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TESTS OF TALL CAVITY WALLS SUBJECTED TO ECCENTRIC LOADING

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ABSTRACT

This paper presents a full scale test program on reinforced slender shear connected cavity walls subjected to an axial compressive eccentric loading. In total, nine walls were tested. All specimens were of partially grouted and reinforced, all were constructed with 190 mm concrete masonry blocks and 90mm brick veneer and all had a slenderness ratio of 27.8. Except for one specimen all walls had a 75 mm cavity. The primary variable, however, was the axial force eccentricity. The eccentricity varied both in magnitude from *t/2* to *t/3*, and in direction, either towards or away from the veneer. Some walls were tested with a single curvature. Others were tested in double curvature. The load-displacement response, failure mode and ultimate load capacities are examined and reported along with the observation and discussion.

INTRODUCTION

A cavity wall constructed with a back up concrete block wythe and a brick veneer wythe separated with an air space and insulation is a wide spread exterior load bearing wall system. However, little information is available on the evaluation of the stiffness and the ultimate load capacity of cavity walls subjected to eccentric vertical loading. Neis et al. (1991) tested six unreinforced and ungrouted tall cavity walls (h/t=30) under a vertical compressive load at an equal end eccentricity. Sakr and Neis (1992) reported a further 15 unreinforced and ungrouted cavity wall series constructed with different tie types at

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slenderness ratios, h/t, of 20 and 30. Goyal et al. (1993) tested seven slender cavity walls (h/t=27.5), four unreinforced and three reinforced specimens, under small eccentricities. This paper presents the experimental phase of a research program aimed to investigate the behavior of partially reinforced tall cavity walls constructed with shear connectors (Hatzinikolas et al. 1994) and subjected to compressive axial forces at large eccentricities of $t/3$ and $t/2$ in various configurations. Four walls were tested under equal top and bottom eccentricities (e_1/e_2=1), three were tested with e_1/e_2=0, and two were tested in double curvature (e_1/e_2=-1)

In the second phase that is also completed and on which a partial report is presented in the same forum (Wang et al. 1995). In it, a nonlinear finite element model of these walls is developed and verified against the experimental results reported herein. In the third phase the finite element model will be used to expand the database to cover parameters not covered in the experimental part. The expanded database will then be used to develop design models to predict the stiffness, ultimate strength and mode of failure of these walls.

MATERIALS AND MATERIAL TESTS

Since the research line projected a nonlinear material model in the numerical phase of the study it was necessary to obtain as much information as possible on the individual components of the system: concrete block units, burnt clay bricks, mortar and grout as well as information on prism properties. The materials used in material tests and full scale wall tests were locally supplied in the Edmonton, Alberta area. Standard tests were conducted on all specimens. The information is summarized in Tables 1 and 2.

Units, Mortar, Grout and Reinforcement
Standard 200 mm hollow concrete block units were used throughout the tests with a nominal compressive strength of 15 MPa (H/15/C/O). Five regular units with a nominal dimension of 200×200×400 mm were tested for uniaxial compressive strength. An additional three regular units were tested to examine their deformation properties. Locally supplied burnt clay brick units were used to construct the veneers of the cavity walls and were used for the brick material tests. Five brick units were tested for the uniaxial compressive strength. Premixed type S mortar was used in constructing the prisms and the walls. Six 50×50×50 mm cubes were cast to test the strength. The grout was mixed in the lab with a concrete mixer. The weight ratio between cement, sand and pea gravel was 1:3.92:2.78. The water cement ratio was 1:1. Five 75×75×150 mm grout prisms were cast and tested to determine the compressive strength of the grout.

Table 1 Unit mechanical properties

		Hollow concrete block units		Brick units		Grout	Mortar
		strength	*E*	*strength*	*E*	*strength*	*strength*
Mean	(MPa)	17.35	16088	29.36	6536	29.40	10.90
Std. Dev.	(MPa)	0.06	-	0.21	-	1.00	0.50

Concrete Masonry and Brick Prisms
Since the 1.2 m wide concrete block wythe of the cavity walls were constructed with only two cores grouted vertically from top to bottom, both grouted and ungrouted prisms were tested for strength and deformation properties.

