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

Simplified formula for estimating maximum strength of multistory framed shear walls and discriminant of their failure modes

M. Mochizuki
Kogakuin University, Tokyo, Japan

N. Onozato
ORS Office, Tokyo, Japan

ABSTRACT: The simplified model and formula for estimating the maximum strength of the multistory framed shear walls are proposed, and the discriminant on their failure modes is also proposed. The validity of the simplified formula and the discriminant are ascertained by a supplementary experiment.

1. OBJECT

In the previous paper (Mochizuki and Onozato 1990) the authors proposed the macro model for estimating the maximum strength of the multistory framed shear walls (hereafter, referred to the shear walls). The analytical results using this model agree well with the observed results in experiment. However the analytical procedure needs many iterative calculations, and is not adequate as the practical design formula of the shear walls.

The objectives of this paper are firstly to propose the simplified formula without iterative calculation for the maximum strength of the shear walls and the discriminant of their failure modes, and secondly to ascertain the validity of the simplified formula and the discriminant by a supplementary experiment.

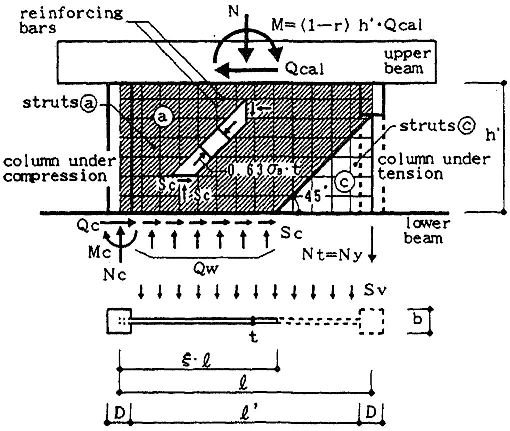


Fig.1 Simplified model

2. SIMPLIFIED MODEL

The simplified formula is derived from the simplified model of the shear walls. Fig.1 shows the simplified model for exhibiting the resisting mechanism at the maximum strength. This model consists of upper and lower beams having large sectional area to simulate the multistory shear wall, two columns with shear resisting capacity, compressive struts ⓐ and ⓒ with same inclination angle of 45 deg., and vertical and horizontal reinforcing bars.

These members in the model are assumed to have the following properties.

1) Both beams are rigid, and do not fail.
2) Column under compression is under flexural yielding at the bottom end. Column under tension is under tensile yielding at the bottom end, and the shearing force at the bottom end is ignored.
3) Struts ⓐ are under yielding, and their yield strength is taken as $0.63\sigma_B$. Struts ⓒ are ignored because the restraint force to the struts ⓒ disappears due to the extension of horizontal crack along the lower beam.
4) All vertical and horizontal reinforcing bars are under yielding.

In 3), the value of $0.63\sigma_B$ is the effective compressive strength of concrete which was proposed by the authors (Mochizuki et al. 1990)

3. SIMPLIFIED FORMULA FOR MAXIMUM STRENGTH

The following equations hold between the external forces and assumed stresses acting on the simplified model shown in Fig.1.

$$Q_{cal} = Q_w + Q_c, \quad Q_w = S_c \cdot \xi \cdot \ell \qquad (1),(2)$$

The equilibrium of moment at the bottom end of the column under compression is expressed including ξ as follows;

$$Mc+M+N\cdot\ell/2-Q_{cal}\cdot h'+Ny\cdot\ell-\frac{Sc\cdot\ell\cdot(\xi\cdot\ell)^2}{2}+Sv\cdot\ell^2/2=0 \quad (3)$$

From consideration on the stress distribution in the neighbor of the bottom end of the column under compression, in which the column is assumed as a cantilever column subjected to uniform load, the shearing force Qc is expressed as follows;

$$Qc=\sqrt{2Mc\cdot St} \quad (4)$$

Mc and Qc are approximated by the following Eqs.(5) and (6),respectively.

$$Mc=Ny\cdot D/2,\ Qc=\sqrt{2Mc\cdot St}=\sqrt{Ny\cdot D\cdot St} \quad (5),(6)$$

Substituting Eqs.(1),(2),(5) and (6) to Eq.(3), and then the following equation on ξ is obtained.

$$\frac{\xi^2}{2}+\eta\cdot\xi-\left\{\frac{Sv}{2Sc}-\frac{\eta\sqrt{Ny\cdot D\cdot St}-N/2-Ny(D/2\ell+1)}{Sc\cdot\ell}\right\}=0 \quad (7)$$

