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EXPERIMENTAL STUDY ON STRUCTURAL PERFORMANCE OF GROUTED RC BLOCK WALL/BEAM COMPOSITION

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ABSTRACT
A reinforced grouted concrete block wall/beam, composed of cast-in-place concrete beam and reinforced grouted block wall, is common in mixed retail/commercial and residential construction in China. Often the ground floor houses a shop and commercial storage and residential flats are built on the floors above. In such buildings the ground floor is built as a reinforced concrete (RC) frame with or without shear walls and the upper floors are built with walls of reinforced grouted concrete blocks. According to Chinese code, the RC beam depth to span ratio for wall/beam composition should be greater than or equal to 1/6 for seismic design. Compared to a RC beam with unreinforced masonry (URM) wall on top of it, the reinforced grouted concrete block wall/beam structure has greater stiffness. The higher stiffness can help reducing the cast-in-place RC beam depth to span ratio, and thus increase the height of the ground floor. In this paper, test results for six different wall/beam compositions are presented. The structural capacity, the load-deformation relationship, force-transferring path, and failure mode are examined. The experiments show that the reinforced block wall/beam acts like a deep beam. It was found that the RC beam depth to span ratio can be reduced from 1/6 to 1/10.5.

KEYWORDS: reinforced grouted concrete block, wall/beam, depth to span ratio.

INTRODUCTION
At present, the reinforced grouted concrete block shear wall structures are promoted in China instead of more traditional un-reinforced clay brick masonry (URM). This type of construction has some advantages over URM such as improved bearing capacity and earthquake-resistance. However, usually it is not used for the lower floors, which house a shop and commercial storage and require large open spaces. Reinforced (RC) frame or RC frame combined with masonry shear walls better meet this requirement for the lower floors. The reinforced grouted concrete block walls of the floor above RC frame sit on the cast-in-place RC beam (trimmer beam). This forms a reinforced masonry wall/trimmer beam composition, which is studied in this paper.

Current Chinese design codes do not provided guidance on the design of such wall/beam compositions. Publications on this topic are also limited. The most relevant one is He and Tang [1]. In this paper it was shown that reinforced masonry wall working together with the trimmer beam forms solid reinforced masonry wall/beam composition and exhibit characteristics similar to a deep RC beam.

The objective of this paper is to gain better understanding of performance of reinforced masonry wall/trimmer beam composition under vertical uniform load. One solid wall/beam composition and five wall/beam compositions with openings in the wall were tested. The effect of wall openings and the depth of the trimmer beam on the composition load capacity were studied, and the authors proposed to use an arch and tie model for strength prediction of these wall/beam compositions. The trimmer beam is modelled as tensile tie and the vertical load forms a compressive arch around opening in the wall. This concept is supported by the crack patterns mapped on the surface of specimens and by strains measured on vertical rebars.

According to Chinese code, the RC beam depth to span ratio for wall/beam composition should be greater than or equal to 1/6 for seismic design. Compared to a RC beam with URM wall on top of it, the reinforced grouted concrete block wall/beam structure has greater stiffness. The higher stiffness can help reducing the cast-in-place RC beam depth to span ratio, and thus increase the height of the ground floor. Hence, another objective of this paper is to propose an appropriate depth to span ratio for a trimmer beam in the wall/beam composition. The authors believe that for depth to span ratio of RC beam the restriction of 1/6 without considering working together between wall and beam for the present Chinese code is too conservative.

SPECIMEN DESIGN AND FABRICATION

Six reinforced grouted masonry wall/RC trimmer beam specimens with overall dimension of 2400 mm - length, 1600 mm (1700 mm) - height and 190 mm - thickness were designed and fabricated. One wall/beam specimen denoted as WB6 was solid, the other five (WB1-WB5) had openings in the wall to study the effect of the opening size and location. The masonry walls were made of concrete blocks with dimension of $390 \times 190 \times 190$ mm or $190 \times 190 \times 190$ mm, reinforced with uniformly distributed vertical and horizontal reinforcement and fully grouted. All wall/beams were designed to be simply supported and the trimmers were reinforced with sectional reinforcement ratio 4.71% and 3.14% of longitudinal main steel for 200 mm and 300 mm deep beams respectively to prevent flexural failure. The cast-in-place top RC beam was formed on top of each specimen to improve load transfer to the wall during testing. For all specimens, the vertical reinforcement ran from the cast-in-place trimmer concrete beam to the top beam with cogs at the top and bottom. The stirrups were mild steel plain rebar, whereas vertical, horizontal reinforcement in wall and the longitudinal reinforcement of trimmer beam were high strength deformed rebar. Design details of these specimens are shown in Table 1 and Figure 1.

