FAILURE MODE, DEFORMABILITY AND STRENGTH OF MASONRY WALLS

Mohamad, Gihad[1]; Lourenço, Paulo Brandão[2]; Rizzatti, Eduardo[1]; Roman, Humberto Ramos[3]; Nakanishi, Elizabete Yukiko[4]

[1] Dr., Professor, Federal University of Santa Maria, Civil Engineering Department, gihad.civil@gmail.com; edu_rizzatti@yahoo.com.br

[2] PhD, Professor, University of Minho, Civil Engineering Department, pbl@civil.uminho.pt

[3] PhD, Professor, Federal University of Santa Catarina, Civil Engineering Department, humberto@ecv.ufsc.br

[4] Dra., Professora, Federal University of Pampa, Civil Engineering Department, elizabete_nakanishi@hotmail.com

For materials such as concrete, the understanding of the failure mode, deformability and strength of block masonry walls are important to simulate the behaviour of the assembly. Still now, there are difficulties on determine experimentally results of the interaction between the materials, as concrete block, mortar and the interface between vertical and bedding joint. Because of this, experimental tests of masonry walls were built to get the deformability, failure modes and compressive strength of the masonry. Experimental tests of tensile and compression on blocks had been done. With the conclusion of experimental tests it is possible to verify that the vertical mortar joint was the main responsible for initiated the failure mechanisms of masonry and further studies of masonry built with high adherence mortar are necessary to improve the ratio between compressive strength of wall and blocks.

Keywords: *Masonry, Deformability, Walls, Failure Mode*

INTRODUCTION

The structural masonry is an anisotropic composed resulting from the interaction between block and mortar. This material under loads could be subjected to a complex stress state that produce failure by reaching the tensile strength of the block or, even, mortar crushing. The failure mechanism of masonry is caused by the initiation and propagation of cracks, which starts often induced by the mortar that exhibits high porosity and different sizes of voids, with a possible initial decrease in volume caused by closing of flaw and voids. An example can be seen using visual analysis on scanning electron microscopy of mortar samples presented on Figure 01 that shows images obtained from bedding mortar. The image (a) of Figure 01 presented the highest magnification of mortar, where is possible to see the macro and micro porous, the contours of the sand and paste. From the magnification of the first image it is possible to observe the interface between paste and grain of sand with macro and micro porous linked by shrinkage cracks (image (b)). The image depicted on Figure 01 (c) shows the pore produced from the capillarities from water exudation.

(a)   (b)   (c)
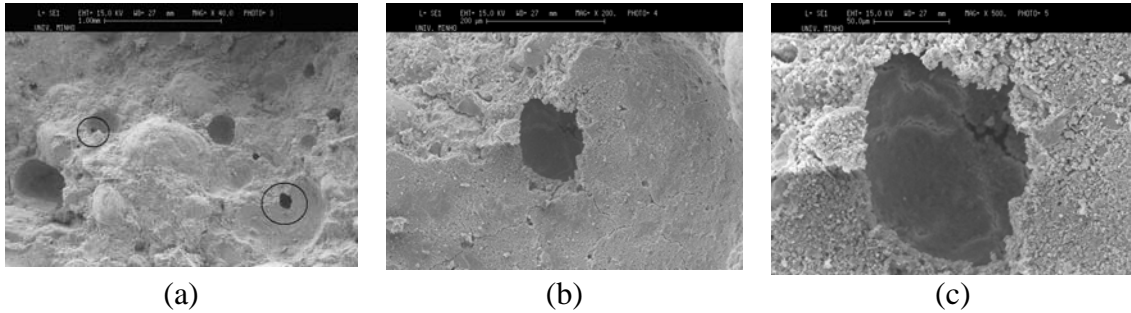
**Figure 1: Images obtained from bedding mortar.**

The lateral deformability between block and mortar is the main responsible for failure of masonry walls and it is important to understand the stress and strain mechanisms developed on block and mortar. The tensile stress developed on block is the main responsible for the low efficiency factor between the block and wall. Thus, the main objective of the study was determined the mechanical properties (axial and lateral deformation) and failure mode of masonry walls under compression.

