SHEAR-FAILING REINFORCED CONCRETE COLUMNS SUBJECTED TO MULTI-AXIAL LOADING

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SUMMARY

It was intended in this paper to study the general nature of shear-failing reinforced concrete columns under multi-axial loading conditions. Two series of tests were conducted: Series 2D and 1D. In Series 2D, bi-lateral loading tests were conducted. A basic loading method was as follows. A specimen was firstly loaded to the vertical direction until a prescribed axial load was attained and secondly to one lateral (Y) direction until a prescribed value of load (YLOAD) was attained. Then with the both loads being kept constant, the specimen was loaded to the other lateral (X) direction until failure. A value of YLOAD was a test parameter. The tests have revealed that, 1) as YLOAD increases, maximum load (shear strength) of the X direction becomes smaller, and the failure surface for bi-lateral loads can be represented by a circle irrespective of loading paths, and 2) as the loading to the X direction proceeds, deformation of the Y direction increases though load of the Y direction is kept constant, and this increase becomes greater as YLOAD increases. In Series 1D, uni-lateral loading tests were conducted to study the interaction between vertical and lateral directions. A value of axial load was a test parameter. It has been shown that as Axial Load Index, as defined as column axial stress divided by concrete strength, increases from 0 to 0.4, maximum lateral load (shear strength) becomes larger but when Axial Load Index is 0.6, it becomes smaller.

INTRODUCTION

Damage to reinforced concrete structures due to destructive earthquakes has demonstrated the strong necessity of experimental researches on reinforced concrete columns under multi-axial (two lateral and one vertical) load conditions. However, past efforts on this issue have been mainly directed toward a flexure-failing type [Li et al.,1988] [Yoshimura et al.,1996], and a shear-failing type has hardly been considered. In addition, the past tests on a shear type, which were a few in number, were mostly those aiming shear strength exclusively [Umehara and Jirsa 1984]. Therefore, even now only a little is known about the general nature of shear columns under multi-axial load conditions [Tsumura et al.,1996]. Considering such situation, it was intended in this study to conduct tests of shear columns subjected to various multi-axial load conditions.

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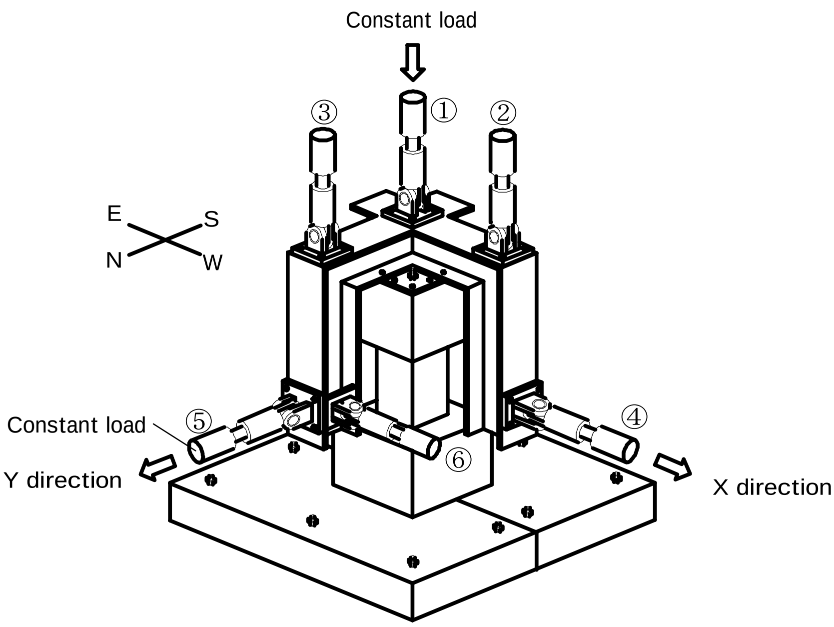


