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# A STUDY ON THE SLIP SHEAR FAILURE OF A LAYERED SHEAR WALL FRAME SYSTEM

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## SUMMARY

This paper describes the behaviors of the layered shear wall frame system in slip shear failure. From the experiments of specimens and the analyses using the truss model for specimens, an experimental formula for estimating the slip shear strength of the system is proposed, and a condition under which the slip shear failure occurs is also shown.

## INTRODUCTION

The behaviors of the layered shear wall frame system (hereafter, refered to as the system) failing in shear depend largely on the stiffness and strength of the columns, and the failure modes are classified into the following three : direct shear failure, shear failure determined by the shear failure of the columns and slip shear failure. The former two occur in the case where the columns are insufficiently stiffened and reinforced. In these failure modes the shear failure of the columns precedes the slip failure (crushing failure of concrete with slip off) of the wall, and after the maximum strength the system can not resist the shear force. The failure is then very brittle.

On the other hand, in the case where the columns are sufficiently stiffened and reinforced not to fail in shear, the slip failure of the wall and the flexural yielding at both ends of the columns simultaneously occur. After the maximum strength, the shear resisting capacity drops rapidly, but the system can keep resisting the shear force corresponding to flexural yielding of the frame alone, and resisting the vertical forces acting on the columns. This failure mode is named Slip Shear Failure after the slip failure of the wall. To make the system be ductile it should be designed to have the slip shear strength and be controlled to fail in overall flexure before shear. From this standpoint this paper aims to clarify the slip shear strength of the system and the condition under which the slip shear failure occurs exactly.

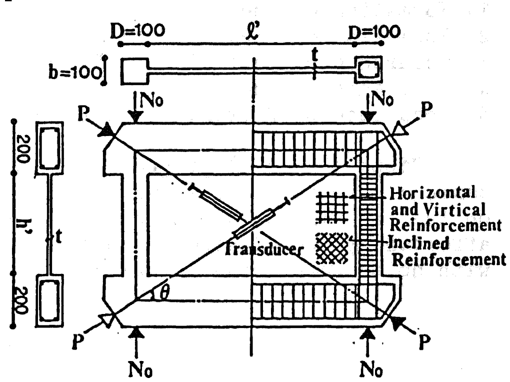
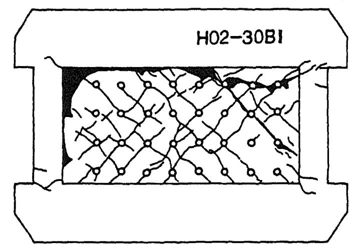



Fig.1 Specimen (unit:mm)

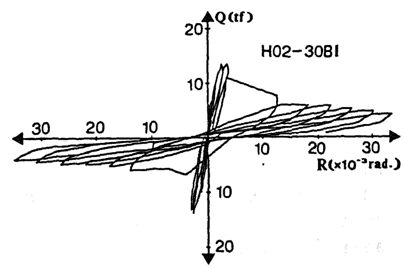
## PROGRAM FOR EXPERIMENT I

Specimen The shape of specimens and the arrangement of reinforcing bars are shown in Fig.1. Taking the preliminary test results into consideration, the columns are designed to have sufficient shear strength not to fail in shear. The beams modeling the layered system are stiffened with large sectional area not to fail in both flexure and shear. The main parameters adopted in experiment I are as follows : the compressive strengths of concrete Fc, the aspect ratios of the wall $\kappa = \ell'/h'$, the shear reinforcement ratios of the wall Ps, the types of shear reinforcement of the wall, the walls with or without holes and the magnitudes of constant axial loads acting on the columns No. The types of shear reinforcement are vertical and horizontal reinforcement, and inclined reinforcement. All data of the parameters are shown in Table 1 with common items.

