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SHEAR DESIGN OF CONCRETE MEMBERS TO MEET DUCTILITY REQUIREMENT

Fumio WATANABE

Department of Architecture, Kyoto University
Sakyo-ku, Kyoto, Japan

SUMMARY

In this paper, a method to assure the required ductility of hinging members subjected to combined bending and shear was examined. Twelve beams and eight columns were tested under reversed bending and shear. Test results showed that to secure a certain ductility, compressive stress of concrete strut in shear resisting mechanisms should be limited in considerably smaller value comparing to the compressive strength of concrete. And this limiting value is given as a function of required ductility.

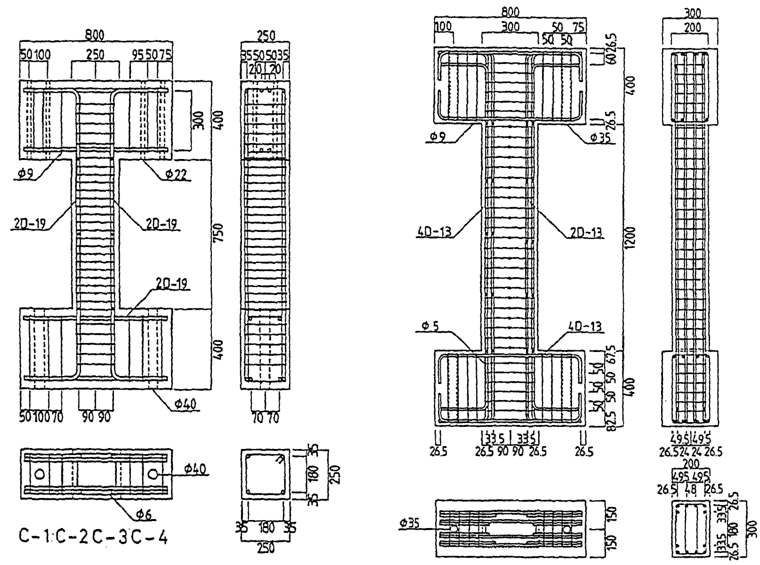
INTRODUCTION

In the seismic design of ductile moment resisting frames, a certain deformation capability should be assured to the constituent member to meet the required ductility as well as the strength. In the members which are primarily subjected to flexure or flexure and axial force, ductility limit would be controlled by the crushing of concrete under flexural compression or the buckling of longitudinal reinforcement. For such members, even if the ductility is not enough it can be easily improved by several methods, for example, the use of closely spaced lateral reinforcement. However, in a framed structure, most hinging members are subjected to combined bending and shear. Accordingly, the shear design to meet ductility requirement is indispensable as well as the ductility design of section under flexure or flexure and axial force. The purpose of this study is to establish a rational shear design method of hinging members to meet the ductility demand. To derive the shear design philosophy of hinging region of ductile members, reversed cyclic loading tests were carried out on 12 beams and 8 columns under combined bending and shear. On the basis of test results, compressive stress of concrete strut in shear resisting mechanisms is discussed as a measure to evaluate the ductility.

OUTLINE OF EXPERIMENTS

Combined bending and shear loading tests were carried out on 12 beams and 8 columns.

Column specimen had a square section of 25x25 cm and reinforced longitudinally by a 19 mm in diameter deformed bar having the yield strength of 372 Mpa at each corner as shown in figure 1.a. Variables in the tests are compressive strength of concrete (f_c'=23.0 46.8 Mpa), shear reinforcement ratio (p_w=0.41



(a) Column specimen (b) Beam specimen

Figure 1. Dimensions and reinforcement arrangements of specimens

0.75%) and axial load (N=324 and 670 KN). Two types of shear reinforcement are used. One is ordinary strength round bar (fy=434 Mpa) and the other one is high strength one (fy=1078 Mpa). Details of column specimens are summarized on table 1.

Beam specimens had a rectangular section of 20x30 cm and reinforced longitudinally by six 13 mm in diameter deformed bars having the yield strength of 400 Mpa at tension and compression side of section as shown in figure 1.b. Variables are shear reinforcement ratio (pw=0.1 0.8%) and yield strength of it (fy=492 838), and compressive strength of concrete (fc'= 29.3 and 43.4 Mpa). Details of beam specimen are summarized on table 2.

Loading method is shown in figure 2. Lateral load is applied by two horizontal jacks. One of them is so controlled automatically as to restrict the rotation of top stub of specimen. Bottom stub of specimen is fixed on the bearing floor by prestressing. That is, moment diagram of specimen becomes anti-symmetric.

