Behavior of Orthogonally Reinforced Concrete Walls Subjected to In-plane Shear Force

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Abstract

The reinforced concrete walls constitute the principal earthquake-resisting components of structures in nuclear power facilities such as reactor buildings and containments. It is, therefore, an important subject to clarify the mechanism of shear resistance of the reinforced concrete wall which is subjected to in-plane shear force.

This study aims at the observation of behavior of reinforced concrete walls subjected to in-plane shear force and the examination of the applicability of existing theories to the subject problem.

Orthogonally reinforced concrete hollow cylinders were subjected to alternating torsional force and constant axial force simultaneously up to failure.

The following results were obtained from this study.

(1) Shear stiffness after cracking, maximum shear strength and a capacity of shear deformation in the reinforced concrete walls subjected to in-plane shear force are strongly influenced by the difference of reinforcement ratio and axial stress. Increase in reinforcement and axial force gives the reinforced concrete walls larger shear stiffness after cracking, larger maximum shear strength and smaller capacity of shear deformation.

(2) Maximum shear strength of the specimens in which reinforcing bars yield can be estimated by a criterion derived based on the truss analogy. In the specimens whose maximum strength was governed by failure of concrete, the maximum shear have an upper limit which is given by, irrespective of the reinforcement, $4.2\sqrt{Fc}$ when axial tensile force or no axial force was applied. But, when the compressive axial force is applied, the maximum strength appreciably increases according to the increase of the reinforcement ratio.

(3) The diagonal compression field theory proposed by M.P.Collins [1] predicted adequately the ultimate shear strength and deformation with regard to the present test series, though further advancement in the shear field theory seems to be required to explain the degrading paths of the stress-strain curves after cracking.

1. Intoroduction

The reinforced concrete walls constitute the principal earthquake-resisting components of structures in nuclear power facilities such as reactor buildings and containments. It is, therefore, an important subject to clarify the mechanism of shear resistance of the reinforced concrete wall which is subjected to in-plane shear force.

Many studies have been published on shear failure in reinforced concrete walls, but the rational shear theory comparable to the bending theories of beams has not yet attained.

For the purpose of obtaining basic data to clarify the shear transfer mechanism, the authors carried out a series of experments, in which twelve R.C. hollow cylinders were subjected to alternating torsion together with constant axial force, parameters being reinforcement ratio and axial stress.

This paper reports the outlines of the experimental series. Also, the diagonal compression field theory proposed by M.P.Collins [1] is applied to the experimental cases to examine its applicability to the R.C. walls in in-plane shearing force.

2. Outline of Test

The shape and reinforcement of the typical test specimen are shown in Fig.1. The hollow cylinder is subjected to pure shear by the application of twisting moment.

A list of parameters for the specimens is shown in Table 2. The behavior of a reinforced concrete wall under the in-plane shearing force is to be influenced by quantity of reinforcement, intensity of axial stress, ratio of vertical and horizontal reinforcements, direction of reinforcement and so on. In this study, the reinforcement ratio and the axial stress were chosen as the parameters as these two were thougth to have a dominant influence. The same amount of reinforcement was provided both in the axial and the hoop directions and three grades of reinforcement ratio were adopted, i.e., 1.01%, 1.75% and 2.44%. The axial stress of four levels was specified, i.e., -25(tensile), 0, 50(compressive) and 100 kg/cm² . The property of deformed bar used, D8, is given in Table 1 and the strength of concrete in Table 2.

Loading system is shown in Fig.2. An alternating twisting moment was applied to the specimen through a loading stab. The moment was produced by tensionning a pair of wire strands by centerhole oil jacks equipped in reaction frames. The constant axial load is imposed to the stab directly from an oil jack.

Items of measurement were loads, circumferential, axial and radial displacement and strains of reinforcing bars and concrete.

