Seventh Canadian Masonry Symposium
McMaster University
Hamilton, Ontario

June 4-7, 1995

TEMPERATURE MEASUREMENTS ON BRICK VENEER

A.H. Paul Maurenbrecher[1] and Samir E. Chidiac[1]

ABSTRACT

Major environmental factors in the durability of exterior walls are temperature and moisture. Temperature is the factor examined in this study. Thermal movements can lead to induced stresses that may be high enough to cause cracking. Temperature cycling about the freezing point may lead to frost damage in wet walls. This paper examines the temperature measurements on an exterior wall of a nine-storey apartment building in the Ottawa-Carleton region. Measurements were taken over a period of two years at one location on the 8th storey with a S-W orientation. The exterior wall consists of loadbearing concrete blockwork, insulated on the inside face, an air gap and a clay brick veneer.

INTRODUCTION

Harsh environments, vulnerable materials, poor design and workmanship and lack of maintenance can all affect the durability of the brick veneer. Problems include cracking, frost damage, corrosion of metal components such as wall ties, efflorescence and salt damage, mortar attack by acid rain and biological growth. Although moisture is the environmental factor most commonly associated with these problems, temperature also has a significant influence on the rate and extent of damage caused by moisture. It directly affects expansion and contraction of the masonry.

Factors affecting temperature in exterior masonry walls include air temperature, wall thickness, density and thermal resistance of wall components, surface colour, orientation, moisture content, and location of the thermal insulation. This paper examines field data of temperatures taken over a period of two years on a masonry wall of a nine-storey

---

[1] Research Officers, Institute for Research in Construction, National Research Council Canada, Ottawa, Ontario, Canada K1A 0R6

Fig. 1 S-W view of nine-storey apartment building

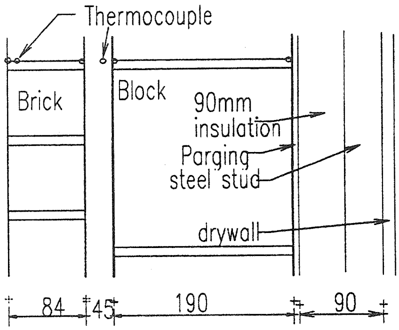

Fig. 2 Wall cross-section at measurement location

apartment building in the Ottawa-Carleton region (Fig. 1). From the recorded data, factors affecting the temperature in the wall and their implications on durability are discussed.

MEASUREMENT AND ANALYSIS PROCEDURES

Experimental Measurements

Measurements were taken at one location across the exterior wall of a 25.8 m high building (storey height 2.84 m except for ground storey). The location was on the 8th storey with a S-W orientation (Figs. 1 & 2). The wall consists of an 82 mm clay brick veneer, an air cavity nominally 30 mm wide, 190 mm loadbearing concrete blockwork parged on the inside face, building paper, 90 mm fibreglass batts between steel studs (the insulation is in contact with the block wall but the 40 mm studs are set back), vapour barrier and 12.7 mm drywall (Fig. 2). Wire truss ties provide lateral support to the brick veneer at every second blockwork course. The brick veneer is vertically supported at the foundation only; there are no intermediate shelf angles. The size of the bricks is approximately 240 mm long, 82 mm wide and 70 mm high. The bricks were extruded with 5 circular perforations. The blocks are 190 m wide with two cores and the colour is a medium tan. Cores are grouted where they contain reinforcement.

Temperature sensors (type T thermocouples) were installed during construction of the building in 1986. The sensors were glued onto a brick and a block before being built into the wall. The relative displacement between the brick veneer and the blockwork was also measured but is only briefly considered in this paper. Measurements were taken with an HP3421 data logger at intervals of an hour except during the warmer period of the day when readings were taken every 20 minutes (11:00 to 19:00 hours until 89-05-24; 14:00 to 18:00 hours thereafter). The sensors were located at the following positions (Fig. 2):

1 mm & 10 mm from outside face of brick
1 mm from inside face of brick
10 mm from block in air cavity
1 mm from outside and inside face of block
Room air temperature (in space above false ceiling)
Exterior air temperature (N-E face)

The data acquisition equipment was kept in a small storage room which also contained major ventilation ducts. Temperature variations in these ducts caused large daily temperature swings in the room during the heating months (October to April). This can cause errors of several degrees in the temperature sensors during the sudden increases or decreases in room temperature. There may therefore be some variablity in data for the colder months although maximum and minimum values were checked to see that they did not occur at a time there was a sudden large swing.

Results

Results from the field data are given in tabular form in Appendix 1. They cover the years 1988 and 1989 and their respective winter periods. The following sections discuss the results in relation to the potential for movement and frost damage.

POTENTIAL FOR THERMAL MOVEMENT

Annual temperature range in wall

Brick veneer. The temperature range in the brick veneer over the year gives an estimate of the total in-plane thermal movement which might be expected (Table 1). The maximum measured surface temperature, 53°C, occurred in July. It is 47% higher than the corresponding air temperature of 36°C. Figure 3 shows the temperature variations in the brick and block over the day the maximum temperatures were reached. The inside surface of the block reached its maximum six hours after the maximum on the exterior brick surface. The minimum brick surface temperature, -22°C, occurred in December 1989, not as low as the corresponding air temperature of -27°C (the coldest December on record; normally the coldest temperatures occur in January). The range in brick surface temperature was 75°C.

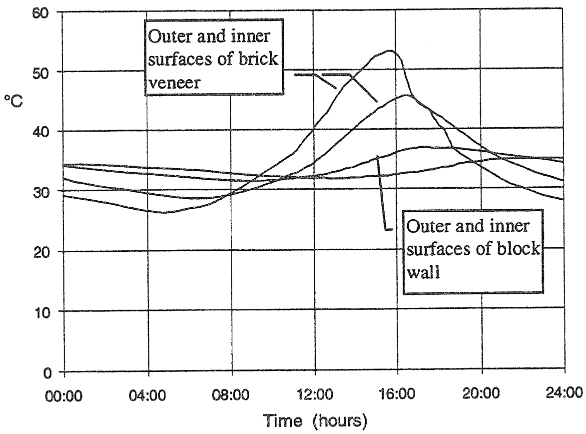

Fig. 3 Temperature at the outer and inner surfaces of the brick and block during the day the maximum temperatures were reached (9 July 1988)

The maximum and minimum temperatures on the inner surface of the brick were 46°C and -12°C respectively with a range of 58°C. The average of the outer and inner surface temperature ranges is about 66°C which is close to the value of 65°C indicated by a transient one-dimensional finite element analysis which used the interior and exterior temperatures as the boundary conditions. The average also happens to be close to the measured air temperature range of 64°C. A temperature change of 65°C is equivalent to an in-plane movement of 0.39 mm/m in an unrestrained brick veneer assuming a coefficient of thermal expansion of 6 µm/m/°C. On the other hand a fully restrained veneer will experience a stress of 8 MPa assuming a modulus of elasticity of 20 GPa.

