In-situ Measurement of Long-term Movements in a Brick Masonry Tower Block

by

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Summary

The paper describes a series of in-situ measurements to monitor long term movements in two highly stressed walls, at basement level, in a brick masonry tower block erected recently in Stoke-on-Trent, England. Measurements commenced when the building was five storeys high and continued until it reached its full height of 10 storeys, and for some two years after that. The results obtained to-date are compared with theoretical creep equations based on laboratory data and a modified Ross equation originally developed for predicting creep in concrete.

Introduction

For a period of over 3 years measurements of strain have been taken in two highly stressed walls, at basement level in a 10 storey block of flats at Stoke-on-Trent, England. The walls enclose a staircase and lift shaft. The purpose of these measurements is to compare movements in an actual building with predictions based on laboratory data. The fact that measurements commenced at an early stage of construction made the comparison particularly useful from the creep strain point of view since a large part of creep occurs soon after loading.

The paper discusses a method developed by the authors for predicting creep strain in brick masonry at any time after loading. It compares predicted values of strain with measured values and discusses the results.

Theory

Notation

Symbol	Description	Units
a,b	Constants	-
ε_c	Creep strain	-
ε_c^{max}	Maximum creep strain	-
ε_{max}	Maximum load strain	-
ε_i	Instantaneous strain	-
E	Elastic modulus	N/mm^2

Notation (Contd.)

Symbol	Description	Units
σ	Stress level	N/mm^2
S_R	Strain ratio	-
f_B	Compressive strength of bricks	N/mm^2
t	Time from load application	Days
ε_c^m	Measured creep strain	-
ε_c^c	Calculated creep strain	-

Using data from creep experiments on storey-high brickwork walls carried out in laboratory the authors studied a number of creep-time functions [1]. It was found that an equation put forward by Ross [2] in 1937 to predict creep in concrete could also be used for predicting creep as a function of time in single leaf brickwork walls.

In its original form the Ross equation is

$$\varepsilon_c = \frac{t}{a+bt} \tag{1}$$

where a and b are constants.

By writing equation (1) in the form

$$\frac{t}{\varepsilon_c} = a+bt \tag{2}$$

it is possible to obtain the constants a and b using linear regression technique.

From equation (1) it is seen that as $t \rightarrow \infty$, $\varepsilon_c \rightarrow \frac{1}{b} = \varepsilon_c^{max}$. Using a parameter defined as

$$S_R = \frac{\text{maximum load strain}}{\text{instantaneous strain}} = \frac{\varepsilon_{max}}{\varepsilon_i} \tag{3}$$

Where $\varepsilon_{max} = \varepsilon_i + \varepsilon_c^{max}$,

equation (3) can be written as

$$S_R = 1 + \frac{\varepsilon_c^{max}}{\varepsilon_i} \tag{4}$$

and rearranging gives

$$\varepsilon_c^{max} = \varepsilon_i(S_R - 1) = \frac{1}{b}$$

and since

$$\varepsilon_i = \frac{\sigma}{E_b}$$

therefore

$$\frac{1}{b} = \frac{\sigma}{E_b}(S_R - 1) \tag{5}$$

Analysis of experimental data has shown that both the strain ratio, S_R, and the elastic modulus of brickwork E_b, can be related to the compressive strength of the bricks, f_B. The most recent analysis has shown that for bricks laid dry

$$S_R = 8.35 - 0.62\sqrt{f_B} \tag{6}$$

and $$E_b = 5171\sqrt{f_B} - 19{,}158 \tag{7}$$

It was also found that the two constants in equation (1) can be related by

$$a\sigma = 3.8\,\mathrm{Ln}(b\sigma) + 18.21 \tag{8}$$

For a given compressive strength of the bricks and a known applied stress it is therefore possible, using equations (5)-(8) to calculate the creep strain in brickwork at any time, t.

In a building still under construction the increase in stress due to increasing load can be treated as a step function. By Boltzmann's principle of superposition, if at any time t, the stress increases from σ by an amount $\Delta\sigma$, then the resultant strain at subsequent time t is given by

$$\varepsilon = \varepsilon\sigma(t_1) + \varepsilon\Delta\sigma(t-t_1) \tag{9}$$

That is, the strain output due to the combination of two arbitrary but different stress inputs at different times equals the sum of the strain outputs from $\sigma(t_1)$ and $\Delta\sigma(t-t_1)$, each acting separately.