For columns, constant axial force is applied by a

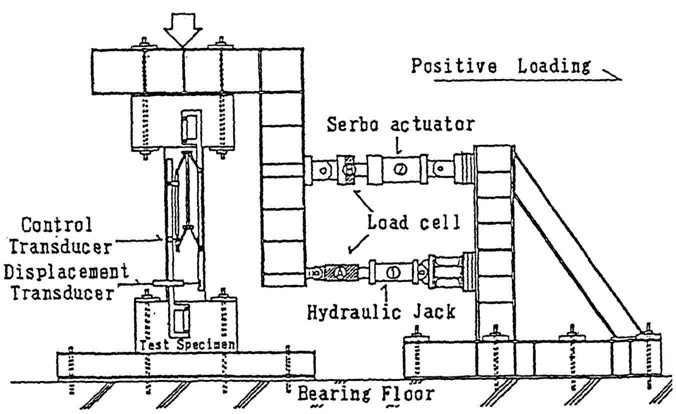


Figure 2. Experimental methods

Table 1. Details of column specimens

Specimen	Detail of Section		Hoop Reinforcement					Concrete		Axial Load (kN)
	Dimension	Reinforcement	Bar Size	fy(MPa)***	As(cm²)	S(cm)	pw(%)	fc'(MPa)	fsp'(MPa)	
C－1		4-D19	φ6	434				23.0	2.69	
C－2			D6*	1078		4.0	0.56			324
C－3	Width B=25(cm) Total Depth D=25(cm) Eff. Depth d=21.5(cm)	Four 19mm in Diameter Deformed Bars Ag=11,48(cm²) pt=1.07(%) fy=372(MPa)	φ6	434				46.8	4.22	
C－4			D6*	1078	0.28**					
C－5			φ6	434		5.5	0.41			
C－6			D6*	1078				44.6	3.71	670
C－7			φ6	434		3.0	0.75			
C－8			D6*	1078						

* High Strength Deformed Bar ** Nominal Sectional Area of Bar *** fy=Ty/As
Actual sectional area of bar φ6mm bar and D6mm bar were 0.234cm² and 0.268cm² respectively.

Table 2. Details of beam specimens

Specimen	Detail of Section		Stirrup						Concrete	
	Dimension	Reinforcement	Size	fy (MPa)	s (cm)	As (cm²)	pw (%)	pw·fy (MPa)	fc (MPa)	fsp (MPa)
DB-1			φ4	492	6.28	0.13	0.400	1.97		
DB-2		4-D13 2-D13 2-D13 4-D13	φ3	696	5.30	0.07	0.267	1.86		
DB-3	WIDTH		φ3	838	7.07	0.07	0.200	1.68	29.3	3.22
DB-4	B=20(cm)		φ5	692	4.91	0.20	0.800	5.54		
DB-5	TOTAL DEPTH		φ4	732	4.71	0.13	0.533	3.90		
DB-6	D=30(cm)	Ag=7.62(cm²)	φ4	876	6.28	0.13	0.400	3.50		
DB-7	EFF. DEPTH	pt=1.45(%)	φ3	582	7.07	0.07	0.200	1.16		
DB-8	d=26.2(cm)	fy=400(MPa)	φ3	696	10.60	0.07	0.133	0.93		
DB-9			φ3	838	14.13	0.07	0.100	0.84	43.4	3.75
DB-10			φ5	692	6.54	0.20	0.600	4.15		
DB-11			φ4	732	6.28	0.13	0.400	2.93		
DB-12			φ3	838	4.71	0.07	0.300	2.51		

servo actuator. During the loading tests, strains of shear reinforcements are measured by wire strain gages for the calculation of shear force to be allotted to truss action.

Typical load deflection curves of beam and column specimen are shown in figures 3 and 4. Available deflection limit is defined at which the load carrying capacity on the envelope of hysteretic restoring force characteristics becomes 80 % of maximum load experienced. In figures 3 and 4 these points are indicated by solid circles.

EVALUATION OF DUCTILITY

Basic shear resisting mechanism

Here, to evaluate the ductility of hinging member which is subjected to combined bending and shear, the shear design procedure based on the superposition of truss and arch mechanism is applied. This has been newly proposed by the Working Group established in the Sub-Committee on Seismic Design of Reinforced Concrete at Architectural Institute of Japan. Internal force equilibrium and geometrical conditions of arch and truss mechanisms assumed are shown in figure 5 and 6, respectively.

