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EXPERIMENTAL STUDY OF CHINESE TRADITIONAL ROWLOCK CAVITY WALLS UNDER IN-PLANE LOW-CYCLE LOADING

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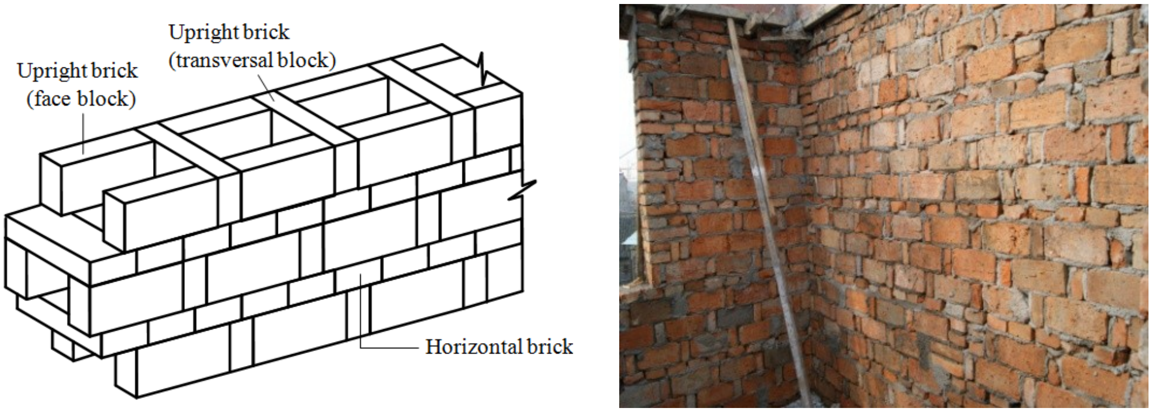
Abstract. *In order to investigate the mechanical behaviour of the rowlock cavity wall, a kind of Chinese unique traditional masonry walls, six rowlock cavity walls with different ratio of height to width and opening of different sizes were designed, and then in-plane low-cycle loading tests were conducted on the walls. From the tests, the cracking patterns, hysteretic behaviour, shear bearing capacity, deformation capacity and energy dissipation were compared and analyzed. The test results indicated that, as the ratio of height to width of the wall increased, the bearing capacity decreased and the ultimate displacement increased, and the failure mode transferred from shear failure to bending failure. As the width of the opening increased, the capacity of shearing resistance and energy dissipation reduced, and the failure mode transferred from shear failure of the entire wall to bending failure of the sidewall. Little influence of the height of the opening was found on the bearing capacity of the walls, but the walls showed a larger ultimate drifting angle.*

1 INTRODUCTION

As a kind of Chinese unique traditional masonry walls, the Chinese traditional rowlock cavity wall (CTRC wall) has been widely used in historic residential constructions since the Ming Dynasty (A.D 1368). Even now, there exist a great number of such structures in historic constructions and rural housing of southern China, and many of them are still in use.

Different from common brick walls, bricks in CTRC walls are divided into two different types, i.e. the upright brick and the horizontal brick. As seen in Figure 1, some upright bricks are put symmetrically along the fringe of horizontal bricks and called face blocks, with some other upright bricks built perpendicular to the wall for support called transversal blocks. In this building way of the wall, a cavity forms among four upright bricks in order to save material.