Experimental Procedure

Both demec and acoustic gauges were used in the measurement of strain in the walls. Figure 1a shows the plan view of the walls being monitored and Figure 1b shows the elevation of the two panels of the wall with the layout of the gauges. The demec gauge had a gauge length of 150 mm.

On the whole, it was found that the demec gauges gave more consistent results. There could be two reasons for this. The first one may have been an instrumental error in the acoustic equipment. The second reason could be that under fluctuating temperatures a temperature correction factor must be applied to the readings. For an acoustic gauge this requires the knowledge of the precise value of the coefficient of thermal expansion for both the brickwork and the steel wire used in the gauge. In the case of a demec gauge, the correction is obtained by simply taking a reference bar reading which is more reliable. In this paper only the demec gauge readings are discussed.

In panel B of the L-shaped wall shown in Figure 1 three bricks were temporarily removed by the contractor and subsequently replaced. It was decided to take strain readings across and adjacent to the replaced bricks to see how the readings compared with those in panel A, which was untouched.

Computation of Strain

One of the main objectives of this investigation was to find out how the computed strains from equations (5)-(8) compared with the in-situ measurements. One drawback was that the computed strain was due to load only whereas the in-situ measurements included some moisture strain as well.

From the design calculations supplied by the consultant engineers the following were the stresses on the wall at various stages of construction.

5 storeys - dead load stress	$= 0.589\ N/mm^2$
7 storeys - dead load stress	$= 0.806\ N/mm^2$
10 storeys - dead load stress	$= 1.131\ N/mm^2$
10 storeys - dead + live load stress	$= 1.246\ N/mm^2$

Taking time t to be zero when the initial set of readings were taken and assuming that the stress acting during the elapsed time between each set of readings was the mean stress, we have:

From $t = 0 - 144$ days	, $\sigma = 0.698\ N/mm^2$
$t = 144 - 384$ days	, $\sigma = 0.969\ N/mm^2$
$t = 384 - 580$ days	, $\sigma = 1.131\ N/mm^2$
$t = 580 - 830$ days	, $\sigma = 1.189\ N/mm^2$
$t = 830$ - days $\rightarrow \infty$	, $\sigma = 1.246\ N/mm^2$

It was assumed that the change in strain between readings was made up of an instantaneous (elastic) component caused by the change in load and a creep component given by equation (1) where the constants <u>a</u> and <u>b</u> can be obtained from equations (5)-(8). Hence we can write the following strain equations:

$$\text{From } t = 0 - 144 \text{ days, } \varepsilon_1 = \frac{t}{a_1 + b_1 t}$$

$$t = 144\text{-}384 \text{ days, } \varepsilon_2 = \varepsilon_1 + \frac{\Delta\sigma_2}{E_b} + \frac{t - 144}{a_2 + b_2(t-144)}$$

$$t = 384\text{-}580 \text{ days}, \quad \varepsilon_3 = \varepsilon_2 + \frac{\Delta\sigma_3}{E_b} + \frac{t - 384}{a_3 + b_3(t-384)}$$

$$t = 580\text{-}830 \text{ days}, \quad \varepsilon_4 = \varepsilon_3 + \frac{\Delta\sigma_4}{E_b} + \frac{t - 580}{a_4 + b_4(t-580)}$$

$$t = 830 - \infty \text{ days}, \quad \varepsilon_5 = \varepsilon_4 + \frac{\Delta\sigma_5}{E_b} + \frac{t - 830}{a_5 + b_5(t-830)}$$

The compressive strength of the bricks used in the building was 48 N/mm^2. Hence, from equations (6) and (7)

$$S_R = 4.08$$
$$E_b = 16{,}677 \ N/mm^2$$

Also, from equations (5) and (8)

For $\sigma_1 = 0.698 \ N/mm^2$, $a_1 = 10.199$, $b_1 = 0.078$
$\Delta\sigma_2 = 0.271 \ N/mm^2$, $a_2 = 26.270$, $b_2 = 0.200$
$\Delta\sigma_3 = 0.162 \ N/mm^2$, $a_3 = 43.945$, $b_3 = 0.334$
$\Delta\sigma_4 = 0.058 \ N/mm^2$, $a_4 = 122.743$, $b_4 = 0.933$
$\Delta\sigma_5 = 0.057 \ N/mm^2$, $a_5 = 124.897$, $b_5 = 0.949$

The computed strains are given in Table 1 and are plotted in Figure 3 together with experimental values.