3. Results of Tests

The principal figures of test results for each specimen are listed in Table 2. As an index of the shearing force intensity, the mean shear stress in the sectional area of the cylinder was used in these results. Fig.3 shows the envelopes of shear stress-strain hysteresis curves for all of the specimens for each group having the indentical reinforcement ratio. Some hysteresis curves for the specimens having an specific ratio of reinforcement of 1.75% are shown in Fig.4. Fig.5 shows shear stress-axial strain relations for representative specimens, and Fig.6 shows the relation between shear stress and strain of a hoop bar of a specimen.

4. Consideration on Test Results

4.1 Stress-Strain Relation in Shear

As seen in Fig.3, the envelopes of shear stress-shear strain curves indicate that every specimen of the same axial stress shows the same stiffness before cracking regardless of ratio of reinforcement. The stiffness after cracking is primarily governed by the amount of reinforcement.

The axial stress in tension lowers the initial stiffness to shear and cracking shear stress. As the axial stress varies from tension to high compression, cracking shear stress becomes higher and the transition to the reduced stiffness occurs at the higher stage of loading.

The characteristics of the hysteresis loops are strongly influenced by the axial force. As shown in Fig.4, when the axial force is tensile , the loops take the pattern of "slip" type, the width of the loop being narrowed in the ricinity of the origin in the diagram. As the axial forces increase in compression, the "slip" action decrease in the hysteresis and the loops take the more elastic type with less amount of the residual deformation.

4.2 Ultimate Shear Strength and Capacity of Shear Deformation

As seen in Fig.7, the increase of the reinforcement brings the increase in the maximum shear stress for the lower range of reinforcement ratio.

Basing on the truss model of shear transfer, the following criterion for determining the ultimate shear stress can be derived.[2]

$$\tau u = \min [(pt\, \sigma y)\, h\ ,\ (pt\, \sigma y)\, v\ ] \qquad (1)$$

where τu : maximum shear strength

$(pt\ \sigma y)h = pt\sigma y$: average tensile stress in hoop direction corresponding the yielding of reinforcement

$(pt\ \sigma y)v = pt\sigma y - \sigma o$: the same in vertical direction

pt : ratio of reinforcement

σy : yield stress of reinforcement

σo : vertical stress due to axial loading (tensile stress is taken positive)

As indicated in Fig.7, the maximum shear stress of the specimen whose reinforcement yielded before failure, i.e. SP−1.0−0 , SP−1.0−50 , SP−1.0−(- 25) and SP−1.7−(- 25) can be well predicted by eq.(1).

On the other hand, for the specimens in tensile axial force and for those without axial force, there is a critical limit of the reinforcement ratio beyond which the increment of reinforcement does not give any rise in the shear strength. For the specimens reinforced beyond this limit gave almost constant value of shear strength. This limiting value of the shear strength for the over-reinforced specimen can be represented by

$$\tau u = 4.2\sqrt{Fc} \qquad (2)$$

For the other over-reinforced specimens subjected to compressive axial force showed a different tendency. In this case, even beyond the critical reinforcement ratio, the increase in the reinforcement brings the increase in the shear strength, though the rate of increment is small. This observation suggests a change of failure mechanism of concrete under the existence of the axial compression.

For the specimen under axial tension and for those without axial force, the capacity of shear deformation has a tendency to decrease as the ratio of reinforcement increases. For the specimen under axial compression, the ultimate deformation is kept almost constant regardless of the reinforcement ratio. The limiting values of the mean shear strain are $\gamma = 4.29 \sim 6.41 \times 10^{-3}$ rad.

Also, specimens having the heavy reinforcement of 2.44% shows almost constant values of the ultimate deformation regardless of the axial force, the limiting values in this case being $\gamma = 4.86 \sim 5.27 \times 10^{-3}$ rad.

4.3 Character of Strain

As seen in Figs.5 and 6, axial mean strain and the strain of horizontal reinforcement exhibit the same types of hysteresis. The behavior symmetric to the loading in both direction is their characteristic feature. The strain hysteresis of the axially tensioned specimen is characterized by the rapid growth of strain amplitude and residual strain caused by the cyclie loading. On the contrary, the axially compressed specimen shows little degrading of hysteresis, which corresponds to the rather elastic behavior of the compressed specimens.