Hollow Block Prisms. Five ungrouted concrete block prisms were tested for the assemblage uniaxial compressive strength, f'_m. Each was five courses high and one unit wide. The specimens were fabricated with mortar laid along the two face shells as well as two side-end shells. At the ultimate loads, the prisms were vertically separated into pieces -- a typical splitting failure pattern. Three similar hollow concrete block prisms with similar dimensions were tested to determine the assemblage modulus of elasticity. The uniaxial deformation of the prisms was measured with a 200 mm Demec Gage. The measuring length on the prisms incorporated both a unit and a mortar layer.

Grouted Prisms. Five grouted concrete block prisms were tested for the uniaxial compressive strength. Each was five courses high and one unit wide. A typical split-off face shell failure pattern was detected. Three grouted concrete block prisms with the same dimensions were tested to determine the modulus of elasticity of grouted masonry assemblages. A 200 mm Demec gage was used to measure the uniaxial deformation.

Burnt Clay Prisms. Five specimens were tested for uniaxial compressive strength of burnt clay brick prisms. Each was five courses high and one unit wide. The failure pattern was a vertical splitting of the prism. Three brick prisms with the same dimensions were tested to determine the modulus of elasticity of the brick assemblage. The uniaxial deformation was measured with a 50 mm Demec gage.

Table 2 Prism properties

	Ungrouted block* prisms		Grouted Block** prisms		Brick prisms**	
	f'_m	E_m	f'_m	E_m	f'_m	E_m
Mean (MPa)	19.30	15606	10.55	8551	18.13	6536
Std. Dev. (MPa)	0.08	-	0.01	-	0.27	-

* based on mortar bedded area
** based on gross cross-sectional area.

FULL SCALE CAVITY WALL TESTS

Specimens
All nine specimens reported herein were 24 courses high and 1.2 m wide. The total height between the top and the bottom hinges was 5.285 m. The back-up wythe was built with 190 mm concrete blocks and the veneer wythe was built with 90 mm burnt clay bricks. The two wythes were tied with shear connectors. All specimens had a 75 mm wide cavity except for specimen W7 that had a 100 mm wide cavity. All specimens were constructed with the same materials. Figure 1 shows a typical specimen and test set-up. Table 3 lists the properties of the individual specimens.

The specimens were constructed I running bond with premixed type S mortar. The concrete block wythes were mortared only at the face shells. Ladder type horizontal joint reinforcement consisting of #9 wires was placed at mortar joints in the block wythes every third course. The second core from each side of the block wythe was grouted. Each grouted core was reinforced with one 15M longitudinal reinforcement with a specified tensile strength of 300 MPa. The grouting for each core was completed in two stages with 12 courses grouted at each stage.

Shear connectors similar to those used by Goyal et al. (1993) were used for all the specimens to tie the block and brick wythes. The positions of the connectors were placed in a constant pattern as shown in Fig. 1b. The vertical and horizontal maximum spacing was 600 mm and 800 mm respectively. More connectors were placed at the top and the bottom ends of the specimens to cope with the load transferred from those areas.

