EXPERIMENTAL RESEARCH IN THE COMPOSITE ACTION OF BRICKWORK AND PRESTRESSED CONCRETE LINTELS

F. H. Malpas B.Sc.(Eng)(Civ) B.Sc.(Eng)(Mech) M.S.A.I.C.E. Pr.Eng.

A Dissertation Submitted to the Faculty of Engineering
University of the Witwatersrand, Johannesburg
for the Degree of Master of Science in Engineering

Johannesburg 1980

DECLARATION

I, Frederick Henry Malpas, hereby declare that the work presented in this dissertation is my own and that it has not been submitted for a degree of another University.

F. H. Malpas.

F.H. Malpas

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	i
ABSTRACT	ii
PRINCIPAL NOTATIONS	iii
CHAPTER 1 - INTRODUCTION	1
CHAPTER 2 - LITERATURE SURVEY OF PREVIOUS WORK DONE ON COMPOSITE WALL CONSTRUCTION	3
CHAPTER 3 - EXPERIMENTAL INVESTIGATION ON THE WALLS	21
3.1 Objectives of Investigation ..	21
3.2 Description of Wall Construction ..	21
3.3 Load Test Apparatus	22
3.4 Load Testing Procedure	23
3.5 Test Measurements Taken	24
3.6 Object of Tests and Comparison of Results	27
CHAPTER 4 - EXPERIMENTAL INVESTIGATION ON THE MATERIALS USED IN THE WALL CONSTRUCTION	30
4.1 Test Procedure and Results of Tests on Concrete Cubes	30
4.2 Test Procedure and Results of Tests on Brick Piers built with Wall 1, the 2m x 5 Brickcourse Wall ..	32
CHAPTER 5 - WALL LOAD-TEST RESULTS	36
5.1 Number and Order of Wall Tests ..	36
5.2 Wall 1, Load-test Results ..	36
5.3 Comments on Test Results and Mode of Failure (Wall 1)	47

TABLE OF CONTENTS (contd.)

	Page
CHAPTER 6 - ANALYSIS OF RESULTS OF TEST SERIES	48
6.1 Ultimate Moment Compared with SHOFCO Values	49
6.2 Ultimate Shear Compared with SHOFCO Values	50
6.3 Maximum Measured Flexure Stresses in Brickwork and Concrete	51
6.4 Maximum Calculated Flexure Stresses in Brickwork and Concrete ..	52
6.5 Measured and Calculated Central Wall Deflections Compared	53
6.6 Summary of Results of Test Series ..	54
6.7 Further Comments on Composite Action	56
6.8 Summarized General Conclusions	60
APPENDIX A - RESULTS OF LOAD TESTS ON BRICK PIERS RELATING TO WALLS 2 TO 9 INCLUSIVE	62
APPENDIX B - RESULTS OF LOAD TESTS ON WALLS 2 TO 9 INCLUSIVE	71
APPENDIX C - RESULTS OF STRESS/STRAIN RELATIONSHIP FOR CONCRETE CUBE TESTS	148
APPENDIX D - DERIVATION OF THEORETICAL FORMULAE USED	149
APPENDIX E - SHOFCO VALUES FOR MOMENT AND SHEAR FOR WALLS	151
APPENDIX F - DERIVATION OF CENTRAL WALL DELECTION	159
APPENDIX G - LINTEL SPECIFICATIONS	161
REFERENCES	162

ACKNOWLEDGEMENTS

I would like to express my gratitude to Professor G.E. Blight of the University of the Witwatersrand for his supervision and valuable suggestions during the period of study.

I would like to thank Mr A.G. Hofmeyr and other colleagues in the Civil Engineering Department for their helpful advice and discussions.

I am indebted to Professor A.W. Hendry, Head of the Department of Civil Engineering and Building Science, University of Edinburgh, for the opportunity to continue further studies in composite action at the University of Edinburgh.

I would like to thank Professor Hendry and also Dr A.W. Page and Dr. S.R. Davies for their helpful discussions.

I would also like to thank the technical staff of the Civil Engineering Department, University of the Witwatersrand and Mrs E.M. Towsey for her careful typing of the manuscript.

ABSTRACT

In many circumstances the walls of a building do not continue down to the foundations but are supported on a framed sub-structure. The large open spaces required in multi-storey buildings are examples of this.

If in the structural analysis of a framed building, a beam spanning an opening is considered to totally support the wall above it, this would result in very large supporting beams and columns.

However, if in the design, the wall and its supporting beam is considered to act as a composite member, the wall loading can be redistributed along the beam, which in effect considerably reduces the beam dimensions.

This dissertation presents an experimental and analytical investigation of composite wall behaviour, comparing experimental and analytical results

The experimental investigations include tests carried out on the materials used in the wall construction to obtain the elastic modulus constants and load tests to failure on nine brick walls supported on pre-cast concrete lintels.

The lintels used in the experimental investigation were supplied by SHOFCO (Structural Hollow Floor Co.) Robertsham, Johannesburg, who also supplied values of Moment and Shear resistance with number of brick courses on the lintel. These values were compared to the results obtained in the load tests.

PRINCIPAL NOTATIONS

d	Total depth of wall
ϵ_b	Maximum flexure strain in brickwork
ϵ_c	Maximum flexure strain in concrete
E_b	Modulus of Elasticity of brickwork
E_c	Modulus of Elasticity of concrete
f_b	Maximum flexure stress in brickwork
f_c	Maximum flexure stress in concrete
I_b	Second moment of area of brickwork about wall neutral axis
I_c	Second moment of area of concrete about wall neutral axis
L	Wall span
M	Bending moment
n	Depth to neutral axis
t	Wall thickness
b	Depth of lintel

CHAPTER 1 - INTRODUCTION

It has long been known to designers that composite construction in its many forms contributed to the stiffening of a structure. The simplest form of composite construction is the reinforced concrete beam, in which two materials acting together resist stresses and deformations to support an applied load.

A more complex form of composite construction is a multi-storey framed building. No matter whether the frame is of reinforced concrete or steel members encased in concrete, the columns and beams of the framework act like the reinforcement in a reinforced concrete beam, in the cellular connection of slabs or shells forming the floors and walls.

When a beam supports a masonry wall over an opening, the in-plane rigidity of the wall makes it act like an arch, spanning the opening. Any additional vertical loads on the wall are not transmitted vertically down but are redistributed towards the ends of the beam and the final loading on the support beam is concentrated mainly near the beam supports. Due to this action the beam acts primarily as a tie and is subjected to greatly reduced bending moments.

Figure 1.1 shows a simplified form of composite action, in which the wall acts as an arch, the beam as a tie and the redistribution of vertical loads on the beam acts near the supports.

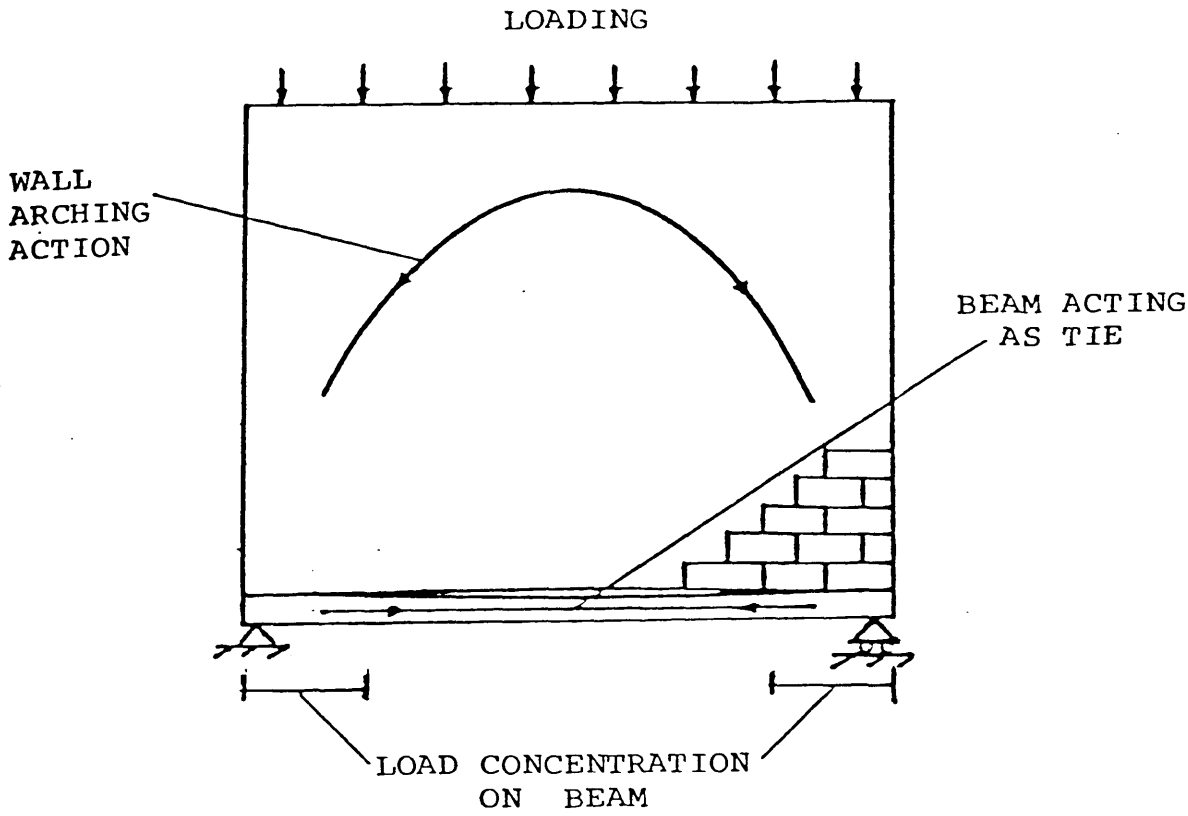


FIGURE 1.1

The high vertical stresses and horizontal shear and bond stresses induced near the supports were a product of arching action through composite behaviour and frequently caused panel failure as can be seen in the experimental results obtained in the wall loading tests.

A study of composite action was therefore of importance for obtaining a much closer approximation of the actual behaviour of a structure.

CHAPTER 2 - LITERATURE SURVEY OF PREVIOUS WORK ON COMPOSITE WALL CONSTRUCTION

This section contains a literature review of work carried out on composite wall construction, beginning in the early fifties.

In 1951, the Building Research Station[1] conducted a series of tests on the New Government Offices, Whitehall Gardens. This building consisted of a steel framework, all the beams and stanchions were encased in concrete at the same time as the solid reinforced concrete floor slabs were poured and with the same concrete. The outside walls were brick faced with Portland stone, 13,5 inches thick overall.

Tests were carried out on part of the steel frame from initial erection through the placing of the walls and floors and subsequent live loading on the complete building. These tests gave a complete stress history of parts of the steel framework and from the results obtained, stresses induced in the beams due to their interaction with floors and walls were reduced by up to ninety per cent. This reduction was a result of composite action throughout the building.

R.H. Wood[2] in 1952 conducted the earliest experimental investigations into the composite action of beams supporting masonry walls. The commonly assumed design loading for a reinforced concrete beam supporting a

masonry wall had been its capacity to support a triangular load of bricks, the base of the triangle being the span of the beam as shown in Figure 2.1.

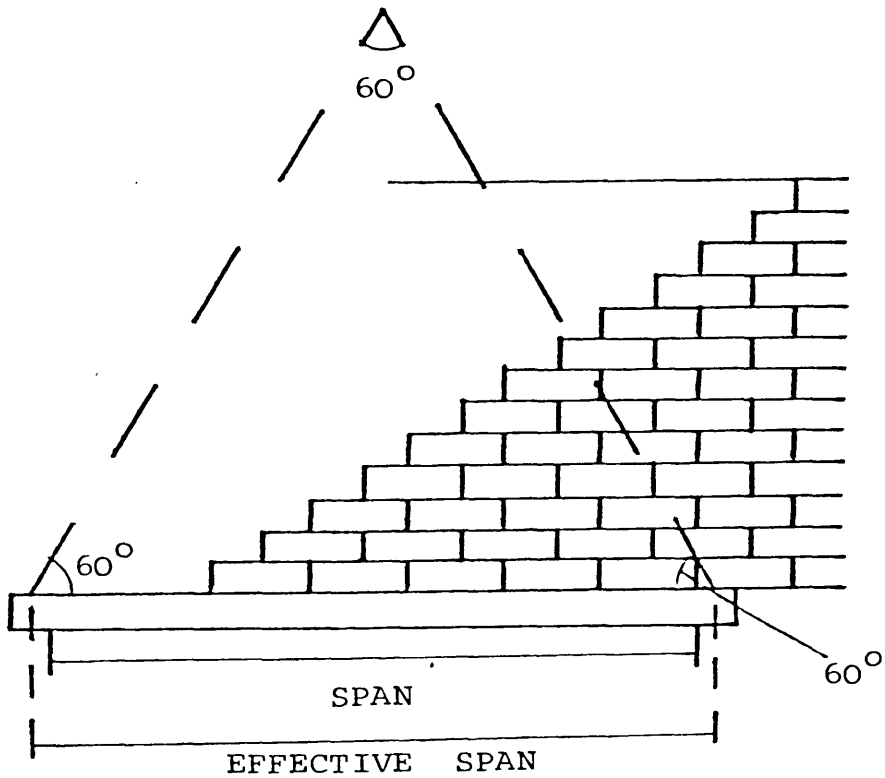


FIGURE 2.1

It was not known what portion, if any, of a superimposed load should be added to the triangular load and was usually neglected. Wood found in his investigations that a beam supporting a brick panel produced an arching effect in the brickwork achieving a greater overall stiffness, the supporting beam mainly acting as a tie reinforcement.

In the experiments carried out, the steel stresses in the supporting beams were determined and found to be very low. Woods consequently determined 'Equivalent' central design moments for beams supporting plain walls. These

moments were as low as Wl/100, where W was the total uniformly distributed load. Further results of tests on a nine inch solid brick wall, eight feet high, supported by a reinforced concrete beam over a ten foot span gave the following equivalent bending moments from the steel stress in the beam.

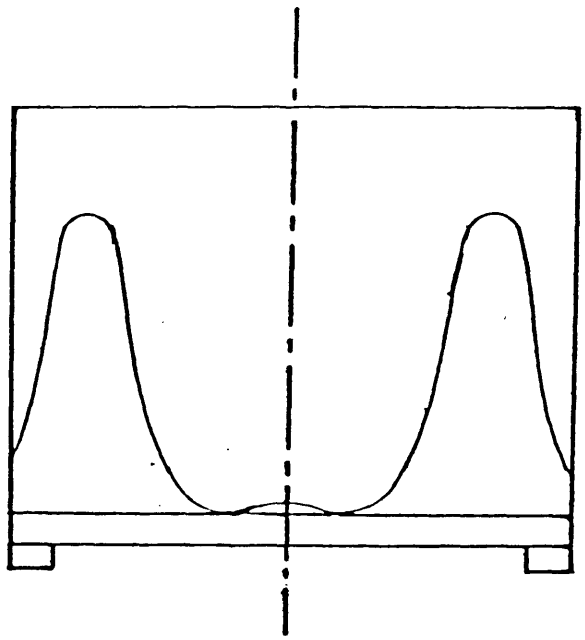
TABLE 2.1

TOTAL APPLIED DISTRIBUTED LOAD (TONS)*	EQUIVALENT BENDING MOMENT (TONS FT)
6	Wl/274
15	Wl/248
18,5	Wl/218
29,8	Wl/130

*Not including dead weight of wall = 4 Tons

Wood concluded that the moments induced in a panel depend on the relative stiffness of beam and brick wall, the greater the beam stiffness, the more it carries at its centre. The more flexible the beam, the brick panel produces a bigger arching effect and tends to become self-supporting.

The composite action induced high local compressive stresses and high shear and bond stresses near the supports. A diagram showing typical results of vertical load distribution on a beam is given in Figure 2.2.



LOAD DISTRIBUTION ON BEAM

FIGURE 2.2

These stress concentrations developed a fixing moment near the support reducing the central beam deflections and moments, but adversely the bricks near the supports were subjected to crushing and vertical cracking due to tensile failure. Wood also presented another conservative design rule for deep panels and this was the 'Limiting Moment Arm Method'. It proposed that the steel reinforcement may be designed using a moment arm of two thirds the depth of the panel with a limit of 0,7 times the wall span.

In 1961, S. Rosenhaupt[3] published a paper 'Elastic Analysis of Composite Walls - A General Theory'. In this paper a general solution for the composite action of masonry walls and the beams or ties stiffening their outer edges was given and the theoretical solutions for particular cases were derived from it. Also the influence of the position and rigidity ratio of wall and ties were studied.

In 1962 S. Rosenhaupt[4] published the results of load tests to failure on twelve model walls, each wall consisting

of masonry supported on a reinforced concrete beam, supporting a uniformly distributed load. These tests showed a concentration of vertical stress in the bottom layer of bricks, near the supports, approximately three to four times higher than the external load. This stress concentration was found to increase with wall height. In some of the tests, vertical edge ties were included which relieved the lower layers of brickwork of the vertical stress concentration, reduced the horizontal shearing stress in the masonry and reduced the deflection.

In 1964 the Structural Clay Products Research Foundation (SCPRF)[5] in the United States published the results of a series of tests on brickwork. The tests were on small scale specimens which were to determine the influence of mortar properties, brick properties and joint thicknesses on brickwork strength. Results of the experiments conducted indicated that higher brick and mortar strengths were associated with higher brickwork strengths and that the thickness of the mortar joints were linear and inversely related to the compressive strength of brickwork.

Prasan, Hendry and Bradshaw[6] in 1965 published the results of tests on seventeen 4,5 inch thick brick walls loaded between reinforced concrete slabs and the following points were noted in their conclusions.

Typical modes of failure were by transverse splitting which indicated that the tensile strength of the brick and also the properties of the horizontal mortar joints, such as Young's Modulus and Poisson's Ratio may be of primary importance in determining the strength of brickwork.

Increases in brickwork strength of over sixty per cent were observed when every bed joint was reinforced horizontally.

Horizontally reinforced brickwork appeared to be advantageous for highly stressed brickwork and under beam bearings.

The code of practice C.P.111 (1964) limit of eighteen for the slenderness ratio of load bearing walls appeared conservative for walls restrained by concrete slabs.

An approximate method of analysis of walls acting compositely with supporting beams was presented by Coull[7] in 1966.

The analysis consisted of expressing the stresses in the wall as power series in the horizontal direction, the coefficients being functions of wall height only. After the equilibrium and boundary conditions were satisfied for both beam and wall, the remaining coefficients were determined by minimizing the strain energy of the system. The problem reduced to solving a fourth order differential equation subject to different boundary conditions. Different sample curves were given to indicate the influence on the stresses of the various stiffness and geometrical parameters involved.

The theory indicated that under the action of a uniform vertical load on the upper edges of the wall, tensile forces existed between the wall and beam interface as shown in Figure 2.3a and shear stresses existed in this same plane as shown in Figure 2.3b. Also the wall height/beam span ratio and wall/beam stiffness ratio affected the magnitudes of the wall stresses much more than the beam depth/wall height ratio.

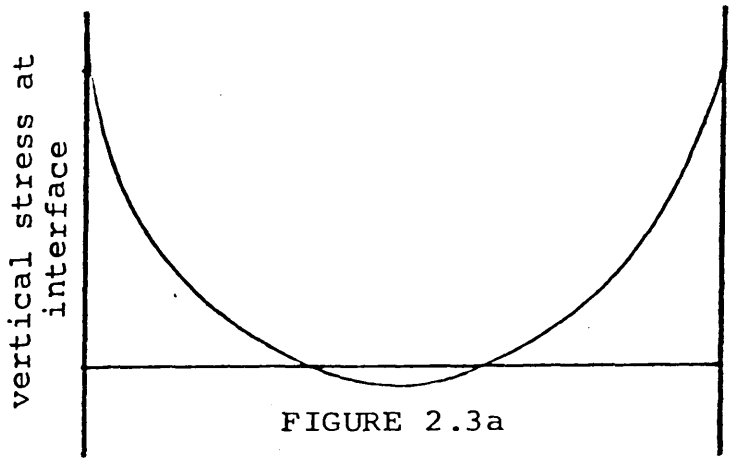


FIGURE 2.3a

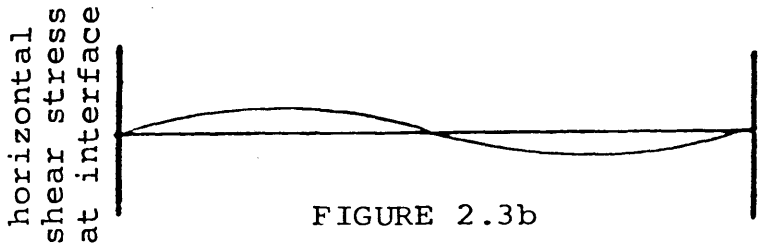


FIGURE 2.3b

He noted finally that for walls whose height is greater than the span, practically no diffusion of stress occurs in a section above the unit depth : span position.

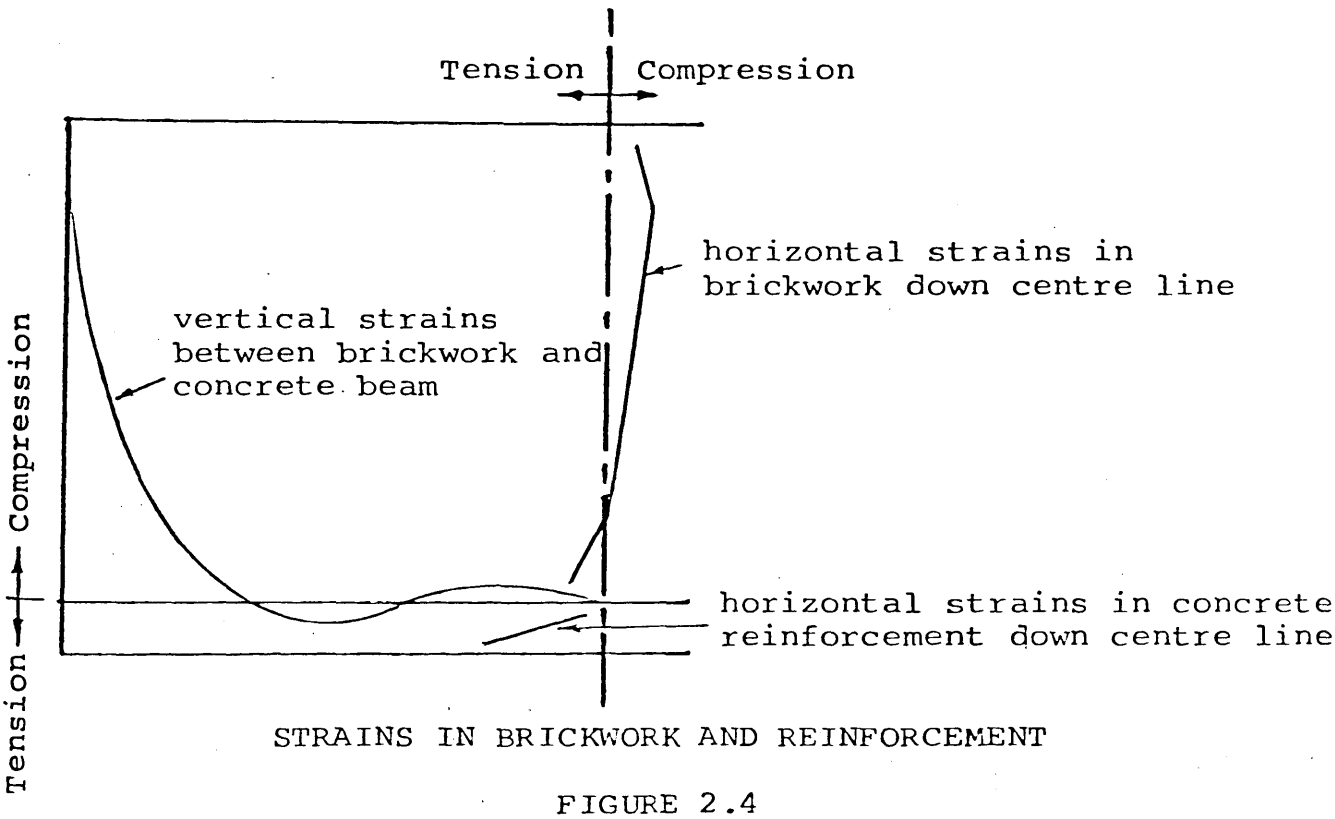
In 1969, P. Burhouse[8] carried out a number of wall tests to failure at the Building Research Station, Watford, England. The walls were simply supported on either encased steel joists or reinforced concrete beams. These tests were mainly concerned with the height to span ratio of the walls and to compare the behaviour of the walls acting in conjunction with reinforced concrete beams and concrete encased steel beams.

Of ten tests carried out, failure in all except one test occurred by crushing of the brickwork at the bottom corner of a panel. Based on a load factor of five, Burhouse compared the working loads obtained with those

given in C.P.111 and suggested that the working loads on the wall forming part of composite beams should be less than the working loads derived in accordance with C.P.111 which assumed a rigid foundation.

Further points he made in his comments were that composite wall action between wall and beam would not take place without the transfer of shear stress across the interface between the two components, nor without transfer of shear stress across the mortar joints between courses of brickwork. The joint between wall and beam had to be capable of transferring a force greater than the calculated tensile force in the beam by a suitable margin.

Considering one of the tests on a brick wall supported by a reinforced concrete beam having top and bottom reinforcement, simply supported and carrying a uniformly distributed load, this gave the strain pattern shown diagrammatically in Figure 2.4.



STRAINS IN BRICKWORK AND REINFORCEMENT

FIGURE 2.4

In 1969, J.R. Colbourne[9] developed theoretical expressions for the stresses induced in wall/beam structures. The wall and beam were represented by a lattice analogy, in which it was assumed that the system remained elastic. The analogy was then used to derive equilibrium equations for points near the edges of the wall and for points affected by the beam. Sets of equations were solved to give displacements which were used to find stresses in the wall and stress resultants in the beam. Results were compared with Rosenhaupt[3] and Coull[7] and a fairly good agreement was obtained.

In 1969, Male and Arbon[10] published a paper in which the Finite Element technique was used to analyse walls resting on simply supported beams. The effect of openings in the wall on the stress distribution was studied and the position of these openings was found to be critical. The interaction between wall, beam and soil was also studied, taking into account the swelling of the soil.

From the analysis they concluded that

(1) For full composite action to develop, shear stresses must be transmitted efficiently across the boundary between wall and beam. Comparatively high shear stresses between wall and beam occurred near the supports in all the cases considered and it was shown that a shear failure at the interface resulted in high tensile stresses being developed in the wall with the probability of cracking.

(2) When the load was applied at floor or beam level, high tensile stresses in the vertical direction occurred at the interface and for full composite action to

take place, the separation of wall and beam must be prevented by prestressing or tensile connectors.

(3) In the case of door openings in the wall, when the opening occurred at mid-span, little disturbance in the stress field occurred. When the opening was placed near to a support, high tensile stresses occurred near the top of the door.

(4) Investigation into the interaction between wall, beam and soil showed that in a typical non-expansive soil, the stresses in both beam and wall were only about one fifth of those which occurred in point support cases. However, when swelling, resulting from expansive soils produced upward heaving at the ends and then at the centre, the stress levels approached those in a wall with simple supports.

In 1969, Wood and Simms[11] carried out further experiments intending to extend Wood's original work on wall/beam interaction and equivalent design moments. The essential point at issue was that if load-bearing 'engineering' walls were heavily loaded right up to the limits given in C.P.111, then there was little or no reserve left for the concentrated brick stress demanded by composite action with its arching. The further tests conducted produced a more conservative design based on an intuitive assessment of composite action in the light of the extra tests carried out and recognising an increased safety factor for brickwork combined with reinforced concrete.

The problem they attempted to solve was to find some sliding scale Equivalent Bending Moment Wl/K where K was a number ranging from a maximum of 100 for full composite action with lightly loaded walls down to a minimum of

$K = 8$ where all composite action had disappeared.

In their analysis they took into account the effect of a horizontal shear force H at the interface between beam and brickwork producing a negative moment of $H(\frac{b}{2})$ where b = depth of beam. The bending moment was related to the stress concentrations in the wall and at wall failure the vertical load on the beam was uniformly distributed close to the supports.

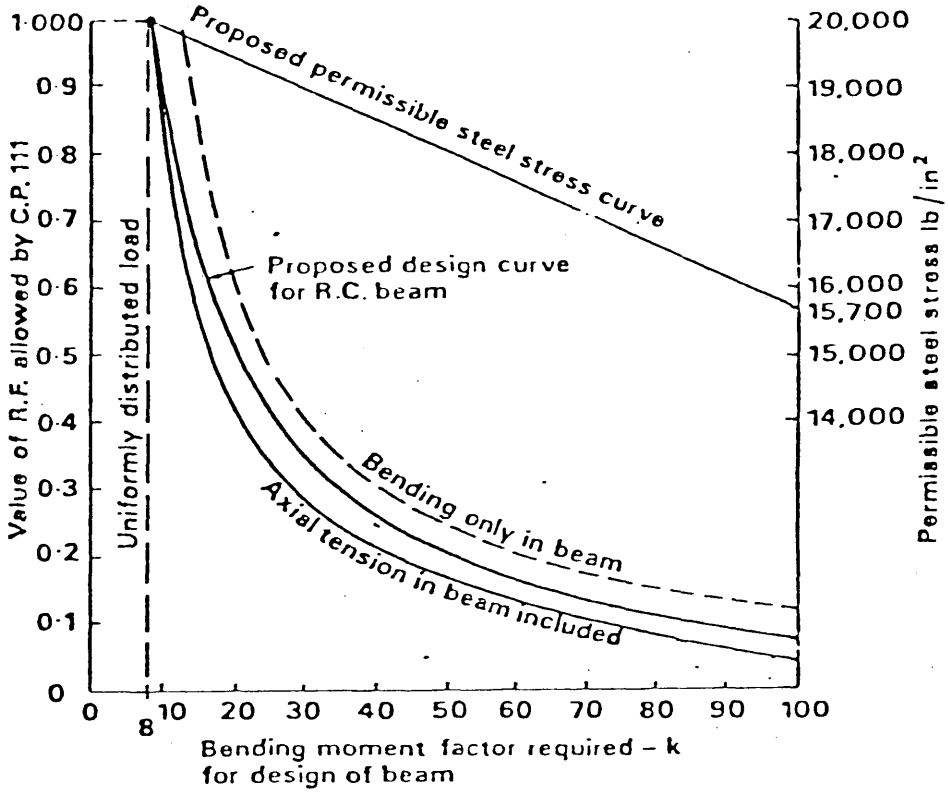
Their final design formula from which K was obtained was -

$$R.F. \geq \frac{(176 + K)(154 - K(K - 8)/92))}{(184)(19,25K)}$$

where R = Stress reduction factor

F = Reduction factor for wall slenderness.

The equivalent bending moment was calculated conservatively using the design curve shown in Figure 2.5.



Composite action with load-bearing walls

Figure 2.5

Yettram and Hirst[12] in 1971 presented an elastic analysis for walls supported by simple beams. They idealised a wall/beam structure as a set of equispaced vertical stringers, which carried direct load, with shear carrying panels between them. Any distribution of vertical load should be considered which included the wall self-weight. An allowance for Poison's Ratio effects were included.

The numerical solution gave ratios of direct vertical stress at varying depth levels down the edge of the wall to vertical stress applied at the top of the wall, it also showed that the bending moments substantially increased all across the span as the beam stiffness increased.

The results compared favourably with those obtained by Colbourne[9] and Rosenhaupt,[3] but when compared with Coull's[7] results they predicted higher values to the stresses over the significant region near the supports.

Smith and Riddington[13] in 1973 presented a paper in which a design method was derived for masonry wall on steel beam structures and the results of a series of tests on models consisting of dental plaster walls on simply supported rectangular steel section beams were analysed.

The authors, when deriving basic formulae stated that when arching action occurred, the beam separated from the wall in the mid-span region as shown in Figure 2.6a and the vertical compressive stress and horizontal shear distribution at the interface of the wall and beam took the form shown typically in figures 2.6b and 2.6c. Both distributions being reasonably approximated by a triangular distribution shown in Figure 2.6d but to a different scale.

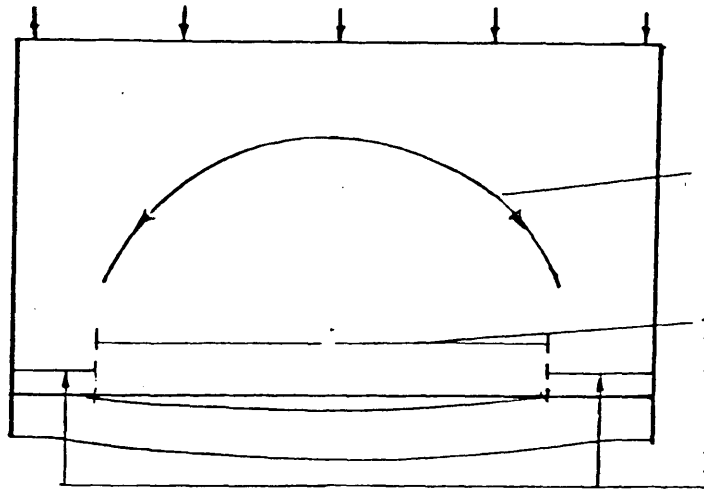


FIGURE 2.6a

FIGURE 2.6b

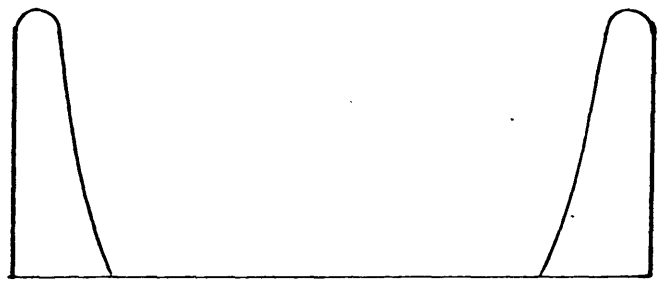


FIGURE 2.6c

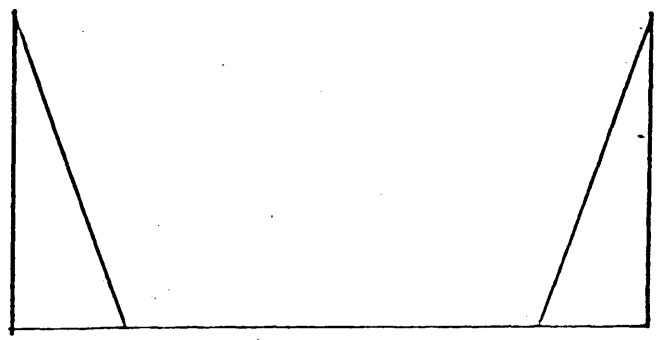


FIGURE 2.6d

In Figure 2.6a, the length of contact 'l' was governed by the relative stiffness of wall and beam, the stiffer the beam, the larger the length of contact.

The length 'l' was expressed by the relationship

$$l/L = B/K \quad \text{or} \quad l = BL/K$$

where B is a constant derived from the peak wall stress or wall crushing strength and K a non-dimensional relative stiffness parameter given by

$$K = \sqrt[4]{E_b t L^3 // I}$$

where EI is the flexural rigidity of the beam. An increase in the value of E_b or a decrease in the value of EI produced a larger K value and a smaller length of contact.

The derivation of the design formula used in the composite action was based on (1) Peak vertical wall stress. (2) Peak bending stress and beam deflection (3) Peak shear stress on wall/beam interface.

Results of the tests which were carried out showed the vertical stress concentration in the wall to be the major design factor. Design curves were plotted which allowed the direct design of the beam to be obtained without any iterative process, as shown in diagrammatic form in Figure 2.7.

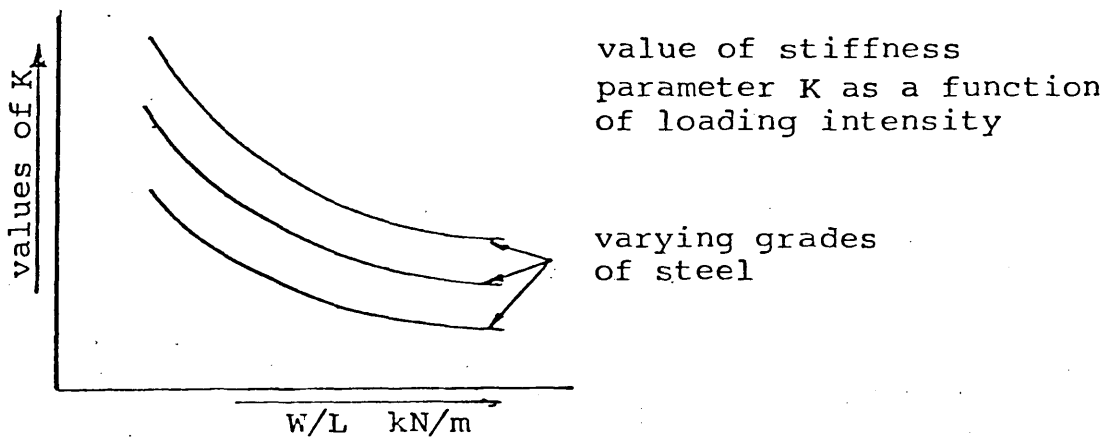


FIGURE 2.7

In 1977, Stafford Smith, Khan and Wickens[14] published the results of tests designed to study the influence of beam stiffness on the vertical strength of wall/beam structures. The conclusions resulting from these tests were as follows:

1. For similar walls, the beam stiffness has a substantial influence on the distribution of stress between the wall and the beam. The more flexible the beam, the greater stress concentrations which occurred near the supports with larger peak stress values.

2. The beam stiffness has a significant influence on the strength of the wall. The stiffer the beam, the greater the wall strength. These tests confirmed that the strength of the wall was approximately proportional to $\sqrt[4]{I}$ of the beam.

3. The magnitude of the tie force in the beam is almost independent of the beam stiffness. The stiffer the beam, the larger the distribution of interacting stress which it causes, increasing the resultant bending moment. The bending moment also varied approximately proportional to the $\sqrt[4]{I}$ of the beam. The combination of tie force and bending moment stresses may be such that in lighter beams, the section is completely in tension.

In 1977, A.E. Ahmed[15] in his PhD thesis on Composite Action gave the results and conclusions of a number of load tests on masonry panels supported on beams. The thesis consisted of a study of the composite behaviour of vertically loaded walls and the influence of significant design parameters under different boundary conditions.

The experimental investigations were carried out on

one-third scale model brick walls, with and without openings and supported on reinforced concrete beams. The investigations were primarily concerned with beam point supports. Other wall support conditions were investigated and these were fixity and continuity over the supports and finite support width. Loading on top of the wall and also at beam level was investigated.

From the experimental results, he concluded the following

(1) The beam and wall behaved compositely as a tied arch. The concentration of stresses near the beam support was the main cause of failure. These stresses must be transmitted efficiently across the interface of wall and beam.

(2) The ultimate resistance of the wall could be increased by using bricks of higher compressive strength, by reinforcing the bed joints at the bottom corners of the wall or by the inclusion of vertical stanchions along the edges of the wall.

(3) The vertical shear stress extended from the support section to about one tenth to one fifth of the span. The maximum bending moment in the beam occurred near the supports.

(4) Walls with central openings had stress distributions similar to those of solid walls. When an opening, such as a doorway occurred near a support, tensile stresses developed around the top corners, the ultimate resistance decreased to approximately one half that of a solid wall, indicating loss of composite action. Excessive beam deflections of up to 2,5 times that of a solid wall were noted.

Figure 2.8 shows a masonry wall supported by a beam with a doorway near its right hand support, the loading applied to the top of the wall. It illustrates a secondary arching action and the redistribution of the vertical stress along the interface.

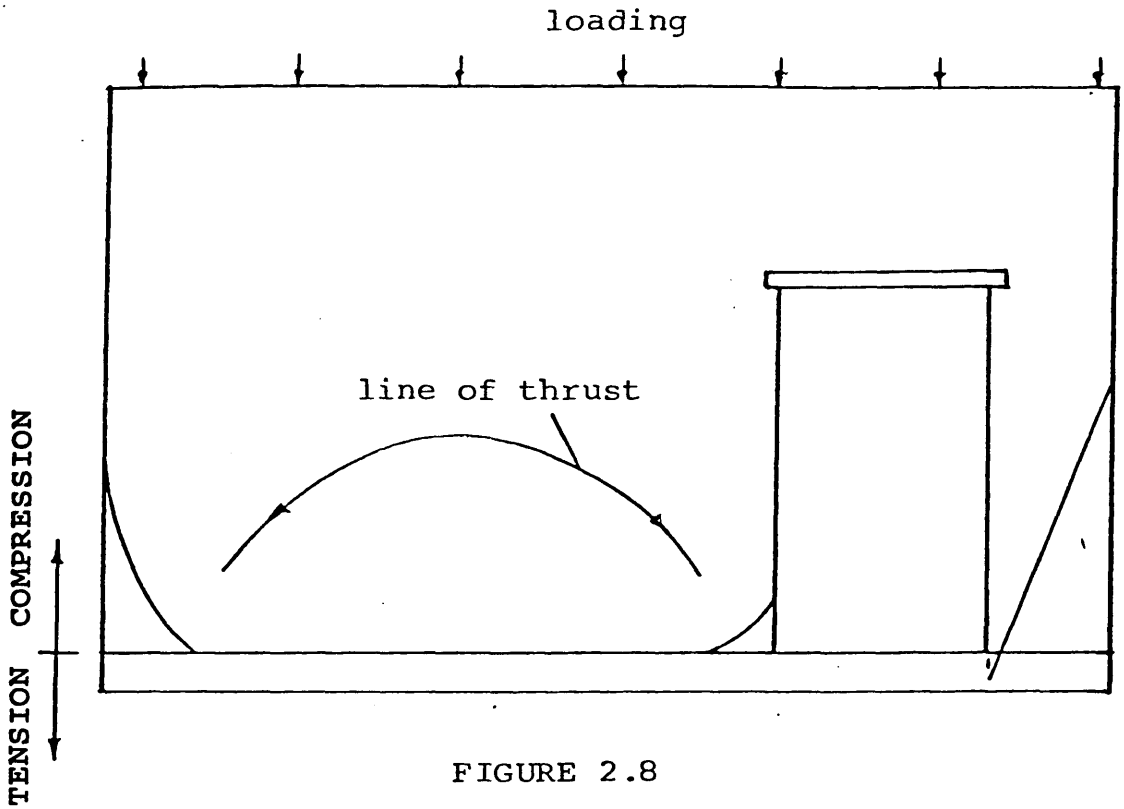


FIGURE 2.8

The arching phenomen is noted in the Standards Association of Australia.[16] It states that the bending produced in a beam or a lintel by a brick wall imposed along the length of the beam can be very much less than would be expected if the full weight of the brickwork were acting on the lower member. It also states that true arching requires that the end supports for the brickwork apply a horizontal restraint as shown below in Figure 2.9.

While this does occur in some measure under the length of a brick wall, recent research has shown that the very light loading of the lintel is to be found not in the arching action, but in the great difference in the flexural stiffness between the wall and its supporting member.

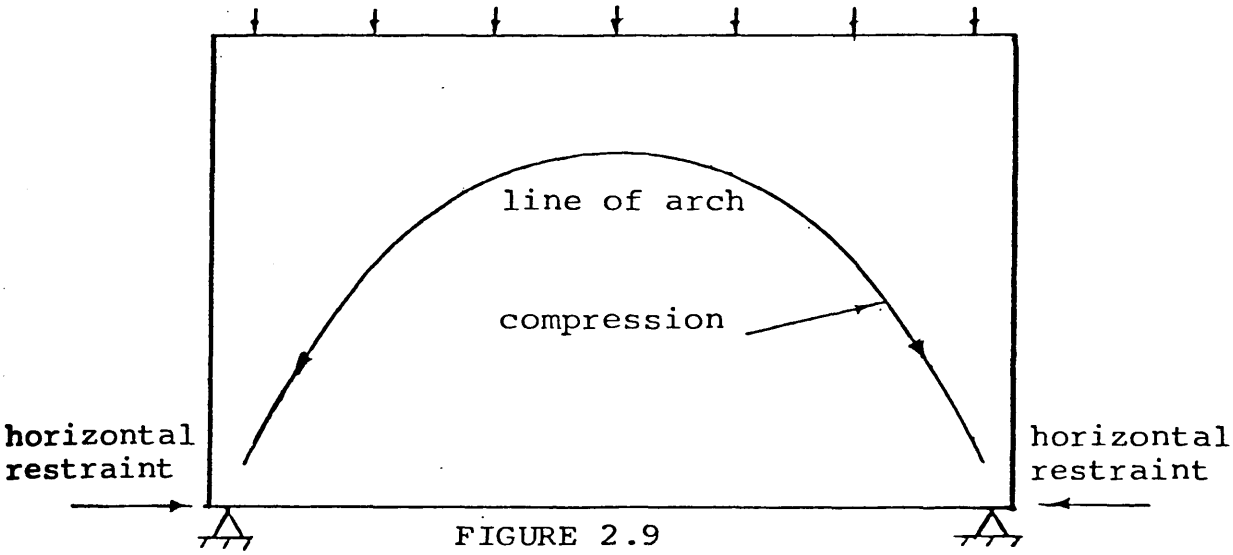


FIGURE 2.9

CHAPTER 3 - EXPERIMENTAL INVESTIGATION ON THE WALLS

3.1 Objectives of Investigation

The investigations were to obtain through strain recordings

1. The dispersion of strains throughout the composite wall.
2. The effects of composite action.
3. the effects of arching action.
4. A comparison of the ultimate loading with the empirical loading.

The essential differences between this investigation and previous investigations were

1. Walls of small height/span ratio were tested.
2. The strain recordings at (b) and (c) had not been taken in previous investigations.
3. Rates of strain, or energy dissipations were noted.

3.2 Description of Wall Construction

Each wall was constructed by first supporting a prestressed lintel* at its ends on single brick supports with a layer of mortar between the concrete and the brick. The lintel was also supported at one metre lengths along the span.

With a layer of mortar on the lintel the bricks were layed using normal building procedures, no special effort being made to produce brickwork with unusually good workmanship.

Face bricks were used to build the walls; they were

* See Appendix G.

frogged but had two 35mm diameter holes spaced symmetrically at 110mm centres. The bricks were cleaned and wetted before use. The mortar used in the wall construction was a nominal mix of three parts of pit sand, one part of river sand and one part cement.

Immediately after each composite wall was built, three single brick piers, one brick wide, were built using the same mortar and having the same number of brick courses as the wall. A total of nine walls were built and tested to failure. Three spans of 2,4 and 6m were used and on each span three walls were built, each wall having either 5,7 or 9 brick courses.

3.3 Load Test Apparatus

The composite wall rested on simple end supports, each consisting of two courses of single brick with mortar joints. The loading was applied vertically through point loads of one brick length on top of the wall by means of a load spreader beam which in turn was loaded by a central load with a spherical seating. The arrangement of the test apparatus is shown in Figure 3.1.

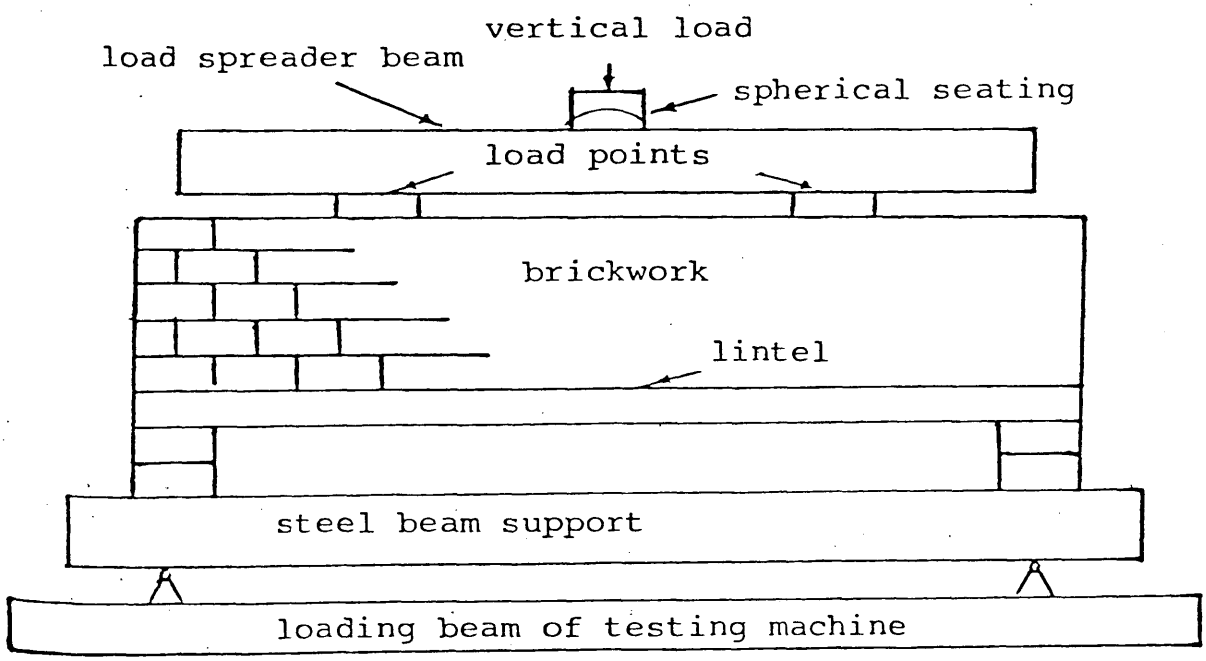


FIGURE 3.1

Loading Testing Procedures

A few days before the load tests were carried out following procedures were conducted.

1. Demec targets were attached to each wall in a specific pattern in order to measure the flexure strains (a), the diagonal strains (b), the differential slip strains (c) and the vertical strains along the centre line between brickwork and lintel (d) as shown in Figure 3.2. A 406mm demec gauge was used to measure these strains.

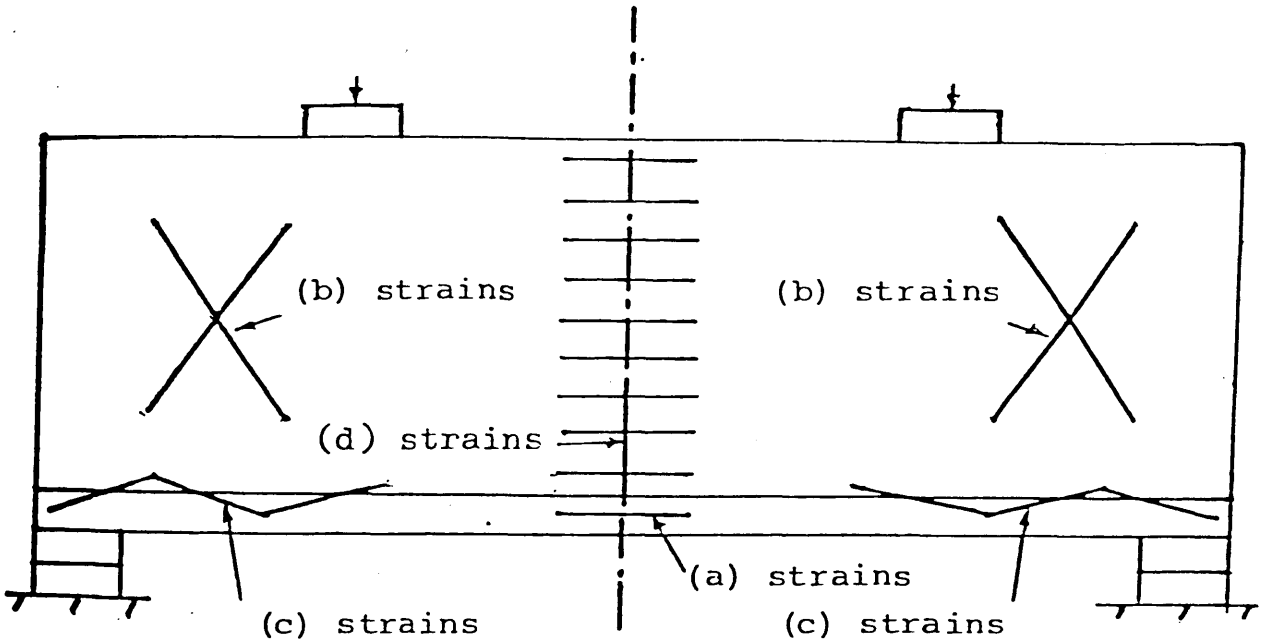


FIGURE 3.2

2. The wall was whitewashed so that cracks could be distinguished (visibly) early and the final mode of failure seen clearly and photographed.

Before any load was applied the temporary props under the beam in between the end supports were removed, a deflection gauge was placed under the beam at its mid-span to obtain zero deflection and subsequent deflections under the load and readings on all the sets of demec targets were taken to obtain zero strain.

The vertical load was applied slowly until approximately one-tenth of the expected load failure was reached. The load was then held constant and all the strain measurements were recorded including the central deflection reading. The vertical load was then increased gradually through approximately equal load steps, all strain readings and central deflections being taken while the load was held constant.

This procedure was repeated until failure occurred, when photographs of the failed wall were taken.

In the first two wall tests demec targets were attached to both sides of the wall and strain readings were taken on both sides for the complete loading tests. The corresponding readings of strain measurement on both sides of the wall were found to be equal and for the remaining tests strain measurements were recorded on one side of the wall only. The loading tests were carried out on the walls and piers twenty-eight days after construction.