Loading and Measuring The loading and measuring method in experiment I is also shown in Fig.1. The specimens were manually loaded with 30tf or 50tf Oil Jacks by controlling the applied load to the maximum strength and subsequently the translation angle R of the specimen. Compressive load worked once alternately on the diagonals of the wall with every constant increase of the applied load or the translation angle. The value of R is given by the following formula: $R=(\delta 1+\delta 2)/2h'\cos\theta$, where $\delta 1$ and $\delta 2$ are the elongation and contraction of the diagonal lengths, respectively, and these values are measured at one side of the specimen.




a) Crack pattern




b) Q-R relationship

Fig.2 Crack pattern and Q-R relationship of H02-30B1

## RESULTS OF EXPERIMENT I

Process to Failure Table 1 shows the results of experiment I and Fig.2 shows the crack pattern at failure and the Q-R relationship of specimen H02-30B1. The process to failure of all the specimens took the following steps in sequence ;

1) Formation of inclined mesh of cracks on the wall
2) Formation of flexural and shear cracks at and between both ends of the columns
3) Occurence of partial slip failure of the wall
4) Occurence of whole slip failure of the wall
5) Occurence of flexural yielding at both ends of the columns

Steps 1) and 2) progressed simultaneously, and at step 5) the load reached maximum. Because the shear cracks at step 2) were local, they had little effect on the overall failure mechanism. The behaviors at these steps were not almost affected by the adopted parameters except that the inclined cracks on the wall with holes were large in number.

## SLIP SHEAR STRENGTH

Proposal of the Formula for Estimating the Slip Shear Strength To obtain the formula for estimating the slip shear strength of the system, the following assumptions are introduced ;