TENSILE TESTS OF BLOCK

In this work, tensile tests on concrete had been done to determine the stress-strain relationship before and after reach the ultimate load. Samples were cutted from the block and used in experimental tests. To induce cracks in a fracture plane under tensile, notches were done on concrete samples. The table 01 presents the dimensions of the samples tests. The tests were done with displacement control mode with a constant velocity of load. The loading rates used for testing were 0,0001 mm/s. Two LVDTs with maximum displacement field of ± 0,5 mm were used.

Table 1: Dimension of concrete samples cutted from block.

Sample	a (mm)	b (mm)	c (mm)	d (mm)	e (mm)	f (mm)	g (mm)	h (mm)	i (mm)	j (mm)	Area (j.g) (mm²)
1	87,9	79,4	14,7	14,2	4,1	4,1	26,3	88,1	79,0	57,2	1504,4
2	91,1	78,2	17,1	16,5	3,9	3,8	26,3	91,4	77,7	56,7	1491,2
3	88,7	79,6	14,4	14,5	3,9	3,9	26,5	89,3	78,9	59,0	1563,5
4	88,9	82,3	15,9	15,0	4,0	4,0	26,4	88,2	81,8	57,0	1504,8
5	93,0	79,9	16,0	15,8	3,8	3,8	27,6	93,4	80,0	58,7	1620,1
6	92,0	81,9	15,6	15,1	3,5	3,7	28,4	92,0	82,3	60,9	1729,6
7	92,2	81,0	14,4	14,4	3,8	3,8	27,8	91,5	81,8	60,0	1668,0
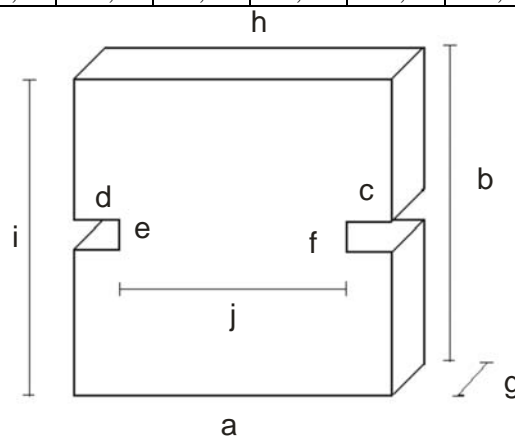
Previously, the concrete samples were bonded under a steel mould guide to ensure the parallelism between the sample and the plate of the servo-hidraulic testing machine. After this, the sample was positioned in the testing machine and the grips were closing. The Figure 2 shows the sample and test machine.
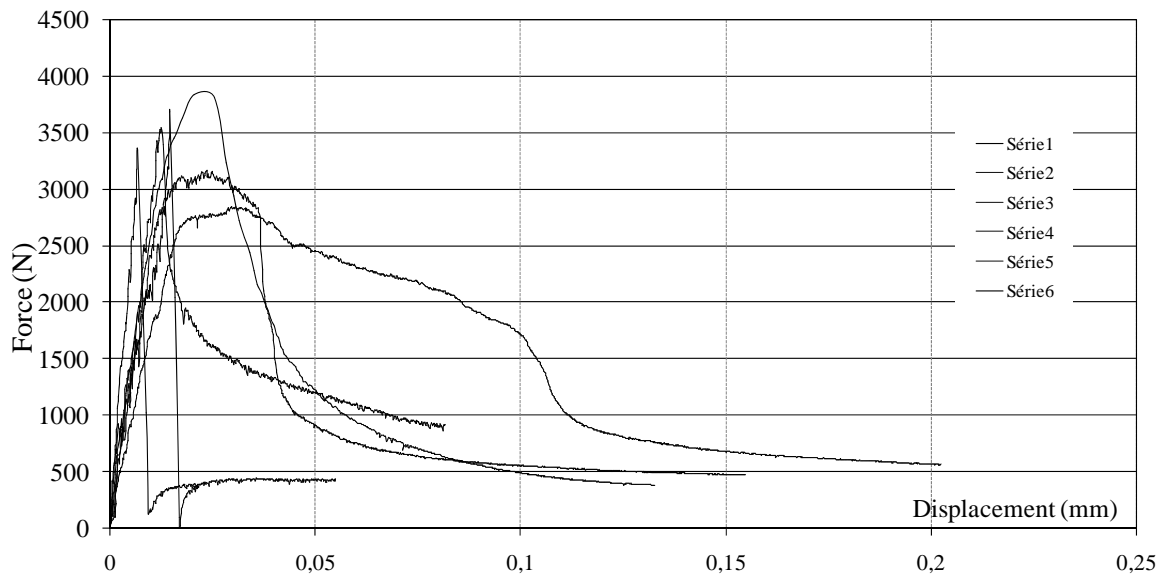