Because the longitudinal beam reinforcement is in tension during testing it needs good anchorage. It was fixed by plug welding to the 10 mm steel plates shown in Fig. 1 (i) installed at both ends of the trimmer beam. The trimmer beams of all specimens were cast by ready-mix concrete. At the same time, the vertical reinforcement bars for the masonry walls were embedded into the trimmer beam. Four lifting hooks for every trimmer beam were also built-in. All trimmer beams were cured for three days after casting before construction of walls. Fine aggregate concrete was used for grouting of masonry. Top beams were cast three days later.

Block, concrete, mortar and reinforcement samples were taken at the time of specimen fabrication. These samples were tested to determine mechanical properties for each material. The average compressive strength for all constituents is presented in Table 2 and the mechanical properties of reinforcement steel in Table 3.

Table 1: Specimen Details

Wall/beam No.	Dimension of Opening (mm)	Vertical Steel in Wall	Horizontal Steel in Wall	Trimmer Beam		
				Beam Depth (mm)	Longitudinal	Stirrup
WB1	800×1000	ø12@200	ø12@400	200	6ø20	ø8@100
WB2	800×800	ø12@200	ø12@400	200	6ø20	ø8@100
WB3	800×1200	ø12@200	ø12@400	200	6ø20	ø8@100
WB4	800×1000	ø12@200	ø12@400	300	6ø20	ø8@100
WB5	600×1000	ø12@200	ø12@400	300	6ø20	ø8@100
WB6	Solid	ø12@200	ø12@400	200	6ø20	ø8@100