Load tests were also carried out on concrete cubes supplied with the lintels and on brick piers built with each wall, to determine their relative E values.

3.5 Test Measurements Taken

Four sets of strain measurements were taken. The relative positions of these strains were shown in Figure 3.2, the strains being labelled a, b, c and d. The purpose of taking these strain measurements at their relative positions were as follows.

The strains (a) were positioned to find the flexural variations down the centre line of the wall and to compare the maximum experimental stresses obtained with the

theoretical values obtained using composite action theory.

The strains (b) were positioned to find the diagonal strains occurring im the shear span. Their rates of increase and maximum values were noted and related with the slip strains (c) and the vertical strains (d) up the centre line of the wall.

The strains (c) were positioned fo find the horizontal slip between the lowest layer of brick and the lintel. These strain increases were noted specifically at the ends of the wall and compared with the diagonal strains (b) and the vertical strains (d).

The strain (d) was positioned to connect the lintel and brickwork along the vertical centre line of the wall and measure the separation between the lintel and brickwork at this point. The magnitude of these strains were compared with the horizontal slip strains (c) and diagonal strains (b)

The variations and magnitudes of the strain measurements taken produced a picture of the strain distribution throughout the wall under increasing load conditions.

The effect that an individual strain or a combination * of the strains might have to produce a failure was noted.

The final test measurement taken was the vertical central wall deflection under the lintel. These readings were not taken up to wall failure and the effect of the stiffening action in the high height/span ratio wall was noted.

* Demec readings represented true strains only untill cracking occurred, thereafter they included the crack widths.

the central wall deflections were only taken during the first part of each test, they were not considered to be an integral part of the test results. They were taken to see if a wall produced zero or excessive deflections under the initial increase in load and in each test there was found to be no initial abnormal deflection.

The graphs shown on page 53 compare the initial measured deflections to a basic calculated deflection.

The calculated deflections are based on an equivalent EI value and on a basic Macaulay deflection formula.

The derivation of the formula used in determining the central wall deflection and a calculated example are given in Appendix F, page 156.

3.5.1 Considering the Flexure Strain Measurements (Strains 'a')

The compressive and tensile flexure strains in the brickwork and the tensile strains in the lintel were determined directly from the flexure set of demec targets. These were spaced equidistant about the centre line of the wall, each pair being placed in the centre of each brick course and going down through the brick courses to include the lintel at the bottom.

3.5.2 Considering the Diagonal Strain Measurements (Stains 'b'

The compressive and tensile diagonal strains in the brickwork were determined directly from the diagonal sets of demec targets. These were attached to the brickwork in line with the centre of the left-hand support and the centre of the left-hand load and also diagonally opposite to these, sloping at the same angle to the vertical. Exactly the same pattern of shear targets was used on the right-hand side of the wall.

3.5.3 Considering the Slip Strain Measurements (Strains 'c')

The horizontal slip strains between the lintel and the layer of bricks directly above it were determined directly from the slip strain set of demec targets set up between the lintel and the layer of bricks above it.

3.5.4 Considering the Vertical Strain Measurements along the Wall-centre line between the Lintel and Brickwork (Strains 'd')

The vertical strains were determined directly from demec targets attached to the wall, measured upwards along the wall vertical centre line from the centre of the lintel.

The final test measurement taken, in addition to the strain measurements was the deflection under the lintel at the centre of the wall. These deflection readings were not taken up to wall failure, for the deflection gauge was removed after about five load increases were applied in case of sudden wall failure.

3.6 Object of Tests and Comparison of Results

From the experimental test values of E_b, obtained from the brick piers, the experimental values of E_c obtained from the concrete cube tests and also the measured strains in the brickwork and concrete, the experimental maximum stress values in the brickwork and concrete were obtained. These same values were determined analytically and the experimental and analytical values were compared for each of the walls.

For each wall, the results of Moment versus the Flexure Strains (a) and Moment versus the Diagonal Strains (b) were tabulated and plotted graphically with the moment axis vertical and with the tensile strains on the right and the compressive strains on the left of the moment axis. Comments were made on each of these strain recordings.

For each wall, the results of Moment versus the Slip Strains (c) were tabulated and plotted graphically with the moment axis vertical and the tensile slip strains to the right of the moment axis. The Vertical Strains measured up the centre line of the wall from the centre of the lintel, strains (d) being only a single strain measurement were added into the slip strain tabulated results and onto the slip strain graphical recordings. Comments were made on

of these strain recordings. The measured central flection results were plotted against calculated values* to obtain comparisons.

From these results, comments on each wall failure were made which included any arching effect due to composite wall action.

The final comparison that was made and one of the main objectives of the tests was to compare the the Ultimate Moment and Shear values in the walls with varing brickwork height with the SHOFCO values.

* See Pages 49 and 50.

CHAPTER 4 - EXPERIMENTAL INVESTIGATION ON THE MATERIALS USED IN THE WALL CONSTRUCTION

4.1 Test Procedure and Results of Tests on Concrete Cubes

With the concrete lintels, nine 101 x 101mm concrete cubes were delivered. Their cube strengths were determined from compression tests. In these tests, pieces of soft board were placed between the cubes and the steel platens of the testing machine to reduce the platen effect and it was noted that vertical failure cracks occurred down the face of the cubes.

The average value of the nine cube strengths was obtained from the test results shown in table 4.1.

Average Cube Strength = 616,6/9 = 68,5 MPa

Table 4.1

CUBE TEST NUMBER	CUBE STRENGTH (MPa)
1	59,7
2	72,4
3	65,8
4	71,3
5	73,7
6	62,0
7	68,1
8	67,8
9	75,8

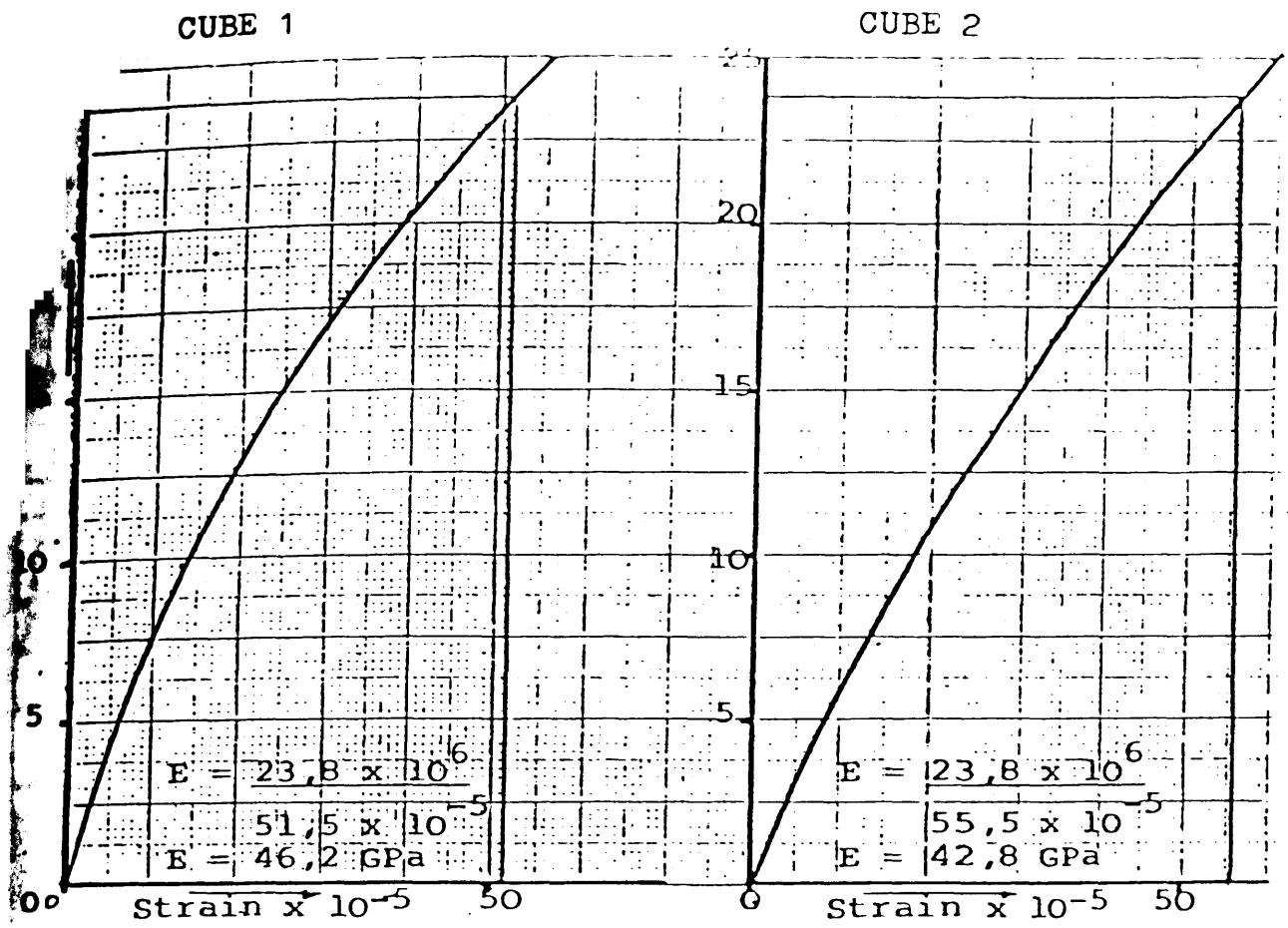


Figure 4.1 - STRESS/STRAIN CURVES ON CUBES TO OBTAIN E VALUE

4.2 Test Procedure and Results of Tests on the Brick Piers built with Wall 1, the 2m x 5 Brickcourse Wall

Each of the three single brick piers which were built with each wall were placed in a compression testing machine and subjected to a gradually increasing compressive load until failure occurred. By means of demec targets attached along a vertical centre line on both sides of each pier a 406mm demec gauge gave a load/deflection and stress/s strain result for each of the piers. Pieces of soft board were placed between the piers and the steel platens of the testing machine to reduce the platen effect and vertical cracks occurred down the piers under failure load as shown in Figure 4.2

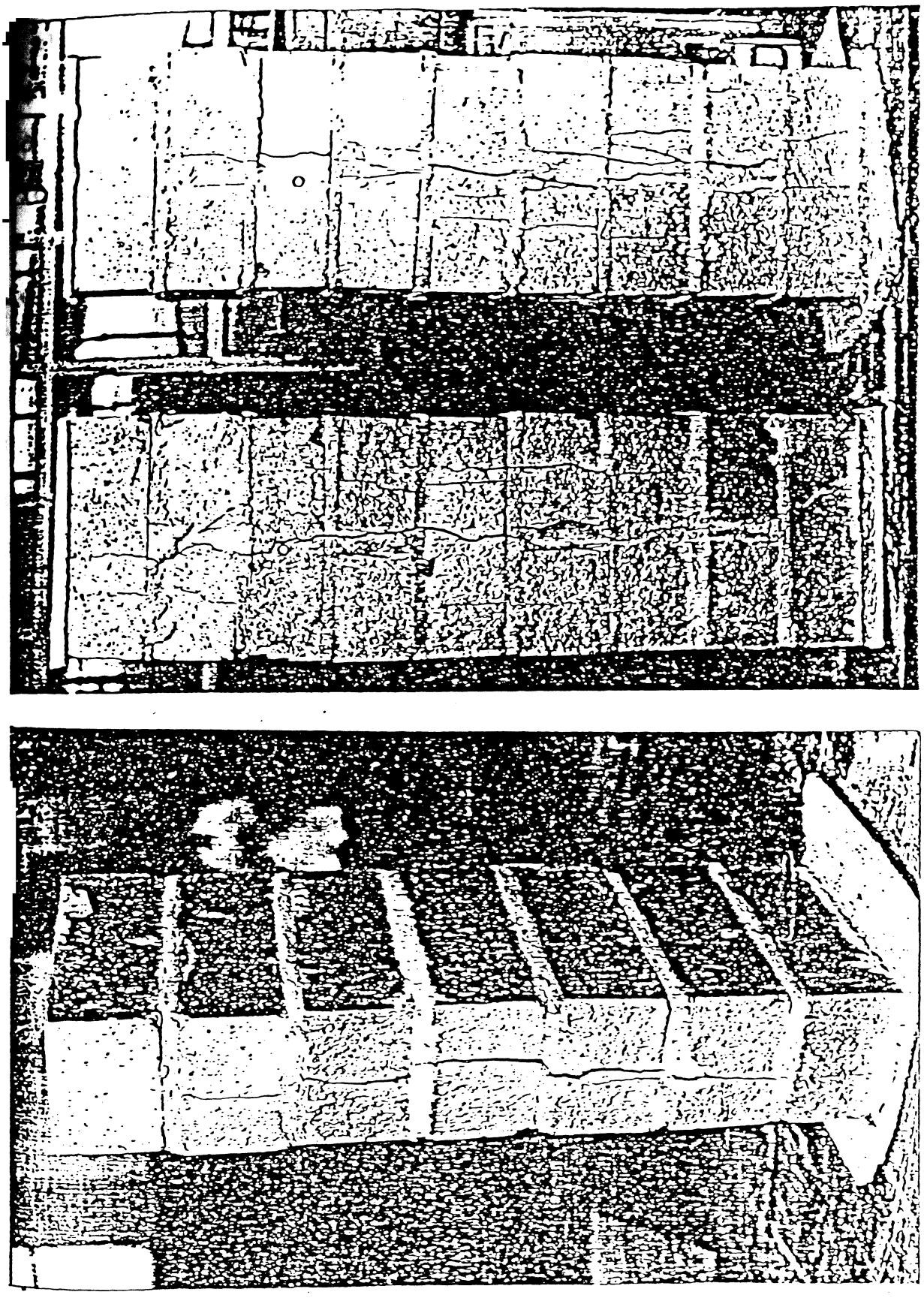


Fig.4.2 BRICK PIERS AFTER LOAD TESTING TO DETERMINE E brickwork

From the loading tests on all the piers built and ted a stress value of 3MPa represented approximately e third of the average maximum stress produced in each the piers. At this stress value, the average slope of he stress/strain curves for each of the three piers built nd load tested with each wall gave the E value for the rickwork for that wall.

One set of typical results was given for the three piers built with wall (1), the 2m x 5 brickcourse wall.

The stress/strain results for each of these three piers was given in Table 4.2 and the graphs produced from these results were given in Figure 4.3. The E value obtained for the brickwork in wall (1), being the average of the slopes of the three curves was determined at 10,0GPa (Figure 4.3.).

The eight sets of results for the remaining piers tested were given in the Appendices, pages 63-70. The Modulus of Elasticity of the brick piers varied from 7,0 GPa to 10,2 GPa and from the test results obtained from the nine piers a value of the Standard Deviation and Coefficient of Variation was obtained.

These values are given below

Standard Deviation $\sigma = \sqrt{\Sigma(x-\bar{x})^2}/n = 0,96$ GPa

Coefficient of Variation = $\sigma/\bar{x}$ (100) = 11%

where x = individual reading

$\bar{x}$ = average readings

n = number of readings

From these high values it was considered preferable in using the individual values of E_b obtained in each of the nine brick pier tests, rather than using the average values.

E 4.2 - COMPRESSIVE STRESS-STRAIN RESULTS FOR THREE 5 SINGLE BRICK PIERS TO OBTAIN E FOR BRICKWORK FOR THE 2m x 5 BRICK COURSE WALL (WALL 1)

PIER 1			PIER 2			PIER 3		
LOAD kN	STRESS MPa	AVERAGE STRAIN x 10^{-5}	LOAD kN	STRESS MPa	AVERAGE STRAIN x 10^{-5}	LOAD kN	STRESS	AVERAGE STRAIN x 10^{-5}
0	0	0	0	0	0	0	0	0
10	0,432	2,8	10	0,432	3,5	10	0,432	6,0
20	0,865	6,2	20	0,865	7,5	20	0,865	10,5
30	1,30	10,0	30	1,30	11,5	30	1,30	14,3
40	1,73	14,1	40	1,73	16,7	40	1,73	19,6
50	2,16	17,6	50	2,16	20,5	50	2,16	24,3
60	2,60	21,5	60	2,60	24,5	60	2,60	30,1
70	3,03	26,0	70	3,03	28,0	70	3,03	36,1
80	3,46	31,2	80	3,46	33,3	80	3,46	40,2
100	4,32	41,5	100	4,32	43,0	100	4,32	50,3
120	5,20	52,4	120	5,20	55,4	120	5,20	67,7
140	6,05	65,5	140	6,05	68,0	140	6,05	84,5

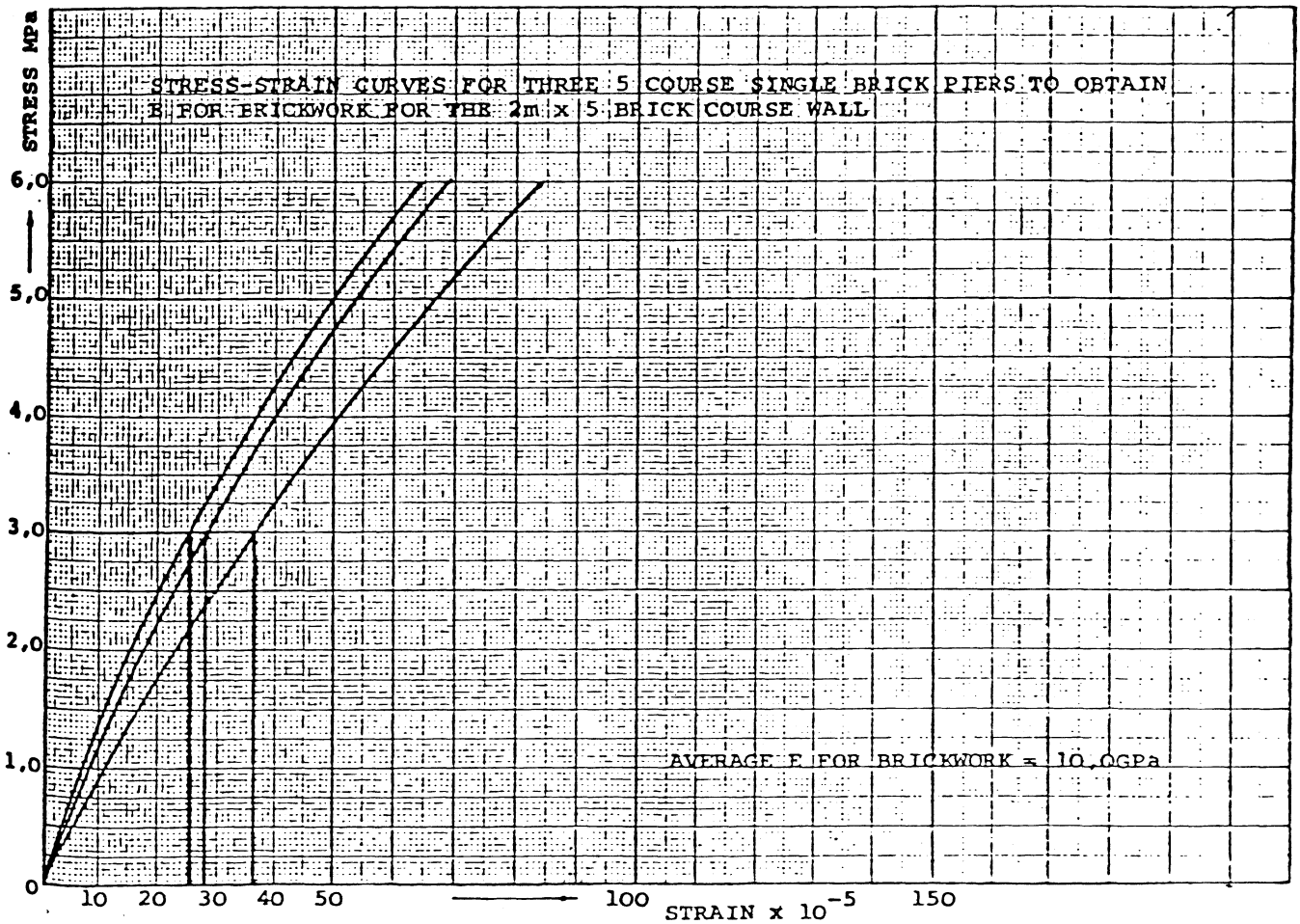


FIGURE 4.3

PTER 5 - WALL LOAD-TEST RESULTS

Number and Order of Wall Tests

The walls were numbered and tested in the following order. aple 5.1.

Wall Number	Wall Size
1	2m x 5 brickcourse
2	2m x 7 brickcourse
3.	2m x 9 brickcourse
4	4m x 5 brickcourse
5	4m x 7 brickcourse
6	4m x 9 brickcourse
7	6m x 5 brickcourse
8	6m x 7 brickcourse
9	6m x 9 brickcourse

The load test procedure given in Chapter 3.4 was applied to each of the walls and the test measurements which were taken, given in Chapter 3.4. In this chapter only the results of the tests on wall (1) are given, the results of the tests on the remaining eight walls are given in the same form as the results in wall (1) in the appendices.

5.2 Wall (1), Load-test Results

The results obtained from the load test on Wall (1), the 2m x 5 brickcourse wall are represented by the following set of tables and diagrams.

A photographic reproduction of the wall, Figure 5.1, ing the final failed position of the whole wall with final crack pattern, together with on the same page, agram which showed the position and number of each ain gauge attached to the wall (Figure 5.2).

A close up photographic reproduction of one half of wall, or in some cases both halves of the wall, giving more detailed view of the failure crack pattern (Figure 3).

An analytical and experimental comparison of the aximum stresses induced in the brickwork and lintel (Table 5.2).

A tabulated result of the applied moment versus the flexure strains (a) at the positions numbered on the walls (Table 5.3).

A graph of the applied moment versus flexure strains, the strains being numbered across at their maximum measured values (Figure 5.5).

A tabulated result of the applied moment versus diagonal strains (b) at the positions numbered on the wall (Table 5.4).

A graph of the applied moment versus diagonal strains, the strains being measured across at their maximum measured values (Figure 5.6).

A tabulated result of the applied moment versus slip strains (c) at the positions numbered on the wall, together with the vertical strain (d) at the positions numbered on the wall (Table 5.5).

A graph of the applied moment versus slip strains

A photographic reproduction of the wall, Figure 5.1, ing the final failed position of the whole wall with final crack pattern, together with on the same page, iagram which showed the position and number of each ain gauge attached to the wall (Figure 5.2).

A close up photographic reproduction of one half of e wall, or in some cases both halves of the wall, giving more detailed view of the failure crack pattern (Figure .3).

An analytical and experimental comparison of the aximum stresses induced in the brickwork and lintel (Table 5.2).

A tabulated result of the applied moment versus the flexure strains (a) at the positions numbered on the walls (Table 5.3).

A graph of the applied moment versus flexure strains, the strains being numbered across at their maximum measured values (Figure 5.5).

A tabulated result of the applied moment versus diagonal strains (b) at the positions numbered on the wall (Table 5.4).

A graph of the applied moment versus diagonal strains, the strains being measured across at their maximum measured values (Figure 5.6).

A tabulated result of the applied moment versus slip strains (c) at the positions numbered on the wall, together with the vertical strain (d) at the positions numbered on the wall (Table 5.5).

A graph of the applied moment versus slip strains

ch included the vertical strain (d), the strains
umbered across at their maximum measured values
e 5.7).

Maximum edge strains obtained by plotting the
ral strains at their heights above and below the neutral
and drawing a line through the plot to obtain the edge
in (Figure 5.8).

Comments are made on the initial measured and
culated central wall deflections taken and these
parisons are shown in graphical form in chapter 6.5, which
ve the calculated and measured central wall deflection for
ch of the nine walls tested.

Comments on the test results and mode of failure.

2m x 5 brickcourses - Wall 1

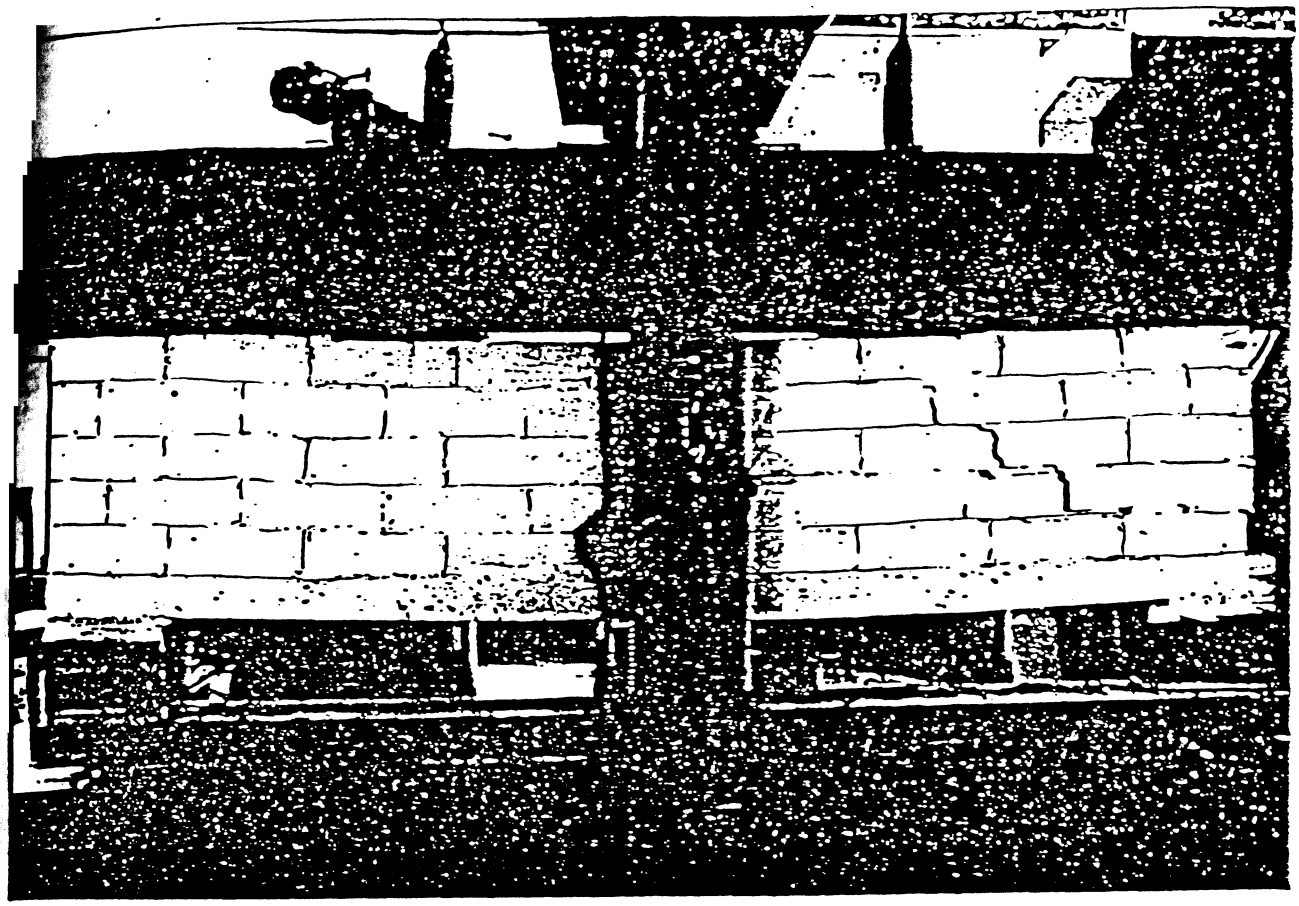
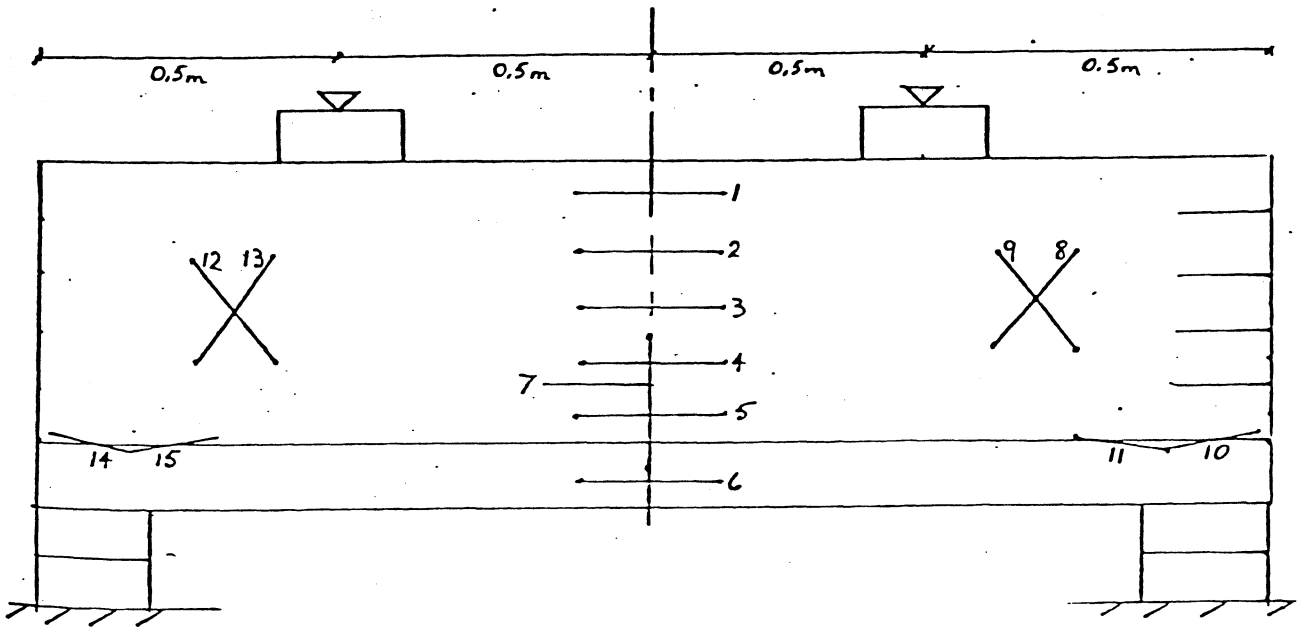


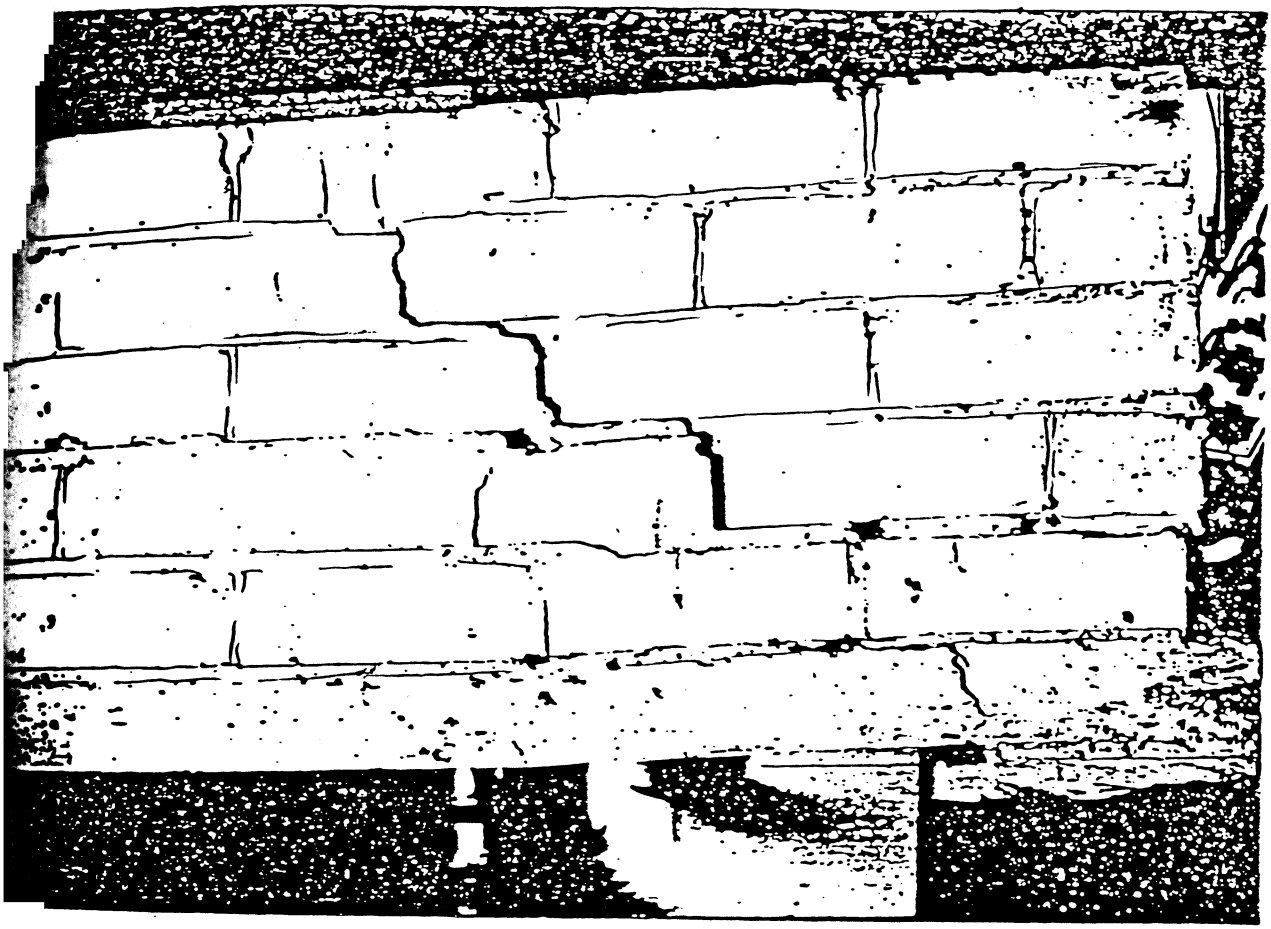
Figure 5.1



Position of strain gauges

Figure 5.2

Wall 1



Failure crack pattern

Figure 5.3

WALL NO 1 - 2m x 5 brickcourse

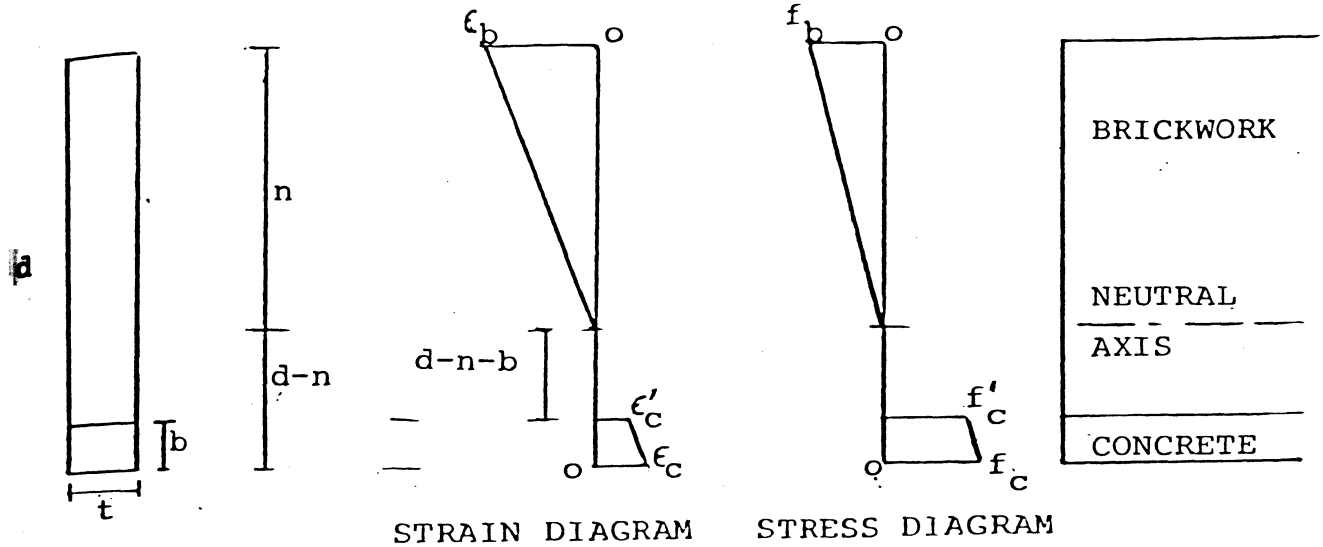


Figure 5.4

E_b = 10GPa E_c = 44,5GPa b = 70mm t = 105mm d = 470mm

m = modular ratio = E_c/E_b = 44,5/10 = 4,45

$$n = \frac{-2mb \pm \sqrt{(2mb)^2 - 4mb(b-2d)}}{2} = 295,2$$

$$f_b = \frac{E_b n M}{E_b \frac{n}{3} t + E_c \frac{bt}{2} . 2(d-n) + 2b(n-d+\frac{b}{3})} = \underline{2,89MPa \text{ (calculated)}}$$

$f_b = E_b \epsilon_b = 10x10^3 x 48,5x10^{-5} = \underline{4,8MPa \text{ (measured)}}$

$$f_c = \frac{E_c (d-n) M}{E_b \frac{n}{3} t + E_c \frac{bt}{2} . 2(d-n) + 2b(n-d+\frac{b}{3})} = \underline{7,62MPa \text{ (calculated)}}$$

$f_c = E_c \epsilon_c = 44,5x10^3 x 22,0x10^{-5} = \underline{9,79MPa \text{ (measured)}}$

Comparison of Load Test Results and Analytical Results

Table 5.2

	Load Test Results	Analytical Results
Maximum stress in brickwork	4,8MPa	2,89MPa
Maximum stress in concrete	9,79MPa	7,62MPa

Table 5.1 - Wall No.1 2m x 5 brickcourse

End reaction kN	Shear in shear span kN	Moment in flexure span kNm	Flexure strains x 10^{-5} at positions numbered on walls								
			1	2	3	4	5	6	7	8	9
0	0	0	0	0	0	0	0	0			
4,45	4,45	2,23	-2,0	-1,0	-0,5	0	+1	+2,0			
8,9	8,9	4,45	-9,0	-5,0	-3,0	0	+3,5	+6,5			
13,35	13,35	6,63	-18,5	-9,0	-6,0	-0,5	+4,5	+9,0			
17,8	17,8	8,9	-20,5	-10,5	-7,5	-0,5	+5,5	+11,5			
22,25	22,25	11,13	-26,5	-14,5	-12,5	-2,5	+7,5	+13,5			
26,7	26,7	13,35	-31,5	-19,5	-17,0	-4,0	+8,0	+16,0			
31,5	31,5	15,75	-42,0	-29,0	-26,5	-4,0	+9,0	+18,0			
32,5	32,5	16,25	F	A	I	L	U	R	E		

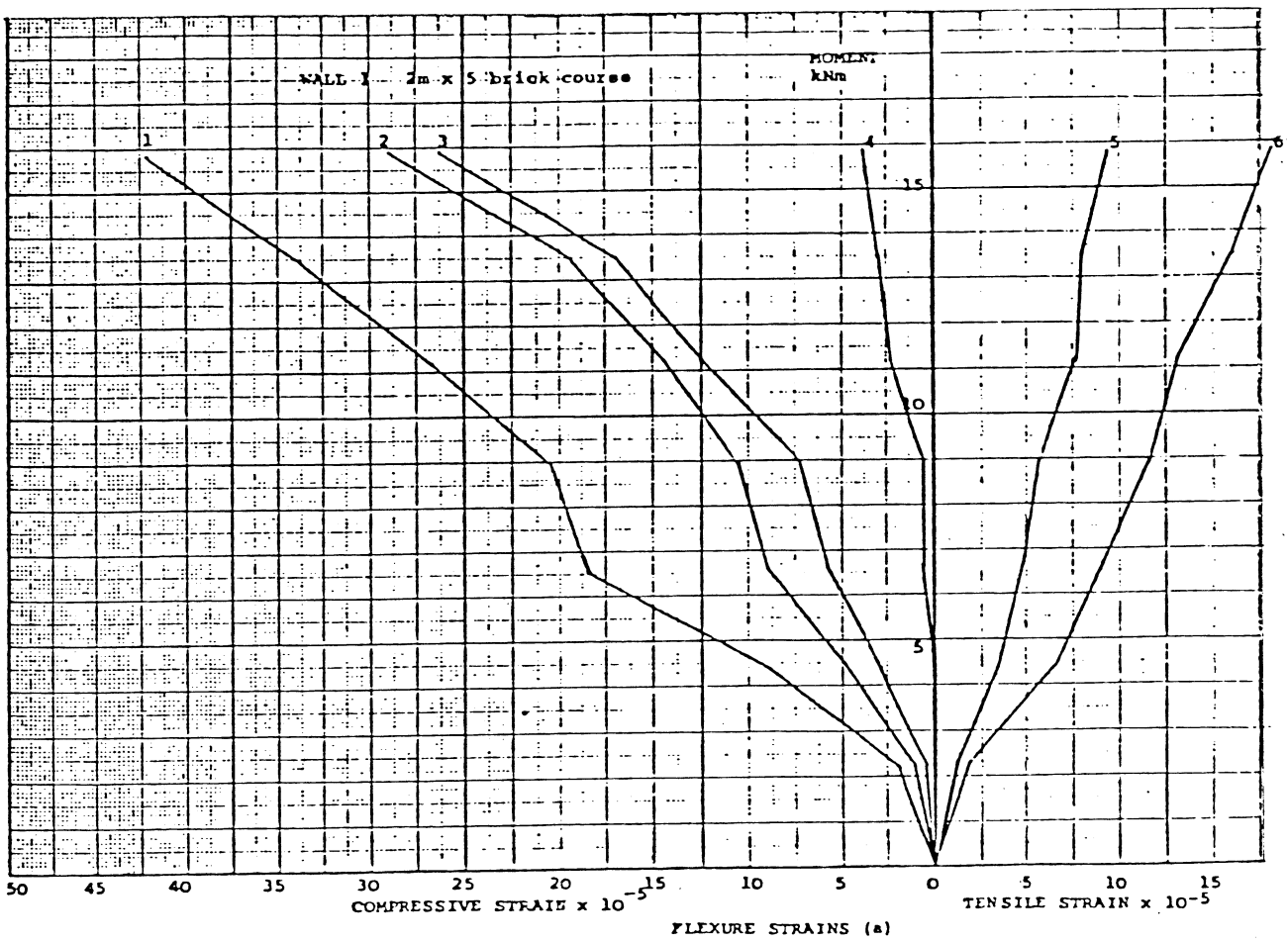


Figure 5.5

Wall No.1 2m x 5 brickcourse

Shear in shear span kN	Moment in flexure span kNm	Diagonal strains x 10^{-5} at positions numbered on wall								
		8	9	12	13					
0	0	0	0	0	0	0	0	0	0	0
4,45	2,23	3,5	-2,0	3,0	-1,0					
8,9	4,45	8,0	-3,5	8,0	-3,0					
13,35	6,63	8,0	-6,0	8,0	-5,5					
17,8	8,9	10,0	8,0	10,0	-6,0					
22,25	11,13	24,5	-13,5	18,5	-8,5					
26,7	13,35	42,5	-18,5	35,0	-,0,5					
31,5	15,75	65,0	-37,5	45,0	-13,5					
32,5	16,25	F A I L U R E								

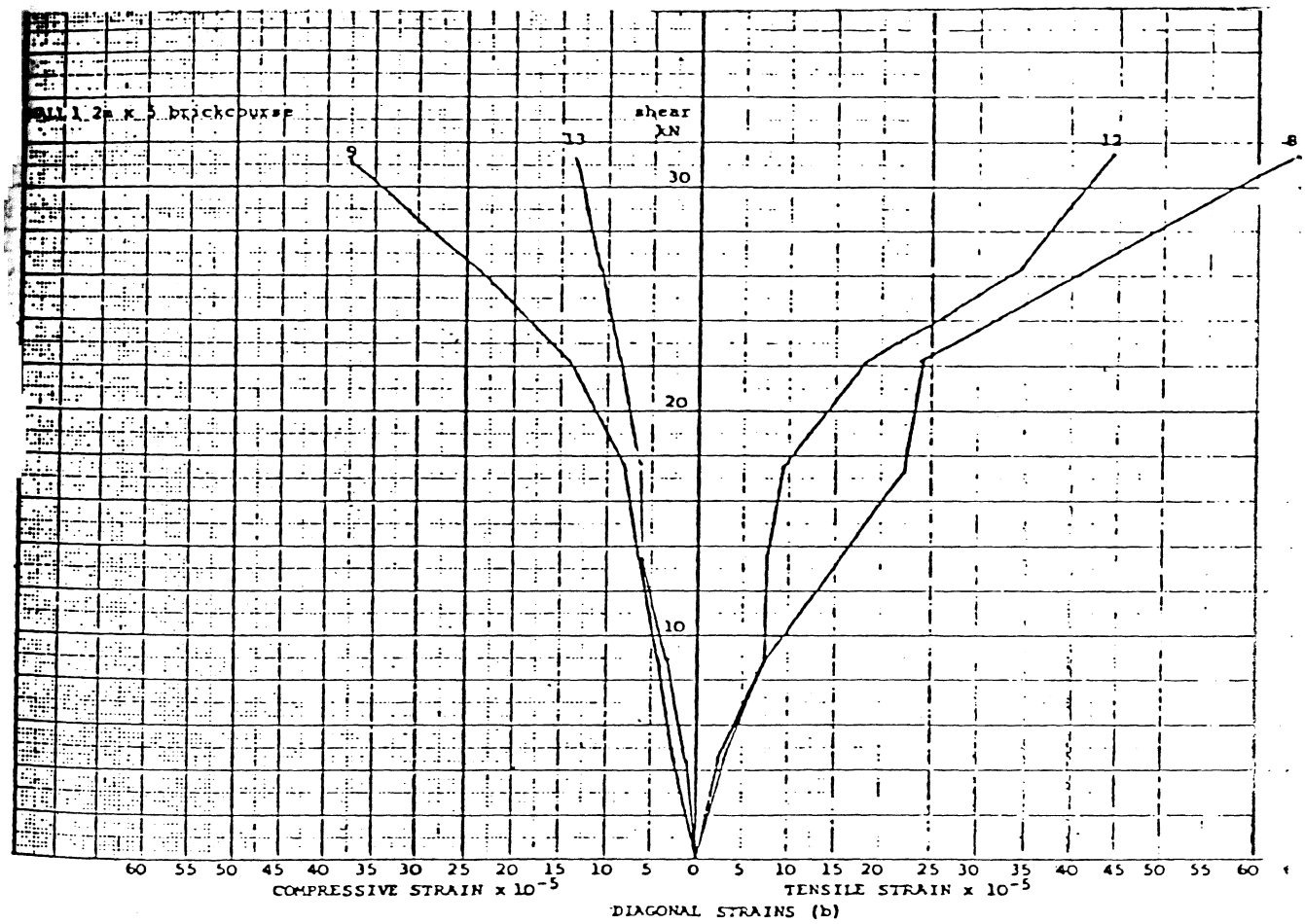


Figure 5.6

Table 5.5 - Wall No.1 2m x 5 brickcourse

Load reaction kN	Shear in shear span kN	Moment in flexure span kNm	Slip strains x 10^{-5} between brickwork and lintel at positions numbered on wall							Central wall deflection mm
			10	11	14	15	7			
0	0	0	0	0	0	0	0	0	0	0
4,45	4,45	2,23	1,0	1,5	0,5	1,0	1,0			0,05
8,9	8,9	4,45	1,0	2,5	1,5	2,0	1,0			0,18
13,35	13,35	6,63	2,5	6,0	5,5	2,5	1,0			0,30
17,8	17,8	8,9	3,0	10,0	5,5	3,5	1,5			0,60
22,25	22,25	11,13	10,5	11,5	10,0	4,0	1,5			
26,7	26,7	13,35	16,5	17,5	20,0	4,0	2,5			
31,5	31,5	15,75	48,5	26,0	53,0	5,5	2,5			
32,5	32,5	16,25	F A I L U R E							

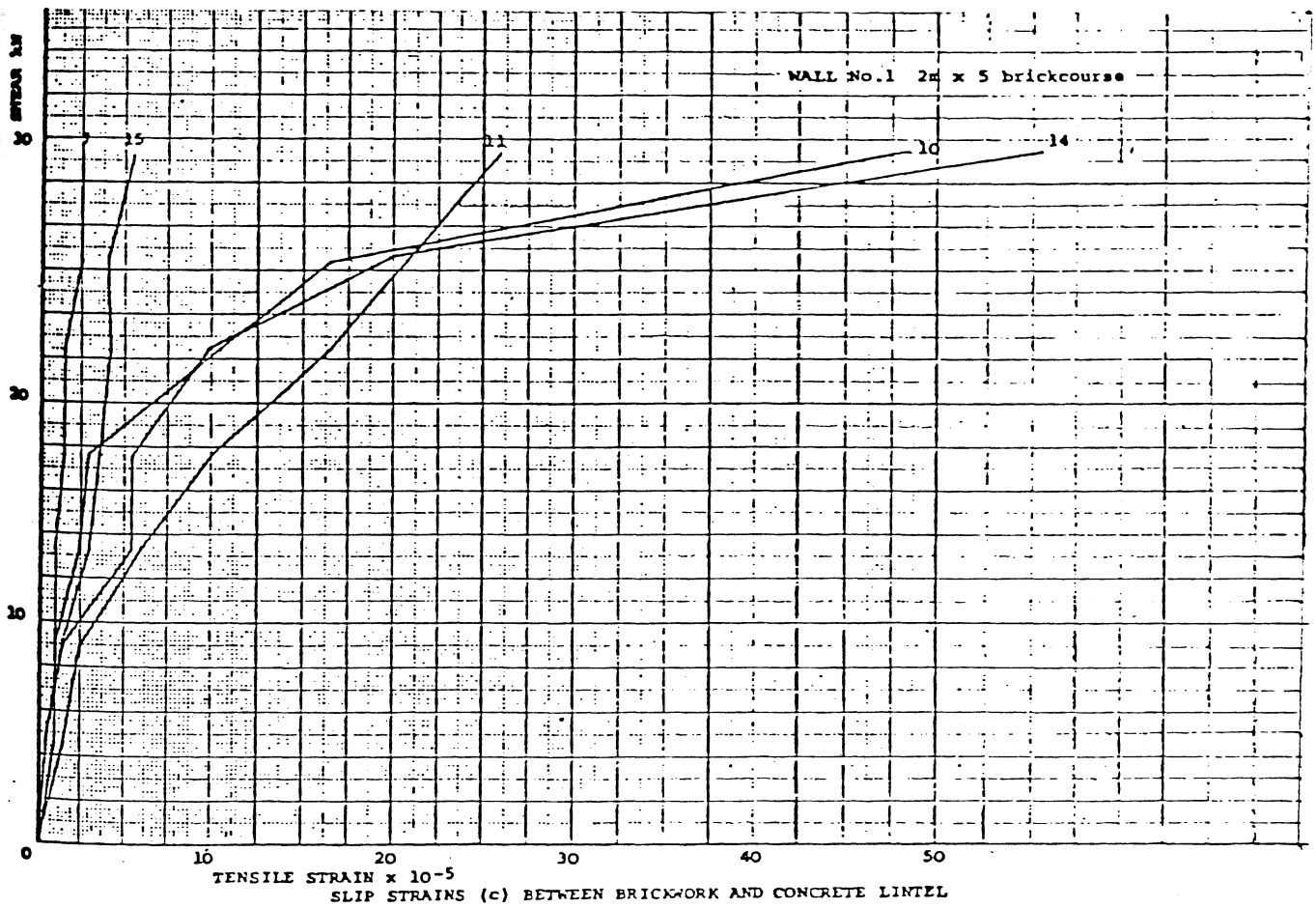
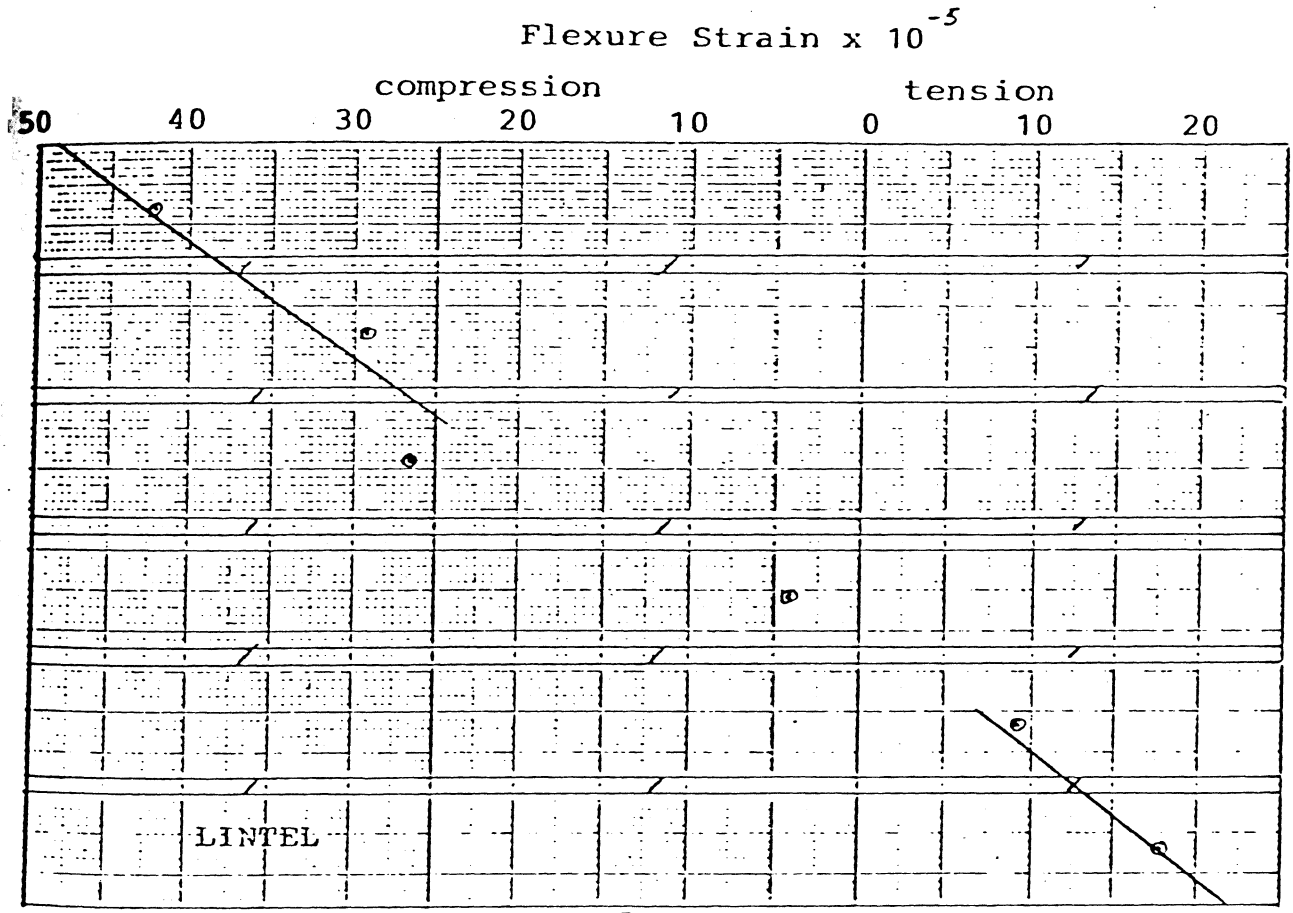


Figure 5.7

The measured top and bottom maximum edge flexure strains were determined by plotting to scale, the strains measured at the centre of each brick course and centre of lintel against wall height. The values being taken at the maximum moment recorded. For wall 1 this was determined as below.