Table 1 Results of experiment I

| Code of Specimen | ℓ'×h' | t | λ | Pt | tσy | Pw | wσy | Ps | sσy | No/(Fc·b·D) | Fc | Qmax | Qs | Qmax/Qs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H2-35A | | | | | | 1.07 | 2107 | | | 0.00 | 323 | 12.9 | 15.0 | 0.86 |
| H2-35B | | | | | | 0.37 | 1789 | | | | 285 | 13.9 | 13.4 | 1.04 |
| H2-35C1 | | | | | | 1.07 | | | | | 309 | 21.7 | 16.4 | 1.32 |
| H2-35C2 | | | | | | | 2167 | | | | 471 | 20.0 | 24.1 | 0.83 |
| H2-35D1 | | | | | | 0.30 | | | | 0.15 | 451 | 21.4 | 23.1 | 0.93 |
| H2-35D2 | | | | | | | | | | | 488 | 23.4 | 24.9 | 0.94 |
| H2-35E1 | 80×40 | 1.5 | 1.67 | 0.55 | 3746 | 0.37 | 1789 | 0.59 | 1921 | | 476 | 21.4 | 24.3 | 0.88 |
| H2-35E2 | θ= | | | (2-6φ) | | | | (2.0φ@35) | | | 480 | 26.5 | 24.5 | 1.08 |
| H2-35F1 | 33.69° | | | | | 1.00 | | | | | 416 | 24.1 | 22.2 | 1.09 |
| H2-35F2 | | | | | | | | | | | 446 | 24.1 | 23.7 | 1.02 |
| H2-35G1 | | | | | | 1.07 | 2167 | | | 0.20 | 428 | 21.7 | 22.8 | 0.95 |
| H2-35G2 | | | | | | | | | | | 449 | 25.8 | 23.8 | 1.08 |
| H2-35H1 | | | | | | 0.80 | | | | | 446 | 27.0 | 23.7 | 1.14 |
| H2-35H2 | | | | | | | | | | | 435 | 25.0 | 23.1 | 1.08 |
| H2-30-1 | | | | | | | | 0.71 | | | 422 | 25.0 | 23.2 | 1.08 |
| H2-30-2 | | | | | | | | (2.0φ@30) | | | 420 | 25.0 | 23.1 | 1.08 |
| X2-20-1 | | | | | | | | 1.06 | | | 450 | 25.2 | 25.2 | 1.00 |
| X2-20-2 | 80×40 | 1.5 | 1.67 | 0.50 | 4637 | 0.8 | 2458 | (2.0φ@20) | 2314 | 0.20 | 483 | 26.6 | 26.8 | 0.99 |
| X2-30-1 | θ= | | | (2-6φ) | | | | | | | 487 | 27.5 | 26.4 | 1.04 |
| X2-30-2 | 33.69° | | | | | | | 0.71 | | | 482 | 24.9 | 26.1 | 0.95 |
| H02-30-1 | | | | | | | | (2.0φ@30) | | | 447 | 22.5 | 24.4 | 0.92 |
| H02-30-2 | | | | | | | | | | | 475 | 23.7 | 25.8 | 0.92 |
| H02-30B1 | | | | | | 0.4 | 2458 | | | 0.20 | 277 | 13.3 | 16.2 | 0.82 |
| H02-30B2 | | | | | | | | | | | 292 | 15.2 | 16.9 | 0.90 |
| ※H02-30-3 | | | | | | | | | | 0.30 | 271 | 16.5 | 16.3 | 1.01 |
| H02-30-4 | | | | | | | | 0.71 | | | 320 | 15.9 | 18.9 | 0.84 |
| X2-30-3 | | | | | | | | (2.0φ@30) | | | 303 | 18.4 | 17.5 | 1.05 |
| ※H2-30-4 | | | | | | | | | | | 323 | 18.3 | 18.4 | 0.99 |
| X02-30B1 | 80×40 | 1.5 | 1.67 | 0.50 | 5419 | 0.8 | 2304 | | 2013 | 0.20 | 314 | 15.0 | 18.0 | 0.83 |
| ※X02-30B2 | θ= | | | (2-6φ) | | | | | | | 260 | 15.1 | 15.3 | 0.99 |
| ※X02-30-1 | 33.69° | | | | | | | | | 0.30 | 296 | 16.9 | 17.6 | 0.96 |
| X02-30-2 | | | | | | | | | | | 247 | 18.3 | 15.0 | 1.22 |
| WX2-30-1 | | | | | | | | 1.08 | | | 328 | 19.3 | 19.3 | 1.00 |
| WX2-30-2 | | | | | | | | (2.0φ@30 | | 0.20 | 326 | 19.5 | 19.2 | 1.02 |
| ※WX02-301 | | | | | | | | +6-3.2φ) | | | 330 | 18.2 | 19.4 | 0.94 |
| WX02-302 | | | | | | | | | | | 286 | 17.6 | 17.2 | 1.02 |
| ※H2-30-5 | 50×50 | | | 0.47 | | | | 0.71 | | | 220 | 9.1 | 9.0 | 1.01 |
| H2-30-6 | θ=45° | 1.5 | 1.33 | (2-6φ) | 3746 | 0.32 | 2251 | (2.0φ@30) | 2193 | 0.20 | 386 | 17.4 | 14.9 | 1.17 |
| ※H2-30-7 | | | | | | | | | | | 400 | 17.0 | 15.4 | 1.10 |
| H2.8-40-1 | 80×50 θ=32° | | 1.00 | 0.48 | | 0.78 | | 0.68 | | 0.20 | 262 | 14.3 | 17.2 | 0.83 |
| H2.8-40-2 | 50×50 | 2.0 | | (2-6φ) | 4390 | 0.80 | 3472 | (2.8φ@40) | 1780 | 0.15 | 280 | 14.1 | 13.5 | 1.05 |
| H2.8-40-3 | θ=45° | | | | | | | | | | 280 | 12.6 | 13.5 | 0.94 |

Common items and Symbols

| | |
|---|---|
| b×D(cm×cm) | : 10×10 |
| H in code | : Horizontal and vertical reinforcement |
| X and WX in code | : Inclined reinforcement |
| O in code | : Wall with holes of which diameter is 20(mm) and spacing is 75 or 90(mm) |
| ℓ'×h'(cm×cm) | : Width×hight of wall |
| t(cm) | : Thickness of wall |
| λ | : b·D/(t·h') |
| Pt(%) and tσy(kgf/cm²) | : Longitudinal reinforcement ratio of column and yield strength of bars |
| Pw(%) and wσy(kgf/cm²) | : Shear reinforcement ratio of column and yield strength of bars |
| Ps(%) and sσy(kgf/cm²) | : Shear reinforcement ratio of wall and yield strength of bars |
| No(kgf/cm²) | : Constant axial load on column |
| Fc(kgf/cm²) | : Compressive strength of concrete cylinder |
| Qmax(tf) | : Observed slip shear strength at failure side |
| Qs(tf) | : Calculated slip shear strength by Eq.(5) |
| ※ | : Specimen used in Fig.5 |

1) Stresses of concrete of the wall is uniformly distributed.
2) All reinforcing bars of the wall yield.
3) Columns yield flexurally at both ends, but they do not yield axially.
4) Applied shear load is resisted by the wall and the two columns.