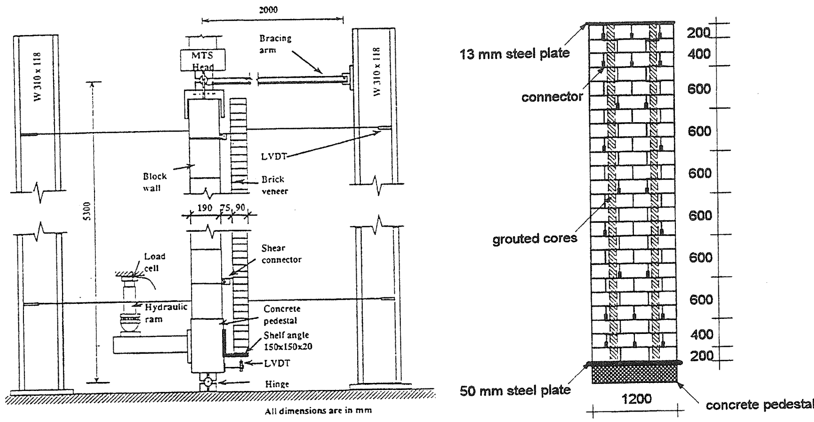
In order to move the specimens into the test machine, the block wythes of the walls were built on top of 1300×240×310 mm concrete pedestals while the veneer wythes were built on 150×150×20 steel angles overhanging from the concrete pedestals. The pedestals were equipped with embedded dowel reinforcement.

Specimens W6, W8, and W9, were tested with an eccentricity of 90 mm at the top. This meant the loading point was at the edge of the block wythe. To distribute the load along the cross-section and to ensure the local bearing resistance, 13 mm thick steel plates were placed at the top of these three specimens. The steel plates had holes that fitted the longitudinal reinforcement. The latter were then welded to the steel plates.

End Conditions. At the bottom end of the specimen, a hinge was placed along the bottom line of the specimen and its center line was carefully aligned with the center line of the block wythe. The hinge was 103 mm wide, 105 mm high, and 1265 mm long. A thin layer of plaster was laid at the top of the hinge and the concrete pedestal sat on the plaster. Several bolts were placed underneath the steel angle to support the veneer wythe during positioning. They were removed once the loading started.

At the top end of the specimen, a built-up 300 mm deep steel channel with a 50 mm thick web and 18 mm thick flanges were placed facing downward. Again a plaster layer was placed under the channel to allow uniform contact with the top of the specimen. On the top of the channel was a hinge assembly was placed and bolted at the two side-ends. To prevent lateral movement the top of the specimen was braced with two parallel steel angles.

Loading System. The vertical load was applied by a 6600 kN MTS machine. The moment was applied at the top end of the specimen by shifting the position of the hinge on the channel. The moment at the bottom end of the specimen was applied through a built-up loading arm that was bolted to the concrete pedestal at one end as shown in Fig. 1(a). At the other end of the loading arm, a manually controlled hydraulic ram was used to apply upwards or downwards pre-calculated loading in accordance with the desired direction of the moment.



(a) Set-up
(after Goyal et al. 1993)

(b) The connector arrangement
(Dimensions in mm)

Fig. 1 A typical specimen and test set-up

Table 3 Summary of the full scale wall tests

Specimens	Slenderness *h/t*	Cavity (mm)	Eccentricity			Ultimate Load (kN)
			value	type	e_1/e_2	
W1	27.81	75	*t/3*[*]	a[**]	1	456.0
W2	27.82	75	*t/3*	a	0	818.0
W3	27.81	75	*t/3*	t[**]	0	651.9
W4	27.84	75	*t/3*		-1	1200.1
W5	27.81	75	*t/3*	a	0	815.5
W6	27.84	75	*t/2*	t	1	251.4
W7	27.82	100	*t/3*	t	1	424.0
W8	27.89	75	*t/2*	a	1	166.0
W9	27.83	75	*t/2*		-1	822.9

[*] *t*: Thickness of the wall. Here, *t/3*=63.3 mm; *t/2*=90 mm.
[**] a: Away from veneer; t: Towards veneer.

Instrumentation. The vertical load was measured by the MTS machine data collection system. The force applied to the loading arm was measured by a load cell. The horizontal displacement of the specimen was recorded by eleven LVDT's, five on the block wythe side and six on the veneer side. On the top of each wythe of the specimen, one LVDT was attached to measure the vertical movement of the specimen. Three rotation meters were mounted on the specimen with one at the top and one at the bottom of the block wythe and one at the bottom of the veneer wythe.

