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SHEAR STRENGTH OF REINFORCED MASONRY WALLS

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SUMMARY

This paper is intended to present available formulas to predict the shear strength of reinforced masonry walls subjected to in-plane shear loads and axial loads, on the basis of the result of testing about 60 concrete masonry walls and 30 brick masonry walls carried out by the author. In some cases, a few test results by other researchers are referred to. The effects of masonry prism strength, shear reinforcement ratio and shear-span ratio are discussed. Influence of the difference of grouting, i.e., of partially grouting and fully grouting, is also discussed.

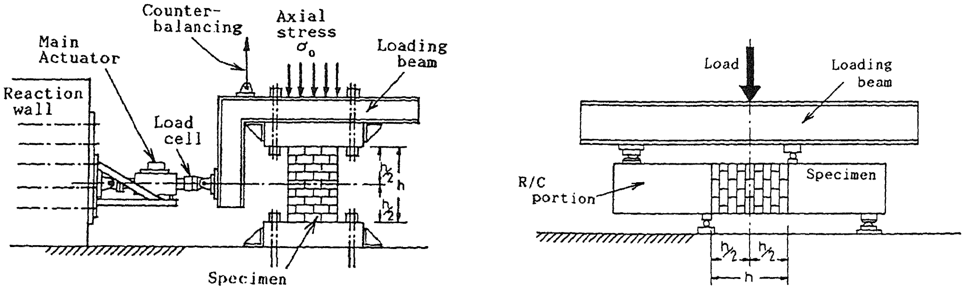
INTRODUCTION

Reinforced masonry structures are composed of masonry shear walls, made of units such as hollow concrete blocks or clay bricks and with steel reinforcement. The author intends to clarify the shear strength and behavior of reinforced masonry walls subjected to in-plane loads by tests (Ref. 1), and to investigate the resistibility of reinforced masonry structures against earthquakes. In the paper formulas are presented for predicting ultimate shear and crack shear strengths of reinforced masonry walls affected with various parameters.

OUTLINE OF TESTING

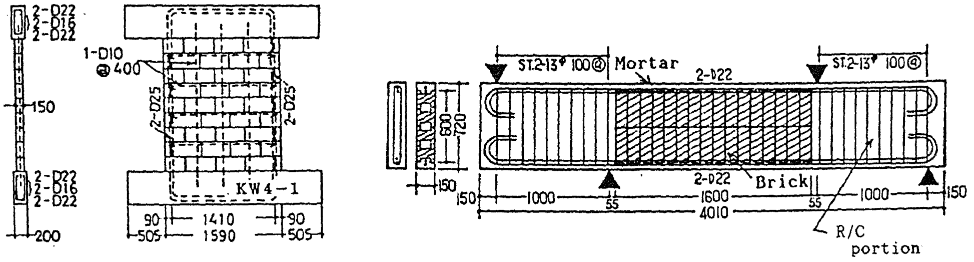
Loading method Two kinds of loading method were used (Fig. 1). In one mothod, walls were subjected to horizontal shear loads with their bases fixed and the tops free to move horizontally only. In the other method, walls were laid horizontally and subjected to vertical shear loads like the loading in restrained deep beam tests. The former method is called "wall type", and the latter "beam type", in the paper. The latter was used generally for small specimens as supplemenary tests. In both loadings, specimens were so loaded as to produce inflection points at the middle of wall height. Most specimens were usually subjected to 4-5 cycles repeating loads before they failed entirely, being added with axial loads of constant value during shear loading.

Specimens Wall specimens are made of hollow concrete block or clay brick units, shown in Fig.3. Specimens for "wall type" loading are full-sized walls with R/C beams at their tops and feet, for the convenience of fixing them to loading apparatus. Most of them are 160 - 180 cm high, 80 - 200 cm wide, and 15 - 19 cm thick in masory portion. The specimens for "beam type" loading are rather small