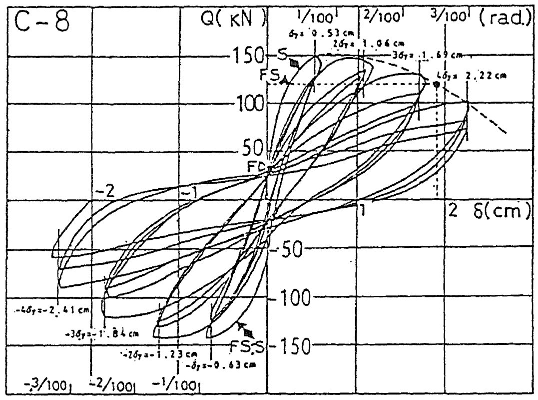


Figure 3. Load deflection curve of column C-8

Shear force carried by truss mechanism Vt and corresponding stress $_c\sigma_t$ generated in compressive strut are given by equations 1 and 2, respectively.

$$V_t = b \cdot j_t \cdot p_w \cdot \sigma_{wy} \cdot \cot\phi \qquad -(1)$$

$$_c\sigma_t = (1+\cot^2) \cdot p_w \cdot \sigma_{wy} \qquad -(2)$$

where, Vt;shear carried by truss, pw ; shear reinforcement ratio, σ_{wy} ;yield strength of shear reinforcement, jt;distance between top and bottom reinforcement, b;width of section, ϕ ;angle of compressive strut and must be assumed to be between 26.6 and 45 degree (Ref.1) $_c\sigma_t$;stress in compression strut.

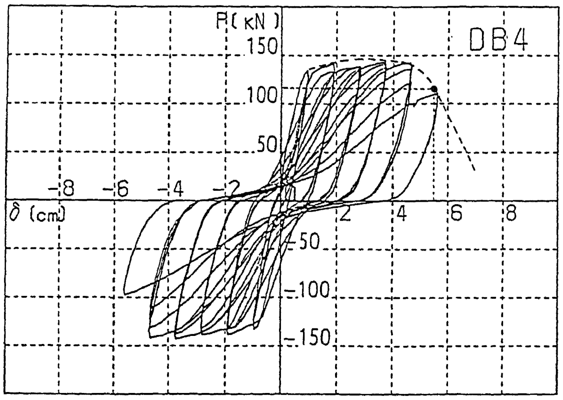


Figure 4. Load deflection curve of beam DB 4

Shear force carried by arch mechanism is given by equation 3 according to Nielsen's proposal (Ref. 2).

$$V_a = b \cdot D \cdot {}_c\sigma_a \left[\sqrt{(L/D)^2+1} - (L/D)\right]/2 \qquad -(3)$$

where, L;length of member, $_c\sigma_a$;stress in arch strut, D;total section height.

By adding equations 1 and 3, shear strength Vu is given by equation 4. The total stress of concrete struts due to truss and arch action is given by equation 5, where the difference between strut angles of truss and arch mechanism is ignored. And in the calculation of shear strength the value of $_c\sigma$ should be less than the effective compressive strength of concrete $\nu\, f_c'$.

$$V_u = V_t + V_a \qquad -(4) \qquad\qquad {}_c\sigma = {}_c\sigma_t + {}_c\sigma_a \leq \nu \cdot f_c' \qquad -(5)$$

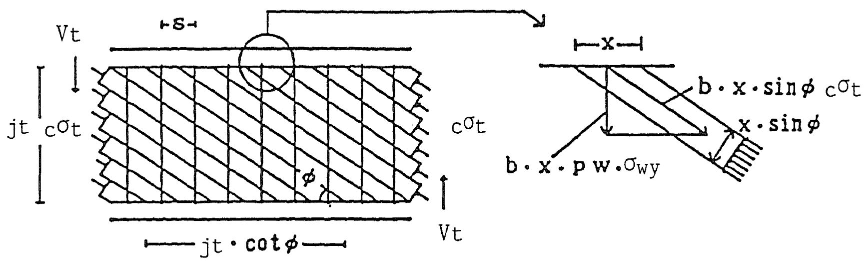


Figure 5. Equilibrium and geometrical condition in truss mechanism

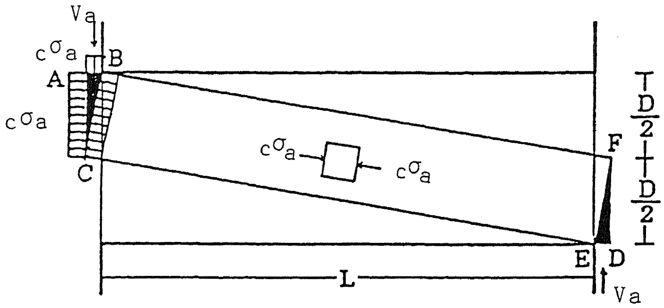


Figure 6. Equilibrium and geometrical condition in arch mechanism

In the shear design equation newly proposed, the effective compressive strength of concrete is given by equation 6 applying Nielsen's proposal (Ref.2). And the angle of is so chosen as to obtain a maximum shear strength, where must have a value between 26.6 and 45 degree and equation 4 should be satisfied.