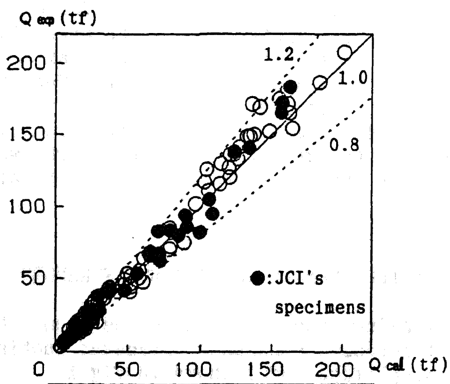
where $\eta=h'\cdot r/\ell$. Solving the above equation, ξ is expressed as follows;

$$\xi=-\eta+\sqrt{\eta^2+\frac{Sv}{Sc}-2\frac{\eta\sqrt{Ny\cdot D\cdot St}-N/2-Ny(D/2\ell+1)}{Sc\cdot\ell}} \quad (8)$$

Where, in the case of $\xi>1.0$ the value of ξ is regarded as 1.0. This is based on the fact that for putting Nt=Ny the stress of the struts must be distributed on the large width corresponding to $\xi>1.0$ to satisfy the equilibrium of moment, but if Nt<Ny the value of ξ does not exceed one.

The equilibrium of moment at the bottom end of the column under tension is expressed including Nc as follows;

$$Mc+M-N\cdot\ell/2-Q_{cal}\cdot h'+Nc\cdot\ell +Sc\cdot\xi\cdot\ell(1-\xi/2)\ell-Sv\cdot\ell^2/2=0 \quad (9)$$



Mean	:1.036
Standard deviation	:0.132
Coefficient of variation	:0.128

Fig.2 Relationship between Q_{exp} and Q_{cal}

From consideration on Eqs.(1),(2),(5) and (6) Nc is expressed as follows;

$$Nc=\eta\sqrt{Ny\cdot D\cdot St}+(\eta+\xi/2-1)Qw+Sv\cdot\ell/2+N/2-Ny\cdot D/2\ell \quad (10)$$

Using Nc in Eq.(10), Mc is calculated from the yield strength formula of column, that is,

$$Mc=Mu(Nc) \quad (11)$$

Then, from Eq.(4) using Eq.(11) the second approximate value of Qc is obtained as follows;

$$Mc=\sqrt{Mu(Nc)\cdot St} \quad (12)$$

Finally,the maximum shear strength Q_{cal} of Eq.(1) is calculated as the summation of Eq.(2) and Eq.(12) without iterative calculation.

4. ANALYTICAL RESULTS

The analyses using the simplified formula were executed for the authors' one hundred and fourteen specimens, the JCI's thirty specimens and the other researchers' sixty specimens. The JCI's specimens are selected by the JCI's committee for verification of the macro model of the shear walls.

Fig.2 shows the relationship between Q_{exp} and Q_{cal} for all the specimens. Figs.3 and 4 show the relationships between Q_{exp}/Q_{cal} and the parameters σ_B and Pg, respectively. Figs.2～4 show that the simplified model and formula are valid.

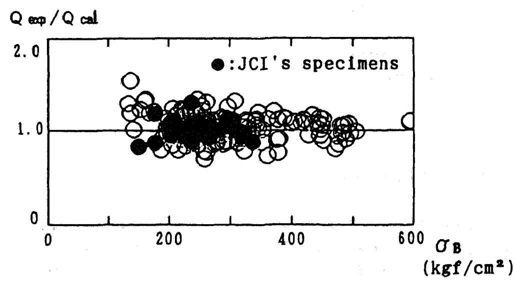


Fig.3 Relationship between Q_{exp}/Q_{cal} and σ_B

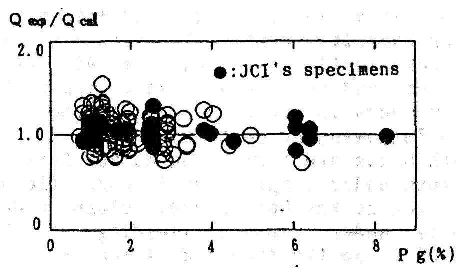
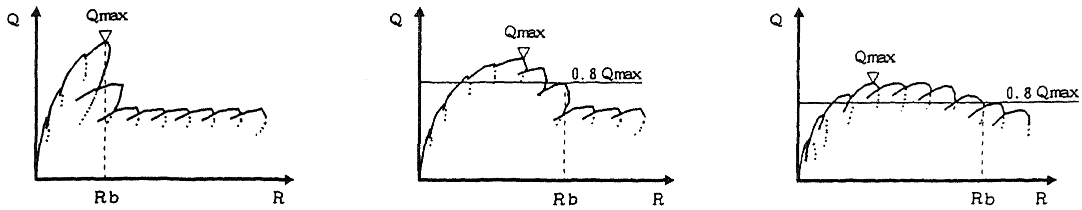


