FLY ASH BLOCK WALL UNDER HORIZONTAL SHEAR LOADING

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ABSTRACT The shearing strength of fly ash block masonry (block dimensions: height 380mm, thickness 240mm) is quite low. If a structurally improved masonry unit is used, such as a block with grooves, hollow-block, or the hollow block with a reinforced concrete core column in its vertical hole, the shearing strength of the masonry will be increased. According to the results of model wall tests described in this paper, these measures also increase the shearing strength of the fly ash block wall.

However, under vertical load on the wall, the mortar swelling in the block hole may increase the lateral load resistance, so the shearing strength of hollow-block masonry in the wall is greater than that obtained in the masonry test.

In addition, the action of the reinforced concrete core column in the block wall shows a hysteresis phenomenon, therefore the effective shearing strength of the core column in the wall is much lower than that obtained in the test on the masonry unit.

Finally, a formula to calculate the shearing strength of the block wall is presented.

This paper also considers the restoring force characteristic and its idealization for the hollow-block wall in which there are none or only a few core columns. The results of block wall tests are compared with the material of the previous brick wall test. There is no obvious difference between the deformation properties of block walls and brick walls.

1. INTRODUCTION

The shearing strength of fly ash block masonry is so low that the seismic load-resisting capacity of block building is very weak. If a structurally improved masonry unit is used, such as a block with grooves, hollow-block, or the hollow block with a reinforced concrete core column in its vertical hole, the shearing strength of the block masonry will be increased. The effect of these measures in block wall will be further studied in this paper by model wall test.

2. TESTING PROGRAM

2.1 The Aim of Test

By the experiment of the fly ash block wall under horizontal shear loading, both the shearing strength and the deformation properties of solid block wall, groove-block wall, hollow-block wall and the hollow-block wall with a few reinforced concrete core columns were compared each and all. Meanwhile, the deformation properties of block walls were also compared with the existing data of brick walls.

2.2 Test Unit

On the basis of the experience of brick wall tests and block wall tests in our country, shear failure will occur in a wall with a height to length ratio of less than or equal to 0.6 and with a normal compression stress of greater than or equal

to 0.6 and with a normal compression stress of greater than or equal to $2\ kg/cm^2$ on it. Hence, the dimensions of test walls were selected as follows: Height 1200mm, length 2700mm, no flange. In addition, the test wall had a top beam cast on its top and a foundation beam bearing it. The walls' basic properties are listed in Table 1.

Wall Type	Amount	Shearing Strength of Block Masonry (kg/cm^2)	Compression Strength of Core Column Concrete (kg/cm^2)	Reinforced Concrete Core Column
1. Solid Block	3	0.90		
2. Block with Grooves	3	1.95		
3. Hollow-block	3	1.38		
4. Hollow-block with Core Column	3	1.38 (6.64^t/column)	255.9	Set a Core Column at the Site of 1/3 length of the Wall, 1Φ16/Column

TABLE 1. Wall Properties

2.3 Loading Program

Vertical compression stress $\sigma_o = 3\ kg/cm^2$ was applied to the test wall by four hydraulic jacks. Every jack could slide along a double layer of shaft. According to the results of the test, the sliding friction force could be neglected. Horizontal load was monotonically applied, by a hydraulic jack in one direction for test wall type 1 or type 2 until the test wall failed, but was reversely and cyclically applied by interchangable hydraulic jacks in opposite direction for test wall type 3 or type 4. For the latter, before the test wall was cracked, the test was controlled by loading value and every loading grade made one cycle. Then, test was controlled by the horizontal deflection of the wall, and every loading grade repeated three cycles until total deflection arrived at $\pm$ 15mm.

The walls (type 1, type 2) were simply placed on the test floor and horizontal tensile bars were set to control the wall footing displacement. The walls (type 3 and 4) were fixed on the test floor perfectly. The full view of wall testing is shown in Fig. 1.