These assumptions are based on the observation of the failure process of all the specimens, but assumptions 1), 2) and 3) are not ascertained experimentally for lack of strain measuring of reinforcing bars and concrete. From these assumptions the slip shear strength Qs may be expressed as follows :

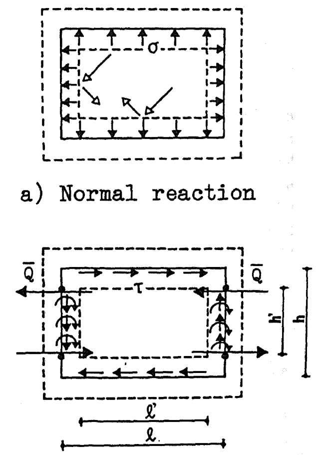
$$Qs = Qw + 2 \cdot cQy \qquad (2)$$

where Qw is the shear strength of the wall and 2•cQy is the shear strength of the two columns when both ends yield flexurally. And from these assumptions, again, Qw and cQy may be experessed by Eqs.(3a) and (3b), respectively.

$$Qw = ( c\tau w + 0.5\ Ps \cdot s\sigma y ) t \cdot \ell' \qquad (3a)$$

$$cQy = \frac{My + My'}{h'} + \bar{Q} \qquad (3b)$$

where cτw is the slip shear strength of concrete, My and My' are the flexural yield strengths at upper and lower ends of the columns and $\bar{Q}$ is the additional shear force due to the gap between the axis of the column and the vertical side of the wall. My and My' are estimated by the ultimate strength formula for column and $\bar{Q}$ is expressed as $\tau \cdot t(\ell - \ell')/2$ in Figs.3(a) and 3(b).



a) Normal reaction

b) Tangential reaction

Fig.3 Reactions of wall

The procedure for derivation of the formula takes the following steps ;

1) Initial value of Qw is set to Qmax by putting 2•cQy = 0.
2) First term in the bracket of Eq.(3a) is divided into two terms as follows:

$$c\tau w = aFc + b \qquad (4)$$

   where, a and b are constant values which are determined by the method of least squares using Qw at step 1).
3) Reactions of the wall are estimated by using Eq.(3a) with cτw at step 2), and then the axial forces of the columns due to the reactions of the wall and the applied loads are calculated.
4) My and My' are estimated by using the axial forces at step 3), and then cQy is obtained by Eq.(3b).
5) Again step 1) through step 4) is repeated by using cQy at step 4).

The procedure is executed for forty two specimens in slip shear failure until the value of Qs becomes constant, and hence the formula for estimating the slip shear strength of the system is obtained as follows ;

$$Qs = ( 0.314Fc + 0.5Ps \cdot s\sigma y - 8.2 ) t \cdot \ell' + 2 \cdot cQy \qquad (5)$$

Fig.4 shows the comparison between the observed slip shear strength and the calculated one by Eq.(5). In this figure, the points other than black are plotted for other specimens which are subjected to different loadings and are in slip shear failure [1],[2]. Fig.5 shows the comparison between the observed slip shear strength and the anayltical one using the truss model (later mentioned). From these figures, it is concluded that Eq.(5) and the truss model are adequate for estimating the slip shear strength of the system subjected to different loadings.