(a) Wall type loading (b) Beam type loading

Fig. 1 Outline of Loading Systems



(a) Specimen for wall type loading (b) Specimen for beam type loading

Fig. 2 Examples of Specimens

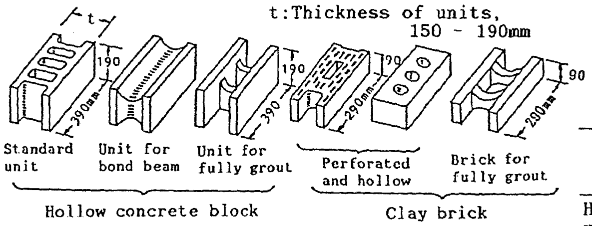


Fig. 3 Shapes and Sizes of Masonry Units

Table 1. Strength of Main Materials

Material	Compressive Strength (MPa) (Gross)	Compressive Strength (MPa) (Net)
Hollow concrete block	10 - 18	23 - 43
Hollow clay brick	23 - 73	46 - 124
Grout (concrete)	22 - 24	
Masonry prism (block)	8 - 31	
Masonry prism (brick)	16 - 40	

ones, having extended R/C wall portions up- and downward, so as to form deep beams when they are laid horizontally. About one-third of specimens are fully grouted. Examples of shapes of specimens are shown in Fig. 2. The strength of main materials are indicated in Table 1.

Test Result Most specimens were failed by shear, accompanied by X-shaped shear cracks and crush of compressive corners of walls. Flexural reinforcing bars were not yielded until the failures in most cases. In this paper, stresses are expressed in gross cross-sectional area even they were partially grouted masonry. Shear stresses are expressed as $\tau = V/Ag$ or $\tau = V/t \cdot j$; where V=shear load, Ag= horizontal gross cross area of wall, t=thickness of wall, $j=(7/8)d$, d=effective width of wall, i.e. distance from extreme compression fiber to centroid of edge tension bars. Test result ranges as follows;

Concrete masonry; for partially grouted τ_u= 0.3 - 1.2 MPa
; for fully grouted τ_u= 1.6 - 2.9 MPa
Brick masonry ; for partially grouted τ_u= 0.3 - 1.2 MPa
; for fully grouted τ_u= 1.7 - 2.2 MPa:

<u>Effect of Prism Strength</u> In masonry walls the compressive strength of masonry prism f'_m (in gross area) is treated as standard strength of material. Three-coursed masonry prisms are used as control specimens of masonry. In Fig. 4 the relations between $\bar{\tau}_u$ and f'_m are shown. Values of $\bar{\tau}_u$ increase corresponding with larger values of f'_m. However, the relationship between them is not linear but increasing rate of $\bar{\tau}_u$ is rather lower with the range of larger f'_m. Consequently, as reported by earlier reseachers it may be acceptable that $\bar{\tau}_u$ increases approximately in proportion to $\sqrt{f'_m}$.

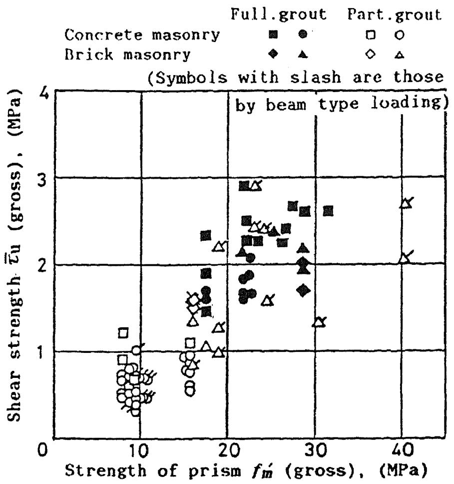
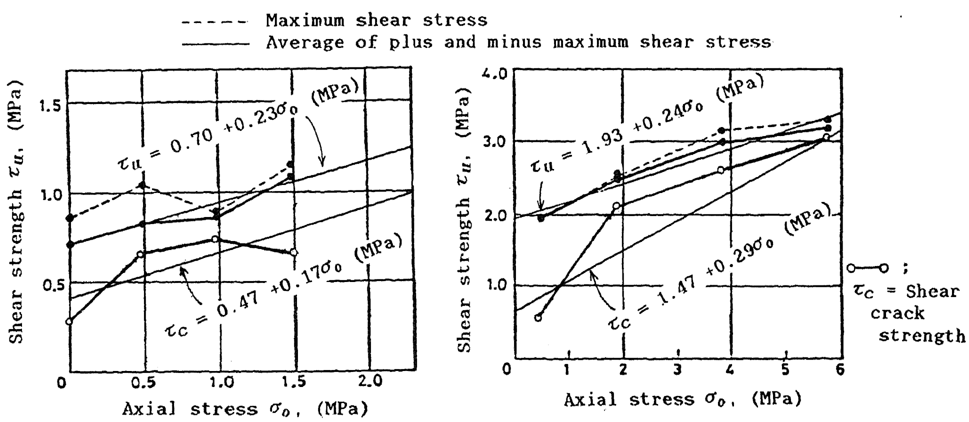