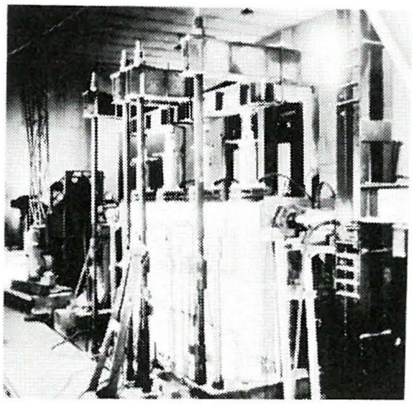

Fig. 1. Full View of Wall Testing

3. THE SHEARING STRENGTH OF WALL

3.1 General Condition of Test Process

In the first stage, a linear relationship existed between horizontal deflection and load. After the first crack of wall appeared, the load-deformation curve was slightly bending. When the horizontal deflection of test wall approached 2mm, the deflection started increasing within a large range, though the horizontal loading increased only in a small quantity. The slope of the load-deformation curve decreased rapidly. The crack in the test wall developed more obviously, but the strain of the reinforcing steels in the core columns was only 100 - 300μ. At the maximum load, the deflection of test walls was 4 - 8mm, cracks exhibited stepped shape along the mortar joints and connected each and all for the most part. The strain of reinforcing steels was 600μ on an average. The continuation of test made the load-deformation curve entering into a descending range. When the deflection of test walls was not over 12mm, the load value still kept in excess of 0.9 multiple of the ultimate load. For a few test walls with core columns, the deflection could even approach 15mm under the same capacity of keeping load.

3.2 Failure Characteristic

All of the cracks in test walls developed along the mortar joints. For test walls type 1, 2 and 3, step-type cracks occurred along the boundary surface between block and mortar due to shear failure. When the step-type cracks connected as a diagonal crack from corner to corner of the test wall, the horizontal loading applied on the wall arrived at the ultimate value.

Because the foundation beam of test wall type 3 was fixed on the test floor perfectly, the boundary surfaces between the wall bottom and foundation beam in two ends of the wall were pulled apart due to reversed bending moments. The weakened bed joint without strengthening of the reinforced concrete core columns was easily destroyed first by shear force, though also some step-type cracks developed in the test wall. So, for wall type 3, the failure of the wall was the shear failure of bed joint and was along the boundary surface between mortar and block too.

3.3 Crack Load and Ultimate Load

Test results are listed in Table 2.

Type of Test Wall	Crack Load (ton)	Ultimate Load (ton)
1. Solid Block	6.00 8.00 Mean 6.68 6.05	16.59 15.94 Mean 16.52 16.42
2. Block with Grooves	12.02 10.02 Mean 10.68 10.00	22.00 19.54 Mean 20.16 18.95
3. Hollow-block	8.60 12.09 Mean 10.25 10.07	21.99 20.94 Mean 21.03 20.17
4. Hollow-block with Core Column	9.30 8.27 Mean 9.38 10.58	23.01 23.42 Mean 24.12 25.92

TABLE 2. Crack Load and Ultimate Load

The crack load of the solid block wall was the lowest. By using the block with grooves or the hollow-block, the crack load of the test walls was increased. Since the deformation of the test walls was small at this time, the core columns hardly carried load and the crack load of the hollow-block walls with core columns could not be further increased.

The ultimate load of the test walls in which the structurally improved masonry units were used was much larger than that of the solid block wall.

The results of masonry test showed that the shearing strength (along the section of bed joints) of the hollow-block masonry was lower than that of the masonry made of block with grooves, but the crack load and ultimate load of the test wall of the former were equal to, or even higher than that of the latter respectively. The cause was that the vertical force was not applied on the masonry specimen during the masonry test, so the slight swelling of mortar in the vertical hole could not be brought into full play; but during the wall test, the slight swelling of mortar under the vertical force took effect of the dowel action to increase the wall's lateral load-resisting capacity. For the hollow-block wall with reinforced core columns, its increased value of the ultimate load, compared with that of the hollow-block wall, was not as large as the shearing strength of the reinforced core columns obtained from the masonry test. Test indicated that when the deflection of test wall was large enough, the part masonry of the wall cracked and lost its shearing strength, then the reinforced concrete core column could take effect. At this time, the better part of the shearing strength of the core columns would be used to compensate the loss of the shearing strength of the cracked masonry in the wall. When the ultimate load arrived, the strain of the reinforcing steels in the core columns was only 600 μ on an average, in which the core column could not be very effectual. Only by continually increasing the deformation of the wall could the core column provide its more shearing strength. On the basis of the test of a few walls, the effective shearing strength provided to the wall's ultimate load by one reinforced concrete core column was only 1.5 ton. It was called a hysteresis phenomenon of the core column.

