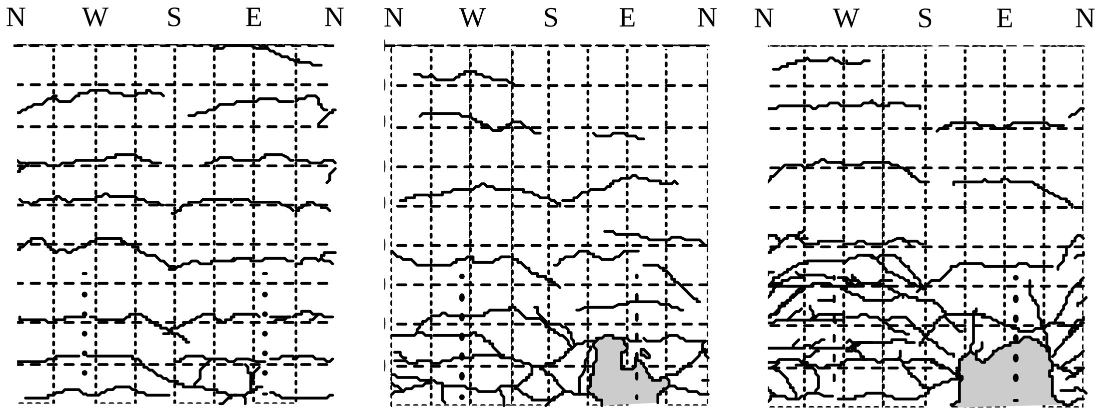


(a) Kobe 70% (b) Kobe 75% (c) Kobe 85%

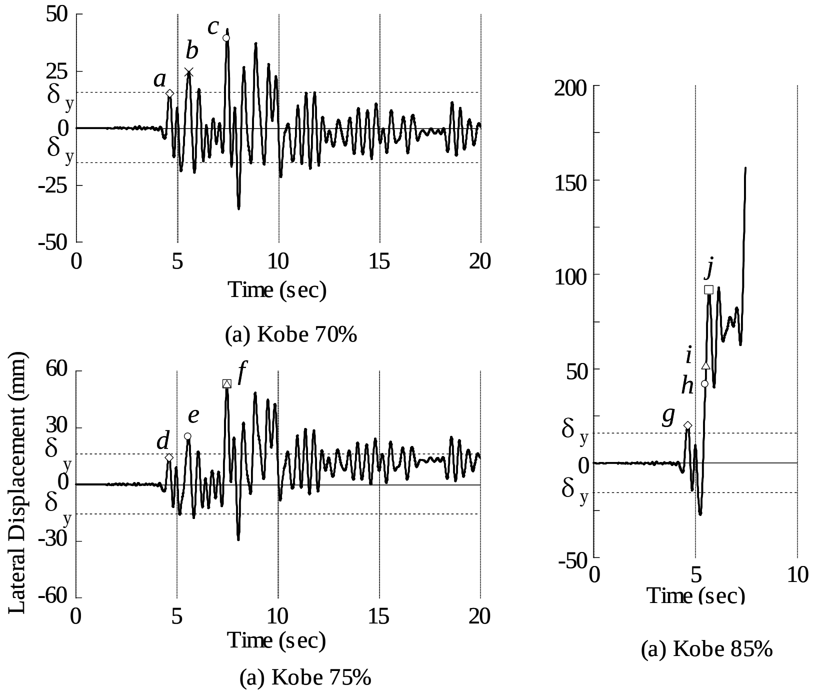
Fig.4.42 Failure Mode of Columns under Hybrid Loading Tests

4) Hybrid Loading Tests

Hybrid loading test is often used to study hysteretic behavior of structural members subjected to strong seismic excitations. Using the same reinforced concrete columns with the ones presented in 4.6 (1), a hybrid loading test was conducted. Features of the test are described here.

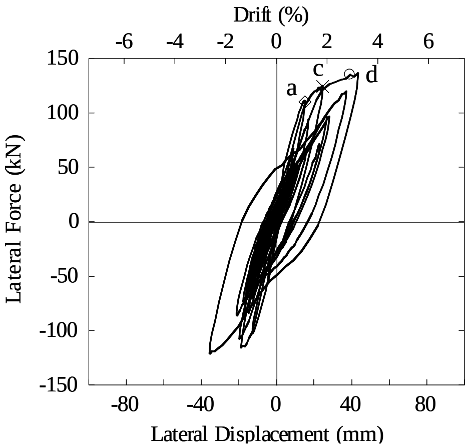
Ground accelerations with only acceleration amplitudes being scaled down to 70%, 75%, and 80% of the original JMA Kobe ground acceleration during the 1995 Kobe earthquake (refer to Fig. 1.1 (a)) was used as an input ground motion. The fundamental natural period is equal to 1 s and damping ratio is 0.02.