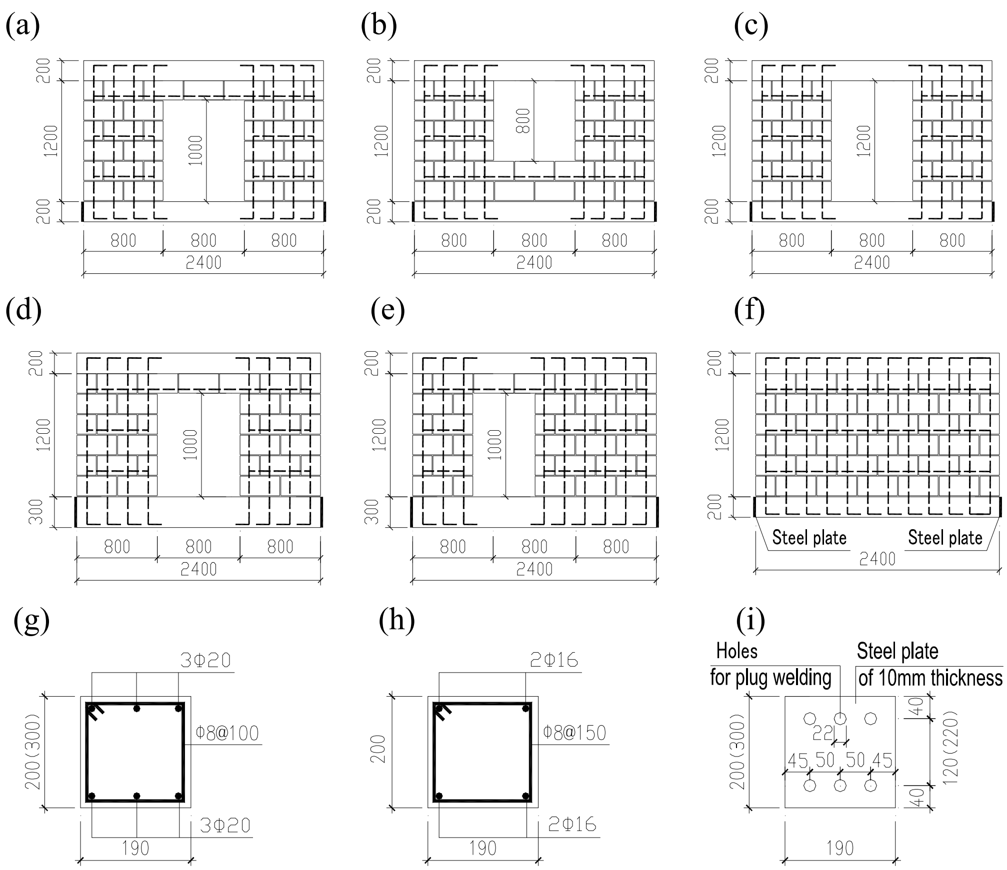

Figure 1: Test Specimens: a) WB1; b) WB2; c) WB3; d) WB4; e) WB5; f) WB6; g) Sectional Steel for Trimmer Beam; h) Sectional Steel for Top-Beam; i) Bolting Steel Plate

Table 2: Average Compressive Strength of Materials

Material	Specimen No	Average Load (kN)	Average compressive strength (N/mm^2)
Block	WB1-WB6	913.1	12.32
Mortar	WB1-WB6	53.0	10.60
Concrete of Top Beam	WB1,WB2	328.5	31.21
	WB3,WB5	454.7	43.20
	WB4,WB6	310.7	29.52
Concrete of Trimmer Beam	WB1,WB6	488.0	46.36
	WB2,WB3	441.0	41.90
	WB4	430.7	40.92
	WB5	439.3	41.73
Concrete Grout	WB1	298.0	28.31
	WB2	284.7	27.05
	WB3	232.0	22.04
	WB4	217.7	20.68
	WB5	202.3	19.22
	WB6	244.0	23.18

Note: The dimensions of material samples are respectively 190×190×390 mm for block, cube of 70.7 mm for mortar and cube of 100 mm for concrete.

Table 3: Mechanical Properties of Reinforcement

Reinforcement	Average yield tensile strength f_y (N/mm^2)	Average ultimate tensile strength f_u (N/mm^2)	Average elastic modulus E_s (N/mm^2)
ø8	290.3	415.5	210000
ø12	383.2	575.2	203400
ø16	361.7	557.2	182000
ø20	358.8	551.0	203300

TEST INSTRUMENTATION AND TESTING PROCEDURE

The test set-up is shown in Figure 2. The monotonic compressive loading is applied to a wall/beam specimen by a hydraulic pressure machine of 5000 kN capacity. Every load increment was about 10% of the expected ultimate load, and it was gradually applied during approximately one minute. The transfer steel beams react to the applied load with approximately uniform pressure on the top beam of the specimen. The rigid seats on the simple supports are designed to prevent stress concentration and premature damage in the support zone. Strains on wall/beam surfaces and in the embedded reinforcement were measured through electronic strain gauges. Load and strains were automatically recorded by a computer data acquisition system during the test. In addition, specimens were constantly checked for crack initiation and propagation. These were marked on the white-washed surfaces of the specimen after each load increment.

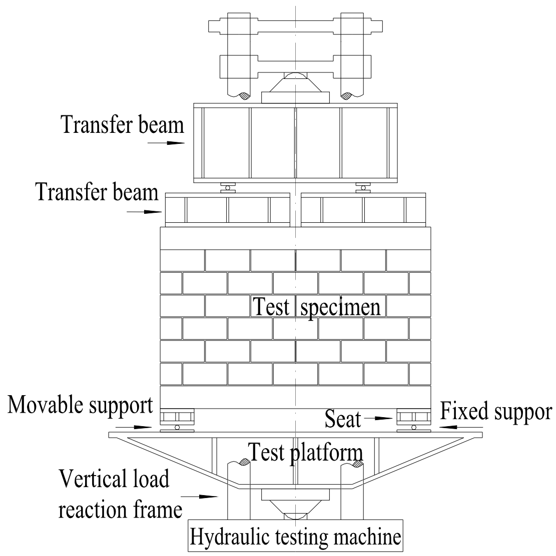

Figure 2: Test Set-up

TEST RESULTS

The first crack load and the ultimate load (i.e. the maximum load during test) of all specimens are presented in Table 4. Regarding the cracking load P_c (the load associated with the formation of fist crack on the specimen) in Table 4, there is a probability that the actual first crack was not found and correctly recorded because it was too difficult to identify small cracks, especially those developing in mortar joints. Hence, the values of P_c in Table 4 might overestimate the actual cracking load.