Fig. 4 Relations between $\bar{\tau}_u$ and f'_m

<u>Effect of Axial Stress</u> The results of two test series in concrete masonry are shown in Fig. 5, in which walls were failed by shear under various values of axial stress σ_o. Putting aside axial loads, specimens and loading method are common to a series of test. In this figure, and further discussions, shear strength is expressed as $\tau_u = V_u / t \cdot j$. Although the result of partially grouted walls were gained by the author, those of fully grouted walls were by Kaminosono (Ref. 2). In the figure, τ_u seems to increase almost linearly with increasing σ_o. The regression lines of results are written in the figures. Simplifying these results, the effect of axial stress on τ_u can be expressed as Formula (1). Even though this effect is not verified in brick masonry, similar tendency would be expected.

$$\tau_u = \tau_{ua} + 0.2\sigma_o \quad \text{(MPa)} \cdots\cdots (1)$$

where σ_o= axial stress(in gross area), τ_{ua}= shear strength without axial stress.



(a) Partially grouted walls (b) Fully grouted walls (Ref.2)

Fig. 5. Effect of Axial Stress on Shear Strength (Concrete Masonry Walls)

<u>Effect of Horizontal Shear Reinforcement Ratio</u> Shown in Fig. 6 are the results of several test series, in which horizontal shear reinforcement ratios are varied

while other parameters unchanged. In the figure, relations between $\tau_u/\sqrt{f_m'}$ and $P_h \cdot {}_h\sigma_y$ (where P_h=horizontal shear reinforcement ratio and ${}_h\sigma_y$=yield stress of reinforcement) are shown. All series show the effectiveness of $P_h \cdot {}_h\sigma_y$ clearly. Having examined the results precisely and considering the effect should be concerned with f_m', the author suggest the following formula which will serve to estimate the effect of shear reinforcement in masonry walls. This formula is referred to the study of reinforced cellular concrete members conducted by the author (Ref.3). The formula was derived by treating test data statistically with the least square method. The test results arranged in this form are plotted in Fig. 7.

$$\Delta\tau_u = 0.18\gamma\delta\sqrt{P_h \cdot {}_h\sigma_y \cdot f_m'} \quad \text{(MPa)} \cdots\cdots (2)$$

where $\Delta\tau_u$ = increment of ultimate shear strength by shear reinforcement
γ = factor concerning the action to confine grout
1.0 ·· for hoop type reinforcement closing grout within it
0.8 ·· for single reinforcing bar with semi-circular hooks at the ends
0.6 ·· for the same reinforcement in partially grouted concrete masonry
δ = factor concerning loading method
1.0 ·· for loading addopted in this test.