Fig. 4.42 shows failure modes after the hybrid loading tests. The columns were loaded in

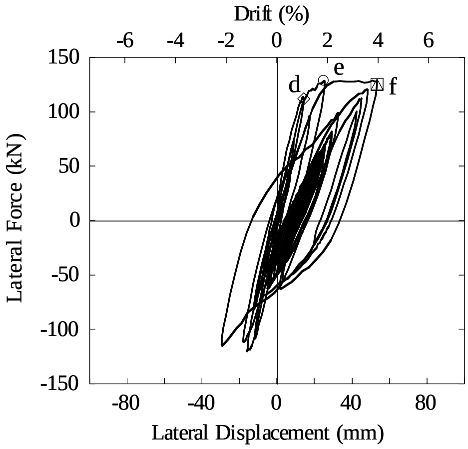


(a) Kobe 70% (b) Kobe 75% (c) Kobe 85%

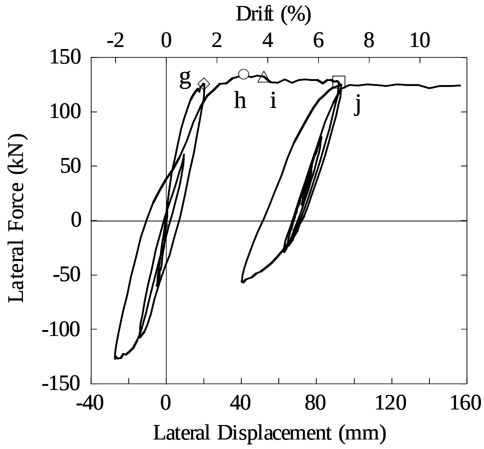
Fig.4.43 Response Displacement of the Columns under Hybrid Loading Tests



(a) Kobe 70%



(b) Kobe 75%



(c) Kobe 85%

Fig.4.44 Lateral Force vs. Lateral Displacement Hystereses of Columns under Hybrid Loading Tests

E-W direction under a constant vertical force of 160 kN. The column subjected to the 70% JMA Kobe ground motion suffered only flexural cracks around the column. Significant compression failure occurs at E surface in the column subjected to the 75% JMA Kobe ground acceleration. On the other hand, only flexural cracks occurred at N surface. This is because the column drifted in E direction, as will be presented. Although damage is more extensive in the column subjected to the 85% JMA Kobe acceleration, feature of the damage is essentially the same to the column subjected to 75% JMA Kobe ground acceleration.

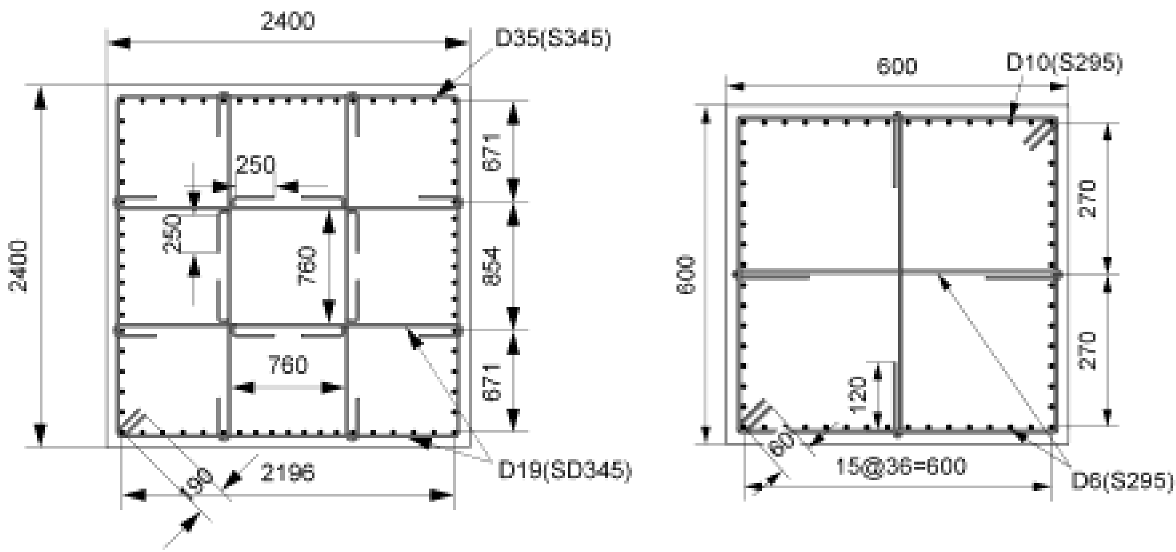
Figs. 4.43 and 4.44 show the response displacements and the lateral force vs. lateral displacement hystereses of the four columns. Responses at several times are marked from “a” to “j” in both figures. The column subjected to 70% JMA Kobe record responds almost in symmetry around the zero axis. The peak response displacement of 40 mm occurs at “c.” On the other hand, the columns subjected to the 75% and 85% JMA Kobe record exhibit residual displacements. It is considerable in the column subjected to the 85% JMA Kobe record. After the response at “h,” the response displacement accumulated only in one direction. Although such a residual displacement cannot be studied in cyclic loading tests under the displacement control, it can be studied by the hybrid loading test similar to a shake table test.