Top Edge Strain = 48,5 x 10^{-5} Maximum Moment = 15,75kNm

Bottom Edge Strain = 22,0 x 10^{-5}

Figure 5.8

WALL 1 - 2m x 5 Brick courses

Comments were given on the following test results

1. The load test values.
2. The calculated and measured stresses and strains in the wall.
3. The central wall deflection.
4. The failure crack pattern.
5. Further comments on the wall resistance to loading during the test procedure.

The ultimate resistance moment of the wall produced a value of 16,26kNm, being 2,6 times the SHOFCO value of 6,3kNm. The ultimate shear resistance of the wall produced a value of 32,5kN, being 5,4 times the SHOFCO value of 6,0kN. The maximum load test tensile flexure stress of 9,8MPa was 29 per cent above the calculated result of 7,62MPa. The maximum load test compressive stress of 4,8MPa was 66 per cent above the calculated result of 2,89MPa. The strains along the tensile diagonals 8 and 12 increased to $65x10^{-5}$ and $45x10^{-5}$ respectively. The slip strains at 10 and 14 produced maximum strains of $48,5x10^{-5}$ and $53x10^{-5}$ respectively with strain 11 increasing to a maximum of $26x10^{-5}$. The measured central wall deflection taken at an end wall reaction of 17,8kN when the central deflection gauge was removed in case of wall failure was 0,60mm being 2,2 times the calculated value of 0,269mm. The load deflection curve left the linear calculated line at an approximate end reaction of 6kN. As can be seen from the photographic reproduction of the failure crack pattern all the bricks above the lintel to the right of the compression diagonal on the right hand side of the wall slipped approximately 1cm to

the right, a crack occurring in the lintel adjoining the right hand support. There were also faint hair line cracks running down the compression diagonal on the left hand side of the wall which cannot be seen on the failure crack pattern reproduction.

The failure occurred suddenly with a slip failure between the lintel and the lowest brick layer and also between the lowest brick layer and the one immediately above it, the final failure crack going directly between the right hand support and the right hand loading point.

5.3 Comments on Test Results and Mode of Failure (Wall 1)

A comparison of the Ultimate Resistance Moment and Shear Resistance with the SHOFCO values was given in graphical form in the 'Analysis of Results of Test Series', Chapter 6.1 and 6.2. A comparison of the maximum calculated and experimental flexure stresses produced in the brickwork and concrete was given in Chapter 6.3 and 6.4.

The graph of flexure strains (a) versus moment showed a more uniform increase in the tensile strains in the lintel, the compressive strains in the brickwork showed irregular increases with moment increase except that the strains in the top brick course maintained a fairly uniform increase over the last four moment increases, reaching a maximum value of $42{,}0 \times 10^{-5}$.

A crack occurred in the lintel adjoining the right hand support. There were also faint hair line cracks running down the compression diagonal on the left hand side of the wall which cannot be seen on the failure crack pattern reproduction.

The failure occurred suddenly with a slip failure between the lintel and the lowest brick layer and also between the lowest brick layer and the one immediately above it, the final failure crack going between the right hand support and the right hand loading point.

CHAPTER 6 - ANALYSIS OF RESULTS OF TEST SERIES

6.1 Ultimate Resistance Moment of Walls Compared with SHOFCO Values.

6.2 Ultimate Shear Resistance of Walls, Compared with SHOFCO Values.

6.3 Maximum Measured Flexure Stresses.

6.4 Maximum Calculated Flexure Stresses.

6.5 Measured and Calculated Central Wall Deflections Compared.

6.6 Summary of Results of Test Series.

6.7 Further Comments on Composite Action.

6.1 Ultimate Resistance Moment of Walls compared with SHOFCO Values.

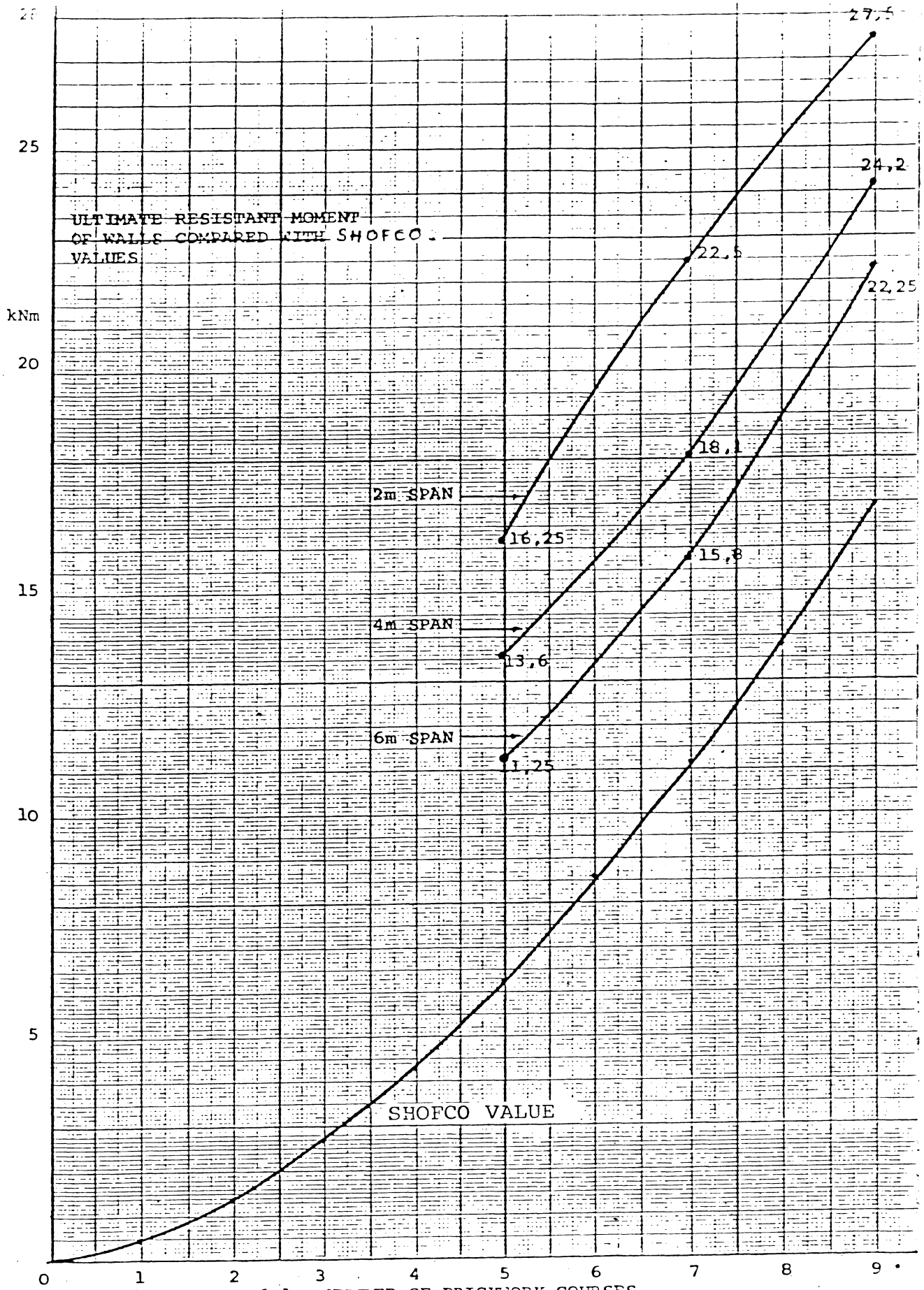


FIGURE 6.1 - NUMBER OF BRICKWORK COURSES

6.2 Ultimate Shear Resistance of Walls compared with SHOFCO Values

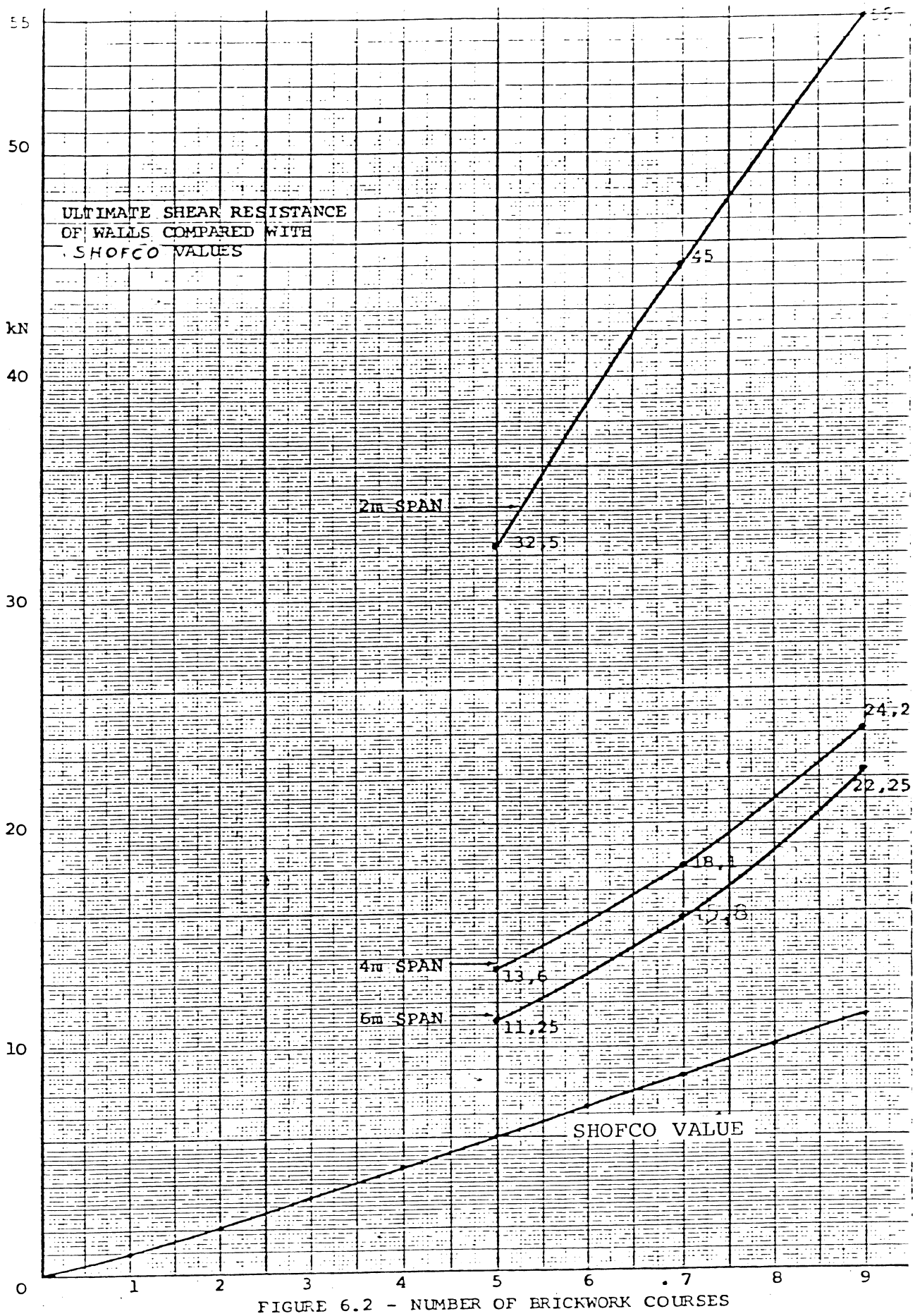


FIGURE 6.2 - NUMBER OF BRICKWORK COURSES

6.3 Maximum Measured Flexure Stresses

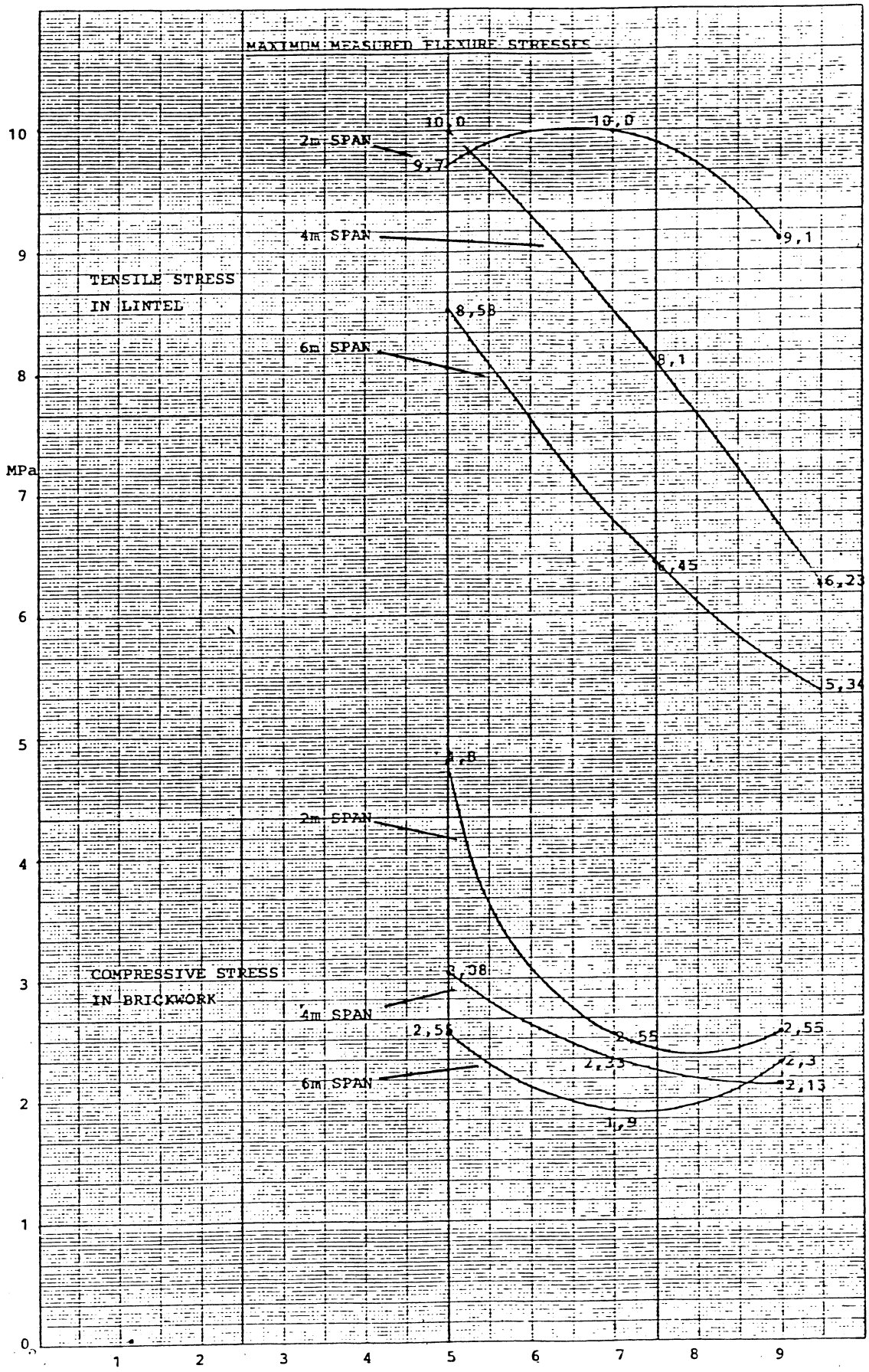


FIGURE 6.3 - NUMBER OF BRICKWORK COURSES

6.4 Maximum Calculated Flexure Stresses

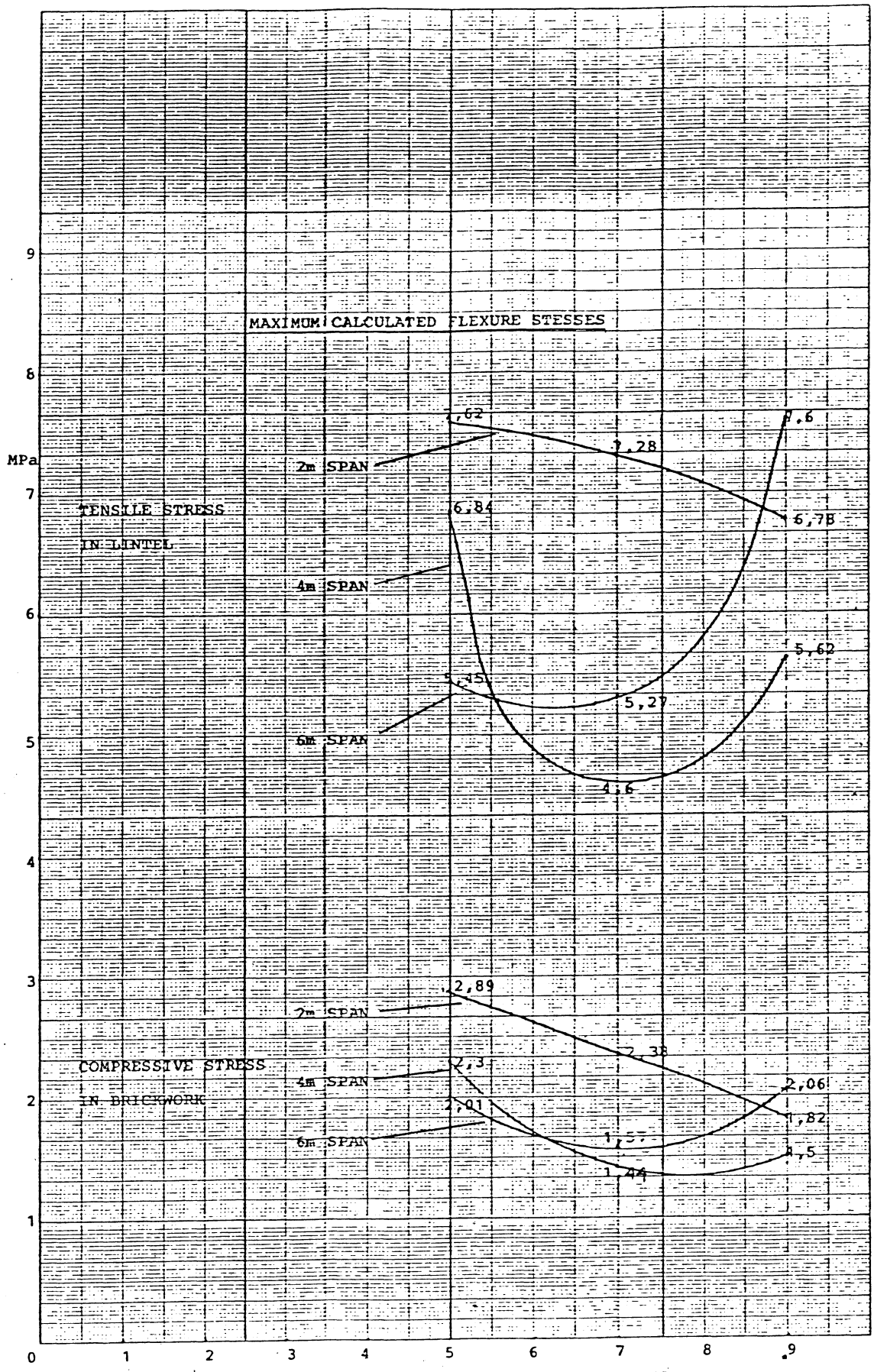


FIGURE 6.4 - NUMBER OF BRICKWORK COURSES

6.5 Measured and Calculated Central Wall Deflections Compared

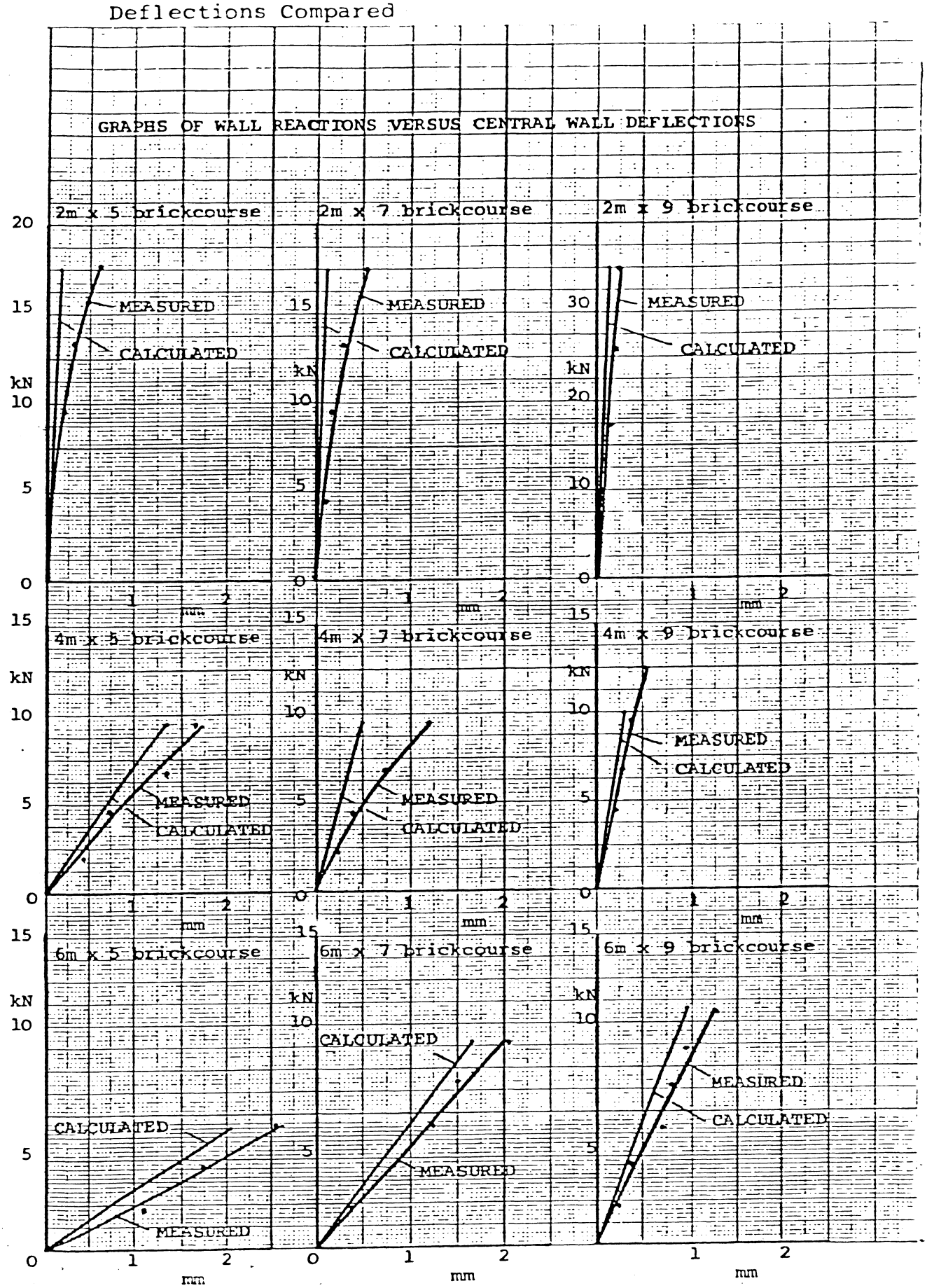


FIGURE 6.5

6.6 Summary of Results of Test Series

One significant feature of the tests carried out, which occurred in every test was that the cracking was audible befor any hair line cracks became visible. The loads at which the first audible cracking sounds were detected could not be noted with any accuracy also the position in the walls from which the sounds came could not be determined. In two of the tests, tests 4 and 7, where the lintel and brickwork separated along the wall centre line the audible cracking sounds could be detected at below half failure load.

The flexure strains in the brickwork and lintel produced fairly uniform increses with moment in 60 per cent of the tests. The measured and calculated maximum flexure stresses in the brick-work on the three, four metre span walls and on the three six metre span walls produced comparable and similar results. These results in the two metre span walls differred and in wall 1, the measured flexure stress was 66per cent higher than the calculated value. Of the maximum measured and calculated flexure stresses in the lintel only the six metre span walls gave comparable values, the remaining walls produced a considerable variation in these stesses

The diagonal strains (b) in the brickwork in all the tests produced irregular increases with moment and in wall tests 3, 4, 5 and 9, the variations were considerable. Only in tests 7 and 8 did these measured strains form uniform groups without single or multiple strains forming suddenly with the creation of a wall failure.

The slip strains (c) and the vertical strains (d) measured up the centre line from the lintel produced very irregular results and could not be compared or related in any way throughout the tests.

The formation of the hair line cracks running in the mortar joints formed very irregular patterns, in that they travelled in certain directions with varying speeds, then stopped, while other cracks formed in different positions going in different directions.

These initial cracks in the walls were not the criteria for the final wall failure as shown in tests 4 and 9. In these tests the wall flexed on the one side dissipating its energy while the other side remained comparatively rigid, storing its energy and then suddenly failing with an instantaneous loss of its energy.

The cause of failure in all the tests was a slip failure, either at one end or at both ends of a wall, or a combination of slip and diagonal failures. The slip failures occurred either between the lintel and brickwork or between the lowest layer of bricks andthe one above it. In most of the walls tested the maximum slip strains occurred at the outer ends of the walls which produced or helped to produce a diagonal tension failure In two of the tests, tests 4 and 7, large strains were recorded on the vertical centre line joining the lintel and brickwork increased in magnitude as they approached the centre line of the wall. In these cases the wall failures were initiated near the centre line of the wall either at the mortar joint between the lintel and the bricks above it or in the brickwork directly above.

The arching action of the brickwork in the composite walls was noted specifically in test 3, the 2m x 9 brick course wall. It supported an ultimate shear of 55kN, which was 4,78 times the SHOFCO value of 11,5kN, producing vertical splitting in the bricks near the supports.

6.7 Further Comments on Composite Action

When a lintel or a large beam supports masonry over an opening, a common design problem is to determine the distribution and magnitude of the resultant loads acting on the support beam. Openings in the wall induce redistribution of these loads causing further design problems. Often the actual behaviour of a masonry wall with its supporting beam acts as a composite unit with the beam acting only as a tension member.

The relative wall/beam stiffness is one of the main factors which influence the degree of composite action between wall and beam. A flexible beam produces arching in the masonry which may in the limit become self supporting. If the masonry and its supporting beam act as a composite unit it will behave as a deep beam resulting in a very high overall stiffness. The development and extent of composite action depends largely on the extent of the shearing force or bond between the beam and masonry especially near the beam supports where high local stresses are induced. These high stresses produce a greater frictional resistance near the supports.

The main factors which influence the attainment of composite action are

(1) The end of the wall restraints, which could be in the form of joint reinforcement, vertical columns at the end of the wall or wall continuity.

(2) The transmission of shear across the interface, which is dependent on the friction resistance between the contact surfaces and the bond and shear properties of the mortar.

(3) The location of the applied load which could be either at beam level or on top of the wall. If the load is applied at beam level it induces additional tensile stresses at the wall/beam interface and could cause separation. Here the use of vertical prestressing or tension connectors would help to maintain composite action.

(4) The strength and elastic modulus ratios of the beam and wall which are considered together because the E value of both concrete and brickwork are related to their compressive strengths

(5) Erection and construction loads can damage the beam, for if the beam has been designed as a composite member and has not been propped adequately the brickwork in its wet state can induce high moments before the wall is high enough to allow the arching effect to take place.

(6) Openings in the wall can have an effect on the composite action. With the opening near the wall centre, the 'arching' action still forms through the brickwork or lintel above the opening. When the opening is near a support, complete or partial breakdown of the 'arching' occurs and secondary 'arching' creates other high local stresses in the beam.

Brickwork, because of its high labour content, is subject to imperfections due to workmanship which can have a critical effect on its behaviour. Current working practices which may be applicable to lightly stressed masonry structures are not always applicable to highly stressed load-bearing brickwork.

Strength reducing factors, such as laying bricks 'frog down', deep furrowing of wet mortar beds, variations in mortar thickness, insufficient perpend filling, insufficient curing, excessive movement of bricks during placing, which reduces the effective contact area and also 'chasing' of recesses in walls for pipes and electrical conduits all unite to give masonry its variable and sometimes critical behaviour.

An investigation into the effects of workmanship and curing on storey height walls was carried out at the Building Development Laboratories, Perth, Western Australia.[16] In the investigation, the walls were laid and load tested by vertical compression in pairs. One built as 'perfect' the other with a pre-determined fault. Piers and prisms were also laid and tested with the same faults.

From these tests the following estimated reductions in the ultimate strength of the walls due to the pre-determined faults were made.

(a)	Furrowed bed	25 per cent
(b)	Outside cure	10 per cent
(c)	No perpends	0 per cent

(d) 16mm bed joints 25 per cent

(e) + 3mm bow 15 per cent

The main factor which must be noted from the effects of these faults is that they are independent of each other and the effects of combinations of these faults are additive.

These faults did not produce the same effects on bond strength. The bed joint thickness produced little effect, whereas outside curing conditions had a significant effect.

6.8 Summarized General Conclusions

From the experimental tests, the following summarized conclusions were made.

1. The average Ultimate Resistance Moment of the walls produced a value of 1,7 times the SHOFCO value.
2. The average Ultimate Shear Resistance of the walls produced a value of 3,0 times the SHOFCO value.
3. The maximum measured flexure stresses in the brickwork and concrete produced the same general pattern with comparable values to the calculated flexure stresses.
4. The diagonal strains and the horizontal slip strains did not produce any stable values throughout the tests, the wall failures were mainly due to these variables.
5. The effect of the vertical strain running up the centre line of the wall on the horizontal slip strains and on the diagonal strains was noted.
6. The audible cracking before any sign of visible cracking was noted.
7. The initial position, size and rate of change in speed of the cracking gave no indication as to the final mode of failure.
8. The arching action in the wall was clearly shown in test 3 where splits occurred in the bricks near the supports, together with diagonal cracks in the lintel near the supports.
9. Each of the nine walls tested produced a different failure pattern, some walls failing at one end while others failed at both ends.

10. In every failure, either the bottom layer of bricks moved horizontally out over the lintels at the ends or a horizontal outward movement took place in the brickwork along a mortar joint in the shear span at the ends.

11. The complete lack of uniformity in the failure modes could be due to (a) workmanship (b) varying brick strengths and mortar properties (c) initial strains set up in the wall due to inadequate wall proping (d) any inaccuracies in the load-test procedure such as strain measurements, for the strains were found to vary slightly with time under constant load.

APPENDICES

APPENDIX A

RESULTS OF LOAD TESTS ON BRICK PIERS RELATING TO WALLS 2 TO 9 INCLUSIVE

Table A.1 COMPRESSIVE STRESS-STRAIN RESULTS FOR THREE 7 SINGLE BRICK PIERS TO OBTAIN E FOR BRICKWORK FOR THE 2m x 7 BRICK COURSE WALL (WALL 2)

PIER 1			PIER 2			PIER 3		
LOAD kN	STRESS MPa	AVERAGE STRAIN x 10^{-5}	LOAD kN	STRESS MPa	AVERAGE STRAIN x 10^{-5}	LOAD kN	STRESS MPa	AVERAGE STRAIN x 10^{-5}
0	0	0	0	0	0	0	0	0
10	0,432	3,2	10	0,432	4,5	10	0,432	5,0
20	0,865	7,5	20	0,865	9,5	20	0,865	11,1
30	1,30	11,0	30	1,30	13,2	30	1,30	16,2
40	1,73	14,45	40	1,73	14,5	40	1,73	20,1
50	2,16	18,3	50	2,16	22,0	50	2,16	23,0
60	2,60	22,1	60	2,60	25,5	60	2,60	28,0
70	3,03	26,9	70	3,03	30,2	70	3,03	31,0
80	3,46	33,1	80	3,46	34,0	80	3,46	34,5
100	4,32	41,1	100	4,32	47,1	100	4,32	55,8
120	5,20	53,0	120	5,20	61,2	120	5,20	70,5
140	6,05	65,9	140	6,05	74,5	140	6,05	87,8

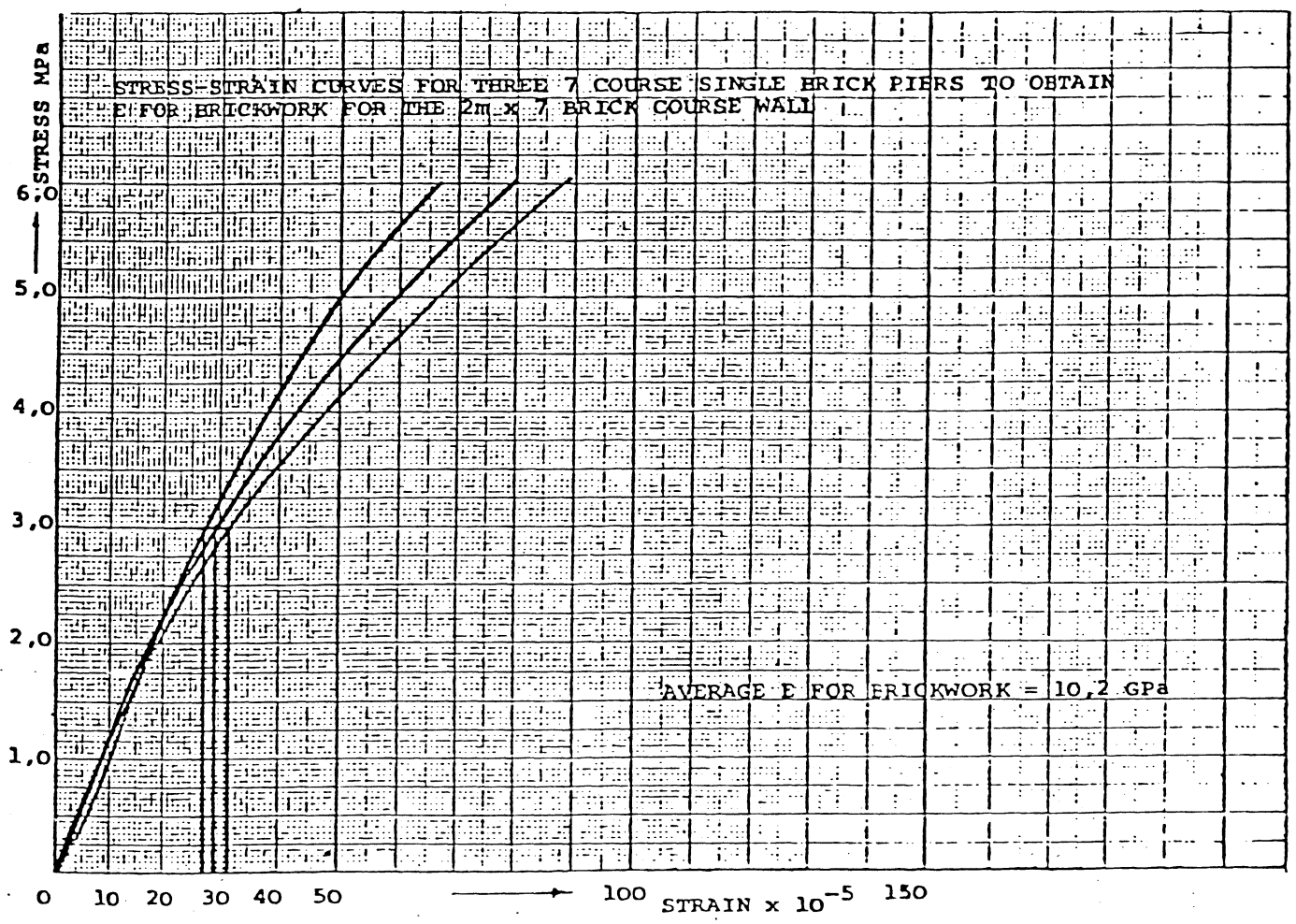


Figure A.1

Table A.2 COMPRESSIVE STRESS-STRAIN RESULTS FOR THREE 9 SINGLE BRICK PIERS TO OBTAIN E FOR BRICKWORK FOR THE 2m x 9 BRICK COURSE WALL (WALL 3)

PIER 1			PIER 2			PIER 3		
LOAD kN	STRESS MPa	AVERAGE STRAIN x 10^{-5}	LOAD kN	STRESS MPa	AVERAGE STRAIN x 10^{-5}	LOAD kN	STRESS MPa	AVERAGE STRAIN x 10^{-5}
0	0	0	0	0	0	0	0 0	0
10	0,432	3,1	10	0,432	5,5	10	0,432	6,1
20	0,865	7,2	20	0,865	12,1	20	0,865	11,5
30	1,30	11,1	30	1,30	15,5	30	1,30	17,5
40	1,73	16,5	40	1,73	22,1	40	1,73	22,2
50	2,16	19,2	50	2,16	25,2	50	2,16	28,0
60	2,60	25,0	60	2,60	32,1	60	2,60	33,5
70	3,03	28,9	70	3,03	38,1	70	3,03	39,0
80	3,46	35,2	80	3,46	44,5	80	3,46	48,0
100	4,32	44,0	100	4,32	59,5	100	4,32	63,1
120	5,20	59,1	120	5,20	74,0	120	5,20	78,0
140	6,05	75,0	140	6,05	87,1	140	6,05	92,5

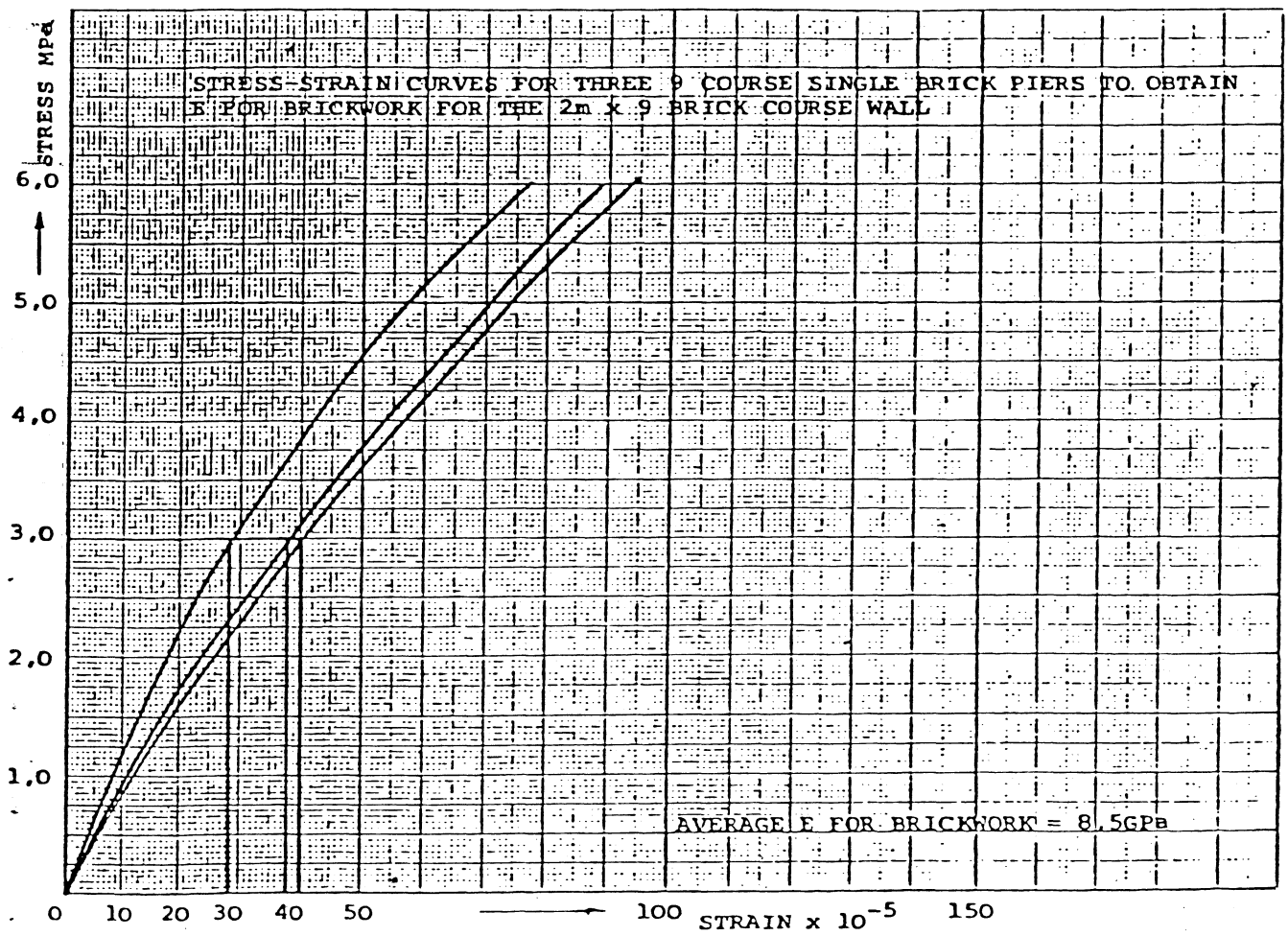


Figure A.2

Table A.3 COMPRESSIVE STRESS-STRAIN RESULTS FOR THREE 5 SINGLE BRICK PIERS TO OBTAIN E FOR BRICKWORK FOR THE 4m x 5 BRICK COURSE WALL (WALL 4)

PIER 1			PIER 2			PIER 3		
LOAD kN	STRESS MPa	AVERAGE STRAIN x 10^{-5}	LOAD kN	STRESS MPa	AVERAGE STRAIN x 10^{-5}	LOAD kN	STRESS MPa	AVERAGE STRAIN x 10^{-5}
0	0	0	0	0	0	0	0	0
10	0,432	4,5	10	0,432	5,0	10	0,432	9,1
20	0,865	9,0	20	0,865	11,2	20	0,865	19,1
30	1,30	12,1	30	1,30	15,0	30	1,30	24,1
40	1,73	19,2	40	1,73	21,8	40	1,73	34,5
50	2,16	23,0	50	2,16	27,2	50	2,16	38,2
60	2,60	32,1	60	2,60	36,0	60	2,60	44,1
70	3,03	37,1	70	3,03	41,0	70	3,03	50,5
80	3,46	41,5	80	3,46	49,5	80	3,46	59,5
100	4,32	57,2	100	4,32	62,2	100	4,32	72,2
120	5,20	70,5	120	5,20	76,1	120	5,20	91,5
140	6,05	79,8	140	6,05	91,0	140	6,05	111,0

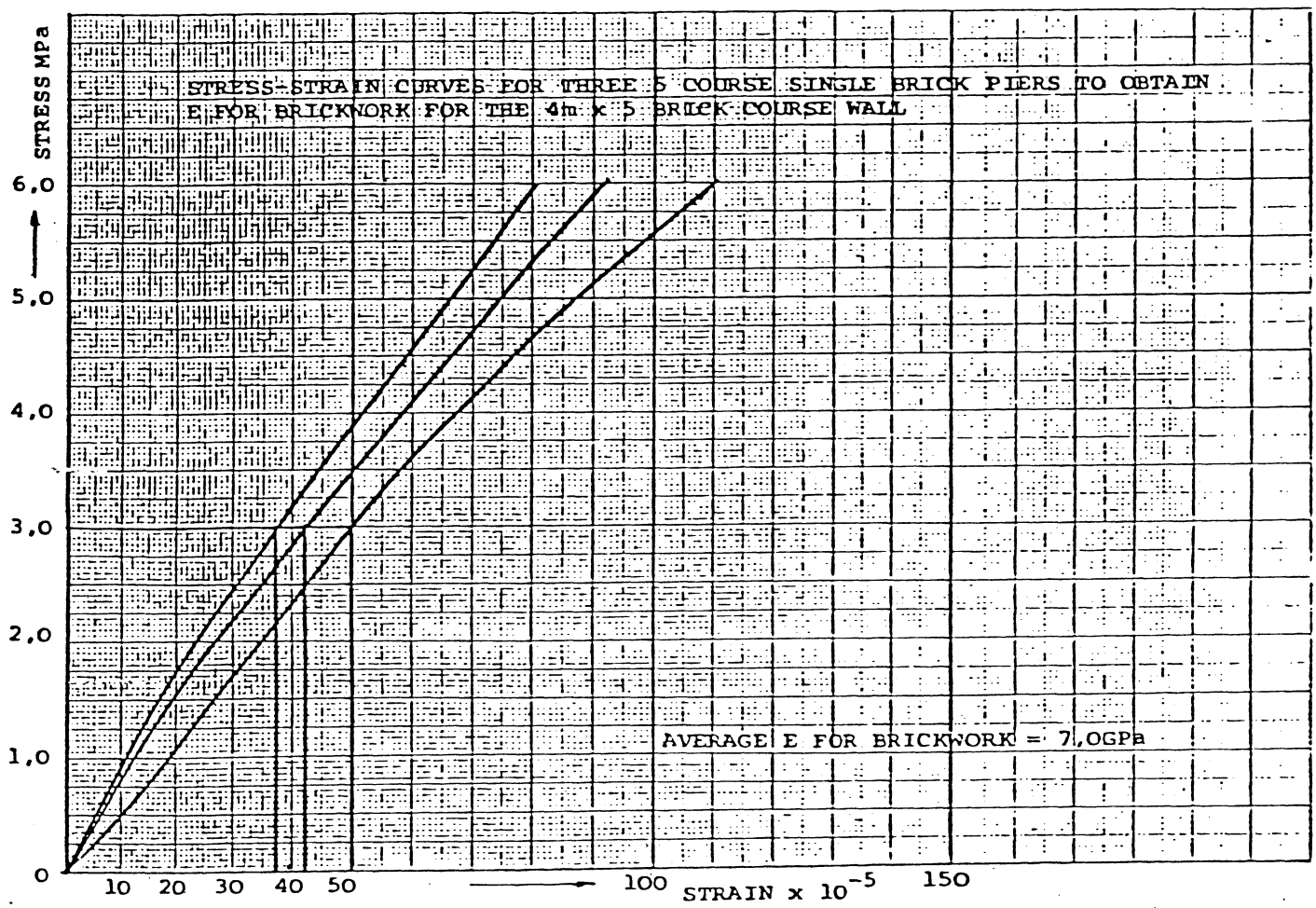


Figure A.3

Table A.4 COMPRESSIVE STRESS-STRAIN RESULTS FOR THREE 7 SINGLE BRICK PIERS TO OBTAIN E FOR BRICKWORK FOR THE 4m x 7 BRICK COURSE WALL (WALL 5)

PIER 1			PIER 2			PIER 3		
LOAD kN	STRESS MPa	AVERAGE STRAIN x 10^{-5}	LOAD kN	STRESS MPa	AVERAGE STRAIN x 10^{-5}	LOAD kN	STRESS	AVERAGE STRAIN x 10^{-5}
0	0	0	0	0	0	0	0	0
10	0,432	3,5	10	0,432	5,0	10	0,432	4,8
20	0,865	7,8	20	0,865	8,9	20	0,865	10,5
30	1,30	12,1	30	1,30	14,6	30	1,30	15,4
40	1,73	16,8	40	1,73	19,0	40	1,73	21,8
50	2,16	21,5	50	2,16	24,8	50	2,16	27,5
60	2,60	27,5	60	2,60	29,5	60	2,60	32,1
70	3,03	32,0	70	3,03	33,8	70	3,03	36,5
80	3,46	37,1	80	3,46	38,6	80	3,46	43,4
100	4,32	48,7	100	4,32	52,1	100	4,32	56,0
120	5,20	60,1	120	5,20	65,2	120	5,20	69,5
140	6,05	73,2	140	6,05	81,5	140	6,05	87,2

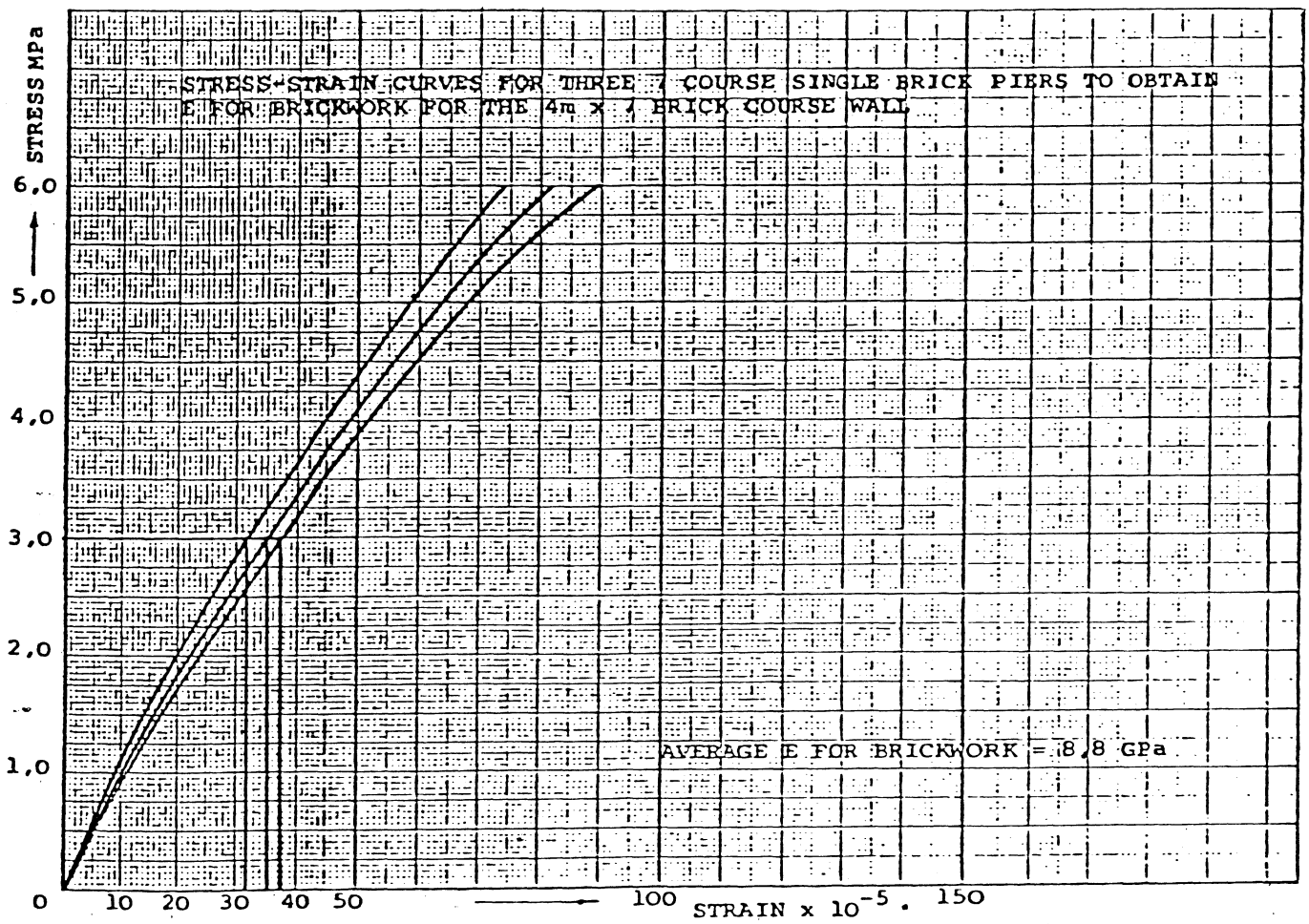


Figure A.4

Table A.5 COMPRESSIVE STRESS-STRAIN RESULTS FOR THREE 9 SINGLE BRICK PIERS TO OBTAIN E FOR BRICKWORK FOR THE 4m x 9 BRICK COURSE WALL (WALL 6)