5. Application of the Diagonal Compression Field Theory

The diagonal compression field theory proposed by M.P. Collins [1] has been successfully used for reinforced and prestressed concrete beams. As this theory is constructed in terms of the average shear stress in neglect of the variation of shear stress across the beam section, it is expected to be applied to the plane field of constant shear stress in the present tests.

The stress-strain curves for the tested specimens were constructed by the step-by-step analysis of Collins' theory , where the vertical reinforcement was taken as the longitudinal steel in beams, hoop bars as the stirrups.

The deformation up to cracking was estimated by the theory of elasticity excluding the stiffness of reinforcement. Cracks were assumed to occur when the principal stress reached the tensile strength of concrete.

The results of the analysis are presented in Fig.8 in comparison with the experimental stress-strain curves. For the latter, both the hysteretic envelopes and the last loops just before failure are represented. The followings can be observed in Fig.8 : i) the analysis predicts adequately both the stress and strain in the ultimate state, ii) the analysis overestimates the deformation at the early stage after cracking but the estimation gradually approaches the experimental values toward the ultimate state, iii) the predicted tangential slope of the stress-strain curve after cracking is more coincident to the one of the last loop than of the envelope.

From the above observations, it can be concluded that the Collins' theory seems to be a theory representing the behavior of a reinforced concrete structure in shear in which the cracks has fully developed such as the present specimens after some cycles of the alternating load. In spite of the above comments, the Collins' theory presents a valuable tool of design which is able to predict both the strength and deformation capacity of the reinforced concrete walls in in-plane shear.

6. Conclusion

The series of tests on hollow cylinders was carried out to know the actual behavior of reinforced concrete walls subjected to both shear and axial forces. The method and the results of the experiment were described. Also, it was examined how the diagonal compression field theory by M.P. Collins could be applied to each case of the present tests. While the analysis by the theory provided adequate predictions of both the strength and the deformation, further studies are required to know the mechanism of progressive failure of cracked walls in shear.

References

〔1〕 M.P.Collins, "Towards a Rational Theory for R.C. Members in Shear" , ASCE ST4, Vol. 104 , pp. 649—666 (Apr. 1978).

〔2〕 Y.Ohsaki, Y. Ibe, Y. Aoyagi, "Drafted Japanese Design Criteria for Concrete Containment", SMiRT—6 , J 1/2, 1981.

〔3〕 Y.Ogaki, M. Kobayashi, T.Takeda, et al., "Shear Strength Tests of Prestressd Concrete Containment Vessels", SMiRT—6 , J 4/3, 1981.

Table 1 PROPERTIY OF D8 BAR

Young's modulus	1.74×10^{6} kg/cm²
Yield stress	4,530 kg/cm²
Maximum tensile stress	6,810 kg/cm²