TABLE 1

Variation of Vertical Strain with Time in Panel A of Lift Shaft Wall at Basement Level.

Elapsed Time (Days)	Vertical Strain x 10^{-5}	
	Experimental	Computed
0	0	0
144	3.8	6.7
384	11.8	14.5
580	15.5	18.8
830	22.0	21.3
1000	22.7	22.9
1202	25.2	23.6

Discussion of Results

Table 2 gives the corrected strains in brickwork in panels A and B at different times after the initial reading which was taken when the building was five storeys high. The corrected strains are also plotted in Figure 2.

Up to 384 days after the initial reading the increase in strain was caused by the combined effect of an increase in dead load from the additional storeys above, creep and moisture movement. At 384 days the building had reached its full height. From then on until 830 days after the initial reading the increase in strain was due to the occupants moving in with their furniture, creep and moisture strain. At 830 days the building was fully occupied and the subsequent increase in strain was due to the combined effect of creep and moisture movement. Unfortunately it was not possible to determine in-situ the moisture strain alone because all walls were loadbearing. The authors believe, however, that at that stage the moisture strain in internal walls was insignificant.

The readings in Table 2 show that the vertical strains in panel B of the L-shaped wall were considerably greater than those in panel A. This was due mainly to the temporary removal of three bricks in panel B which resulted in higher compression of the panel. As would be expected this was more noticeable across the bricks which have been removed where the mean strain was about three times higher than in panel A which was undisturbed. Even in the vicinity of the bricks which were temporarily removed the vertical strain was almost twice as high as in panel A.

There was considerable scatter in the in-situ strain readings in both panels of the wall under investigation. The mean compressive strain*in panel A was 25×10^{-5} which represents a compressive movement of just under 1 mm over a storey height. 13 percent of this movement occurred after 830 days from the initial reading, that is, after the wall has been subjected to its full dead and live load, and was caused by creep alone. Of course, the movement recorded before the full occupancy of the building was caused partly by elastic compression and partly by creep.

A movement of about 1 mm over a storey height may not seem much in itself. Nevertheless, a differential movement of this amount could cause cracks to occur in the brickwork and, more significantly, in a composite construction, with elements of different deformation properties, could also lead to a substantial redistribution of load between the components.

Gauge 10 in Table 2 shows the horizontal strains in panel A of the lift shaft wall. The strains this time show an extension which is caused by the Poisson's effect. The maximum strain of 11.5×10^{-5} at 1202 days gives a Poisson's ratio of 11.5/25.0 or 0.46 which is high for brickwork. The horizontal extension in brickwork under compressive load may be important when the member is restrained laterally as it can generate compressive stresses in the wall and possible bending in the restraining members.

* after 1202 days

The main object of this investigation was to relate the in-situ measurements to information obtained in the laboratory. Equations (5)-(8) of the paper were developed from the laboratory data and it was the authors' intention to compare the in-situ strain measurements with the computed strains based on the above equations. Table 1 shows the comparison between the measured vertical strains in panel A of the wall and the computed values. The results are plotted in Figure 3. It is gratifying to see that there is quite good agreement between the two sets of results and it follows that equations (5)-(8) put forward by the authors can be used with reasonable accuracy to predict the elastic and creep movements in brick masonry, even under varying load conditions.

Conclusions

In-situ strains have been monitored in a liftshaft wall at basement level in a ten-storey loadbearing brick masonry tower block over a period of 3½ years. The work is part of a programme to relate in-situ long term movements in loadbearing brick masonry buildings with laboratory data which has been collected over the past 12 years. The authors put forward equations, based on the laboratory results, to predict elastic and creep movements in loadbearing brick masonry members. The comparison between the observed and predicted movements is encouraging. The method outlined here may therefore be used to predict long term movements caused by loads in loadbearing brick masonry provided that moisture movement is not significant. If moisture movement is present its effect would be to counteract the compressive movement caused by the elastic strain and creep, and the computed results would then give the upper limit of the compressive movement in the brick masonry.