PIER 1			PIER 2			PIER 3		
LOAD kN	STRESS MPa	AVERAGE STRAIN x 10^{-5}	LOAD kN	STRESS MPa	AVERAGE STRAIN x 10^{-5}	LOAD kN	STRESS MPa	AVERAGE STRAIN x 10^{-5}
0	0	0	0	0	0	0	0	0
10	0,432	4,0	10	0,432	4,0	10	0,432	4,2
20	0,865	9,7	20	0,865	9,8	20	0,865	12,0
30	1,30	14,5	30	1,30	15,4	30	1,30	17,9
40	1,73	18,7	40	1,73	21,3	40	1,73	25,1
50	2,16	23,5	50	2,16	26,0	50	2,16	29,5
60	2,60	29,0	60	2,60	32,5	60	2,60	37,0
70	3,03	33,2	70	3,03	36,5	70	3,03	42,9
80	3,46	37,2	80	3,46	42,2	80	3,46	48,1
100	4,32	50,1	100	4,32	52,1	100	4,32	60,5
120	5,20	63,0	120	5,20	65,4	120	5,20	74,5
140	6,05	74,1	140	6,05	79,0	140	6,05	90,0

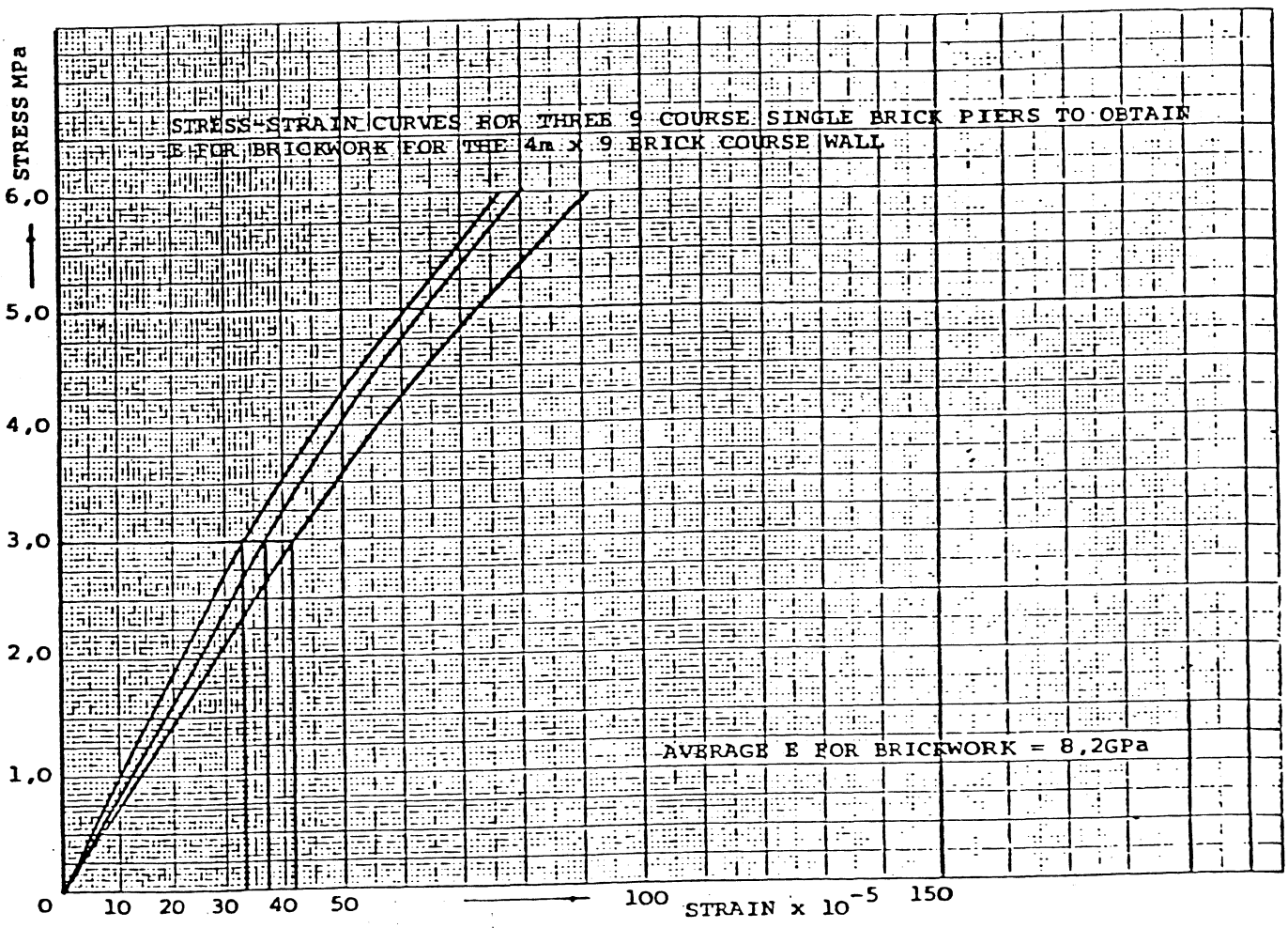


Figure A.5

Table A.6 COMPRESSIVE STRESS-STRAIN RESULTS FOR THREE 5 SINGLE BRICK PIERS TO OBTAIN E FOR BRICKWORK FOR THE 6m x 5 BRICK COURSE WALL (WALL 7)

PIER 1			PIER 2			PIER 3		
LOAD kN	STRESS MPa	AVERAGE STRAIN x 10^{-5}	LOAD kN	STRESS MPa	AVERAGE STRAIN x 10^{-5}	LOAD kN	STRESS	AVERAGE STRAIN x 10^{-5}
0	0	0	0	0	0	0	0	0
10	0,432	2,5	10	0,432	4,5	10	0,432	5,5
20	0,865	6,1	20	0,865	8,5	20	0,865	11,1
30	1,30	6,8	30	1,30	14,5	30	1,30	15,6
40	1,73	12,4	40	1,73	18,6	40	1,73	20,1
50	2,16	15,1	50	2,16	23,2	50	2,16	27,5
60	2,60	21,5	60	2,60	31,5	60	2,60	33,0
70	3,03	29,7	70	3,03	35,1	70	3,03	36,9
80	3,46	29,1	80	3,46	41,2	80	3,46	44,0
100	4,32	39,1	100	4,32	52,1	100	4,32	56,2
120	5,20	48,1	120	5,20	62,5	120	5,20	66,5
140	6,05	62,0	140	6,05	76,1	140	6,05	80,8

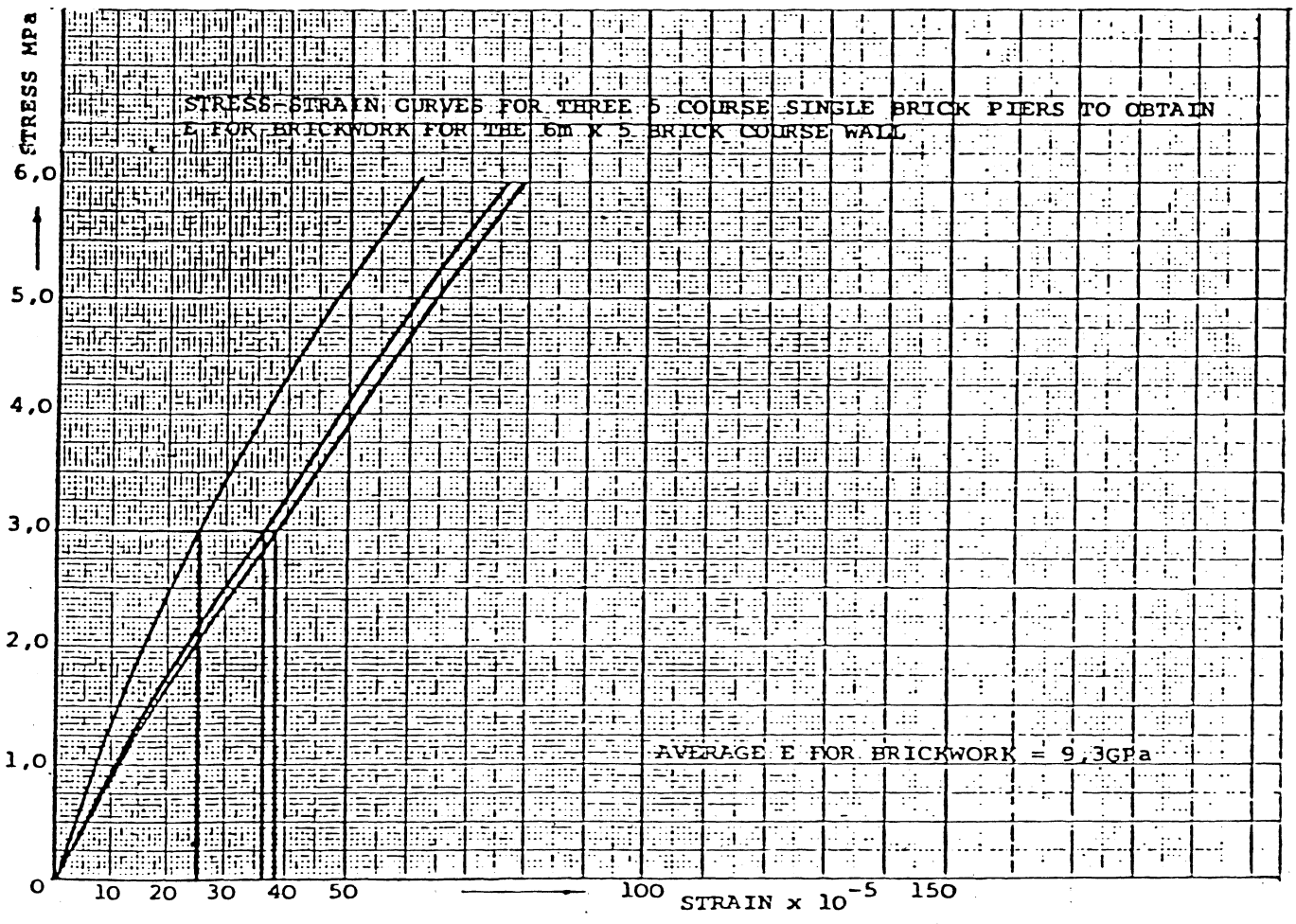


Figure A.6

Table A.7 COMPRESSIVE STRESS-STRAIN RESULTS FOR THREE 7 SINGLE BRICK PIERS TO OBTAIN E FOR BRICKWORK FOR THE 6m x 7 BRICK COURSE WALL (WALL 6)

PIER 1			PIER 2			PIER 3		
LOAD kN	STRESS MPa	AVERAGE STRAIN x 10^{-5}	LOAD kN	STRESS MPa	AVERAGE STRAIN x 10^{-5}	LOAD kN	STRESS MPa	AVERAGE STRAIN x 10^{-5}
0	0	0	0	0	0	0	0	0
10	0,432	2,0	10	0,432	2,5	10	0,432	5,5
20	0,865	7,2	20	0,865	7,4	20	0,865	10,5
30	1,30	11,1	30	1,30	14,5	30	1,30	16,1
40	1,73	17,1	40	1,73	15,2	40	1,73	24,5
50	2,16	20,5	50	2,16	24,5	50	2,16	31,6
60	2,60	29,2	60	2,60	32,2	60	2,60	38,2
70	3,03	36,0	70	3,03	37,0	70	3,03	43,5
80	3,46	39,5	80	3,46	44,2	80	3,46	51,1
100	4,32	56,5	100	4,32	60,1	100	4,32	58,8
120	5,20	60,4	120	5,20	79,5	120	5,20	87,2
140	6,05	85,1	140	6,05	97,4	140	6,05	104,2

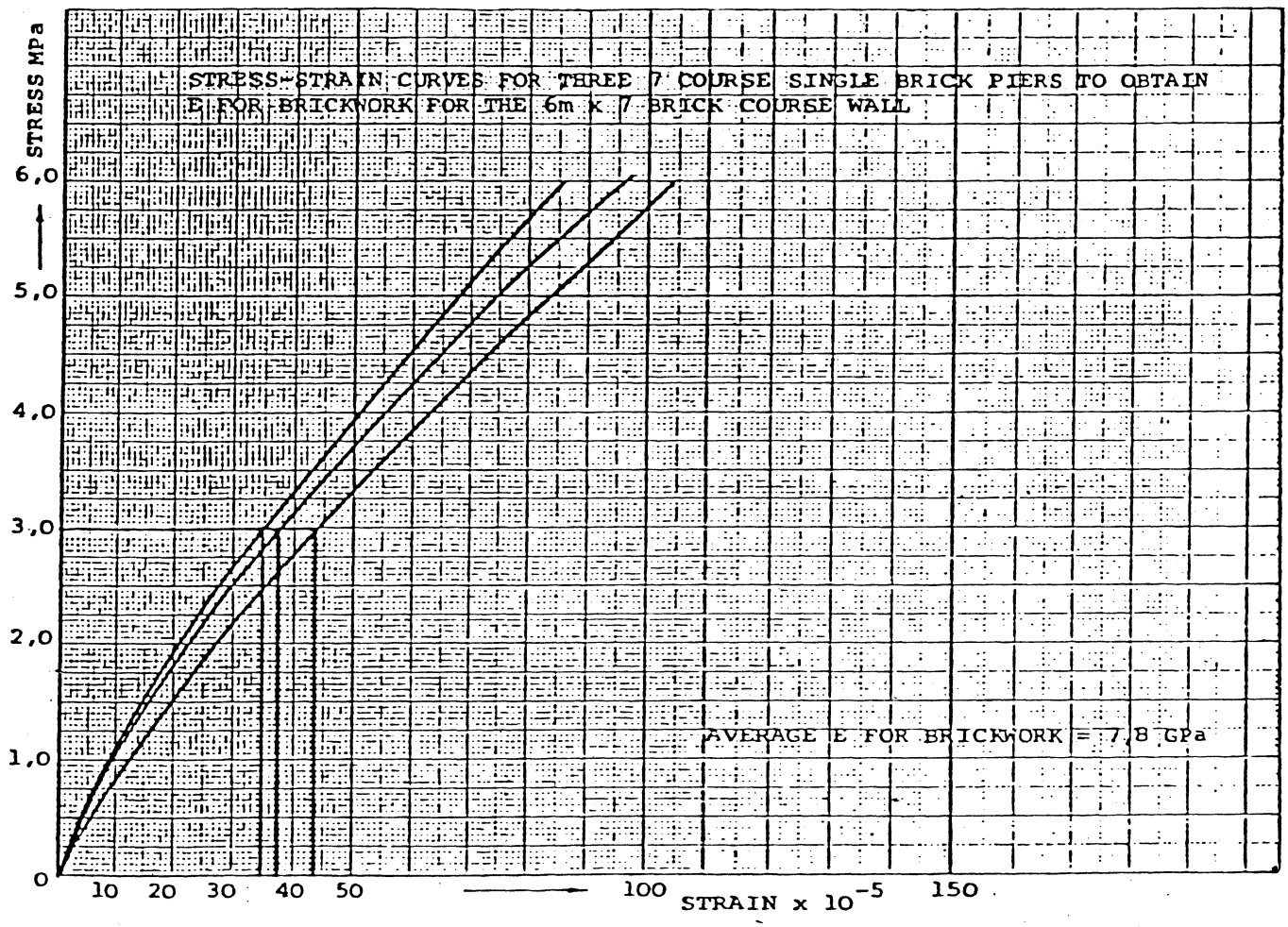


Figure A.7

Table A.8

COMPRESSIVE STRESS-STRAIN RESULTS FOR THREE 9 SINGLE BRICK PIERS TO OBTAIN E FOR BRICKWORK FOR THE (E x 9 BRICK COURSE WALL (WALL 9)

PIER 1			PIER 2			PIER 3		
LOAD kN	STRESS MPa	AVERAGE STRAIN x 10^{-5}	LOAD kN	STRESS MPa	AVERAGE STRAIN x 10^{-5}	LOAD kN	STRESS MPa	AVERAGE STRAIN x 10^{-5}
0	0	0	0	0	0	0	0	0
10	0,432	3,5	10	0,432	3,3	10	0,432	5,2
20	0,865	7,5	20	0,865	7,2	20	0,865	10,6
30	1,30	9,6	30	1,30	12,1	30	1,30	18,0
40	1,73	12,6	40	1,73	17,1	40	1,73	22,6
50	2,16	16,3	50	2,16	19,2	50	2,16	32,1
60	2,60	23,1	60	2,60	26,2	60	2,60	36,3
70	3,03	28,5	70	3,03	32,0	70	3,03	45,1
80	3,46	31,2	80	3,46	35,6	80	3,46	51,8
100	4,32	44,8	100	4,32	52,0	100	4,32	58,3
120	5,20	53,1	120	5,20	66,7	120	5,20	81,8
140	6,05	69,2	140	6,05	86,1	140	6,05	96,1

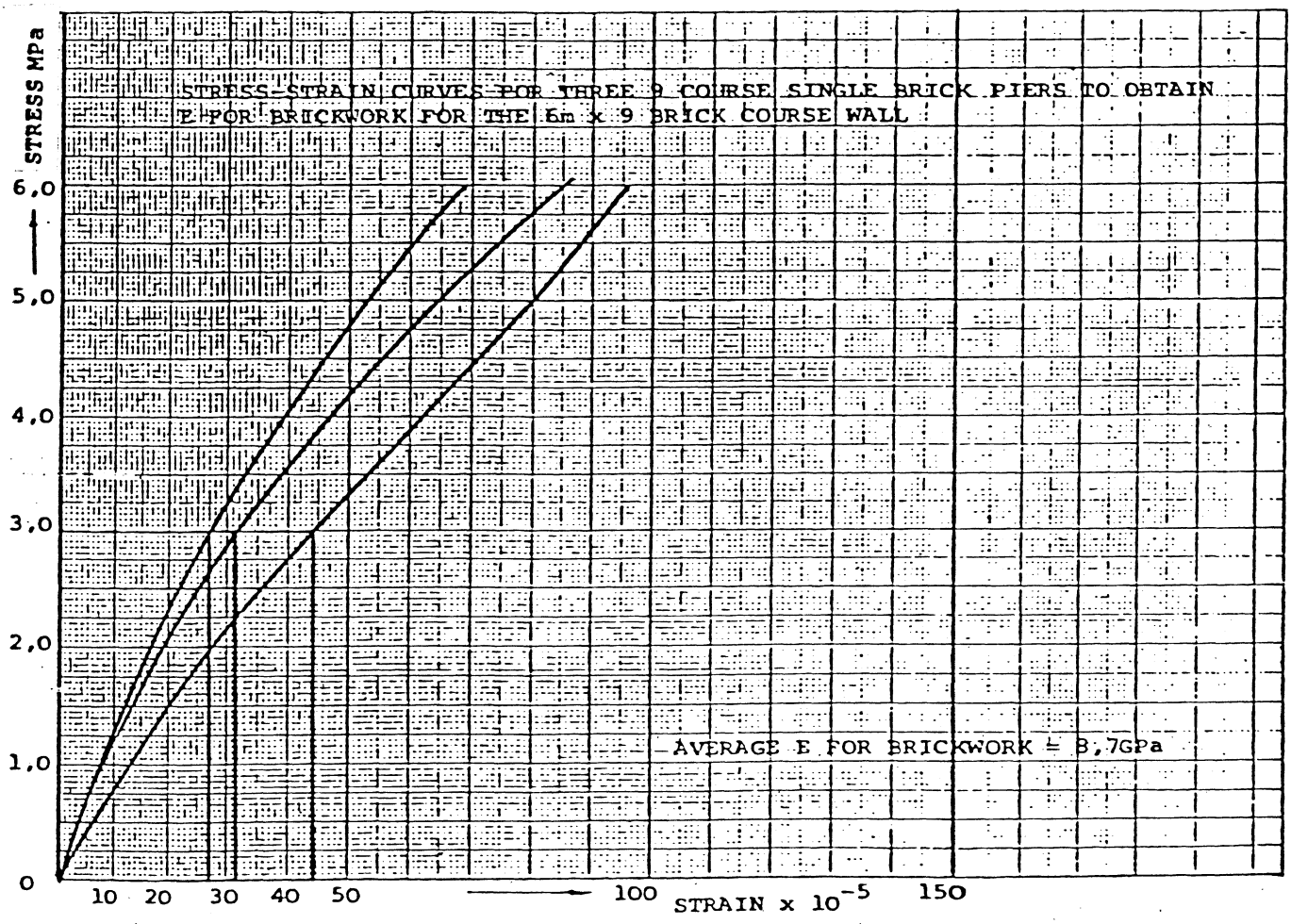


Figure A.8

APPENDIX B

RESULTS OF LOAD TESTS ON WALLS 2 TO 9 INCLUSIVE, GIVEN IN THE SAME ORDER AND FORM AS THE RESULTS OF THE TESTS ON WALL 1, CHAPTERS 5.2 AND 5.3

WALL 2 - 2m x 7 brick course

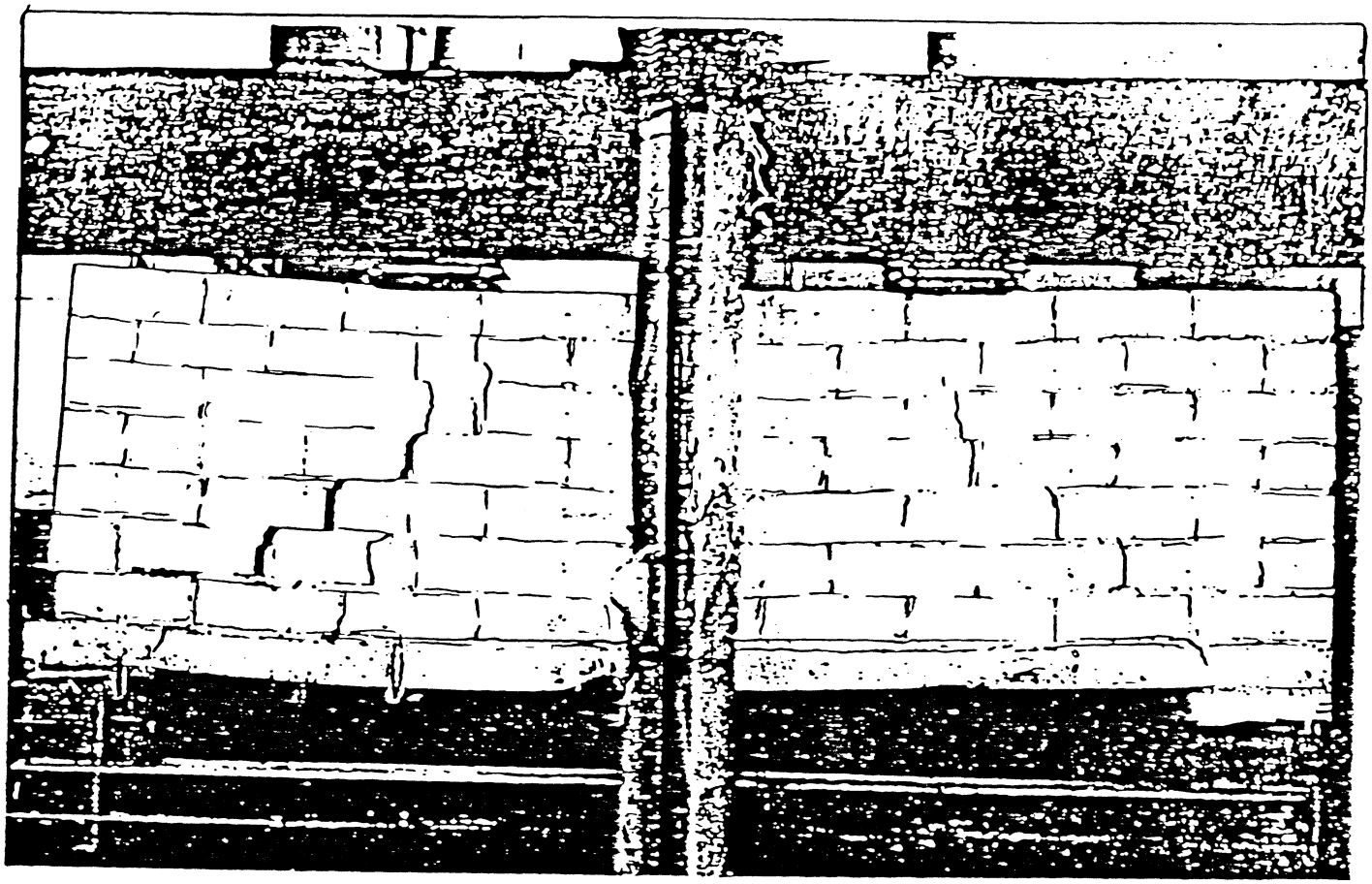
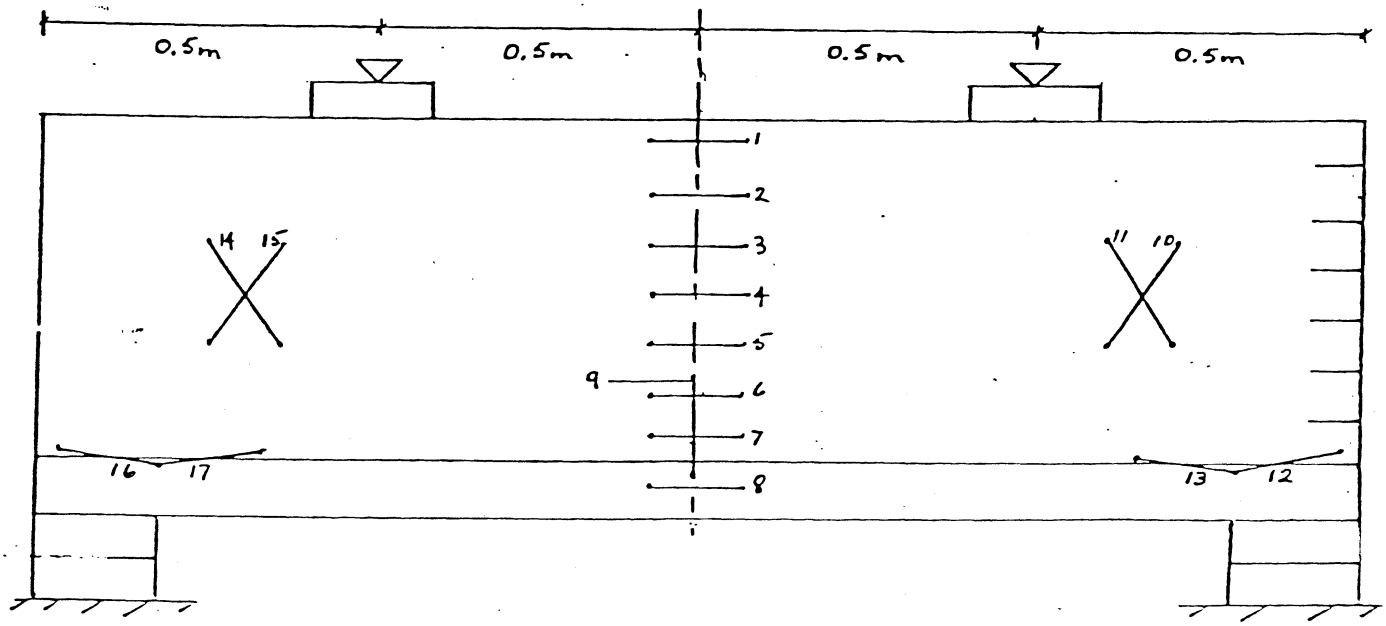


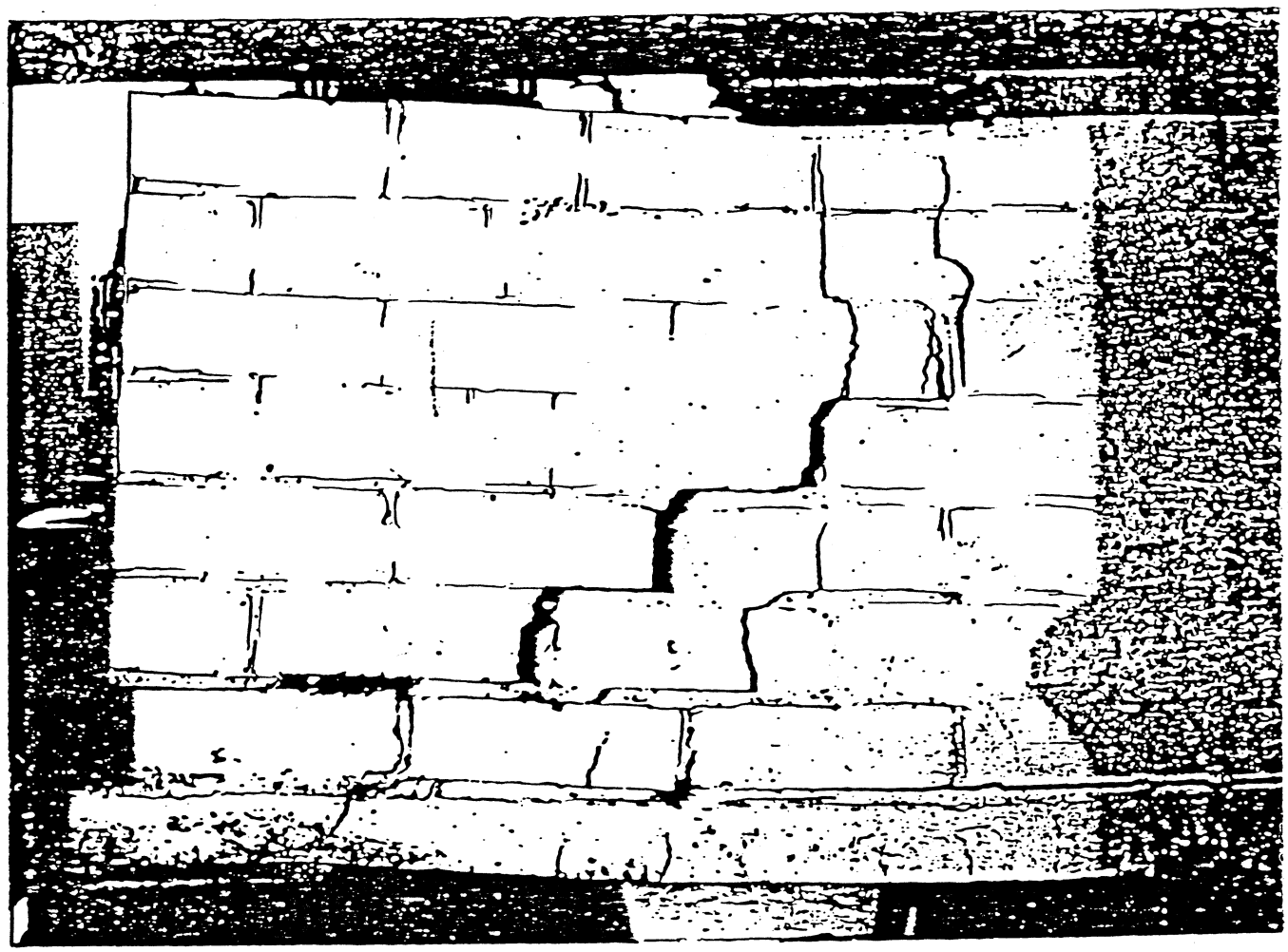
Figure B1



Position of strain gauges

Figure B2

WALL 2



Failure crack pattern

Figure B3

WALL NO 2 - 2m x 7brickcourse

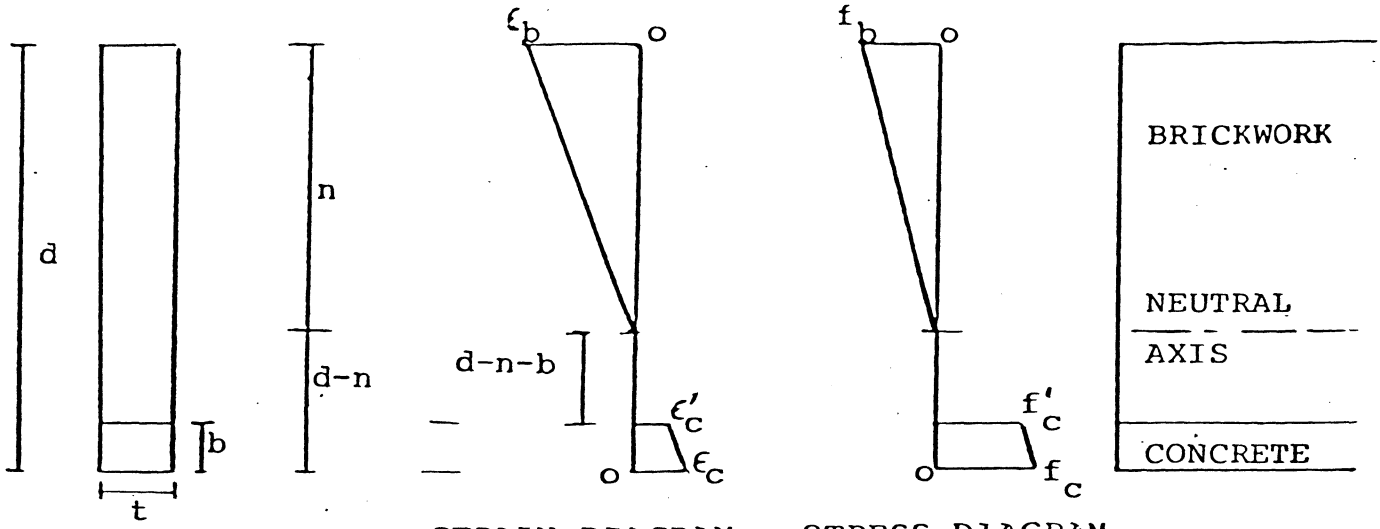


Figure B.4

E_b = 10,2GPa E_c = 44,5GPa b = 70mm t = 105mm d = 630mm

m = modular ratio = E_c/E_b = 44,5/10,2 = 4,36

$$n = \frac{-2mb \pm \sqrt{(2mb)^2 - 4mb(b-2d)}}{2} = 370,3mm$$

$$f_b = \frac{E_b nM}{E_b\frac{n.t}{3} + E_c\frac{bt}{2}.2(d-n) + 2b(n-d+\frac{b}{3})} = \underline{2,38MPa \text{ (calculated)}}$$

$f_b = E_b\epsilon_b = 0,2x10^3 x 25,010^{-5} = \underline{2,55MPa \text{ (measured)}}$

$$f_c = \frac{E_c(d-n)M}{E_b\frac{n.t}{3} + E_c\frac{bt}{2}.2(d-n) + 2b(n-d+\frac{b}{3})} = \underline{7,28MPa \text{ (calculated)}}$$

$f_c = E_c\epsilon_c = 4,5x10^3 x 22,5x10^{-5} = \underline{10,0MPa \text{ (measured)}}$

Comparison of Load Test Results and Analytical Results

Table B.1

	Load Test Results	Analytical Results
Maximum stress in brickwork	2,55MPa	2,38MPa
Maximum stress in concrete	10,0MPa	7,28MPa

Table B2 - Wall No.2 2m x 7 brickcourse

End reaction kN	Shear in shear span kN	Moment in flexure span kNm	Flexure strains x 10^{-5} at positions numbered on walls								
			1	2	3	4	5	6	7	8	9
0	0	0	0	0	0	0	0	0	0	0	
4,45	4,45	2,23	-1,5	-1,0	-1,0	-0,5	-0,5	+0,5	+1,5	+2,0	
8,9	8,9	4,45	-2,5	-1,5	-1,5	-0,5	0	+1,0	+2,0	+3,5	
13,5	13,5	6,63	-4,5	-2,5	-2,0	-1,0	+0,5	+2,0	+4,0	+5,5	
17,8	17,8	8,9	-5,5	-3,5	-3,0	-1,5	0	+3,0	+5,5	+7,0	
22,25	22,25	11,13	-7,0	-4,5	-3,0	-1,5	+0,5	+4,0	+8,0	+9,0	
31,15	31,15	15,57	-10,5	-6,5	-4,0	-1,5	+0,5	+4,5	+9,5	+12,0	
40,05	40,05	20,03	-15,5	-8,0	-6,0	-2,0	+0,5	+6,0	+12,0	+15,0	
44,5	44,5	22,25	-22,5	-13,0	-6,5	-2,5	-1,0	+6,5	+16,5	+18,0	
45,0	45,0	22,5			F	A	I	L	U	R	E

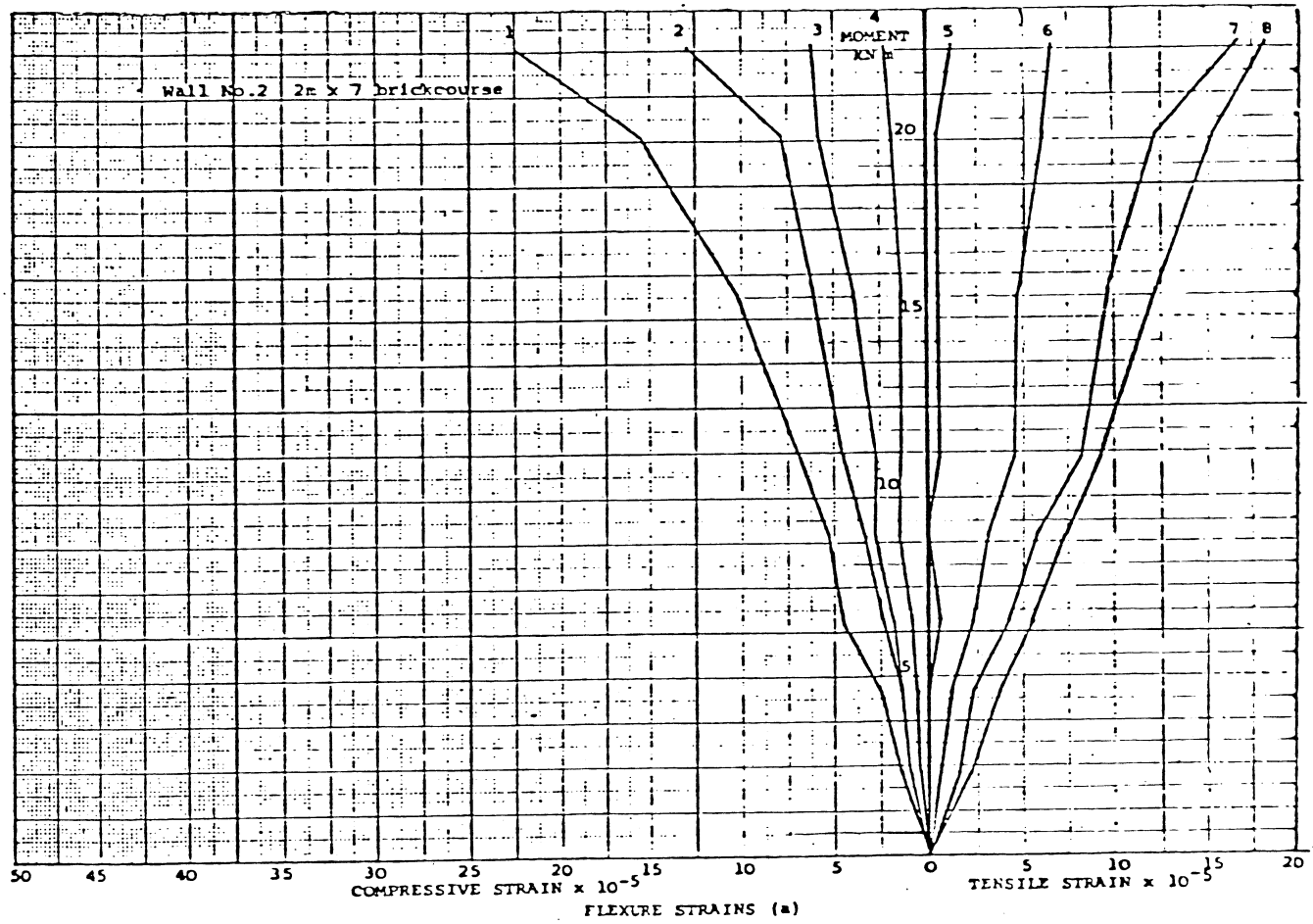


Figure B5

Table B3 - Wall No.2 2m x 7 brickcourse

End reaction kN	Shear in shear span kN	Moment in flexure span kNm	Diagonal strains x 10^{-5} at positions numbered on wall								
			10	11	14	15					
0	0	0	0	0	0	0	0	0	0	0	0
4,45	4,45	2,23	1,0	-1,5	+1,0	-1,0					
8,9	8,9	4,45	1,0	-2	2,5	-2,0					
13,5	13,5	6,63	1,5	-6,5	3,0	-3,5					
17,8	17,8	8,9	2,0	-10	8,0	-6,0					
22,25	22,25	11,13	2,0	-14	20,5	-9,5					
31,13	31,15	15,57	11,5	-20,5	31,5	-10					
40,05	40,05	20,03	15	-24	40,5	-15,5					
44,5	44,5	22,25	33,5	-29,5	62,5	-24,5					
45,0	45,0	22,5	F A I L U R E								

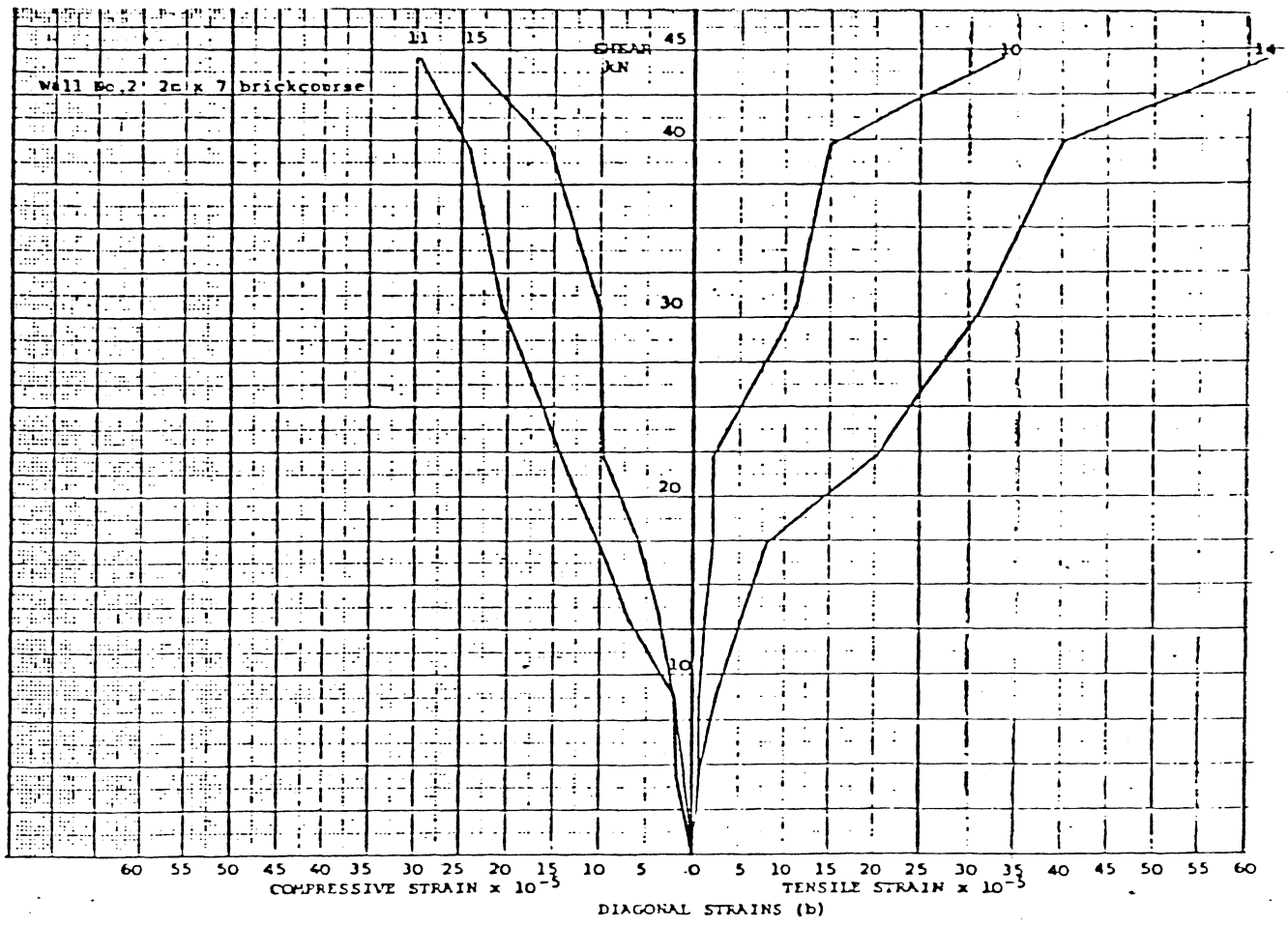


Figure B6

Table B4 - Wall No.2 2m x 7 brickcourse

End reaction kN	Shear in shear span kN	Moment in flexure span kNm	Slip strains x 10^{-5} between brickwork and lintel at positions numbered on wall							Central wall deflection mm
			12	13	16	17	9			
0	0	0	0	0	0	0	0	0	0	0
4,45	4,45	2,23	1,0	0	0,5	0	0			0,10
8,9	8,9	4,45	2,0	0	1,0	1,0	0			0,16
13,5	13,5	6,63	4,5	2	4,0	3,5	0			0,32
17,8	17,8	8,9	7,5	4,5	4,0	3,5	0			0,45
22,25	22,25	11,13	11,5	6,5	6,0	4,0	0,5			
31,15	31,15	15,57	15,0	10,5	16,5	7,5	0,5			
40,05	40,05	20,03	30,5	14,5	48,0	18,0	0,5			
44,5	44,5	22,25	51,0	18,8	60,0	23,5	1,0			
45,0	45,0	22,5	F A I L U R E							

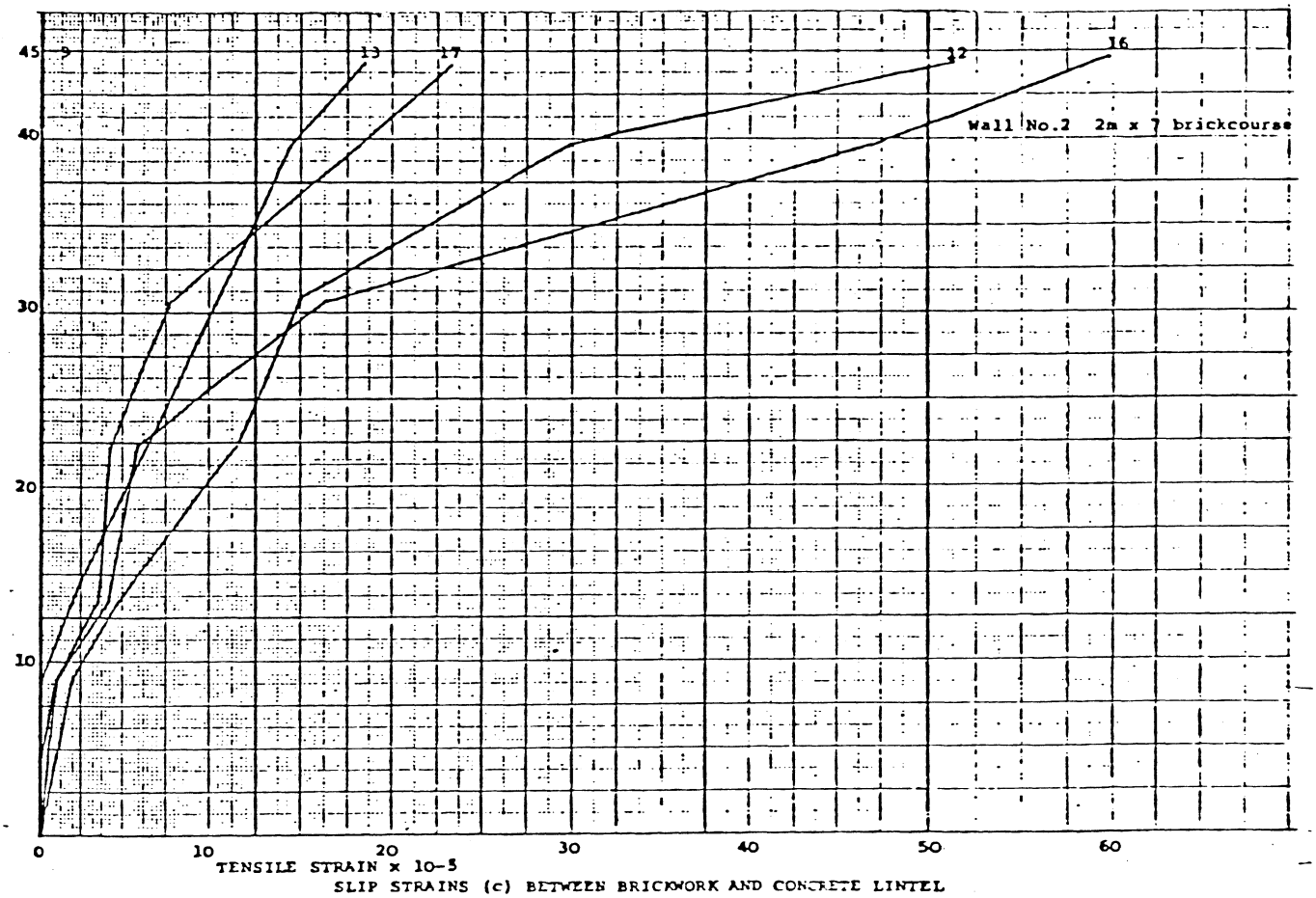
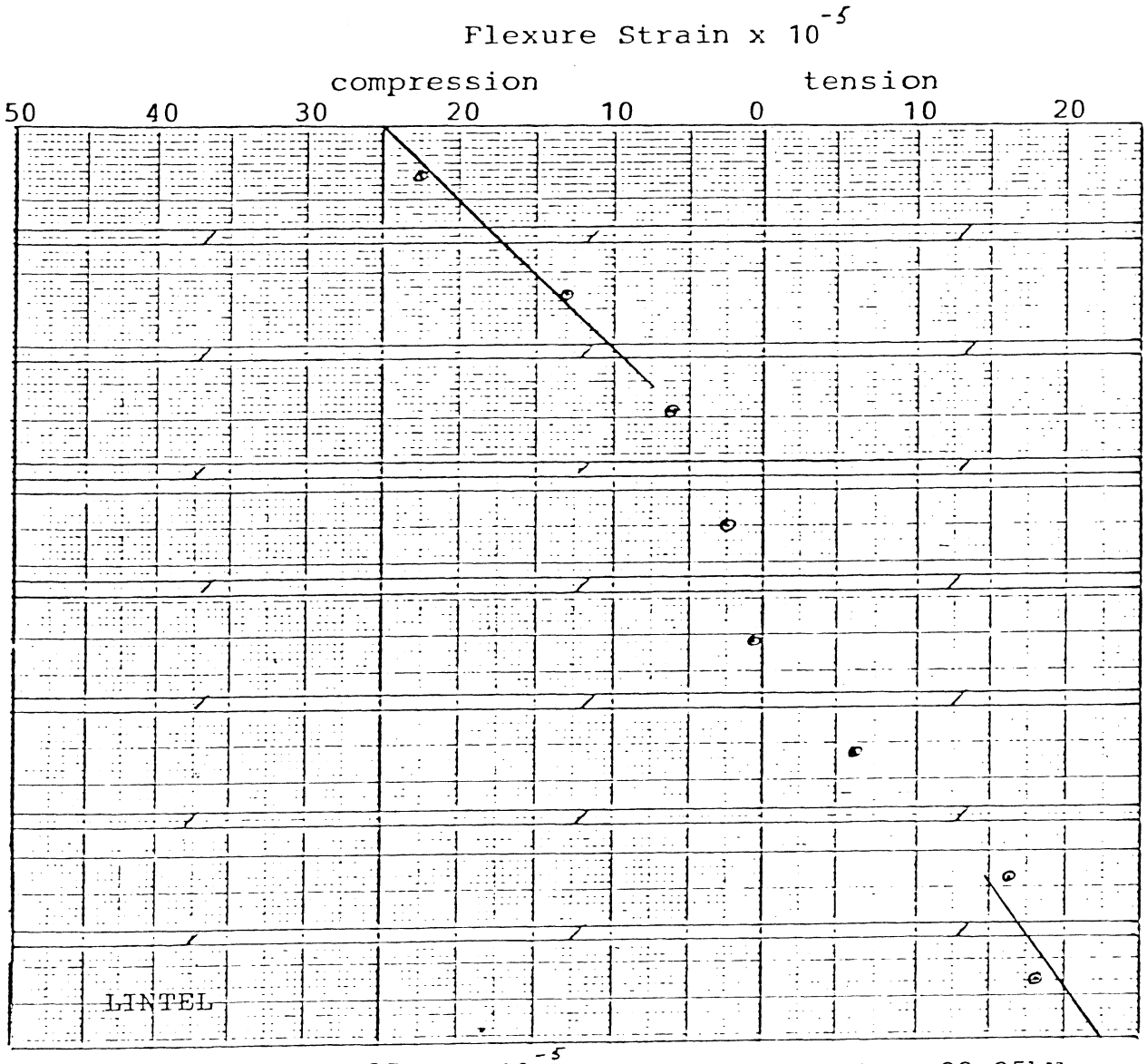


Figure B7

The measured top and bottom maximum edge flexure strains were determined by plotting to scale, the strains measured at the centre of each brick course and centre of lintel against wall height. The values being taken at the maximum moment recorded. For wall 2 this was determined as below.



