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EXPERIMENTAL SIMULATION OF PROGRESSIVE COLLAPSE OF PERIMETER FRAMES DUE TO OUT-OF-PLANE BEHAVIOR

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ABSTRACT :

The framed-tube structure consists of rigid moment frames in the perimeters and floor-system which provides lateral-supports to prevent perimeter column buckling. When perimeter columns deform towards the outside of the structure, simple connections between perimeter columns and floor-system may break in tension. This behavior is simulated by static tests for laterally-supported columns, where lateral drift is imposed at each story under the constant axial load. Drift mode shape, axial loading level, and the number of lateral-supports are varied. Major findings are: (1) the test results are similar to the predicted response, (2) as the lateral-support strength decreases and as the constant axial load increases, the break of lateral-supports occur at smaller drift demand level, accelerating the progressive collapse, and (3) when higher drift mode shape is imposed on the column with small lateral-support strength, the progressive collapse may occur at small drift demand level less than 2% story drift angle.

KEYWORDS : High-rise Framed-tube Structure, Perimeter Frame, Lateral-supports, Progressive Collapse

INTRODUCTION

The framed-tube structure consists of (1) a few rigid moment frames often located at the perimeters to support seismic and/or wind loading and (2) a floor-system to support gravity loading as illustrated in Figures 1(a) and (b). This framing system is attractive to designers because this provides flexibility for floor layout. Recently in Japan, combined with the introduction of base-isolation system enable to reduce lateral forces required in design, the framed-tube system with a few moment-resisting frames has become popular for many super-high-rise structures.

In the framed-tube structure, floor-system provides lateral-supports to perimeter columns. When perimeter column deforms towards the inside of the structure, floor-system provides the constraint to the deformation of perimeter column, maintaining column stability as illustrated in Figure 1(c). When perimeter column deforms towards the outside of the structure, tensile force acts on simple connections between perimeter columns and the floor-system as illustrated in Figure 1(d). If the tensile force exceeds the capacity of the connection, the connection breaks elongating the column buckling length and possibly resulting in progressive collapse. The relatively small tensile strength of the simple connections between perimeter columns and floor-system is considered to be one of many factors that contributed to the progressive collapse of the World Trade Center Building in New York[1)].

Many axial compression tests have been conducted for columns with lateral-supports providing identical resistance in compression and tensile direction. In the simulation of progressive collapse of the framed-tube structures, lateral-supports should be modeled to (1) have non-symmetric resistance in compression and tensile directions and (2) break occurs if tensile force exceeds the capacity of the lateral-supports. Very few or none of such experiments have been conducted so far.

In order to investigate the progressive collapse of perimeter columns in the framed-tube structure, the authors conducted monotonic compression tests[2)] for laterally-supported columns as illustrated in Figure 2(a). The lateral-supports are modeled to break in tension when tensile force exceeds the capacity of the lateral-support, but to have large stiffness and strength in compression as illustrated in Figure 2(c). The test data shows that (1) larger strength of lateral-supports can mitigate progressive collapse and (2) lateral-supports with 1% of column yield strength do not break before column yielding, implying that only 1% lateral-support strength is sufficient to prevent progressive collapse for columns under axial compression loading for design. In these tests, however, lateral drift imposed at each story is not simulated. Lateral drifts, which are likely to occur during earthquake excitation, may cause connection breaks and further, progressive collapse of perimeter columns even under the constant axial load. In this study, structural model in previous study illustrated in Figure 2(a) is modified to the one as illustrated in Figure 2(b), where lateral drift can be imposed at each story under the constant axial loading. During earthquake loading, the top and bottom of perimeter column in actual structure may have displacements as illustrated in Figure 2(d). If perimeter column has linear lateral drift distribution over the height, the lateral-supports except at the top and bottom stories are not subjected to the forces. Therefore, in this simulation, the 1st- and 2nd-mode lateral drifts (δ_i), which are equal to lateral drifts in actual structure (d_i) minus the linear drift distribution, are given to perimeter column as illustrated in Figure 2(d).