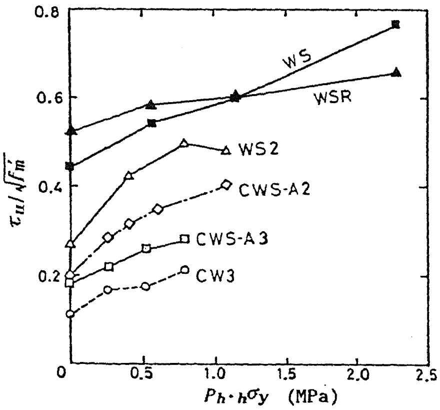


Fig. 6. Relationship Between $\tau_u/\sqrt{f_m'}$ and $P_h \cdot {}_h\sigma_y$

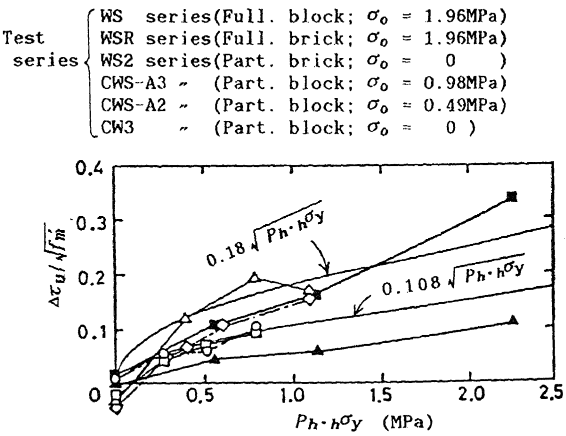


Fig. 7. $\Delta\tau_u/\sqrt{f_m'}$ vs. $P_h \cdot {}_h\sigma_y$

Influence of Shear-span Ratio To examine influence of shear-span ratio or aspect ratio some series of test were conducted. Result of tests is shown in Fig. 8 as relations between $\tau_u/\sqrt{f_m'}$ and shear-span ratio h/d, where h=height of masonry portion of walls. In each series, variation was set on shear-span ratio only while other parameters unchanged. At a glance, it is evident that $\tau_u/\sqrt{f_m'}$ decrease hyperborically with increasing of h/d. Since the test result is affected by amount of axial stress and shear reinforcment, etc., it is necessary to delete these influences from the result. Referring to the preceding discussions, a normalized shear strength as shown in formula (3) is put in place of $\tau_u/\sqrt{f_m'}$, in which k_P represents a factor affected by flexural reinforcement ratio P_t. This relationship is indicated in Fig. 8.

$$\frac{1}{k_P}\left\{\frac{\tau_u}{\sqrt{f_m'}} - 0.18\gamma\delta\sqrt{P_h \cdot {}_h\sigma_y} - 0.2\frac{\sigma_0}{\sqrt{f_m'}}\right\} \cdots\cdots (3)$$

where k_P=1.16$P_t^{0.3}$, P_t=$a_t/t \cdot d$ (%), a_t=cross area of edge tension bar(s).

Thus, the next work is to find the prausible formula of hyperbolic curve adaptable to the tendency of the relationship. Again, the author present a formula for it referring to preceding study (Ref.3). This curve is shown in Fig.

Test series:

- KW series (Full. block; P_h = 0.19%, σ_0 = 0.49MPa)
- CW'series (Full. block; P_h = 0.15%, σ_0 = 0.49MPa)
- CW series (Part. block; P_h = 0.07%, σ_0 = 0.49MPa)
- NS series (Part. brick; P_h = 0%, σ_0 = 0)
- CNS-1 series(Full. block; P_h = 0.07%, σ_0 = 0)
- CNS-0 series(Full. block; P_h = 0%, σ_0 = 0)

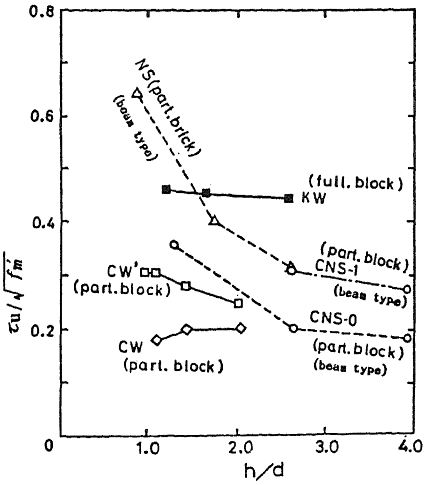


Fig. 8. $\tau_u/\sqrt{f_m'}$ vs. h/d in Test Series

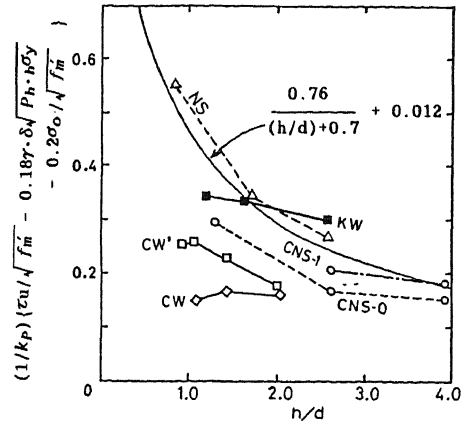


Fig. 9. Relations Between Normalized τ_u and h/d

9 together. Figure shows this formula seems to imitate the tendency of the test data, though some deviation is still left.