(a) Composite of rowlock cavity wall (b) In-Situ picture of rowlock cavity walls

Figure1: Building Method of Chinese Rowlock Cavity Walls

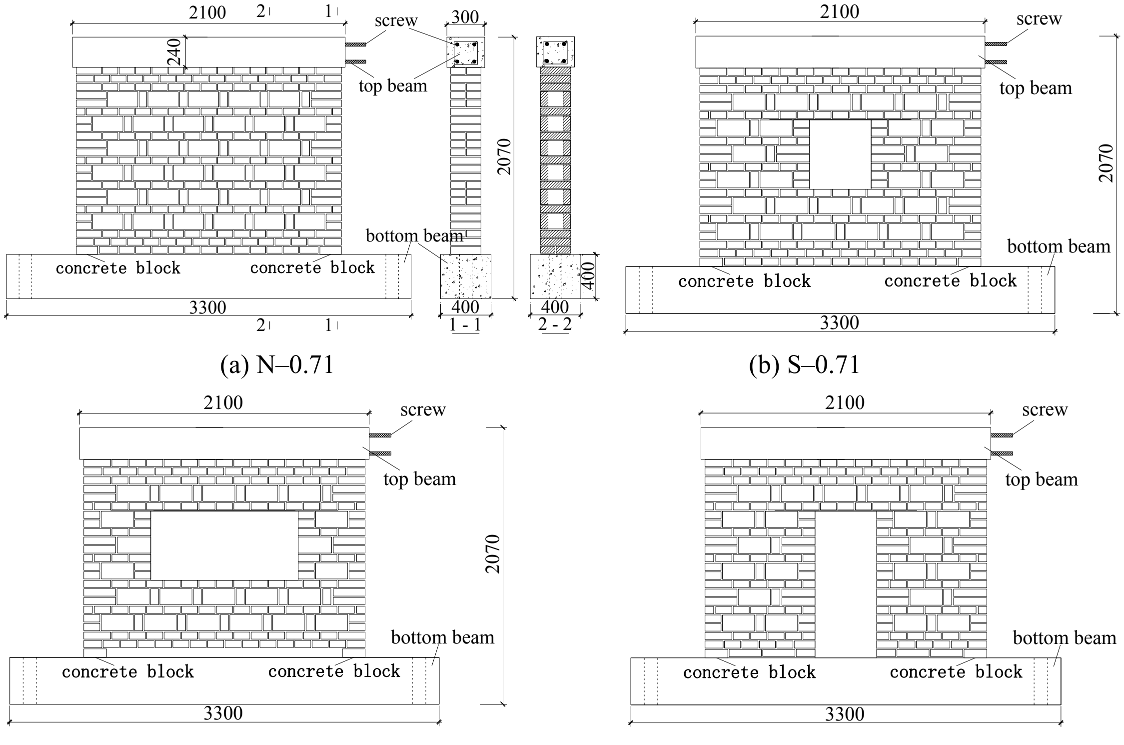
Compared with common solid masonry walls, CTRC walls possess such advantages as high economic performance, lightweight, good thermal and sound insulation. Therefore, it was extensively used in many historic constructions including residential buildings and temples. However, its vulnerability to earthquake disaster can be imagined due to the reduction of efficient shearing area and the less integrity. In order to protect these historic residential constructions from severe earthquake damage, it is very necessary to investigate the seismic behaviour of the CTRC walls, taking the impact of opening into consideration, such as a window or a door[1][2].

An experimental study was carried out, in which, six scaled rowlock cavity walls with different ratio of height to width (aspect ratio) and opening of different sizes were designed, and then in-plane low-cycle loading tests were conducted on the walls[3].The influence of aspect ratio and opening on failure modes, hysteretic behaviour,bearing capacity, deformation capacity and energy dissipation was analyzed.

2 IN-PLANE LOADING TEST OF CTRC WALLS

2.1 Design and preparation of CTRC walls

In order to investigate the seismic behaviour of the CTRC wall , in-plane low-cycle loading tests on the cavity wall were carried out to study its in-plane shearing properties[4]. Six test specimens were designed and made to consider the two main factors, that is, ratio of the height to the width of a wall and the size of opening in the wall. The specimens were casted in the traditional way together with the top and bottom reinforced concrete beams, as shown in Figure 2. In the wall, a layer of upright bricks were laid between two layers of horizontal bricks.



(a) N–0.71

(b) S–0.71

(c) L–0.71

(d) D–0.71

Figure 2: Dimensions of CTRC wall specimen (mm)

Test specimens were numbered according to the size of opening and the aspect ratio of the walls. Take specimen, N-0.71, as an example, N means “No opening”, and 0.71 is its aspect ratio. There are four types of opening in the walls, i.e. no opening (N), small opening 455mm×510mm (S), large opening 1075mm×510mm (L), and door opening 455mm×1075mm (D), and three aspect ratios in the walls, i.e. 0.71, 0.90 and 1.10. Widths of the walls are the same, equals 2055mm, but the height is different to get different aspect ratios. Because most of rural houses of CTRC walls in China are two-story buildings, the vertical stress in real structure’s walls is estimated to be about 0.08MPa [5]. Therefore, the vertical stress in all specimens was chosen to be 0.10MPa in the test, ignoring the contribution of opening areas. Parameters of each specimen are given in Table 1.