Acknowledgements

The work described in this paper is part of a research programme which was sponsored by the Science Research Council, the Brick Development Association and the Structural Clay Products Ltd. The authors wish to thank the sponsors for providing funds which made this investigation possible. They also wish to thank the Director of Environmental Services, City of Stoke-on-Trent, for his kindly co-operation and Donovan H. Lee and Partners, Consultant Civil Engineers, for supplying the design data which was used in the computations.

References

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2. ROSS, A.D. 1937. "Concrete Creep Data". The Struct. Eng. Vol.15, No.8

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TABLE 2

In-situ Load-strains in Brickwork Wall at Basement Level, Forest Court, Stoke-on-Trent

Elapsed Time (Days)	PANEL A						PANEL B					
	Vertical strain† x 10^{-5}					Horizontal Strain x 10^{-5}	Vertical strain x 10^{-5}					
	Gauge No.					Gauge No.						
	5	7	9	11	Mean	10	1	3	Mean	2*	4*	Mean*
0	0	0	0	0	0	0	0	0	0	0	0	0
144	5.4	4.3	3.2	2.1	3.8	-4.9	0.5	6.9	3.7	9.6	23.5	16.6
384	12.8	15.0	10.7	8.6	11.8	-4.0	17.4	21.7	19.6	37.5	59.9	48.7
580	17.1	21.4	12.8	10.7	15.5	-5.4	23.5	26.7	25.1	48.5	68.5	58.5
830	23.5	28.9	19.3	16.1	22.0	-7.0	30.4	33.6	32.0	67.0	88.8	78.1
1000	23.5	31.0	19.3	17.1	22.7	-6.3	36.7	39.9	38.3	66.3	93.1	79.7
1202	24.6	35.3	21.4	19.3	25.2	-11.5	38.7	43.0	40.9	69.3	98.4	83.9

*Gauge points 2 and 4 were across bricks which were temporarily removed

† +ve values indicate compression

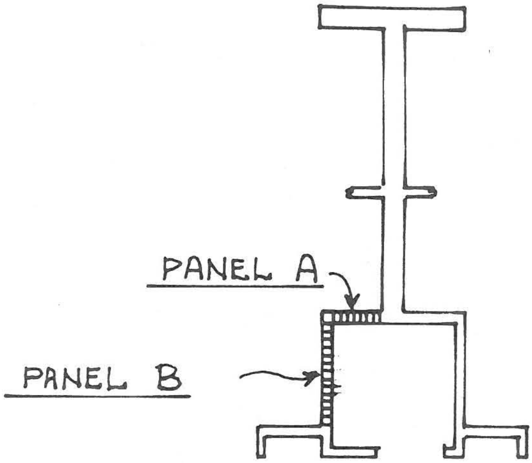

FIG. 1(a)

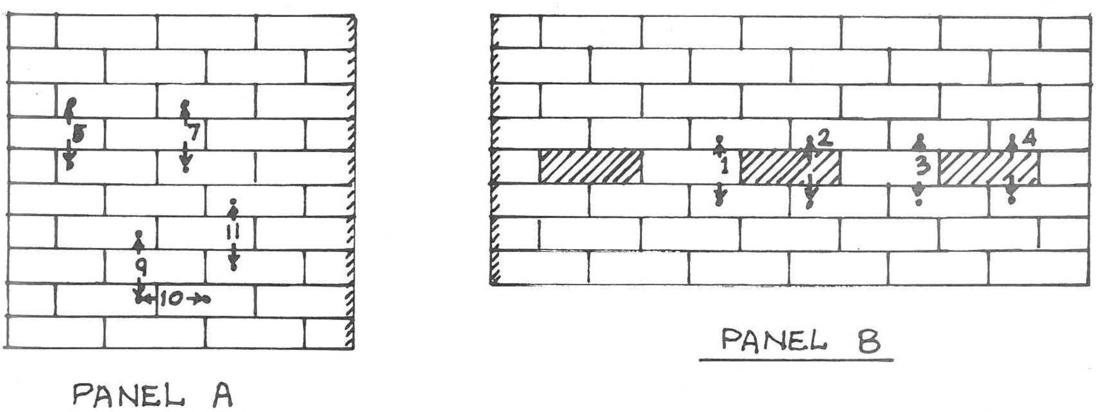

FIG. 1(b)