3.4 Checking Shearing Strength of Wall

There are two viewpoints about checking shearing strength of wall. They are respectively built on the basis of main tensile stress failure form and shear failure form.

From "Design and Construction Provisions of Medium Block Building" (JGJ 5-80) in force, the formulas for calculating the shearing strength of block wall are as follows:

$$KQ \leq \frac{R_{\tau} A}{m \xi} \quad , \quad R_{\tau} = R_z \sqrt{1 + \frac{\sigma_o}{R_z}} \quad , \quad R_z = R_j \quad ,$$

here,
- K - safety factor;
- Q - shear force;
- R_{τ} - equivalent shearing strength of block masonry;
- A - sectional area;
- ξ - uneven factor of the shear stress in the section;
- m - integral factor of block masonry, for solid block m = 1.10, for hollow-block m = 1.20;
- σ_o - compression stress on the average;
- R_z - the strength of block masonry to withstand the main tensile stress;
- R_j - shearing strength of block masonry along the section of bed joints;

It seems unreasonable for medium block masonry to suggest that its strength to withstand the main tensile stress be equal to its shearing strength along the section of bed joints. Meanwhile, it is difficult to obtain the main tensile strength of the medium block masonry from test. In addition, the formula just calculates the failure of one point in the wall. In fact, the ultimate load of wall is much larger than the crack load. On the basis of the above formula and the test results, the following formula for calculating the shearing strength of the hollow-block wall with core columns may be recommended

$$KQ \leq \frac{R_{\tau} A}{m \xi} + 0.07\ R_a A_a$$

here,
- R_a - compression strength of the core column concrete;
- A_z - sectional area of the core column.

The test values of the shearing strength of test walls were much larger than the calculated values obtained by using the formula provided by the medium block building provision in force. For the test walls of solid block, block with grooves, hollow-block and hollow-block with core column, the test value to calculating value ratios were respectively 1.77, 1.32, 1.91 and 1.71 on the average.

According to the other failure form, the formula for calculating the shearing strength of block wall may be as follows:

$$KQ \leq (R_j + f \sigma_o) A / \xi$$

here,
- K - safety factor;
- Q - shear force;
- R_j - shearing strength of block masonry along the section of bed joints;
- f - friction factor;
- σ_o - compression stress on an average;
- A - sectional area;
- ξ - uneven factor of the shear stress in the section.

The shear force is borne by the shearing strength and friction of wall. This idea coincides with the breakage phenomenon in practice and it is easy to obtain the shearing strength of block masonry along the section of bed joints from masonry test. But the formula also only calculates the failure of one point in the wall. It is a weakness to consider the shearing strength provided by all the section.

Before the test wall approached the ultimate state, the cracks occurred and gradually developed along the section of the mortar joints, then they connected with each other and formed a step-type shape. It was evident that the shearing strength would disappear at the crack region in the wall. It was reasonable to consider that the horizontal ultimate load would consist of the friction and the shearing strength of the uncracked section. Meanwhile, the following assumption was taken:

1. The length of the uncracked section was proportional to the length of the compression zone of the wall bottom; from statistics of 21 walls' test data collected (the height to length ratio of wall from 0.34 to 0.59; compression stress from 0.41 kg/cm^2 to 5.30 kg/cm^2), 2.0 was taken as the ratio value;

2. According to the measurement of the longitudinal strain of the wall, a triangle was approximately taken as the stress distribution diagram in the compression zone of the wall bottom;

3. The friction factor f was taken as 0.5 for solid block and 0.8 for structurally improved block;

4. The uneven factor of shearing stress was not considered. From the force equilibrium of the wall, the ultimate load formula was obtained.

$$KQ \leq (3R_j + f\sigma_o)A/(1 + 6R_j h/\sigma_o L)$$

here, R_j - shearing strength of block masonry along the section of bed joints;
h - wall height;
L - wall length.

