REINFORCING PRINCIPLE AND SEISMIC RESISTANCE OF BRICK MASONRY WALLS

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SUMMARY

Fundamental mechanical properties of bricks and static loading tests of masonry walls made of miniature bricks and full-scale bricks are reported first, and elastic-plastic behavior, maximum load carrying capacity, degradation in load capacity, and deformability and ductility are discussed. As the synthetic fruit of the static wall tests failing in shear and flexure, an elasto-plastic analysis, a shaking table test and a dynamic response analysis using formulated hysteresis loops, an earthquake-resistant design principle for brick masonry buildings is discussed in the latter half and a rational design recommendation is proposed for reinforced brick masonry buildings to resist and survive severe earthquakes in a ductile manner.

INTRODUCTION

Brick masonry is one of the most popular structural systems in the world which has a long history and is beautiful in appearance. However, earthquake kills a large number of people by destroying masonry structures despairingly, especially masonry residences. In Japan, new brick masonry structures have seldom been constructed for quite a long time, attaching suspicion to their earthquake-resistant capability, since a number of masonry structure were severely destroyed due to the 1891 Nobi-Earthquake and the 1923 Kanto-Earthquake. There are few researches on brick masonry in Japan contrasting with active and abundant works in many countries.[1)-12)] This paper reports the fundamental mechanical properties of typical bricks produced in Japan, load carrying capacity and deformability of unreinforced and reinforced brick masonry walls in the former part. Discussion is concentrated on the effect of the vertical or horizontal reinforcements on the load carrying capacity and ductility of the walls made of hollow bricks which fail in shear or in flexure, and the theoretical method for the prediction of the elastic-plastic behavior of the walls is developed. The formulation of the hysteretic characteristics to apply to a response analysis is summarized, confirming the applicability of the formulated loops to a dynamic response analysis following-up the behavior in the shaking table test. Finally, a rational earthquake-resistant design principle and recommendation for reinforced brick masonry buildings are proposed, emphasizing the method of reinforcing to maintain the load carrying capacity without severe deterioration after the attainment of the maximum load.

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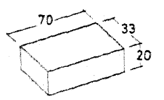
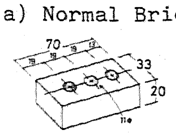
FUNDAMENTAL PROPERTIES OF BRICKS AND WALLS

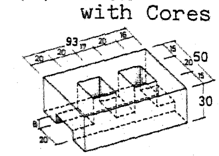
Fundamental mechanical properties of typical bricks produced in Japan and their units with mortar joints are listed in Table 1. Fundamental properties of brick wall elements were investigated experimentally using three types of miniature bricks which were reduced in 1/3 scale of proto-type bricks. Shapes and dimensions are shown in Fig. 1. Average compressive stress versus contraction relationships of wall elements and a brick itself are illustrated in Fig. 2, comparing with the analytical results under the assumed stress-strain relationships as shown in the figure. Envelope curves for hysteretic characteristics of the miniature brick walls under alternately repeated horizontal load are shown in Fig. 4. Details of the experiments were reported in Ref. 13). Behaviors of the unreinforced single wall (type 2) and the single wall reinforced only by vertical reinforcements (type 4) are quite similar. Maximum load carrying capacity and the story-drift angle at the maximum load increased in the cases of the H-type walls (type 1 and type 3) with the end-wall elements which were perpendicular to the main shear wall. The skeleton curves of the single walls which were made of block-type hollow bricks shown in Fig. 1(c) and reinforced by vertical and horizontal reinforcements were rather similar to that of the H-type walls. The story-drift angle at the maximum load and deformability increased to some extent by horizontal reinforcements, as shown in Fig. 4(b). The average shear stress at the maximum load was about 20-30 kg/cm^2 (average mortar strength = 240 kg/cm^2).



(a) Normal Brick



(b) Brick with Cores



(c) Block-type Brick

Fig. 1 Shapes and Dimensions of Bricks.