Table 1 Parameters of CTRC wall specimens

Specimen	Type of opening	Aspect ratio	Opening dimensions(mm)	Specimen dimensions (mm)	Average mortar strength (MPa)
N-0.71	non	0.71	-	2055×1450×240	2.0
N-0.90	non	0.90	-	2055×1850×240	2.0
N-1.10	non	1.10	-	2055×2250×240	3.6
S-0.71	small	0.71	455×510	2055×1450×240	2.2
L-0.71	large	0.71	1075×510	2055×1450×240	2.2
D-0.71	door	0.71	455×1075	2055×1450×240	4.0

To determine the compressive strength of bricks, ten specimens of 120×120×120mm were made and were loaded on the universal testing machine[6], as shown in Figure 3a. The average compressive strength of bricks is 15.09MPa. The wall specimens were built for four batches. For each batch of the walls, three cubic mortar specimens with the length of 70mm were made, and their compression strengths were tested[7] (Figure 3b) and given in Table 1.

(a) Compression test of brick specimens (b)Compression test of motar specimens

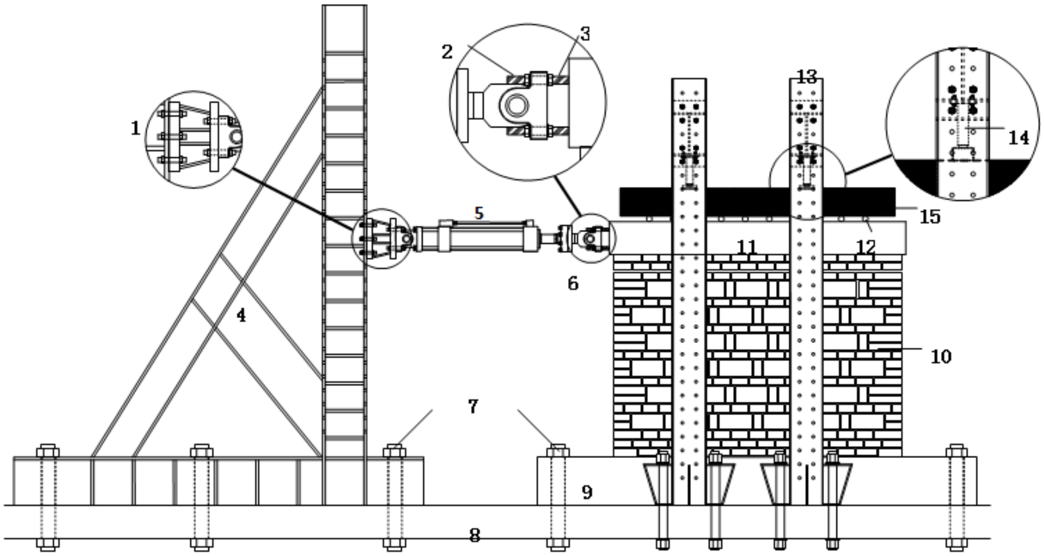
Figure 3: Compression test of brick and mortar specimens

2.2 Test setup and loading method

A 200kN hydraulic servo actuator, was used in the test to apply in-plane low-cycle loading. The vertical load was applied by two 100kN hydraulic jacks on the top of the wall. The test setup is shown in Figure 4.

