Gravity Load Collapse of Reinforced Concrete Columns with Brittle Failure Modes

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Abstract
During the 1995 Kobe earthquake, dozens of concrete buildings suffered complete collapse at an intermediate story. Such collapse is believed to have occurred due to the gravity load collapse following shear failure of Steel Reinforced Concrete (SRC) or Reinforced Concrete (RC) columns at a certain intermediate story. To study this collapse tests of RC column specimens were conducted. Test parameters were axial load and loading history. The tests have revealed that: 1) collapse occurs when shear force decreases to about zero, 2) axial load level is decisive for the collapse behavior, 3) loading history occasionally has a significant effect on the collapse behavior including a failure mode, and 4) a change in vertical deformation increment vs. lateral drift increment relations until collapse can be explained by the flow rule in plastic theory considering reduced failure surface.

Keywords: collapse; axial load; loading history; failure mode; lateral drift

1. Introduction
During the 1995 Kobe earthquake, dozens of concrete buildings suffered complete collapse at an intermediate story (Architectural Institute of Japan, 1998). Though all of the collapse buildings were designed according to the old code, many buildings designed according to this code still exist and they are very hazardous regarding future earthquakes.

The Intermediate-story collapse is believed to have occurred due to gravity load collapse following shear failure of SRC or RC columns at a certain intermediate story. To prevent future intermediate-story collapse, the process of column failure preceding collapse has to be revealed. However, in the past, while a number of seismic tests of RC columns with a shear mode were conducted, most of the tests were ended before collapse, while those tests which continued until collapse were few (Lynn et al., 1996; Yamanaka and Yoshimura, 2000).

Thus it is intended in this study to simulate how RC column specimens lose their gravity load carrying capacity after shear failure. Rather low axial loads are applied to represent intermediate-story columns. Discussions are focused on various structural properties in the event of collapse, such as lateral drift, vertical deformation and others.

2. Specimen, test apparatus and test parameters
Four specimens were fabricated. They were all the same, being designed so that shear failure might surely result. Reinforcement details of the entire specimen and a column section are shown in Figs. 1 and 2. The height-to-depth ratio was three. This ratio was selected to be consistent with the columns of the collapse buildings. Tension longitudinal reinforcement ratio (Pₜ) and lateral reinforcement ratio (Pₗ) was 1.32% and 0.21%, respectively. Material properties are listed in Table 1. Concrete strength shown in the table is an average of those determined before the first test and after the last test (25.0MPa and 28.0MPa).

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Table 1. Material properties

(a) Steel

|         | Yield stress (MPa) | Strain at yield stress (%) |
|---------|--------------------|----------------------------|
| D16     | 380                | 0.24                       |
| D6      | 375                | 0.19                       |

(b) Concrete

|         | Max. stress (MPa) | Strain at max. stress (%) |
|---------|-------------------|---------------------------|
| 26.5    |                   | 0.23                      |

Test apparatus is shown in Fig. 3, where the pantograph is used so that the loading beam at the column top does not rotate (double curvature deformation is realized). The vertical actuator was supported by a roller and pin, and the lateral actuator by two pins. The loading method is as follows. The specimens were loaded statically to the lateral direction until collapse under constant axial load. The vertical actuator was controlled by load while the lateral actuator was by displacement. The tests were terminated by the limiter of the vertical actuator that was set to operate when vertical deformation came to 5.6% of the column height (50mm).

The test parameters were axial load and loading history as shown in Table 2. Two levels of axial stress, 0.18 and 0.27 times as much as the concrete strength ($f_c$), were considered. As for the loading history, monotonic and cyclic loadings were considered. The reason why the monotonic loading was included was that according to the dynamic analysis results of the Kobe earthquake motions, lateral deformations were observed to shift to one lateral direction (Yoshimura et al., 1998). The detailed loading history used for each specimen is shown in Fig. 4, where lateral drift is expressed as drift angle. All specimens were finally loaded to the positive direction until the constant axial load could not be maintained.

Shear, flexural, and bond-splitting strengths computed for each specimen by the conventional equations in Japan are listed in Table 3 (Architectural Institute of Japan, 1991 for shear and flexural strengths and Architectural Institute of Japan, 1997 for bond-splitting strength).