Fig.4 Relationship between Q_{exp}/Q_{cal} and Pg



(a) Shear (b) Flexural-shear (c) Flexural

Fig.5 Failure modes

5. DISCRIMINANT OF FAILURE MODES

The authors define the failure modes of the shear walls as follows;

1) Shear failure mode

$$Nt/Ny<1.0,\ R_b \fallingdotseq 5.0\times 10^{-3}\text{rad.}$$

2) Flexural-shear failure mode

$$Nt/Ny=1.0,\ R_b \geqq 5.0\times 10^{-3}\text{rad.} \qquad (13)$$

3) Flexural failure mode

$$Nt/Ny=1.0,\ R_b \geqq 10.0\times 10^{-3}\text{rad.}$$

Fig.5 shows the typical patterns of the failure modes. The above definitions are based on the following facts; the shear failure mode occurs when the column under tension is not under tensile yielding and its behavior is brittle, and the flexural-shear or the flexural failure mode occurs when the column under tension is under tensile yielding and their behaviors are both ductile. In the simplified model of Fig.1 the column under tension is under tensile yielding when the value of ξ in Eq.(8) is smaller than 1.0. But the tensile yielding of the column dose not necessarily occur in the case that the value of ξ is smaller than 1.0 when the flexural yield strength of the column is small.

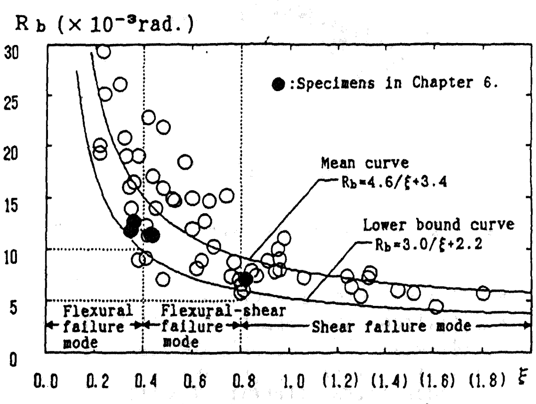


Fig.6 Relationship between R_b and ξ

Fig.6 shows the relationship between the values of R_b and ξ. The number of specimens in the figure are fifty six, of which the Q-R relationships are mentioned in detail, among two hundred and four specimens used in the analysis.

From consideration of the definition on the failure modes and Fig.6, the discriminant of the failure modes is proposed as follows;

1) Shear failure mode

$$0.8< \xi \leqq 1.0$$

2) Flexural-shear failure mode

$$0.4< \xi \leqq 0.8 \qquad (14)$$

3) Flexural failure mode

$$\xi \leqq 0.4$$

6. VERIFICATION BY EXPERIMENT

Here, a supplementary experiment is shown for verification of the simplified formula and the discriminant. Fig.7 shows the dimension, bar reinforcement,and loading method of the specimens. The specimens have upper and lower beams, which are sufficiently reinfoced and stiffened to simulate the multistory shear wall, and two columns reinforced not to fail in shear. The specimens are subjected to alternately reversible horizontal forces acting on the upper beam by an actuator.

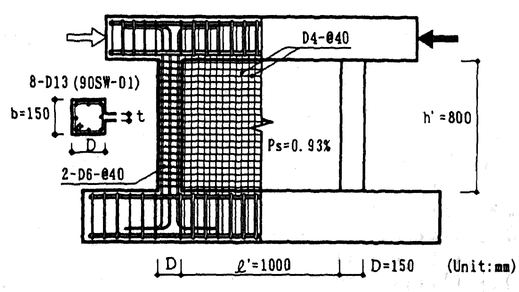


Fig.7 Specimen

Table 1 Properties and experimental results of specimens

Code of Specimen	t (cm)	P_g (%)	$_g\sigma_y$ (kgf/cm²)	P_s (%)	$_s\sigma_y$ (kgf/cm²)	σ_B (kgf/cm²)	Q_{exp} (tf)	Q_{cal} (tf)	Q_{exp}/Q_{cal}	R_b ($\times 10^{-3}$rad.)	ξ	Failure mode (observed)
90SW-01	3.1	4.62	3614	1.00	3050	320.9	36.2	41.4	0.88	7.1	0.82	Shear
90SW-03	3.1	2.31	3606	0.99	3050	293.2	20.3	19.1	1.07	11.4	0.36	Flexural
90SW-04	3.3	2.31	3606	0.95	3050	293.2	19.5	19.2	0.99	13.1	0.35	Flexural
90SW-05	3.4	1.37	3614	0.92	3050	335.9	26.9	27.7	0.97	12.0	0.43	Flexural-shear
90SW-06	3.4	1.37	3614	0.93	3050	335.9	26.2	27.6	0.95	11.4	0.44	Flexural-shear