5) Verification of Seismic Performance using Plot-size Models

As a result of the limited capacity of loading facilities, it is common to use scale models in loading tests. However there exist various scale effects to be considered in the interpretation of loading test results derived from small-scale models. For example, the confinement of concrete by ties depends on section size and bar diameter regardless of whether the tie reinforcement ratio is the same. The plastic hinge length and the effect of longitudinal bars pull out from the footing depends on the bar diameter. This generally provides a large influence on the evaluation of ductility and strength capacities of columns. Hence, the calibration of test results from small-scale models is important to evaluate the strength and ductility capacities of prototype columns. However few test data derived from prototype models are available at this moment. Two such examples that were conducted recently are presented here.

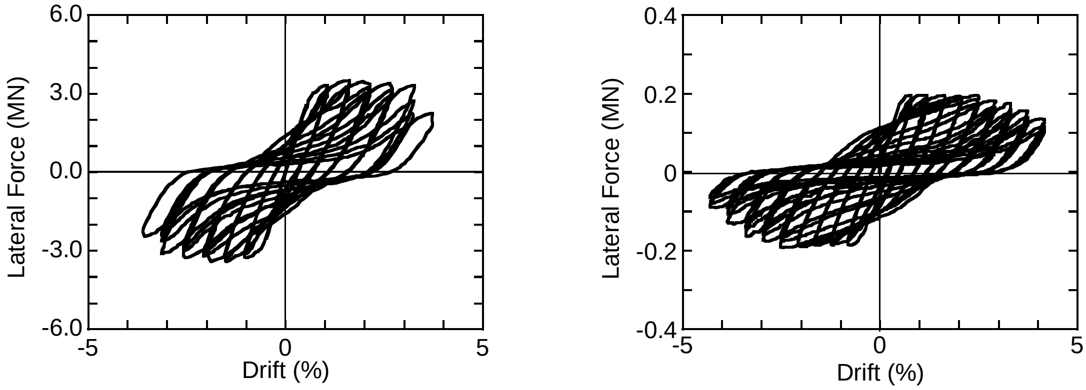
Cyclic loading tests for 9.6 m tall rectangular columns with a section of 2.4 m by 2.4 m and a 2.4 m tall rectangular column with a section of 0.6 m by 0.6 m were conducted (Hoshikuma, Unjoh and Nagaya 2002). The smaller column was a 1/4-scale model of the prototype columns. Fig. 4.45 shows the columns used in the test. In one prototype column, 72 deformed bars with a 25 mm diameter (D35) were provided with 122 mm intervals. The longitudinal reinforcement ratio was 1.2%. Deformed tie bars with a 19 mm diameter (D19) were provided at 150 mm intervals in the entire column height. They were anchored by 135 degree bent hooks with a length of 10 times the bar diameter (190 mm). Two D19 cross ties were provided in the longitudinal and transverse directions, respectively. They were anchored by 180 degree bent hooks at both ends, and spliced at the center with a splice length of 40 times the bar diameter (760 mm). The volumetric tie reinforcement ratio was 0.89%.