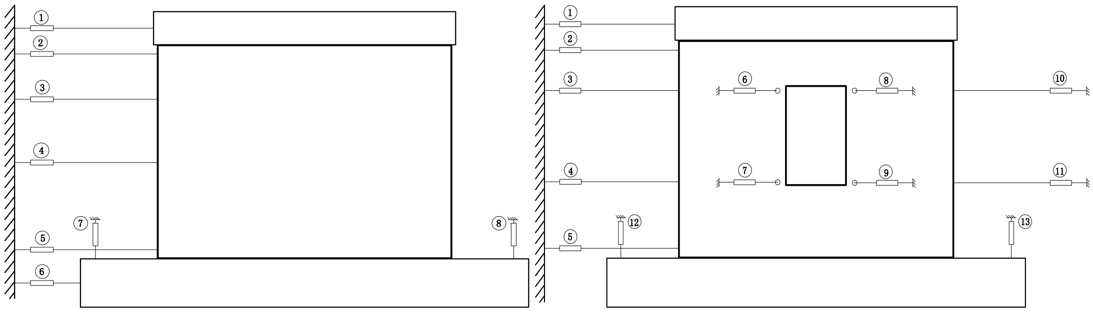
Displacement meters were utilized to determine the deformation of the wall during loading, as shown in Figure 5. Therefore, the absolute displacements at the top, middle, and bottom parts were measured during the test. For the specimens with opening, several displacement meters were also installed at four corners to measure and then analyze the absolute displacement of the side walls.

To achieve 0.1 MPa vertical stress, 49.32kN vertical load was applied on the top of the wall including the weight of the top beam and distribution beam. The vertical load remained unchanged during the test. Then 25% of cracking load was applied for pre-loading, where the cracking load was estimated as 70% of the predicted bearing capacity. Formal loading started with loading control before cracking. Each step of the horizontal reciprocating load was repeated 3 to 5 times. After the wall cracked, the displacement control was used. At the beginning, two times of cracking displacement was applied, then three times of cracking displacement was applied, and so on until the wall failed.



1,2,6. Screw connection; 3. Pre-embedded rebar; 4. Triangular reaction frame; 5. 200kN hydraulic servo actuator; 7. Ground anchor; 8. Pedestal; 9. Bottom concrete beam; 10. Wall specimen; 11. Top beam; 12. Horizontal guide rail; 13. Gantry; 14. Hydraulic jack; 15. Distribution beam

Figure 4: Test setup of CTRC wall specimens



(a) N–0.71，N–0.90，N–1.10 (b) S–0.71，L–0.71

Figure 5: Determination of displacement

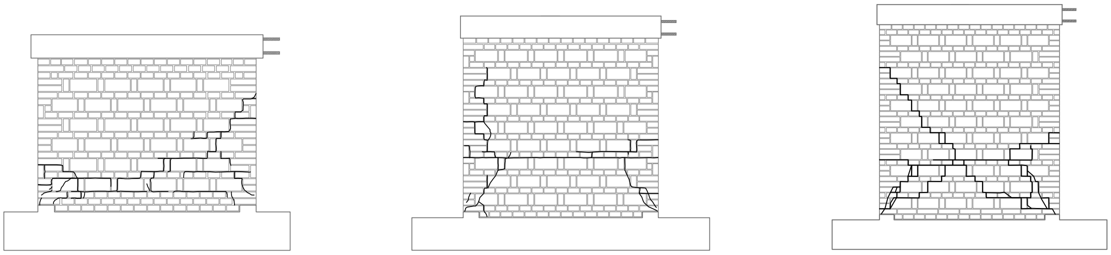
3 TEST RESULTS AND DISCUSSION

3.1 Failure modes

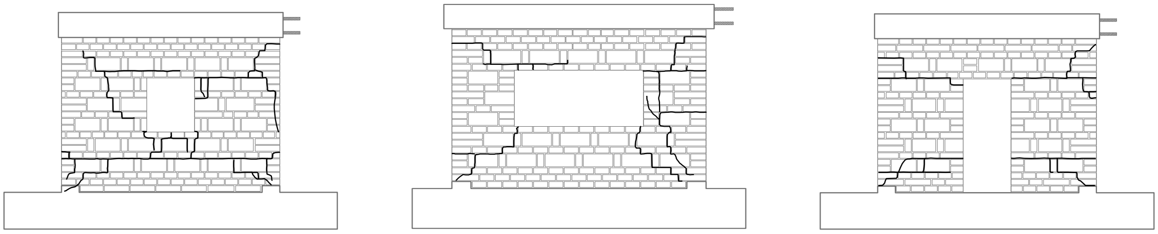
The failure process of the CTRC wall in the test could be divided into three stages: elastic, elasto-plastic and damage stage. When the horizontal load was less than 40% of the ultimate load, the displacement measured on top of the wall was approximately linear to the load. As the load increased further, up to about 50% to 70% of the ultimate load, cracks appeared at the bottom of the wall, and developed with the increasing of load. When the horizontal load achieved the ultimate load, cracks developed continuously with the cyclic loading, and eventually formed the horizontal thorough slit or X shape slit. Failure modes for all the wall can be seen in Figure 6.