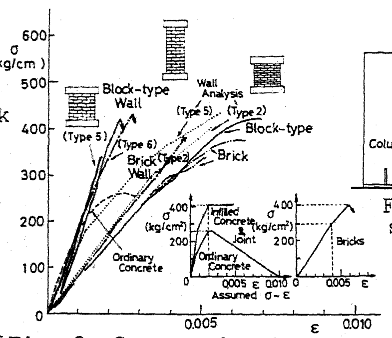


Fig. 2 Compressive Stress vs. Contraction Relationships.

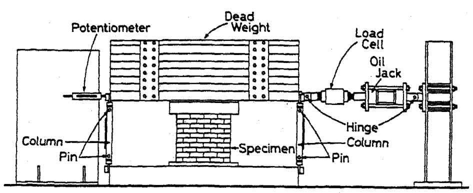


Fig. 3 General View of Set-up of static Tests of Miniature Models.

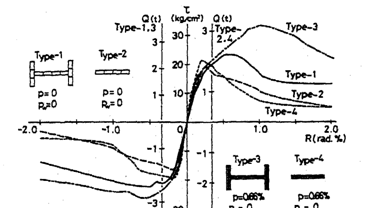
Table 1 Fundamental Mechanical Properties of Proto-type Bricks.

			Maximum Strength (kg/cm^2) normally burnt	Maximum Strength (kg/cm^2) excessively burnt
Single Brick	Comp.	normal	386	376
		with cores	422	422
		normal	487	453
		with cores	366	301
	Bend.	normal	70.5	69.0
		with cores	67.6	42.4
		normal	59.0	96.5
		with cores	74.2	69.7
	Shear	normal	33.1	30.1
		with cores	34.1	13.4
		normal	46.4	61.8
		with cores	77.8	39.4
Unit with Joint *	Comp.	normal	192	-
		with cores	224	185
	Shear	normal	12.4	-
		with cores	13.1	9.7
	Bond	with cores	25.9	45.2

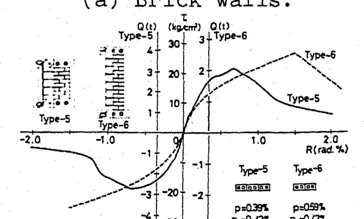
* Compressive strength of joint mortar was 186 kg/cm^2

Table 2 Compressive Strength of Miniature Bricks.

Bricks		σ_c (kg/cm^2)
	normal	354
	with cores	454
	block-type	306
	normal	273
	with cores	249



(a) Brick Walls.



(b) Block-type Brick Walls.

Fig. 4 Envelope Curves for Static Tests of Miniature Models.

EXPERIMENTS Cyclic horizontal loading tests for reinforced brick masonry walls which were made of full-scale bricks shown in Fig. 5 and reinforced vertically and horizontally as shown in Fig. 6, were done using the test set-up shown in Fig. 7. Efficiency of horizontal reinforcements and the effect of the vertical load on the maximum shear capacity and ductility of the walls were investigated. The test results are shown in Fig. 8. Horizontal reinforcements more than p_w = 0.85 % is required to expect ductile shear failure as shown in Fig. 8(a). The maximum shear capacity was not affected very much by the amount of horizontal reinforcements.

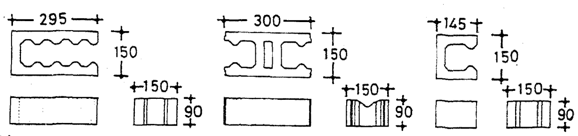


Fig. 5 Shapes and Dimensions of Hollow Bricks.

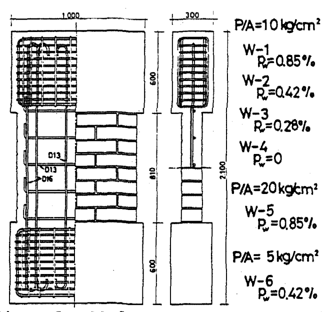


Fig. 6 Wall Test Specimen Failing in Shear.

Table 3 Material Strength.