On the other hand, 60 D10 longitudinal bars were provided at 36 mm intervals in the 1/4-scale model. Since the bar diameter of the prototype model was 35 mm, it was preferable to use 8.75 mm diameter bars in the 1/4-scale model. However D10 bars were used since 8.75 mm diameter bars were not available. The longitudinal reinforcement ratio of the 1/4-scale model was set to 1.2% by slightly adjusting the number of longitudinal bars. Similarly, since a



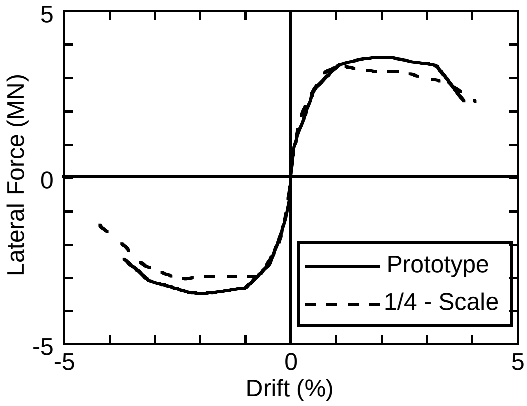
(a) Prototype (b) 1/4-Scale

Fig.4.45 Section of Model Columns

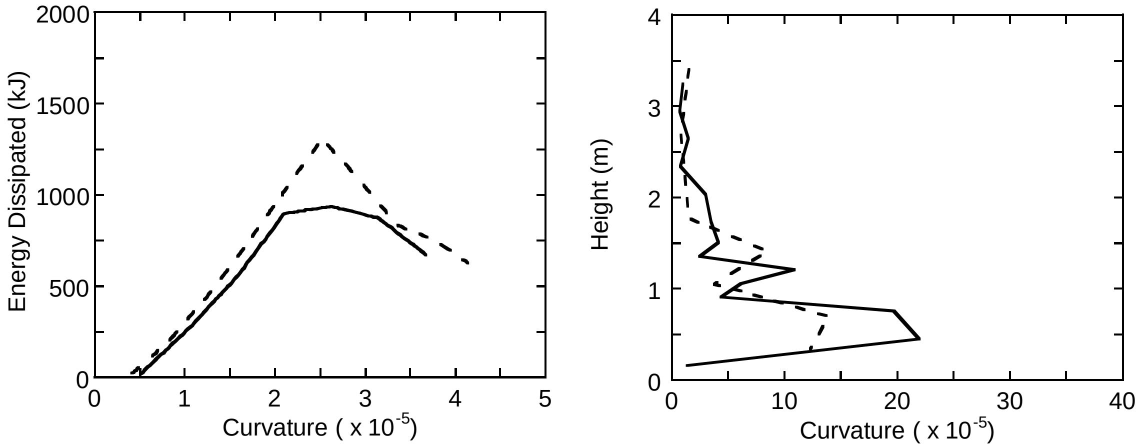


(a) Prototype (b) 1/4-Scale

Fig.4.46 Lateral Force vs. Lateral Displacement Hystereses
[Hoshikuma,Unjoh, Nagaya 2002]



(a) Envelop of Hysteresis



(b) Energy Dissipation per Cycle (c) Curvature Distribution

Fig. 4.47 Comparison of Hysteretic Behavior
[Hoshikuma,Unjoh, Nagaya 2002]

direct scale-down of the tie bars was not feasible, D6 bars with 135 bent hooks with a length of the 20 times the bar diameter (120 mm) and D6 cross ties with 180 degree bent hooks with a length of 20 times the bar diameter (120 mm) were provided. Since the buckling length of longitudinal bars depends on the interval of tie bars and cross tie bars, it was set to 45 mm. This interval resulted in a volumetric tie reinforcement ratio of 1.04% that was close to the volumetric tie reinforcement ratio of 0.89% in the prototype column.

Both the prototype and the 1/4-scale column were laterally loaded. Lateral displacement was increased stepwise with an increment of the yield displacement δ_y; 50 mm (0.52% drift) in the prototype column and 10 mm (0.42% drift) in the 1/4-scale column. They were not vertically loaded due to a restriction of the testing facility.