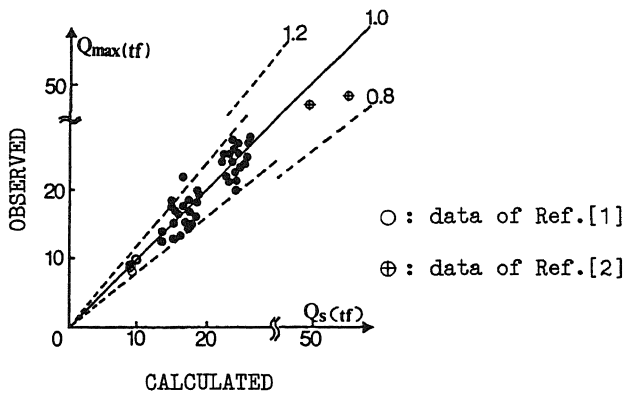



Fig.4 Comparison between Qmax and Qs

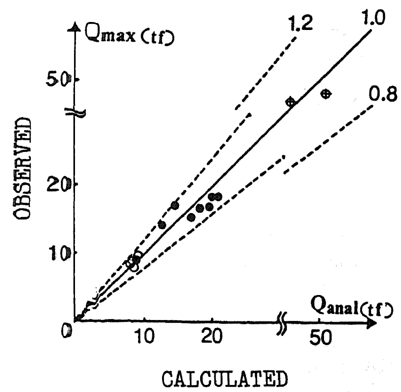



Fig.5 Comparison between Qmax and Qanal

## CONDITION ON SLIP SHEAR FAILURE

The slip shear failure only occurs in the case where the columns do not fail in shear. When the shear failure of the columns precedes the other failure modes occur, and hence Eq.(5) may not be used. The condition under which the slip shear failure develops without the shear failure of the columns is, here, examined experimentally and analytically.

Experiment II The shape of specimens, the arrangement of reinforcing bars, and the loading and measuring method in experiment II are similar to those in experiment I. The ratios of sectional area of the column to vertical ones of the wall $\lambda = b \cdot D/(t \cdot h')$ are adopted as parameters. Table 2 shows all data of the specimens and the experimental results. The specimens failed either in shear of the columns or both in shear of the columns and in slip failure of the wall.

Analysis Elasto-plastic analyses of the specimens taking the shear failure of the columns into consideration are executed by using the truss model. The properties of each member are assumed as follows ;

1) Tension and compression braces have perfectly elasto-plastic properties. The yield strength of the tension braces is taken as $s\sigma y$, and the horizontal stress of the compression braces at yielding is taken as the bracket term of Eq.(5).
2) Properties of beams are elastic in flexure, compression and tension, but the beams do not fail.
3) Properties of columns are perfectly elasto-plastic in combination with both compression or tension and flexure, but the columns do not yield axially.

Table 2 Results of experiment II

| Code of Specimen | b×D (cm×cm) | at (cm²) | tσy (kgf/cm²) | te (cm) | Fc (kgf/cm²) | λe (=bD/teh') | Qmax (tf) | Qs (tf) |
|---|---|---|---|---|---|---|---|---|
| 86SWI-2-1 | 10.0× 5.0 | 0.49 | 3458 | 2.90 | 230 | 0.43 | 16.14 ※1 | 18.97 |
| 86SWI-2-2 | 10.0× 5.0 | | | 2.75 | 226 | 0.45 | 14.64 ※1 | 17.63 |
| 86SWI-3-1 | 10.0× 7.5 | (2-6φ) | Et | 2.83 | 278 | 0.66 | 17.64 ※1 | 22.81 |
| 86SWI-3-2 | 10.0× 7.5 | | =2.07×10⁶ | 2.85 | 275 | 0.66 | 17.64 ※1 | 22.72 |
| 86SWI-5-1 | 10.0×10.0 | 1.67 | 3320 | 2.79 | 245 | 0.90 | 21.55 ※1 | 22.61 |
| 86SWI-5-2 | 10.0×10.0 | | Et | 2.47 | 295 | 1.01 | 22.72 ※2 | 23.86 |
| 86SWI-6-1 | 10.0×12.5 | (2-D10) | =1.79×10⁶ | 2.51 | 312 | 1.25 | 24.21 ※2 | 26.71 |