Concrete	Mix proportion ; C : S : G = 1 : 2.5 : 2.5 W/C = 0.79 , Slump = 23 cm			
	Specimen	σ_c (kg/cm²)	σ_t (kg/cm²)	Age at Test (days)
	W - 1	161	11.3	28
	W - 2	163	14.0	31
	W - 3	148	14.7	33
	W - 4	161	14.1	36
	W - 5	175	18.8	38
	W - 6	191	18.5	41
Bricks		369	—	—

Reinforcements		σ_y (t/cm²)	σ_u (t/cm²)	ε_u (%)
Vertical Reinforcements	D16	3.80	5.80	21.8
	D13	3.71	5.47	22.3
Horizontal Reinforcements	D13	3.73	5.61	21.4

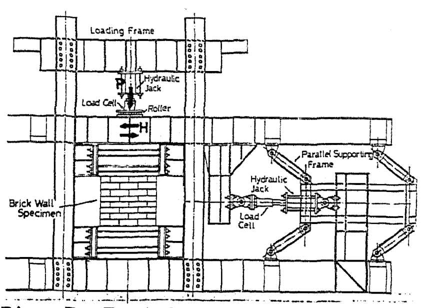


Fig. 7 Test Set-up of Wall Test.

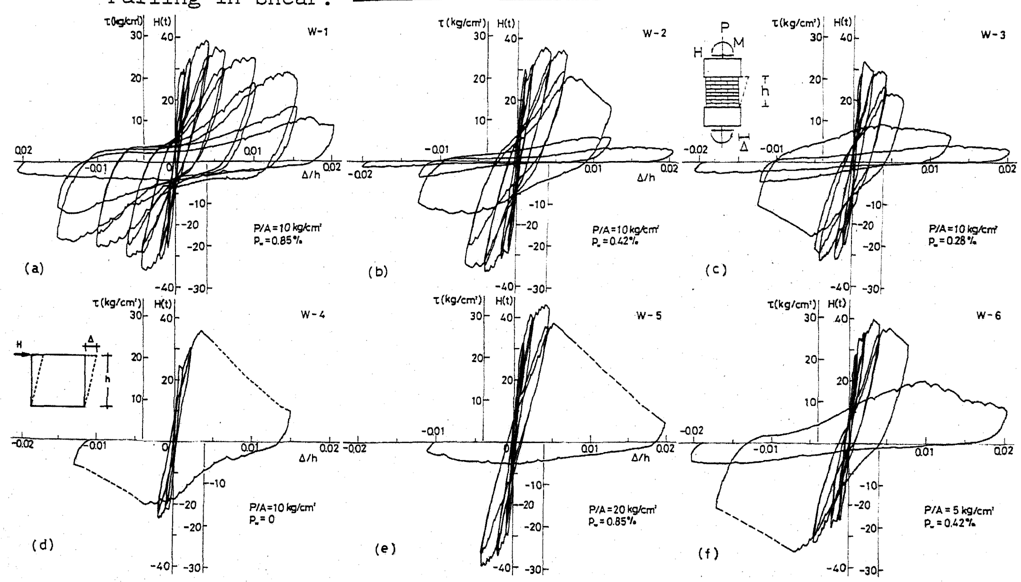


Fig. 8 Test Results (Horizontal Force vs. Story-Drift).

ANALYSIS Theoretical analysis for the wall which failed in shear was made using two-types of physical models which represent the resisting mechanisms against shear. Concept of physical models of an arch-mechanism and a truss-mechanism to estimate the maximum shear capacity which was reported in Ref. 14) was extended to trace a load versus story-drift relationship of a wall failing in shear. Physical models and symbols are illustrated in Fig. 9. Basic equations are developed in the incremental form as shown in Eqs. (1) ~ (8). The first two equations for each mechanism are compatibility conditions and the last two are equilibrium equations. Load versus story-drift relationship for each mechanism are given analytically by the fourth equation when the instantaneous rigidity and the effective cross sectional area at an arbitrary stage of loading are known. Total behavior of the wall is given by the summation of the behaviors of two mechanisms. Analytical results are shown in Fig. 11, comparing with the experimental results. The maximum load carrying capacity, ductility and degrading behavior in load capacity were beautifully caught by the analysis under the reasonable assumptions for the stress-strain relationship for the diagonally compressed brick wall based on Refs.15) and 16).