Table 4: Summary of Test Results

Specimen No	cracking load P_c（kN）	ultimate load P_u(kN)	P_c/ P_u	Maximum Mid-Span Deflection (mm)
WB1	1000	2650	0.38	4.44
WB2	800	2500	0.32	5.16
WB3	1000	2200	0.45	4.52
WB4	600	2800	0.21	5.57
WB5	900	2100	0.43	4.67
WB6	1100	3160	0.35	5.94

The first crack location and the crack pattern at the failure for all specimens are shown in Figure 3. The load deflection curves of all the six specimens are shown in Figure 4. Figure 4 shows that the mid-span deflection in all tests appeared to grow linearly with the load except for the final stages of the test when specimens are already damaged. The last one or two readings from the displacement dial indicators just before the failure and potential collapse of specimens were not recorded due to the safety reasons. Comparing specimens with openings (WB1-WB5) to the solid specimen WB6, the deflection of specimens with openings was slightly greater (except WB1) than the solid WB6 for the same external load. It was expected because an opening reduces the stiffness of a wall/beam composition. The deflection of specimen WB1 was only measured by a displacement meter at mid-span, while the deflections of WB2-WB6 were obtained by three dial indicators at mid-span and two quarter spans, respectively. Also, there are consistent data between the deflections of three dial indicators for each specimen of WB2-WB6. So, an error of the displacement meter for WB1 may be one of the reasons that the specimen WB1 appeared to be stiffer than a solid specimen WB6. Also, the specimen WB1 had the highest strength of concrete grouted than the other five of specimens.

It appears that the deflection of specimens was less influenced by the depth of the trimmer beam and the size of the opening and more dependent on the opening position and its obstruction to the formation of an effective compressive arch. The ratio of the deflection at failure to the span was approximately 1/350-1/480.