FIGURE 1. PLAN AND ELEVATION OF LOADBEARING WALL

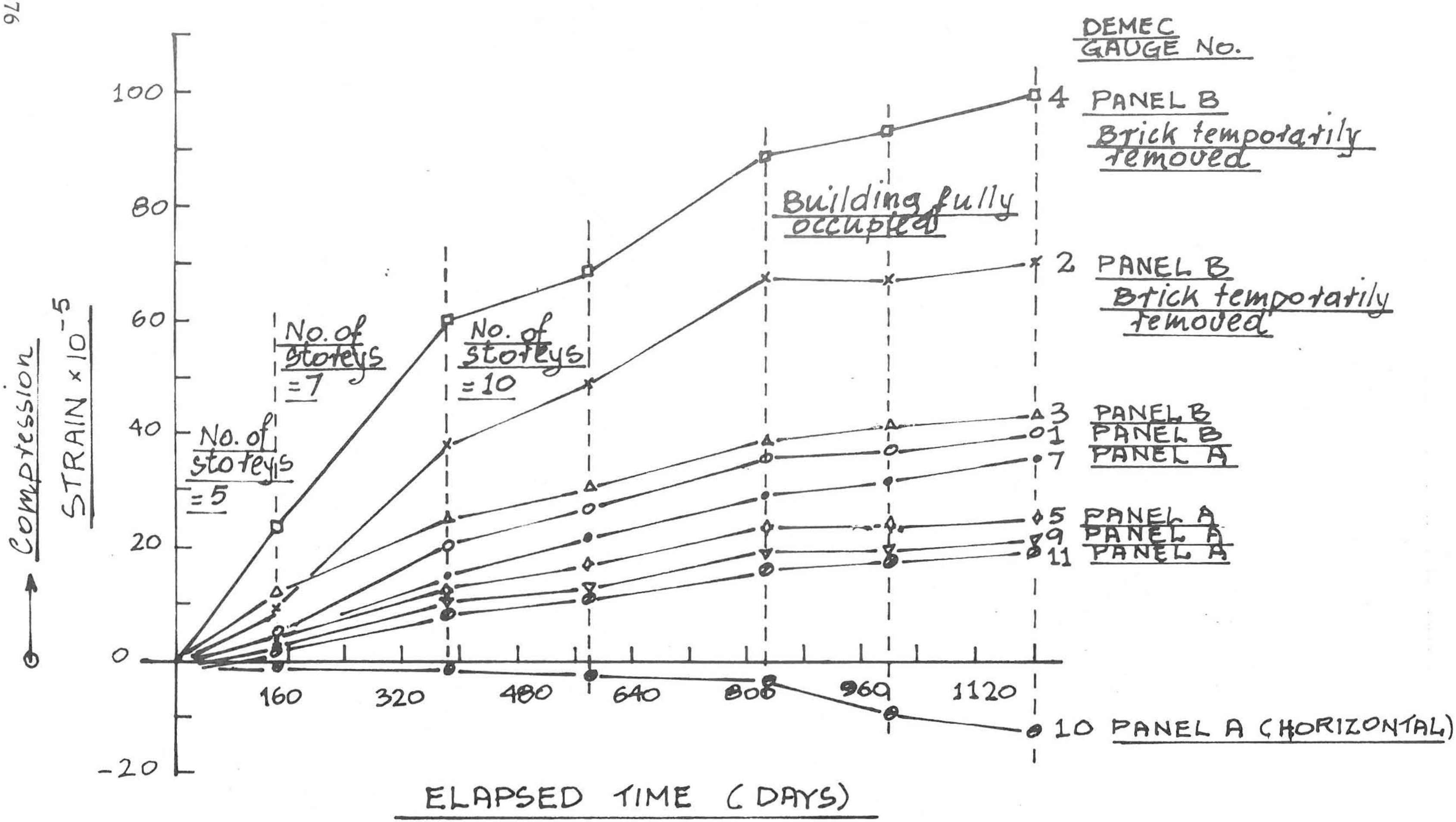

FIGURE 2. MEASURED STRAINS IN BRICKWORK WALL