Specimen L-0.71 initiated with stair-stepping cracks around the corners of the opening. While all other walls began with horizontal cracks and then stair-stepping cracks generated as the load increased. Finally CTRC walls failed with the simultaneous growing of both load and cracks.

For the walls with a small opening or without an opening, horizontal cracks appeared earlier than stair-stepping cracks, and developed quickly to form a thorough slit. Stair-stepping cracks emerged and developed in the later stage close to failure. The ultimate displacement at failure increases as the aspect ratio increases, showing a tendency of failure mode transferring from shearing failure to flexural failure. However, for the walls with a larger opening, i.e. L-0.71and D-0.71, damage of the walls initiated with stair-stepping cracks around the corners of the opening, (and the walls finally failed by one of the sidewalls.) and the entire wall failed with the separate failing of two sidewalls. and the entire wall failed with two sidewalls failing one by one.



(a) N-0.71 (b) N-0.90 (c) N-1.10



(d) S-0.71 (e) L-0.71 (f) D-0.71

Figure 6: Cracking of CTRC wall specimens

3.2 Hysteretic curves and skeleton curves of load-displacement

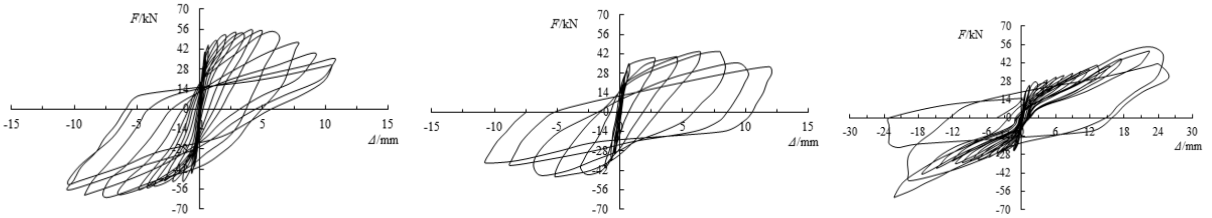
Hysteretic curves and skeleton curves of load-displacement for specimens are showed in Figure 7 and Figure 8.

Before cracking, hysteretic curves are nearly linear, meaning that their stiffness remains nearly unchanged. After cracking, their stiffness decreases, with the curves showing inclined to X-axis.

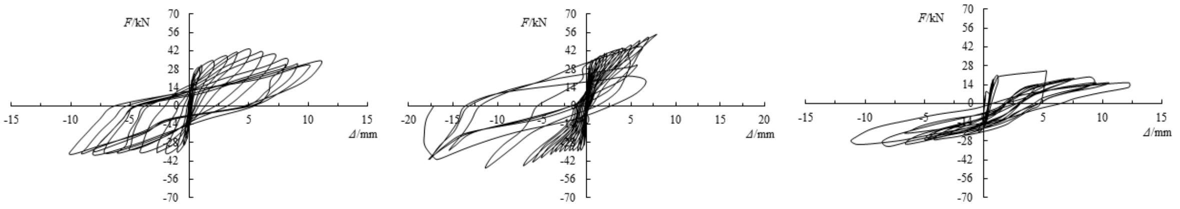
It can be seen from Figure 8a, the maximum displacement increases for the walls with a increaseing aspect ratio, but the hysteresis loop area gradually reduces, which means worse energy dissipation performance.