The maximum surface temperatures were similar to those found by Fenton (1984) who measured surface temperatures at four orientations on a similar building in Ottawa (Table 2). Fenton's minimum values were lower probably because the measurements were taken on the parapet, a colder location. Table 2 also shows the effect of orientation on temperature. The north wall as expected had the smallest temperature range, 24% less than the west wall with the highest range. There is therefore the potential for cracks to develop at the intersection of west and north facing walls.

Concrete block wall. The brick veneer protects the block wall from the extremes in temperature. The block wall experienced a much smaller temperature range (Table 1). The temperature range for the exterior face of the block was 41°C and 38°C for the interior face. Assuming an average temperature range of 39°C, this would translate into an annual in-plane movement of 0.35 mm/m in an unrestrained wall assuming a coefficient of thermal expansion of 9 µm/m/°C. Thus although the temperature range is much smaller, the movement approaches that of the brick veneer because the coefficient of thermal expansion is higher. This will reduce the differential thermal movement between the block and brick walls. Fenton (1984) discusses this in detail. The actual differential thermal movement will depend on the initial temperature of the wall during construction. If insulation were installed in the cavity instead of the interior face of the blockwork, the differential movement would be much larger.

The total relative movement over the height of the building was measured between the brick veneer and the block wall. In 1988 & 1989 the differential movements between the time of maximum and minimum brick veneer temperature were 1.57 & 0.68 mm (0.06 & 0.03 mm/m). These values include movement due to moisture and creep. They do nevertheless indicate that the annual differential movement is small and confirm the small difference in movement indicated by the temperature ranges.

Daily temperature range
Brick veneer. In 1988, the temperature range over a day varied from 1.4 to 42°C for the outside face of the brick and from 1.0 to 26.7°C for the inside face (Table 3). The median range is approximately half the maximum daily range. Assuming a maximum temperature range of 34°C at the centre of the veneer, this is equivalent to a movement of 0.2 mm/m, half the maximum annual movement.

This value can be compared to that obtained by Bergquist (1979) who measured the differential movement between a clay brick wall and its concrete backup wall in Sweden (cavity space insulated; latitude 59°). The maximum daily differential movement was 0.18 mm/m. The average was about 40% of the maximum. The Swedish building code limits the allowable deflection of wall ties to $0.002L^2/d$ for wire ties fixed at either end and twice this value if the tie is hinged at one end (L is the span of the tie across the cavity; d is the tie diameter) (Bergquist 1979). This limitation is meant to avoid fatigue failure of the tie due to the daily movement between the brick veneer and its backup. With an air cavity of 30 mm and a tie with a diameter of 3.6 mm fixed at both ends, the allowable movement would be 0.5 mm (with a truss tie where the wire goes diagonally across the cavity the movement allowed could be nearly twice as much). This could limit the height of a wall with a similar exposure to that in this study to two storeys. The actual limit will depend on the relative movement between the veneer and backup wall.

Concrete block wall. In 1988, the temperature range over a day varied from 0.5 to 9.8°C for the outside face of the block and from 0.3 to 7.1°C for the inside face (Table 3). If a maximum temperature range of 8°C at the centre of the veneer is assumed (average of exterior and interior at time when exterior maximum was reached), this is equivalent to an unrestrained thermal movement of 0.07 mm/m, a fifth of the maximum annual movement. The maximum movement in the concrete block wall is thus about a third of the movement in the brick veneer and it will also be out of phase by several hours (Fig. 3).

The total relative movement over the height of the building was measured between the brick veneer and the block wall. In 1988 & 1989 the maximum daily relative movements were 1.19 & 1.00 mm (0.05 & 0.04 mm/m). The estimated movement ranges for the brick veneer and block wall were 0.2 & 0.07 mm/m. The differential movement will depend on the initial temperatures but it is likely to significantly exceed the annual movement. Fenton (1984) predicted that the daily thermal movement should be larger than the annual movement (0.11 mm/m vs 0.05 mm/m for a 95 mm brick veneer and 75 mm insulation on inside face of the block wall). The differential movements will be the subject of a future paper.

Temperature difference between brick veneer and air temperature
The largest temperature difference between the brick veneer and the ambient air temperature occurs in the winter months with the most sunshine (February and March). The maximum measured, about 42°C, occurred during the month of March (Table 4). The air temperature was -16°C but solar radiation increased the surface temperature of the brick veneer to 26°C.

Fenton (1984) measured a maximum difference of 31°C on east and south facing walls (Table 2). The reason for this lower value is not clear. He may have missed the days the maximum difference occurred. The measuring equipment was down for 95 days but not during the extreme temperature periods (probably January & July).

The supplement to the National Building Code (NRC 1990a) assumes a typical temperature increase above ambient air temperature of 10 to 15°C for masonry. This increase is added onto the July 2.5% design air temperature to give an estimate of the likely maximum temperature for design. The measured temperature increase of the average brick temperature was of the order of 18 to 19°C. Thus the NBC underestimates the increase for the S-W facing brick veneer on this building. The NBC assumes a temperature decrease below ambient air temperature due to radiation loss into a dark clear sky of 5°C for masonry. This decrease is added onto the January 2.5% design temperature to give an estimate of the likely minimum temperature for design. The measured temperature decrease below ambient during January was never less than 1°C and this occurred at air temperatures above 0°C (Table 5). The lowest measured brick surface temperatures were about 5°C above the corresponding air temperature (Table 1).

Temperature gradients across brick veneer
Temperature difference. The temperature difference across the brick veneer gives an indication of the out-of-plane movement which might occur (Table 6). The maximum differences occur during the colder, sunnier months. The maximum differences in each month, ranging from 10 to 15°C, occurred in the afternoon while sun was shining on the wall. The minimum differences, ranging from -5 to -12°C, occurred from late afternoon to early morning.