Figure 1: Test apparatus and basic loading method

2. TEST APPARATUS AND BASIC LOADING METHOD

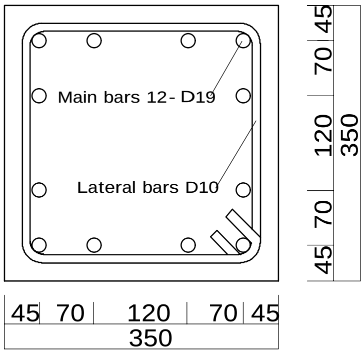
To enable us to do bi-lateral loading tests under which a column is subjected to double curvature deformation, the test apparatus, as shown in Figure 1, was developed. Six hydraulic jacks are used. Jack 1 is used to apply axial load. Jacks 4 and 5 are to apply lateral load respectively to the X and Y directions. Jacks 2 and 3 are to keep the double curvature deformation (zero rotation at the column top) for both directions. And Jack 6 is to prevent the twisting in the horizontal plane.

A basic loading method is as follows. A specimen is firstly loaded to the vertical direction until a prescribed value of axial load is attained, and secondly loaded to the Y direction until a prescribed value of lateral load of the Y direction (YLOAD) is attained. Then with the both loads being kept constant, the specimen is loaded to the X direction until failure by gradually increasing deformation of this direction.

3. SPECIMENS AND TEST PARAMETERS

Specimens are outlined in Table 1, and a section of the column portion and reinforcement details of the entire specimen are shown in Figures 2 and 3. Material properties are listed in Table 2.

All specimens were same in dimension and reinforcement with a 35cm×35cm square section. Shear span ratio was rendered small (height to depth ratio of 2) and reinforcement with high yield stress (496MPa) was used as main bars so that shear failure might surely result. The specimens being totally nine in number were classified into two groups depending on the load pattern: Those for which YLOAD was applied were denoted as Series 2D, and those for which YLOAD was not applied were as Series 1D. Series 2D was intended to examine the bi-lateral interaction with respect to load and deformation, while Series 1D was to examine the effect of axial load.



p_g=1.41%, p_w=0.41%

Figure 2 : Column section

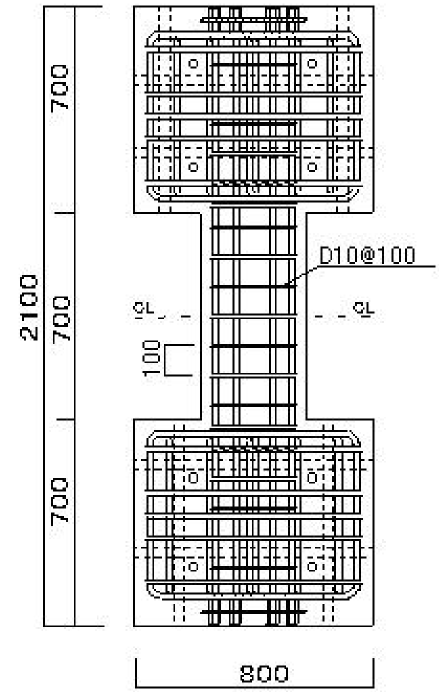


Figure 3: Reinforcement details

A standard specimen was used for discussions of both series.

A numeral after the alphabet N in a specimen name denotes the level of axial load. This numeral corresponds to column axial stress divided by concrete strength (referred to as Axial Load Index and shown in the parentheses). A numeral after the alphabet Y in a specimen name denotes a level of YLOAD. For example for N2Y3, Axial Load Index = 0.2 and YLOAD = 294KN (30tonf). N2Y3D and N2YDXD, both being special specimens among Series 2D, were prepared to examine the effect of load paths differing from the basic one. For N2Y3D, when the prescribed level of YLOAD (294KN) was attained, the control mode of Jack 5 (jack used for the loading to the Y direction) was changed from force control to displacement control. And throughout the loading to the X direction, deformation of the Y direction was kept constant as equal to the value attained at YLOAD of 294KN. N2YDXD was loaded to the direction with 45 degrees.