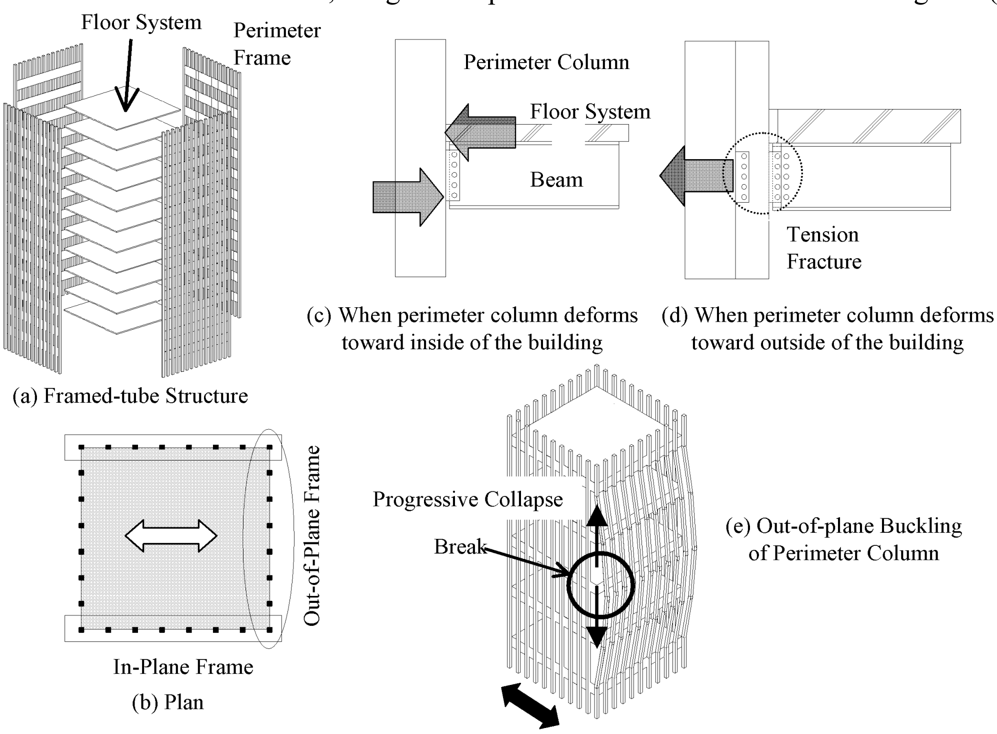


Figure 1. Progressive Collapse of Perimeter Frames due to Out-of-Plane Behavior in Framed-tube Structure

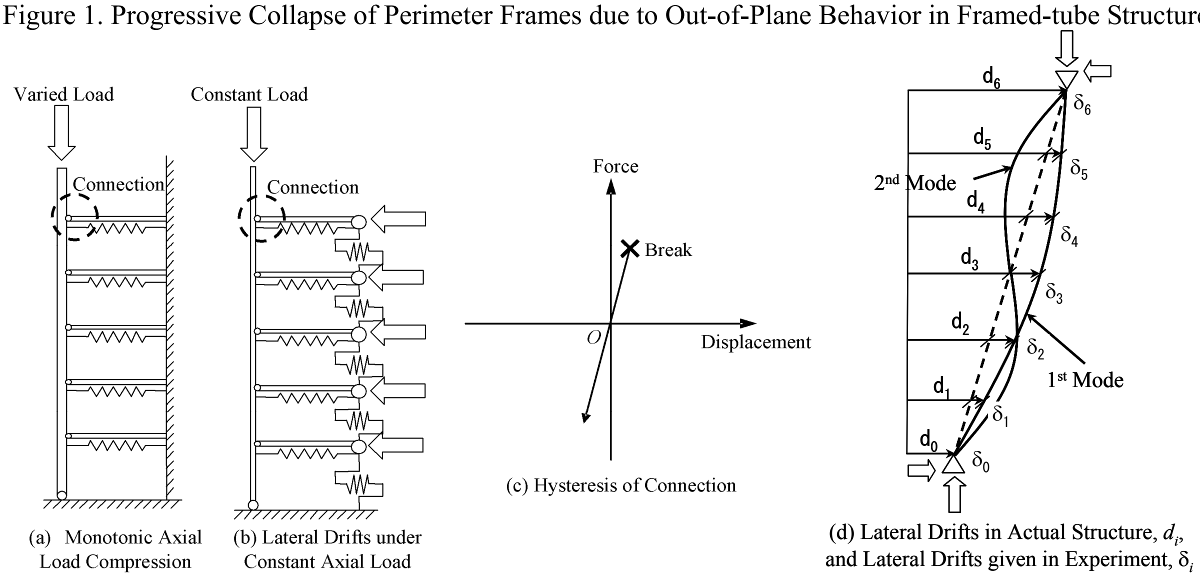


Figure 2. Structural Models for Experiments

2. EXPERIMENTAL PLAN

2.1 Specimens and Experimental Devise

Static loading tests are carried out for the 6-story column, which is a model of the bottom 6 stories of the perimeter columns in the framed-tube structure. Lateral drifts are imposed on the columns under the constant axial load. The details of the experimental devise and column specimen are illustrated in Figures 3 and 5. The column has a rectangular section of 19mm×30mm and is made of SS400. Each story height is 120mm and the total height of the column is 720mm, which provide the slenderness ratio of 21.9 for each story and 131 for the total height. The results of material tests using JIS-1A coupon are given in Table 1. The top and bottom of the column is supported by the knife-edges providing free rotation. The columns have lateral-support at each story, which are designed to have a specified strength in tension, and large stiffness and strength in compression.