As the opening area of wall increases, both hysteresis loop area and horizontal peak load decrease, showing a worse energy dissipation performance, as shown in Figure 8b.

Specimen D-0.71, with a door opening, has a similar hysteretic curve with specimen N-1.10 in the early stage, reflecting a similar characteristic to the high aspect ratio wall. But in the later stage, due to severe wall cracking, two sidewalls work separately, which results in its hysteretic curve deviating from the origin.

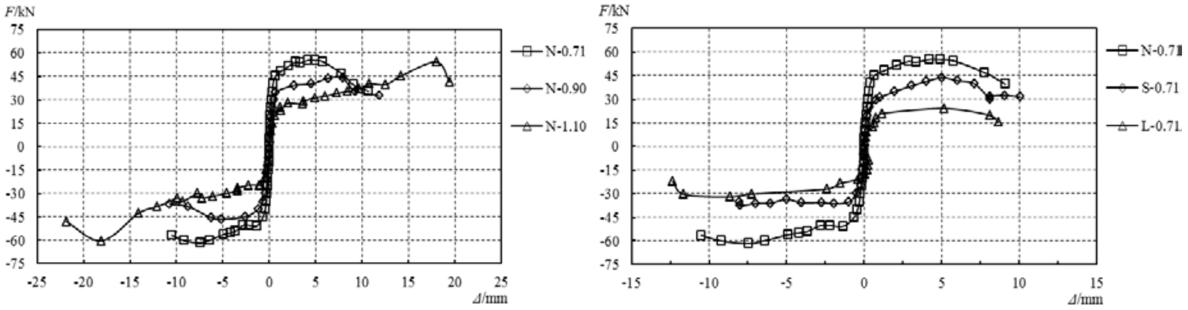


(a) N-0.71 (b) N-0.90 (c) N-1.1

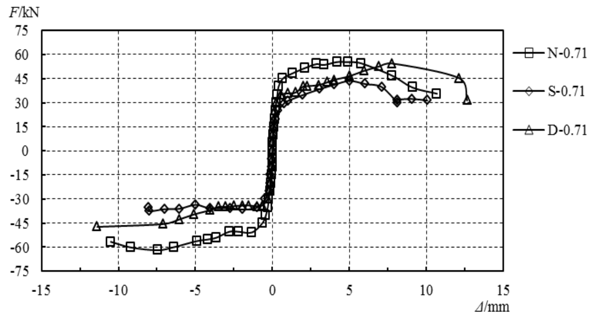


(d) S-0.71 (e) L-0.71 (f) D-0.71

Figure 7: Hysteretic curves for CTRC wall specimens



(a) Walls with different aspect ratio: (b) Walls with different opening width:



(c) Walls with different opening height

Figure 8: Skeleton curves of load-displacement relationship

3.3 Bearing capacity and deformation capacity

Characteristic load and displacement of the tested walls are given in Table 2. It can be seen that, for the walls without opening, both the cracking load and ultimate load decrease as the aspect ratio increases, while the corresponding displacement increases. For specimens N-0.71 and N-0.90, the ratio of cracking load to ultimate load ranges from 0.727 to 0.813, showing high brittleness. As the aspect ratio increases to 1.10 (N-1.10), the ratio of cracking load to ultimate load rapidly decreases to 0.414 ~ 0.460, meaning the brittleness of the wall reduced. It also indicates that the failure mode transfers from shear failure to bending failure with the increasing aspect ratio.

Compared with the wall without opening, It can also be found that the wall with an opening has a reduced ultimate bearing capacity, and the wall with the wider opening has the lower bearing capacity. However, it can be derived that, the increasing width of the opening has no significant impact on the ultimate deformation capacity, since the ultimate displacement and drifting angle are just slightly changed. The increasing of the height of the opening has little effect on the bearing capacity of the wall, but results in a larger ultimate drifting angle.