For the hollow block wall with core columns, the strain of the reinforcing steels was taken as 600μ. The ultimate load was:

$$KQ \leq (3R_j A(1+2\sigma_a A_g L'/\sigma_o AL) + \sigma_o fA+0.07R_a A_z)/(1+6R_j h/\sigma_o L)$$

here, $\sigma_a = 600\ E_a$;

A_g - area of the reinforcing steel;

L' - space between two core columns;

E_a - elastic modulus of the steel bar.

The ultimate load for resisting shear calculated by above two formulas was close to and less than the test value. Therefore the calculated value of the ultimate load was safety. The results of calculating are listed in Table 3.

Type of Test Wall	Test Value (ton)	Calculating Value	Test Value / Calculating Value
1. Solid Block	16.32	15.55	1.05
2. Block with Grooves	20.16	20.07	1.00
3. Hollow-block	21.03	19.41	1.08
4. Hollow-block with Core Column	24.12	20.86	1.16

TABLE 3. Ultimate Load

The method mentioned above is based on the ultimate state and also reflects the effect of the height to length ratio of the wall and the compression stress applied on the wall, i.e. the effect of eccentric compression of the wall, therefore the calculation results are close to the quantity of practical measurement. It may be used to estimate the practical horizontal load-resisting capacity of walls.

4. THE RESTORING FORCE CHARACTERISTIC AND DEFORMATION CAPACITY OF WALLS

The deformation properties and the restoring force characteristic of hollow-block walls and hollow-block walls with core columns are specially introduced here. The deformation capacity of solid block walls and groove-block walls is much the same as that of hollow-block walls. The previous test results of brick walls are mentioned to compare with the results of block wall test. The dimensions and the properties of brick walls are as follows: height 1 m, length 2.5 m, thickness 24 mm, compression stress σ_o = 2.67 kg/cm^2, the shearing strength of brick masonry R_j = 1.92 kg/cm^2. They all correspond with block walls.

4.1 Hysteresis Curve

The hysteresis curves of hollow-block wall, hollow-block wall with core columns and brick wall are shown in Fig. 2. At the elastic stage, all the hysteresis loops of three type walls were straight lines. For the hollow-block wall with core columns, the displacement was reduced very obviously during unloading.

The area of hysteresis loop increased gradually along with the increasing of displacement. It indicated that energy was consumed with developing crack and deformation of wall. The deformation energy may be calculated from the load-deformation curve and the energy dissipation during the hysteretic response of walls is shown by the area of hysteresis loop. Because both the ultimate load and displacement of the hollow-blovk wall with core columns were the largest, its deformation energy at this time occupied first place, the hollow-block wall's deformation energy took second and the brick wall's was minimum. The shearing strength of brick wall was artificially raised to be the same level with that of block wall in order to compare the energy dissipation. For hollow-block walls with core columns, the reinforcing steel pulled the wall backward during unloading to decrease the remaining deformation and the area of hysteresis loop. But the excessive remaining deformation was unallowable, because it was easy to load walls to collapse and difficult to repair walls after earthquake. If the remaining deformation was limited to 1/200 of wall height, the hollow-block wall with core columns would have the maximum effective energy dissipation. The ratio of the

effective energy dissipation for three type walls was as follows: hollow-block wall with core columns: brick wall: hollow-block wall = 1.17: 1.00: 0.96.