A temperature difference of 14°C across a simply supported 80 mm brick veneer panel 2.8 m high would cause a bow of 1 mm assuming a uniform temperature gradient (BRE 1979).

Rate of temperature change. The maximum warming and cooling rates occurred at the exterior surface during the colder months, 12 & -16°C/hour in 1988 (Table 7). The maximum rates on the interior surface were 7 & -6.6°C. The rates in the table are based on hourly readings. Rates based on 20 minute readings are much higher: the maximum warming and cooling rates at the surface become 22 & -32°C/hour.

Design air temperatures

Table 8 gives the design air temperatures in the National Building Code (NRC 1990b) and those derived from the temperature measurements (air temperature not exceeded more than 2.5% of the hours). The maximum design temperatures based on the experimental data were 34 to 35°C. These values are higher than the NBC value of 30°C. In contrast the measured minimum 2.5% design temperatures, -21 to -22°C, were not as low as the NBC value of -25°C. The NBC values are based on average data over 10 to 16 years up to 1966. The recent warming trend may explain the reason the maximum design temperatures were exceeded.

POTENTIAL FOR FROST DAMAGE

The number of cycles about the freezing point (freeze-thaw cycles) which a masonry veneer experiences becomes important when the moisture level in the masonry reaches a critical level (e.g. 75-80% of the total pore volume in extruded clay bricks). The greater the number of cycles the earlier the failure will occur. The rate of freezing is important too since it may affect the form of failure: slow freezing rates promote ice-lensing in the laminations sometimes found in extruded clay bricks.

Temperature cycling about the freezing point

The total numbers of freeze-thaw cycles on the brick exterior were 96 and 104 for the two winters measured (Table 9). The corresponding air temperature cycles were 54 and 73. The larger number of cycles experienced by the brick veneer is due to solar radiation warming the wall during the colder months of the year. The number of cycles 10 mm within the brick was nearly the same, while the number on the interior face of the brick was 50% less in 1988 and 33% less in 1989.

A similar number of cycles was recorded by Ritchie & Davison (1968) in the centre of a brick with a southern exposure in Ottawa (Table 10). Their results, over two winters, also show the effect of orientation. The south facing brick had the greatest number of cycles while the bricks facing north had the least. There is a significant difference between the two winters, as in the current study for the interior face of the brick (Table 9). The north and east facing bricks received a significant amount of moisture from rain which may also reduce the number of freeze-thaw cycles (bricks with moisture will take longer to freeze and thaw). In Ottawa even though a south facing wall receives the most cycles because of solar heating, it also receives little precipitation during the fall and winter months. Furthermore the solar heating will also promote drying so that the high number of cycles is usually not critical for such walls. But if there is a high moisture level then failure will occur much sooner in a south wall (e.g. concentrated sources of water such as melting snow draining straight onto the wall).

The effect of colour on the number of freeze-thaw cycles is shown in Table 11 (Ylä-Mattila, 1987). Colour can affect the number of cycles although the effect in this case is not large when the sunnier months of February to April are considered. The reduced number of cycles for the sand lime bricks may be due to their larger mass. The table also shows effect of latitude. In Finland, which is much further north than Ottawa (60°10' vs 45°25'), the number of freeze-thaw cycles on a south facing wall is relatively lower in December and January because the sun is much lower in the sky.

The use of air temperature to determine the number of freeze-thaw cycles in a wall does not provide a good estimate of the cycles in the wall except possibly for a north facing wall. The weathering index map in the CSA standard on clay brick uses the number of cycles based on air temperature and therefore under-estimates the number of freeze-thaw cycles for walls exposed to significant solar radiation during the winter (CSA 1987).

Rate of temperature change when brick veneer temperature was below 0°C

The maximum cooling rate on the exterior of the brick over January to March 1988 was 4.9°C per hour but the rate was usually much less than this (Table 7). Figure 4 shows the warming and cooling rates in February. The maximum cooling rate was 3.3°C/hour but 90% of the rates were less than 1.7°C/hour (the median was 0.7°C /hour). The maximum cooling rate 10 mm within the brick is slightly higher while it is less on the inside face. These rates apply to relatively dry bricks; in Ottawa a S-W orientation receives little driving rain or freezing rain over the winter months. Low cooling rates in bricks with high moisture content will tend to promote ice-lensing at laminations.

Ritchie & Davison (1968) measured cooling rates of 1 to 1.5°C/hour (2 to 3°F) with a maximum of 5.5°C/hour (10°F) at the centre of four bricks exposed to four orientations. It was based on temperatures measured half-hour either side of 0°C.

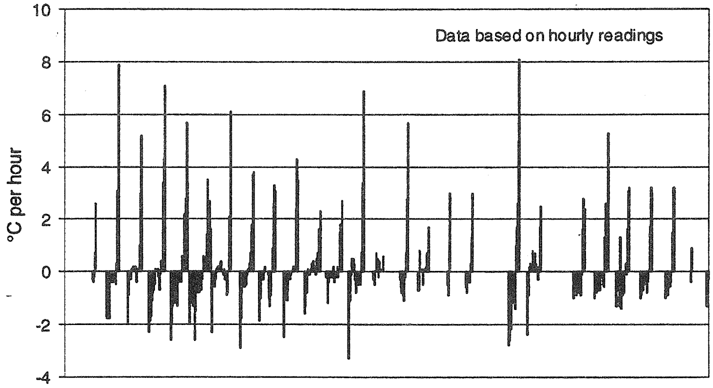

Fig. 4 Rate of cooling and warming of the surface of the brick veneer for the month of February 1988 (surface temperature less than 0°C)

SUMMARY & CONCLUSIONS

Most of the measurements described in this paper were taken at one location on a wall with a SW orientation. They give an indication of how temperature affected this particular wall. Other walls may behave differently depending on such things as orientation, thickness, solar radiation, thermal insulation, moisture content and mass.

The brick veneer is directly affected by environmental factors such as air temperature, solar radiation, rain and freeze-thaw cycles. The concrete block backup wall see the influence of these factors to a much lesser extent.

The annual temperature range in the brick veneer was approximately 65°C compared to 39°C in the block wall. Although the difference is large in terms of temperature, it is much less in terms of thermal movement because the block wall has a coefficient of thermal expansion 50% larger than the clay brick veneer.