Table 1: Test specimens

Name	Axial load (KN)	YLOAD (KN)	Series
N2Y0	588(0.2)	0	Standard
N2Y1	588(0.2)	98	2D
N2Y2	588(0.2)	196	
N2Y3	588(0.2)	294	
N2Y3D	588(0.2)	dis. control	
N2YDXD	588(0.2)	dis. control	
N0Y0	0	0	1D
N4Y0	1176(0.4)	0	
N6Y0	1764(0.6)	0	

Table 2: Material properties

Steel	Yield stress (1) (MPa)	Max. stress (MPa)	Strain at (1) (%)	Young's modulus (MPa)
D10	377	532	0.21	179000
D19	496	708	0.28	178000

Concrete	Max. stress (1) (MPa)	Strain at (1) (%)	Young's modulus (MPa)
	23.5	0.31	17300

4. FAILURE

All specimens failed in a shear mode. Lateral reinforcement yielded for all specimens while main reinforcement did not yield for any specimen.

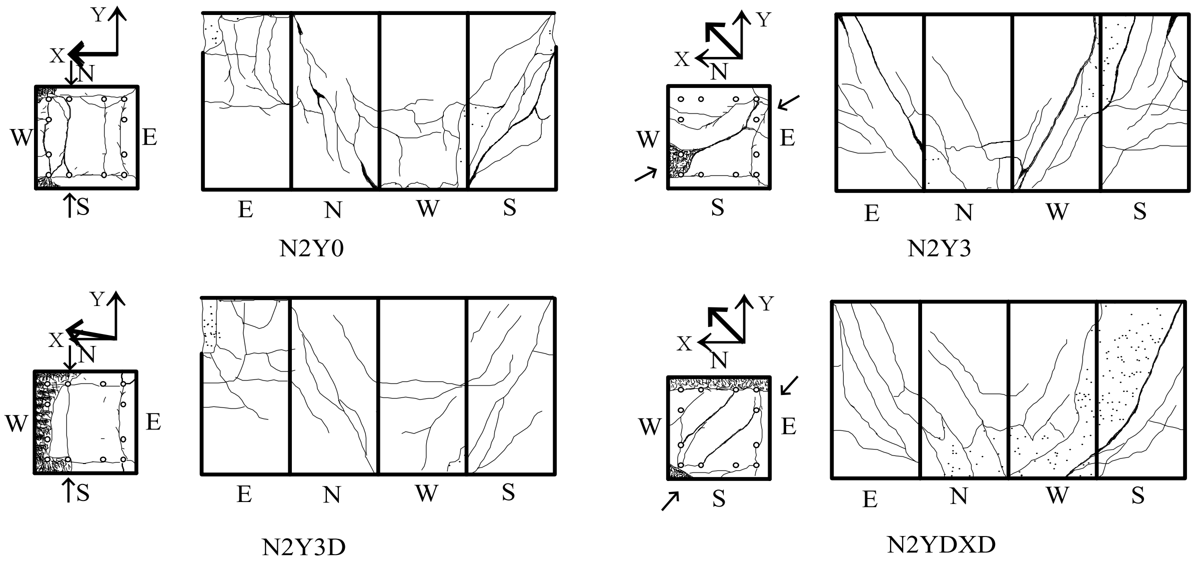


Figure 4: Crack patterns

(a) N2Y0 (b) N2Y3

Photo 1: Damage patterns

Crack patterns observed at column four faces are shown in Figure 4 for some specimens. For Series 1D, which is represented by N2Y0, shear cracks formed at the North and South faces, and the widening of these cracks resulted in pronounced strength deterioration. For Series 2D shear cracks formed at all four faces (except for N2Y3D). N2Y3D, for which the Y direction was controlled by displacement, showed crack patterns close to those of N2Y0, for which YLOAD was zero. Damages observed at the South and West faces are shown in Photo 1 for N2Y0 and N2Y3. Severe damages occurred at both faces for N2Y3 while they did only at the South face for N2Y0.

After the tests were over, the specimens were cut at the middle height of a column along the horizontal plane. Crack patterns observed at this section are also shown in Figure 4, where a thin arrow marks a predominant crack and a thick arrow marks direction of lateral load at its maximum value. It can be seen that the direction of the load at a maximum was almost perpendicular to the direction of the predominant crack.