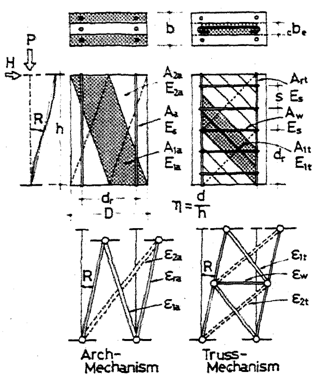


Fig. 9 Illustration of Physical Models.

(i) Arch Mechanism

$$\dot{\varepsilon}_{1a} = \frac{1}{1+\eta^2}(\dot{\varepsilon}_{ra} + \eta \dot{R}) \qquad (1)$$

$$\dot{\varepsilon}_{2a} = \frac{1}{1+\eta^2}(\dot{\varepsilon}_{ra} - \eta \dot{R}) \qquad (2)$$

$$\frac{1}{1+\eta^2}(A_{1a}E_{1a}\dot{\varepsilon}_{1a} + A_{2a}E_{2a}\dot{\varepsilon}_{2a}) + 2A_{ra}E_s\dot{\varepsilon}_{ra} = 0 \qquad (3)$$

$$\dot{Q}_a = \eta\frac{(b-{}_cb_e)D}{2(1+\eta^2)}(E_{1a}\dot{\varepsilon}_{1a} - E_{2a}\dot{\varepsilon}_{2a}) - P\dot{R} \qquad (4)$$

(ii) Truss Mechanism

$$\left(\frac{{}_cb_e h^2 E_{1t}}{12A_{rt}E_s d_r} + 2\right)\dot{\varepsilon}_{1t} - \frac{{}_cb_e h^2 E_{2t}}{12A_{rt}E_s d_r}\dot{\varepsilon}_{2t} - \dot{\varepsilon}_w = \dot{R} \qquad (5)$$

$$\frac{{}_cb_e h^2 E_{1t}}{12A_{rt}E_s d_r}\dot{\varepsilon}_{1t} - \left(\frac{{}_cb_e h^2 E_{2t}}{12A_{rt}E_s d_r} + 2\right)\dot{\varepsilon}_{2t} - \dot{\varepsilon}_w = \dot{R} \qquad (6)$$

$$\frac{1}{2}{}_cb_e d_r(E_{1t}\dot{\varepsilon}_{1t} + E_{2t}\dot{\varepsilon}_{2t}) + A_w(d_r/s)E_w\dot{\varepsilon}_w = 0 \qquad (7)$$

$$\dot{Q}_t = \frac{1}{2}{}_cb_e d_r(E_{1t}\dot{\varepsilon}_{1t} - E_{2t}\dot{\varepsilon}_{2t}) - P\dot{R} \qquad (8)$$

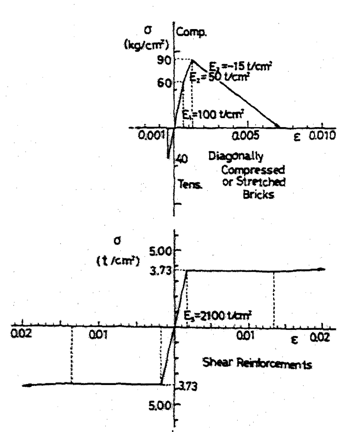


Fig. 10 Assumed Stress-Strain Relationships.

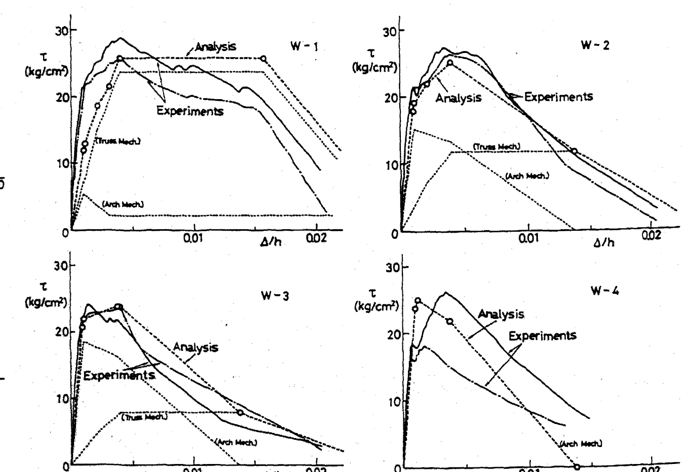


Fig. 11 Comparison between Analyzed and Experimental Results.