Top Edge Strain = 25,0 x 10^{-5} Maximum Moment = 22,25kNm

Bottom Edge Strain = 22,5 x 10^{-5}

Figure B.8

WALL 2 - 2m x 7 Brick course

Comment were given on the following test results.

1. The load test values.
2. The calculated and measured stresses and strains in the wall.
3. The central wall deflection.
4. The failure crack pattern.
5. Further comments on the wall resistance to the loading during the test procedure.

The ultimate resistance moment of the wall produced a value of 22,5kNm, being 2,01 times the SHOFCO value of 11,2kNm. The ultimate shear resistance of the wall produced a value of 45 kN, being 5,1 times the SHOFCO value of 8,75kN.

The maximum load test tensile flexure stress in the lintel, of 10,0MPa and 37 per cent above the calculated result of 7,28MPa. The maximum load test compressive flexure stress in the brickwork of 2,55MPa was 7 per cent more than the calculated result of 2,38MPa. The graph of the flexure strains (a) versus moment showed a uniform increase except for the final applied moment when the strains 1 and 2 at the top of the wall and strains 7 and 8 at the bottom of the wall produced increased values. The strains along the tensile diagonals 10 and 14 increased to $33,5 \times 10^{-5}$ and $62,5 \times 10^{-5}$ respectively. The slip strains at 12 and 16 at both ends of the wall over the wall supports suddenly increased to 51×10^{-5} and 60×10^{-5} respectively, these four above strains produced the final wall failure.

The measured central wall deflection, taken at an end wall reaction of 17,8kN when the central deflection gauge

was removed in case of wall failure gave a galue of 0,45mm, 4,1 times the calculated central deflection of 0,11mm. The test deflection values did not coincide with the linear calculated values the test values being erratic and not producing a smooth curve.

As can be seen from the photographic reproduction of the failure crack pattern all the bricks above the lintel and even more pronounced all the bricks above the lowest layer of bricks to the left of the compression diagonal on the left hand side of the wall slipped approximately 2cm to the left, a crack also occurring in the lintel at 45 degrees adjoining the left hand support. There was also a similar failure crack on the right hand side of the wall, as can be seen, but not so severe as the left hand side. The cracks on both sides of the wall appeared at approximately the same time, running along the same failure pattern diagonally from the inside of the supports to the inside of the loading points.

WALL 3 - 2m x 9 brick courses

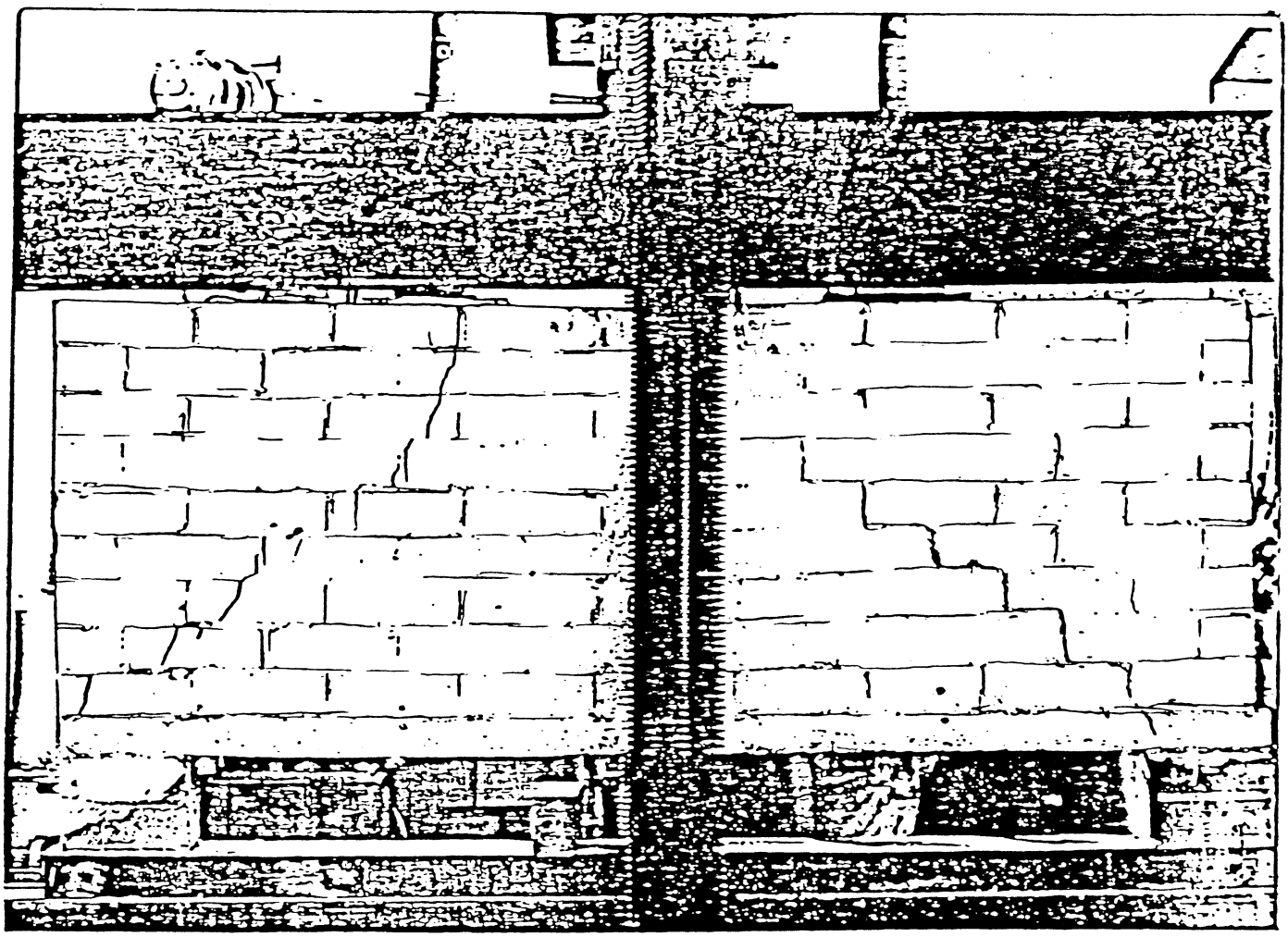


Figure B8

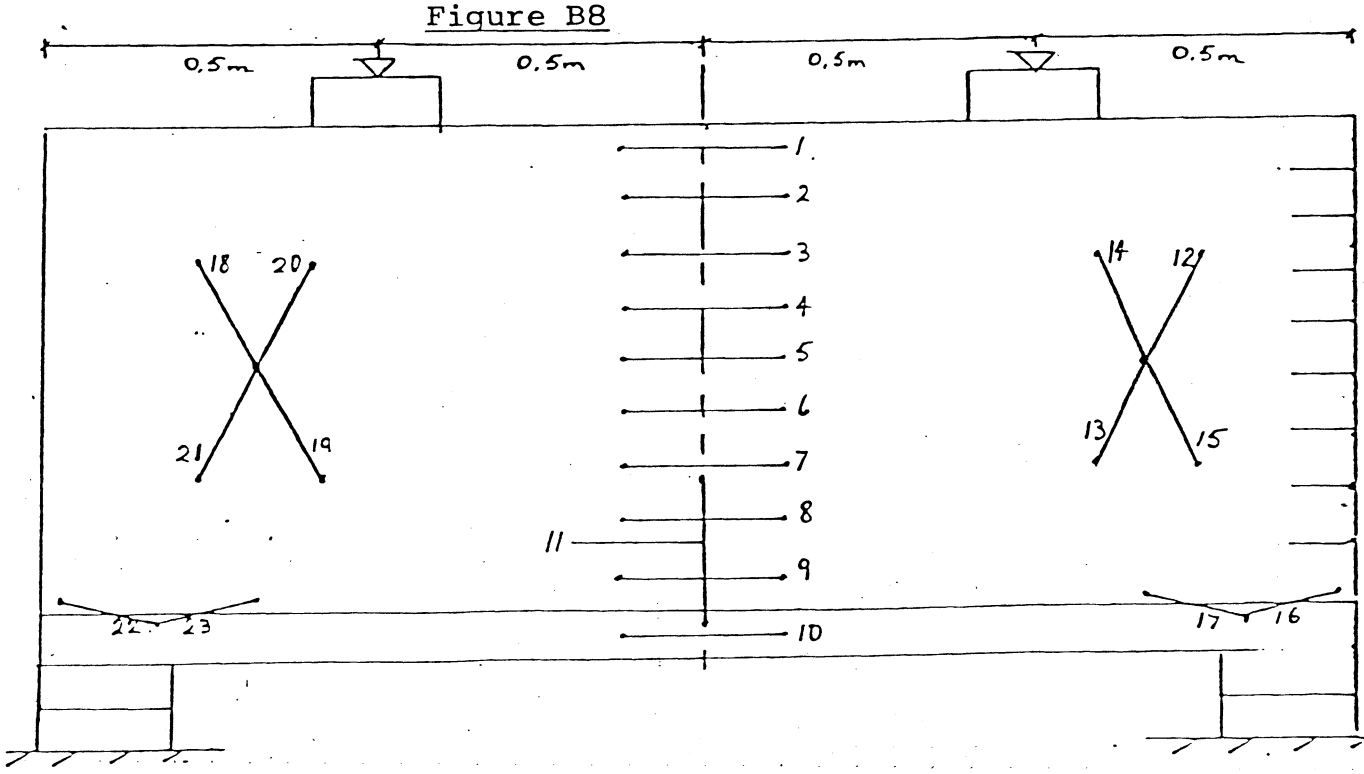
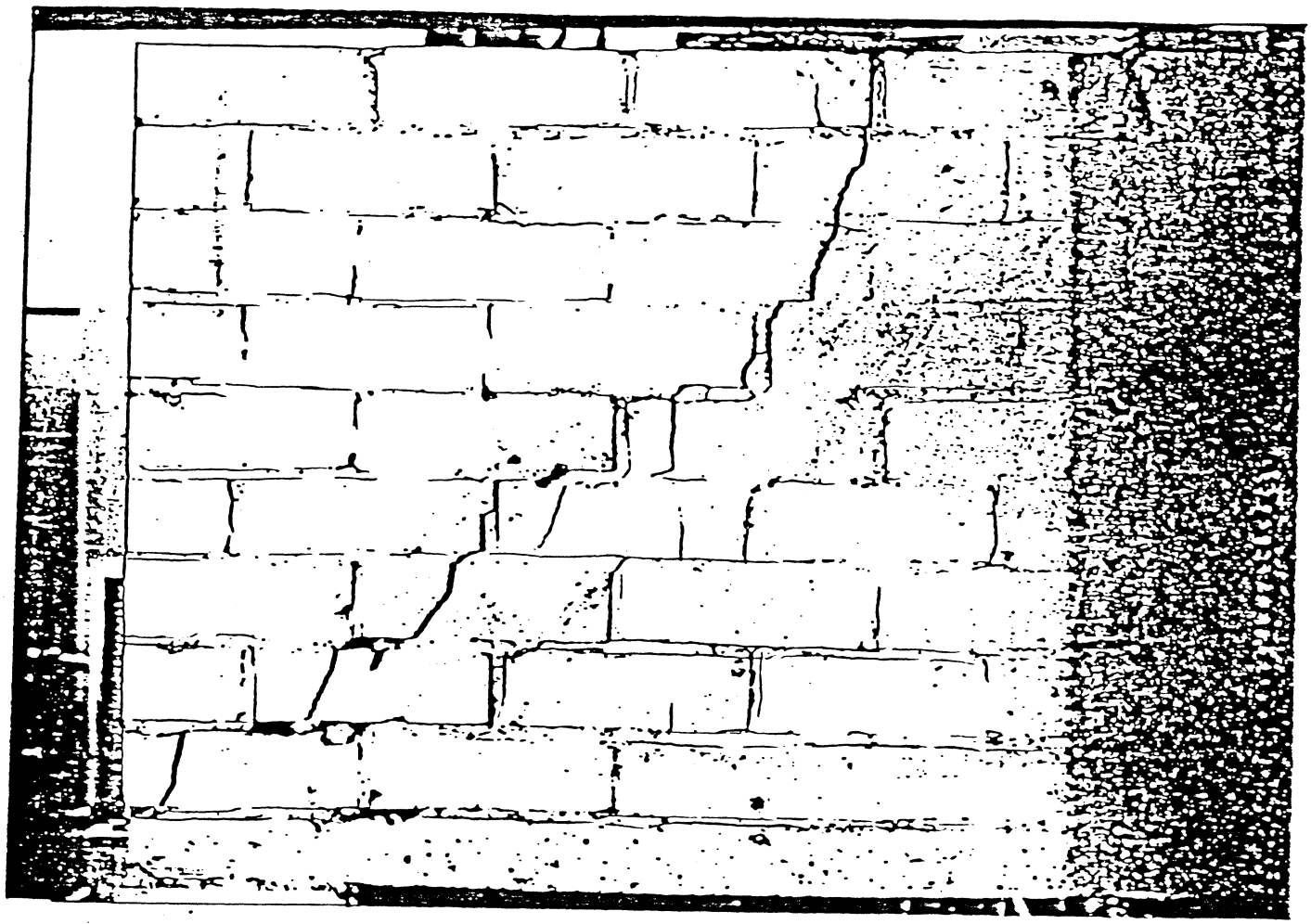


Figure B9

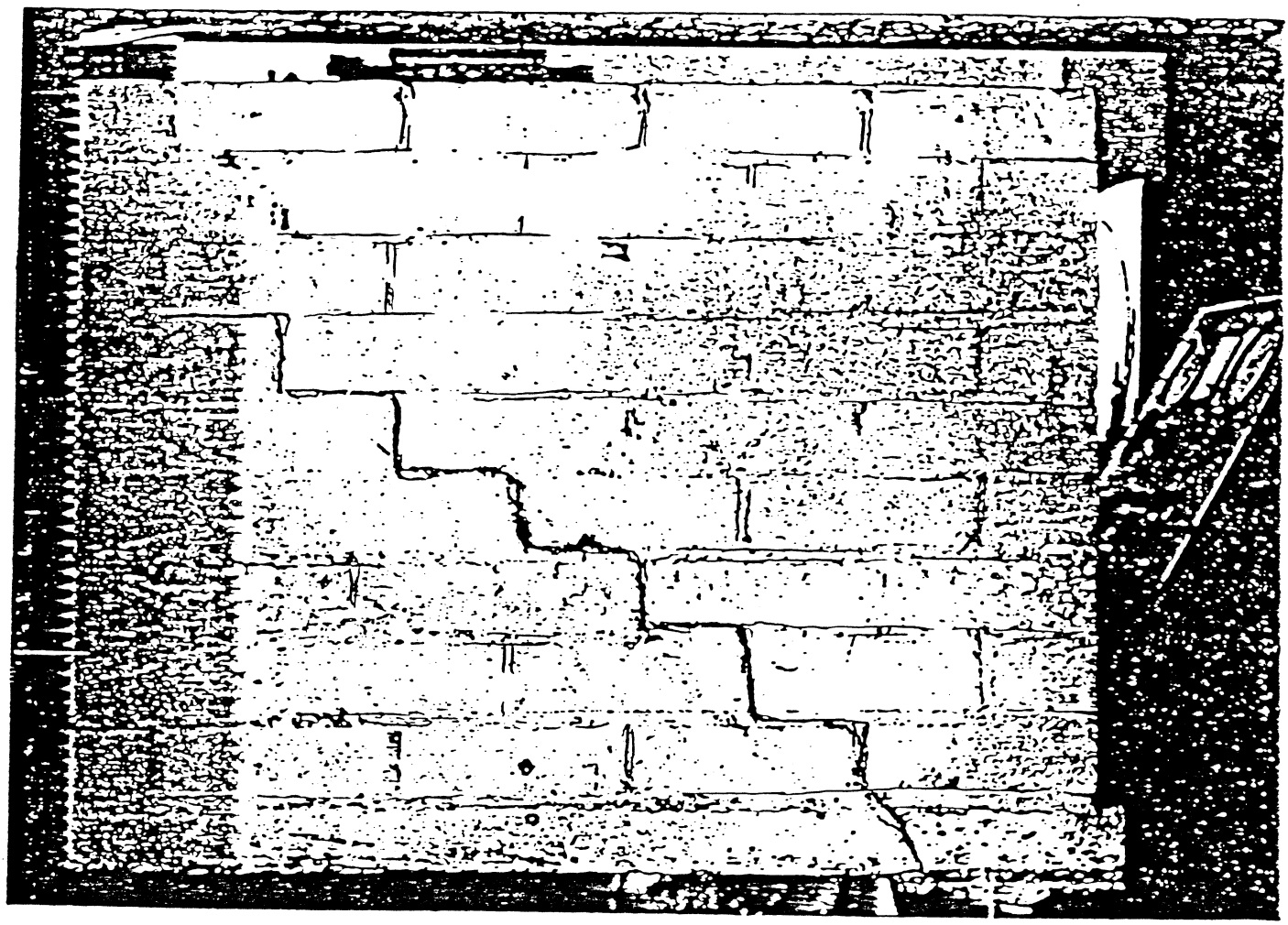
WALL 3



Failure crack pattern

Figure B10

WALL 3



Failure crack pattern

Figure B.11

WALL NO 3 - 2m x 9brickcourse

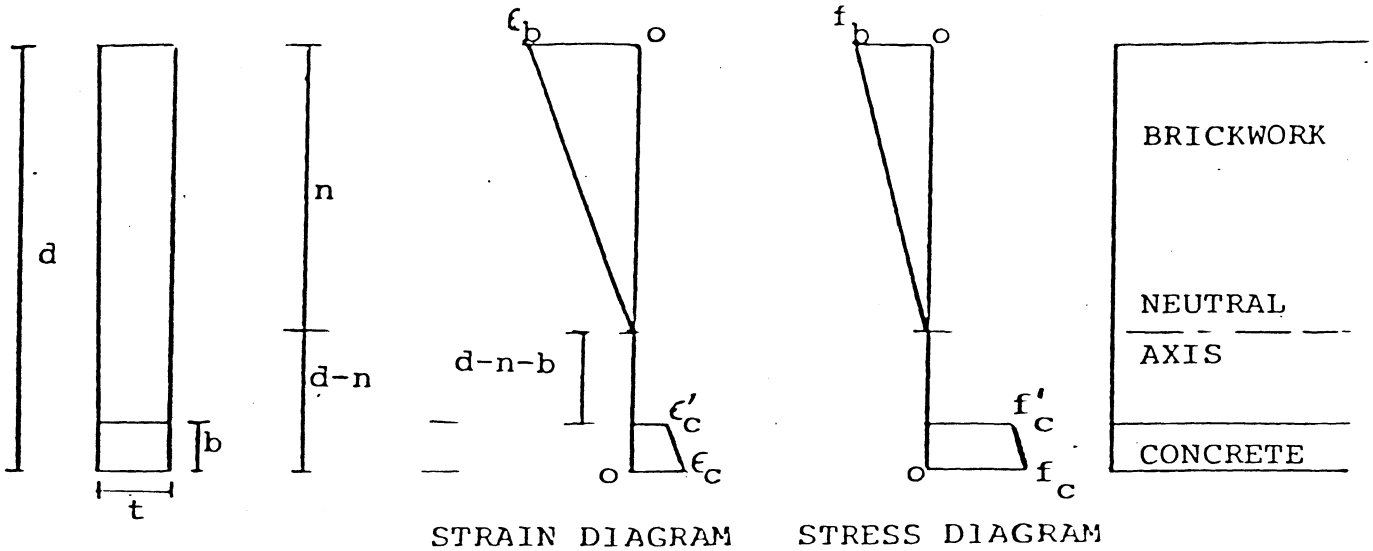


Figure B.12

E_b = 8,5GPa E_c = 44,5GPa b = 70mm t = 105mm d = 790mm

m = modular ratio = E_c/E_b = 44,5/8,5 = 5,23

$$n = \frac{-2mb \pm \sqrt{(2mb)^2 - 4mb(b-2d)}}{2} = 462,6$$

$$f_b = \frac{E_b n M}{E_b \frac{n}{3} t + E_c \frac{bt}{2} 2(d-n) + 2b(n-d+\frac{b}{3})} = \underline{1,82MPa \text{ (calculated)}}$$

$$f_b = E_b \epsilon_b = 8,5x10^3 x 30x10^{-5} = \underline{2,55MPa \text{ (measured)}}$$

$$f_c = \frac{E_c (d-n) M}{E_b \frac{n}{3} t + E_c \frac{bt}{2} 2(d-n) + 2b(n-d+\frac{b}{3})} = \underline{6,78MPa \text{ (calculated)}}$$

$$f_c = E_c \epsilon_c = -44,5x10^3 x\ 20,5x10^{-5} = \underline{9,12MPa \text{ (measured)}}$$

Comparison of Load Test Results and Analytical Results

Table B.5

	Load Test Results	Analytical Results
Maximum stress in brickwork	2,55MPa	1,82MPa
Maximum stress in concrete	9,12MPa	6,78MPa

Table B6 - Wall No.3 2m x 9 brickcourse

End reaction kN	Shear in shear span kN	Moment in flexure span kNm	Flexure strains x 10^{-5} at positions numbered on walls									
			1	2	3	4	5	6	7	8	9	10
0	0	0	0	0	0	0	0	0	0	0	0	0
8,9	8,9	4,45	-3,5	-2,5	-1,5	-1,0	-1,0	-0,5	+1,5	+2,0	+2,0	+4,5
17,8	17,8	8,9	-6,0	-3,5	-3,0	-2,0	-2,0	+0,5	+2,0	+3,5	+3,5	+7,0
26,7	26,7	13,4	-9,5	-6,0	-5,5	-3,5	-3,5	0,0	+2,5	+4,0	+4,5	+9,0
35,6	35,6	17,8	-13,0	-7,0	-6,5	-4,5	-4,5	0,0	+3,0	+4,5	+7,0	+11,5
44,5	44,5	22,3	-21,0	-11,0	-10,0	-6,0	-6,0	-0,5	+3,5	+7,0	+8,5	+15,0
53,4	53,4	26,7	-27,0	-17,0	-15,0	-7,5	-6,5	-0,5	+4,0	9,0	+10,0	+18,0
55,0	55,0	27,5	F A I L U R E									

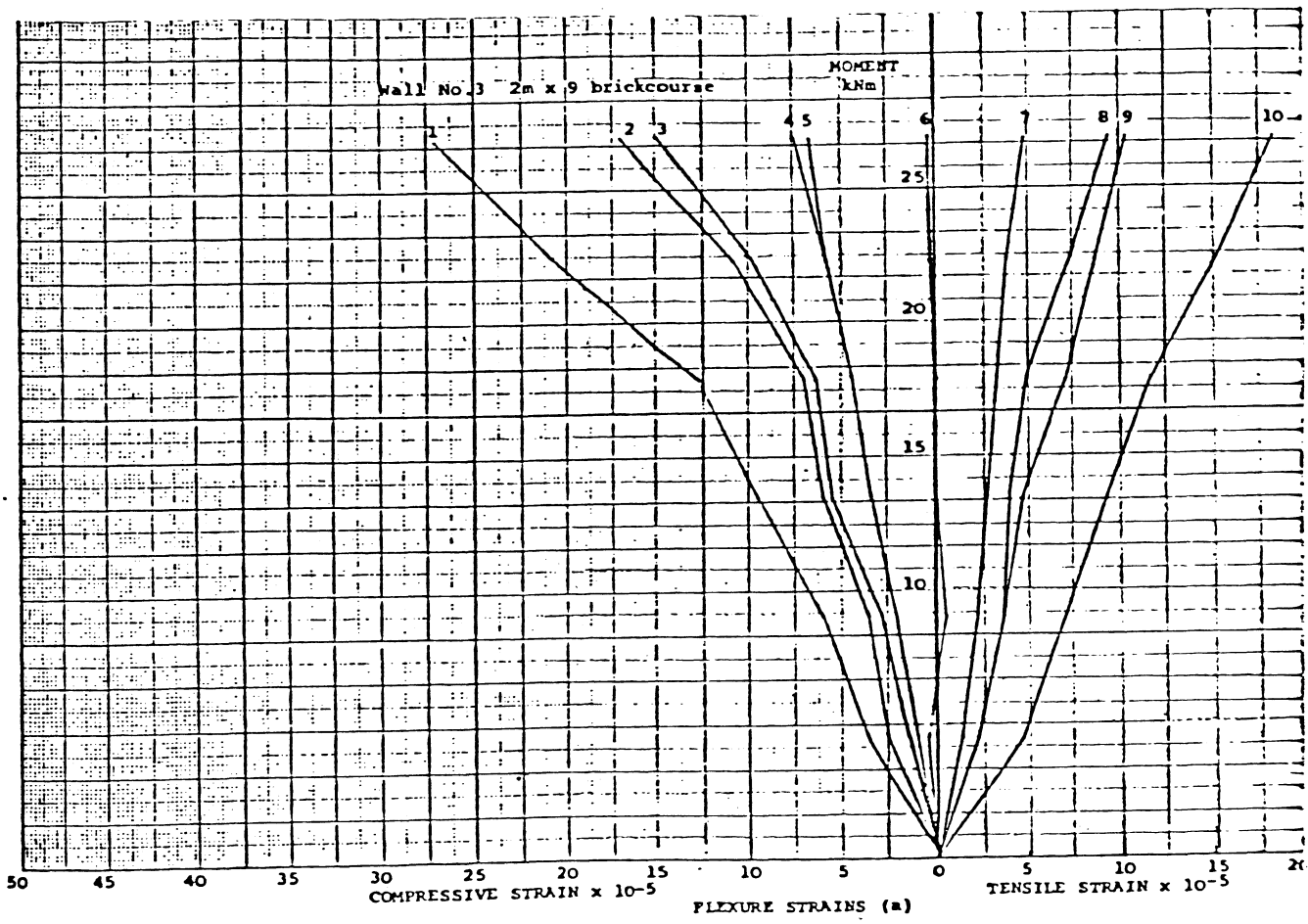


Figure B13

Table B7 - Wall No.3 2m x 9 brickcourse

End reaction kN	Shear in shear span kN	Moment in flexure span kNm	Diagonal strains x 10^{-5} at positions numbered on wall								
			12	13	14	15	18	19	20	21	
0	0	0	0	0	0	0	0	0	0	0	0
8,9	8,9	4,45	0	1,0	-2,0	-2,0	0	+4,0	-1,0	-2,5	
17,8	17,8	8,9	0,5	4,5	-3,0	-4,0	0	+8,5	-5,5	-5,5	
26,7	26,7	13,0	1,5	5,0	-5,5	-6,0	+0,5	13,5	-7,0	-8,5	
35,6	35,6	17,8	2,5	7,5	-8,0	-12,0	+0,5	22,0	-15,5	-16,0	
44,5	44,5	22,3	3,0	20,0	-12,0	-17,5	+1,0	30,5	-18,0	-28,5	
53,4	53,4	26,7	3,0	55,0	-16,5	-26,0	+1,0	43,0	-24,0	-38,0	
55,0	55,0	27,5			F A I L U R E						

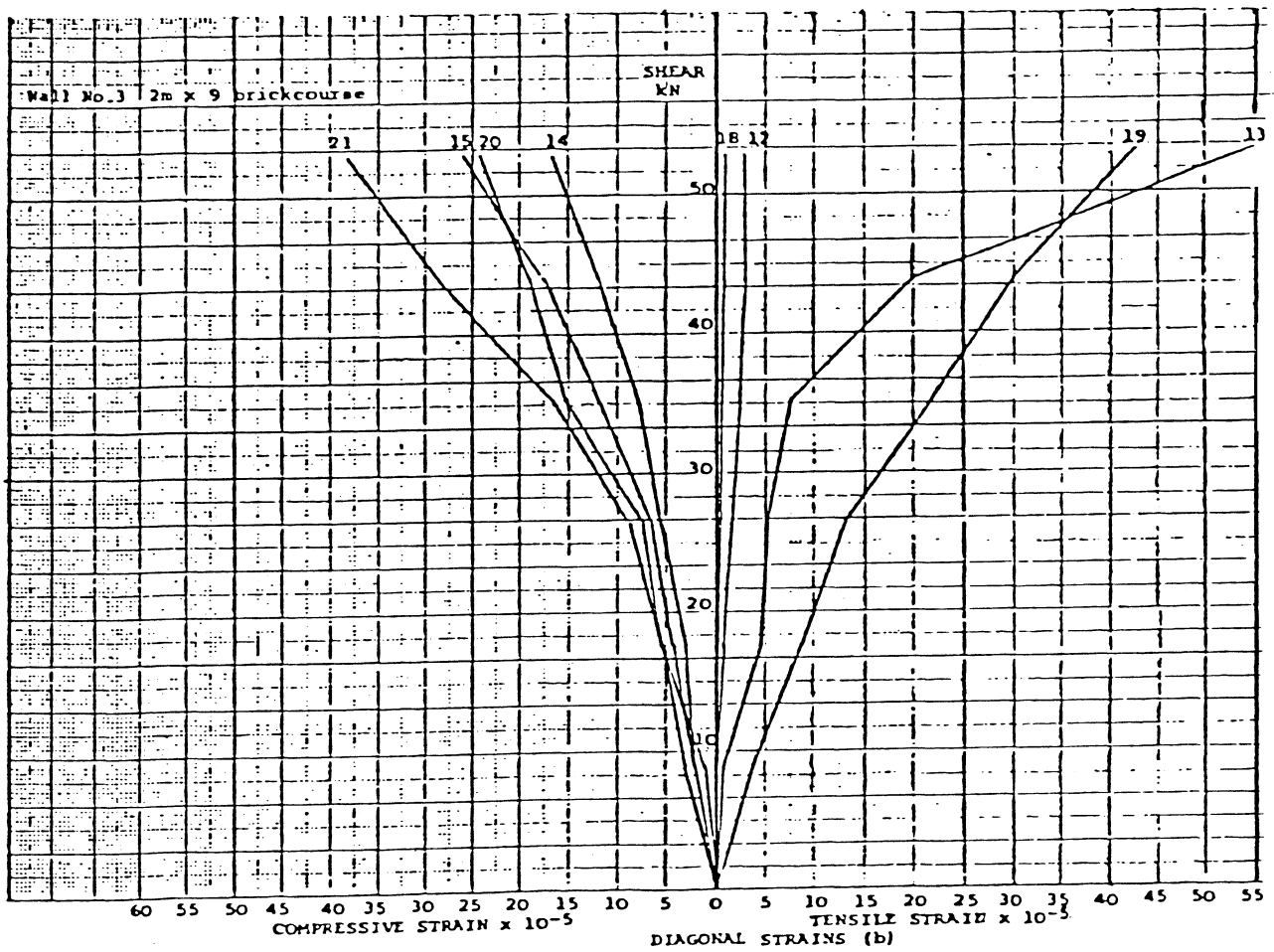


Figure B14

Table B8 - Wall No.3 2m x 9 brickcourse

End reaction kN	Shear in shear span kN	Moment in flexure span kNm	Slip strains x 10^{-5} between brickwork and lintel at positions numbered on wall 16	17	22	23	11			Central wall deflection mm
0	0	0	0	0	0	0	0			0
8,9	8,9	4,45	0	0	1,5	0	0			0,05
17,8	17,8	8,9	1,5	0	3,0	1,0	0			0,15
26,7	26,7	13,4	3,5	1,0	5	3,0	0			0,21
35,6	35,6	17,8	6,0	4,5	10,0	7,0	0			0,28
44,5	44,5	22,3	22,5	8,5	15,0	11,5	0			
53,4	53,4	26,7	41,0	11,5	31,0	16,0	0			
55,0	55,0	27,5	F A I L U R E							

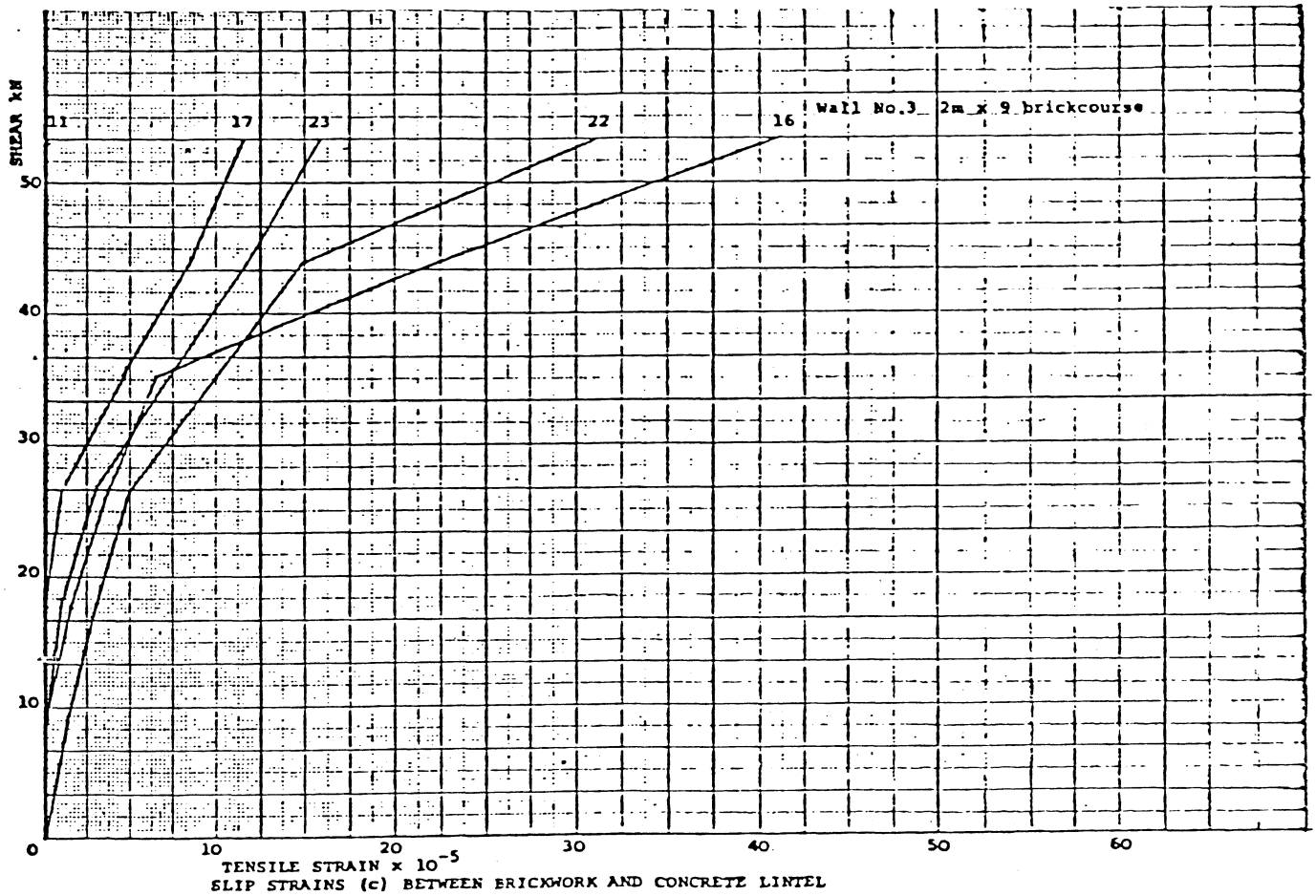
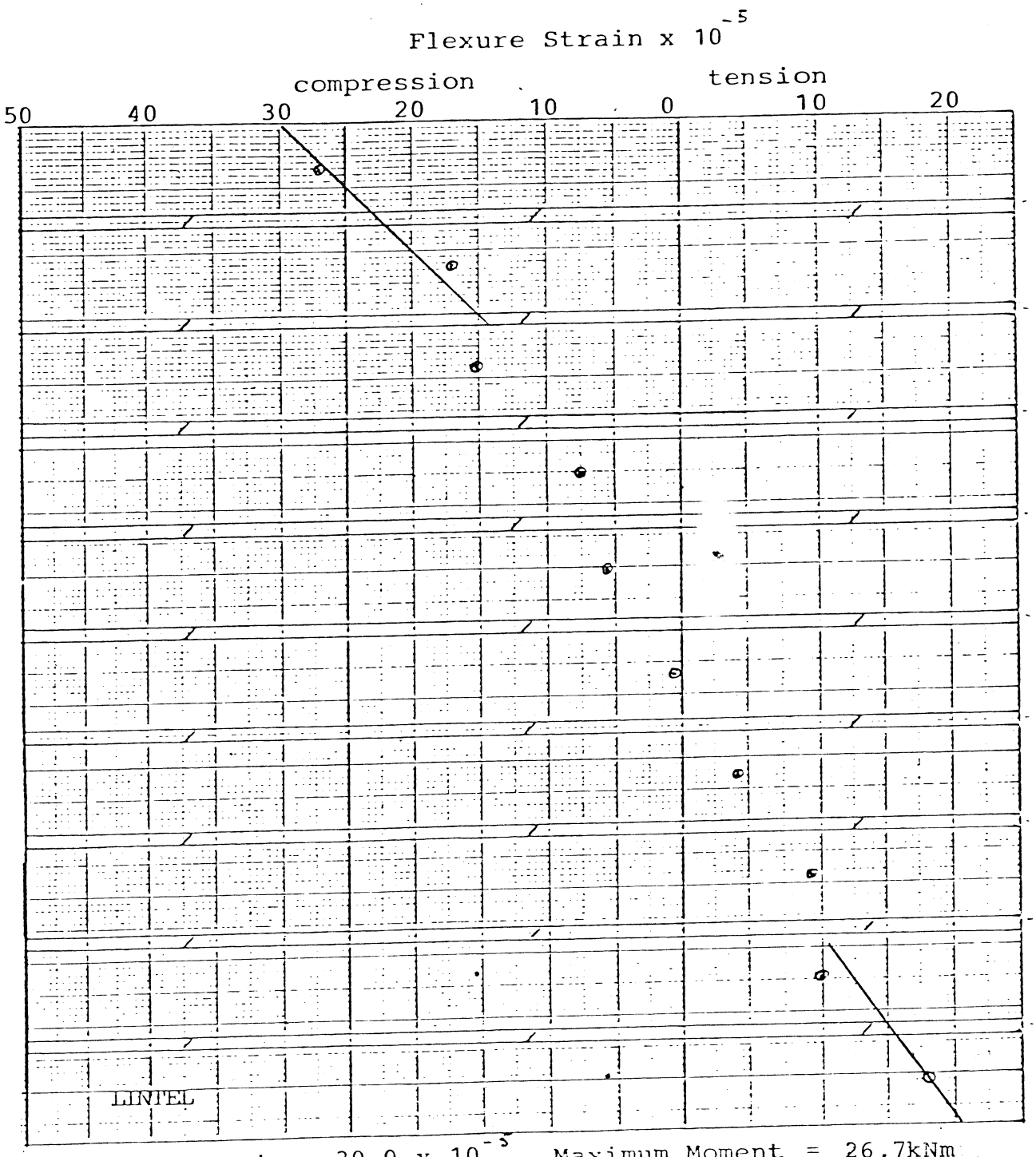


Figure B15

The measured top and bottom maximum edge flexure strains were determined by plotting to scale, the strains measured at the centre of each brick course and centre of lintel against wall height. The values being taken at the maximum moment recorded. For wall 3 this was determined as below.



Top Edge Strain = 30,0 x 10^{-5} Maximum Moment = 26,7kNm

Bottom Edge Strain = 20,5 x 10^{-5}

Figure B.16

WALL 3 - 2m x 9 Brick course

Comments were given on the following test results:

1. The load test values.
2. The calculated and measured stresses and strains in the wall.
3. The central wall deflection.
4. The failure crack pattern.
5. Further comments on the wall resistance to loading during the test procedure.

The ultimate resistance of the wall produced a value of 27,5kNm, being 1,6 times the SHOFCO value of 17kNm. The ultimate shear resistance of the wall produced a value of 55kN, being 4,78 times the SHOFCO value of 11,5kN

The maximum load test tensile flexure stress in the lintel of 9,12MPa was 34 per cent above the calculated result of 6,78MPa. The maximum load test compressive flexure stress in the brickwork of 2,55MPa was 40 per cent greater than the calculated result of 1,82MPa. The graph of the flexure strains (a) versus moment showed a uniform increase except for the two final applied moments producing increased strain values. The strains along the diagonals 12 and 18 produced small tensile values of $3,0x10^{-5}$ and $1,0x10^{-5}$ respectively, whereas strains at 13 and 19 in the same line of action increased to maximum tensile values of $55x10^{-5}$ and $43x10^{-5}$ respectively, showing a great difference between them and showing the big variation of strain and stress at various positions in the wall especially when crossing the diagonals connecting the load support points.

The strain along the diagonals 14 and 15 increased to maximum compressive values of $16,5x10^{-5}$ and $26x10^{-5}$

respectively. On the opposite side of the wall the diagonal strains 20 and 21 increased to maximum compressive values of 24×10^{-5} and 38×10^{-5} respectively. The slip strains at 16 and 22 at the outer ends of the wall increased to maximum tensile values of 41×10^{-5} and 31×10^{-5} respectively. In this wall and in the following walls tested, because of the increase in size of the walls, two demec gauge lengths were fitted into each diagonal on each side of the wall. The measured central wall deflection at an end section of 35,6kN, when the central deflection gauge was removed in case of wall failure gave a value of 0,28mm, being twice the calculated value of 0,14mm. The test deflection values maintained a straight line and tended to come even closer to the calculated values at the final readings taken.

As can be seen from the photographic reproductions of the failure crack pattern, in this test both sides of the wall were reproduced, the final position of the wall remained much the same as in the unloaded case. The crack pattern in the right hand side of the wall carried on from the brickwork through into the lintel at a section adjoining the right hand support, showing the high vertical shearing forces at this section.

The very high shears and moments sustained by this wall having the smallest span and largest number of brick courses clearly illustrates the arching action of the wall. After the wall failure the lintel retained its initial straight length along the span with no final buckling or curvature deformation, which was noted in all the other walls tested. The low deflection values in the lintel pointed to

to the fact that the lintel carried very little weight over the centre portion of the span.

To obtain a true arch, the end supports for the brickwork required a horizontal restraint. The only horizontal restraint in this wall was the horizontal shear between the lintel, mortar and brickwork, there being no reinforcement.

The vertical strain 11 running up the centre line of the wall connecting the lintel to the brickwork remained at zero showing there was no separation between the lintel and brickwork at this point.

The slip strains in conjunction with the tensile strains produced the final wall failure.

The deep wall such as the 2m x 9 brickcourse wall can be regarded as a frame ABCD with AB as a horizontal tension member, DC a horizontal compression member and AD and BC as sloping compression members, as shown in the diagram below.

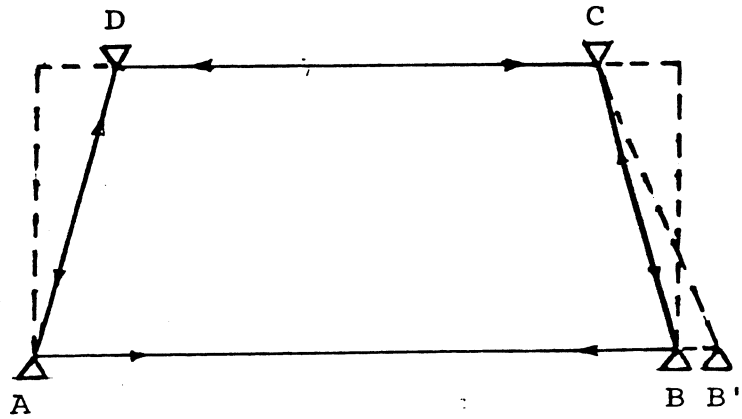


Figure B.17

When a slip failure occurs in the brickwork or between lintel and brickwork causing B to move to B' it is equivalent to stretching or cutting the tensile member AB causing failure of the framework. Further notes on arching action are made in the conclusions at the end of the report.

WALL 4 - 4m x 5 brick courses

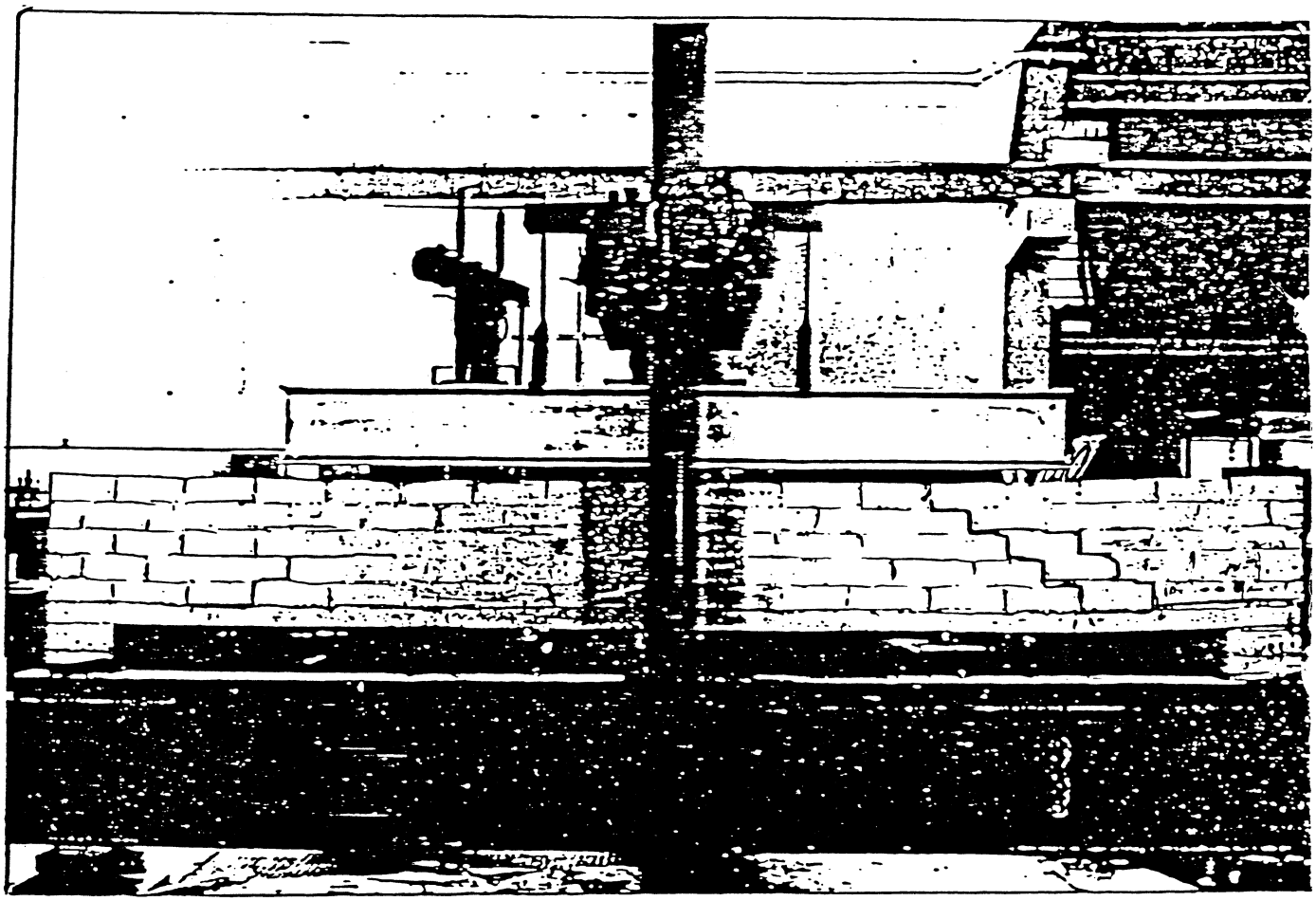
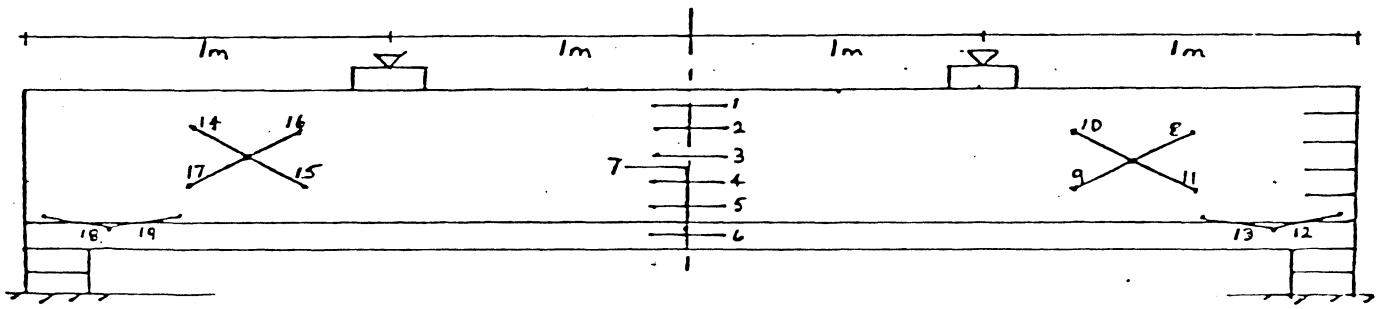


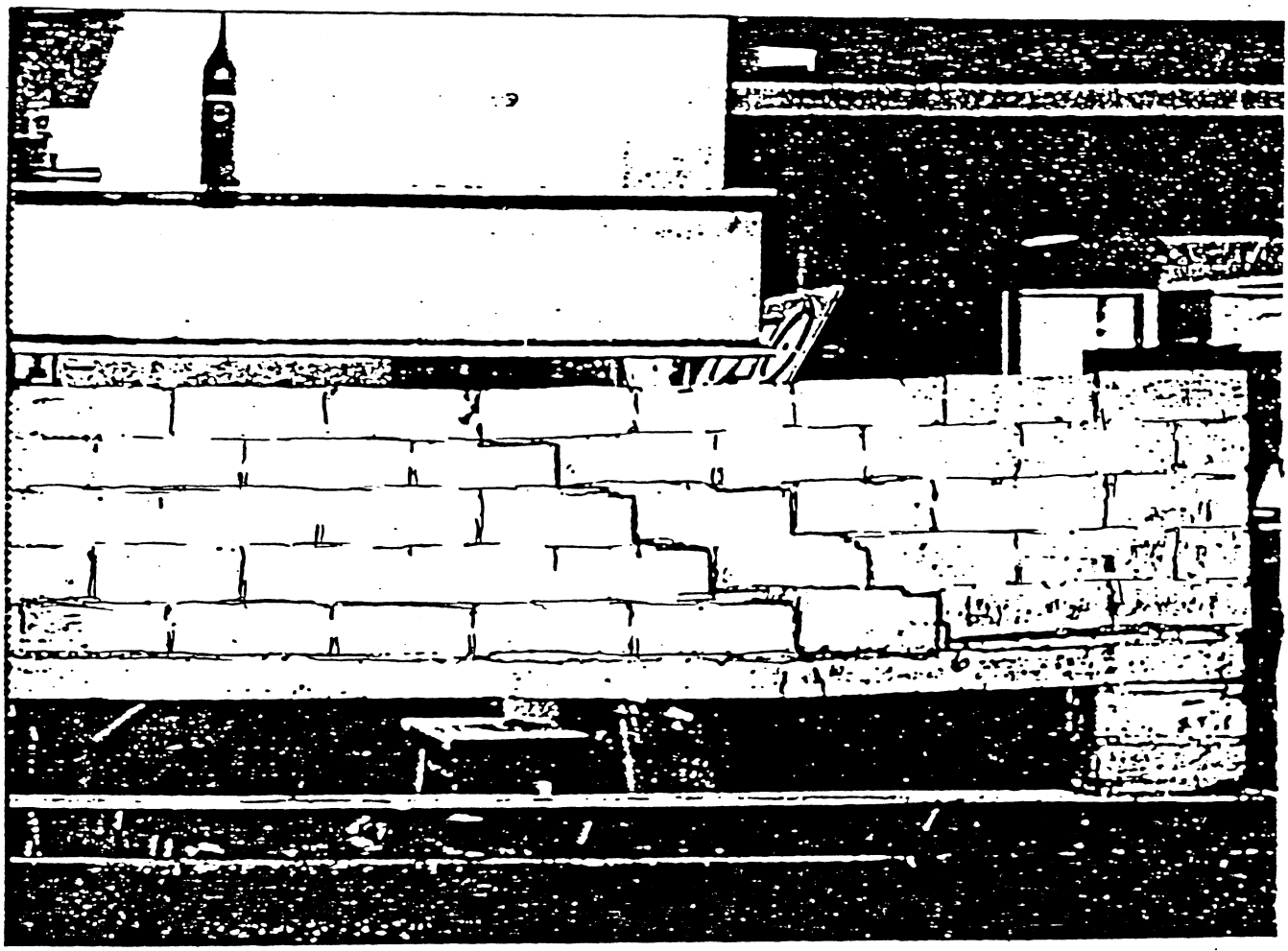
Figure B17



Position of strain gauges

Figure B18

WALL 4



Failure crack pattern

Figure B19

WALL NO 4 - 4m x 5brickcourse

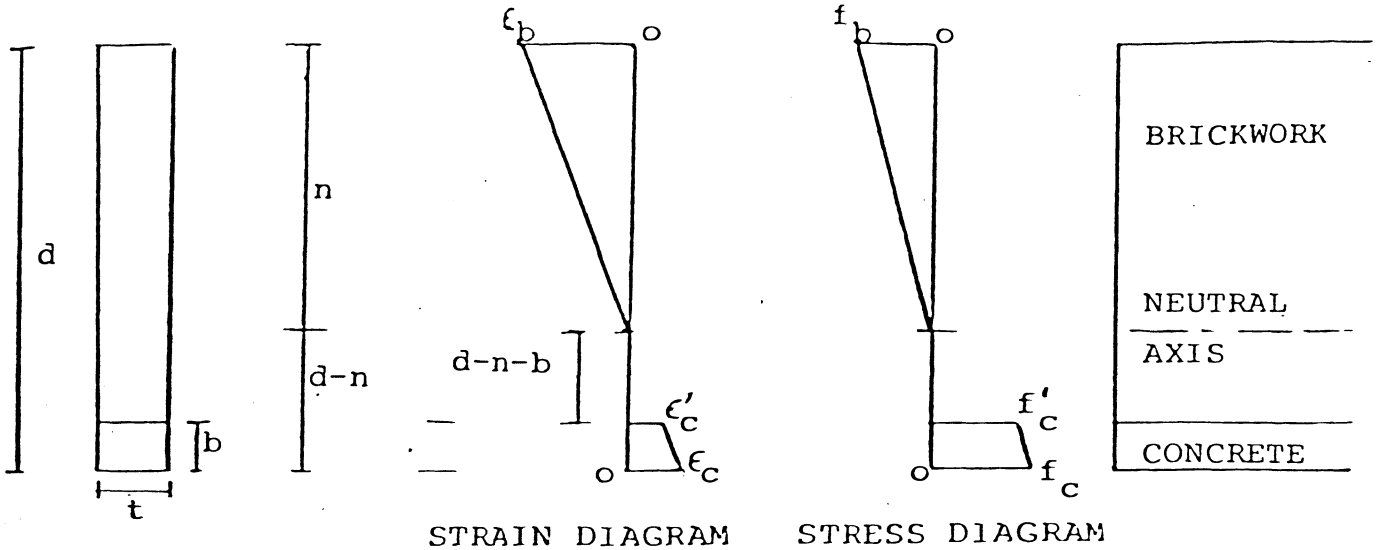


Figure B.20

E_b = 7,0GPa E_c = 44,5GPa b = 70mm t = 105mm d = 470mm

m = modular ratio = E_c/E_b = 44,5/7,0 = 6,36

$$n = \frac{-2mb \pm \sqrt{(2mb)^2 - 4mb(b-2d)}}{2} = 320mm$$

$$f_b = \frac{E_b nM}{E_b \frac{n.t}{3} + E_c \frac{bt}{2}.2(d-n) + 2b(n-d+\frac{b}{3})} = \underline{2,29MPa \text{ (calculated)}}$$