5. LOAD AND DEFORMATION FOR SERIES 2D

Actual lateral load on a laterally deformed specimen differs from the jack load because of the effect of axial load and the other lateral load, or P-Δeffect. Lateral load was, therefore, evaluated by modifying the jack load considering such effect. Hereafter actual loads of the X and Y directions are referred to as PX and PY (PY is close to but not same as YLOAD), and deformations of the two directions are as DX and DY. Deformation was measured as relative displacement between the two column ends.

DX-PX relations are shown in Figure 5 for Series 2D excluding N2Y3D and N2YDXD. A mark ●denotes Maximum Load Point (MLP), where lateral load was at a maximum, and a mark ×does Limit Load Point (LLP), where a specimen came to be unable to sustain the prescribed value of YLOAD. For N2Y3 and N2Y2, a downward arrow is depicted at Limit Load Point. This means if YLOAD had been maintained, drastic strength drop would have occurred for the X direction. Except for N2Y1, as YLOAD increases, a maximum value of PX becomes smaller, which is apparently a result of the bi-lateral interaction. It is also noted that as YLOAD increases, strength deterioration after MLP becomes greater.

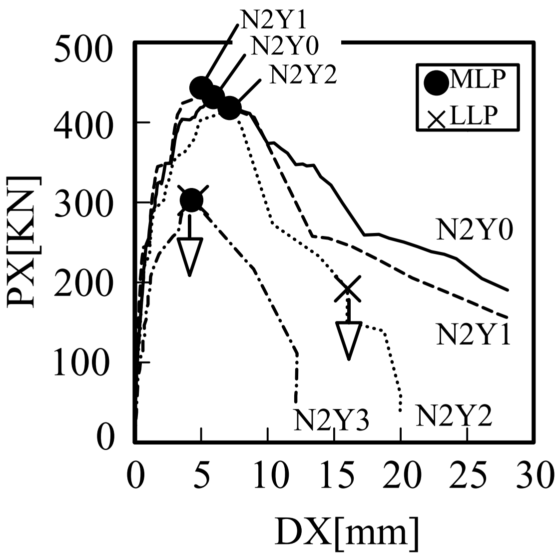


Figure 5: DX-PX relations

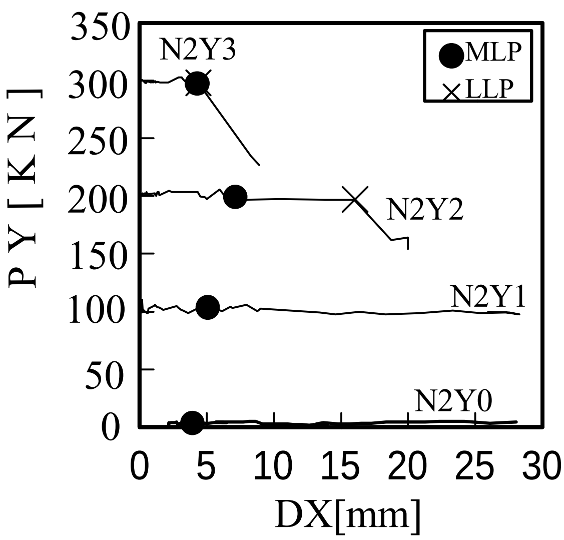


Figure 6: DX-PY relations

DX-PY relations are shown in Figure 6 for Series 2D excluding N2Y3D and N2YDXD. It can be seen that for N2Y3 and N2Y2, YLOAD could not be maintained after LLP. As YLOAD increases, deformation of the X direction at LLP becomes smaller.

PX-PY relations are shown in Figure 7, where results up to MLP are depicted. This graph directly indicates the bi-lateral load interaction. A circle with the radius of shear strength of a standard specimen (N2Y0) is described in the figure. All plots for MLP lie near this circle, clearly indicating that the failure surface for bi-lateral loads can be represented by a circle irrespective of load paths. For N2Y3D, as the loading to the X direction proceeds, PY is decreasing (294KN→96KN). This is again a result of the bi-lateral interaction and such great decrease of PY is a reason why the crack patterns of N2Y3D were close to N2Y0.