Load carrying capacity and ductility of the reinforced walls failing in flexure are discussed in this section. Test specimen is illustrated in Fig. 12. Typical hysteretic load-displacement relationship under constant compression and alternately repeated horizontal load is shown in Fig. 13. Behavior is quite ductile as shown in the figure and ductility is not affected by the magnitude of axial compression in the range of average compressive stress less than 20 kg/cm^2. The maximum bending capacity of the wall was well predicted by the additive strength method in which the maximum load capacity was given by the sum of that of reinforcements and that of brick portion as shown in Fig. 14. In the case of out-of-plane bending for walls, behavior was also very ductile and the maximum load capacity was predicted in reasonable accuracy by the same manner of the analysis for singly reinforced concrete beams as shown in Fig. 15.

Table 4 Infilled Concrete and Reinforcements.

	Mix proportion ; C : S : G = 1 : 2.5 : 2.5			W/C = 0.79 , Slump = 23 cm				
Concrete	Specimen	σ_c (kg/cm^2)	σ_t (kg/cm^2)	Reinforcements		σ_y (t/cm^2)	σ_u (t/cm^2)	ε_u (%)
	WB-1	203	15.0	Vertical Reinforcements	D16	3.80	5.80	21.8
	WB-2	224	12.4					
	WB-3	210	18.2	Horizontal Reinforcements	D13	3.73	5.61	21.4
Bricks		369						

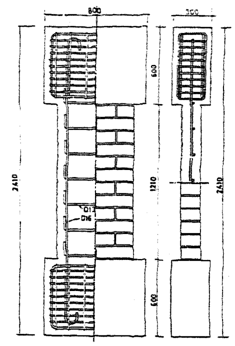


Fig. 12 Wall Test Specimes Failing in Flexure.

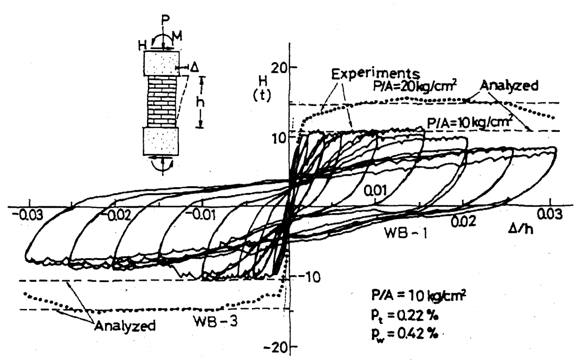


Fig. 13 In-plane Bending Test Results.

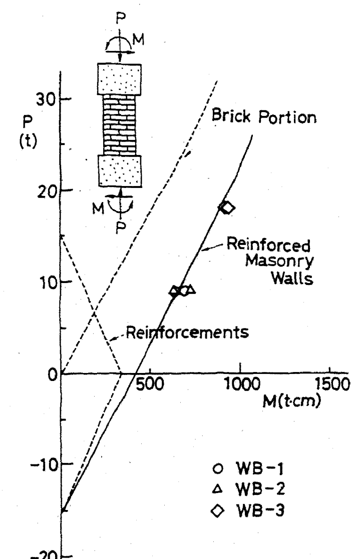


Fig. 14 Prediction of Maximum Load Capacity (Additive Strength Method).

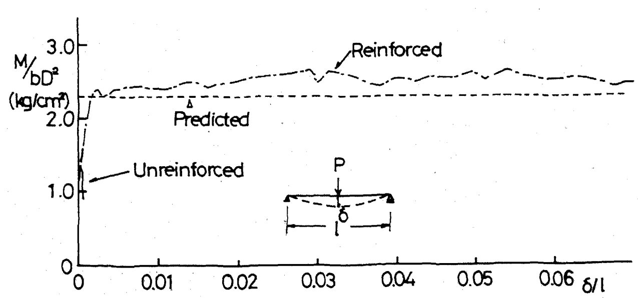


Fig. 15 Out-of-Plane Bending Test Results.