$f_b = E_b \epsilon_b = 7,0x10^3 x 44,0x10^{-5} = \underline{3,08MPa \text{ (measured)}}$

$$f_c = \frac{E_c(d-n)M}{E_b \frac{n.t}{3} + E_c \frac{bt}{2} 2(d-n) + 2b(n-d+\frac{b}{3})} = \underline{6,84MPa \text{ (calculated)}}$$

$f_c = E_c \epsilon_c = 44,5x10^3 x 22,5x10^{-5} = \underline{10,0MPa \text{ (measured)}}$

Comparison of Load Test Results and Analytical Results

Table B.9

	Load Test Results	Analytical Results
Maximum stress in brickwork	3,08MPa	2,29MPa
Maximum stress in concrete	10,0MPa	6,84MPa

Table B10 - Wall No.4 4m x 5 brickcourse

End reaction kN	Shear in shear span kN	Moment in flexure span kNm	Flexure strains x 10^{-5} at positions numbered on walls								
			1	2	3	4	5	6	7	8	9
0	0	0	0	0	0	0	0	0			
2,23	2,23	2,23	-8,0	-6,5	-3	-2,0	+0,5	+3,0			
4,45	4,45	4,45	-15,5	-12,5	-5	-2,0	+1,0	+5,0			
6,67	6,67	6,67	-19,5	-16,0	-7,5	-3,0	+1,5	+7,5			
8,9	8,9	8,9	-26,0	-20,5	-12,5	-6,5	+1,5	+11,5			
11,13	11,13	11,13	-31,5	-23,0	-20,0	-8,0	+3,5	+13,5			
13,35	13,35	13,35	-37,0	-33,5	-23,5	-9,0	+4,0	+16 5			
13,6	13,6	13,6									

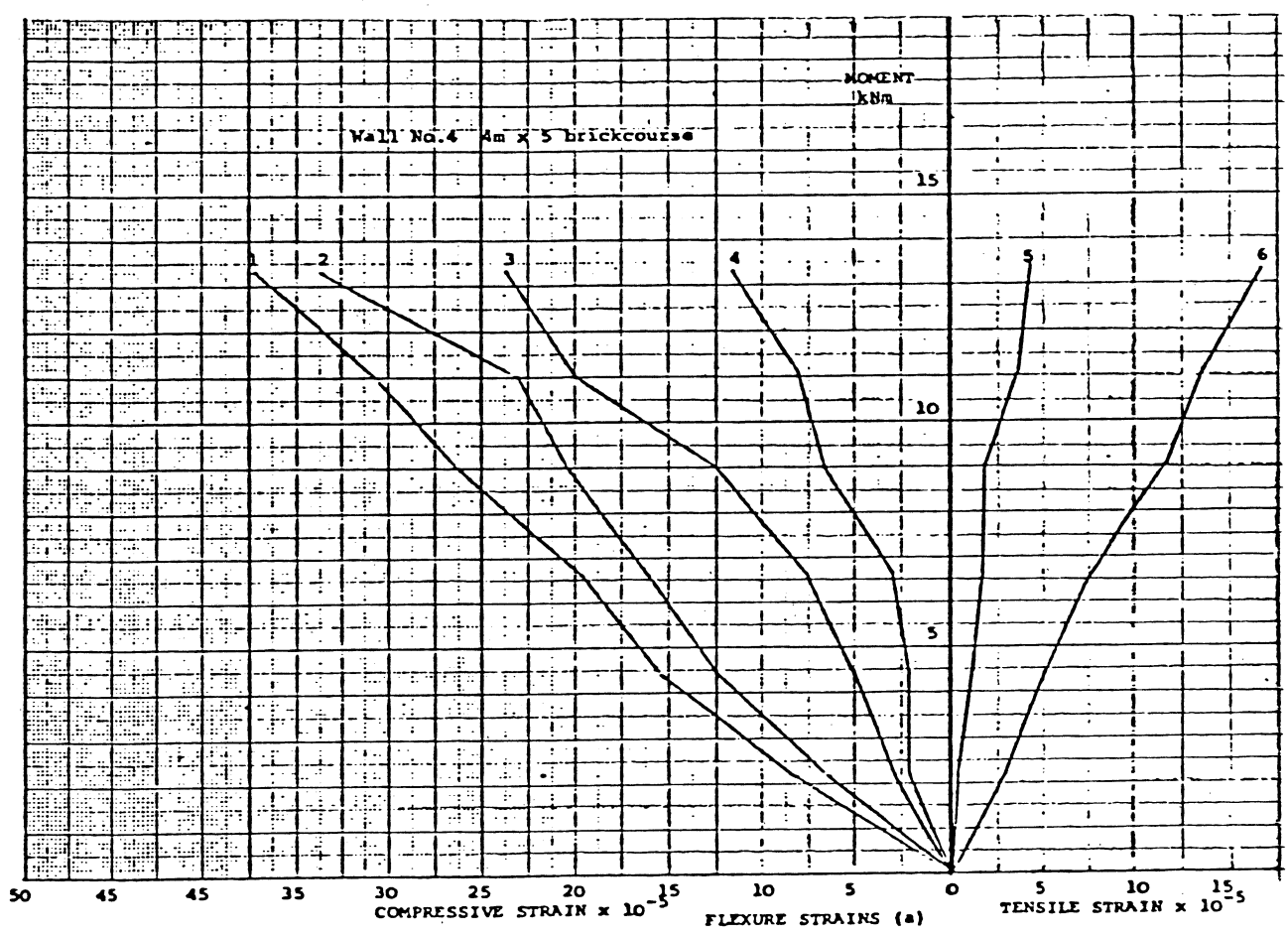


Figure B21

Table B11-Wall No.4 4m x 5 brickcourse

End reaction kN	Shear in shear span kN	Moment in flexure span kNm	Diagonal strains x 10^{-5} at positions numbered on wall								
			8	9	10	11	14	15	16	17	
0	0	0	0	0	0	0	0	0	0	0	0
2,23	2,23	2,23	-0,5	0	-2,5	-5,5	0	1,0	-4	-1.0	
4,45	4,45	4,45	-0,5	1,5	-4,0	-5,5	-1,0	2,0	-5	-1,5	
6,67	6,67	6,67	-0,5	1,5	-7,0	-6,0	-1,0	3,0	-6,5	-2	
8,9	8,9	8,9	-0,5	3,0	-9,0	-6,0	-1,5	3,5	-8,5	-2,5	
11,13	11,13	11,13	-0,5	5,0	-10,5	-6,5	-1,0	4,0	-10,5	-2,5	
13,35	13,35	13,35	-2,0	5,0	-14,5	-7,0	-0,5	4,0	-18	-8,0	
13,6	13,6	13,6		F	A	I	L	U	R	E	

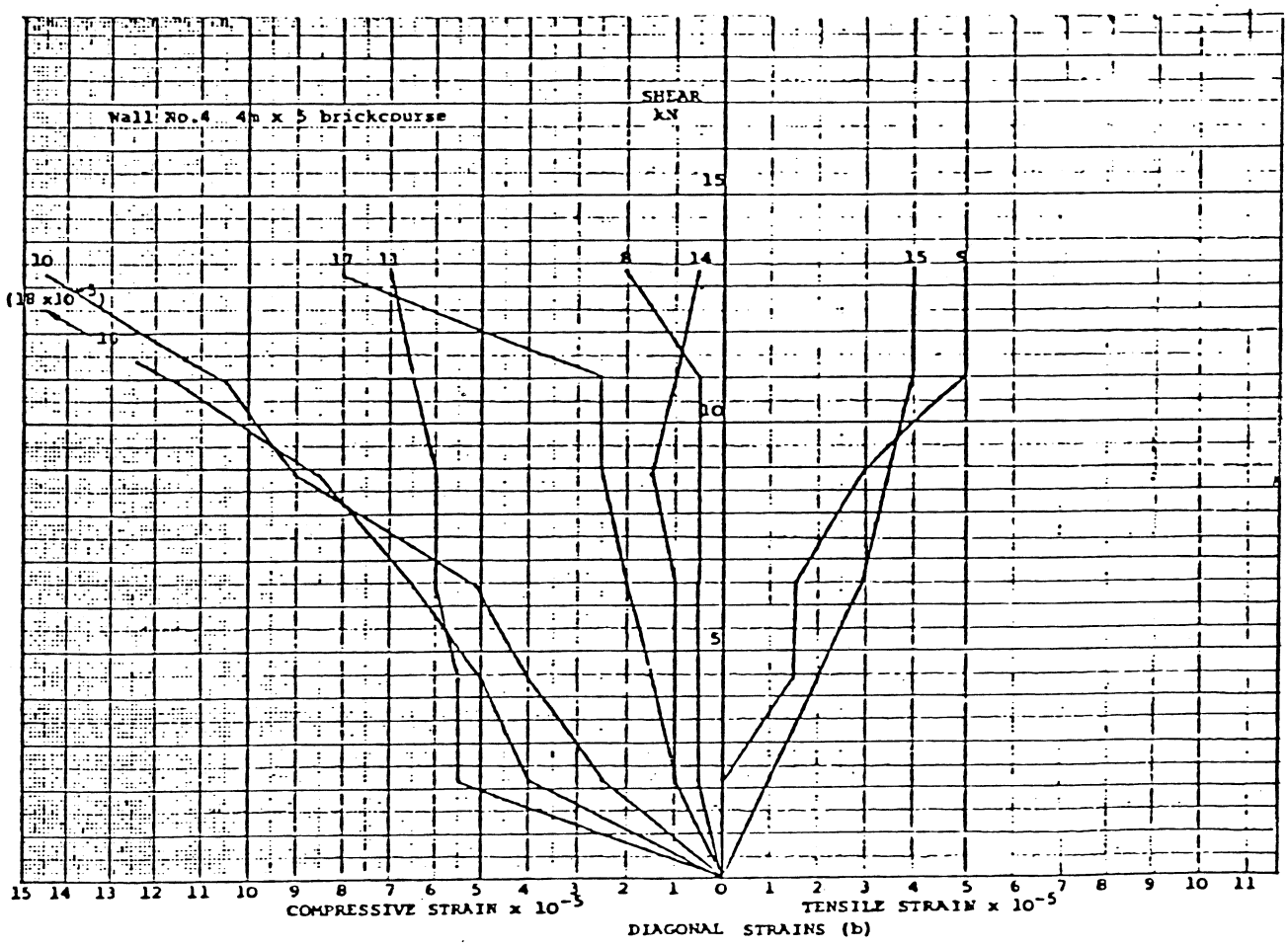


Figure B22

Table B12 - Wall No.4 4m x 5 brickcourse

End reaction kN	Shear in shear span kN	Moment in flexure span kNm	Slip strains x 10^{-5} between brickwork and lintel at positions numbered on wall 12	13	18	19	7			Central wall deflection mm
0	0	0	0	0	0	0	0	0	0	0
2,23	2,23	2,23	0	0	1	0	1,0			0,36
4,45	4,45	4,45	0	0	1,5	0	1,5			0,75
6,67	6,67	6,67	1,0	0	2,0	0	2,0			1,38
8,9	8,9	8,9	2,0	1,0	3,0	1,5	12,5			1,83
11,13	11,13	11,13	3,5	2,5	3,0	2,0	14,0			
13,35	13,35	13,35	4,0	6,0	18,5	16,0	17,0			
13,6	13,6	13,6	F	A	I	L	U	R	E	

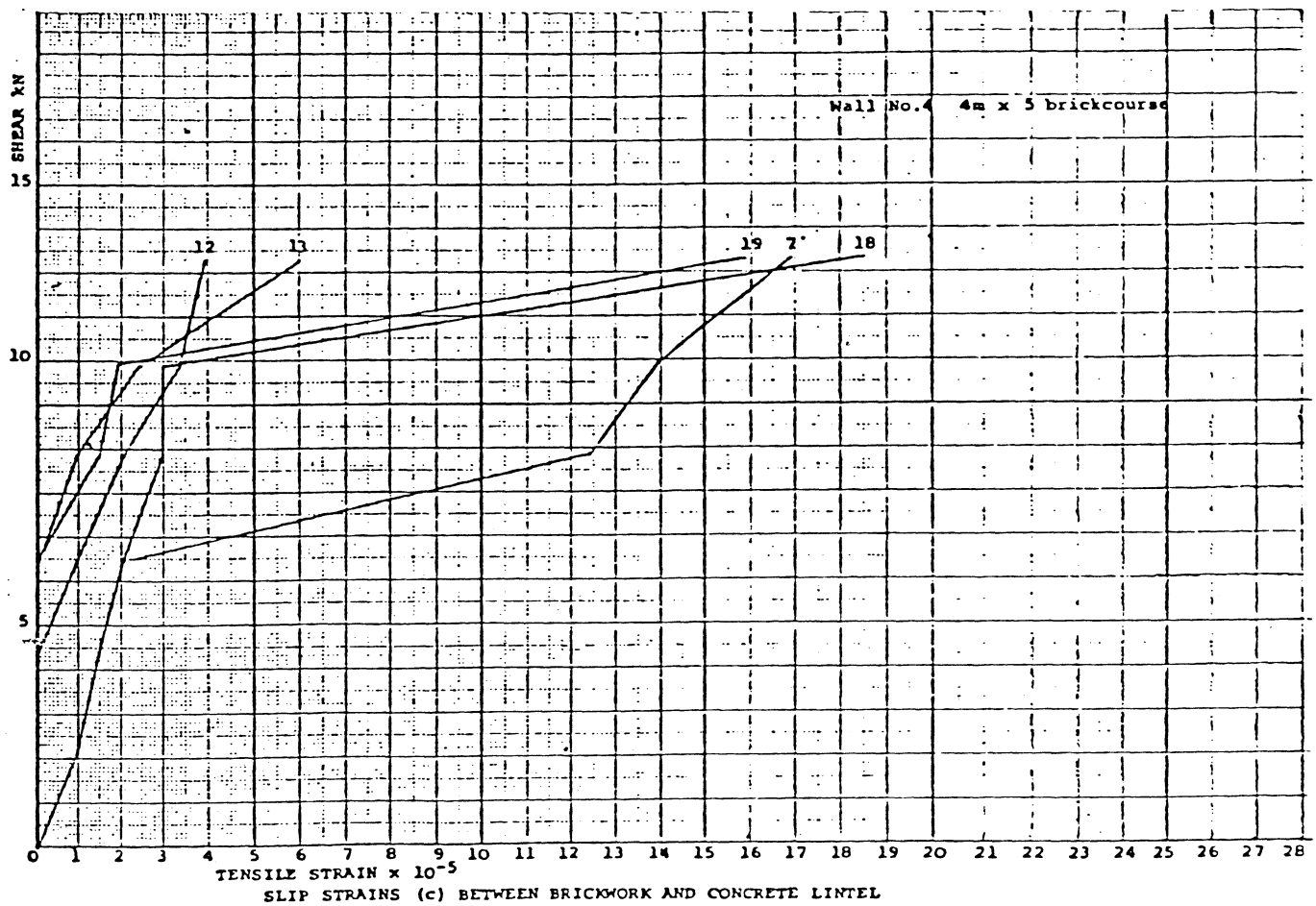
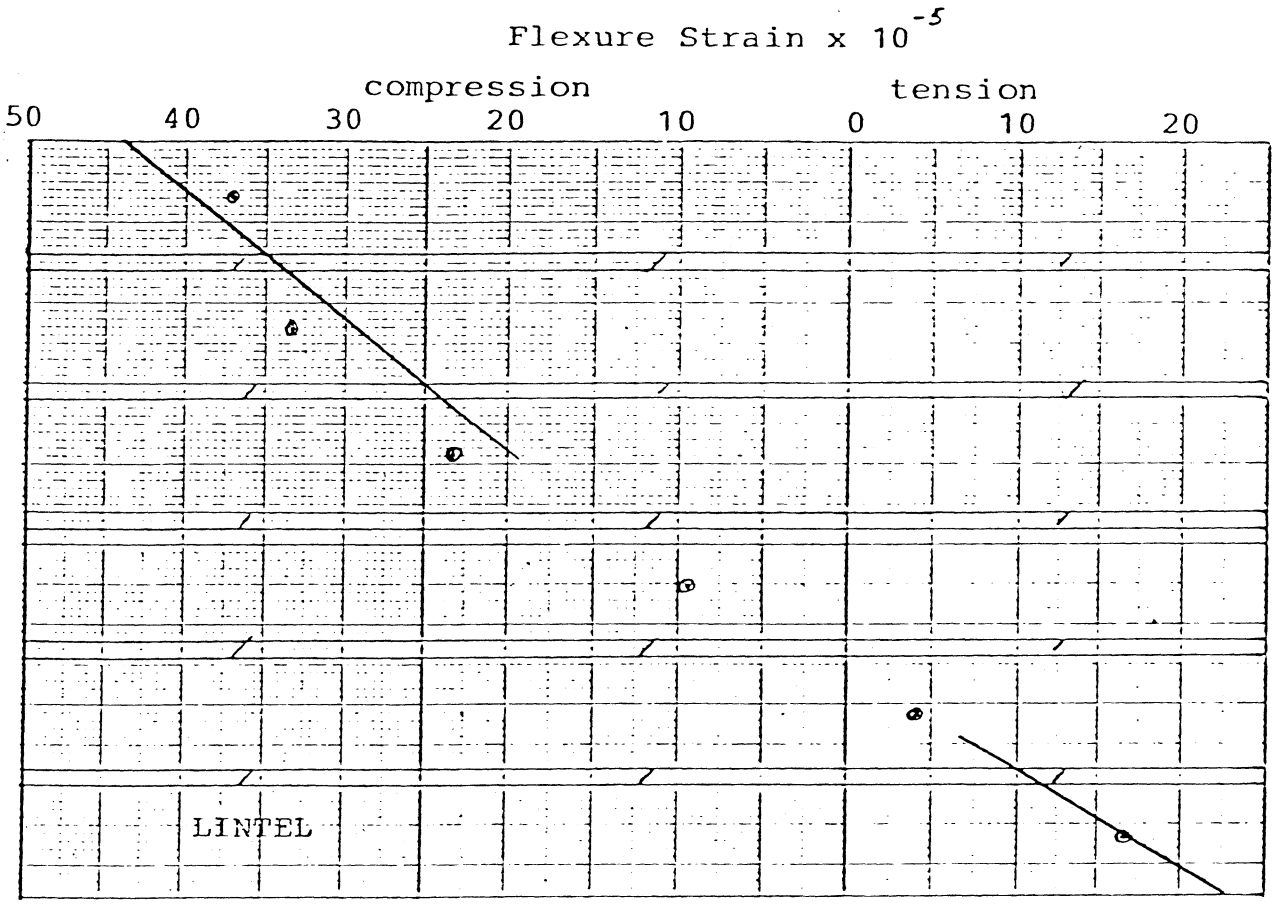


Figure B23

The measured top and bottom maximum edge flexure strains were determined by plotting to scale, the strains measured at the centre of each brick course and centre of lintel against wall height. The values being taken at the maximum moment recorded. For wall 4 this was determined as below.



Top Edge Strain = 44,0 x 10^{-5} Maximum Moment = 13,35kNm

Bottom Edge Strain = 22,5 x 10^{-5}

Figure B.24

WALL 4 - 4m x 5 Brick course

Comments were given on the following test results

1. The load test values.
2. The calculated and measured stresses and strains in the wall.
3. The central wall deflection.
4. The failure crack pattern.
5. Further comments on the wall resistance to the loading during the test procedure.

The ultimate resistance of the wall produced a final value of 16,6kNm, being 2,2 times the SHOFCO value of 6,3kNm. The ultimate shear resistance of the wall produced a value of 13,6kN, being 2,5 times the SHOFCO value of 5,5kN.

The maximum load test tensile flexure stress in the lintel of 10,0MPa was 46 per cent above the calculated result of 6,84MPa. The maximum load test compressive stress in the brickwork of 3,08MPa was 34 per cent above the calculated result of 2,29MPa.

The graph of flexure strains (a) versus moment produced consistent uniform increases up to the maximum value. The strains measured along the tensile and compressive diagonals did not give uniform results, but varied considerably. Strains 9, 11 and 15 remained constant over a moment increase. The vertical strain measurement running up the centre line of the wall at strain 7 showed a sudden increase at approximately half the applied maximum load to increase to a maximum strain of 17×10^{-5}. This showed a parting between the lintel and brickwork or in the brickwork at this point and may have caused the variance in the diagonal strains. Faint hair

cracks in this wall first occurred in the right hand half of the wall and then when the failure was expected to occur here a slip failure suddenly occurred in the left hand side of the wall in strains 18 and 19 producing final measured strains of 18,5, 10 and 16,0, 10 respectively.

The measured central wall deflection at an end reaction of 8,9kN, when the central deflection gauge was removed in case of wall failure gave a value of 1,83mm, being 1,35 times the calculated value of 1,35mm. There was a fairly good agreement between the test and calculated values.

As can be seen from the photographic reproduction, slip and diagonal failures were produced on both sides of the wall, the major slip failure occurring on the left hand side. However cracks first appeared on the right hand side of the wall when there were no cracks noticeable on the left hand side and then suddenly the wall failed at the left hand support with a slip failure. The test to failure showed strain energy being dissipated in the right hand half of the wall as it dispersed the energy through its length, while the left hand half of the wall stored its energy until it produced the sudden wall failure. When the ultimate load was reached the slip failure between the lintel and the brickwork spread across the whole length of the wall.

The brickwork as a solid whole, outside the failure diagonals running between support and load point and above the lintel was pushed outwards on both sides of the wall approximately 1cm.

Wall No.5 - 4m x 7 brickcourses

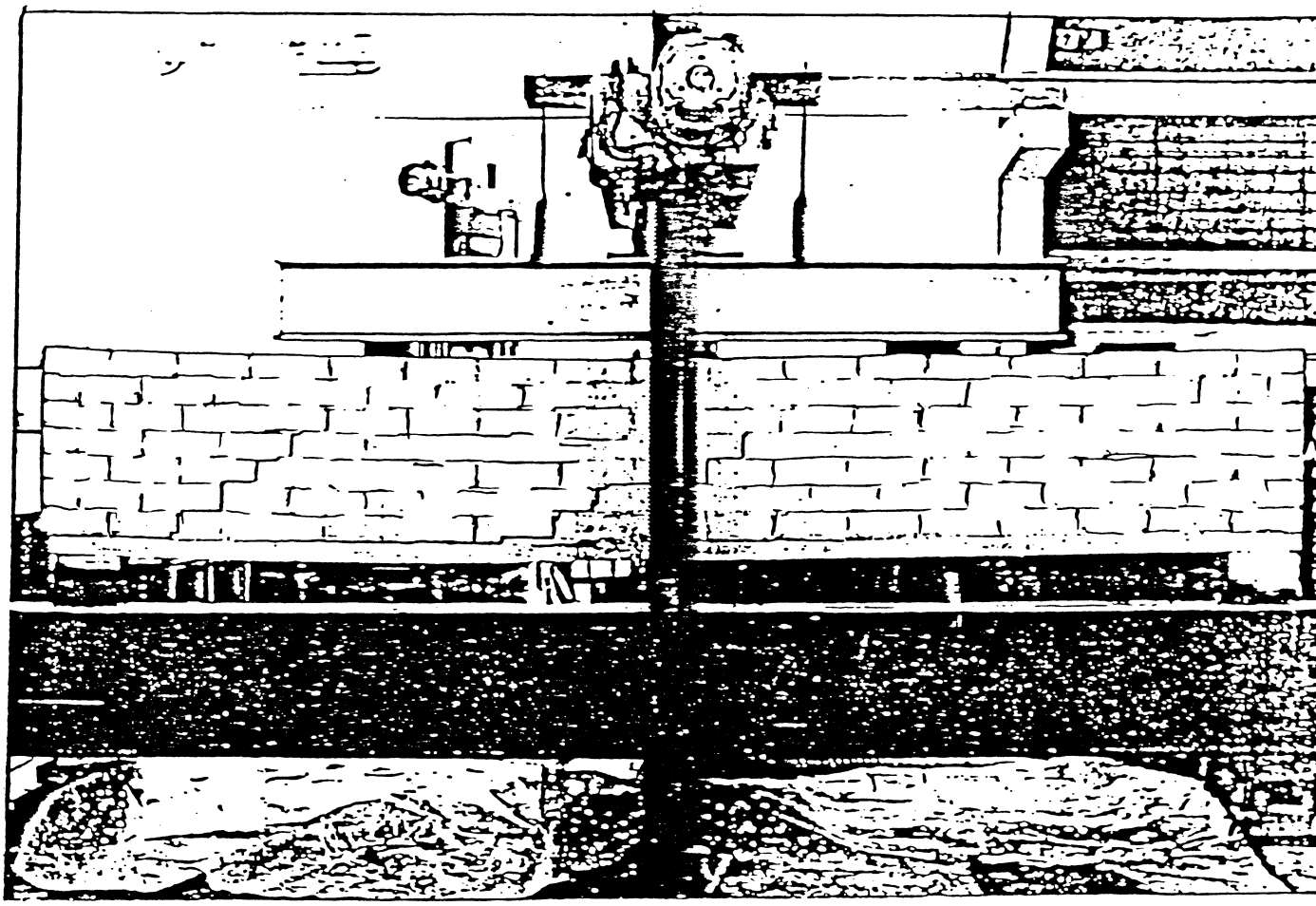
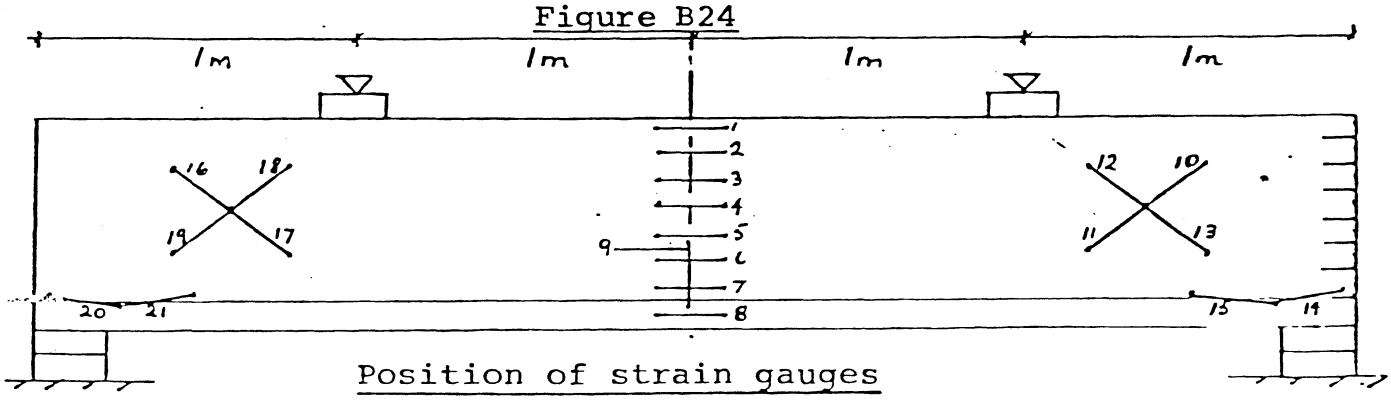


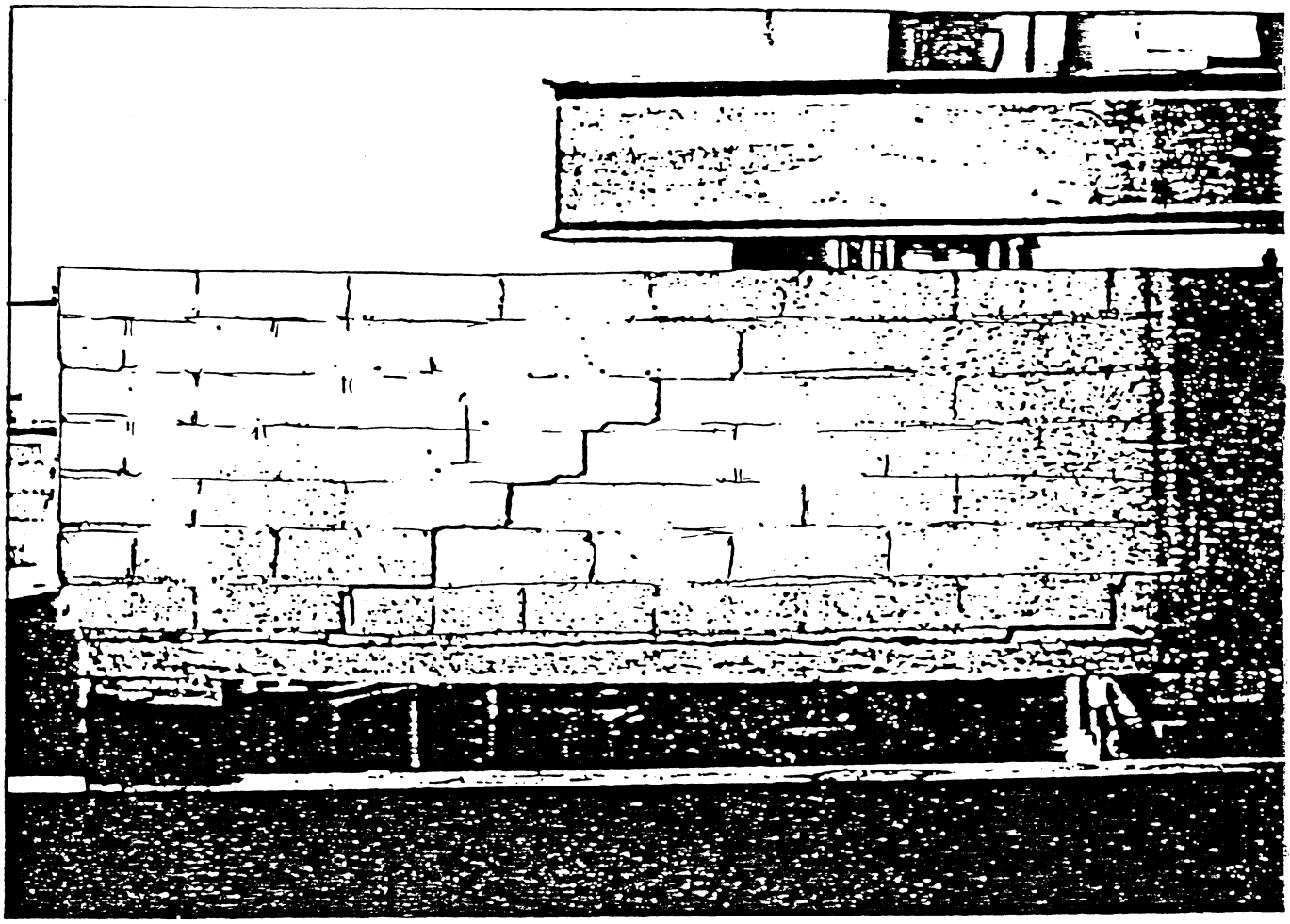
Figure B24



Position of strain gauges

Figure B25

Wall No.5



Failure crack pattern

Figure B26

WALL NO 5 - 4m x 7brickcourse

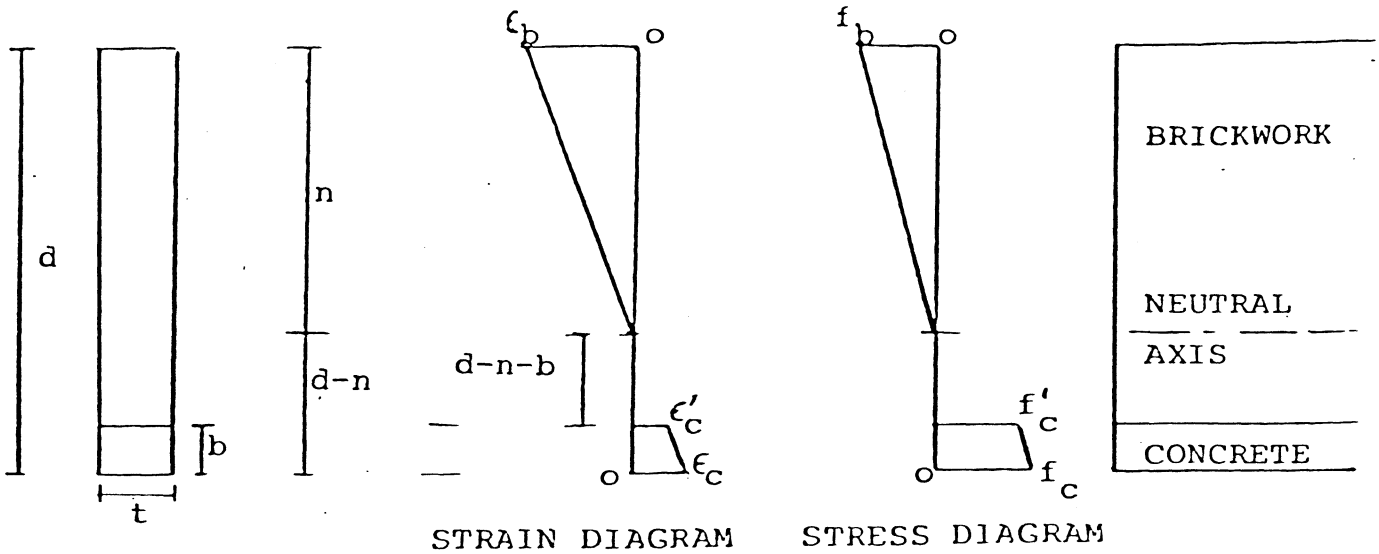


Figure B.27

E_b = 8,8GPa E_c = 44,5GPa b = 70mm t = 105mm d = 630mm

m = modular ratio = E_c/E_b = 44,5/8,8 = 5,05

$$n = \frac{-2mb \pm \sqrt{(2mb)^2 - 4mb(b-2d)}}{2} = 385,15$$

$$f_b = \frac{E_b n M}{E_b \frac{n}{3} t + E_c \frac{bt}{2} 2(d-n) + 2b(n-d+\frac{b}{3})} = \underline{1,44MPa \text{ (calculated)}}$$

$f_b = E_b \epsilon_b = 8,8x10^3 x 26,5x10^{-5} = \underline{2,33MPa \text{ (measured)}}$

$$f_c = \frac{E_c (d-n) M}{E_b \frac{n}{3} t + E_c \frac{bt}{2} 2(d-n) + 2b(n-d+\frac{b}{3})} = \underline{4,6MPa \text{ (calculated)}}$$

$f_c = E_c \epsilon_c = 4,5x10^3 x 18,0x10^{-5} = \underline{8,01MPa \text{ (measured)}}$

Comparison of Load Test Results and Analytical Results

Table B.13

	Load Test Results	Analytical Results
Maximum stress in brickwork	2,33MPa	1,44MPa
Maximum stress in concrete	8,01MPa	4,6MPa

Table B14 - Wall No.5 4m x 7 brickcourse

End reaction kN	Shear in shear span kN	Moment in flexure span kNm	Flexure strains x 10^{-5} at positions numbered on walls								
			1	2	3	4	5	6	7	8	9
0	0	0	0	0	0	0	0	0	0	0	
2,23	2,23	2,23	3,0	2,5	2,0	2,0	1,0	+0,5	+2,0	+4,0	
4,45	4,45	4,45	-5,5	-4,5	-2,5	-2,5	-1,0	+1,0	+4,5	+5,5	
6,67	6,67	6,67	-7,5	-6,0	-3,5	-3,0	-1,0	+1,0	+5,5	+7,0	
8,9	8,9	8,9	-9,0	-7,5	-5,5	-4,5	-1,0	+1,5	+7,5	+9,5	
11,13	11,13	11,13	-13,5	-10,0	-7,5	-6,5	-1,5	+2,0	+8,5	+10,5	
13,35	13,35	13,35	-18,0	-12,5	-10,0	-9,0	-2,5	+2,0	+10,0	+12,0	
15,58	15,58	15,58	-22,0	-16,5	-13,0	-11,5	-3,5	+2,5	+11,0	+13,5	
17,8	17,8	17,8	-25,0	-18,5	-16,5	-14,5	-5,0	+3,0	+12,5	+14,5	
18,1	18,1	18,1	F	A	I	L	U	R	E		

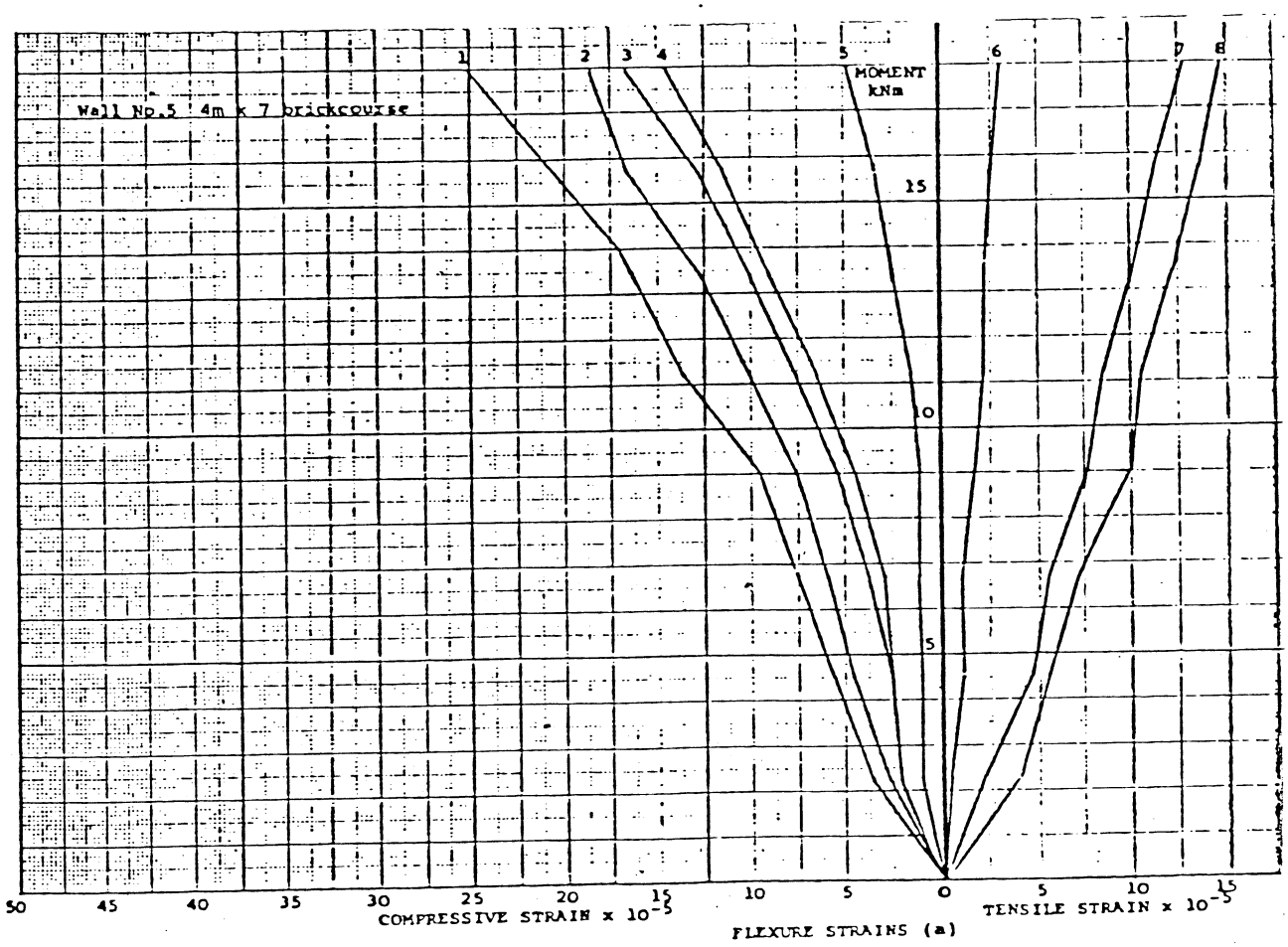


Figure B28

Table B15 - Wall No.5 4m x 7 brickcourse

End reaction kN	Shear in shear span kN	Moment in flexure span kNm	Diagonal strains x 10^{-5} at positions numbered on wall								
			10	11	12	13	16	17	18	19	
0	0	0	0	0	0	0	0	0	0	0	0
2,23	2,23	2,23	-0,5	0,5	-0,5	-1,0	0	0	-0,5	0	
4,45	4,45	4,45	-0,5	0,5	-1,0	-1,0	0	1,0	-1,5	-2,0	
6,67	6,67	6,67	-1	1	-2,0	-2,0	0	1,5	-2,5	-3,0	
8,9	8,9	8,9	-1,5	1	-3,5	-2,0	-1,0	2,0	-4,0	-3,0	
11,13	11,13	11,13	-1,5	1,5	-5,0	-2,5	-1,0	2,0	-5,5	-4,5	
13,35	13,35	13,35	-2	1,5	-7,0	-3,0	-1,5	3,0	-7,0	-6,5	
15,58	15,58	15,58	-2	2	-9,5	-5,0	-1,5	3,5	-9,0	-7,0	
17,8	17,8	17,8	-2	2,5	-11,0	-6,0	-2	4,5	-10,5	-8,0	
18,1	18,1	18,1	F A I L U R E								

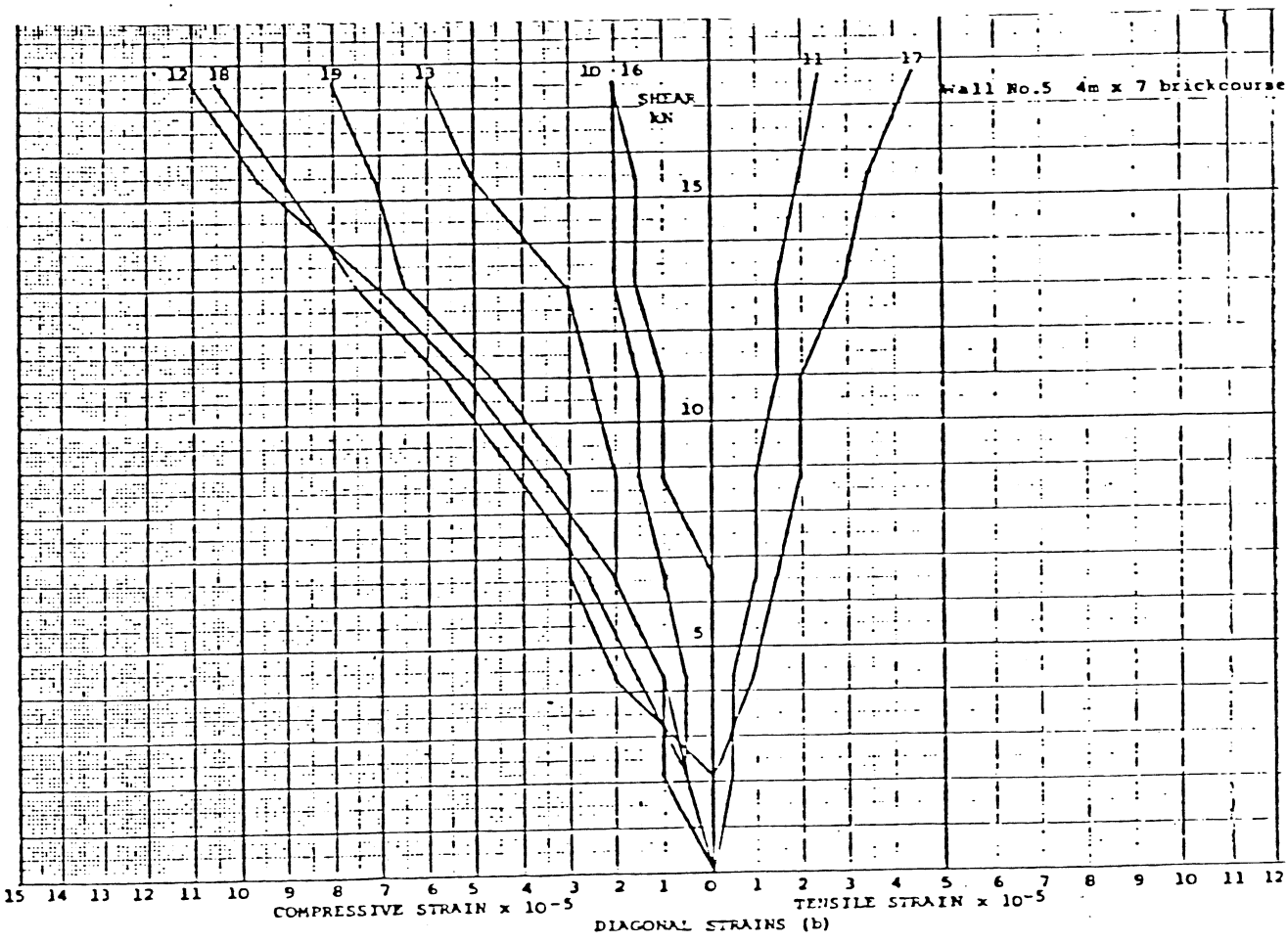


Figure B29

Table B16 - Wall No.5 4m x 7 brickcourse

End reaction kN	Shear in shear span kN	Moment in flexure span kNm	Slip strains x 10^{-5} between brickwork and lintel at positions numbered on wall							Central wall deflection mm
			14	15	20	21	9			
0	0	0	0	0	0	0	0	0	0	0
2,23	2,23	2,23	0	0	0	0	0			0,24
4,45	4,45	4,45	0	0	0	0	0,5			0,40
6,67	6,67	6,67	0	0	0,5	0	1,0			0,75
8,9	8,9	8,9	0,5	0	0,5	0,5	1,0			1,22
11,13	11,13	11,13	0,5	0,5	1,0	1,0	1,5			
13,35	13,35	13,35	1,0	0,5	1,5	1,0	2,0			
15,58	15,58	15,58	2,0	1,0	3,0	2,0	2,0			
17,8	17,8	17,8	2,5	1,5	3,5	3,0	2,0			
18,1	18,1	18,1	F A I L U R E							

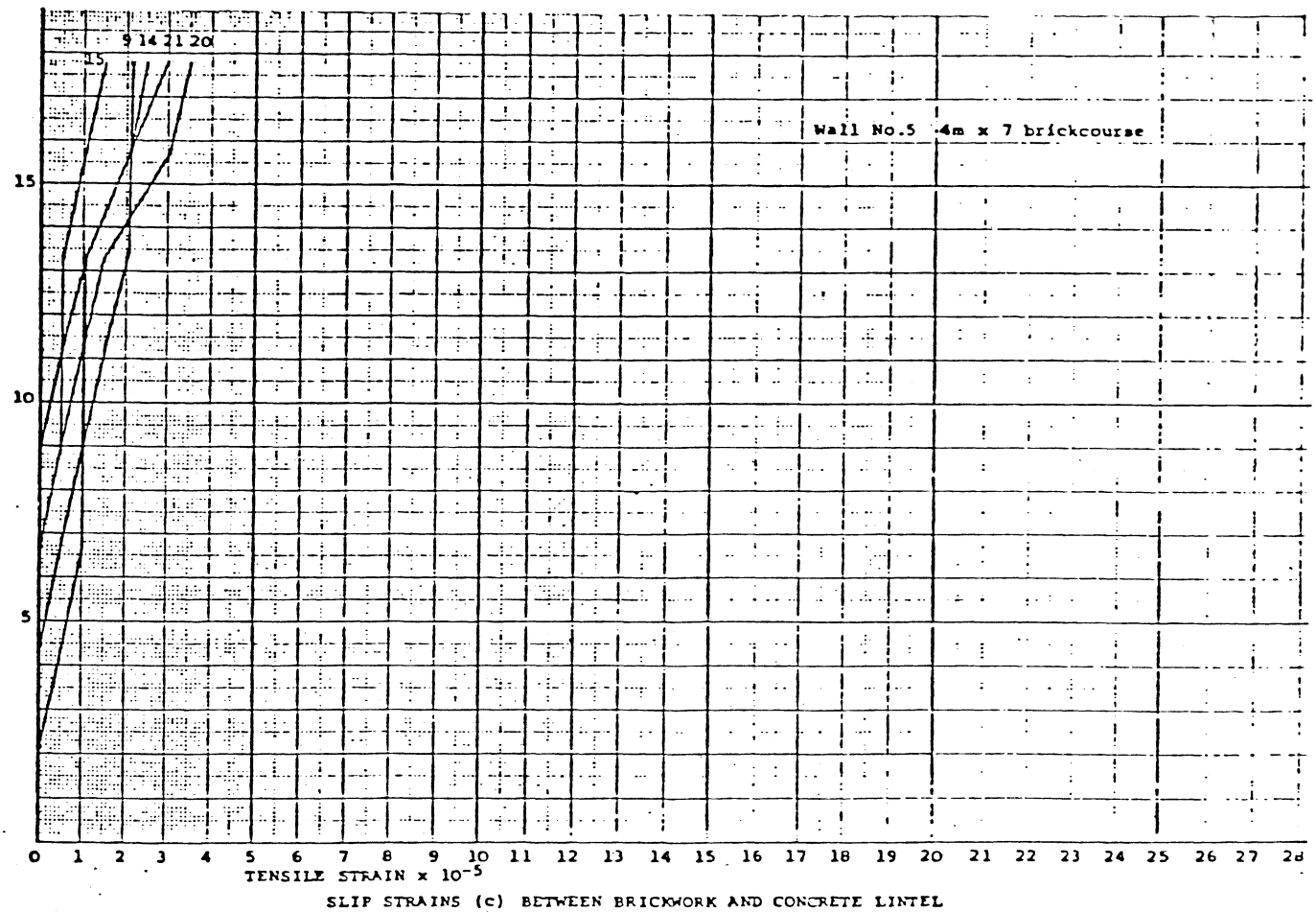
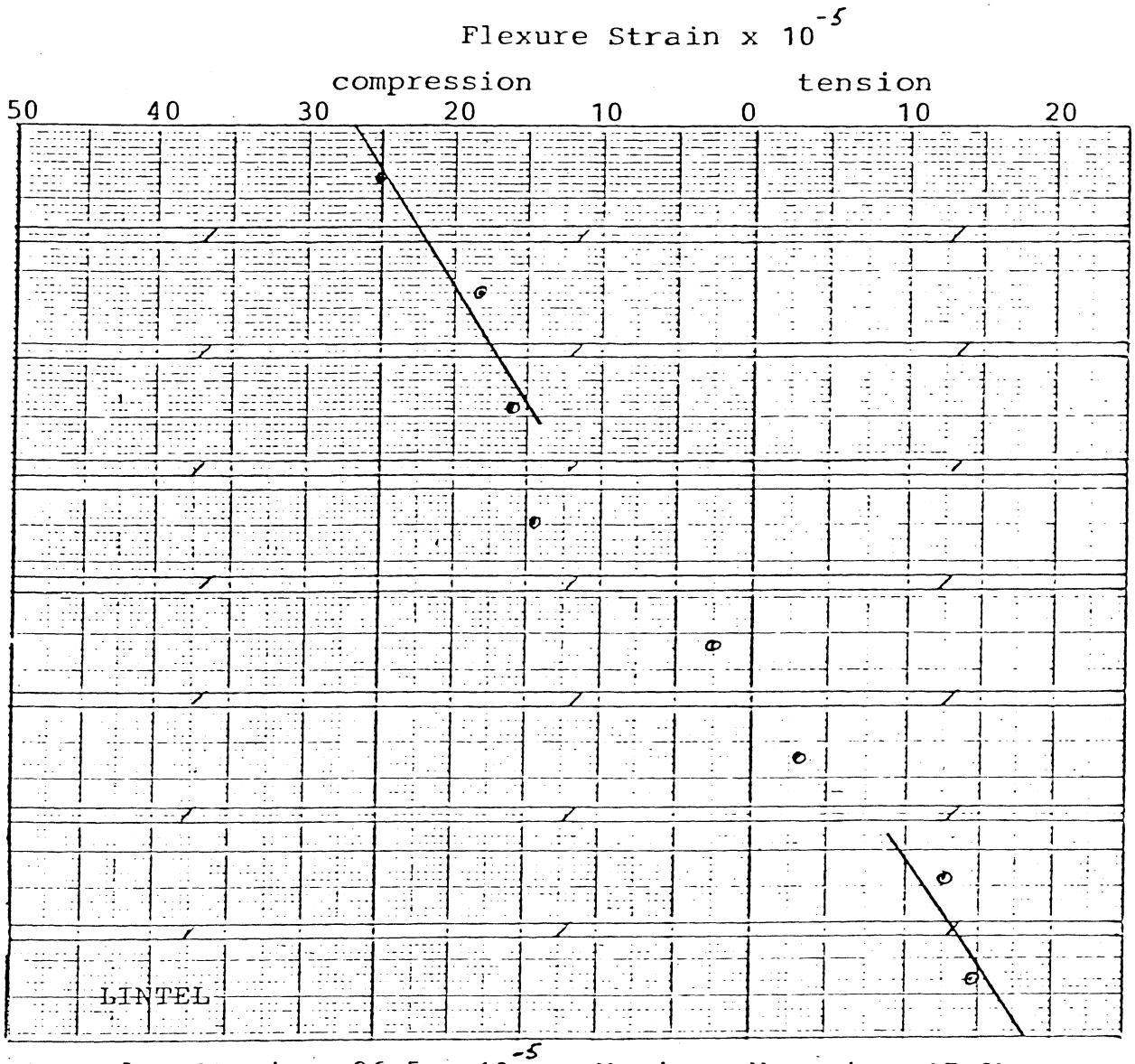


Figure B30

The measured top and bottom maximum edge flexure strains were determined by plotting to scale, the strains measured at the centre of each brick course and centre of lintel against wall height. The values being taken at the maximum moment recorded. For wall 5 this was determined as below.



