Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Vertical splitting failure of high-strength RC columns after flexural yielding

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ABSTRACT: Remarkable vertical splitting occurred after flexural yielding in the seismic test of RC columns using high strength concrete and reinforcing bars. It divided the specimen into two sections. The surface of this splitting failure was perpendicular to the loading direction and located at the center of the column section where the intermediate longitudinal bars and tie bars existed. The lateral load carrying capacity decreased significantly due to this failure. This failure is possibly one of typical failure patterns of columns using high strength concrete. Occurrence of the vertical splitting is predicted comparing the splitting strength of concrete with the shear stress on the splitting surface calculated from the proposed failure mechanism.

1. INTRODUCTION

Remarkable vertical splitting occurred in the testing of RC columns using high strength concrete and reinforcing bars under combined stresses of anti-symmetric bending and shear and constant high axial compression. The surface of this splitting failure was perpendicular to the loading direction and located at the center of the column section where intermediate longitudinal bars existed. The lateral load carrying capacity decreased significantly due to this failure. The objective of this paper is to ascertain the generating mechanism for the failure and the strength of RC column by comparing this results with passed experimental results.

2. CIRCUMSTANCES OF VERTICAL SPLITTING FAILURE

Fig. 1 shows the representative specimen in which the vertical splitting failure occurring along side intermediate longitudinal bars was observed. Fig. 2 shows a typical pattern of the vertical splitting failure cut parallel to the lateral loading direction. This vertical splitting spread through the interior of the specimen along inner tie bars, separated it into two parts. It was confirmed that the vertical split penetrated the whole section and extended throughout except at the both ends where the flexural hinge developed.

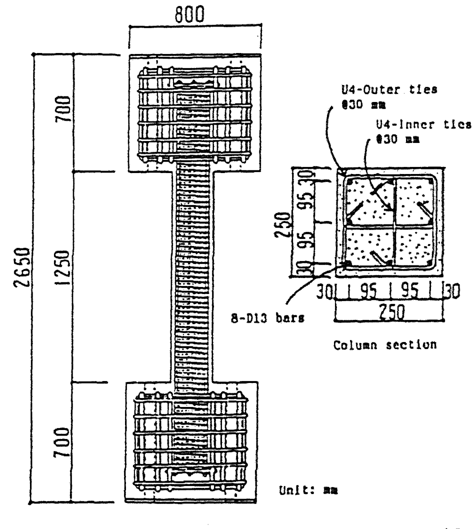

Fig.1. Typical reinforcing details of column test specimen

3. MECHANISM OF VERTICAL SPLITTING FAILURE

Fig. 3 shows the deformation model and acting forces of the column after flexural yielding under combined stresses of anti-symmetric bending, shear and constant high compression. The deformation model in Fig. 3-(a) was assumed by the pattern of the vertical splitting failure. Two hinge zones were assumed at the both ends of the column.