The maximum daily range in the brick veneer was about 34°C compared to 8°C in the block wall. Daily differential movements are expected to be much larger than the annual movement because of the larger relative difference in temperature and because the maximum daily temperatures in the brick and block are several hours out of phase.

The National Building Code (NBC) underestimates the increase in brick veneer temperature above ambient air temperature for a S-W orientation (10-15°C vs 18-19°C). On the other hand it overestimates the drop in brick veneer temperature below ambient air temperature (-5°C vs +5°C at the lowest brick surface temperature). The maximum design air temperature measured in the field measurements exceeded the recommended value in the NBC by 5°C.

The number of freeze-thaw cycles experienced by the brick veneer is strongly dependent on solar radiation which in turn depends on wall orientation and latitude. A south-facing wall has a far larger number of cycles than a north-facing wall. The number of cycles based on air temperature underestimates the cycles in the outer part of walls facing all orientations except north. The number of cycles on the inside surface of the brick veneer is much less. The block wall only experienced a few cycles during the coldest months.

The maximum rate of cooling in the brick veneer when its temperature was below freezing in February1988 was 3.3 °C per hour but it usually was much less (90% of the rates were below 1.7°C per hour).

REFERENCES

Bergquist L. (1979). Masonry veneer walls. Proceedings of the 5th International Brick Masonry Conference. Brick Institute of America. p 275-279

BRE (1979). Estimation of thermal and moisture movements and stresses. Parts 1-3. Digests 227-229. Building Research Establishment, Britain.

CSA (1987). CSA standard A82.1, Burned Clay Brick (Solid masonry units made from clay or shale). Canadian Standards Association. Rexdale, Ontario. 17 p.

Fenton G A (1984). Differential movements and stresses arising in masonry veneers of highrise structures. M.Eng. thesis. Faculty of Engineering. Carleton University. 263 p.

NRC. 1990a. Commentary D Effects of Deformations in Building Components. Supplement to the National Building Code. National Research Council of Canada. pp 174-177.

NRC. 1990b. Chapter 1. Climatic information for building design in Canada. Supplement to the National Building Code. National Research Council of Canada. pp 3-30.

Ritchie T & Davison J I. 1968. Moisture content and freeze-thaw cycles of masonry materials. ASTM Journal of Materials, JMLSA, Vol 3, No 3, Sep, pp 658-671.

Ylä-Mattila R. 1987. Frost damage to masonry structures and tests for frost resistance. Masonry International. Vol 1, No 3, Dec. p 93-95

APPENDIX 1 EXPERIMENTAL RESULTS

Table 1
Maximum and Minimum Temperatures in Exterior Wall

	Max	Air	Date/Time	Min	Air	Date/Time	Range
1988							
Brickwork							
exterior	53.1	36.4	07-09/15:40	-20.1	-24.6	01-14/08:00	73.2
10 mm in	52.7	36.5	07-09/16:00	-19.3	-24.6	01-14/08:00	72.0
interior	45.6	36.3	07-09/16:20	-10.2	-24.6	01-14/08:00	55.8
Air cavity	39.6	36.2	07-09/16:40	-2.1	-9.8	02-07/14:00	41.7
Blockwork							
exterior	36.9	35.9	07-09/17:20	-1.7	-9.9	02-07/14:40	38.8
interior	35.0	27.6	07-09/22:00	-0.2	-9.9	02-07/14:20	35.2
Air							
interior	30.6	30.7	07-11/17:20	18.2	-8.2	01-02/04:00	12.4
exterior	37.1	-	07-08/17:20	-25.1	-	01-14/07:00	62.2
at airport	35.8	36.7	07-08/15-16	-29.4	-23.9	01-14/≈09:00	65.2
1989							
Brickwork							
exterior	51.3	28.5	07-31/16:00	-21.6	-27.0	12-27/06:00	72.9
interior	44.6	35.2	07-26/16:40	-12.2	-26.8	12-27/07:00	56.8
Blockwork							
exterior	36.4	34.7	07-26/17:20	-4.1	-22.2	12-23/06:00	40.5
interior	34.4	29.1	07-26/23:00	-2.5	-22.2	12-23/06:00	36.9
Air							
exterior	35.6	-	07-25/14:20	-28.2	-	12-30/07:00	63.8
at airport	34.4		07-24/≈15:00	-29.1		12-27/≈08:00	63.5

Notes:

(1) Eastern Standard time.

(2) Record high and low air temperatures at Ottawa airport since Nov 1938
Maximum: 37.8 °C Aug 1944; Minimum: -36.1°C Feb 1943
Latitude 45°19' N, Longitude 75°40' W; 10.5 km south of city centre

Table 2
Effect of orientation on brick veneer surface temperature (Fenton 1984)

	Max	Min	Annual Range	Max surface-air
North	35.7	-26.3	62	13
East	51.5	-24.6	76	31
South	45.4	-25.2	71	31
West	55.0	-27.4	82	27
Air				
exterior	33	-29	62	
at airport	34	-31	65	
Authors' building	53.1	-21.6	75	42

Notes:
(1) Temperatures measured at 2 hour intervals over a period of a year from Nov 1981. Loss of 95 days due to equipment breakdown. Down times generally short and did not result in a loss of extreme temperature periods.
(2) Temperature sensor on brick surface at parapet level (brick a red-brown colour). 12 storey building.
(3) Wall construction: 95 mm brick, 25 mm cavity, 194 mm block, 38 mm rigid insulation, dry wall.
(4) Ambient air temperature measured in shade on north side of penthouse.

Table 3 Maximum and minimum daily temperature ranges for 1988

	Min	Date	Max	Date	Average	Median
Brickwork						
exterior	1.4	08-24	42.2	02-27	20.7	22.1
interior	1.0	09-17	26.7	02-27	12.4	12.9
Blockwork						
exterior	0.5	01-20	9.8	02-08	4.1	4.0
interior	0.3	08-29 & 07-26	7.1	12-31	2.8	2.7

Notes: Corresponding range for interior of block on day exterior was at its maximum of 9.8°C: 6.6°C

Table 4 Maximum increase of brick surface temperature above ambient air temperature

	1988	Date/Time	1989	Date/Time
Over the year	40.0 (29.0/16.5/-11.0)	02-08/15:00	42.3 (25.8/14.0/-16.5)	03-07/14:20
July	21.6 (50.1/42.9/28.5)	07-31/16:40	22.8 (51.3/41.8/28.5)	07-31/16:00

Note: Values in brackets are corresponding temperatures of the brick outer and inner faces, and the air.