Top Edge Strain = 26,5 x 10^{-5} Maximum Moment = 17,8kNm

Bottom Edge Strain = 18,0 x 10^{-5}

Figure B.31

WALL 5 - 4m x 7 Brick course

Comments were given on the following test results

1. The load test values.
2. The calculated and measured stresses and strains in the wall.
3. The central wall deflection.
4. The failure crack pattern.
5. Further comments on the wall resistance to the loading during the test procedure.

The ultimate resistance of the wall produced a value of 18,1kNm, being 1,6 times the SHOFCO value of 11,2kNm. The ultimate shear resistance of the wall produced a value of 18,1kN, being twice the SHOFCO value of 8,75kN.

The maximum load test tensile flexure stress in the lintel of 8,01MPa was 74 per cent above the calculated result of 4,6Mpa. The maximum load test compressive stress in the brickwork of 2,33MPa was 61 per cent above the calculated result of 1,44MPa.

The graph of flexure strains (a) versus moment showed uniform increases up to their maximum values.

The compressive and tensile diagonal strains on both the left and right hand halves of the wall produced uniform increasing values with increasing moment. The diagonal strains at 12 and 18 producing maximum values of $11,0 \times 10^{-5}$ and $10,5 \times 10^{-5}$ respectively. The slip strains up to the final moment measured also produced fairly uniform results.

The measured central wall deflection taken at an end wall reaction of 8,8kN when the central deflection gauge was removed in case of wall failure gave a value of 1,22mm,

being 2,7 times the calculated central deflection of 0,45mm

The measured deflections were not on a uniform curve and did not equate very well to the calculated deflections.

A sudden slip failure occurred between the lintel and the brickwork over the left hand support producing a diagonal crack between the left hand support and left hand load point at the ultimate resistance moment of 18,1kNm. A diagonal crack also occurred in the flexure span at failure. When the ultimate load was reached the slip failure between the lintel and brickwork spread across the whole length of the wall.

Wall No.6 - 4m x 9 brickcourses

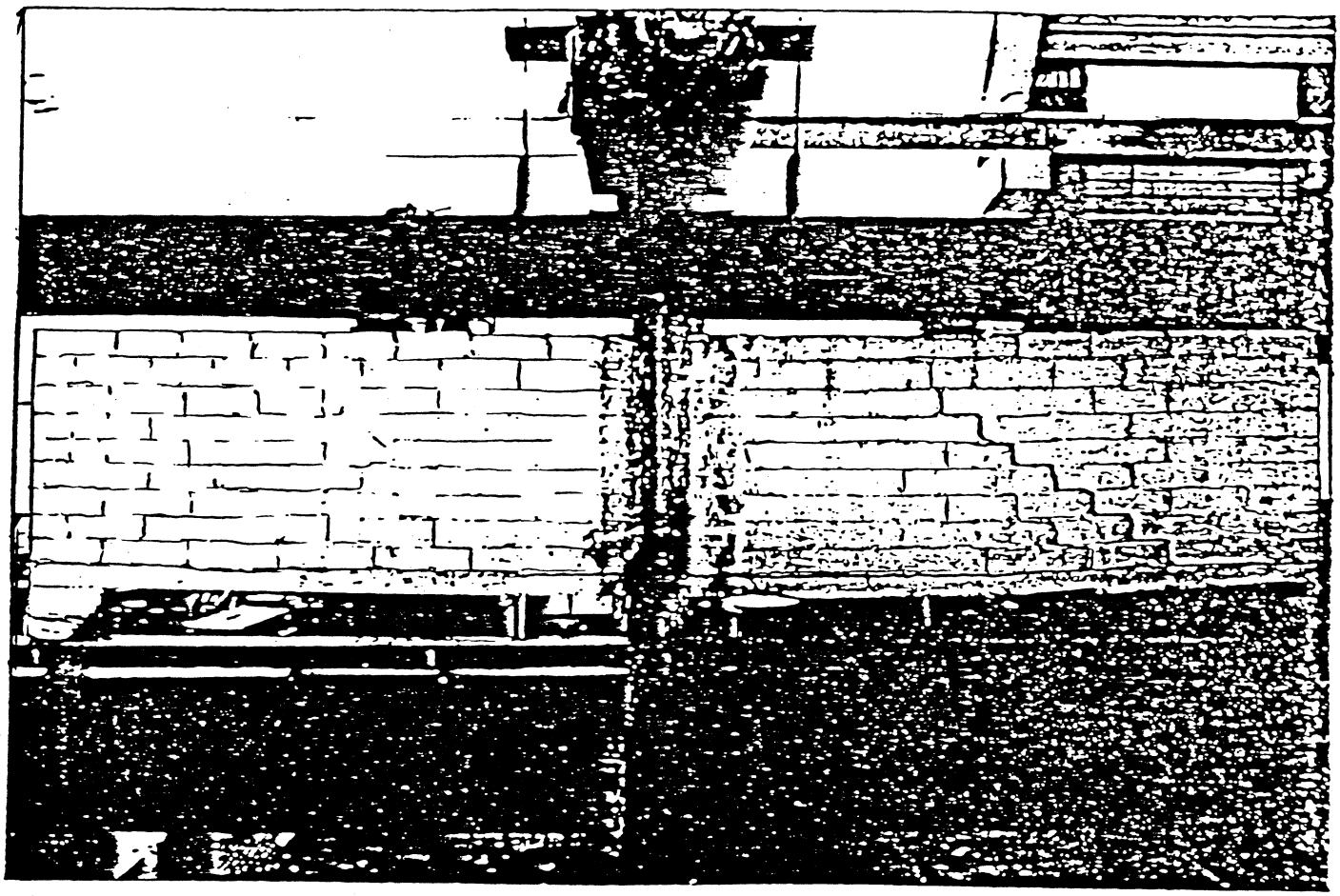
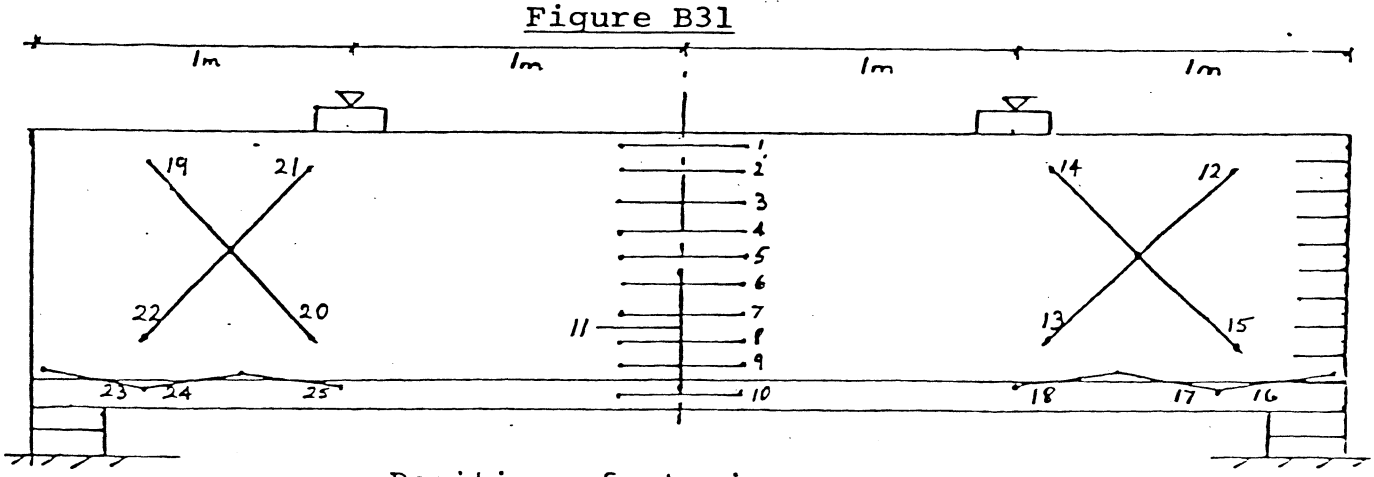


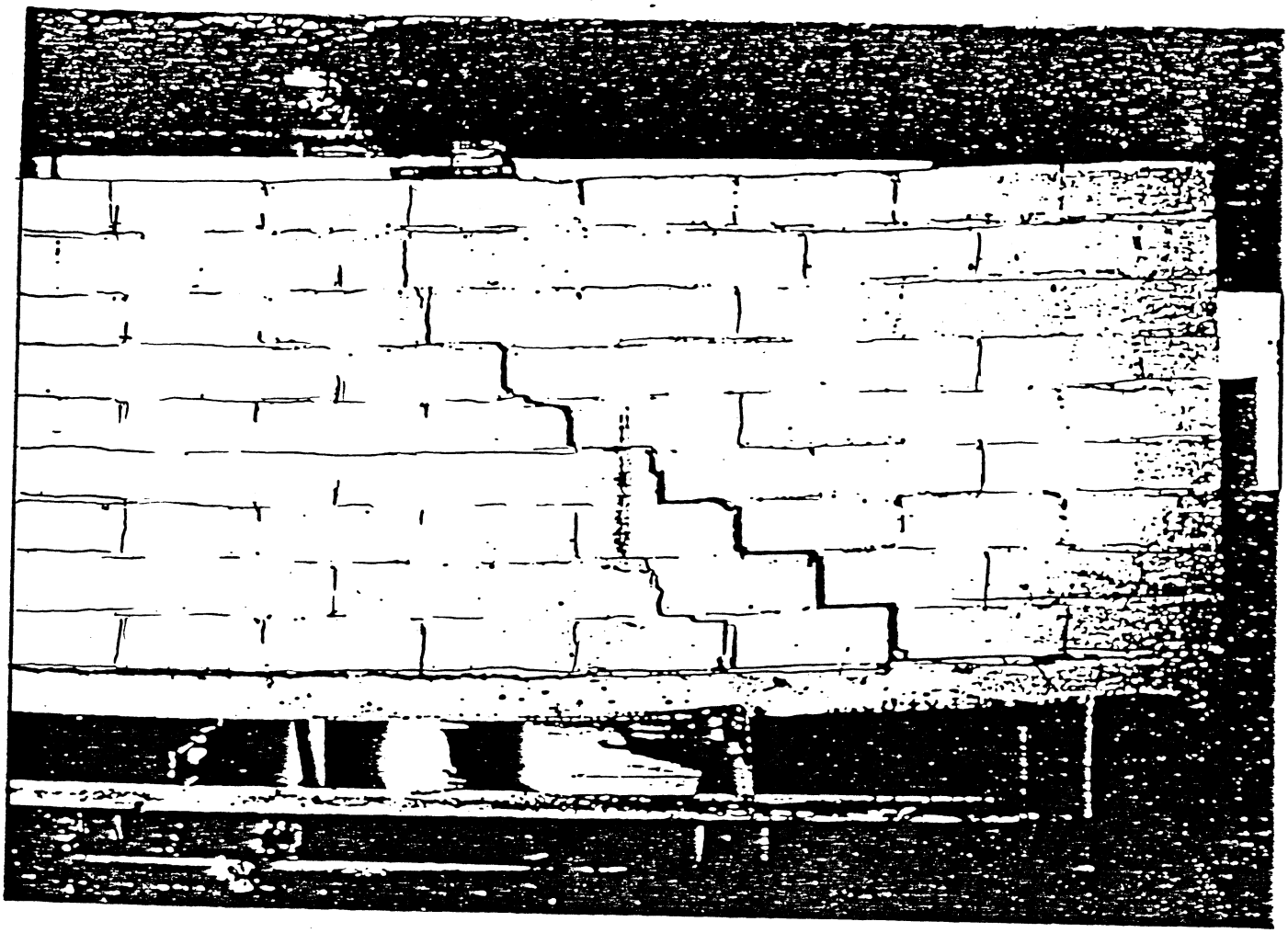
Figure B31



Position of strain gauges

Figure B32

Wall No.6



Failure crack pattern

Figure B33

WALL NO 6 - 4m x 9brickcourse

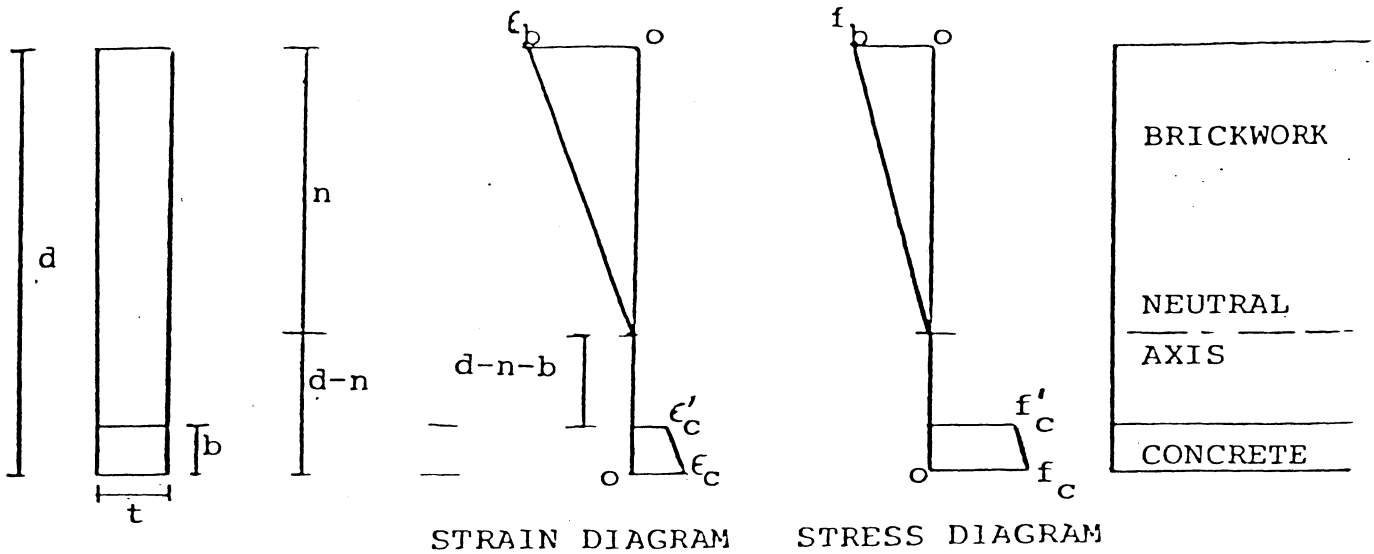


Figure B.34

E_b = ,2GPa E_c = 44,5GPa b = 70mm t = 105mm d = 790mm

m = modular ratio = E_c/E_b = 44,5/8,2 = 5,42

$$n = \frac{-2mb \pm \sqrt{(2mb)^2 - 4mb(b-2d)}}{2} = 467,25mm$$

$$f_b = \frac{E_b nM}{E_b\frac{n}{3}t + E_c\frac{bt}{2}2(d-n) + 2b(n-d+\frac{b}{3})} = \underline{1,50MPa \text{ (calculated)}}$$

$f_b = E_b\epsilon_b = 8,2x10^3x26,0x10^{-5} = \underline{2,13MPa \text{ (measured)}}$

$$f_c = \frac{E_c(d-n)M}{E_b\frac{n}{3}t + E_c\frac{bt}{2}2(d-n) + 2b(n-d+\frac{2b}{3})} = \underline{5,62MPa \text{ (calculated)}}$$

$f_c = E_c\epsilon_c = 44,5x10^3x14,0x10^{-5} = \underline{6,23MPa \text{ (measured)}}$

Comparison of Load Test Results and Analytical Results

Table B.17

	Load Test Results	Analytical Results
Maximum stress in brickwork	2,13MPa	1,50MPa
Maximum stress in concrete	6,23MPa	5,62MPa

Table B18 Wall No.6 4m x 9 brickcourse

End reaction kN	Shear in shear span kN	Moment in flexure span kNm	Flexure strains x 10^{-5} at positions numbered on walls									
			1	2	3	4	5	6	7	8	9	10
0	0	0	0	0	0	0	0	0	0	0	0	0
4,45	4,45	4,45	-4,5	-2,5	-2,0	-1,0	-0,5	+0,5	+1,5	+1,5	+3,5	+3,5
8,9	8,9	8,9	-11,0	-4,5	-3,0	-2,5	-0,5	0	+2,0	+3,0	+7,5	+7,5
13,5	13,5	13,5	-17,5	-9,0	-4,5	-3,0	-1,0	0	+3,0	+3,5	+8,5	+8,5
17,8	17,8	17,8	-20,0	-12,0	-5,5	-3,5	-0,5	+0,5	+3,0	+4,5	+10,0	+11,0
22,25	22,25	22,25	-22,0	-14,5	-6,0	-4,0	-0,5	+0,5	+4,5	+5,0	+10,5	+12,5
24,2	24,2	24,2	F	A	I	L	U	R	E			

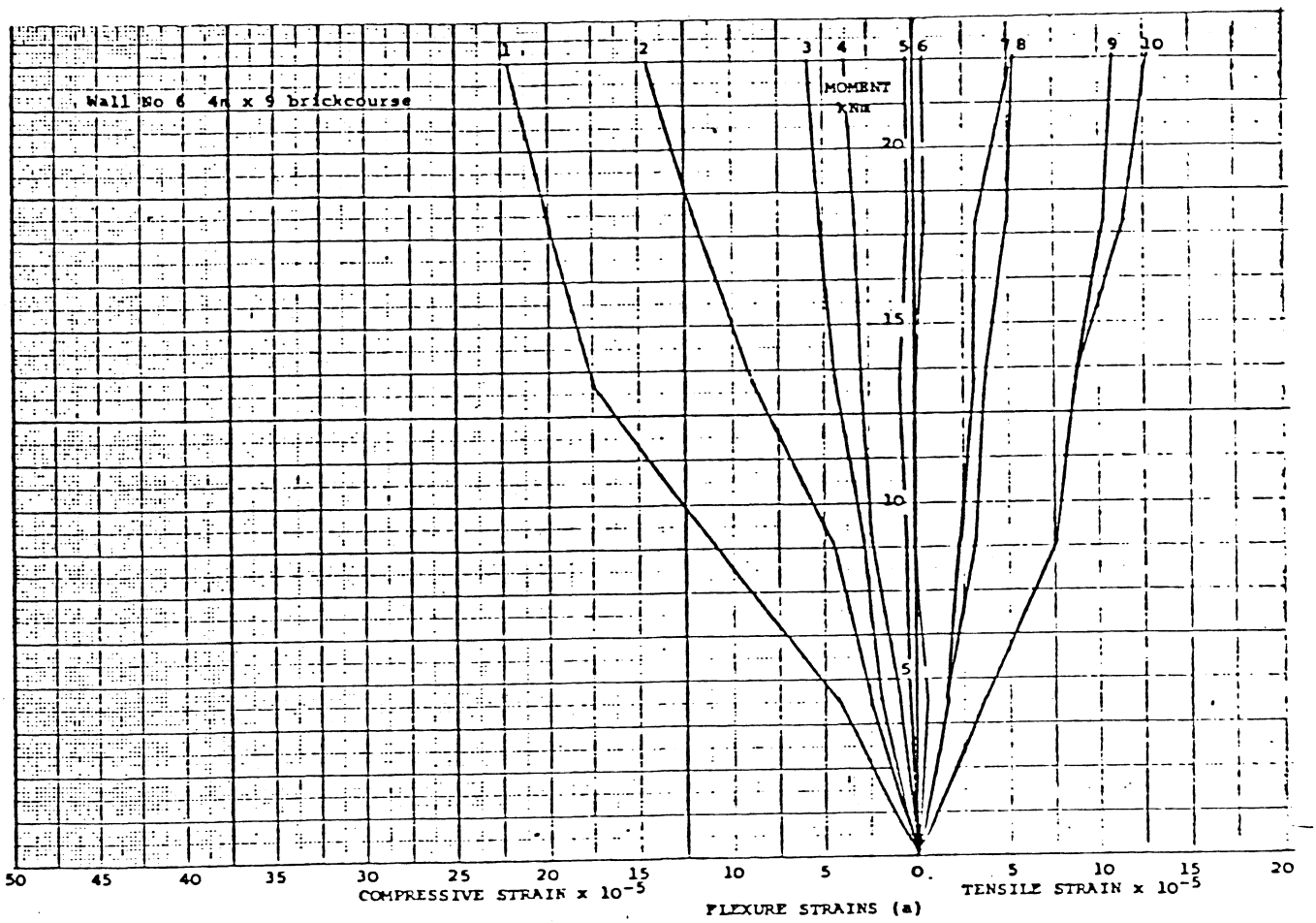


Figure B35

Table B19 - Wall No.6 4m x 9 brickcourse

End reaction kN	Shear in shear span kN	Moment in flexure span kNm	Diagonal strains x 10^{-5} at positions numbered on wall									
			12	13	14	15	19	20	21	22		
0	0	0	0	0	0	0	0	0	0	0	0	0
4,45	4,45	4,45	0,5	1,0	-1,0	-1,0	1,0	2,5	-2,0	-1,0		
8,9	8,9	8,9	2,0	2,5	-3,5	-2,0	2,0	5,0	-2,5	-3,0		
13,35	13,35	13,35	2,5	3,0	-5,5	-2,5	2,0	9,5	-6,0	-3,5		
17,8	17,8	17,8	3,0	3,5	-7,0	-3,5	2,5	11,5	-8,5	-5,0		
22,25	22,25	22,25	3,0	5,0	-8,0	-4,0	3,5	20,5	-10,0	-6,5		
24,2	24,2	24,2	F	A	I	L	U	R	E			

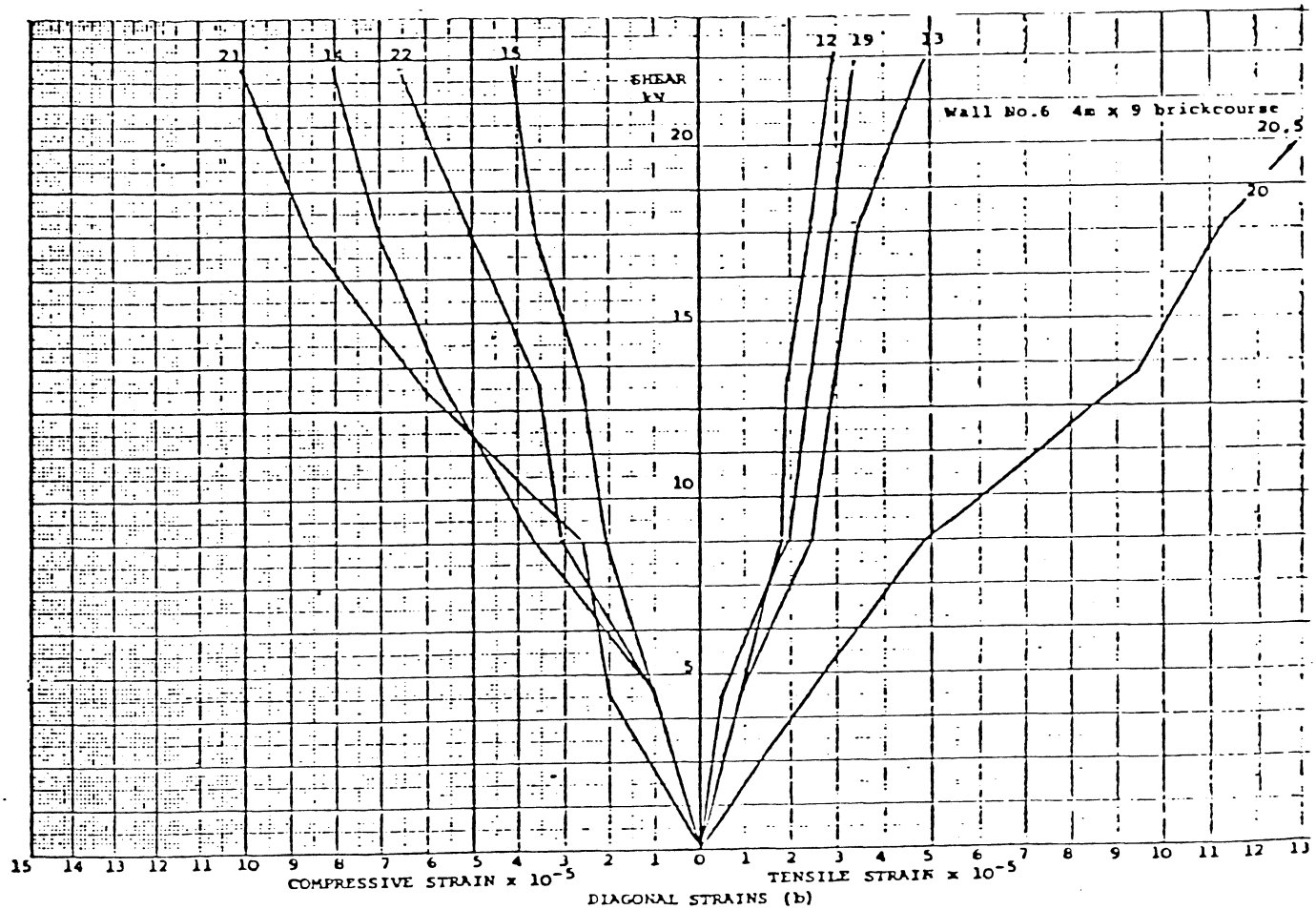
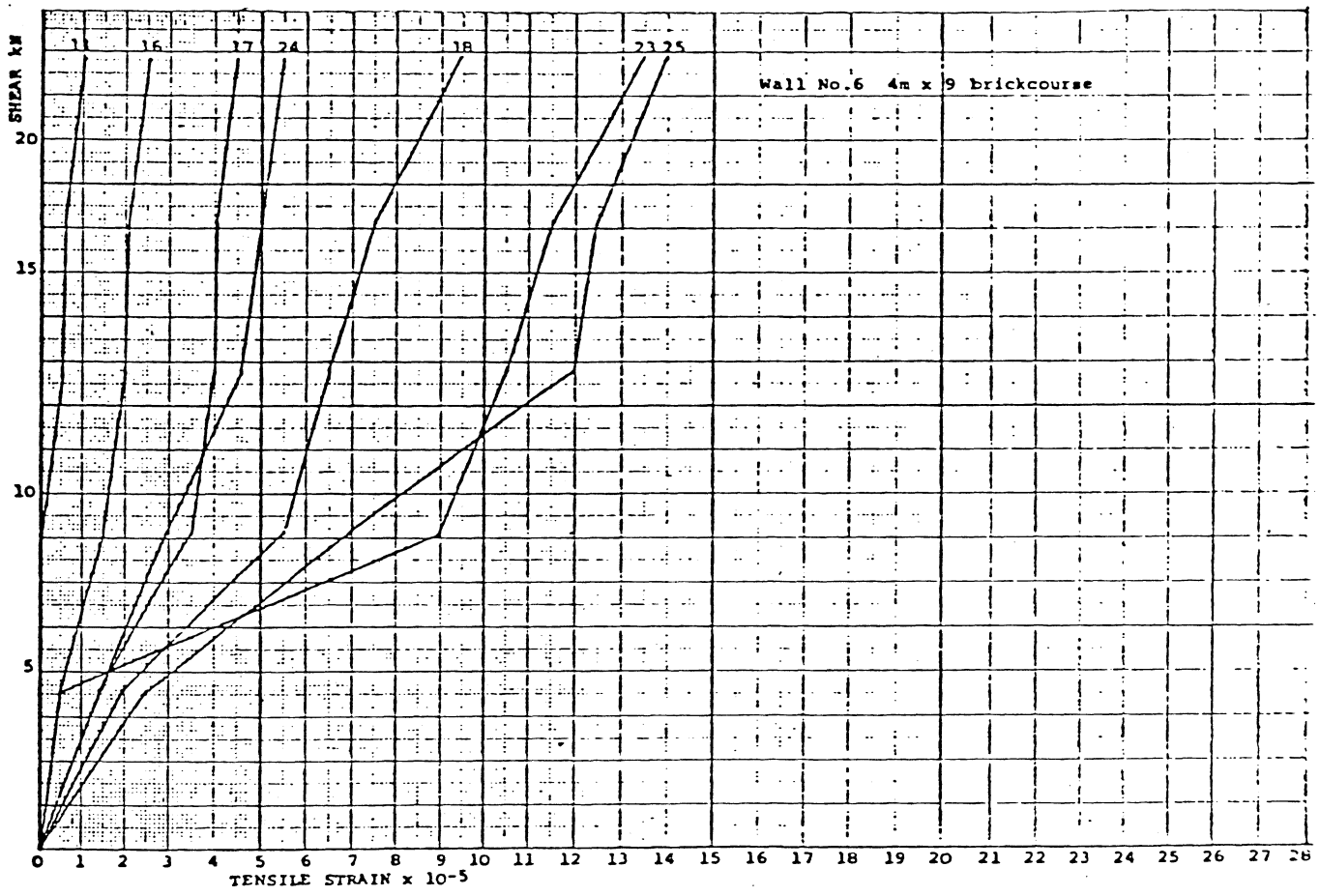


Figure B36

Table D20 - Wall No.6 4m x 9 brickcourse

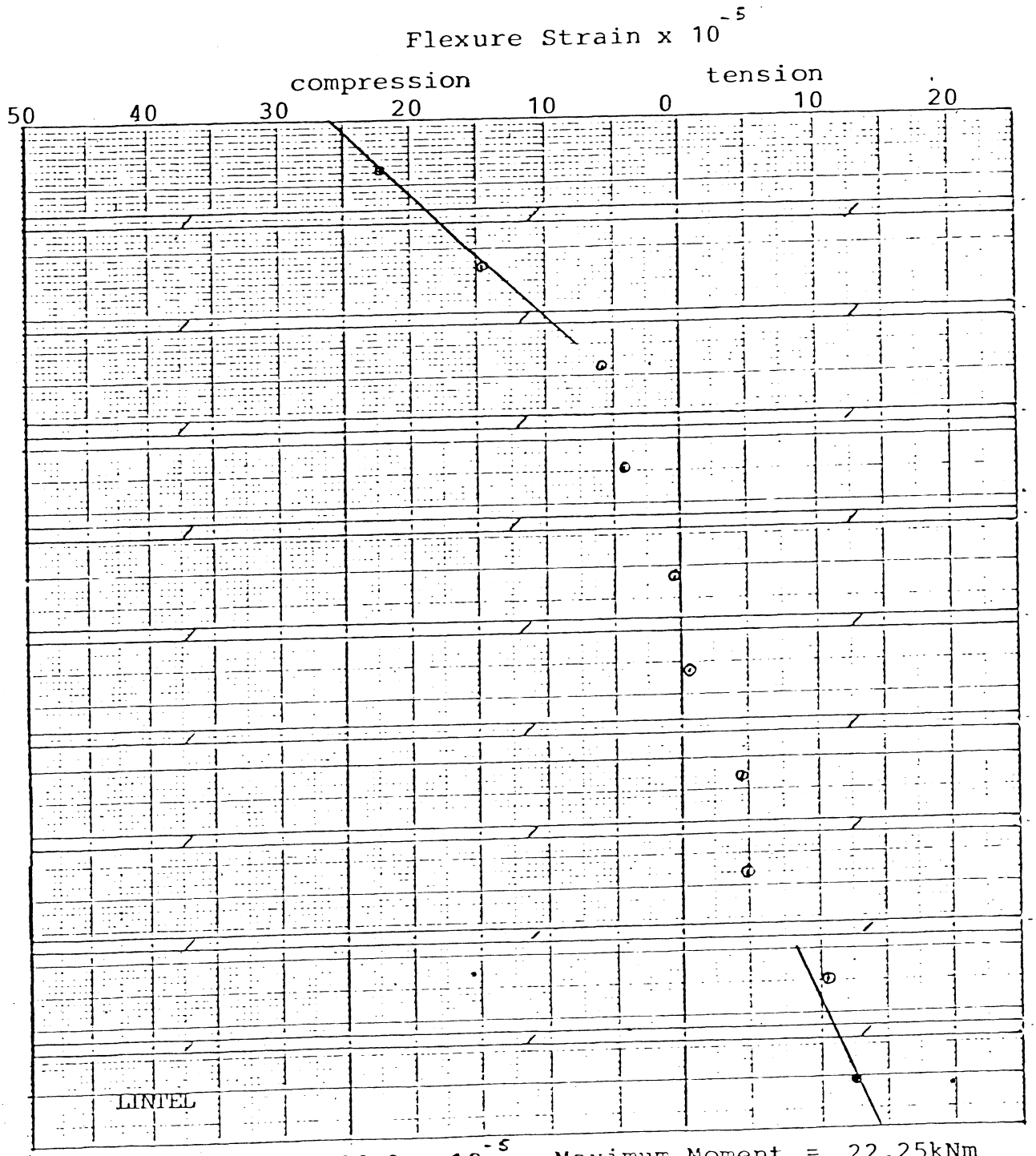
End reaction kN	Shear in shear span kN	Moment in flexure span kNm	Slip strains x 10^{-5} between brickwork and lintel at positions numbered on wall							Central wall deflection mm
			16	17	18	23	24	25	11	
0	0	0	0	0	0	0	0	0	0	0
4,45	4,45	4,45	0,5	1,5	2,0	0,5	1,5	2,5	0	0,18
8,9	8,9	8,9	1,5	3,5	5,5	9,0	3,0	7,0	0	0,35
13,35	13,35	13,35	2,0	4,0	6,5	10,5	4,5	12,0	0,5	0,52
17,8	17,8	17,8	2,0	4,0	7,5	11,5	5,0	12,5	0,5	
22,25	22,25	22,25	2,5	4,5	9,5	13,5	5,5	14,0	1,0	
24,2	24,2	24,2	F	A	I	L	U	R	E	



SLIP STRAINS (c) BETWEEN BRICKWORK AND CONCRETE LINTEL

Figure B37

The measured top and bottom maximum edge flexure strains were determined by plotting to scale, the strains measured at the centre of each brick course and centre of lintel against wall height. The values being taken at the maximum moment recorded. For wall 6 this was determined as below.



Top Edge Strain = 26,0 x 10^{-5} Maximum Moment = 22,25kNm

Bottom Edge Strain = 14,0 x 10^{-5}

Figure B.38

WALL 6 - 4m x 9 Brick course

Comments were given on the following test results

1. The load test values.
2. The calculated and measured stresses and strains in the wall.
3. The central wall deflection.
4. The failure crack pattern.
5. Further comments on the wall resistance to the loading during the test procedure.

The ultimate resistance moment of the wall produced a value of 24,2kNm, being 1,42 times the SHOFCO value of 17kNm. The ultimate shear resistance of the wall produced a value of 24,2kN, being 2,1 times the SHOFCO value of 11,5kN.

The maximum load test tensile flexure stress in the lintel of 6,23MPa was 12 per cent above the calculated result of 5,62MPa. The maximum load test compressive flexure stress in the brickwork of 2,13MPa was 42 per cent above the calculated result of 1,5MPa

The graph of flexure strains (a) versus moment showed a uniform increase up to their maximum values.

The diagonal tensile strain at 20 increased to a maximum measured value of 20,5 10 while the adjacent slip strain at 25 increased to a maximum measured value of 14,0 10. The slip strain between the lintel and brickwork at 23 over the left hand support also reached a high maximum value of 13,5 10. The slip strains between the lintel and brickwork at 16, 17 and 18 near the right hand support also increased in value with strain 18 reaching 9,5 10.

The measured central wall deflection taken at an end wall reaction of 13,35kN when the central deflection gauge was removed in case of wall failure gave a value of 0,52mm, being 1,23 times the calculated central deflection of 0,42mm. The measured and calculated central deflection values were close as far as the readings were taken.

A slip failure occurred at both ends of the wall, which when the ultimate load was reached spread across the length of the wall. Diagonal shear failures occurred on both sides of the wall between the supports and the near loading points.

Wall No. 7 - 6m x 5 brickcourses

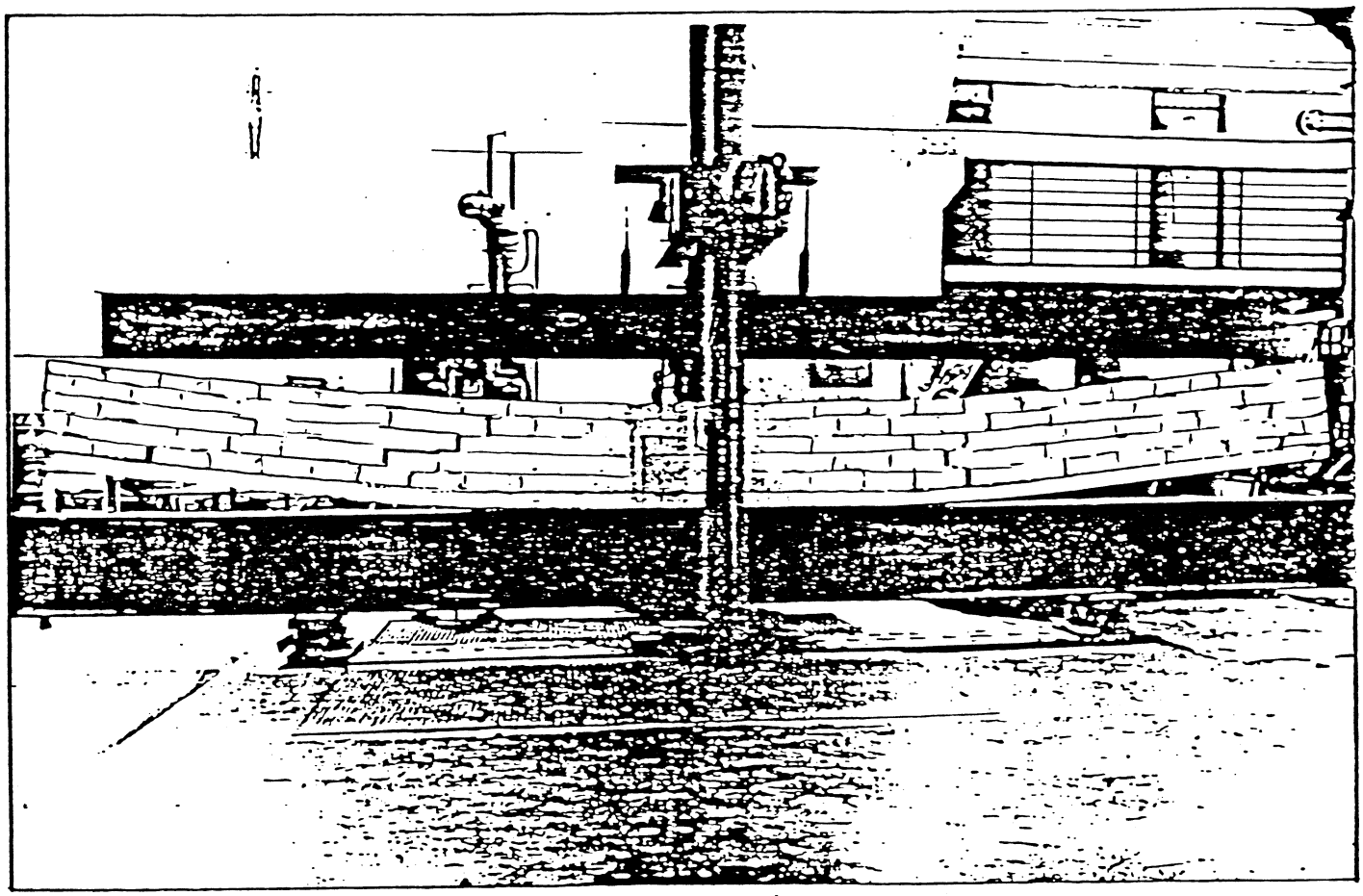
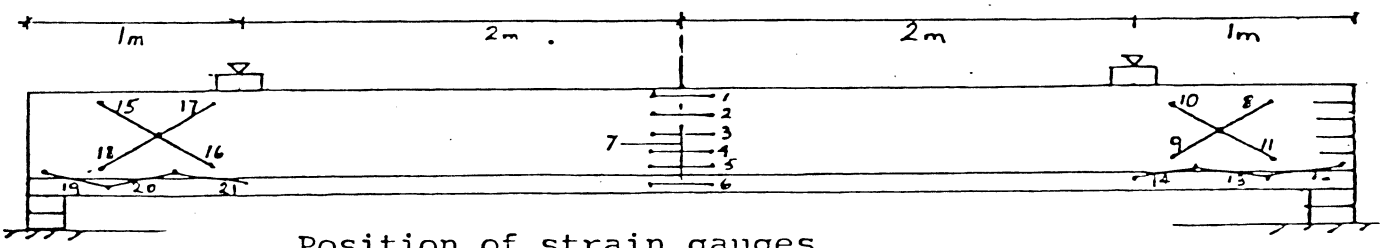


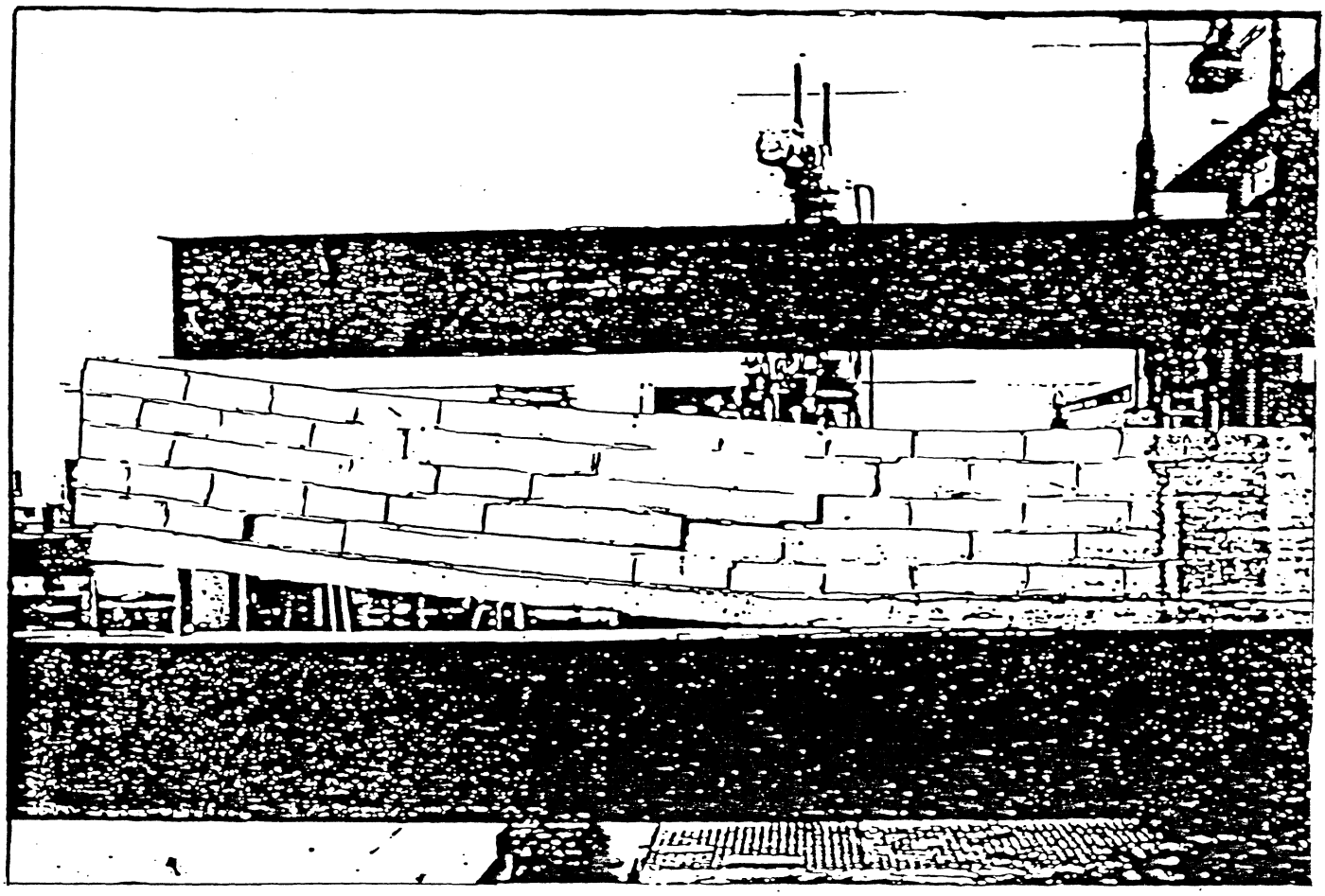
Figure B38



Position of strain gauges

Figure B39

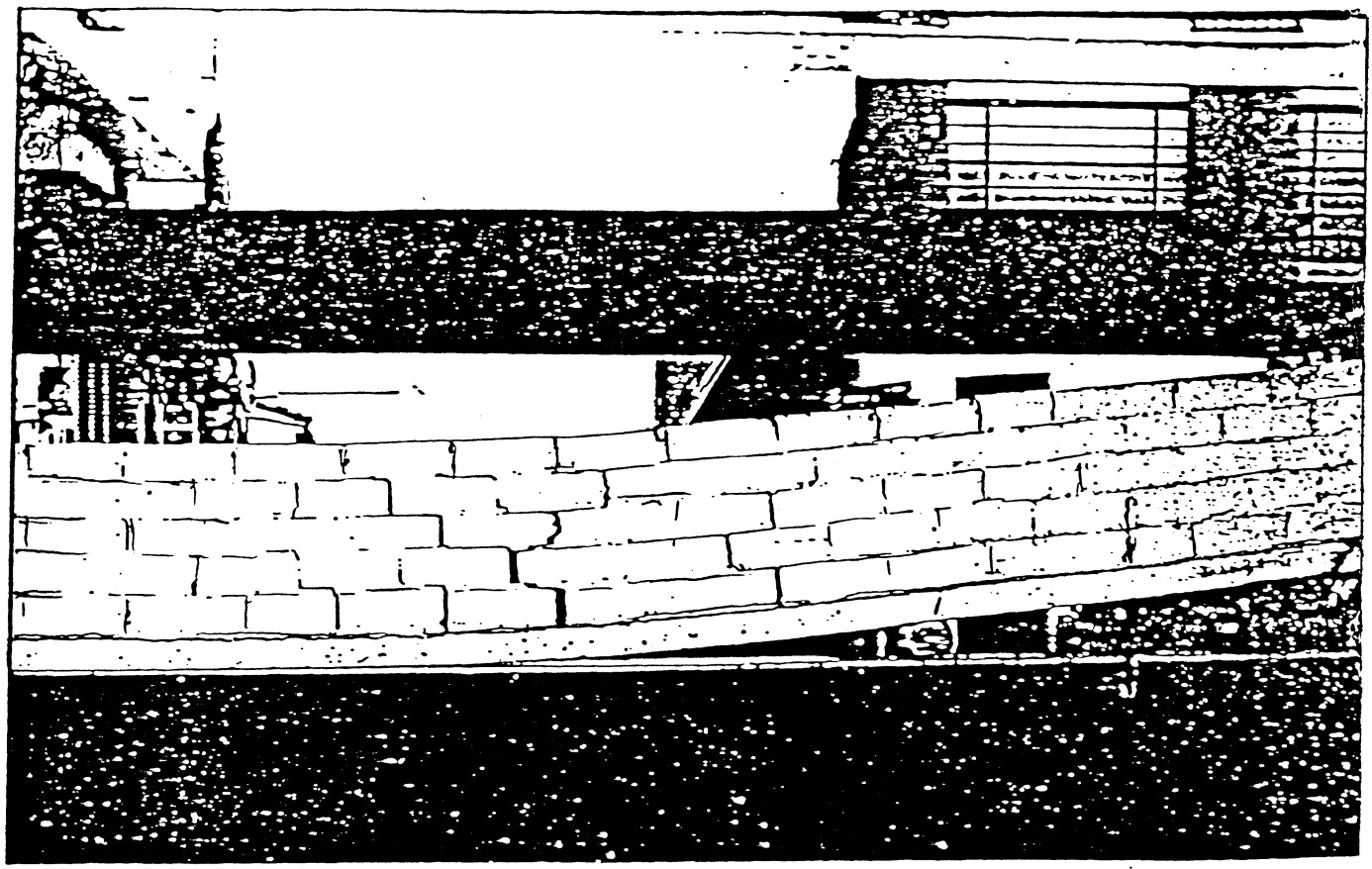
Wall No. 7



Failure crack pattern

Figure B40

Wall No.7



Failure crack pattern

Figure B41

WALL NO 7 - 6m x 5brickcourse

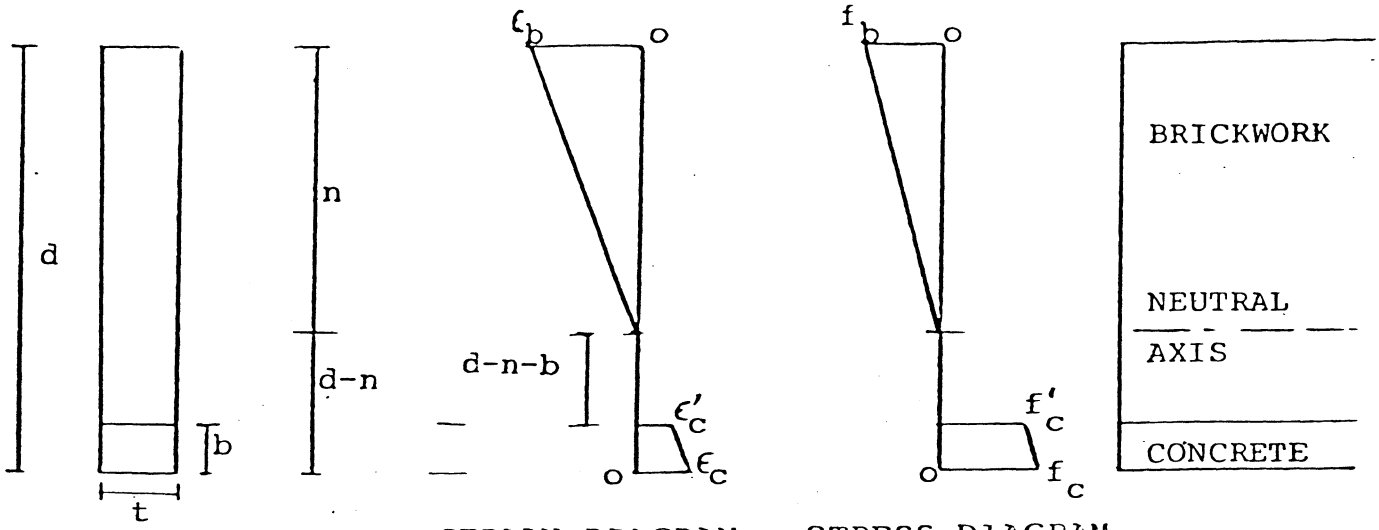


Figure B.42

E_b = 9,3GPa E_c = 44,5GPa b = 70mm t = 105mm d = 470mm

m = modular ratio = E_c/E_b = 44,5/9,3 = 4,78

$$n = \frac{-2mb \pm \sqrt{(2mb)^2 - 4mb(b-2d)}}{2} = 300,26mm$$

$$f_b = \frac{E_b nM}{E_b\frac{n}{3}t + E_c\frac{bt}{2}2(d-n) + 2b(n-d+\frac{b}{3})} = \underline{2,01MPa \text{ (calculated)}}$$