$$\nu \cdot f_c' = (0.7 - f_c'/196) \cdot f_c' \qquad \text{(Mpa)} \qquad -(6)$$

Relations between strut stress and ductility ratio

Shear force Vt' carried by truss at available deflection limit is calculated by substituting measured average stress σ_{ws} of shear reinforcements at hinging region into σ_{wy} in equation 1, where the angle ϕ of concrete strut is assumed to be 45 degree. And corresponding stress $_c\sigma_t'$ of concrete strut in truss mechanism is obtained from equation 2 in same manner.

$$Vt' = b \cdot jt \cdot p_w \cdot \sigma_{ws} \qquad -(7) \qquad\qquad {}_c\sigma_t' = 2 \cdot p_w \cdot \sigma_{ws} \qquad -(8)$$

where, Vt';shear force carried by truss action, σ_{ws};measured average stress of shear reinforcement in hinging region, $_c\sigma_t'$;stress of strut due to truss action.

Likely compressive stress $_c\sigma_a'$ of concrete strut in arch mechanism is given by equation 9 based on equation 3.

$${}_c\sigma_a' = 2 \cdot (0.8V_{max} - V_t')/[\sqrt{(L/D)^2+1} - (L/D)]/(b \cdot D) \qquad -(9)$$

where, Vmax;maximum load carrying capacity obtained from loading test

Finally, the resultant stress of concrete strut is obtained by adding the values of $_c\sigma_t'$ and $_c\sigma_a'$ in equations 8 and 9.

$${}_c\sigma' = {}_c\sigma_t' + {}_c\sigma_a' \qquad -(10)$$

Calculated resultant total stresses are indicated in figure 7, where x axis is ductility ratio at available deflection limit and y axis is resultant total strut stress normalized by effective compressive strength proposed by Nielsen (Ref.2). From this figure, it is seen that the required ductility ratio for members can be obtained by reducing the effective strength of concrete when shear design is performed. And as a conservative evaluation, following equation is proposed for compressive strength of concrete strut in hinging member.

$$\overline{\nu \cdot f_c'} = \begin{cases} (0.7 - f_c'/196) \cdot f_c' & \mu < 1.0 \\ (0.7 - f_c'/196)(-\mu/6 + 7/6) \cdot f_c' & 1.0 \leq \mu \leq 4.0 \\ (0.7 - f_c'/196) \cdot 0.5 f_c' & 4.0 < \mu \end{cases} \quad \text{-(11)}$$

μ; ductility ratio

Here the strain of shear reinforcement at the deformation limit is not considered. However, the excessive opening of diagonal crack is not desirable to make sure the stress transfer along cracked surfaces. So, the yield strength of 800 Mpa is proposed tentatively as a maximum available limit from experimental stress measurement of shear reinforcements.

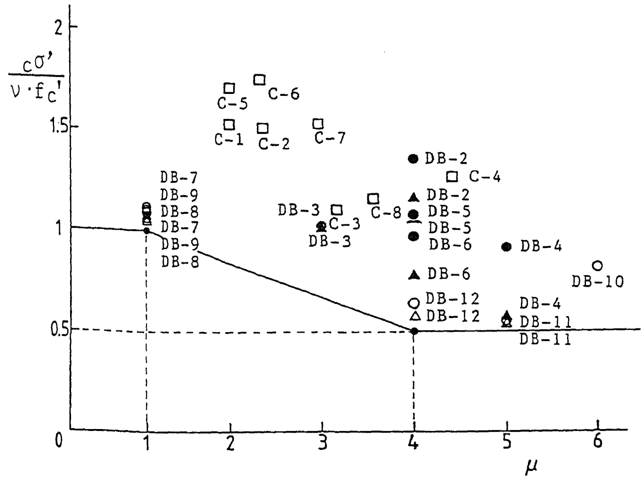


Figure 7. Total compressive stress of concrete strut at available limit ductility ratio

CONCLUSIVE REMARKS

For the evaluation of ductility of hinging members which are subjected to combined bending and shear, the compressive stress of concrete strut in shear resisting mechanisms is a good measure of ductility.

ACKNOWLEDGMENT

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Working Group : F.Watanabe, K.Minami, S.Sugano, T.Kabeyasawa, T.Ichinose
H.Kuramoto, A.Sumi, H.Shiobara, I.Shiraishi, S.Hayashi
T. Arakawa, Y.Arai, T. Shibata, K.Yoshioka, O.Joh

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