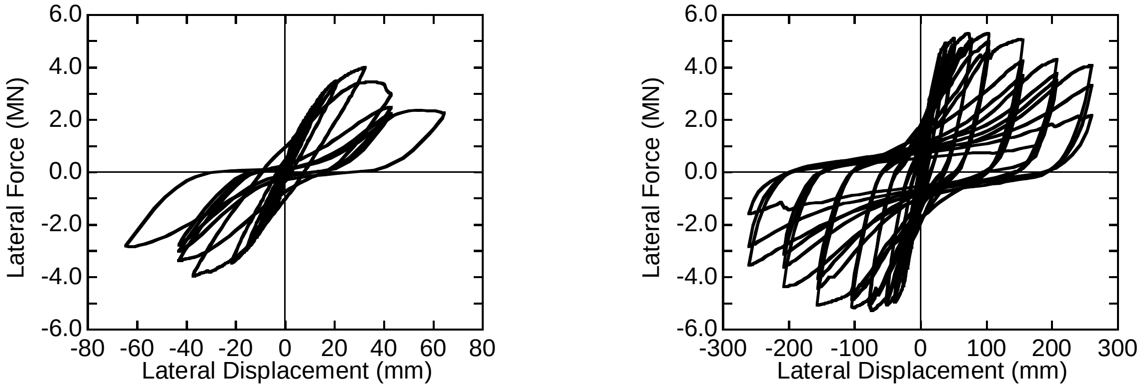
Failure of the prototype column was initiated by the buckling of longitudinal bars and the spall-off of covering concrete at 2.5% drift, and proceeded to the outward-deformation of tie bars and the failure of core concrete at 3% drift. Rupture of longitudinal bars at 3-3.5% drift resulted in a significant decrease of the lateral restoring force. The failure progressed in a similar manner in the 1/4-scale column although it progressed slightly later than the prototype column; the extensive spall-off of covering concrete, buckling of longitudinal bars and outward deformation of ties occurred at 2.6-3.2% drift, and rupture of longitudinal bars started to occur at 3.6% drift.

Fig. 4.46 compares the lateral force vs. lateral displacement relation of the prototype column and the 1/4-scale column. The hysteresis is stable until $5\delta_y$ (2.6% drift) in the prototype column, while it is stable until $6\delta_y$ (2.5% drift) in the 1/4-scale column. The restoring force significantly deteriorates when the local buckling of longitudinal bars and the spall-off of covering concrete occur in both the prototype and the 1/4-scale columns.

Fig. 4.47 compares the hysteretic behavior of the two columns in terms of the envelopes of the hysteresis loops, the energy dissipation per cycle, and the curvature distribution. The restoring force, the energy dissipation, the curvature, and the lateral displacement of the 1/4-scale column are modified in Fig. 4.47 by multiplying by s^2, s^3, $1/s$ and s, respectively, in which s is the scale factor (=4). The envelopes of the hysteretic loops are quite similar in the two columns. The energy dissipation is similar between the two columns until 2% drift, while it is 20% smaller in the prototype column than the 1/4-scale column at 2-3% drift. The curvature distribution is also quite similar in both columns.

Another unique prototype test was conducted on a 5.5 m tall rectangular reinforced concrete column with a section of 2 m by 2 m in order to verify the effectiveness of repair by steel jacketing after shear failure (Iwata, Otaki and Iemura 2001). The column was designed based on the pre-1995 Kobe earthquake design specifications of railway bridges [23]. Thirty six D51 longitudinal bars at 200 mm lateral intervals and D16 tie bars at 300 mm vertical intervals were provided. Since the flexural and the shear capacities were 5 MN and 3.35 MN, respectively, it was expected that the column would fail in shear. The column was loaded in the lateral direction. The vertical load was not provided due to facility restriction.

In the test, the column failed in shear, as expected, at the first excursion with the displacement ductility factor of one (0.5% drift), as shown in Fig. 4.48 (a). The column was repaired by injecting epoxy resin and polymer-cement slurry into flexural cracks and shear cracks, respectively. A rectangular steel jacket was then provided with a 30 mm gap between the steel jacket and the column surface. The gap was injected with non-shrinking mortar. Fig. 4.48 (b) shows the hysteresis of the repaired column. The repaired column exhibits stable performance until the first load cycle at 3% drift, however a remarkable deterioration of the restoring force occurred beyond 3% drift. Since the column was repaired by the cross jacket, the lateral confinement was insufficient. It is noted that the repair evidently enhances the ductility based on a prototype model test.



(a) As Built Column (b) Retrofitted Column

Fig.4.47 Lateral Force vs. Lateral Displacement Hystereses

[Iwata, Otaki, Iemura, 2001]