Figure 2: Tensile test machine and the concrete sample.

The experimental results of tensile force, tensile strength and the strain at failure are presented on the Table 2. The compressive strength of the concrete block used in the experimental tests was 23 MPa.

Table 2: Tensile strength results of concrete samples.

Sample	Tensile Force (N)	f_t (MPa)	ε_t
1	3183	2,12	0,00157
2	2858	1,92	0,00197
3	4100	2,62	0,00095
4	3621	2,41	0,00043
5	3595	2,22	0,00084
6	4134	2,39	-
7	4125	2,47	0,00153
Average	**3659**	**2,31**	**0,00121**
Standard-desviation	501,8	0,24	0,00057
Coeficient of variation	13,71%	10,23%	47,00%

Experimental results of force (N) and displacement (mm) of concrete samples is depicted in Figure 3, where it is possible to show the behaviour of the concrete samples under tensile. It can be observed, from experimental tests, that the post peak behaviour of concrete is a hard task due to the fragile nature of the material and the sudden crack growth. Because of this, the coefficient of variation of axial strain obtained in middle of the samples was considered high (47%). The results of tensile strength obtained in experimental tests indicate that the relation between tensile strength was approximately 10% of the compressive strength.

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Figure 3: Experimental results of force (N) and displacement (mm) of concrete sample.

EXPERIMENTAL TEST ON WALL

It is widely accepted that the failure of masonry is mostly governed by the difference in behaviour of mortar and unit and, normally, the mortar is being usually softer and weaker than units. Because of this, is important to understand the deformability modes of the masonry walls under compression to improve the mechanical proprieties of the set.