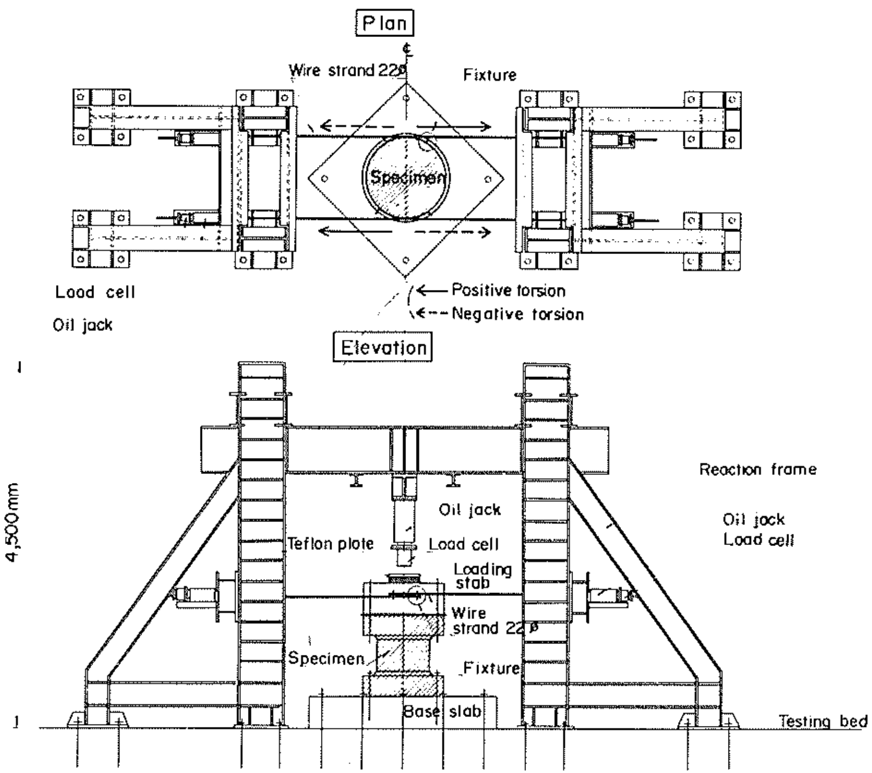

Fig.2 LOADING SYSTEM

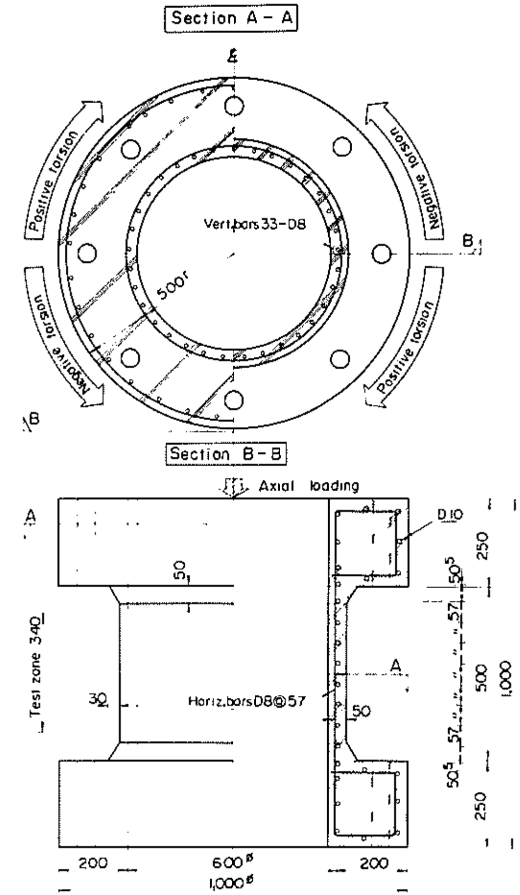

Fig.1 TEST SPECIMEN UNIT : mm
(RATIO OF REINFORCEMENT 1.75%)

Table 2 TEST PARAMETERS AND TEST RESULTS

Specimen ※1	Ratio of reinforcement (%)	※2 Axial stress (kg/cm²)	Compressive strength of concrete ※3 (kg/cm²)	Initial shear cracking		Horiz. bar yielding		Vert. bar yielding		Maximum strength	Failure mode ※5
				Positive torsion ※4	Negative torsion ※4	Positive torsion ※4	Negative torsion ※4	Positive torsion ※4	Negative torsion ※4		
SP-1.0- 0	1.01	0	208	8.8	12.8	39.8	–	43.4	–	46.7	Both rebars yielded
				0.17	0.19	5.76	–	7.09	–	9.78	
SP-1.7- 0	1.75	0	213	11.1	14.2	–	–	–	–	61.9	Concrete crashed
				0.11	0.24	–	–	–	–	6.22	
SP-2.4- 0	2.44	0	250	20.3	14.3	–	–	–	–	62.8	Concrete crashed
				0.35	0.18	–	–	–	–	4.86	
SP-1.0- 50	1.01	50	181	20.7	17.2	49.5	–	–	–	51.5	Horiz. bar yielded
				0.35	0.17	5.40	–	–	–	6.41	
SP-1.7- 50	1.75	50	199	25.0	21.0	–	–	–	–	61.7	Concrete crashed
				0.43	0.25	–	–	–	–	5.48	
SP-2.4- 50	2.44	50	202	29.7	24.6	–	–	–	–	72.3	Concrete crashed
				0.49	0.41	–	–	–	–	5.08	
SP-1.0-100	1.01	100	220	26.8	29.4	–	–	–	–	63.9	Concrete crashed
				0.43	0.32	–	–	–	–	4.73	
SP-1.7-100	1.75	100	233	22.6	19.0	–	–	–	–	69.0	Concrete crashed
				0.22	0.25	–	–	–	–	4.29	
SP-2.4-100	2.44	100	215	36.3	35.7	–	–	–	–	79.5	Concrete crashed
				0.60	0.57	–	–	–	–	4.86	
SP-1.0-(-25)	1.01	-25	265	8.5	9.5	32.7	–	25.0	–	33.8	Both rebars yielded
				0.38	0.30	7.90	–	3.58	–	9.89	
SP-1.7-(-25)	1.75	-25	186	8.8	7.7	–	–	56.0	–	56.5	Vert. bar yielded
				0.19	0.19	–	–	5.73	–	6.78	
SP-2.4-(-25)	2.44	-25	183	10.7	10.8	–	–	–	–	58.8	Concrete crashed
				0.32	0.17	–	–	–	–	5.27	