2.2 Devise to provide Lateral Drift and Lateral-Support

The mechanism of the devise to provide lateral drift and lateral-support simultaneously is illustrated in Figure 4. The column is attached to movable Plates A and B through half-circled rods. Plate A is connected to the reaction floor through steel rod, load-cell, and rotation handle. Plates A and B are connected by the lateral-support and move as a whole with no friction on the reaction floor unless the lateral-support breaks.

When the rotation handle is rotated clock-wise, Plate A moves forwards, pushing the column as illustrated in Figure 4(a). The column pushes Plate B, further, providing Plates A and B with almost identical displacements. In this case, no axial force acts on the lateral-support. However, when lateral drift becomes large, the column deforms outwards by itself due to *P*-δ effect. This results in the gap between Plates A and B and then tensile force acting on the lateral-support between these plates. When tensile force exceeds the capacity of the lateral-support, the lateral-support breaks.

When the rotation handle is rotated counter clock-wise, Plate B moves backwards and tensile force acts on the lateral-support right after imposing the drift.

2.3 Lateral-support

The detail of the lateral-supports made from aluminum board (Al1050H24) with 3mm thickness is illustrated in Figure 6. The AIJ Recommendation for Limit State Design of Steel Structures[3)] specifies lateral-support strength as 3% of column yield strength. The lateral-supports of 2% and 6% of column yield strength are prepared for the tests adjusting the notch width and considering the lever action as illustrated in Figure 4. It should be noted that lateral-support has sufficiently large stiffness to prevent the transition of lateral-support points when the column buckles in higher-mode shape. And then, the strength of lateral-supports, rather than stiffness, is evaluated in this study.

2.4 Experimental Parameters

Parameters of the experiments are (1) strength of lateral-support (2% and 6% of column yield strength), (2) number of lateral-supports (5: installed at each story, 1: installed at mid-story only), (3) mode-shape of lateral drifts imposed (1st- and 2nd-mode), and (4) the level of constant axial force (30%, 50% of column yield force).

2.5 Loading and Measuring Method

After the constant axial force, *P*, is loaded to the column by the testing machine, lateral drifts are imposed on the stories of the column gradually. The top of the column moves downward due to the deflection, sometimes causing a little decrease of axial load. In this case, axial load is adjusted to the constant level. When lateral-support breaks, axial load often drops suddenly. In this case, axial force is increased to the constant level immediately. The drifts are imposed on columns until all lateral-supports break or the column cannot maintain the constant axial load within the functional capacity of experimental devise. The axial force, *P*, is measured by the load-cell installed inside the testing machine. The lateral drift, δ_N, is measured by lazar transducers as illustrated in Figure 5(c). The lateral force, Q_N , is measured by the load-cell installed to the devise which provides lateral drift.

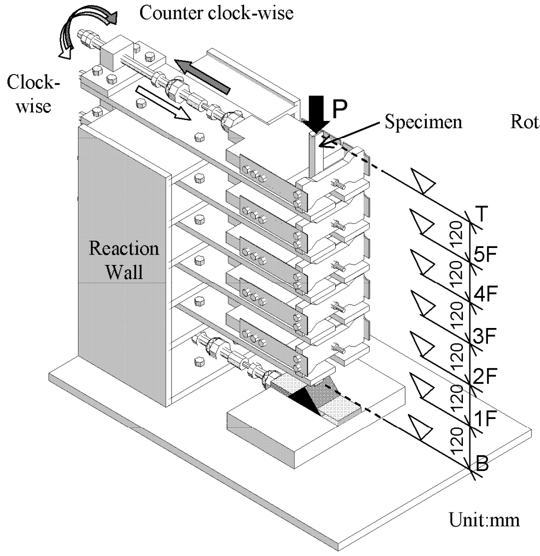
2.6 Computation of Column Moments

The moment distribution over column height is illustrated in Figure 7. The reaction forces at the top and bottom of the column, R_t and R_b, are given by Equations (1) and (2), respectively. Further, using R_t and R_b, the bending moment at each story, R_t, is obtained. For example, the moment at the mid-story, M_3, is given by Equation (3).

$$R_b = -(Q_1 \times h + Q_2 \times 2h + Q_3 \times 3h + Q_4 \times 4h + Q_5 \times 5h)/6h \tag{1}$$

$$R_t = -(Q_5 \times h + Q_4 \times 2h + Q_3 \times 3h + Q_2 \times 4h + Q_1 \times 5h)/6h \tag{2}$$

$$M_3 = R_b \cdot 3h + Q_1 \cdot 2h + Q_2 \cdot h = R_t \cdot 3h + Q_5 \cdot 2h + Q_4 \cdot h \tag{3}$$