The main purpose of this work was determine the influence of the vertical and the bedding joint on the deformability characteristic and failure mode of the set. Experimental program had been done to evaluate the stress and strain relation of concrete masonry block.
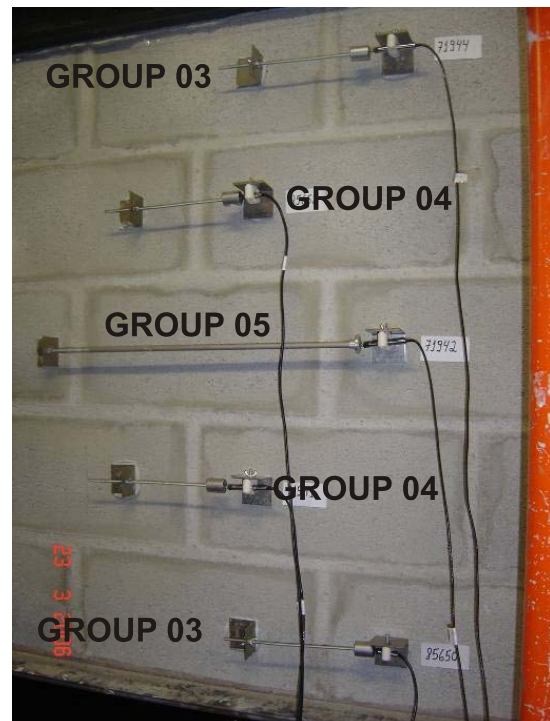
The walls were built under rigid steel beam, which was previously levelled surface and could be carried to the machine test without flexural. The first course of masonry walls was levelled using a cement paste. The mortar used for experimental tests was the medium strength, as indicated in the standards ASTM C-270 and BS-5628, which de cement:lime:sand proportioned in volume was 1:0,5:4,5 and the water/cement ratio was 1,07. It was used in experimental program only one mortar, because the main purpose of this work is determine the deformability and failure mode of structural masonry walls. So, this work isn´t intended to evaluate the influence of the mortar in the masonry strength results. The tests of compressive strength of masonry walls were carried out using a hydraulic servo-controlled machine test with displacement control and the apparatus is presented in Figure 4. To increasing the stiffness of the apparatus for testing the masonry walls, two vertical rods were fixed at both sides of the equipment. A total of ten (10) LVDTs with different displacement fields were used to obtain the vertical and horizontal displacement and were divided by groups. The LVDTs of group 01 were for measuring the axial strain of two bedding joint; two LVDTs were used for measuring axial strain of four bedding mortar (group 02). Two LVDTs were positioned at the first and fifth layer of the wall for measuring horizontal displacement (group 03). Two LVDTs were positioned at the second and fourth layer (group 04). One LVDT was

positioned for measuring horizontal strain of two vertical joint (group 05). The instrumentation layout of the compression test is shown in Figure 5.

Figure 4: Overall view of hydraulic servo-controled machine test.

Figure 5: Positioning of LVDTs groups for compression tests of masonry.