Table 5 Maximum decrease of brick surface temperature below ambient air temperature in January

	1988	Day/Time	1989	Day/Time
Exterior face	-0.7 (2.7/3.4)	16/21:00	-0.5 (1.8/2.3)	11/00:00
Interior face	-0.8 (8.6/9.4)	31/11:40	0.0 (3.3/3.3)	08/08:00

Note: Values in brackets are corresponding brick and air temperatures.

Table 6 Maximum and minimum difference in temperature between outer and inner faces of brick veneer

	1988	Date/Time	1989	Date/Time
Maximum	13.9 (35.8/21.9)	02-18/14:00	14.7 (38.8/24.1)	01-29/14:40
Minimum	-11.7 (-6.4/5.3)	01-13/18:00	-11.6 (-10.7/0.9)	01-21/00:00

Note: Values in brackets give corresponding outer and inner surface temperatures of brick veneer

Table 7 Maximum rate of temperature change in brick veneer

(°C per hour)

	Exterior face		10 mm in from face		Interior face	
	Warming	Cooling	Warming	Cooling	Warming	Cooling
Jan 1988	12.3	-14.0	10.9	-12.6	7.0	-5.8
< 0°C	12.3	-4.9	10.9	-5.3	5.1	-3.9
Feb 1988	10.4	-16.4	10.0	-14.1	6.7	-6.3
< 0°C	8.1	-3.3	8.2	-3.6	5.7	-1.2
Mar 1988	11.5	-15.4	10.4	-13.8	5.3	-6.6
< 0°C	5.6	-2.7	5.6	-2.9	3.0	-1.1

Notes: (1)Values based on hourly readings
(2) < 0°C : rate when sensor temperature was below 0°C.

Table 8 Design air temperatures for Ottawa

	1988	1989	NBC 1990
January 2½%	-20.7	-21.9	-25
1%	-24.0	-24.6	-27
July 2½%	35.4	34.1	30

Note:
The National Building Code bases the minimum design temperatures on air temperatures in January which will not be exceeded more than 1% or 2½% of the hours and the maximum design temperature on air temperatures in July which will not be exceeded more than 2½% of the hours.

Table 9 Freeze-thaw cycles at different location across the wall

	Winter 87/88								Winter 88/89							
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	Tot	Oct	Nov	Dec	Jan	Feb	Mar	Apr	Tot
Brick																
exterior	1	13	17	22	25	18	0	96	1	5	25	27	24	19	3	104
10 mm in	1	12	15	22	25	17	0	92	1	5	25	28	23	20	2	104
interior	0	2	5	19	15	7	0	48	0	0	18	21	21	10	0	70
Blockwork																
exterior	0	0	0	5	2	0	0	7	0	0	3	3	0	0	0	6
interior	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
Air																
exterior	1	11	15	8	7	12	0	54	2	11	5	19	8	18	10	73
at airport	9	11	14	5	5	11	5	60	8	13	7	14	2	9	15	68

Notes:
(1) One freeze-thaw cycle occurs when temperature changes from a negative to a positive value.
(2) Airport air cycles based on daily max/min temperatures.

Table 10 Effect of orientation on the number of freeze-thaw cycles Ottawa (Ritchie & Davison 1968)

Brick orientation	1963-64	1964-65
North	47	65
East	51	70
South	81	98
West	63	79
Air at airport (Nov-Apr)	64	62

Notes: (1) A brick with a thermocouple in the centre was exposed to each of four orientations.
(2) Air freeze-thaw cycles determined by authors of current paper.

Table 11 Effect of colour on freeze-thaw cycles (Ylä-Mattila 1987)

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	Total
Dark red	1	4	11	8	21	17	10	72
Red	1	4	7	5	20	15	10	62
Yellow	2	6	7	6	20	17	11	69
Sandlime	1	4	4	5	17	16	11	58
Air at weather station	4	10	2	3	1	11	14	45

Notes: (1) Brick cavity wall in Finland facing south (the 150 mm cavity is filled with mineral wool)
(2) Light grey colour. The sandlime walls have a larger mass than the other walls.

Seventh Canadian Masonry Symposium
McMaster University
Hamilton, Ontario
June 4-7, 1995

INPLANE DISTORTION OF UNREINFORCED MASONRY PANELS INFILLING RC FRAMES

DUKUZE[1], A. AND DAWE[2], J.L.

ABSTRACT

Since excessive and uncontrolled lateral displacements can create severe structural damage in high-rise buildings, lateral drifts have been codified in various building codes. The present study investigates the inplane distortion of reinforced concrete (RC) frames infilled with unreinforced brick masonry panels subjected to inplane lateral loading. Tests were conducted on one-third scale RC infilled frames in order to examine the effect of the height-to-length ratio, H/L, and the beam-to-column moment of inertia ratio, I_b/I_c, on inplane distortion of the composite system. Ultimate distortions are compared to common values of interstorey drifts specified by various codes including UBC-85, BOCA-87 and NBCC-90. In addition to analyzing experimental results with respect to distortion at the occurrence of the first crack and ultimate strength, the study presents formulations which can be used to predict the load sustained by an open RC frame due to lateral loading.

---

[1]PhD Student, [2] Professor and Executive Director of Atlantic Masonry Research and Advisory Bureau Inc., Department of Civil Engineering, University of New Brunswick, P.O. Box 4400, Fredericton, NB, Canada, E3B 5A3.

INTRODUCTION

Masonry panels infilling reinforced concrete or steel frames are vulnerable to inplane distortions caused either by lateral displacements in buildings under wind or seismic action or by vertical movement of supports due to differential settlement of foundations. In recent earthquakes, most extensive damage had derived from cracking of masonry partitions or infills whose flexibility had given rise to lateral displacements exceeding those tolerable by masonry. Codes specify allowable interstorey drifts in order to provide structures which are sufficiently stiff and ductile to avoid excessive structural damage. Since these limitations are mainly related to damageability of masonry panels (Meli, 1982) quantitative information in this regard is needed in order to assess the code requirements with respect to the actual performance of RC infilled frames. Little information has been reported on distortion of various configurations of masonry infilled frames to date. This paper presents the results of an experimental study designed to assess the distortion of infilled frames subjected to inplane lateral loads.