※1 SP — $\underline{1.0}$ — $\underline{50}$
Ratio of reinforcement — Axial stress

※2 Compression is taken positive.

※3 The experimental results are the average of three measurements.

※4

upper column	shear stress (kg/cm²)
lower column	shear strain ($\times 10^{-3}$ rad)

※5 Yielding of rebars was followed by crashing of concrete.

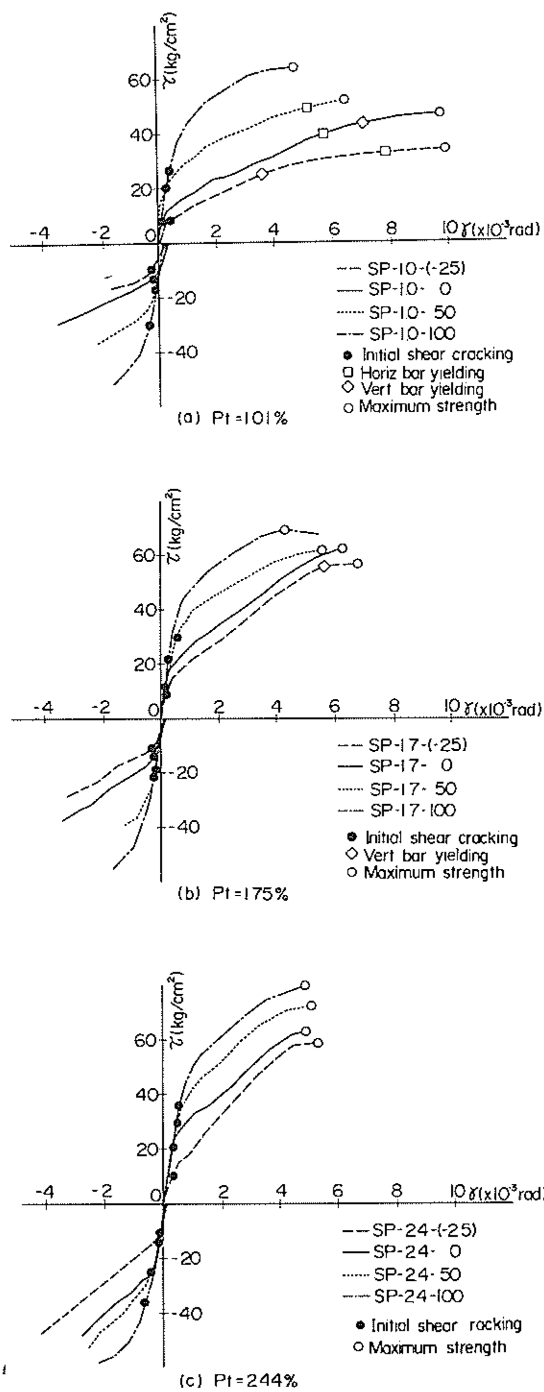

Fig.3 ENVELOPES OF THE LOAD
—DISPLACEMENT RELATIONS

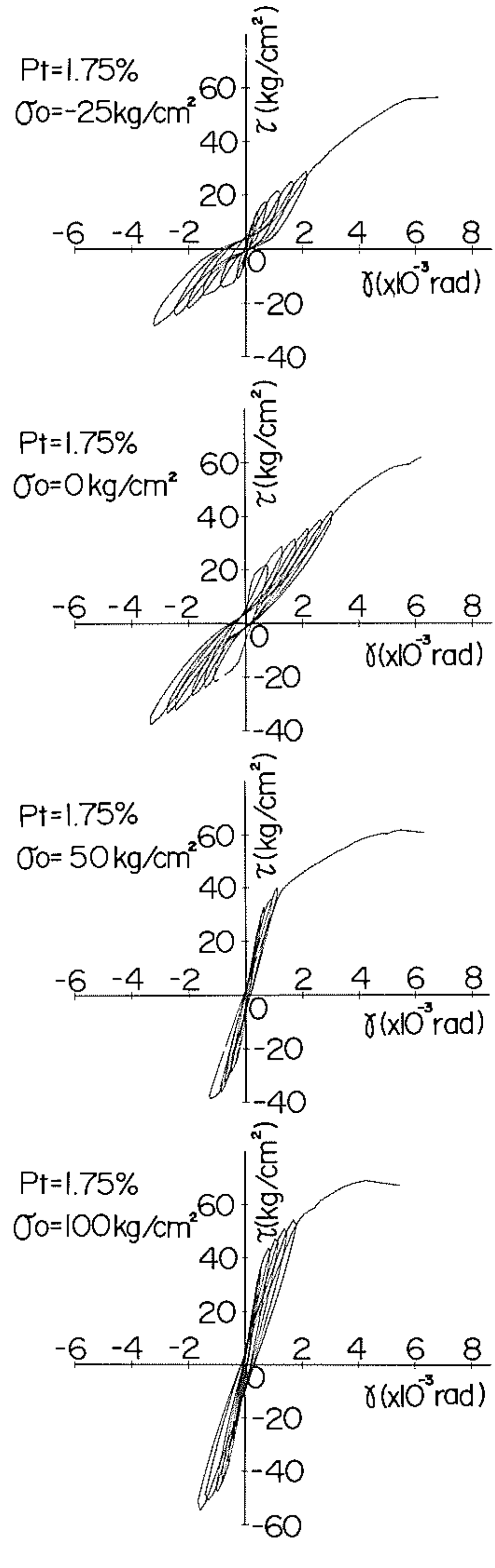

Fig.4 LOAD—DISPLACEMENT RELATIONS

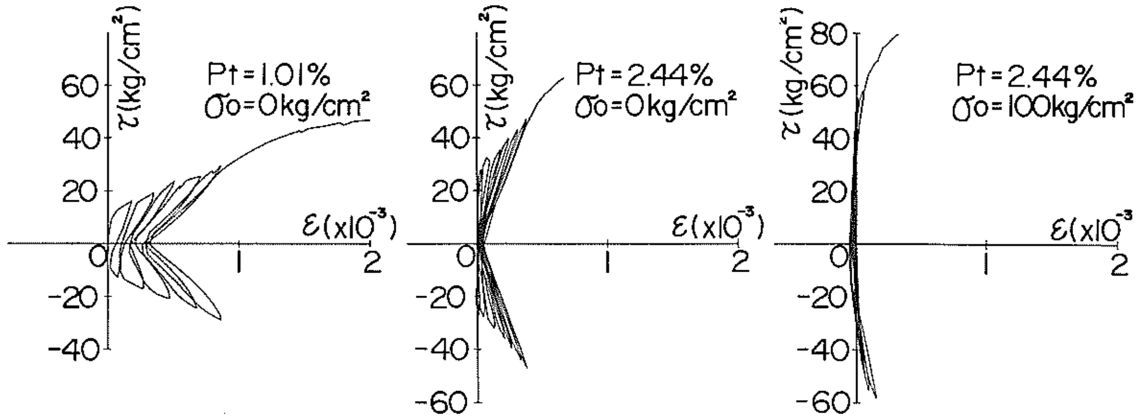

Fig.5 LOAD—AXIAL MEAN DISPLACEMENT RELATIONS