Procedure. To allow the moment introduced at the bottom and the top of the specimen to be of the desired value, the load applied at the loading arm was controlled by a pre-calculated load schedule for each load increment throughout the test. The vertical loading from the MTS machine was carried out by the stroke control method. For the specimens loaded in double curvature, the initial loading condition was carefully controlled to create a very slight initial double curvature imperfection. Loads, displacements and rotations were monitored and recorded automatically by a Fluke data acquisition system that was directly connected to the measuring.

TEST RESULTS AND DISCUSSION

The ultimate loads of all specimens are shown in the last column of Table 3. The mid-height load deflection plots for all single curvature specimens are shown in Fig. 2. The double curvature walls, W4 and W9 are shown separately in Figs. 3 and 4. It is to be noted that the eccentricity e is measured from the centre line of the block wythe. The term "t" here refers to the thickness of the block wythe which in this series was 190 mm.

Specimen W1 (Cavity=75 mm, $e_1/e_2=1$, $e=t/3$)
This specimen was loaded with an eccentricity away from the veneer wythe. The specimen deflected towards the brick veneer in single curvature. Figure 2(a) shows the load versus mid-height deflection of the block wythe.

The deflection response of the specimen was linear up to a load level of 320 kN. At about 300 kN, the first crack in the veneer wythe was observed at the 34^{th} mortar joint (mid-height) where a V-Tie was embedded. As the load increased, more cracks occurred at the mortar joints of the veneer at or close to the positions of the shear connectors. As the ultimate load was passed, the brick veneer was separated into several rigid brick assemblages. In the block wythe of the specimen, cracking started at the mid-height mortar joint. More cracks at the mortar joints occurred as the load increased. Cracks in the block wythe, then, appeared at all mortar joints from the fourth to the 18^{th} joint from the bottom. That means that the mortar cracking range was two thirds of the total height of the block wythe. The formation of the horizontal cracks started with debonding between the mortar and the units. The ultimate load was 456 kN. After reaching the ultimate load, the specimen could still sustain the load at the same level even though large deformation had been developed. The test was stopped at a mid-height deflection about 45 mm. The failure was, therefore, ductile.

Figure 2(a) shows also the response curve of a single masonry wall with similar material, dimensions and loading pattern as specimen W1 (Goyal et al., 1993). It can be observed that the effect of the interaction between the block wythe and the shear connected brick veneer is significant since the strength and the initial stiffness of the wall were improved significantly.