EXPERIMENTAL PROGRAM

In order to investigate the general behaviour of RC frames infilled with masonry panels, an extensive experimental program was initiated and is currently in progress. This program is aimed at assessing the effects of various parameters including the aspect ratio, *H/L*, the ratio of beam-to-column moment of inertia, I_b/I_c, and the presence of an opening on various aspects of the behaviour of infilled RC frames. In the present paper, findings related to inplane distortions with respect to cracking of infills and ultimate state of the composite structural system is reported. Experiments have been arranged in factorial design of 2 x 2 x 3 with three replicates as shown in Table 1. In order to accommodate existing testing facilities, tests were conducted on one-third scale specimens. In total, 36 specimens were cast and stored in a laboratory environment for testing.

Table 1. Parameters under investigation

Aspect Ratio *H/L*	Moment of Inertia ratio $I_r = I_b/I_c$	Opening Size*
R	1	B
S	5	W
		P

* R: Specimen with H/L= 0.5 S: Specimen with H/L= 1
B: Open frame W: Infill with door opening P: Infilled Frame

Ten days after casting the RC frames, an experienced mason installed masonry panel infills. On the day of testing, specimens were moved from the curing area to the testing room and set in a universal testing machine with a capacity of 900 kN. Special care was taken during handling and, in order to reduce stress concentration during testing, masonite pads were inserted between the machine head and the specimen. The specimen configuration consisted of one-storey, one-bay RC infilled frames constructed according to the experimental design outlined above. The reinforced concrete frames were built according to CAN-3 A-23-3 M84 and ACI 318-83 as applicable. Rebars were #10M and #15M while stirrups were made of galvanized 9WG steel wire of 3.9mm diameter. Concrete was modelled by microconcrete whose mix proportion was obtained after a series of trial mixes.

TEST SETUP AND INSTRUMENTATION

In order to simulate the behaviour of infilled frames subjected to inplane forces, specimens were compressed along one diagonal from corner to corner. This procedure has been successfully used by numerous investigators including Polyakov 1956, Simms 1967, Smith 1966 and Esteva 1966. The load was increased in monotonic fashion up to failure while a series of parameters including the change in specimen diagonal lengths were monitored by providing linear strain convertors (LSC) along two diagonal directions as shown in Fig. 1. At each load increment, readings were recorded by a data acquisition system. Progressive cracking was traced at each load increment and reported on a chart. Specimens were loaded until they underwent substantial damage due to corner crushing, complete failure of the masonry panel, or distortion.

TEST RESULTS AND DISCUSSION

Interstorey Drift Index

To ensure safety and comfort in the use of buildings subjected to lateral loads, present codes prescribe allowable lateral displacements which are applicable to part or all of a structure. These allowable limits (interstorey drift indices) are mostly given in terms of the ratio of relative lateral displacement of a particular level to associated storey height representing inplane lateral distortion of the composite system.

The maximum interstorey drift index required by UBC-85 and BOCA-87 is 0.005 for seismic action while the National Building Code of Canada (NBCC-1990) limits it at 0.002 for wind and gravity loads. In addition, both NEHRP-85 and NBCC-90 specify 0.01 as the upper interstorey drift limit for earthquake post-disaster buildings whereas they allow different values for all other buildings namely 0.015 and 0.02 respectively.

Test Results

Tests were performed on thirty-six specimens with a series of measurements taken along the diagonals of respective test units. Subsequently, from these experimental data, inplane distortions, γ_{cr}, at the occurrence of the first crack in the masonry panel and γ_{ult}, at the ultimate strength of the infilled frame were derived. The distortion, γ, is the change in the right angle at the loaded corner between a column and a beam. The average distortion from each specimen group is summarized in Table 2.

Discussion

Inspection of the load vs distortion diagrams of various open frames revealed that the inplane distortion of open frames can be used to estimate the load resisted by an open frame in an infilled frame configuration.

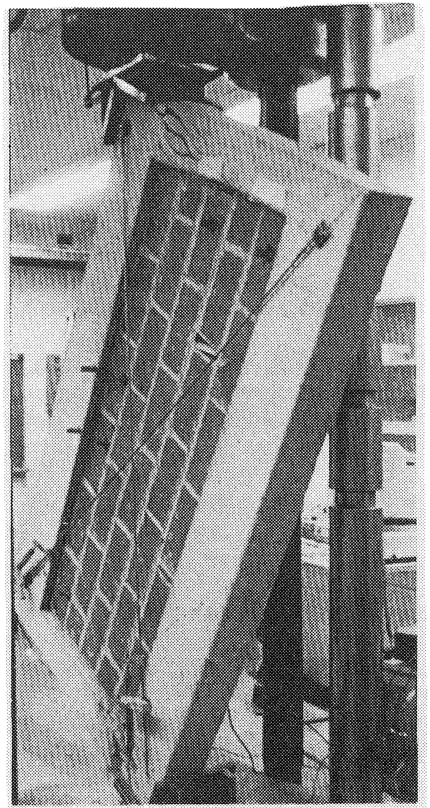

Fig. 1. Test setup and Instrumentation.

Table 2. Summary of Results

Specimens[*]	Distortion ($\times 10^{-3}$ rad)	
	γ_{cr}	γ_{ult}
S1B	-	10.4
S1W	2.2	9.4
S1P	0.9	11.5
S5B	-	14.3
S5W	3.7	12.8
S5P	0.7	14.6
R1B	-	23.5
R1W	1.4	52.8
R1P	1.3	23.6
R5B	-	12.4
R5W	1.8	67.4
R5P	1.1	45.1

[*]Specimens are designated according to Table 1.
1 and 5 refer to moment of inertia ratios, I_b/I_c.

Regression analyses performed on racking load vs distortion data obtained from different open frame specimens suggested that the best curve fit is a forth degree polynomial. In a normalized form, the relationship yields an expression of the form:

$$\frac{N}{N_{ult}} = a_o + a_1 \frac{\gamma}{\gamma_{ult}} + a_2 \left[\frac{\gamma}{\gamma_{ult}}\right]^2 + a_3 \left[\frac{\gamma}{\gamma_{ult}}\right]^3 + a_4 \left[\frac{\gamma}{\gamma_{ult}}\right]^4 \qquad [1]$$

where N is the racking force, N_{ult} is the ultimate strength of an open frame, γ_{ult} is the inplane angular distortion at N_{ult}, and γ is the actual distortion at racking force N.