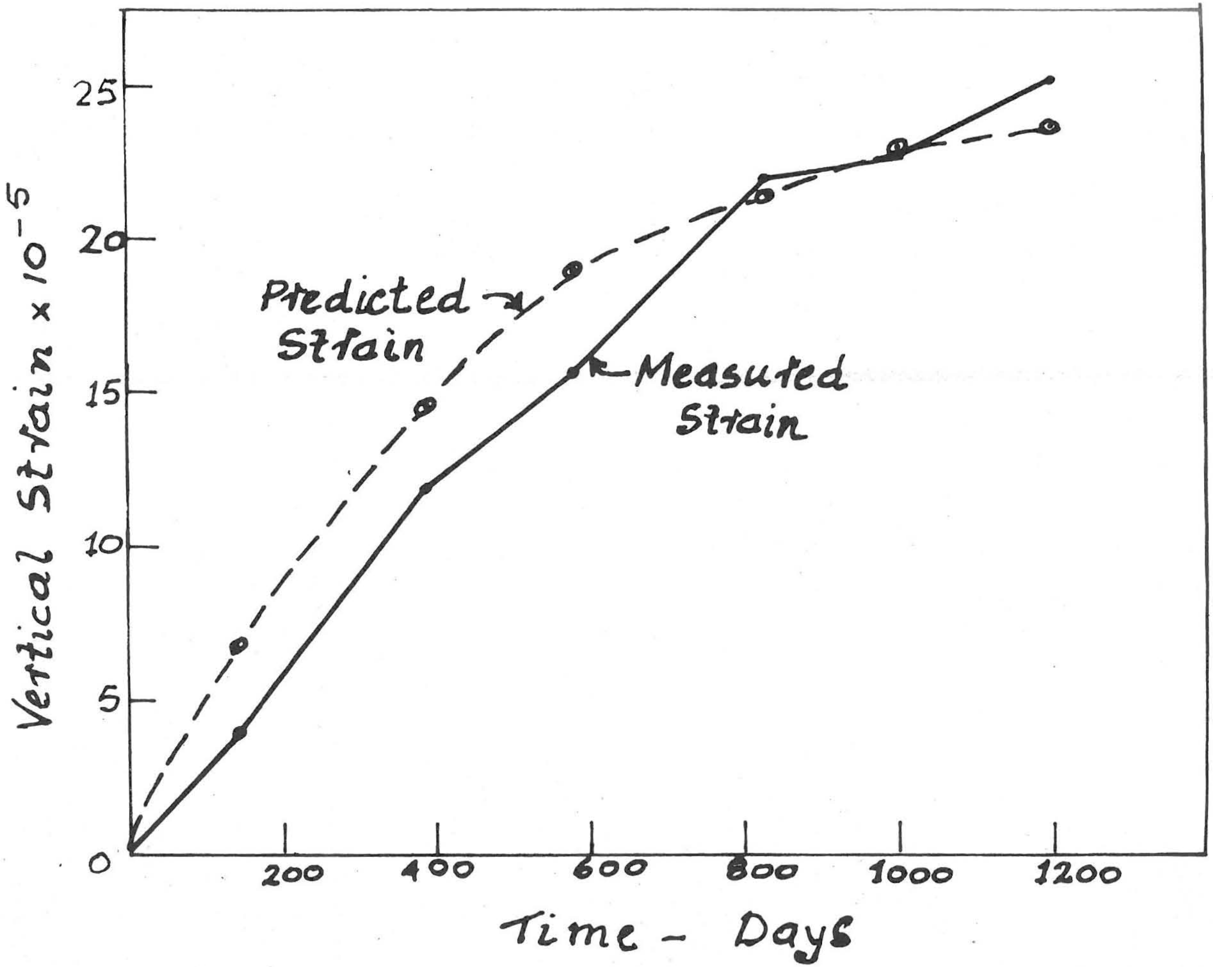

FIGURE 3. COMPARISON OF MEASURED AND PREDICTED VERTICAL STRAINS IN BRICKWORK WALL