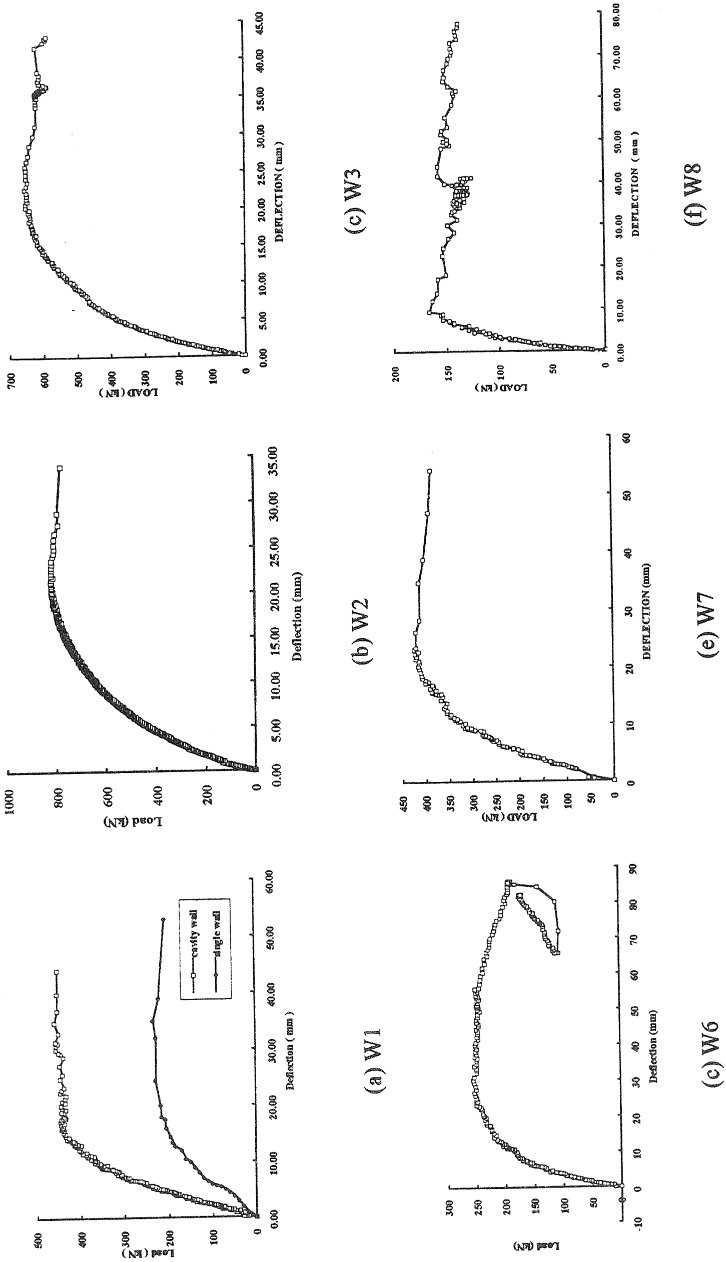


Fig. 2 Mid-height load deflection plots for some specimens

Specimens W2 and W5 (Cavity=75 mm, $e_1/e_2=0$, $e=t/3$)
Specimen W2 was loaded with an eccentricity away from the veneer wythe, but only at the top end of the specimen. The specimen deflected in a single curvature towards the veneer. Figure 2(b) shows the load versus mid-height deflection of this specimen.

The response was linear up to a load of 500 kN. As the load increased, the deflection developed at a more rapid rate. The cracking in the veneer started at the 50^{th} mortar layer (Height=3.9 m) which was one brick layer close to the shear connector position. Subsequent cracking in the veneer occurred in the mortar joints at or close to the shear connector positions. The cracks in the block wythe of the specimen were also at the mortar joints and were spread in the upper part of the block wythe. Cracking in both wythes was due to debonding between the mortar joints and the units. The ultimate load of the specimen was 818.5 kN.

Specimen W5 was a duplicate of specimen W2. The test results were similar to those of specimen W2. The ultimate load was 815.5 kN.

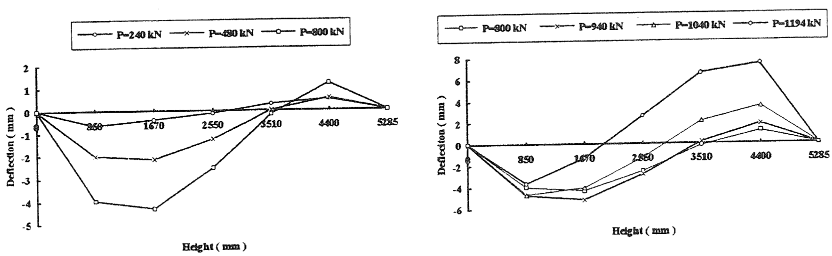
Specimen W3 (Cavity=75 mm, $e_1/e_2=0$, $e=t/3$)
Specimen W3 was identical to specimen W2 except that the eccentricity at the top was towards the veneer. The specimen deflected in a single curvature towards the block wythe. The load versus mid-height deflection curve for specimen W3 is shown in Fig. 2(C).