The masonry walls specimens were tested in a load controlled testing machine with a loading rate of 0,1 KN/s, 0,2 KN/s, 0,5 KN/s, 1,0 KN/s and 1,5 KN/s. The displacement on step 12 were checked, as depicted on Figure 6. The Figure 7 presents the results of the displacement for different velocity of load. From the experimental results, it was possible to conclude that the displacement of the wall was influenced by the velocity of load. Thus, with increasing of load it was observed a decrease on the displacement of masonry and, by low velocity of load, the time of the test was increasing so much, which turns the tests impractical. So, for compression test of masonry wall it was used a velocity of load of 0,5 kN/s.
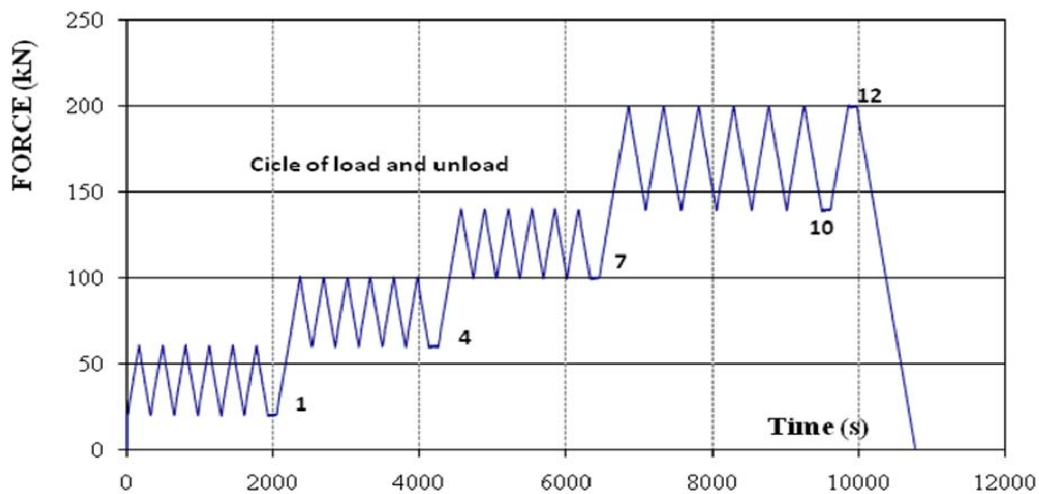
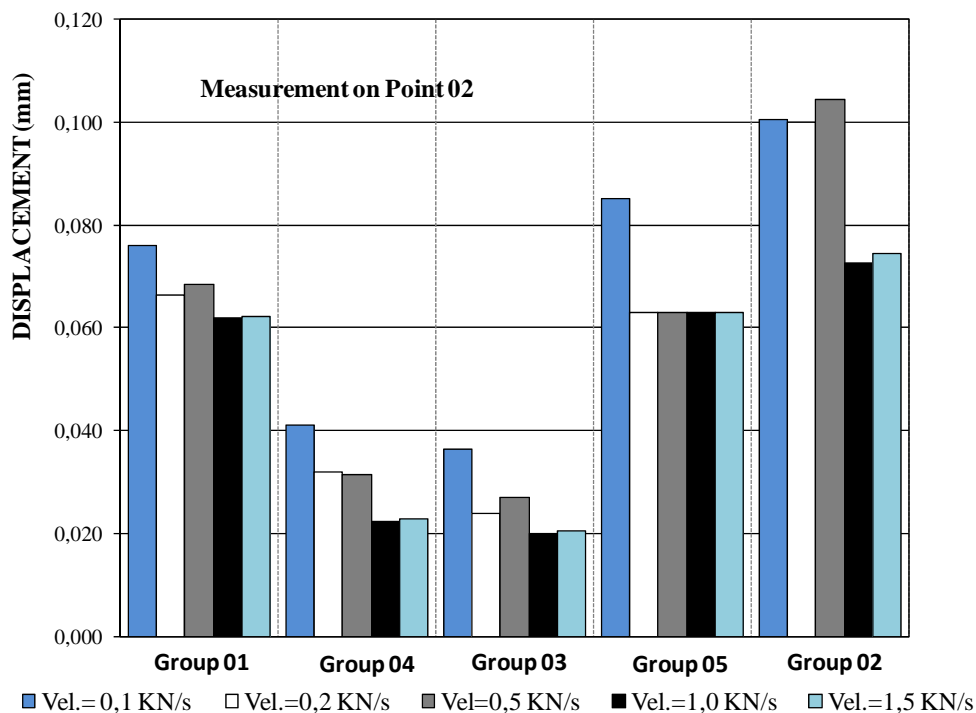**Figure 6: Cicle of load and unload on masonry.**

**Figure 7: Measurement of displacement for different velocity of load.**

The Table 2 shows the strain and stress level reached by the groups of LVDTs, using a load velocity of 0,5 kN/s.

Table 2: Strain and stress level measuring on the different groups.

Velocity (kN/s)	Step	Group 01	Group 04	Group 03	Group 5	Stress level (MPa)
	1	0,000044	0,000080	0,000068	0,000054	0,23
	4	0,000080	0,000103	0,000103	0,000070	0,69
0,5	7	0,000118	0,000128	0,000121	0,000090	1,15
	10	0,000171	0,000158	0,000135	0,000126	1,61
	12	0,000192	0,000160	0,000150	0,000128	2,31