The coefficients applicable to different types of open frames are given in Table 3. Each value, a_i, was determined from results obtained from three similar specimens.

Results indicate that the first crack in a rectangular infill panel occurs at a constant distortion of approximately *0.0014 rad* for specimens with an aspect ratio of 0.5 (rectangular) while it is consistently greater than *0.002 rad* for square specimens (H/L=1) with panels provided with a doorway.

Table 3: Polynomial coefficients

Test units*	a_o	a_1	a_2	a_3	a_4	N_{ult} kN	γ_{ult} 10^{-3} rad
S1B	-0.04134	1.6575	-0.70012	0.03379	0.01785	12.78	10.37
S5B	0.014455	2.4419	-2.19	0.82659	-0.11852	20.15	14.33
R1B	0.003575	2.0418	-1.315	0.27389	-0.01054	21.33	23.55
R5B	0.026814	2.0852	-1.483	0.38059	-0.03313	26.70	12.37

*The designation of the test units refers to Table 1.

The value is less than *0.001 rad* for square specimens with solid infill. A further analysis reveals that none of the investigated parameters had a significant effect on the distortion at the occurrence of the first crack. Similar observations have been reported by Meli 1982. The maximum observed value of γ_{cr} was *0.0037 rad.* For square specimens, the first crack of specimens provided with an opening occurred at a distortion ranging from 20 to 25 percent of the ultimate distortion of a related open frame while it dropped markedly in a range of 5 to 8 percent for test units with solid infills. Although rectangular frames with solid infills had their first crack within almost the same range as square specimens (6 to 9%), γ_{cr} for those provided with a doorway occurred within a lower range of 6 to 15 percent. In addition, it was noticed that, after the occurrence of the first crack, the stiffness of a composite system deteriorates up to the ultimate capacity of the test unit followed by a strength degradation accompanied by an extensive inplane distortion.

Among the parameters investigated in this study, only the aspect ratio, H/L, and the presence of openings in infilled frames significantly affect the ultimate distortion, γ_{ult}. This effect is more pronounced for rectangular frames with door openings than for square units. The ultimate distortion of rectangular test units attained more than twofold that of corresponding open frame.

While the ultimate distortion of square specimens (H/L=1), increases slightly with inertia ratio I_b/I_c, experimental data show that γ_{ult} steps up for rectangular test units (H/L=0.5). The greatest increase is recorded for those specimens with door openings.

Among square specimens with the same inertia ratio, I_b/I_c, the ultimate distortion did not change noticeably with respect to that of an open frame in the same category. However, for rectangular frames with panels provided with door openings, γ_{ult} was more than twice that of an open frame of the same type. In addition, for rectangular frames with continuous panels, it was one to four times that of a corresponding open frame.

Regarding the wind action, the interstorey drift index allowed by NBCC-90 was found to be in good agreement with respect to the occurrence of the first crack in the infill panel. For seismic action, UBC-85 and BOCA-87 are more restrictive than NEHRP-85 and NBCC-90 which allow realistic values of relative lateral displacements of structures. Figures 2 to 5 illustrate typical experimental curves plotted in the (N, γ) plane for different specimens groups. Each plot includes three curves which relate to RC frames infilled with either a continuous masonry panel (*Infilled Frame*) or a panel provided with a door opening (*Door Opening*) along with a curve which shows the response of an open frame (*Open Frame*). For comparison to experimental values of γ_{cr} and γ_{ult}, requirements prescribed by UBC-85, BOCA-87, NEHRP-85 and NBCC-90 are indicated by vertical lines.