Common items and Symbols
$l \times h' = 90 \times 40$ (cm×cm)
$P_w = 0.80\%$ (3.2φ@20)
$w\sigma y = 1836$ (kgf/cm²)
$E_w = 1.65 (\times 10^6$ kgf/cm²)
$P_s = 0.62 \sim 0.72\%$ (2.6φ@30)
$s\sigma y = 1614$ (kgf/cm²)
$E_s = 1.93 (\times 10^6$ kgf/cm²)
te:Observed thickness of wall
※1: Shear failure of column
※2: Shear failure of column and slip failure of wall

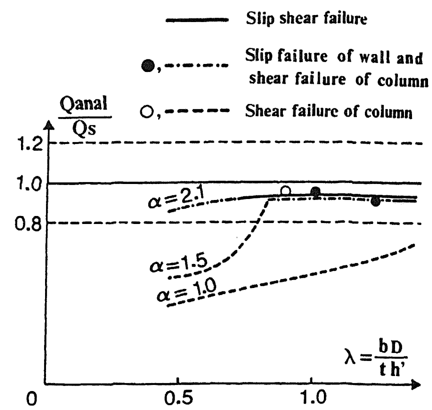
Flexural yield strength is estimated by the ultimate strength formula for column. Shear strength is estimated by the following formula:

$$Qu = \{\ \alpha \cdot Ku \cdot Kp \cdot (180+Fc) \cdot \frac{0.12}{M/(Q \cdot d)+0.12} + 2.7\sqrt{Pw \cdot w\sigma y} + 0.1 \cdot \sigma o\ \} b \cdot j \qquad (6)$$

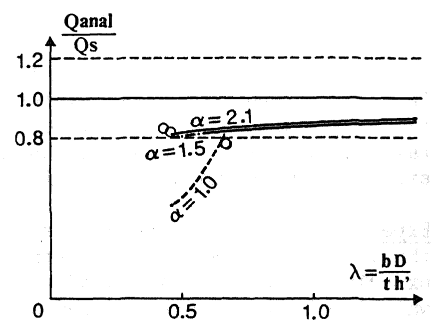
where the factor $\alpha$ takes a value between 1.0 and 2.1 which correspond to upper and lower bounds of Eq.(6), respectively.

Except for the case where the flexural yielding of the columns between both ends is allowed, these assumptions are equivalent to those adopted in the derivation of Eq.(5). Analyses are executed for two cases of Fc=300 $kgf/cm^2$, at=1.67 $cm^2$ and Pw=0.80 % , and Fc=250 $kgf/cm^2$, at=0.49 $cm^2$ and Pw=0.80 %. These values closely correspond to those of the test specimens. In each case, the parameter $\lambda$ is discretely varied, and the factor $\alpha$ is taken as 1.0, 1.5 and 2.1.

Condition on Slip Shear Failure Figs.6(a) and 6(b) show the relationship between Qanal/Qs and $\lambda$ for the above two cases, where Qanal is the analytical shear strength. The experimental results are also plotted in these figures. The analytical results are close to the experimental ones for $\alpha$ = 1.5. The difference between Qs and Qanal in the slip shear failure zone is based on the ground that in the truss model the flexural yielding between both ends of the columns is allowed. From these figures and values of $\lambda$ in Table 1, it is concluded that the condition, under which the slip shear failure occurs exactly, is $\lambda \geqq 1.33$ on the safe side.




(a) Fc=300kgf/$cm^2$,at=1.67$cm^2$ and Pw=0.80%




(b) Fc=250kgf/$cm^2$,at=0.49$cm^2$ and Pw=0.80%

Fig.6 Relationship between Qanal/Qs and $\lambda$=bD/th'

## CONCLUSIONS

The conclusions of this paper are summarized as follows;

1) Eq.(5) is adequate for estimating the slip shear strength of the system.
2) The condition, under which the slip shear failure of the system occurs without the shear failure of the columns, is $\lambda \geqq 1.33$ for diagonal compression loading.

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[2] Tokuhiro, I., Mitani, I. and Miyazaki, H., "Experimental Studies on Fracture Patterns and Ultimate Strength of Shear Walls with Various Boundary Frame", Journal of Structural and Construction Engineering (Transactions of AIJ), 355, 88-98, (1985).