Table 2. Test parameters

| Specimen | Axial stress | Loading          |
|----------|--------------|------------------|
| N18M     | 0.18$f_c$   | Monotonic        |
| N18C     |              | Cyclic           |
| N27M     | 0.27$f_c$   | Monotonic        |
| N27C     |              | Cyclic           |

Table 3. Computed strengths

| Specimen | Shear (kN) | Flexure (kN) | Bond-splitting (kN) | Shear/Flexure |
|----------|------------|--------------|---------------------|---------------|
| N18M     | 215        | 277          | 230                 | 0.78          |
| N18C     | 230        | 313          |                     | 0.73          |
| N27M     |             |              |                     |               |
| N27C     |             |              |                     |               |
3. Test results and discussions

3.1 Failure mode

Damage patterns observed before and after collapse are shown in Fig. 5. All specimens finally lost their axial load carrying capacity and the tests were terminated by the limiter. If the limiter had not been set, the specimens would have collapsed completely.

Both specimens with axial stress of 0.27$f_c$ failed in shear. However, a failure mode of the specimens with axial stress of 0.18$f_c$ differed: N18C failed in bond splitting while N18M did in shear. Computed shear and bond-splitting strengths were almost identical for the four specimens. However, the reason why a failure mode of N18C alone was different is not obvious. Note that bond-splitting failure tends to occur under the cyclic loading (Architectural Institute of Japan, 1990). However, this result indicates that the loading history occasionally influences the failure mode.

3.2 Lateral load vs. lateral drift relations

Lateral load vs. lateral drift relations are shown in Fig. 6. Shear force was defined as force in the direction perpendicular to the column axis and evaluated, as shown in Fig. 7. The relations between shear force and deformation for this direction are also shown in Fig. 6. Lateral load at collapse was a considerably negative value. But associated shear force was nearly zero because of the contribution of the vertical load to it, as shown in Fig. 7. It can be said collapse occurred when shear force decreased to about zero. The comparison of N18M and N27M shows that although lateral load at about 3% drift is almost equal, load drop after this drift is steeper for N27M resulting in smaller collapse drift for this specimen, as compared to N18M.
In Fig. 6, mark indicates maximum load. Maximum load and associated lateral drift are listed in Table 4. Maximum loads were about 20% greater than the computed values listed in Table 3. Associated lateral drifts were 0.8% and 0.5%, respectively for the monotonic and cyclic specimens.

Table 4. Maximum load and associated lateral drift

| Specimen | Maximum load (kN) | Lateral drift (%) |
|----------|------------------|------------------|
| N18M     | 263              | 0.8              |
| N18C     | 264              | 0.5              |
| N27M     | 288              | 0.8              |
| N27C     | 263              | 0.5              |

Lateral drifts at collapse are compared in Fig. 8. They are 10.3% (N18M), 20.6% (N18C), 4.7% (N27M) and 3.0% (N27C): the values for N27M and N27C were much smaller than those for N18M and N18C, indicating axial load level was decisive for the collapse drift. The comparison of N18M and N18C indicates the loading history also has a significant effect on the collapse drift. It is widely accepted to think that the collapse drift is smaller for the cyclic specimen than for the monotonic one. But in these cases the opposite result. Such result is believed to relate to the fact that a failure mode of N18C was bond splitting. As seen in Fig. 5, a collapsed portion of N18C is longer than that of N18M, probably because of the effect of bond-splitting failure widely expanding along the longitudinal reinforcement. This may have lead to larger collapse drift for N18C.

3.3 Vertical deformation vs. lateral drift relations

Vertical deformation vs. lateral drift relations are shown in Fig. 9. Vertical deformation did not increase during the cyclic loading for both of the cyclic specimens (it increased only during the last collapse loading). Vertical deformations at collapse are compared in Fig. 10. They are 2.0% (N18M), 4.5% (N18C), 1.1% (N27M) and 0.8% (N27C): the values for N27M and N27C were much smaller than those for N18M and N18C, indicating axial load level was decisive for vertical deformation at collapse. The comparison of N18M and N18C again indicates the loading history has a significant effect on the collapse.

From Figs. 8 and 10 it is apparent that the collapse of columns subjected to the same axial load does not occur when lateral drift or vertical deformation reaches a constant value.
3.4 Input energy

An amount of input energy, or works done by the external load may relate to the collapse. To study this, external works done by the lateral load and vertical load were computed. They are denoted as \( E_L \) (lateral energy) and \( E_V \) (vertical energy). Lateral energy, vertical energy and the sum of them (total energy) are shown in Fig. 11. For the cyclic specimens vertical energy did not increase, though total and lateral energy increased, during the cyclic loading.

