REINFORCING PRINCIPLE AND SEISMIC RESISTANCE OF BRICK MASONRY WALLS

Minoru Wakabayashi (I)
Takeshi Nakamura (II)
Presenting Author: T. Nakamura

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 elastoplastic 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. 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 elastoplastic 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.

(I) Professor, Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji-city, Kyoto Prefecture, Japan.
(II) Associate Professor, Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji-city, Kyoto Prefecture, Japan.
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 prototype 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/cm² (average mortar strength = 240 kg/cm²).

![Fig. 3 General View of Set-up of static Tests of Miniature Models.](image)

![Fig. 4 Envelope Curves for Static Tests of Miniature Models.](image)

<table>
<thead>
<tr>
<th>Table 1 Fundamental Mechanical Properties of Proto-type Bricks.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>normal</td>
</tr>
<tr>
<td>with cores</td>
</tr>
<tr>
<td>block-type</td>
</tr>
<tr>
<td>normal</td>
</tr>
<tr>
<td>with cores</td>
</tr>
<tr>
<td>normal</td>
</tr>
<tr>
<td>with cores</td>
</tr>
<tr>
<td>normal</td>
</tr>
<tr>
<td>with cores</td>
</tr>
<tr>
<td>normal</td>
</tr>
<tr>
<td>with cores</td>
</tr>
</tbody>
</table>

![Fig. 2 Compressive Stress vs. Contraction Relationships.](image)

![Fig. 1 Shapes and Dimensions of Bricks.](image)

![Table 2 Compressive Strength of Miniature Bricks.](image)

![Fig. 5 General View of Set-up of static Tests of Miniature Models.](image)
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 $p_x = 0.85\%$ 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.](image)

![Fig. 6 Wall Test Specimen Failing in Shear.](image)

![Fig. 7 Test Set-up of Wall Test.](image)

![Fig. 8 Test Results (Horizontal Force vs. Story-Drift).](image)
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).

(1) Arch Mechanism
\[ \dot{\varepsilon}_a = \frac{1}{1 + \eta} (\ddot{\varepsilon}_a + \dot{\varepsilon}_a) \]  
(2) Arch Mechanism
\[ \dot{\varepsilon}_a = \frac{1}{1 - \eta} (\ddot{\varepsilon}_a - \dot{\varepsilon}_a) \]  
(3) Arch Mechanism
\[ \frac{1}{1 + \eta} (A_a E_a \dot{\varepsilon}_a + A_2 E_2 \dot{\varepsilon}_2) + 2 A_2 E_2 \dot{\varepsilon}_2 = 0 \]  
(4) Arch Mechanism
\[ \dot{\varepsilon}_a = \eta \frac{2}{(1 + \eta)} (E_1 \dot{\varepsilon}_1 - E_2 \dot{\varepsilon}_2) - \dot{\varepsilon}_a \]  

(5) Truss Mechanism
\[ \frac{c_b h^2 E_1}{12 A_t E_s} \dot{\varepsilon}_1 - \frac{2}{12 A_t E_s} \dot{\varepsilon}_2 - \dot{\varepsilon}_w = \dot{\varepsilon}_s \]  
(6) Truss Mechanism
\[ \frac{c_b h^2 E_1}{12 A_t E_s} \dot{\varepsilon}_1 - \frac{2}{12 A_t E_s} \dot{\varepsilon}_2 - \dot{\varepsilon}_w = \dot{\varepsilon}_s \]  
(7) Truss Mechanism
\[ \frac{1}{T_c} (c_1 \dot{\varepsilon}_1 + c_2 \dot{\varepsilon}_2) + A_w \left( \frac{d}{a} \right) E_w \dot{\varepsilon}_w = 0 \]  
(8) Truss Mechanism
\[ \dot{\varepsilon}_w = \frac{1}{T_c} (c_1 \dot{\varepsilon}_1 + c_2 \dot{\varepsilon}_2) - \dot{\varepsilon}_w \]  

Fig. 9 Illustration of Physical Models.

Fig. 10 Assumed Stress-Strain Relationships.

Fig. 11 Comparison between Analyzed and Experimental Results.
REINFORCED MASONRY WALLS FAILING IN FLEXURE

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/cm². 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.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>ρc (g/cm²)</th>
<th>ρb (g/cm²)</th>
<th>Reinf.</th>
<th>ρs (l/sec)</th>
<th>ρa (l/sec)</th>
<th>Es (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WB-1</td>
<td>203</td>
<td>15.0</td>
<td>Vert.</td>
<td>3.80</td>
<td>5.80</td>
<td>21.8</td>
</tr>
<tr>
<td>WB-2</td>
<td>224</td>
<td>12.4</td>
<td>Vert.</td>
<td>3.63</td>
<td>5.61</td>
<td>21.4</td>
</tr>
<tr>
<td>WB-3</td>
<td>210</td>
<td>18.2</td>
<td>Horiz.</td>
<td>3.73</td>
<td>5.61</td>
<td>21.4</td>
</tr>
<tr>
<td>Bricks</td>
<td>368</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 12 Wall Test Specimens 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 parameter 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.

\[
\begin{align*}
Q &= \{(1-D)R + DQ_s\} + \{(1-B) + B\}
\end{align*}
\]

Fig. 16: Schema of Formulated Hysteresis Loops.

(a) Formulated Loops.  
(b) Experimental Loops.

Fig. 17: Comparison between Formulated and Statical 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 \( \tau_c = 7 \text{ kg/cm}^2 \) and \( \tau_u = 10 \text{ kg/cm}^2 \), respectively. The previous experiments guaranteed about \( \tau_c = 20 \text{ kg/cm}^2 \) 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).

\[
\tau_y = p_w \cdot \sigma_y = \tau_{cr}
\]

where \( \tau_y \), \( p_w \) and \( \sigma_y \) 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).

\[
a_v = 0.5 t h' p_w
\]

where \( a_v \), \( t \) 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 fundamental 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 hysteretic 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 manner 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 DFRI, 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 Research of Ministry of Education, Japan, Project No. 58850129. Miniature bricks and block-type hollow bricks were trially manufactured by Matsumoto Brick Company, in Japan.

REFERENCES