COMPRESSIVE STRENGTH OF MASONRY WALL

The concrete masonry walls were tested until reach the failure. The compressive strength of the bedding mortar was 8,3 MPa and the block was 23,1 MPa. The Figure 8 shows the stress and axial and lateral strain diagram of masonry walls for different groups of LVDTs.
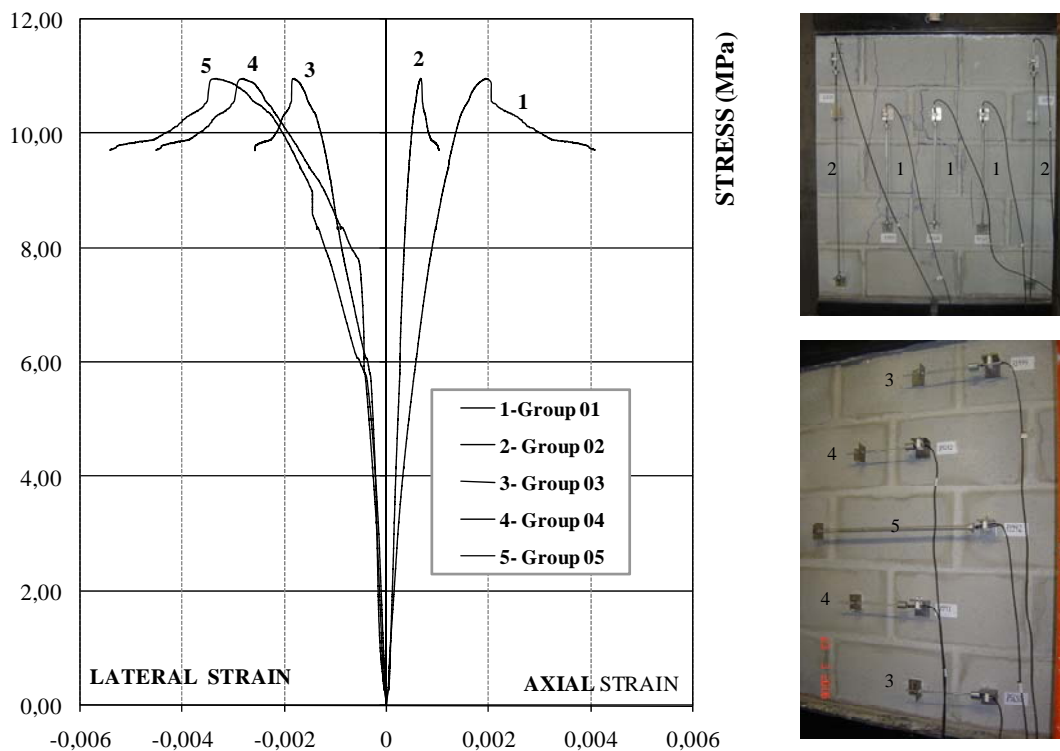
**Figure 8: Stress and strain diagram of masonry wall.**

The LVDTs groups 3, 4 and 5 had the same strain until reach 55% of the ultimate stress, after these occurred an increasing on the strain provoked by the confinement of the steel plate. When the proportion of the stress and strength level reached 60%, starts to appear cracks on the middle of the walls between block and mortar. It is possible to observe on Figure 8 a change on the inclination of stress and lateral strain up to 60% of the compressive strength of the masonry wall for LVDTs groups 3, 4 and 5. From these results, it is possible to conclude

that the interface between block and mortar was the weakness point of the set. It is possible to observe that when the stress of the wall reached 8 MPa the cracks prolonging and cutting the block and bedding joint. The failure modes of the walls were crushing of the bedding mortar and tensile stress, which cut the block and the vertical mortar joint. The Table 3 presents the mechanical results of compressive strength of block, mortar and wall and tensile strength of block and the relation between then.

Table 3: Mechanical proprieties of block, mortar and wall.

Wall	f_{block} (MPa)	f_{mortar} (MPa)	f_t (MPa)	f_{wall} (MPa)	f_{wall}/f_{block}	f_{mortar}/f_{block}
Dimension (1m x 1m)	23,1	8,3	2,30	10,96	0,47	0,36

The Figure 9 depicts the distribution of cracks on both sides, noting on the wall the cracks type for a classification. These cracks were designated as types 1, 2, 3 and 4. Cracks of type 1 were caused by the opening of vertical joints and the subsequent crushing of the mortar (usually this type of cracking occurs when the ratio of stress / strength were 0,60); the cracks type 2 were produced by tensile stress that crossed the block (these cracks were usually the continuing of the crack type 1 and occurs when the ratio of stress / strength reaches 0.80 to 0.90); the cracks type 3 were due to crushing of the bedding mortar (happened simultaneously with the cracks of type 2); the cracks type 4 were by horizontal detachment between block and mortar (the rotation of the wall causes the detachment of the contact of block and mortar).