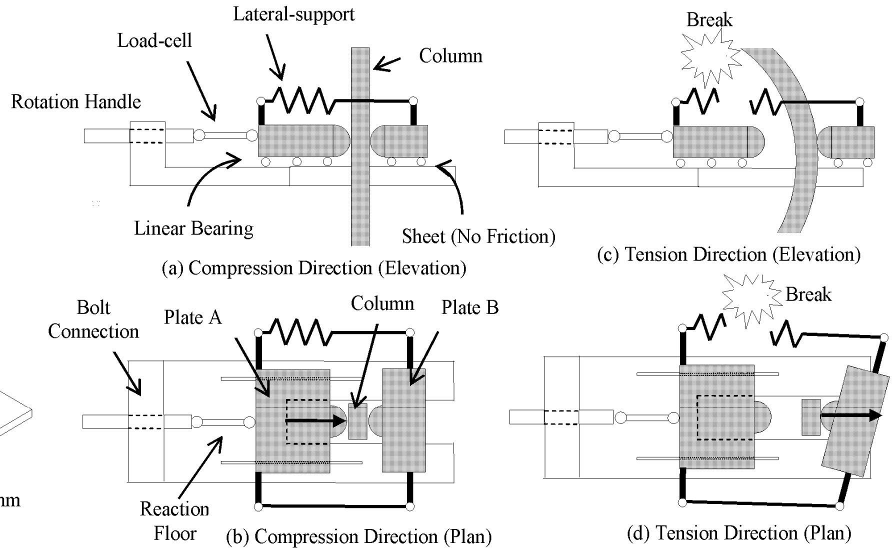
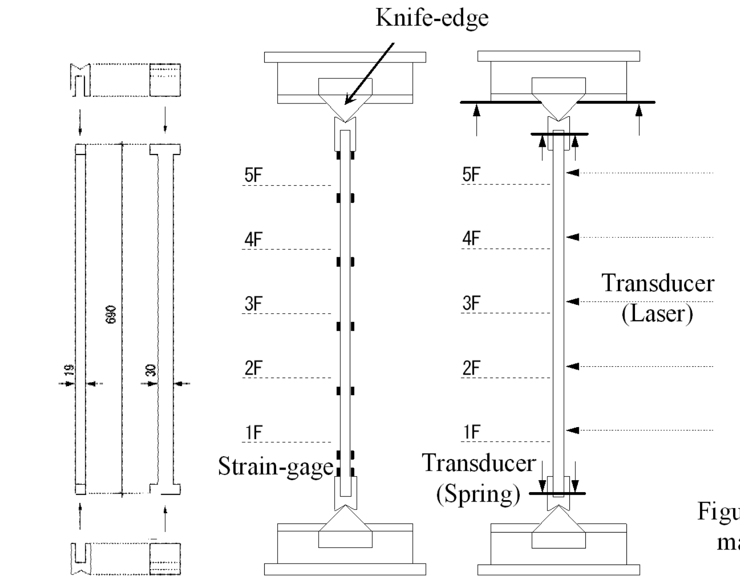


Figure 3. Experimental Devise Figure 4. Mechanism of Devise to provide Lateral Drift and Lateral-support



(a) Set-up of Column (b) Strain-gage (c) Displacement Transducer

Figure 5 Specimen and Measurement Location

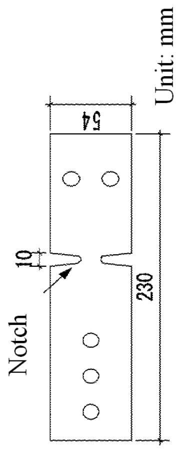


Figure 6 Lateral-support made from Aluminum

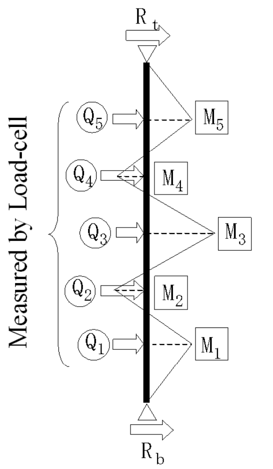


Figure 7 Moment Distribution

Table 1 Material Properties

	Yield Strength	Ultimate Strength	Elongation	Yield Ratio
Steel	285(N/mm^2)	446(N/mm^2)	31.9%	0.64
Aluminum	123(N/mm^2)	127(N/mm^2)	17.3%	0.96

Table 2 Parameters for Experiments

	Mode-shape	Location of Lateral-	Stregnth of Lateral-	Axial Force Ratio
Specimen 1	1st	Mid-story	2%	30%
Specimen 2	1st	All-story	2%	30%
Specimen 3	1st	All-story	6%	50%
Specimen 4	2nd	All-story	6%	50%
Specimen 5	2nd	All-story	2%	50%

3. Prediction of Behavior of Laterally-supported Columns

The behavior of three laterally-supported columns subjected to lateral drifts as illustrated in Figure 8 is predicted. The relations of bending moments ($M_{p\delta}$: bending moment resulting from P-δ effect, M_o: bending moment ignoring P-δ effect, $M_{p\delta}$: bending moment including P-δ effect) and lateral drift, δ, at the section where the maximum drift occurs are illustrated in Figure 9(a).