The response was again almost linear up to a load level of 350 kN. The deflection increased more rapidly after this load level. The cracks in the veneer occurred at the 43^{rd} mortar joint (height=3.8 m) which was close to a connector position. The mortar layer cracked through showing complete debonding. No more cracks were observed in the other mortar layers of the brick veneer wythe until failure of the specimen. Cracking in the block wythe started at the 17^{th} mortar joint (height = 3.7 m). As the ultimate load was approached, cracks were observed at all mortar joints of the upper part of the block wythe. The ultimate load was 651.9 kN. After reaching the ultimate load, the specimen sustained the load at a high level up to 45 mm mid-height deflection.

Recalling that specimen W2 was identical to specimen W3 except that the former was loaded with an eccentricity away from the veneer while specimen W3 was loaded towards the veneer. The ultimate load of specimen W3 was, however, 20% less than that of specimen W2. Since we have two specimens (specimens W2 and W5) with similar test results for the latter case, and since the loading eccentricity of specimen W3 was towards the veneer which locates the line of action of the load closer to the centroid of the cross-section of the cavity wall, we may conclude that the ultimate load capacity of specimen W3 was lower than expected.

Specimen W4 (Cavity=75 mm, $e_1/e_2=-1$, $e=t/3$)
Specimen W4 was loaded in double curvature with opposite eccentricities at both ends of the wall. Figure 3 shows the deformed shape along the height of the block wythe at several load levels.

The specimen deflected initially in double curvature. As the load increased, unwinding of the specimen to the direction of the upper end could be observed but was not significant. The moment at the lower end of the specimen was maintained constant after the vertical load reached 800 kN. Subsequently, the upper curve developed more quickly since the upper end had a larger moment. During the test, a crack was observed at the 57th (height = 4.4 m) mortar joint of the veneer wythe. Due to the direction of the curvature and the difficulty of observation, small cracks, if any, in the lower part of the veneer wythe and in the block wythe were not observed. At the ultimate load of 1200 kN, the face shells of the blocks at the top end of the specimen spalled. Crushing of the block was sudden without warning. The loading dropped off rapidly from the ultimate point and the test was stopped. No post-ultimate part of the response curve was captured.



(a) P ≤ 800 kN (b) P ≥ 800 kN

Fig. 3 Deflected Shape of W4 a different loading levels

Comparing the specimens W1, W2 and W4, the properties of the specimens and the magnitudes of the loading eccentricities were the same, but the ratios of e_1 over e_2 (e_1/e_2) were different. The corresponding values of the ultimate load capacities were 451 kN, 818 kN, and 1200 kN respectively. As can be seen, the capacities of the specimens were strongly influenced by the end eccentricity ratios. On the other hand, the ductility decreased as the end eccentricity ratio changed from the positive to the negative values.

Specimen W6 (Cavity=75 mm, $e_1/e_2=1$, $e=t/2$)

Specimen W6 was loaded with a large eccentricity towards the veneer. The specimen deflected in a single curvature towards the block wythe. The load verses mid-height deflection curve is shown in 3(d).

It can be observed that the deflection increased at a faster rate as the load beyond the level of 150 kN. Two cracks in the veneer wythe were observed at the mortar layers at mid-height and at a height of 4.5 m. When approaching failure, these two mortar joints were completely debonded causing a through crack in the mortar layer. Cracks appeared at several mortar joints in the middle part of the block wythe. The cracks at the mid-height, however, were most developed. One crack spread into a block unit. The ultimate load was 251.4 kN.

Specimen W7 (Cavity=100 mm, $e_1/e_2=1$*, e=t/3)*
Specimen W7 was loaded with an eccentricity towards the veneer. The specimen deflected in single curvature towards the block wythe. The load versus mid-height deflection response of the block wythe is shown in Fig.2(e). The response was approximately linear up to a load of 320 kN. The curve then gradually changed its curvature and reached an ultimate load of 424.0 kN.