FRONT   BACK
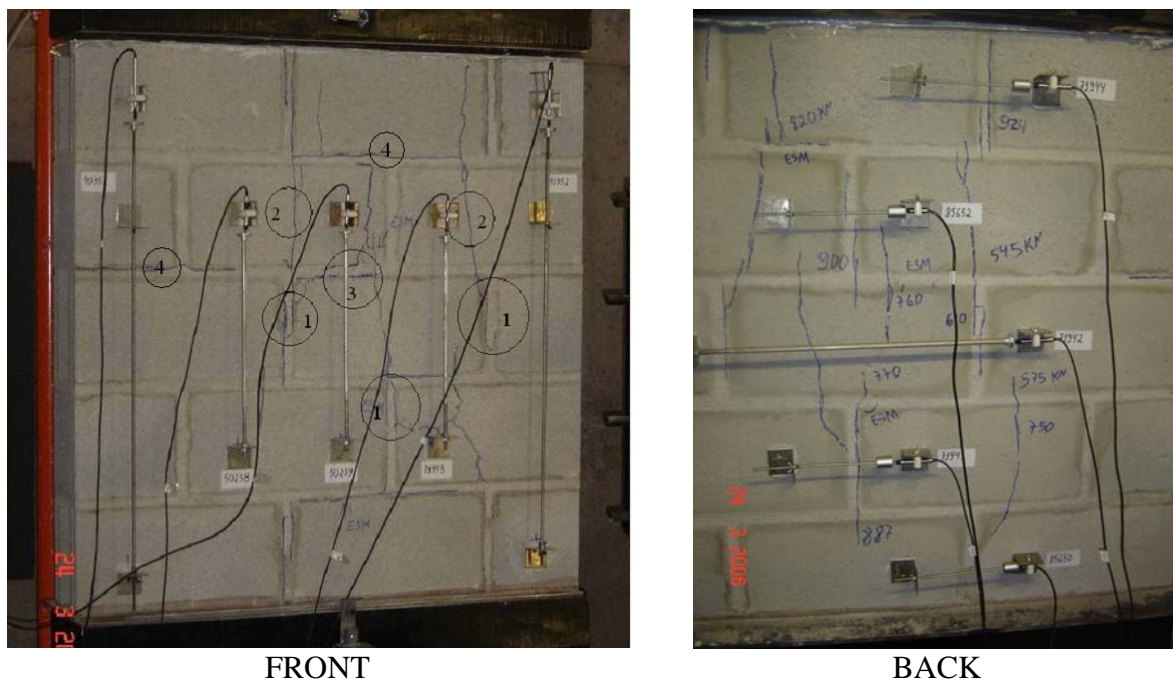
Figure 9: Failure mode of masonry wall.

It can be observed that the experimental tests must have the same condition of similarities between the top and bottom of the wall. The failure modes of the walls were symmetrical on

both sides of the wall. It wasn´t observed horizontal cracks produced by flexural due to eccentricity of load on the wall test.

CONCLUSIONS

The main conclusions of the present study are:

- The appearance of non-linearity in masonry corresponds to an increase in the lateral strain due to extensive cracking of the material and to a progressive increase in the Poisson ratio.
- The vertical mortar joint governs the non-linear behavior of masonry and was the main responsible for failure of masonry.
- It can be concluded from experimental tests that the friction in upper and lower surfaces can cause cracking at the contact between the block and the vertical mortar joint, increasing the deformation measurements.
- It is possible to conclude that the interface between block and mortar was the weakness point of the set.
- The failure modes of the walls were crushing of the bedding mortar and tensile stress, that cut the block and the vertical mortar joint.

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