3.1 Behavior of Column with Lateral-support at Mid-story (1st-Mode)

The column with lateral-support at mid-story only subjected to constant axial load P and lateral drift imposed on mid-story only as illustrated in Figure 8(a) is considered. When the column behaves in elastic range, the relation of M and δ is approximately expressed in Equation (4). Here, E is Young modulus and L is the column length.

$$M = M_o - M_{P\delta} = (12EI/L^2 - P)\cdot\delta \qquad (4)$$

When lateral drift increases, the slope of M decreases due to yielding of the column. Assuming that the material property of the column is elastic-perfectly plastic, M becomes negative due to the combined effects of column yielding and P-δ effect. The point of the maximum M is refereed to "stability limit[4)]" in this study.

When lateral drift increases further, $M_{p\delta}$ increases and M becomes zero as illustrated in Figure 9(a). The point where M becomes zero is referred to as "the loss of lateral resistance (of the column)" in this study. The lateral-drift at this point, δ_f, is given by Equation (5), using plastic moment of the column, M_{cp}.

$$\delta_f = M_{cp}/P \qquad (5)$$

After this point, M becomes negative. However, the column does not collapse at this point. This is because the lateral-support provides the lateral resistance to the column as illustrated in Figure 9(b). However, when tensile force acting on the lateral-support exceeds the capacity of it, the break occurs. The lateral-drift at the break of lateral-support, δ_b, is given by Equation (6), using the lateral-support strength, Q_{max}.

$$\delta_b = (M_{cp} + Q_{\max}\cdot L/4)/P \qquad (6)$$

3.2 Behavior of Column with Lateral-supports at all Stories (1st-Mode)

The column with lateral-supports at all stories subjected to constant axial load P and lateral drifts with the 1st-mode sinusoidal distribution as illustrated in Figure 8(b) is considered. When the column is elastic, the relation of M and δ at mid-story is given by Equation (7).

$$M = (EI(\pi/L)^2 - P)\cdot\delta \qquad (7)$$

Assuming that M_o at that point is equal to M_{cp}, δ_f is given by Equation (5). The δ_b is influenced by the distribution of column moment at the break of lateral-support. If the equivalent length (the distance between the loading point and the equivalent reaction point) is h' as illustrated in Figure 10(b), δ_b is given by Equation (8). Here, the assumption of h' equal to h results in the conservative estimation.

$$\delta_b = (M_{cp} + Q_{\max}\cdot h'/2)/P \qquad (8)$$

3.3 Behavior of Column Laterally-supported at Each Story (2nd-Mode)

The column with lateral-supports at all stories subjected to constant axial load P and lateral drifts with the 2nd-mode sinusoidal distribution as illustrated in Figure 8(c) is considered. When the column is elastic, the relation of M and δ at the 1st, 2nd, 4th, 5th stories is given by Equation (9).

$$M = (EI(2\pi/L)^2 - P)\cdot\delta \qquad (9)$$

Assuming that M reaches M_{cp}, δ_f, is given by Equation (5). When the 2nd-mode drift shape is given, in the story where Plate A moves backwards, lateral-support is subjected to tensile force right after the loading. Assuming that the material property is elastic-perfectly plastic and referring to moment distribution as illustrated in Figure 10(c), when $Q_{max} \le M_{cp}(1-PL^2/(4\pi^2 EI))/(L/6)$, the lateral-support breaks in tension before the stability limit in the story where Plate A moves backward. In this case, δ_b is given by Equation (10). When $Q_{max} \le M_{cp}(1-PL^2/(4\pi^2 EI))/(L/6)$, the lateral-support breaks in tension in the story where Plate A moves forwards. In this case, δ_b is given by Equation (11).