Specimen W8 (Cavity=75 mm, $e_1/e_2=1$*, e=t/2)*
This specimen was loaded with an eccentricity away from the veneer. The specimen deflected in single curvature towards veneer wythe. Figure 2(f) shows the load-displacement response of the specimen.

The response curve was approximately linear at the initial loading stage. When the load reached about 160 kN, a large crack appeared at the 38th mortar joint at mid-height of the veneer wythe. The mortar joint cracked through immediately after at a deflection of 9 mm. Cracks in the block wythe also occurred at mid-height. After this cracking, the deflection increased rapidly while the load was barely increased but sustained for quite a long time. The ultimate deflection was about 90 mm, ten times the deflection at the ultimate load. The ultimate load capacity was 166 kN.

Comparing specimen W6 with W8, The physical properties of the specimens and the loading conditions were the same except the direction of the eccentricities. Specimen W6 was loaded with an eccentricity towards the veneer while specimen W8 was loaded away from the veneer. The ultimate load capacity of specimen W6 was higher than that of specimen W8.

Specimen W9 (Cavity=75 mm, $e_1/e_2=-1$*, e=t/2)*
Specimen W9 was loaded in double curvature with opposite eccentricities at the top and bottom ends. Unlike specimen W4, the moment ratio between the top end and the bottom end of specimen W9 was kept unchanged throughout the test.

The deflection shapes along the height of the specimen are plotted at different load levels in Fig. 4. As can be seen, the specimen initially deflected in double curvature. As the load increased, unwinding of the specimen occurred towards the lower end of the specimen. This unwinding phenomenon was not significant and the specimen remained in double curvature until the failure. At the load of 822 kN, compression failure started at the face shells of the block units at the top end of the block wythe. The failure caused the face shell to spall. The failure was brittle. No descending part of the curve was obtained in the test. The ultimate load capacity was 822.9 kN

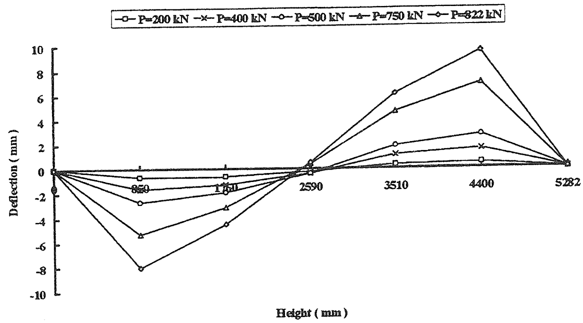


Fig.4 Deflected shape of specimen W9

SUMMARY OF THE TEST RESULTS

As expected, the behavior of the cavity walls is affected by the magnitude of the eccentricities as well as the end eccentricity ratios. The ultimate load decreases while the ductility increases as the magnitude of the eccentricities increased. Both observations are true also as the value of the end eccentricity ratio changes from -1 to +1. The ultimate load capacity is also affected by the direction of the loading eccentricity, either towards or away from the veneer. Compared with the single masonry wall, the ultimate load capacity and the initial stiffness of the shear connected cavity wall increased significantly.

At least two failure patterns were captured by the tests. Specimens W4 and W9, which were loaded with e_1/e_2=-1, showed material compression failure patterns. The other specimens, which were loaded with either e_1/e_2=0 or e_1/e_2=1, failed by the buckling of the specimens due to large deformation caused by the initial moments, the vertical loads and the second order effects. Specimen W8, however, may be an exception since its response curve changed direction suddenly at about the ultimate load level.

The cracking of the specimen in both the brick veneer and the block wythes occurred at the mortar layers. The cracking started with debonding between the units and the mortar joints. Most cracks developed within the mortar layers but a few of the cracks in the block wythes extended into the units. The cracking in the veneer wythes was concentrated at a few mortar layers near the locations of the shear connectors. The cracking in the block wythe, however, was more uniformly distributed in several mortar layers since the block wythes were reinforced and partially grouted.

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