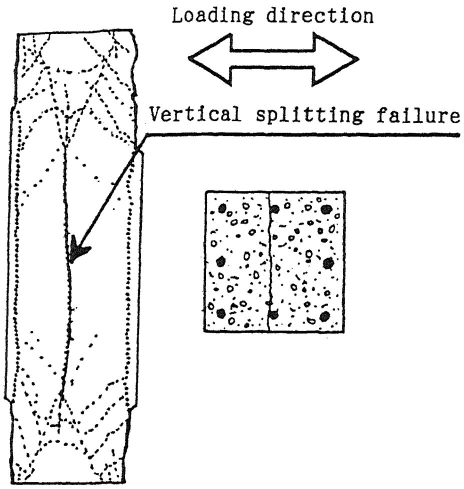

Fig.2. Typical pattern of the vertical splitting failure

Still more each hinge zone was parted into two zones. One was the compression hinge zone where the compressive strain concentrated the other was the tension hinge zone where the tensile strain concentrated. It was assumed that the axial compressive force was transmitted through the compression hinge zone because the compressive stress of concrete in the critical section was concentrated on the compression hinge zone . And the tensile bars yielded in the tensile hinge zones. According to the truss analogy, the compression strut force (Cd) was balanced by all forces of lateral reinforces across the tensile hinge zone (Tw) and the bond force (ΔT) in the tension hinge zone (see Fig. 3-(b)). After flexure yielding the bond force ΔT among the acting forces in Fig. 3-(b) was nearly zero because the concrete at hinge zone was almost spalling and cracking. The compression force Cd and the force of lateral reinforces Tw are balanced because of the assumption that was zero. Fig. 3-(c) shows actions on the assumed model. Fig. 4 shows the stress acting on the plane of the vertical split. The plane of vertical splitting failure was assumed that it was a center plane that was perpendicular to the lateral loading direction,the assumed length of the vertical split (Lc) might be written as

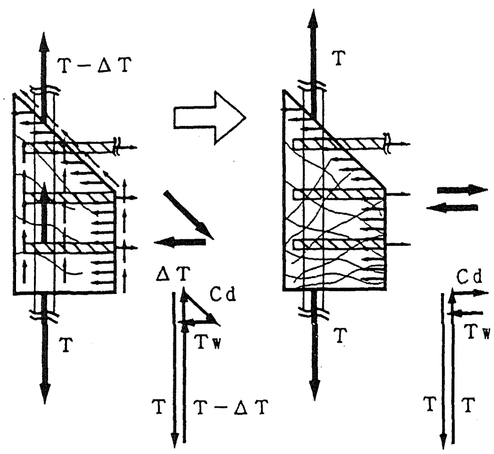

Fig.3-(b). Equilibrium in the tension hinge zone

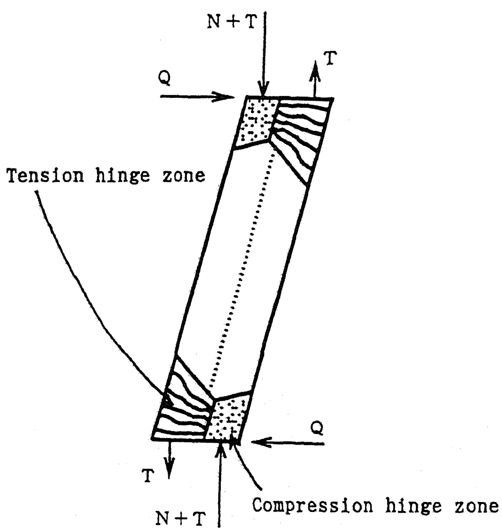

Fig.3-(a). Deformation model

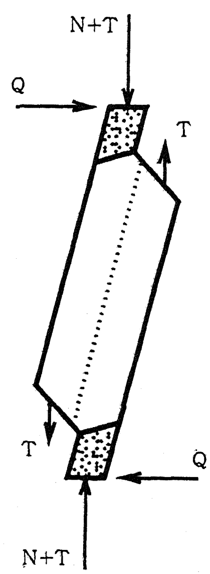

Fig.3-(c). Actions on assumed model

$L_c = L - D$

Where L = length of column

D = depth of column

N = axial load

Q = lateral load

T = $A_s \cdot f_y$ =resultant internal tensile force

A_s= area of tension bars

f_y= yield strength of tension bars

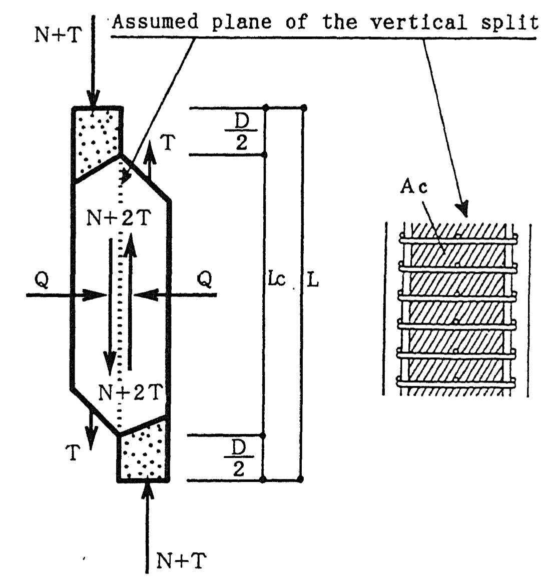

Fig.4. Stresses acting on the plane of the vertical splitting failure

4.SHEAR STRESS AND SPLITTING STRENGTH

The vertical component of forces acting on the face of the vertical splitting failure is shown in Fig.4, the shear stress (τ_s) can be obtained as follows:

$$\tau_s = \frac{N + 2 \cdot T}{A_c} \quad (1)$$

where Ac= assumed area of vertical splitting face

The shear strength of the vertical split (τ_{su}) can be computed by the modified shear-friction theory by Hermanson and Cowan (1974) as expressed by:

$$\tau = C + \phi \cdot \tan\phi \quad (2)$$

where C = apparent cohesion in concrete

ϕ = vertical stress acting on vertical splitting face

$\tan\phi$ = coefficient of friction

When the value of C is to be $5.64\sqrt{\sigma_B}$ by Takeda et al. (1988) and the $\tan\phi$ is to be 1.4 by Mast (1968). Eq.(2) changes Eq.(3) as expressed by:

$$\tau_{su} = 5.64\sqrt{\sigma_B} + 1.4\left(\frac{Q_u}{A_c} + p\right) \quad (3)$$

where σ_B= compressive strength of concrete

Qu= ultimate shear strength by Standard for Structural Calculation of RC structures (1988),in Japan

p = stress of lateral reinforcement

Table 1. Summary of test results

Specimenn	Shear span to depth ratio	Depth of section D (cm)	Width of section b (cm)	Span L (cm)	Longitudinal Reinforcement		Lateral Reinforcement		Compressive strength of concrete σ_B (MPa)	Axial Stress Ratio η	Ultimite Load Qu (kN)	τS (MPa)	τSU (MPa)	$\tau S / \tau SU$ Ratio	Vertical Spritting Failure	Remarks
					ρt (%)	σy (MPa)	ρw (%)	σwy (MPa)								
1*	2.5	25	25	125	0.41	658.0	0.64	995.6	33.7	0.47	158.4	8.6	11.7	0.74	DID'T OCCUR	Without inner tie bar
2*	2.5	25	25	125	0.41	658.0	0.47	995.6	51.0	0.38	204.4	9.9	14.4	0.68	DID'T OCCUR	Without inner tie bar
3*	2.5	25	25	125	0.41	658.0	0.47	995.6	51.0	0.31	189.3	8.3	14.3	0.58	DID'T OCCUR	Without inner tie bar
4*	2.5	25	25	125	0.81	330.5	0.64	995.6	51.0	0.31	189.5	8.6	14.3	0.60	DID'T OCCUR	Without inner tie bar
5*	2	25	25	100	0.81	831.0	0.64	808.5	78.4	0.4	446.1	21.9	21.0	1.04	OCCURRED	Without inner tie bar
6*	2	25	25	100	0.81	831.0	0.64	808.5	78.4	0.6	466.1	31.9	21.3	1.45	OCCURRED	Without inner tie bar
7*	2	25	25	100	0.81	831.0	0.96	808.5	78.4	0.5	474.7	27.7	21.4	1.26	OCCURRED	Without inner tie bar
8	2	25	25	100	0.81	831.0	0.96	1109.2	79.2	0.4	466.0	24.3	21.3	1.08	OCCURRED	With inner tie bar
9	2	25	25	100	0.81	831.0	0.96	1109.2	79.2	0.45	475.2	26.4	21.5	1.12	OCCURRED	With inner tie bar
10	2	25	25	100	0.81	831.0	0.96	1109.2	79.2	0.45	475.2	26.4	21.5	1.12	OCCURRED	With inner tie bar
11	2.5	25	25	125	0.81	700.0	0.51	980.7	83.8	0.35	352.1	16.4	19.3	0.85	OCCURRED	With inner tie bar
12**	5	25	25	125	0.81	700.0	0.51	980.7	87.5	0.35	181.2	9.8	18.0	0.54	DID'T OCCUR	With inner tie bar
13**	5	25	25	125	0.81	700.0	0.51	980.7	87.5	0.35	181.2	9.8	18.0	0.54	DID'T OCCUR	With inner tie bar
14**	5	25	25	125	0.81	700.0	0.51	980.7	90.7	0.6	193.0	14.1	18.4	0.77	DID'T OCCUR	With inner tie bar