MODEL OF HYSTERESIS LOOPS

Formulation of hysteresis loops which is valid not only in the small deformation range but also in the large plastic deformation range is very important to estimate dynamic response behavior of this type of structures under a severe earthquake. The first author et al. proposed the new method for the formulation of hysteresis loops in Ref. 17). Concept of the formulation is shown in Fig. 16. The formulated hysteresis loops (Fig. 16(a)) are represented by the summation of three basic loops; a degrading model having an arbitrary skeleton curve (Fig. 16(b)), a slip model which is able to present the load deterioration of the arbitrarily prescribed magnitude (Fig. 16(c)), and a bi-linear model (Fig. 16(d)). When a skeleton curve, share parameters of basic loops for load carrying capacity B and D, and a deterioration paramenter are given, the hysteresis loops are fixed determinately. A skeleton curve can be given experimentally or analytically as mentioned previously. B, D and the deterioration parameter are given on the basis of experimental investigations. Examples of the formulated hysteresis loops are shown and compared with the statical experimental results in Fig. 17. The results of a dynamic response analysis using the formulated loops are shown in Fig. 18 comparing with the shaking table test results which were reported in detail in Ref. 13). The formulated loops traced the static loading test results very well and the dynamic response analysis can predict the response in the shaking table test in reasonable accuracy.

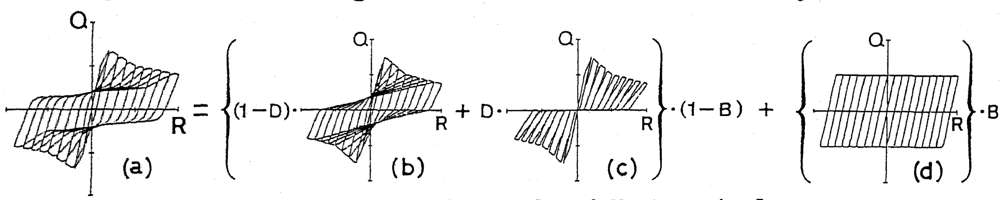
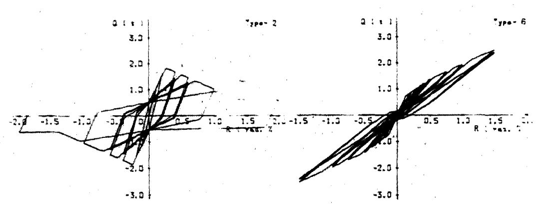
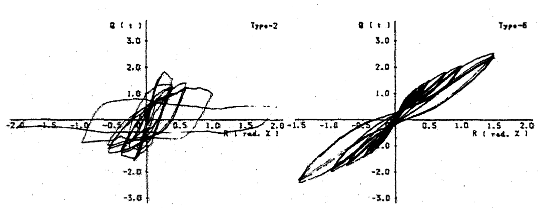


Fig. 16 Schema of Formulated Hysteresis Loops.

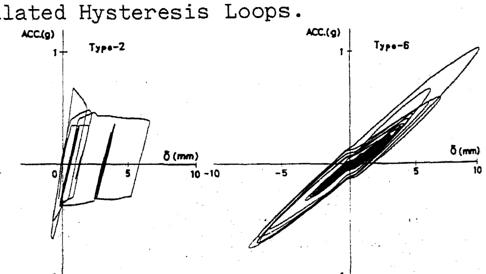


(a) Formulated Loops.

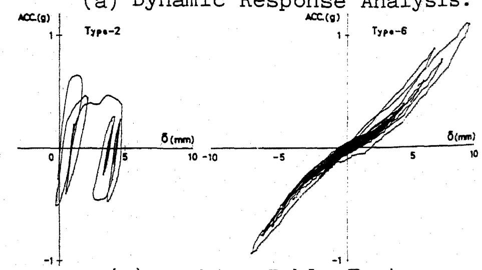


(b) Experimental Loops.

Fig. 17 Comparison between Formulated and Statically Experimental Hysteresis Loops.



(a) Dynamic Response Analysis.



(b) Shaking Table Tests.

Fig. 18 Comparison between Response Analysis and Shaking Table Tests.