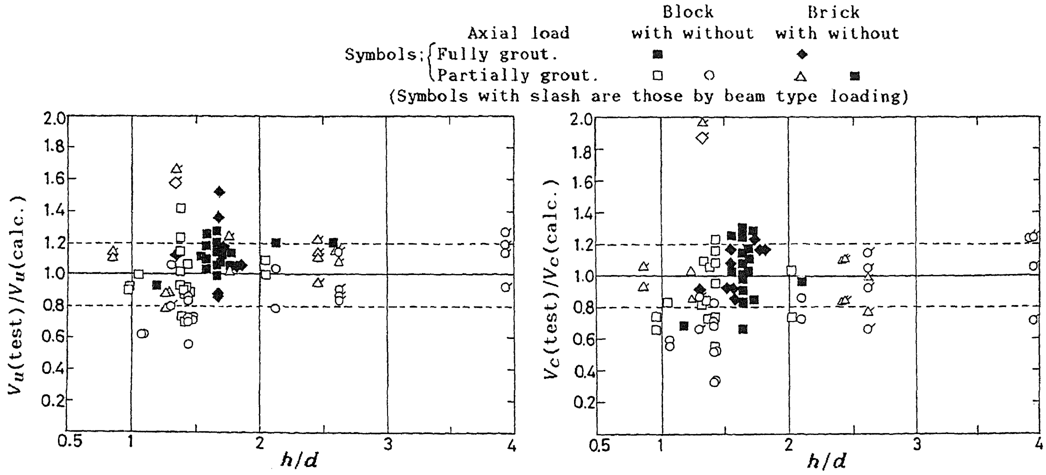
<u>A Formula to Predict Ultimate Shear Strength</u> Considering preceding discussions, to this end, formula (4) is suggested to predict the ultimate shear strength of reinforced masonry walls by introducing new coefficient k_u, a reduction factor corresponding to respective difference due to the kind of masonry or method of loading. Using this formula, the shear strength (ultimate shear force) of every sort of reinforced masonry walls can be estimated relatively close to test results. Comparison of the test results to the values calculated by formula (4) is shown in Fig. 10(a), as relationship between V_u(test)/V_u(calc.) and h/d. About 70% of these ratios are distributed within the limits of ±0.2. This indicates the formula is effective to predict the ultimate shear strength of reinforced masonry walls.

$$V_u = \{k_u \cdot k_P \left[\frac{0.76}{(h/d)+0.7} + 0.012 \right] \sqrt{f_m'} + 0.18\gamma\delta\sqrt{P_h \cdot {}_h\sigma_y \cdot f_m'} + 0.2\sigma_0\} t \cdot j \cdot 10^3 \quad \text{(KN)} \cdots\cdots (4)$$

where k_u=1.0 ·· for fully grouted masonry
0.8 ·· for partially grouted brick masonry
0.64·· for partially grouted concrete masonry
(the aboves shall be multiplied by 1/0.8 for "beam type" results)
k_P, γ and δ····the same as in explanations in Formulas (2) and (3),
stresses are in MPa unit(per gross area), lengths are in meter unit.

SHEAR CRACK STRENGTH

Shear crack strength is defined as a shear stress when first shear crack occurred. This is expressed as $\tau_C = V_C/t \cdot j$, where V_C=shear load make first shear crack occur. Examination is made with similar way in case of ultimate shear strength. Effect of axial stress on shear carck strength is derived also from Fig. 5. Influence of reinforcement on shear crack strength is not evident.



(a) Ultilmate shear strength (b) Shear crack strength

Fig. 10. Comparison of Test Results With Calculated Values in Relation to Shear-span Ratio h/d

Influence of shear-span ratio could be observed. Introducing modification factors for kind of masonry, and referring to Ref.3, following Formula (5) to predict shear crack load is obtained. Comparative ratios between V_c(test) and V_c(calc.) by Formula (5) are distributed within 1±0.2 about 60% of them. These ratios are indicated with relation to h/d in Fig. 10(b).

$$V_c = \{k_c \frac{1}{(h/d)+2}\sqrt{f_m'} + 0.3 \cdot \alpha \cdot \sigma_0\} t \cdot j \cdot 10^3 \quad (\text{KN}) \cdots\cdots (5)$$

where $k_c = k_u$, i.e. the same as in explanation of Formula (4)
α = 1.0··for fully grouted masonry
0.6··for partially grouted masonry.

CONCLUSION

The followings were found out, concerning the shear strength of reinforced masonry walls, through the tests.

1) Ultimate shear strength is affected by many parameters, such as prism strength, shear reinforcement ratio, axial stress, shear-span ratio and kind of grouting.
2) Shear crack strength is affected strongly by axial stress and shear-span ratio, while other parameters have little effect on it.
3) Ultimate shear load and shear crack load can be predicted by Formulas (4) and (5) presented by the author with considerable accuracy.

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