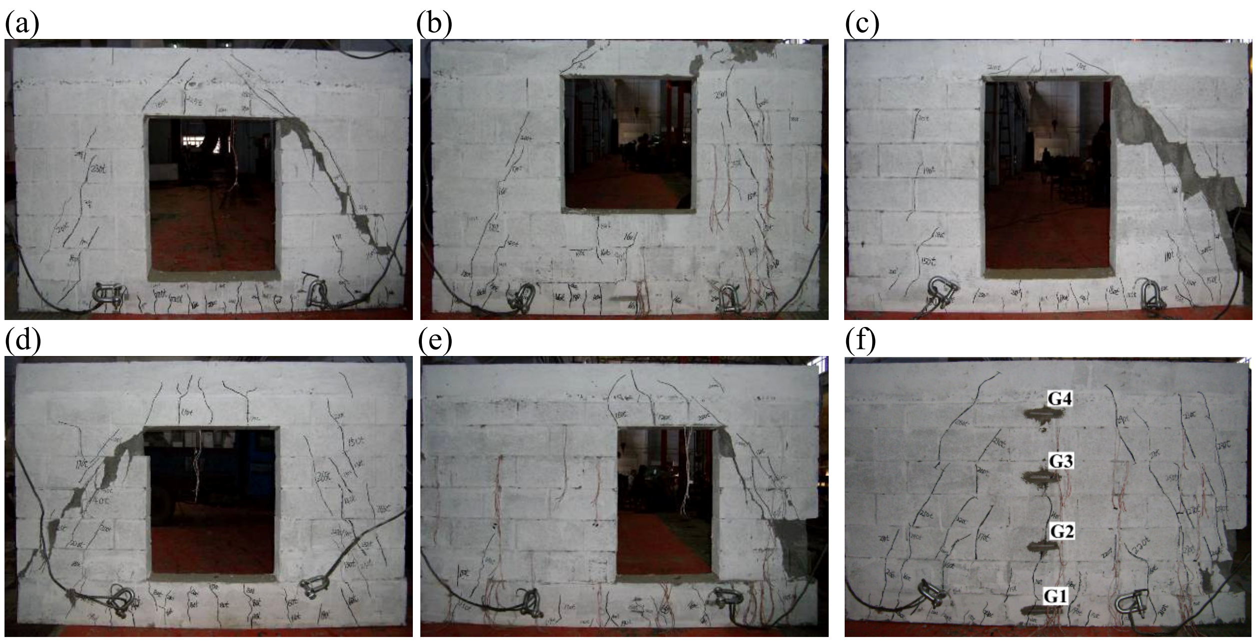

Figure 3: Crack Patterns: a) WB1; b) WB2; c) WB3; d) WB4; e) WB5; f) WB6

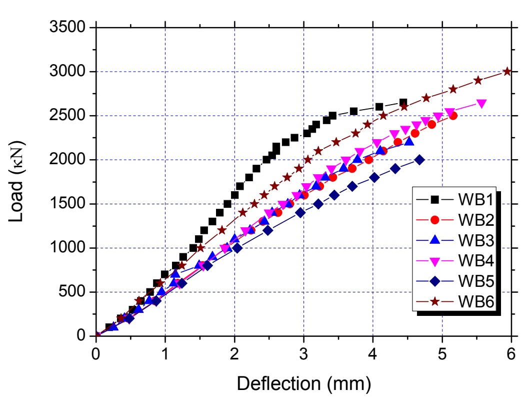

Figure 4: Mid-Span Deflection of Specimens

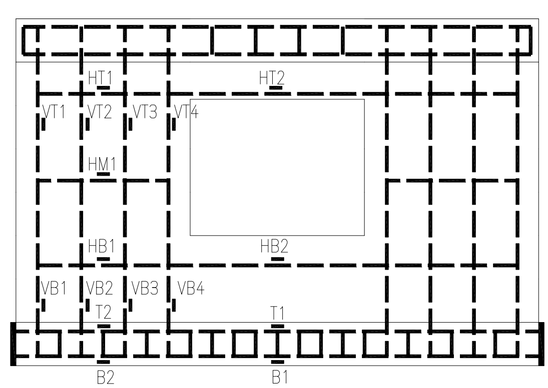

Figure 5: Locations of Strain Gauges

STRAIN OF THE LONGITUDINAL REBARS IN TRIMMER BEAM

Four strain gages were attached to longitudinal rebars inside the trimmer beam (see Figure 5). The evolution curves of the rebar strains in the trimmer beams of WB2 and WB6 are shown in Figure 6 (a) and (b). The strain of the longitudinal rebar at the bottom layer (B1, B2) and top layer (T1, T2) is plotted against applied load. Clearly, none of the rebars yielded. The strains in the bottom rebar were mostly larger than ones in the top rebar, and the strain at the top and bottom was approximately equal at the same location. It indicates that the trimmer beam behaves as an eccentrically tensioned member.

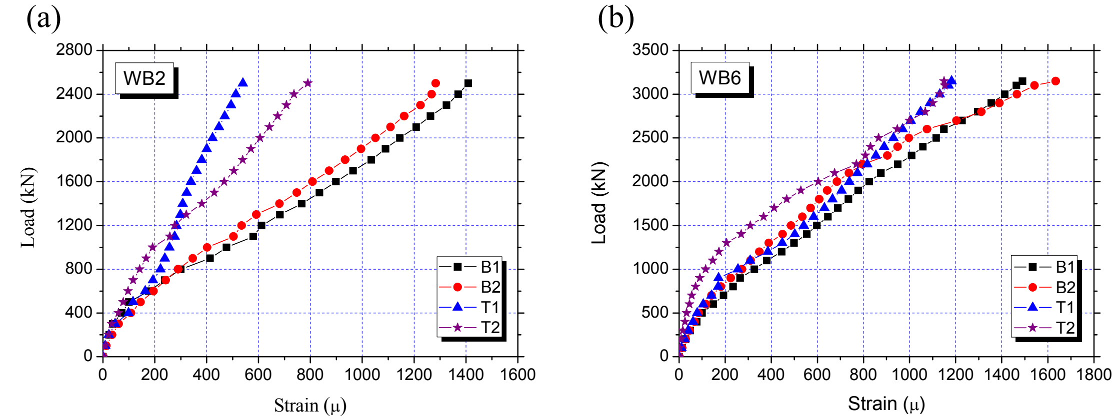

Figure 6: Strains of Longitudinal Bars in Trimmer Beam: a) WB2; b) WB6

STRAIN OF THE VERTICAL BARS IN REINFORCED MASONRY WALL

Figure 7 show the strain evolution curves for vertical reinforcement inside masonry wall WB2 (see Figure 5 for strain gage locations). Figure 7 (a) shows the rebar strains in the bottom layer of the wall and Figure 7 (b) shows the strains in the top layer. A review of Figure 7 indicates that (i) the highest compressive strains in the bottom layer were near the support and (ii) the highest compressive strains in the top layer were near the opening. This supports the concept of load transfer in reinforced grouted concrete block wall by compressive arch-action, namely, the vertical load is mostly transferred along arch down to two support seats, which is similar to the load transfer mode for masonry bridge [2,3]. There is a stress change for VB2 in figure 7 (a), which can be explained by relative sliding of masonry along the diagonal crack.