$$\delta_b = Q_{\max}\cdot L/6\cdot 1/(4\pi^2 EI/L^2 - P) \qquad (10)$$

$$\delta_b = (M_{cp} + Q_{\max}\cdot h)/P \qquad (11)$$

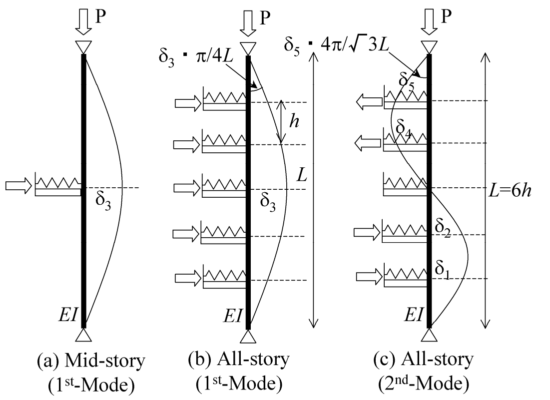


Figure 8. 3 Types of Columns investigated

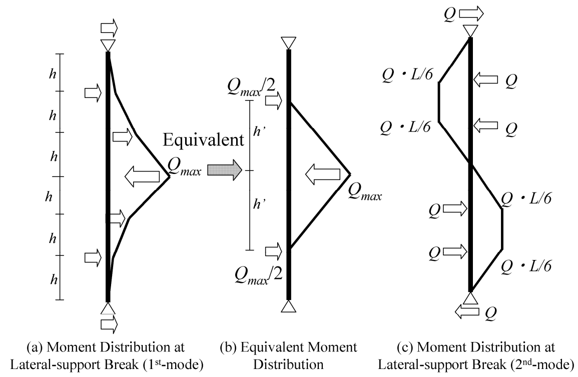


Figure 10. Column Moment Distribution

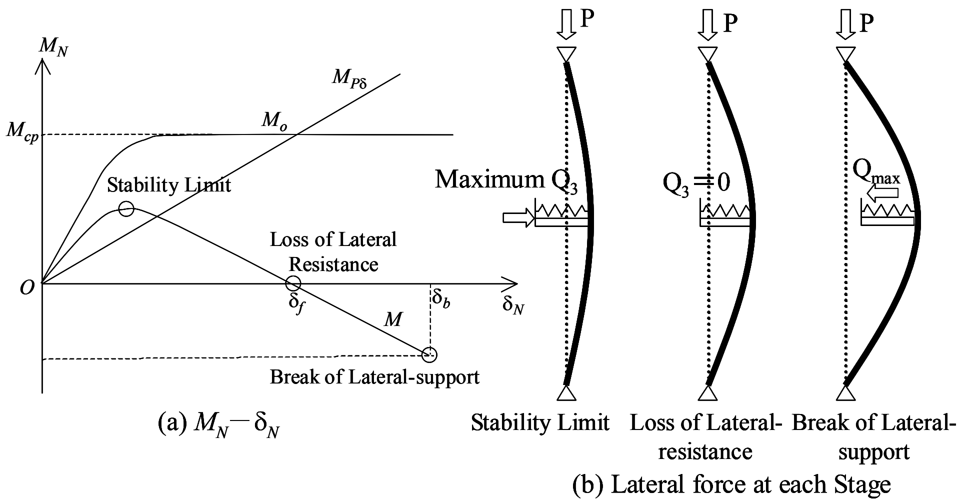


Figure 9. Relation of Moment-Lateral Drift

4. Experimental Results

4.1 Behavior for 1st-Mode Shape

CASE 1: 2% Lateral-support at Mid-story, 30% Axial Force

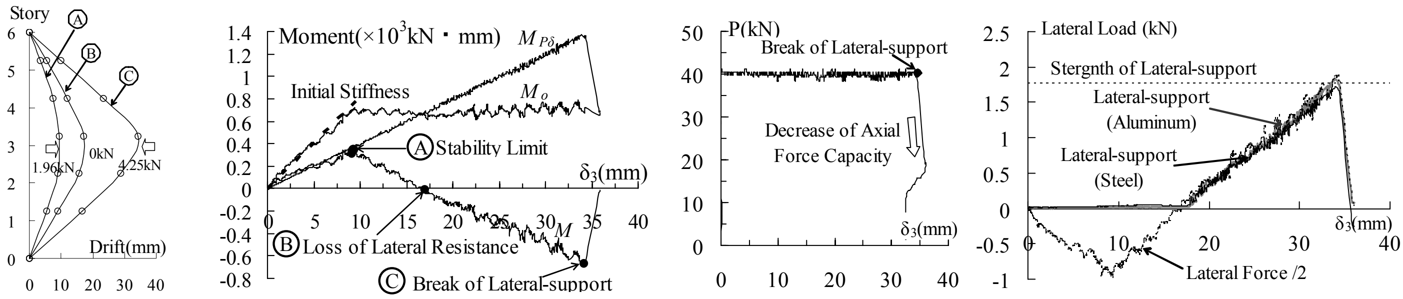
Lateral drift is imposed gradually on the mid-story of the 6-story column with 2% lateral-support installed at the mid-story under 30% constant axial force as shown in Figure 11(a). The M increases with the initial stiffness similar to that derived by Equation (4) and decreases after the stability limit as shown in Figure 11(b). The lateral-support starts to be subjected to tensile force when M decreases to negative as shown in Figure 11(d). The lateral-support breaks in tension when δ reaches approximately 33mm. At this point, the column is unable to maintain the constant axial load and collapses as shown in Figure 11(c). The δ_f predicted by Equation (5) is 17.4mm and δ_b predicted by Equation (6) is 33.2mm, both of which are close to those obtained by the experiments.