t :Thickness of wall (measured)
P_g :Gross longitudinal reinforcement ratio of column
P_s :Shear reinforcement ratio of wall
$_g\sigma_y$:Yield strength of longitudinal bar of column
$_s\sigma_y$:Yield strength of reinforcing bar of wall

Table.1 shows the properties of the specimens, the observed maximum strength, and the value of ξ. Fig.8 show the Q-R relationships for specimens 90SW-01, 90SW-06, and 90SW-04. These observed results in the experiment agree well with the calculated results by the simplified formula and the failure modes predicted by the discriminant.

7. CONCLUSIONS

The conclusions of this paper are summarized as follows;

1) The simplified formula for estimating the maximum strength of the shear walls is adequate.
2) The discriminant of the failure modes of the shear walls is also adequate.

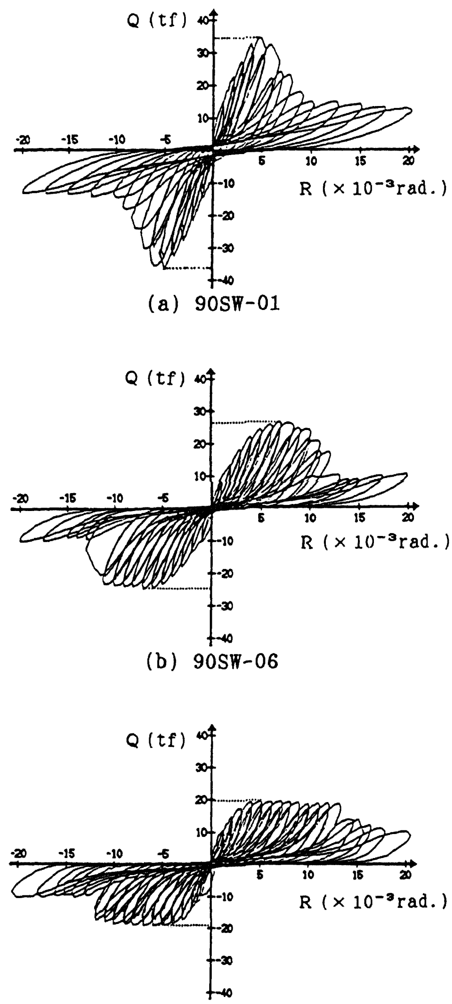
8. REFERENCES

Mochizuki,M. and Onozato,N.1990.Macro model of multistory framed shear walls and its analytical method. Concrete research and technology.J.C.I.Vol.1.No.1:121～132.

Mochizuki,M. Takehara,M and Onozato,N.1990. Slip shear strength of shear walls surrounded with reinforced and stiffened frame.Journal of structural and construction engineering. A.I.J.NO.416:79～89.

9. NOTATIONS

M :Moment acting on shear wall
M_c:Flexural yielding strength of column under compression
M_u:Flexural yield strength of column
N :Vertical force acting on shear wall
N_c:Axial force at bottom end of column under compression
N_t:Axial force at bottom end of column under tension
N_y:Tensile yield strength of column
Q_{cal}:Calculated maximum shear strength of shear wall
Q_w :Shearing force of struts ⓐ
Q_c :Shearing force of column under compression
Q_{exp}:Observed maximum shear strength of shear wall
γ :Inflection point height ratio of bending moment



(a) 90SW-01

(b) 90SW-06

(c) 90SW-04

Fig.8 Q − R relationships of specimens

R :Story angle of shear wall
R_b:Maximum story angle defined in Fig.5
$S_c=0.63\cdot\sigma_B\cdot t/2$　　$S_v=P_s\cdot{}_s\sigma_y\cdot t$
$S_h=\min\{S_c, S_v\}$　　$S_t=S_c-S_h$
σ_B:Compressive strength of concrete
$\xi\cdot\ell$:Effective horizontal width of struts ⓐ