DX-DY relations are shown in Figure 8 for Series 2D excluding N2Y3D and N2YDXD. An upward arrow is depicted at LLP for N2Y3 and N2Y2, which means that if YLOAD had been maintained, drastic increase of DY would have occurred. As DX is increasing, DY is increasing though PY is nearly constant. The increase of DY becomes pronounced after MLP for N2Y1 and N2Y2 and even before MLP for N2Y3. It is also noted as YLOAD increases, the increase of DY becomes greater.

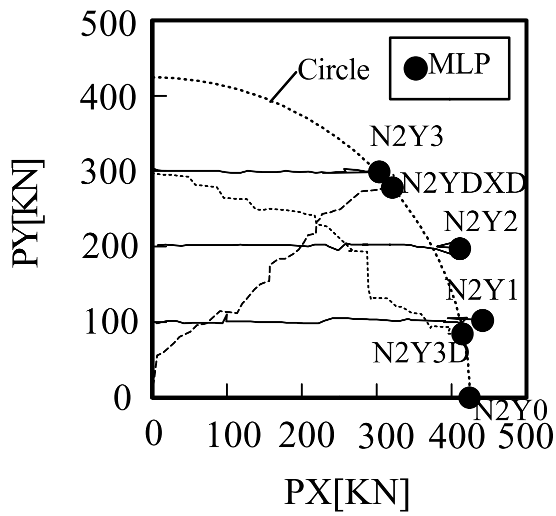


Figure 7: PX-PY relations

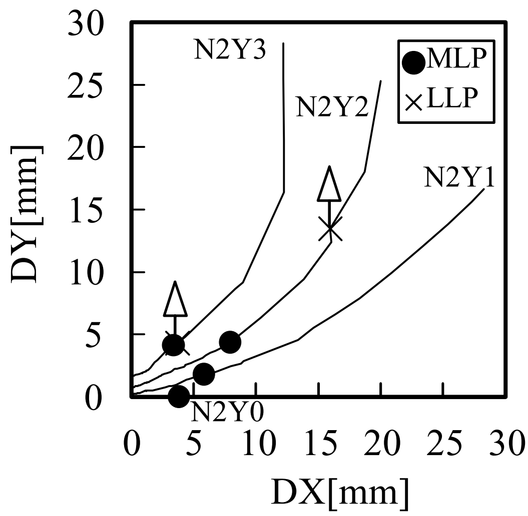


Figure 8: DX-DY relations

6. LOAD AND DEFORMATION FOR SERIES 1D

Values of Axial Load Index used for Series 1D were 0, 0.2, 0.4 and 0.6. DX-PX relations are shown in Figure 9. As axial load increases, stiffness before MLP becomes higher: For example, secant stiffness at about PX=250KN are 99.0KN/mm, 281KN/mm, 354KN/mm and 564KN/mm, respectively for N0Y0, N2Y0, N4Y0 and N6Y0. And as axial load increases, strength deterioration after MLP becomes greater. It can be seen as Axial Load Index increases from 0 to 0.4, a maximum value of lateral load (shear strength) becomes larger, but when Axial Load Index is 0.6, it becomes smaller.

The relations between shear strength and axial load are plotted in Figure 10. A vertical line in the figure is an average of the four values of shear strength. A coefficient of variation is 7.7%. A real curve is a shear strength-axial load interaction curve determined by the least square method, where an ellipse was assumed as basic function. Axial Compression Strength (ACS) was computed as a sum of concrete strength by column area and bar yield stress by total bar areas, and Axial Tension Strength (ATS) was as bar yield stress by total bar areas. A coefficient of variation for this case is 4.6%, which is much smaller than the value obtained assuming shear strength is independent of axial load.

DX-axial deformation relations are shown in Figure 11. Axial deformation, which started from axial shortening due to initial axial load, moved to elongation at first but turned toward shortening at near MLP. As axial load increases, an amplitude of axial shortening at the final stage becomes larger.