*Hiraishi et al.(1989,1990) **Cantilever column

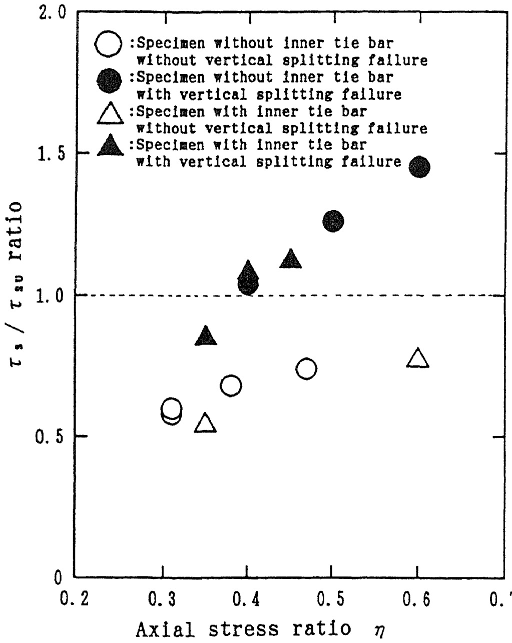

Fig.5. Relationship between τ_s / τ_{su} ratio and axial stress ratio

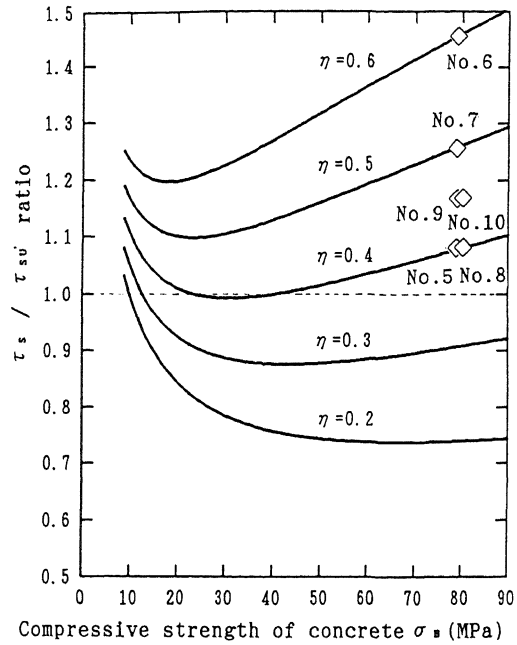

Fig.6. τ_s / τ_{su} ratio due to increase in compressive strength of concrete and axial stress ratio

5.COMPARISON OF EXPERIMENTAL RESULTS

Table 1 shows a summary of some representative test results including the test results by Hiraishi et al.(1989,1990) and comparison between τ_s values and τ_{su} values calculated by proposed model. Fig. 5 shows the relationship of τ_s / τ_{su} ratio to axial load level (η). When the vertical splitting failure occurred the strain of lateral reinforcement was approximately zero. The p value assumed to be zero. In this comparison specimens experimenting the vertical splitting failure had a greater τ_s / τ_{su} ratio than those which did not. Fig. 6 shows the relationship of τ_s / τ_{su} ratio to the compression strength of concrete at various levels of axial load. These curves of τ_s / τ_{su} ratio were obtained from the detail of specimen 5.And the τ_s / τ_{su} ratio of specimen 5,6,7,8,9,and 10 in which the vertical splitting failure occurred were plotted in Fig.6 . It was clear from Fig.6 that with an increase in axial stress ratio η and compressive strength of concrete σ_B , τ_s / τ_{su} ratio was increased. The trend shows that the vertical splitting failure occurred in the column using high strength concrete under high axial load.

6.CONCLUSIONS

The vertical splitting is typical failure of high strength concrete columns under high axial load. Occurrence of the vertical splitting is predicted comparing the splitting strength of concrete with the shear stress on the splitting surface calculated from the proposed failure mechanism.

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