Energy values at collapse are compared in Figs. 12 through 14. All of the three figures decisively that show energy values are much smaller for axial stress of 0.27\( f_c \) than for axial stress of 0.18\( f_c \). Again the effect of axial load is pronounced. It should also be noted that energy values of N18C are much larger than that of N18M because of the larger lateral drift and vertical deformation of the former, indicating the collapse of columns subjected to the same axial load does not occur when lateral energy, vertical energy or total energy reaches a constant value.

3.5 Deformation increment ratio

Figure 9 indicates that slope of vertical deformation vs. lateral drift curve tends to increase with the increase of lateral drift, or the decrease of lateral load. To study this phenomenon, the slope, as defined as a ratio of vertical deformation increment to lateral drift increment was computed. This ratio is called hereafter Deformation Increment (DI) ratio.

DI ratios are shown in Fig. 15(a) and (b) for the two axial stress levels. For the cyclic specimens only the last loading with lateral drift of more than 4\% (N18C) and 1\% (N27C) was considered for the simplicity of discussion. The graph, although it includes some plots where DI ratio changes very rapidly, shows a general trend that DI ratio increases as the loading proceeds.
The smoothing of observed data was attempted, to ignore the effect of possible experimental errors and have a clearer understanding of the DI ratio. The observed data were approximated by a cubic equation using a least square method. Figure 16 compares the observed vertical deformation vs. lateral drift relations and smoothed ones. The smoothed curve just fits the observed. DI ratios based on the smoothed data are shown in Fig. 17. It is apparent that DI ratio increases as lateral drift increases.

The reason why the DI ratio increases as the loading proceeds is discussed below. Figure 18 shows a conceptual sketch of shear strength – axial strength interaction curve (failure surface). Initial failure surface, which corresponds to the state of maximum load, was described as an ellipse such that the points of initial axial compression strength and initial axial tension strength might lie on it. The failure progress occurring after the maximum load is believed to accompany the deterioration of concrete, resulting in the reduction of axial compression strength as well as shear strength. But axial tension strength is considered to maintain an initial value because it is not affected by concrete strength. It is also assumed that the failure surface is reduced with the shape similar to the initial condition after the maximum load. Reduced failure surface in the figure was depicted by considering the above. One can know from the flow rule in plastic theory that DI ratio is equivalent to a direction normal to the failure surface. Although strictly speaking DI ratio has to be evaluated on the basis of plastic deformation, it is not a problem in this case because elastic deformation is small. As is shown in the figure, DI ratio increases as the loading proceeds (failure surface is reduced), which coincides with the observations.

DI ratios at collapse are shown in Fig. 19. They are 0.42 (N18M), 0.45 (N18C), 0.57 (N27M) and 0.64 (N27C). The values are almost equal for the same axial load. According to the above discussions, DI ratio will be identical when failure surface is of the same size. This implies that collapse occurs when the failure surface is reduced to a constant size.
These results, though derived from a limited number of tests, suggest DI ratio may be a feasible index to identify the gravity load collapse of columns.

As stated before, the specimens collapsed when the shear force decreased to about zero. However, according to this model, the DI ratio becomes infinite when the shear force is zero. There is a difference between the DI ratio at collapse from the test and model. Further studies are necessary for this model.

4. Conclusions
Seismic tests of RC columns subjected to rather low axial load were conducted. The tests were continued until collapse. The major findings from the study are as follows:
(1) Collapse occurs when shear force decreases to about zero.
(2) Axial load level is decisive for the collapse behavior. Lateral drift and vertical deformation at the collapse were about 3 to 5% and 1% for axial stress of $0.27f_c$ while they were about 10 to 20% and 2 to 5% for axial stress of $0.18f_c$.
(3) Loading history has a significant effect on the collapse behavior including a failure mode. Although it is widely accepted to assume that lateral drift at collapse is smaller for the cyclic loading than for the monotonic one, the opposite may occasionally result when a failure mode is altered.
(4) A change in deformation increment ratio (DI ratio) until collapse can be explained by the flow rule in plastic theory considering reduced failure surface.

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