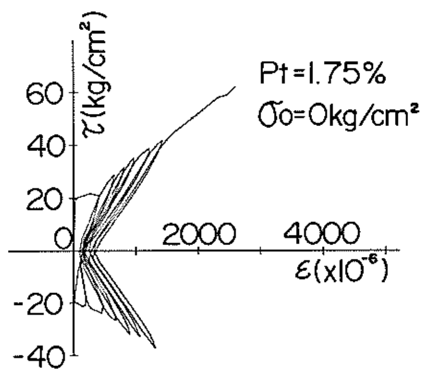

Fig.6 LOAD—STRAIN RELATION OF HOOP

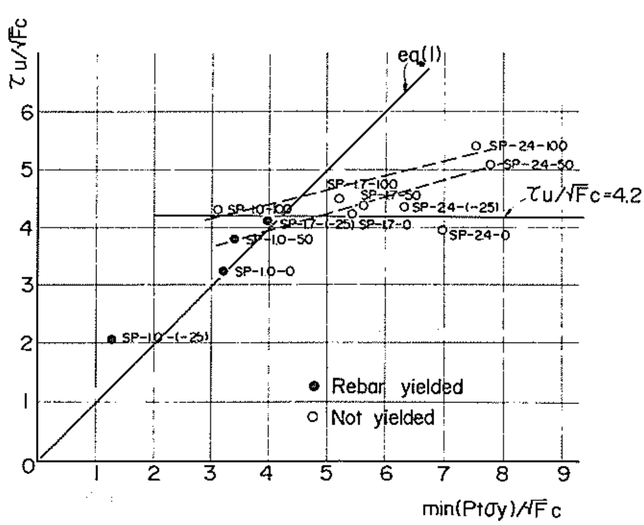

Fig.7 RELATIONSHIPS BETWEEN ULTIMATE SHEAR STRESSES AND EFFECTIVE SHEAR REINFORCEMENT INDICES

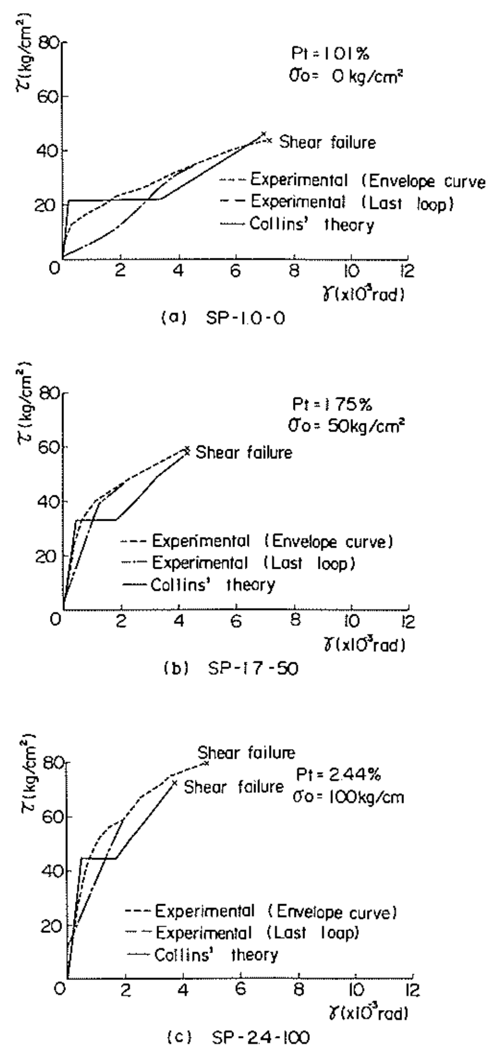

Fig.8 CALCULATED AND EXPERIMENTAL LOAD—DISPLACEMENT RELATIONS