DESIGN RECOMMENDATION FOR REINFORCED BRICK MASONRY BUILDINGS

On the basis of the experimental and theoretical investigations mentioned in the preceding sections, the authors propose a reinforcing principle and an earthquake-resistant design recommendation for brick masonry buildings, especially for two- or three-storyed brick masonry residences. The proposed design recommendation is applicable to the type of structures which would be made of the bricks shown in Fig. 5 or bricks with the same quality as them, and reinforced by completely infilled concrete in cores, and vertical and horizontal reinforcements.

Principle and recommendation (1) Ultimate horizontal load carrying capacity is ensured by an appropriate arrangement of walls and columns having the prescribed cross sectional area. Minimum requirement for a wall cross sectional area is based on the following principle. Story shear coefficients at the attainment of the allowable shear stress of the walls, at initial shear cracking in the walls and at the maximum load carrying capacity should be 0.25, 0.7 and 1.0, respectively. Assumed average shear stresses at cracking and the ultimate state are τ_{cr}=7 kg/cm^2 and τ_u=10 kg/cm^2, respectively. The previous experiments guaranteed about τ_{cr} = 20 kg/cm^2 at cracking. The prescribed minimum wall area corresponds to 23cm length of the wall with 15 cm thickness per square meter of the floor area in the case of the 1st story of two-storyed buildings.

(2) Amount of horizontal reinforcements in walls and columns is determined so as to be able to maintain the initial shear cracking stress of the wall only by shear reinforcements, satisfying Eq. (9).

$$\tau_y = p_w \cdot \sigma_y = \tau_{cr} \qquad (9)$$

where τ_y, p_w and σ_y denote shear stress at yielding of horizontal reinforcements, horizontal reinforcement ratio and yield stress of reinforcements, respectively.

(3) Amount of vertical reinforcements in walls and columns against bending is given so as to yield in tension just when the wall or column attains its shear cracking stress, satisfying Eq. (10).

$$a_t = 0.5\ t\ h'\ p_w \qquad (10)$$

where a_t, t and h' denote the required cross sectional area of vertical reinforcements, the thickness of walls or columns and the clear height of walls or columns, respectively.

(4) Main reinforcements and shear reinforcements in spandrel beams and wall elements attached to the spandrel beams are to be determined to ensure that the walls and columns could attain the prescribed ultimate strength.

Referring that the previously mentioned experimental results guarantee the greater shear strength than the assumed value, all elements in the structure designed according to the proposed design recommendation could be expected to fail in flexure and behave in a satisfactorily ductile manner.

CONCLUSION

On the basis of the experimental and analytical investigations, the following conclusions can be drawn.

(1) Masonry walls made of block-type hollow bricks with cores can be appropriately reinforced by vertical and horizontal reinforcements and can be ductile even when shear failure takes place with more horizontal reinforcements than p_w = 0.85 %.

(2) Ultimate shear strength and a skeleton curve of brick masonry walls can be predicted analytically in reasonable accuracy by the compound physical model analysis based on an arch-mechanism and a truss-mechanism.
(3) Behavior of brick walls failing in flexure is very ductile in both cases of out-of-plane bending and in-plane bending. Maximum flexural load capacity can be predicted by the additive strength method.
(4) Hysteretic restoring force characteristics of brick walls can be formulated by the proposed model which is composed of the sum of three fundemental models; a degrading model, a slip model and a bi-linear model, through the whole range of loading including load deterioration and degradation. Dynamic behavior can be caught by an elasto-plastic response analysis to which the formulated hysteresis loops were applied.
(5) Building structures designed according to the proposed reinforcing principle and the design recommendation can be expected to behave in quite a ductile mannar under a severe earthquake.

ACKNOWLEDGEMENT

Static loading tests and shaking table tests of miniature models of brick walls were performed under the cooperation of Prof. T. FUJIWARA of DPRI, Kyoto Univ. and Messrs Miha TOMAZEVIC from Yugoslavia and Y. ORITO. The authors present them sincere gratitude for their contribution. Full-scale experiments were financially supported by a Grant in Aid for Scientific Researchs of Ministry of Education, Japan, Project No. 58850129. Miniature bricks and block-type hollow bricks were trially minufactured by Matsumoto Brick Company,in Japan.

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