Table 2: Characteristic load and displacement of CTRC wall specimens

Specimen number	Compression stress σ_0 (MPa)	Mortar strength f_2 (MPa)	Cracking		Ultimate		P_c/P_u	Ultimate drifting angle
			Load P_c (kN)	Displacement Δ_c (mm)	Load P_u (kN)	Displacement Δ_u (mm)		
N-0.71	0.1	2.0	+45.00	+0.66	+55.38	+7.77	0.813	1/146
			-45.00	-0.66	-61.87	-10.21	0.727	
N-0.90	0.1	2.0	+35.00	+0.72	+43.83	+9.26	0.799	1/176
			-35.00	-0.69	-46.62	-10.72	0.751	
N-1.10	0.1	3.6	+25.00	+1.58	+54.36	+24.14	0.460	1/114
			-25.00	-1.42	-60.36	-19.68	0.414	

S-0.71	0.1	2.2	+25.00	+0.38	+43.61	+8.09	0.573	1/145
			-25.00	-0.20	-37.57	-10.07	0.665	
L-0.71	0.1	2.2	+24.00	+1.54	+24.16	+7.51	0.993	1/147
			-21.00	-0.37	-32.01	-10.06	0.656	
D-0.71	0.1	4.0	+15.00	+0.40	+54.48	+12.14	0.275	1/119
			-22.98	-0.29	-47.37	-11.58	0.485	

3.4 Energy dissipation capacity

The equivalent viscous damping coefficient h_e, proposed by Jcobson, is adopted to evaluate the seismic energy dissipation capacity of CTRC wall [8]. It is calculated according to Equation 1, where S_{ABC} and S_{OBD} represent the envelope area of the corresponding shapes in Figure 9.The calculation results for the specimens are given in Table 3.

$$h_e = \frac{1}{2\pi} \times \frac{S_{ABC}}{S_{OBD}} \tag{1}$$

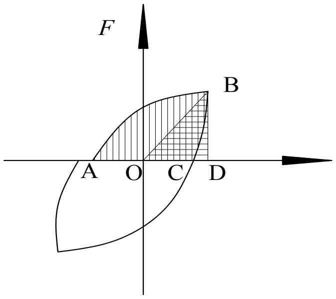


Figure 9: Calculation method of equivalent viscous damping coefficient

Table 3: Equivalent viscous damping coefficients

Number	Cracking load			Ultimate load			Failure load		
	S_{ABC} (N·m)	S_{OBD} (N·m)	h_e	S_{ABC} (N·m)	S_{OBD} (N·m)	h_e	S_{ABC} (N·m)	S_{OBD} (N·m)	h_e
N-0.71	11.91	15.08	0.13	355.15	230.16	0.25	326.20	276.30	0.19
N-0.90	4.85	12.61	0.06	195.80	120.28	0.26	402.11	197.91	0.32
N-1.10	8.80	17.75	0.08	286.77	672.41	0.07	727.41	494.86	0.23
S-0.71	3.83	4.74	0.13	101.99	109.46	0.15	204.77	190.71	0.17
L-0.71	50.76	18.87	0.43	101.67	128.84	0.13	74.13	73.42	0.16
D-0.71	0.74	0.52	0.23	72.17	212.20	0.05	338.65	139.07	0.38

It can be seen from Table 3 that all the equivalent viscous damping coefficient of CTRC walls are less than 0.5, giving the conclusion that CTRC walls perform poor energy dissipation ability as expected. Through further comparison, it can be found that, the equivalent viscous damping coefficient of the wall without opening decreased with increasing aspect ratio. Comparing h_e of the specimen N-0.71, S-0.71 and D-0.71, it can be concluded that, the energy dissipation ability decreases obviously as the height of opening increases.

4 CONCLUSION

CTRC walls showed poor seismic performance in the test. Generally, horizontal cracks through the mortar appear and develop at the early stage of loading. After that, stair-stepping cracks appear, and quickly lead to brittle failure.

The wall with a larger aspect ratio has a larger ultimate drifting angle and a lower energy dissipation ability, showing a tendency of transferring from shearing failure to flexural failure.

The increasing opening area in the wall aggravates its seismic bearing capacity and energy dissipation ability by showing lower cracking and ultimate load. However, the height of the opening seems to have little influence on the bearing capacity. Due to the side walls with a higher aspect ratio, the wall with a higher opening has a larger ultimate drifting angle.

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