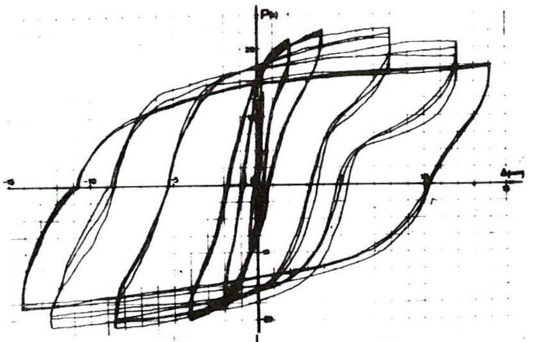

Fig. 2-1 The Hysteresis Curve of Hollow-block Wall III-3

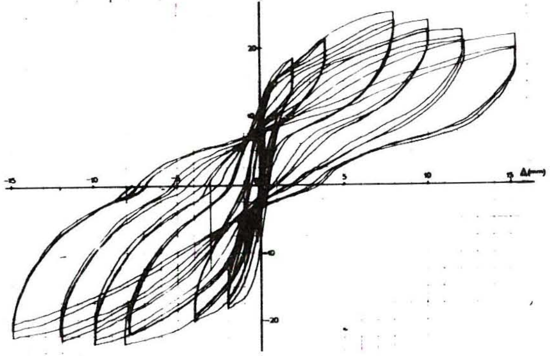

Fig. 2-2 The Hysteresis Curve of Hollow-block Wall with Core Columns IV-5

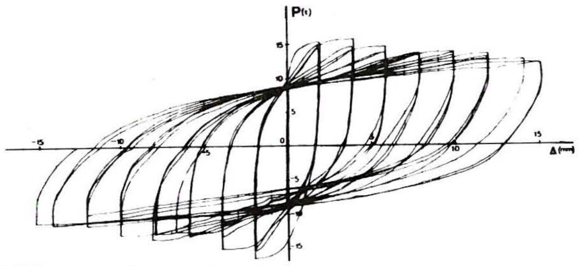

Fig. 2-3 The Hysteresis Curve of Brick Wall SZQ-3

4.2 Stiffness Degradation

Stiffness is defined as a force required for producing a unit displacement. A concept of average stiffness is used to show the stiffness of test wall under reversed cyclic loading here, namely,

$$K = \frac{|P| + |-P|}{|\Delta| + |-\Delta|}$$

here K - stiffness of wall;
P - load;
Δ - displacement.

From hysteresis curve, the stiffness of walls degraded along with the increasing of displacement. By the regression of test data, the stiffness degradation curves of three type walls shown as Fig. 3 were obtained, in which the stiffness degradation of brick walls was the more severe.

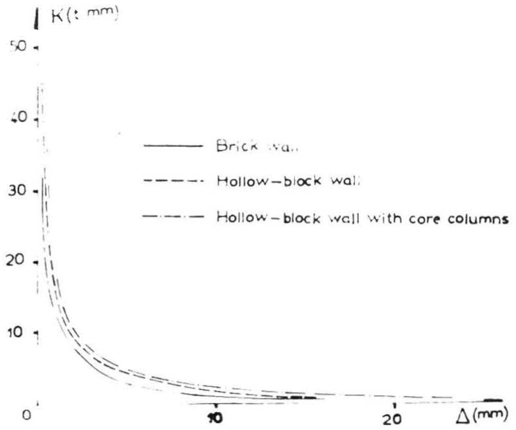

Fig. 3 Stiffness Degradation Curves of Three Type Walls

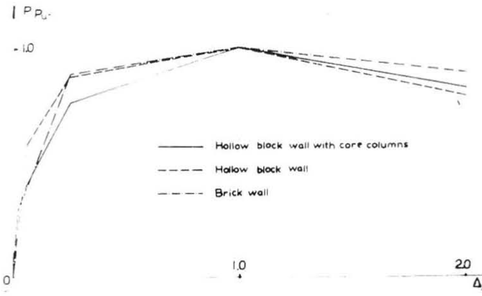

Fig. 4 The Load-Deformation Curve of Three Type Walls

4.3 Loss of Strength

Two parameters were used roughly to estimate the level of strength loss. They were the factor of loading degradation and the factor of loading loss, namely,

$$\gamma = \frac{P_m - P_{m+1}}{P_m} , \quad \beta = \frac{P_{min}}{P_{max}} .$$

Test results are listed in Table 4.