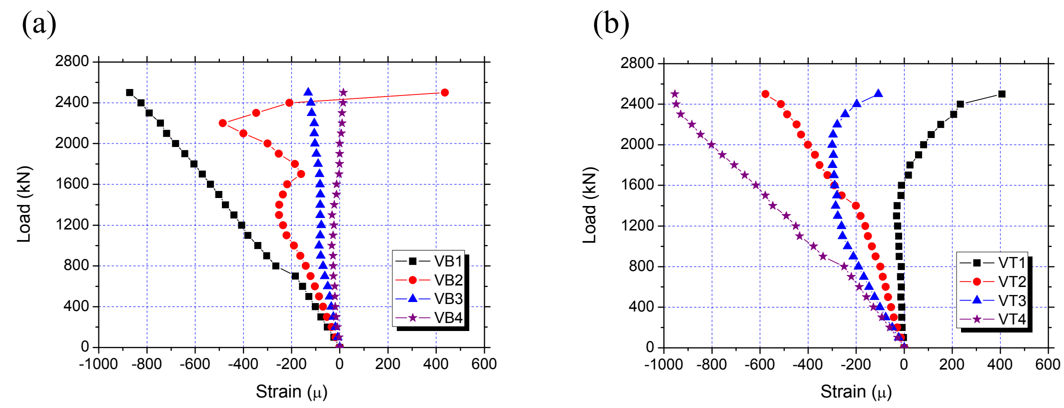

Figure 7: Strains of vertical Bars in Masonry Wall WB2: a) In Bottom; B) In Top

STRAIN OF THE HORIZONTAL BARS IN REINFORCED MASONRY WALL

Figure 8 shows the strain evolution curves for horizontal reinforcement inside masonry wall WB1 (see Figure 5 for strain gage locations). The tensile strain HB1 is linear at the beginning and then the strain rate increases as the wall experiences more cracking. The tensile strain HM1 is within the assumed compressive arch. It is also linear at the beginning and then strain rate increases rapidly and strain jumps over the yield limit as diagonal cracks develop. Strain HT1 is at about 45º to the principal compressive stress in the assumed compressive arch. Hence it is compressive at the beginning. It changes to a tensile strain and also jumps over the yield limit as diagonal cracks develop. The yield of reinforcement means diagonally cracked grouted masonry sheds its load to the horizontal steel at the location of diagonal cracking and it can be illustrated by crack patterns at failure of wall WB1, see Figure 3 (a). The tensile strain HT2 increases linearly until approximately 1000 kN load. Then, as a compressive arch is formed above it, strain HT2 remains almost constant and increases only slightly just before the failure of the wall.

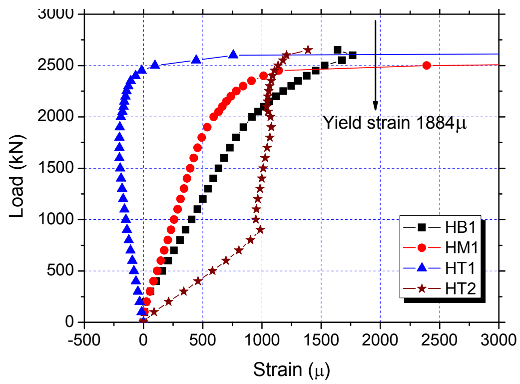

Figure 8: Strains of Horizontal Bars in Masonry Wall WB1

STRUCTURAL BEHAVIOUR OF WALL/BEAM COMPOSITION

The trimmer beam has strong reinforcement, which did not yield in all the six specimens. The six reinforced masonry walls failed in shear, which can be seen from the crack patterns.

Based on the observed crack patterns of specimens and the strain of reinforcement, the load paths in the reinforced grouted masonry wall/trimmer beam composition can be characterised by arch action as shown in Figure 9. This is similar to a RC deep beam [4-6].