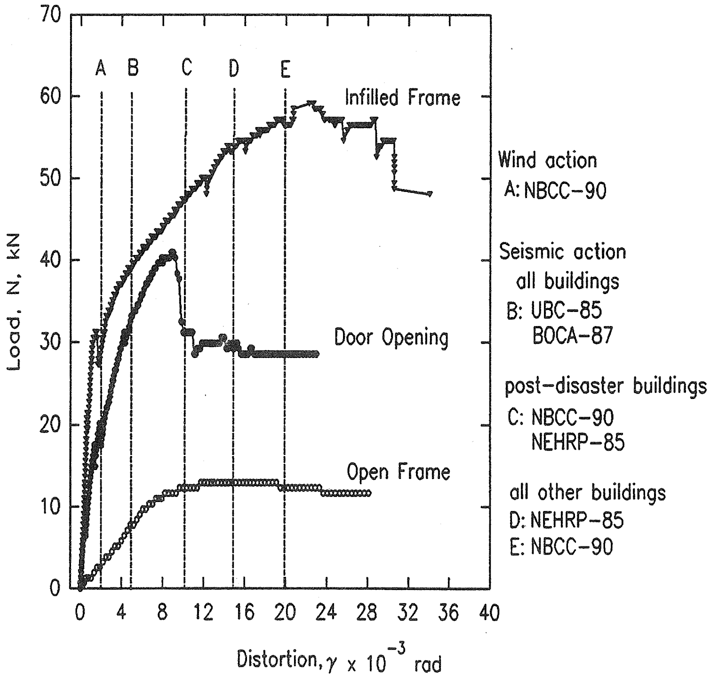

Fig. 2. Horizontal Load vs Shear Distortion for S1 Specimens

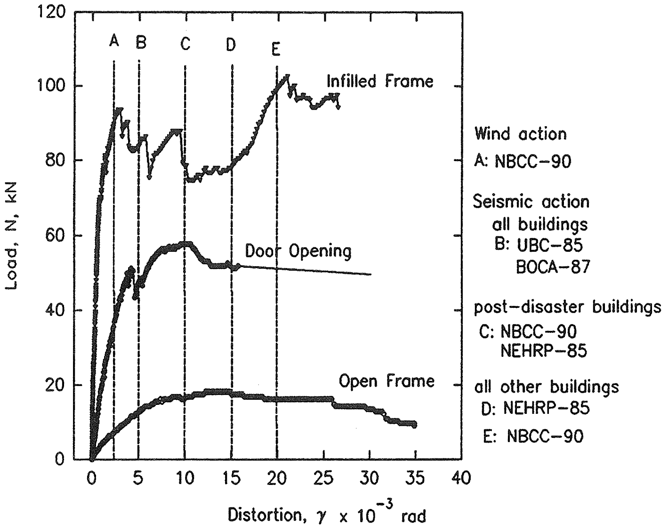

Fig. 3. Horizontal Load vs Shear Distortion for S5 Specimens

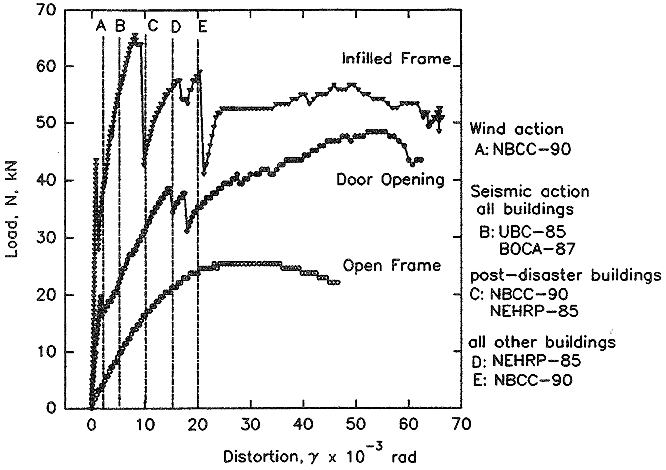

Fig. 4. Horizontal Load vs Shear Distortion for R1 Specimens

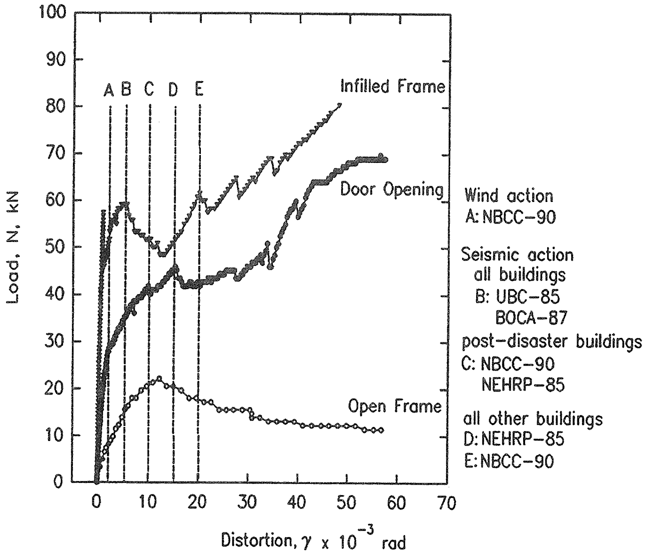

Fig. 5. Horizontal Load vs Shear Distortion for R5 Specimens

Actual results show that ultimate distortions, γ_{ult}, of square infilled frames fall within a range of 0.01 to 0.015. To mobilize all their strength, rectangular infilled frames (H/L=0.5) undergo extensive distortion which may reach more than three times the ultimate distortion of similar bare frames. The presence of a door opening in these units increases γ_{ult} significantly leading to an interstorey drift index of 0.07 which is greater than provisions allowed by existing building codes.

CONCLUSIONS

An analysis of the test results indicates that, among investigated parameters only the aspect ratio and the presence of a doorway opening significantly affect the ultimate distortion of RC infilled frames. In general, rectangular specimens with a door opening underwent greater ultimate distortion compared to square test units. The distortion at the first crack was not markedly affected by the studied parameters. A formulation which relates the racking force to inplane distortion for various types of open frame has been proposed. While for γ_{cr}, the actual experimental data show that the limitation required by NBCC-90 is likely, values specified by UBC-85 and BOCA-87 are conservative with respect to provisions related to seismic action. In addition, for seismic requirements, NEHRP-85 and NBCC-90 specifications are in good agreement with performances of square infilled RC frames while they are conservative regarding rectangular infilled frames. Excluding post-disaster buildings, building codes should allow greater interstorey drift indices for rectangular infilled frame configurations with H/L=0.5.

ACKNOWLEDGEMENTS

The authors wish to express their sincere gratitude to L.E. Shaw Ltd. and the Atlantic Masonry Research and Advisory Bureau, Inc. for their financial support.

BIBLIOGRAPHY

ACI 318-83, 1983. Building Code Requirements for Reinforced Concrete. American Concrete Institute, Detroit, Michigan.

Building Officials and Code Administrators International, 1987. The BOCA Basic Building Code. Homewood, Illinois.

CSA CAN-3 A23-3 M84, 1984. Design of Concrete Structures for Buildings, Canadian Standards Association, Rexdale, Ontario.

Esteva, L. 1966. Behaviour under Alternating Loads of Masonry Diaphragms Framed by Reinforced Concrete Members. Proc. of Int. Symp. on Repeated Loading of Materials and Structures, Rilem, Vol. 5, Mexico, sec.13-6.

Federal Emergency Management Agency, 1986. 1985 Edition of NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings. FEMA-86, Feb.-1986.

Holmes, M. 1961, "Steel Frames with Brickwork and Concrete Infilling", Proc. of I.C.E., Vol. 19, pp. 473-478.

International Conference of Builfings Officials, 1985. Uniform Building Code, Whittier, California.

Mainstone, R.J. 1971. On the Stiffness and Strength of Infilled Frames. Supplement of Proc. of ICE, Vol. 48, pp. 57-90.

Meli, R. 1982. Control of Earthquake Damage in Buildings with Masonry Walls. Proc. of the 8th International Brick and Block Masonry Conference, Rome 1982, pp. 1021-1032.

NRC, 1990. National Building Code of Canada 1990. Associate Committee on the

National Building Code. National Research Council of Canada, Ottawa, Ontario.

Polyakov, S.V. 1960. On the Interaction between Masonry Filler Walls and Enclosing Frame when Loaded in the Plane of the Wall. Translation in Earthquake Engineering, EERI, San Fransisco.

Simms, L. G. 1967. The Behaviour of No-fines Concrete Panels as the Infill in Reinforced Concrete Frames. Civil Engineering and Public Works Review, November 1967, pp. 1245-1250.

Smith, B. S. 1966. Behaviour of Square Infilled Frames. Proc. of Structural Div. Journ., ASCE, ST-6, Vol. 92, pp. 381-403.