Type of Test Wall	γ 1-2 percent	γ 2-3 percent	β
B rick Wall	4.93	3.00	0.926
Hollow-block Wall	6.40	3.92	0.922
Hollow-block Wall with Core Columns	4.09	3.20	0.935

TABLE 4. Loss of Strength

Hence, the hollow-block wall with core columns had the smallest loss of strength, the brick wall came second.

4.4 Load-Deformation Curve

The load-deformation curve is obtained by connecting the unloading points on the hysteresis curve. As mentioned above, the whole test process might be divided into four stages. The load-deformation curve was linear elastic for low loads. After the first crack occurred in the wall, the curve became slightly bending and the elastoplastic stage started. After the wall displacement was large enough, (for instance 2mm for block wall) the slope of the curve rapidly decreased. The displacement increased a large amount but the loading only increased a small quantity. The third stage ended at ultimate load. The last portion was the descending range, the wall could continuously bear a certain load. For simplification, four straight lines were used instead of the real curve. The equations of the simplified load-deformation curve were obtained by regression of the load-deformation non-dimensionalized test data. The equations of load-deformation curve for three type walls are listed in Table 5 and showed in Fig. 4.

Type of Test Wall	Elastic Stage	Elastoplastic Stage I	Elastoplastic Stage II	Descending Stage
Brick Wall	$P/P_u = 11.012\,\Delta/\Delta_u$	$P/P_u = 0.227 + 2.608\,\Delta/\Delta_u$	$P/P_u = 0.849 + 0.151\,\Delta/\Delta_u$	$P/P_u = 1.104 - 0.104\,\Delta/\Delta_u$
Hollow-block Wall	$P/P_u = 11.036\,\Delta/\Delta_u$	$P/P_u = 0.501 + 1.535\,\Delta/\Delta_u$	$P/P_u = 0.837 + 0.163\,\Delta/\Delta_u$	$P/P_u = 1.197 - 0.197\,\Delta/\Delta_u$
Hollow-block Wall with Core Columns	$P/P_u = 8.052\,\Delta/\Delta_u$	$P/P_u = 0.319 + 1.785\,\Delta/\Delta_u$	$P/P_u = 0.688 + 0.312\,\Delta/\Delta_u$	$P/P_u = 1.175 - 0.175\,\Delta/\Delta_u$

TABLE 5. Equations of Load-Deformation Curve

here, P_u - ultimate load;

Δ_u - displacement at ultimate load.

The displacement corresponding to every turning point of load-deformation curve is listed in Table 6.

Type of Test Wall	Δ_c mm	Δ_c/H %	Δ_u mm	Δ_u/H %	Δ_w mm	Δ_w/H %	Δ_u/Δ_c %	Δ_w/Δ_c %
Brick Wall	1.28	0.128	5.06	0.506	10.27	1.027	3.95	8.02
Hollow-block Wall	1.99	0.166	8.13	0.678	12.25	1.021	4.09	6.16
Hollow -block Wall with Core Columns	1.99	0.166	7.95	0.663	12.50	1.042	3.99	6.28

TABLE 6. Displacement of Turning Points on Load-Deformation Curves

here, Δ_c - displacement, corresponding to that the crack develops obviously in wall and the displacement starts to increase rapidly;

Δ_w - work displacement, corresponding to that the load-deformation curve enters into the descending range, the loading gradually decreases to 90% of ultimate load and the crack development in wall is not too severe;

H - height of wall.

From Table 6, when the load-resisting capacity was kept to 90% of ultimate load, the hollow-block wall with core columns had the maximum relative displacement Δ_w/H, namely, the descending range of its load-deformation curve sloped gently and its decreasing of load-resisting capacity was the slowest. According to the comparison among the ratios Δ_u/Δ_c or Δ_w/Δ_c of three type walls, there were no obvious difference about their ductilites.