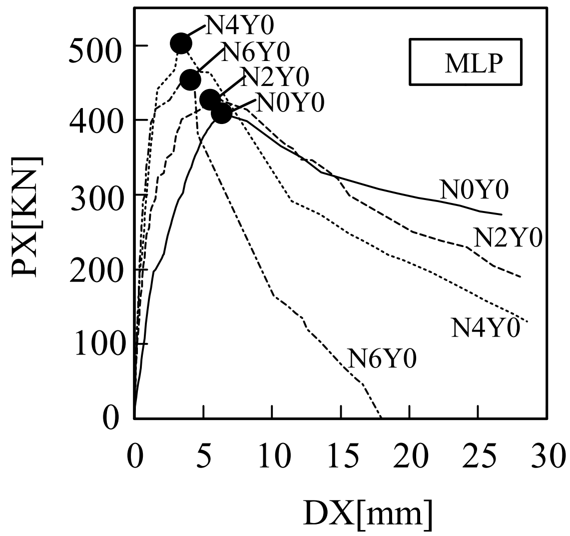


Figure 9: DX-PX relations

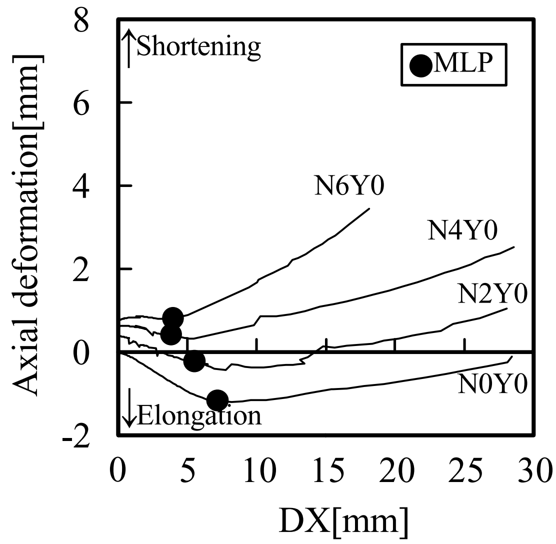


Figure 11: Lateral deformation - axial deformation relations

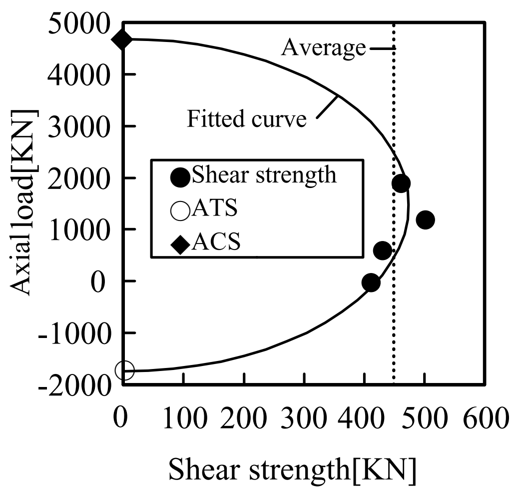


Figure 10: Shear strength - axial load relations

7. CONCLUSION

Tests on shear columns subjected to various multi-axial load conditions were conducted. The tests included two series: In Series 2D bi-lateral loading tests were done and in Series 1D uni-lateral loading tests were done. The major findings from the study are as follows:

1) As YLOAD (constant jack load of the Y direction) increases, maximum load (shear strength) of the X direction becomes smaller, and the failure surface for bi-lateral loads can be represented by a circle irrespective of loading paths (from Series 2D).

2) Deformation of the Y direction increases as the loading to the X direction proceeds though load of the Y direction is kept constant, and as YLOAD increases, this increase becomes greater. (from Series 2D).

3) As Axial Load Index increased from 0 to 0.4, shear strength becomes larger but when Axial Load Index is 0.6, it becomes smaller (from Series 1D).

4) It is more reasonable to think that there is dependence of shear strength upon axial load (from Series 1D).

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