CASE 2: 2% Lateral-support at All Stories, 30% Axial Force

The 1st-mode drift shape is imposed gradually on the 6-story column with 2% lateral-supports installed at all stories under 30% constant axial force as shown in Figure 12(a). The M increases with the initial stiffness similar to that derived by Equation (7) and decreases after the stability limit as shown in Figure 12(b). Since M_o does not reach M_{cp}, δ_f obtained by the experiment (15mm) becomes smaller than δ_f predicted by Equation (5) (17.4mm). If the equivalent length of the lateral-support, h', is assumed to be equal to the story height h, δ_b predicted by Equation (8) is 22.7mm, which is close to that obtained by the experiment. When the lateral-support in the 3rd-story breaks, the column does not collapse since it maintains the constant axial load as shown in Figure 12(c). However, when lateral drift increases to approximately 30mm, lateral-supports in the 2nd and 4th-story break consecutively as shown in Figure 12(d). After the break of them, the column cannot maintain the constant axial load and thus collapses. Since the lateral-supports do not break until the maximum story drift angle (SDA) of 9% delaying column collapse, it can be concluded the lateral-supports with 2% strength function well to the 6-story column under 30% constant axial load.

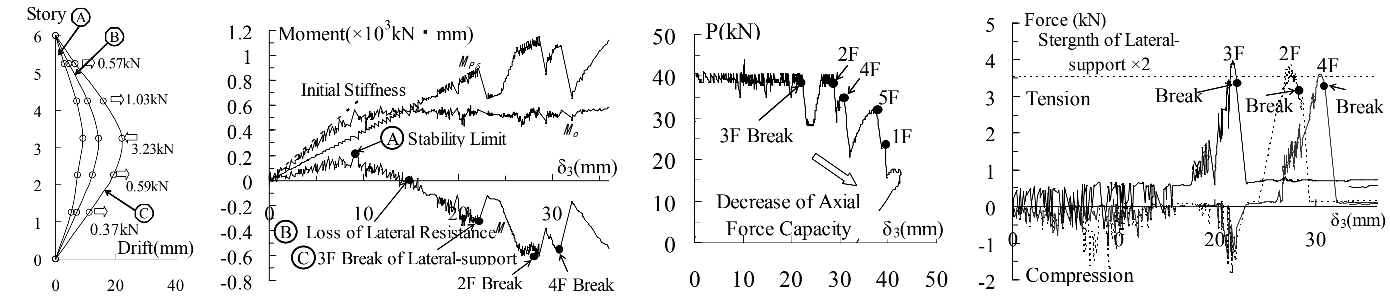
CASE 3: 6% Lateral-support at All Stories, 50% Axial Force

The 1st-mode drift shape is imposed gradually on the column with 6% lateral-supports installed at all stories under 50% constant axial force as shown in Figure 13(a). Right after lateral drifts are imposed on the column, the slope of M is small as $(EI(\pi/L)^2\text{-}P)$=0.1(kN) causing almost no lateral resistance for lateral loading as shown in Figure 13(b). The δ_f predicted by Equation (5) is 7.31mm, which is close to δ_f obtained by the experiment. The M_o decreases after the loss of the lateral resistance as shown in Figure 13(b). This is because Plate B pushes back the column with large stiffness of 6% lateral-supports and the reactions of it are supported by the 2nd and 4th-stories causing the unloading of steel material as shown in Figure 13(d). As a result, δ_b obtained by the experiment (16mm) is smaller than that predicted by Equation (8) (17.1mm). After the 3rd-story lateral-support breaks, lateral-supports in the 2nd and 4th-story break consecutively as shown in Figure 13(d), resulting column collapse. It can be concluded that, if the lateral-support has large stiffness, M_o may decrease after the loss of the lateral resistance, resulting in smaller δ_b than that predicted by Equation (8).



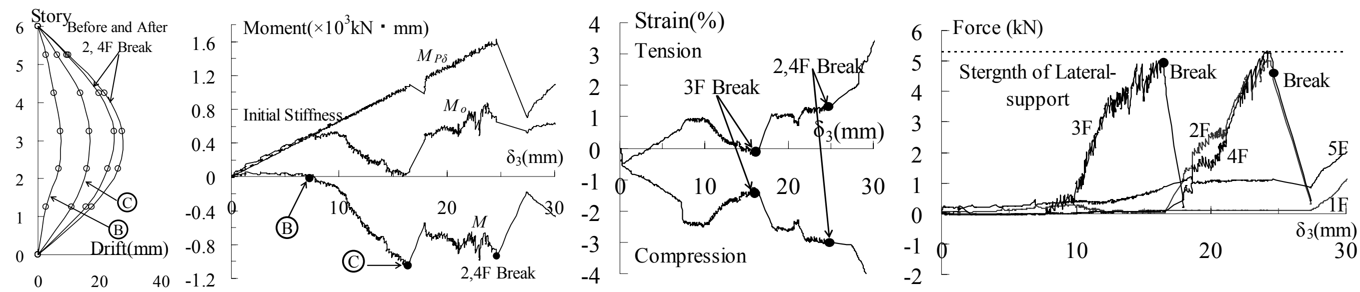
(a)Lateral-drift Distribution (b)M-δ Relation (c)Axial Force (d)Lateral Force