4.5 Idealization of Hysteresis Loop

By investigating the hysteresis curve of block walls, the hysteresis loop of hollow-block walls in every loading cycle might be replaced with a parallelogram. Two top points of the parallelogram were on the load-deformation curve, the other two were put in the second and fourth quadrants of a right-angle coordinate. The equation of hysteresis loop in every loading or displacement grade was determined in accordance with test data. The hysteresis loop of the hollow-block wall with core columns was more complicated and not easy to simplify. A parallelogram would also be used roughly replacing it here. Two top points of the figure were on the load-deformation curve and the other two were put on Δ-axis. The equation of hysteresis loop was defined on the basis of the principle of energy equivalence. The idealization of hysteresis loop is shown in Fig. 5. The slope equations of the straight line sides of the hysteresis loop models were defined by regression of the slopes of the equations obtained above.

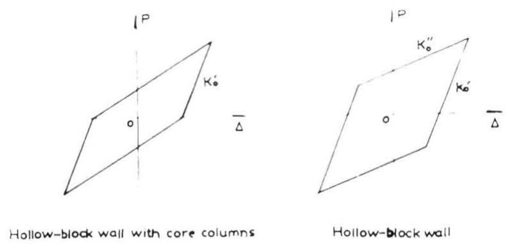

Fig. 5. Idealization of Hysteresis Loop for Block Wall

For hollow-block wall: $K'_o = K_o(\Delta/\Delta_o)-0.51$, $K''_o = 8.96(\Delta/\Delta_o)^{-0.96}$;

For hollow-block wall with core columns: $K'_o = K_o(\Delta/\Delta_o)^{-0.46}$.

here, K_o - initial stiffness;

Δ_o - displacement at first crack in wall.

4.6 Calculating Model of Restoring Force

After idealizing the load-deformation curve and the hysteresis loop for block wall, a suggestion that the calculating model of restoring force be taken as a degrading stiffness quadrulinear model could be presented. This model might present the relationship between load and displacement in every loading cycle. The model is shown in Fig. 6.

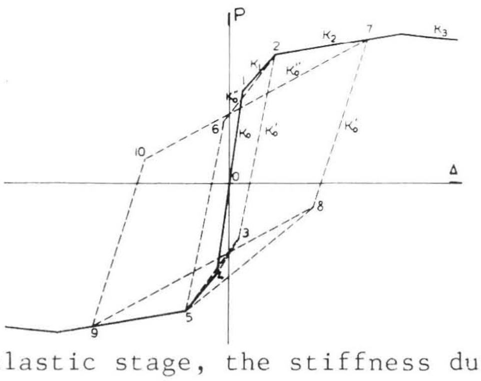

Fig. 6. Calculating Model of Restoring Force

For elastic stage, the stiffness during loading and unloading was K_o ; from first crack to obvious crack, the stiffness was K_1 ; from obvious crack to

ultimate load, the stiffness was K_2 ; in descending range, the stiffness was K_3 until work load Pw and appropriate displacement Δ_w . For hollow-block walls with core columns, the unloading stiffness was K'_o, and the control points 8 and 10 were on Δ-axis. For hollow-block walls, two control points could be obtained by intersecting points of two adjacent sides of hysteresis loop. The slopes of two sides of hysteresis loop were K'_o and K''_o respectively. During the hysteresis response of block walls under reversed cyclic loading, after unloading or then reversed loading to the control point, the process would direct the farthest unloading point having reached along the loading direction.

5. CONCLUSION

1. There is no obvious difference between deformation properties of brick walls and block walls. While Block walls are strengthened by a few reinforced concrete core columns, its deformation properties are not raised too much. Connecting reinforced concrete core columns with ring beams can restrain the deformation of block walls to increase the collapse-resisting capacity.

2. If using a structurally improved masonry unit, such as a block with grooves, hollow-block, or the hollow block with a reinforced concrete core column in its vertical hole, the shearing strength of fly ash block walls will be increased obviously. Practical ultimate loads of above three block walls are multiple of that of solid block wall, i.e. respectively 1.24, 1.29 and 1.48 multiple.

3. From the calculating results the calculation method of the block wall's shearing strength presented accordance with the ultimate state and the shear failure form is much more corresponding to practical state and in safety. It may be used to estimate the practical shearing strength of medium block walls.

4. The calculating model of restoring force under reversed cyclic horizontal loading is tentatively presented for medium fly ash block walls. It will present a possibility to analyse the response of block walls under seismic load.

6. REFERENCES

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