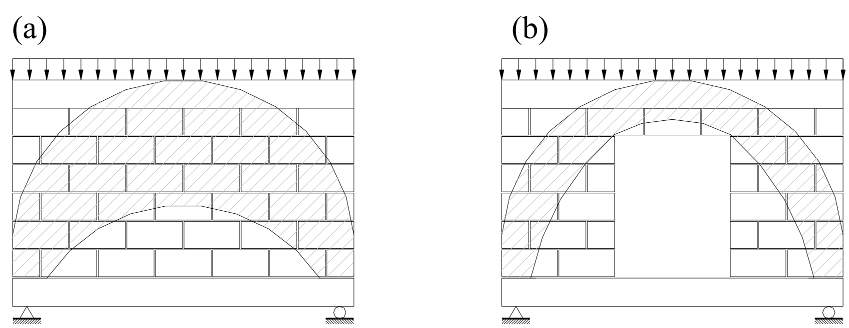

Figure 9: Arch Action of Simply Supported Reinforced Concrete Masonry Wall/Beam: a) Wall/Beam without Opening; b) Wall/Beam with Opening

DISCUSSION ABOUT DEPTH OF TRIMMER BEAM AND WALL OPENING

Specimens WB1 and WB4 have the same position and dimension of wall opening but different depth of trimmer beam (the depth is 200 mm for WB1 and 300 mm for WB4). There is no significant difference in bearing capacity, which is greater by 5.7% for WB4 with 300 mm trimmer beam. It indicates that the bearing capacity of reinforced grouted concrete block wall/beam is not strongly influenced by the depth of the trimmer beam.

The test results show that the failures of all specimens were not caused by failure of trimmer beams, so the depth to span ratio of 1/10.5 used in this test appears to be adequate. There is a possibility to further decrease the size of the beam and revise the restriction of Chinese codes [7,8]. According to Chinese code GB 50011 [7] a depth-to-span ratio of at least 1/10 is need to be satisfied for the frame-supported trimmer beam and URM wall on it. Another Chinese technical specification JGJ 3 [8] also suggests that the depth to span ratio should be greater or equal to 1/8 for a trimmer beam above which are concrete components for non-seismic design and 1/6 for seismic design. In addition, the results from [1] also show that for solid reinforced grouted block masonry wall/beams the depth-to-span ratio can reach 1/17. The results from this study indicate that the simply-supported trimmer depth-to-span ratio can at least be reduced to 1/10.5. This can help to increase clear height of the ground floor to improve its use and economic efficiency. However, the reduction of beam height can leads to the enlargement of stress concentration on the walls near the supports according to the information from some references [9-11].

The bearing capacity of solid specimen WB6 is respectively 1.19, 1.25 and 1.44 times higher than WB1, WB2 and WB3 with central opening. Although the central opening does not completely hinder the arch transfer path, the results show that it may result in a decrease of load-bearing capacity, especially for this type of large opening.

The difference between specimens WB1 and WB3 is one additional row of masonry 190 mm high for WB1, however, the bearing capacity for WB1 increased by 20.5%. Hence, the small increase in the height of wall above an opening plays a significant role in formation of a compressive arch to transfer the load.

Specimens WB4 and WB5 have the same trimmer height of 300 mm and different opening position and dimension (central opening of 800 mm $\times$ 1000 mm for WB4 and non-central opening of 600 mm $\times$ 1000 mm for WB5). But, the bearing capacity for WB5 with smaller non-central opening is less than WB4 by 33.3%. Therefore, the opening position has a significant influence on bearing capacity because the short-leg wall in two of asymmetrical walls may become vulnerable place in arch-transferring path.

CONCLUSIONS

In this paper test results for six reinforced grouted concrete block wall/RC trimmer beam compositions including one solid specimen and five specimens with openings are reported. Masonry wall and cast-in-place RC trimmer beam work together by core columns with vertical reinforcement, and the horizontal reinforcement in the block grooves can provide resistance to shear. Test results show that wall opening can reduce the ultimate bearing capacity of a wall/beam composition, especially non-centrally located openings. The trimmer beam depth, the opening and its position and dimensions have little influence on the deflection of simply supported wall/beams. The deflection-to-span for a wall/beam is about 1/350~1/480. The structural behaviour of reinforced grouted concrete block masonry wall/RC beam composition is a typical tie-arch and it is similar to a RC deep beam. The trimmer beam is modelled as an eccentric tensile member with tensile stress on the whole section. The simply-supported trimmer depth-to-span ratio can be reduced to at least 1/10.5 without causing critical stress concentration on the walls near the supports.

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