Figure 11. Behavior of Specimen 1



(a)Lateral-drift Distribution (b)M-δ Relation (c)Axial Force (d)Lateral Force

Figure 12. Behavior of Specimen 2



(a)Lateral-drift Distribution (b)M-δ Relation (c)Axial Force (d)Lateral Force

Figure 13. Behavior of Specimen 3

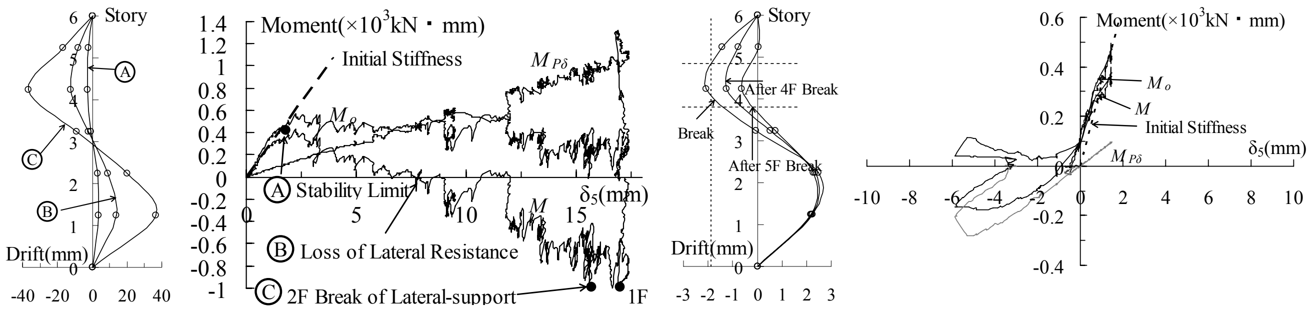
4.2 Behavior for 2nd-Mode Shape

CASE 4: 6% Lateral-support at All Stories, 50% Axial Force

The 2nd-mode drift shape is imposed gradually on the column with 6% lateral-supports installed at all stories under 50% constant axial force as shown in Figure 14(a). The M_5 increases with the initial stiffness similar to that predicted by Equation (9) as shown in Figure 14(b). Comparing with the column subjected to the 1st-mode shape, column yielding occurs at smaller drift level due to larger curvature of the column. The δ_f obtained by the experiment (7.5mm) is close to that predicted by Equation (5). The break of the lateral-support occurs firstly at the 2nd-story, where Plate A moves forwards. The δ_b obtained by the experiment is approximately 18mm, corresponding to the maximum SDA of 17.1%. This value is much larger than that for the column subjected to the 1st-mode drift shape. Therefore, it can be concluded that, when the 2nd-mode drift shape is imposed on the column with lateral-supports with sufficient strength and the lateral-support does not break in the story where the perimeter column deforms towards the inside of the structure, the column does not collapse until large SDA.

CASE 5: 2% Lateral-support at All Stories, 30% Axial Force

The 2nd-mode drift shape is imposed gradually on the column with 2% lateral-supports installed at all stories under 30% constant axial force as shown in Figure 14(c). The initial stiffness of M is close to that predicted by Equation (9) as shown in Figure 14(d). The lateral-supports in the 4th- and 5th-story break before the stability limit. The δ_b obtained by the experiment is almost identical to that predicted by Equation (10) (1.93mm). This corresponds to the maximum SDA of approximately 2%. After the lateral-supports in the 4th and 5th-story break, all lateral-supports in other stories break, resulting in column collapse. It can be concluded that, if the 2nd-mode shape is imposed on the column laterally-supported with small strength, lateral-support may break in the story where the perimeter column deforms towards the inside of the structure, resulting in column collapse.



(a)Lateral-drift Distribution (b)M-δ Relation (c)Lateral-drift Distribution (d)M-δ Relation

Figure 14. Behavior of Specimens 4 and 5

5. CONCLUSIONS

In order to simulate the progressive collapse of perimeter columns in the framed-tube structure during earthquake excitation, lateral drifts are imposed on the 6-story columns with lateral-supports designed to be fragile in tension under the constant axial load. Major findings include:

1. The collapse of the column can be delayed by the lateral-supports, which provide lateral resistance to the column after the loss of lateral resistance of the column. However, when the lateral-support breaks in tension, successive break of lateral-supports in other stories often occurs, resulting in the progressive collapse.
2. For the 6-story column subjected to the 1st-mode drift shape and 30% constant axial load, lateral-supports with 2% strength do not break until the maximum story drift angle of more than 9%. Lateral drift at the break of lateral-support obtained by the experiments is similar to those predicted.
3. For the 6-story column with 6% lateral-support strength subjected to the 2nd-mode drift shape, the lateral-supports do not break in the story where column deforms towards the inside of the structure. However, the column with 2% lateral-support strength, lateral-supports break in the story where the column deforms towards the inside of the structure, resulting in the progressive collapse at very small drift level.

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