$f_b = E_b\epsilon_b = 9,3x10^3x27,5x10^{-5} = \underline{2,55MPa \text{ (measured)}}$

$$f_c = \frac{E_c(d-n)M}{E_b\frac{n}{3}t + E_c\frac{bt}{2}2(d-n) + 2b(n-d+\frac{2b}{3})} = \underline{5,45MPa \text{ (calculated)}}$$

$f_c = E_c\epsilon_c = 44,5x10^3x19,9x10^{-5} = \underline{8,85MPa \text{ (measured)}}$

Comparison of Load Test Results and Analytical Results

Table B.21

	Load Test Results	Analytical Results
Maximum stress in brickwork	2,55MPa	2,01MPa
Maximum stress in concrete	8,85MPa	5,45MPa

Table B22-Wall No.7 6m x 5 brickcourse

End reaction kN	Shear in shear span kN	Moment in flexure span kNm	Flexure strains x 10^{-5} at positions numbered on walls								
			1	2	3	4	5	6	7	8	9
0	0	0	0	0	0	0	0	0			
2,23	2,23	2,23	-2,0	-1,0	-0,5	+0,5	+1,0	+2,5			
4,45	4,45	4,45	-5,5	-3,0	-0,5	+1,5	+2,5	+6,5			
6,76	6,76	6,67	-19,5	-10,5	-2,5	-1,0	+3,5	+10,5			
8,9	8,9	8,9	-19,5	-17,5	-10,0	-1,0	+8,0	+13,0			
11,13	11,13	11,13	-24,0	-19,5	-11,0	-1,5	+9,5	+14,5			
11,25	11,25	11,25	F	A	I	L	U	R	E		

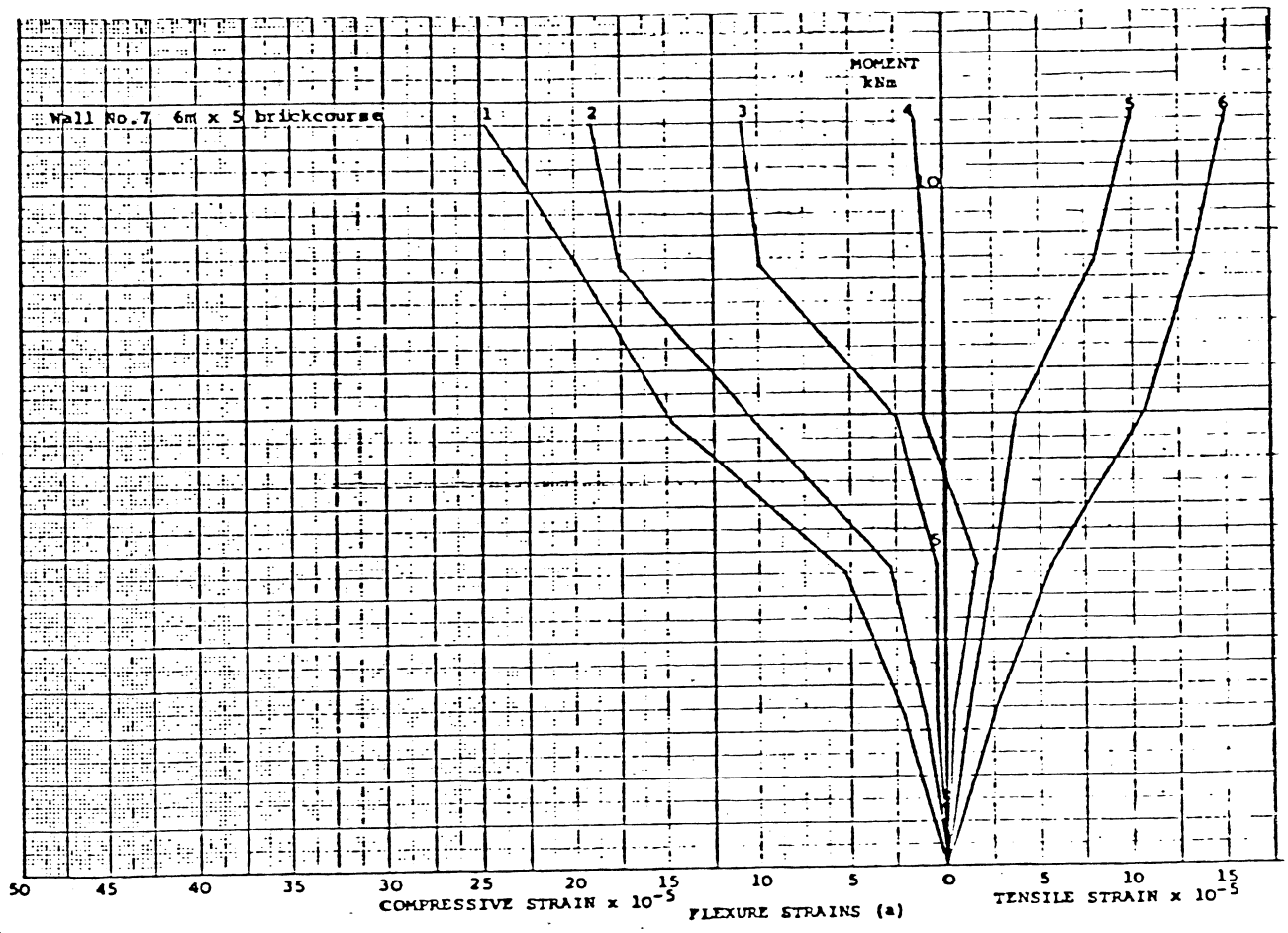


Figure B43

Table B2) - Wall No.7 6m x 5 brickcourse

End reaction kN	Shear in shear span kN	Moment in flexure span kNm	Diagonal strains x 10^{-5} at positions numbered on wall								
			8	9	10	11	15	16	17	18	
0	0	0	0	0	0	0	0	0	0	0	0
2,23	2,23	2,23	+0,5	+0,5	-1,5	-1,5	0	1,0	-2,0	-0,5	
4,45	4,45	4,45	+1,0	+1,0	-2,0	-2,0	0	1,5	-3,5	-1,5	
6,76	6,76	6,76	+1,5	+1,0	-4,0	-6,0	1,0	3,0	-5,5	-2,5	
8,9	8,9	8,9	+2,0	+1,0	-5,5	-8,0	3,5	3,5	-7,5	-3,5	
11,13	11,13	11,13	+2,0	-1,0	-8,0	-10,0	4,0	6,0	-11,0	-5,5	
11,25	11,25	11,25	F	A	I	L	U	R	E		

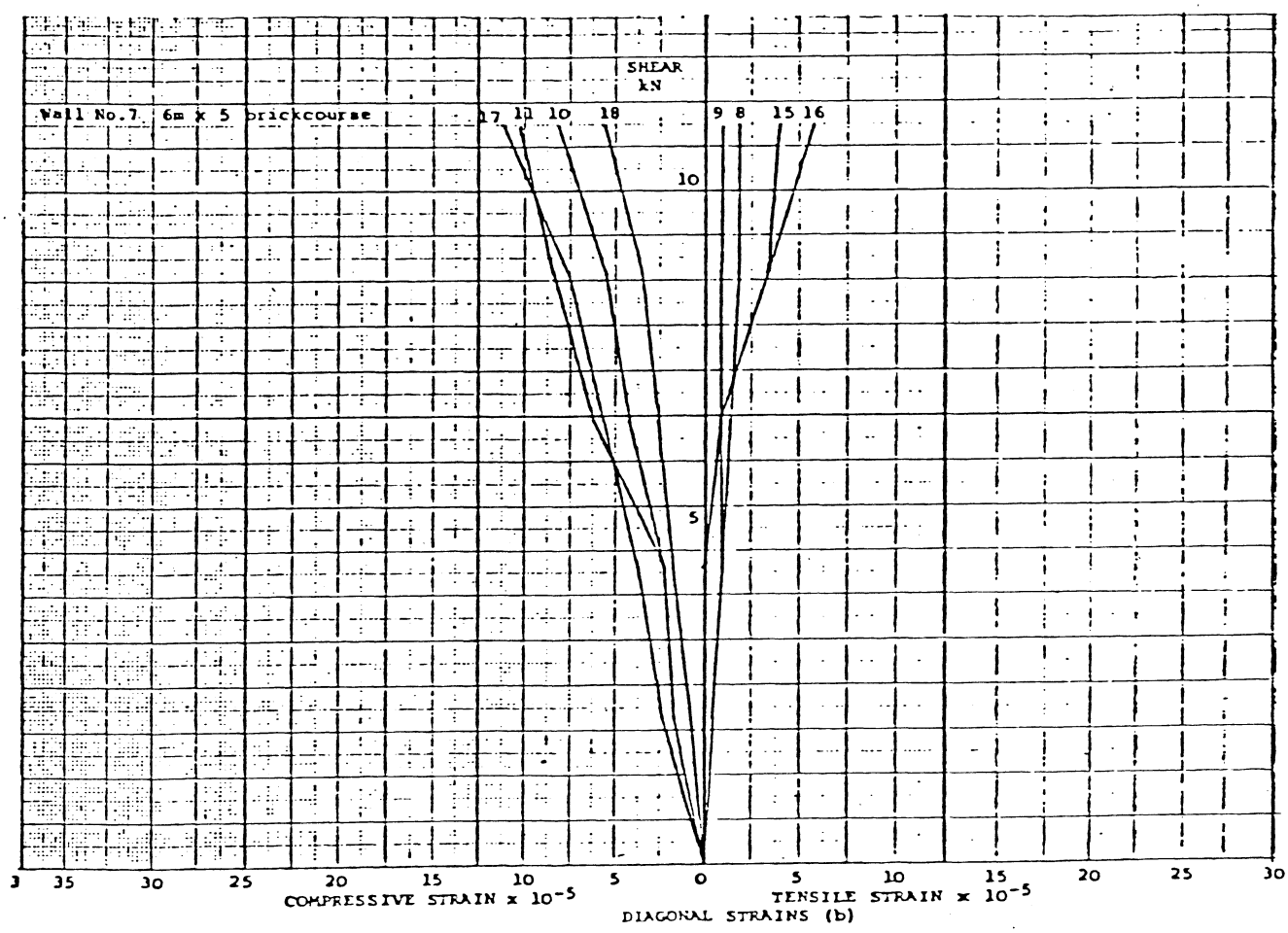


Figure B44

Table B24 - Wall No.7 6m x 5 brickcourse

End reaction kN	Shear in shear span kN	Moment in flexure span kNm	Slip strains x 10^{-5} between brickwork and lintel at positions numbered on wall							Central wall deflection mm
			12	13	14	19	20	21	7	
0	0	0	0	0	0	0	0	0	0	0
2,23	2,23	2,23	0	0	1,5	1,0	0	4,5	0	1,17
4,45	4,45	4,45	0	0	3,5	1,5	0	7,5	0	1,75
6,76	6,76	6,76	2,0	3,5	10,5	2,0	1,0	8,5	3,0	2,57
8,9	8,9	8,9	4,5	11,5	20,0	2,0	2,0	10,0	15,0	
11,13	11,13	11,13	6,5	18,0	25,0	5,0	3,0	11,5	19,5	
11,25	11,25	11,25		F	A	I	L	U	R	E

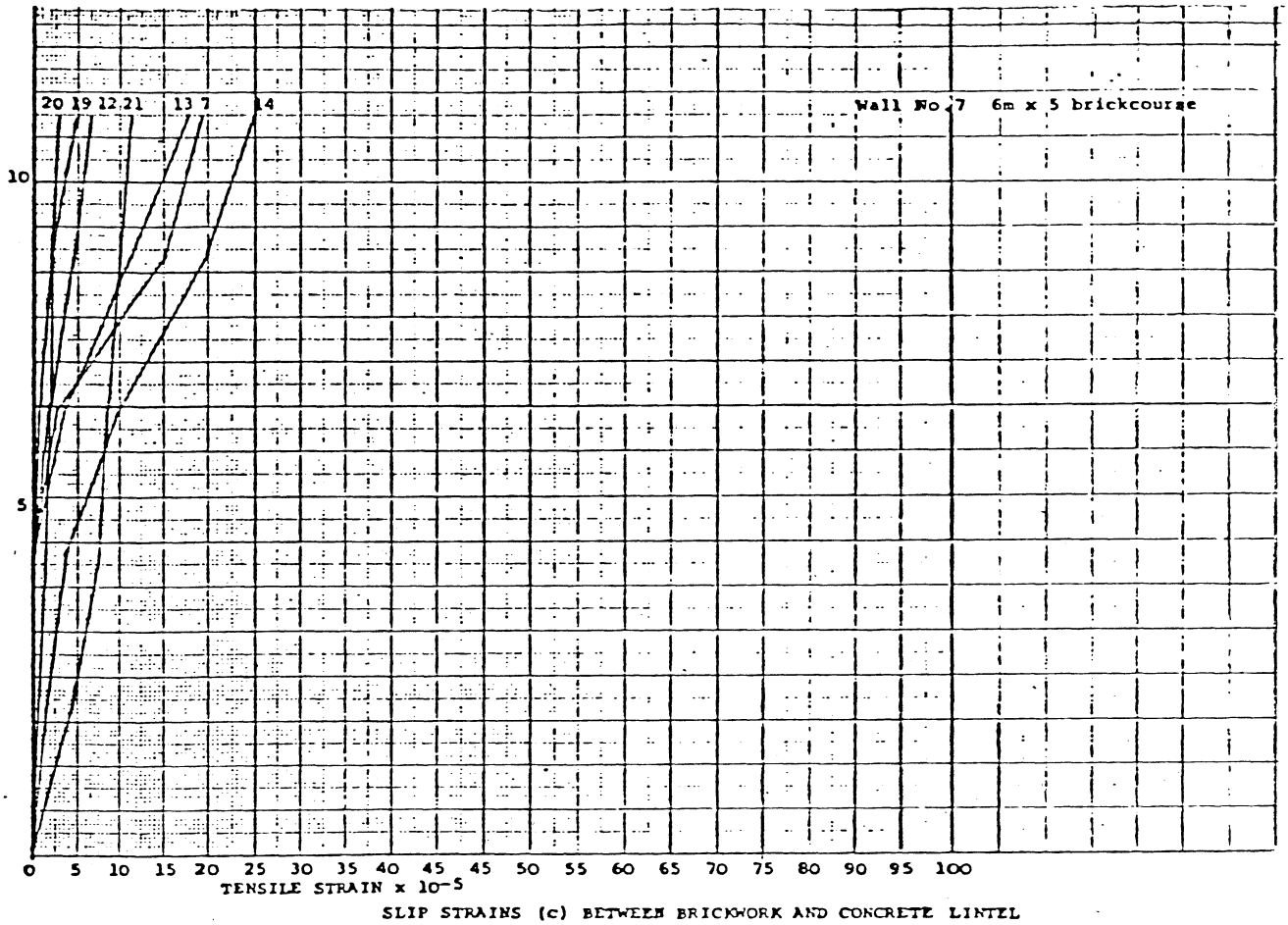
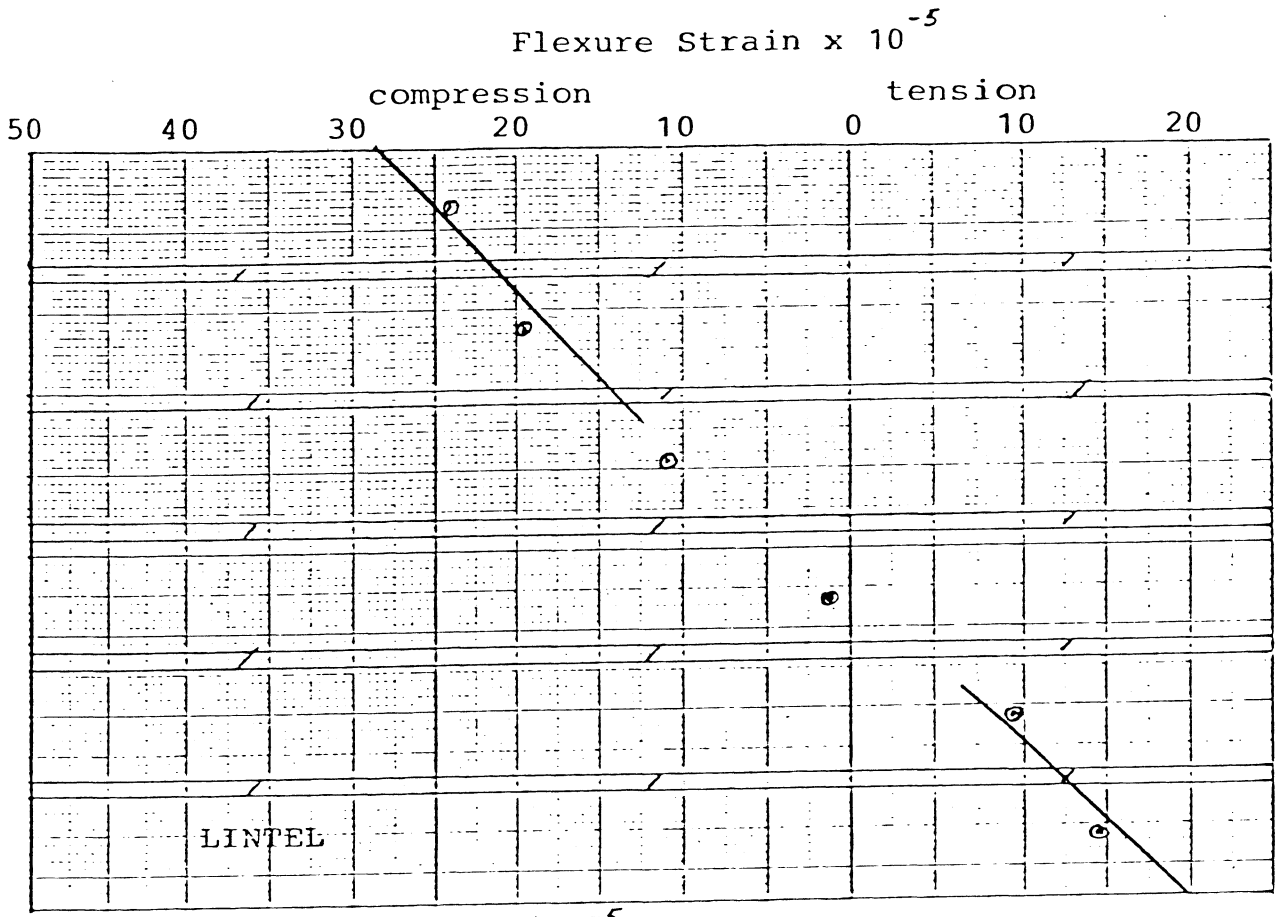


Figure B45

The measured top and bottom maximum edge flexure strains were determined by plotting to scale, the strains measured at the centre of each brick course and centre of lintel against wall height. The values being taken at the maximum moment recorded. For wall 7 this was determined as below.



Top Edge Strain = 27,5 x 10^{-5} Maximum Moment = 11,13kNm

Bottom Edge Strain = 19,9 x 10^{-5}

Figure B.46

WALL 7 - 6m x 5 Brick course

Comments were given on the following test results

1. The load test values.
2. The calculated and measured stresses and strains in the wall.
3. The central wall deflection.
4. The failure crack pattern.
5. Further comments on the wall resistance to the loading during the test procedure.

The ultimate resistance moment of the wall produced a value of 11,25kNm, being 1,8 times the SHOFCO value of 6,3 kNm. The ultimate shear resistance of the wall produced a value of 11,25kN, being 1,9 times the SHOFCO value of 6,OkN.

The maximum load test tensile flexure stress in the lintel of 8,85MPa was 62 per cent above the calculated result of 5,45MPa. The maximum load test compressive stress in the brickwork of 2,55MPa was 27 per cent above the calculated result of 2,01MPa.

The graph of flexure strains (a) versus moment showed fairly uniform strain increases with moment. The graph of diagonal strains (b) verses moment showed uniform increases. The strain at 16 produced a maximum tensile value of $6x10^{-5}$. The slip strains also produced fairly uniform increases, with increase in moment, the strains at 12, 13 and 14 produced maximum values of $6,5x10^{-5}$, $18,0x10^{-5}$ and $25,0x10^{-5}$.

The measured central wall deflection, taken at an end wall reaction of 6,76kN when the central deflection gauge was removed in case of wall failure, gave a value of 2,57mm

being 1,3 times the calculated central deflection of 2,02mm. The measured deflections did not produce a smooth curve but were fairly close to the calculated values.

In this wall test, the strain at 7, running vertically up the centre line of the wall, connecting the lintel to the brickwork suddenly increased to a value of $15x10^{-5}$ at an end wall reaction of 8,9kN this load being the penultimate one. The slip strains at 14 and 21 being nearest to the centre of the wall produced large values of $25x10^{-5}$ and $11,5x10^{-5}$ respectively.

During this test, hair line cracks formed on both sides of the wall, the position and length and relative travel showed the wall flexing first on one side and then the other. The large central deflections and the parting of the lintel from the brickwork at the wall centre produced a slip failure between the lintel and brickwork along the whole length of the wall. Horizontal slip failures occurred in the brickwork and diagonal failures occurred both in the shear span and flexure span travelling from the bottom to the top of the wall when the ultimate load was reached.

After wall failure, when the load was removed, the wall remained in its collapsed position.

being 1,3 times the calculated central deflection of 2,02mm The measured deflections did not produce a smooth curve but were fairly close to the calculated values.

In this wall test, the strain at 7, running vertically up the centre line of the wall, connecting the lintel to the brickwork suddenly increased to a value of $15x10^{-5}$ at an end wall reaction of 8,9kN this load being the penultimate one. The slip strains at 14 and 21 being nearest to the centre of the wall produced large values of $25x10^{-5}$ and $11,5x10^{-5}$ respectively.

During this test, hair line cracks formed on both sides of the wall, the position and length and relative travel showed the wall flexing first on one side and then the other. The large central deflections and the parting of the lintel from the brickwork at the wall centre produced a slip failure between the lintel and brickwork along the whole length of the wall. Horizontal slip failures occurred in the brickwork and diagonal failures occurred both in the shear span and flexure span travelling from the bottom to the top of the wall when the ultimate load was reached.

After wall failure, when the load was removed, the wall remained in its collapsed position.

Wall No.8 - 6m x 7 brickcourses

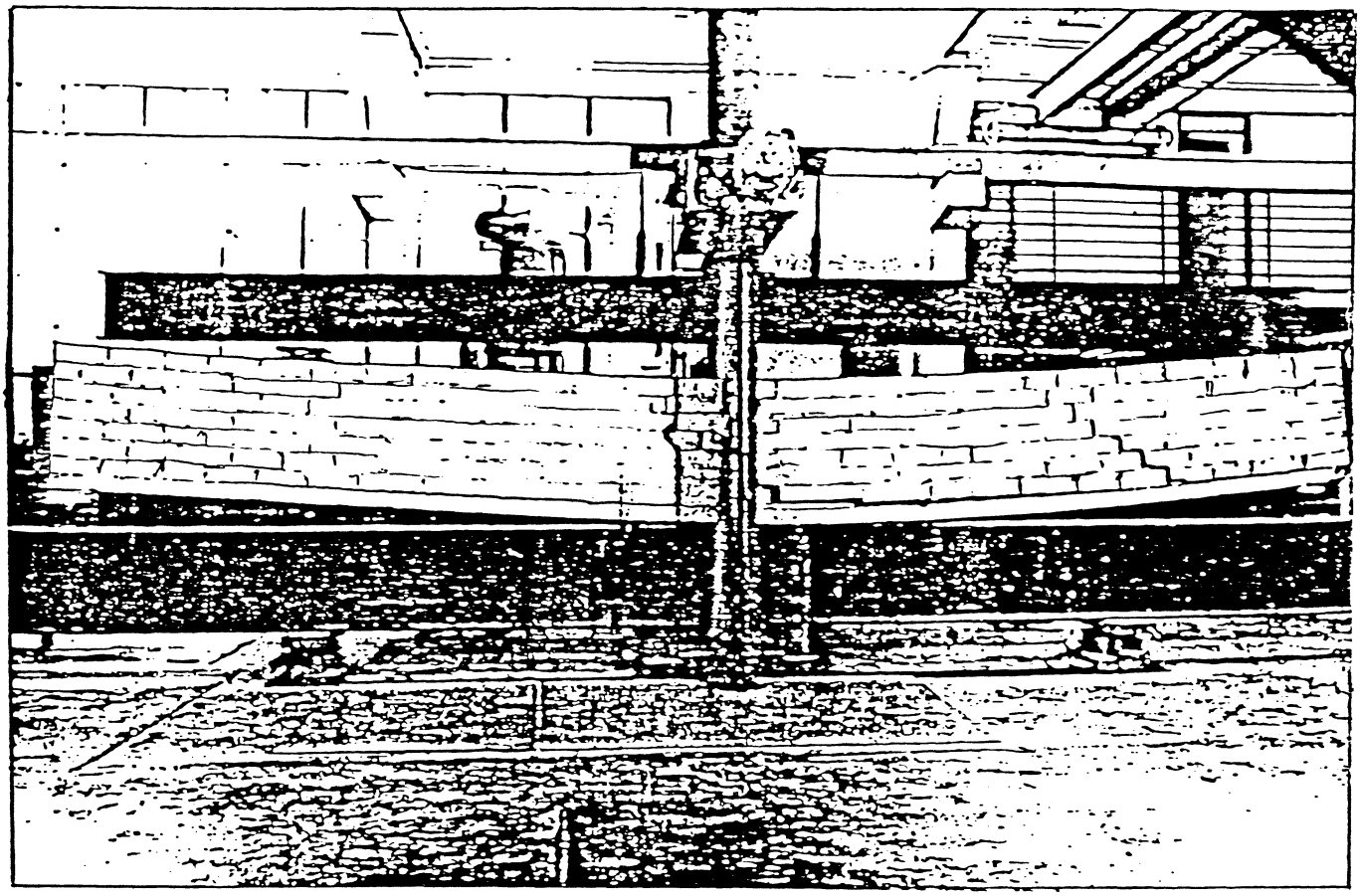
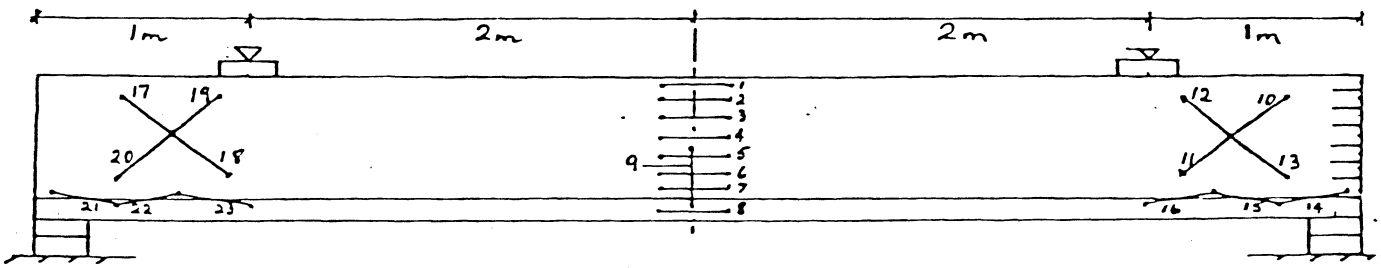


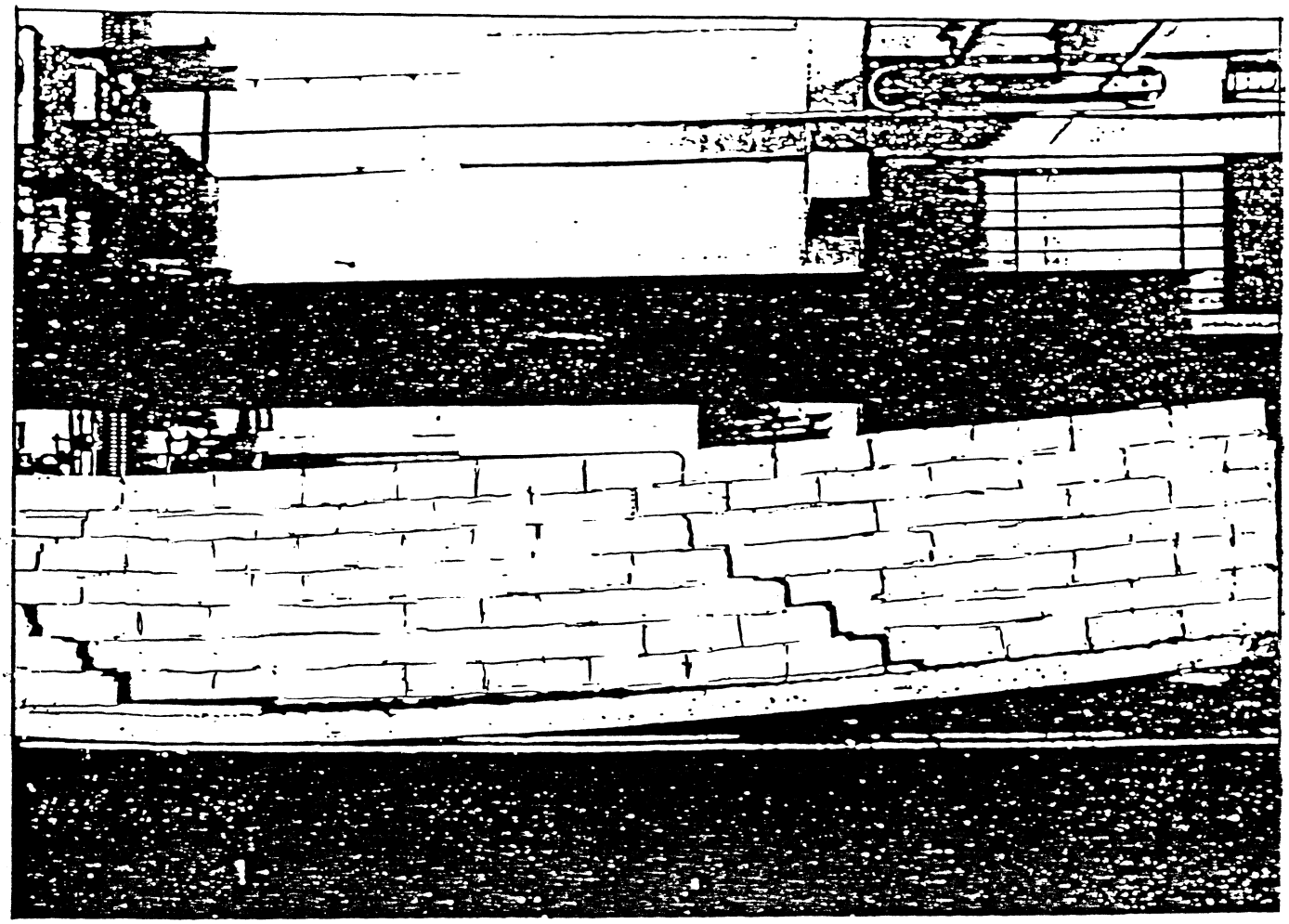
Figure B46



Position of strain gauges

Figure B47

Wall No.8



Failure crack pattern

Figure B48

WALL NO 8 - 6m x 7brickcourse

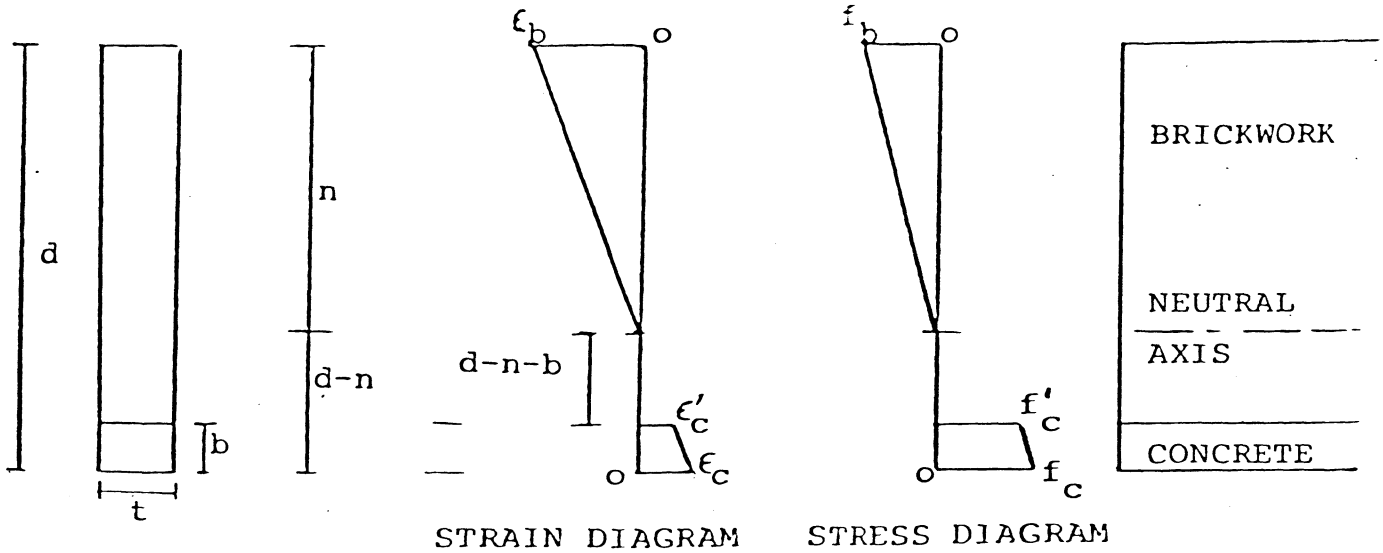


Figure B.49

E_b = 7,8GPa E_c = 44,5GPa b = 70mm t = 105mm d = 630mm

m = modular ratio = E_c/E_b = 44,5/7,8 = 5,7

$$n = \frac{-2mb \pm \sqrt{(2mb)^2 - 4mb(b-2d)}}{2} = 397,25mm$$

$$f_b = \frac{E_b n M}{E_b \frac{n}{3} t + E_c \frac{bt}{2} 2(d-n) + 2b(n-d+\frac{b}{3})} = \underline{1,57 \text{ MPa (calculated)}}$$

$f_b = E_b \epsilon_b = 7,8x10^3 x 24,5x10^{-5} = \underline{1,91MPa \text{ (measured)}}$

$$f_c = \frac{E_c (d-n) M}{E_b \frac{n}{3} t + E_c \frac{bt}{2} 2(d-n) + 2b(n-d+\frac{b}{3})} = \underline{5,27MPa \text{ (calculated)}}$$

$f_c = E_c \epsilon_c = 44,5x10^3 x 14,5x10^{-5} = \underline{6,45MPa \text{ (measured)}}$

Comparison of Load Test Results and Analytical Results

Table B.25

	Load Test Results	Analytical Results
Maximum stress in brickwork	1,91MPa	1,57MPa
Maximum stress in concrete	6,45MPa	5,27MPa

Table D26 - Wall No.8 6m x 7 brickcourse

End reaction kN	Shear in shear span kN	Moment in flexure span kNm	Flexure strains x 10^{-5} at positions numbered on walls								
			1	2	3	4	5	6	7	8	9
0	0	0	0	0	0	0	0	0			
2,23	2,23	2,23	-2,0	-1,0	-1,0	0	0	+0,5	+1,5	+2,0	
4,45	4,45	4,45	-4,0	-2,5	-2,0	-0,5	-0,5	+1,0	+2,5	+5,0	
6,67	6,67	6,67	-7,0	-4,5	-3,0	-2,0	-1,0	+1,5	+4,0	+6,0	
8,9	8,9	8,9	-11,5	-5,0	-3,5	-2,5	-1,0	+2,0	+4,5	+7,0	
11,3	11,3	11,3	-12,0	-8,0	-5,5	-3,5	-1,0	+3,0	+5,0	+8,0	
13,35	13,35	13,35	-15,5	-9,5	-6,5	-4,0	-1,0	+3,0	+5,5	+9,5	
15,57	15,57	15,57	-22,0	-16,5	-11,5	-5,5	-2,0	+3,0	+6,5	+12,0	
15,8	15,8	15,8	F	A	I	L	U	R	E		

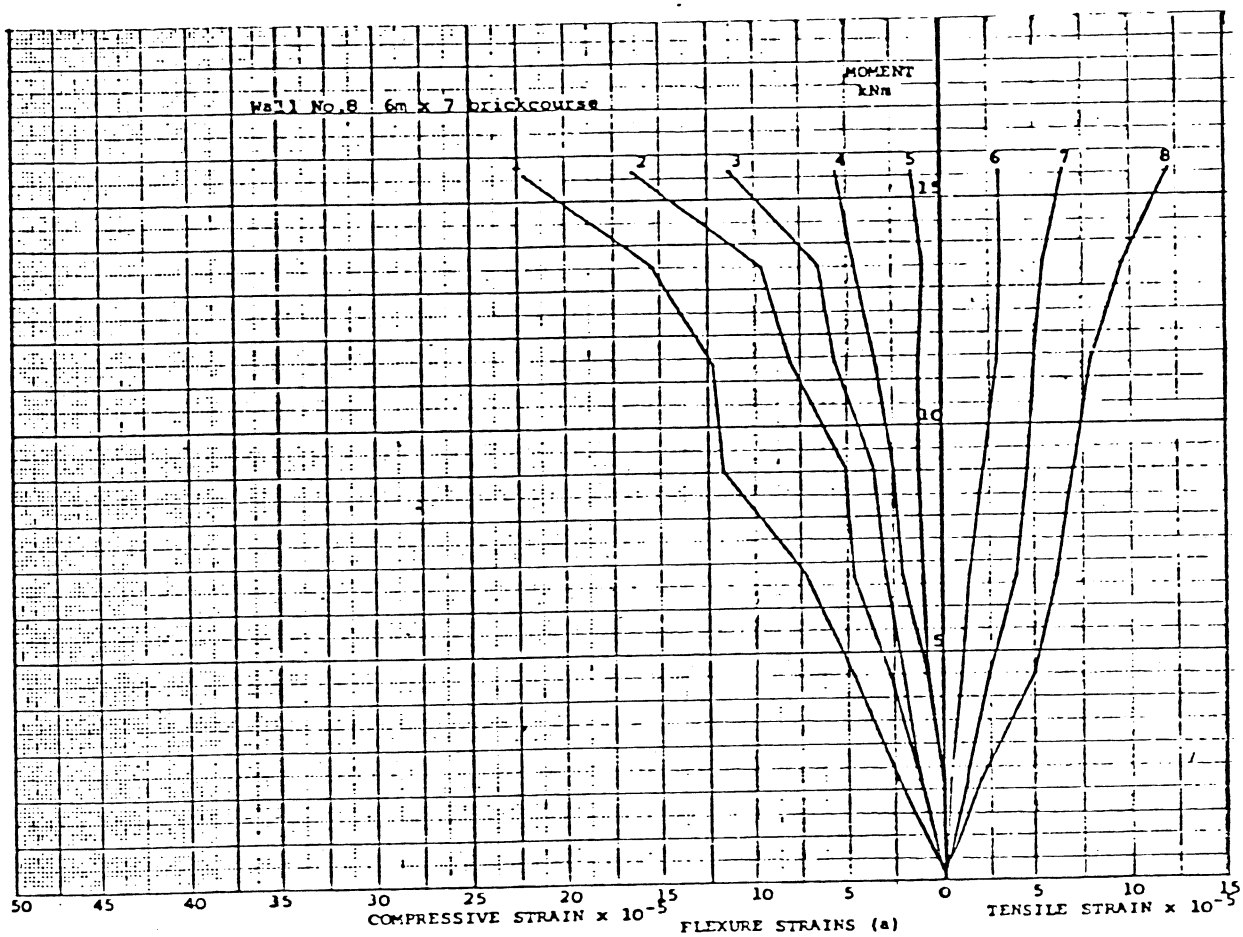


Figure B50

Table B27 - Wall No.8 6m x 7 brickcourse

End reaction kN	Shear in shear span kN	Moment in flexure span kNm	Diagonal strains x 10^{-5} at positions numbered on wall								
			10	11	12	13	17	18	19	20	
0	0	0	0	0	0	0	0	0	0	0	0
2,23	2,23	2,23	0	0	-0,5	-0,5	0	0,5	-0,5	-0,5	
4,45	4,45	4,45	0,5	0,5	-2,0	-2,0	0,5	1,0	-1,5	-1,5	
6,67	6,67	6,67	0,5	1,5	-2,5	-2,5	0,5	1,0	-2,0	-2,0	
8,9	8,9	8,9	0,5	2,5	-3,0	-3,0	1,0	1,5	-2,5	-2,5	
11,3	11,3	11,3	1,0	3,0	-3,5	-3,5	1,0	2,5	-3,5	-3,5	
13,35	13,35	13,35	1,0	3,0	-4,5	-4,0	1,0	3,0	-4,0	-4,5	
15,57	15,57	15,57	1,0	3,5	-5,0	-4,5	1,5	3,5	-4,5	-5,5	
15,8	15,8	15,8			F	A	I	L	U	R	E

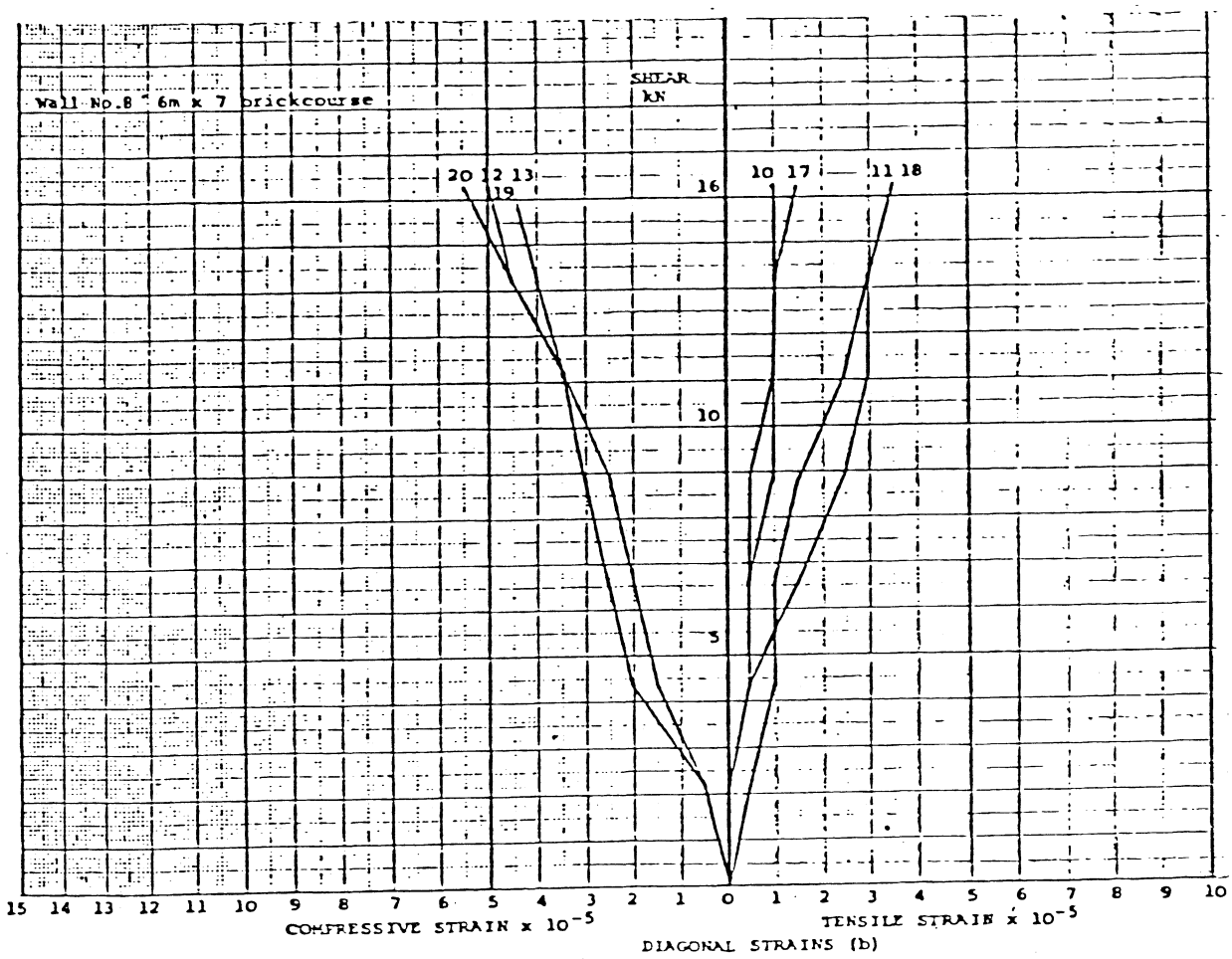


Figure B51

Table B28 - Wall No.8 6m x 7 brickcourse

End reaction kN	Shear in shear span kN	Moment in flexure span kNm	Slip strains x 10^{-5} between brickwork and lintel at positions numbered on wall							Central wall deflection mm
			14	15	16	21	22	23	9	
0	0	0	0	0	0	0	0	0	0	
2,23	2,23	2,23	0	0	1,0	0	0,5	1,0	0	0,40
4,45	4,45	4,45	0,5	0,5	2,0	0,5	1,0	2,5	0,5	0,82
6,67	6,67	6,67	0,5	1,0	2,5	0,5	1,5	3,0	0,5	1,27
8,9	8,9	8,9	0,5	1,0	3,5	1,0	2,0	4,0	1,0	1,50
11,3	11,3	11,3	1,0	1,0	5,5	1,5	2,5	5,5	1,0	2,05
13,35	13,35	13,35	1,5	1,0	7,0	1,5	3,0	6,0	1,0	
15,57	15,57	15,57	2,0	2,0	8,5	1,5	3,5	7,0	3,0	
15,8	15,8	15,8	F	A	I	L	U	R	E	

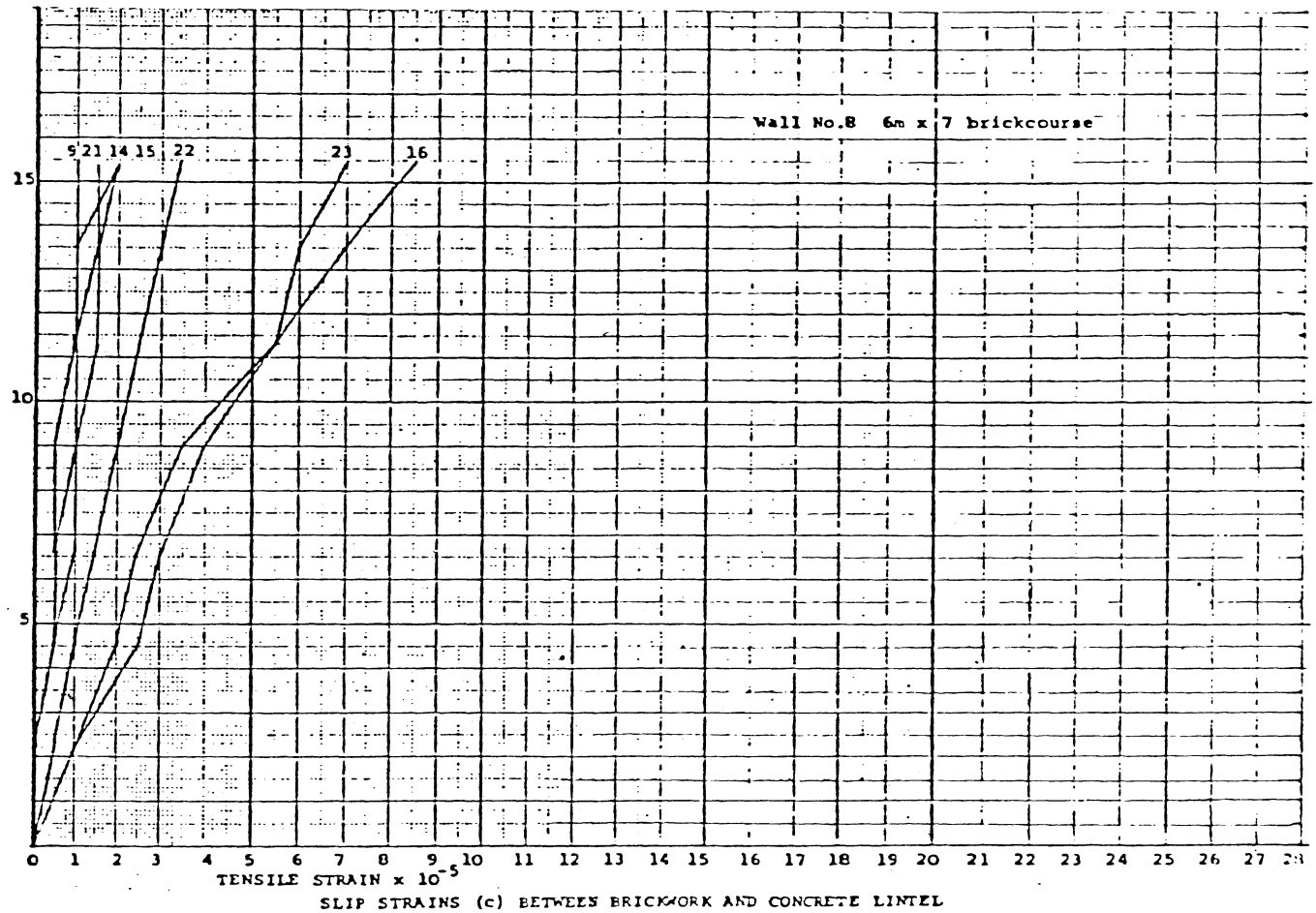
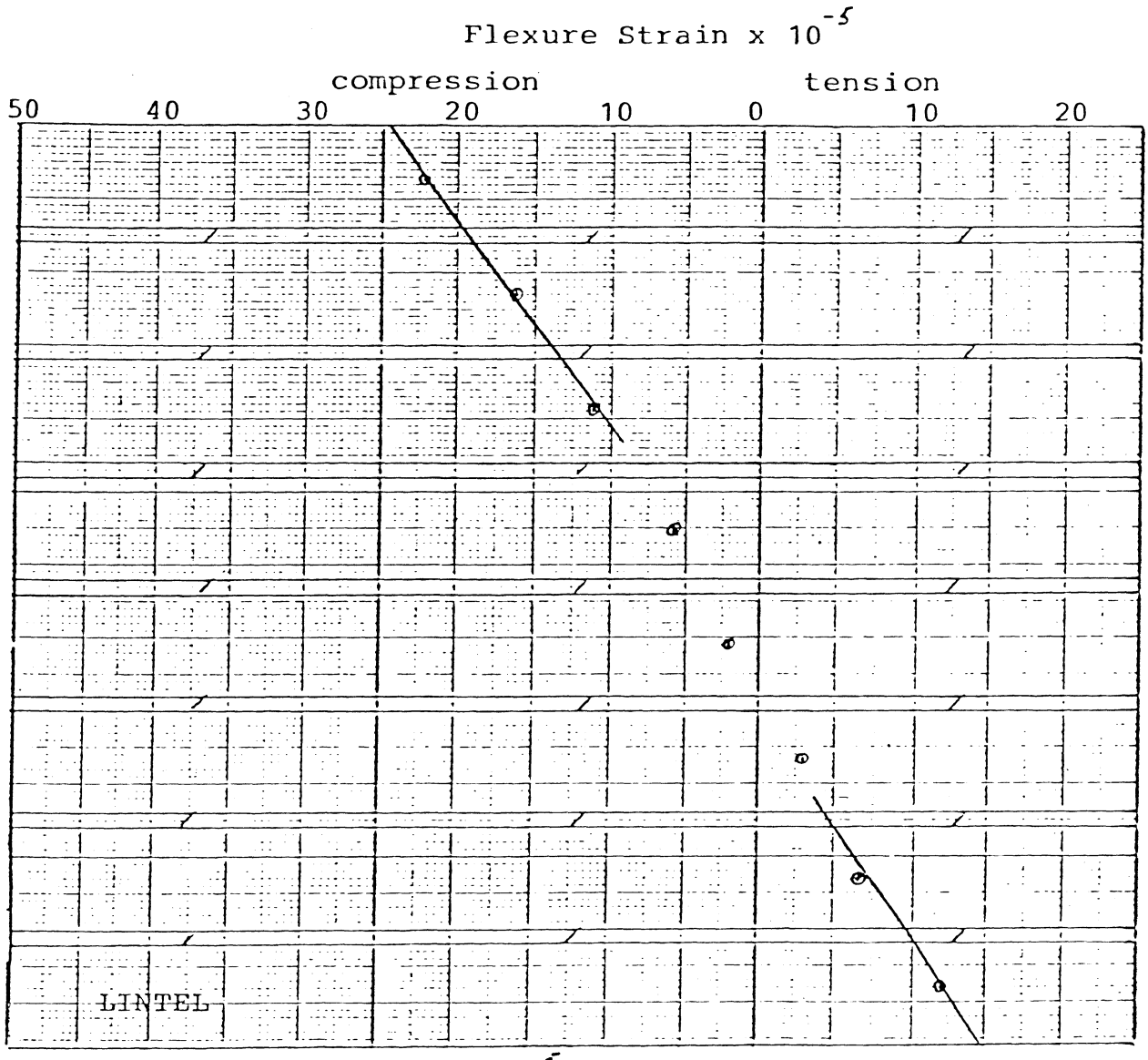


Figure B52

The measured top and bottom maximum edge flexure strains were determined by plotting to scale, the strains measured at the centre of each brick course and centre of lintel against wall height. The values being taken at the maximum moment recorded. For wall 8 this was determined as below.

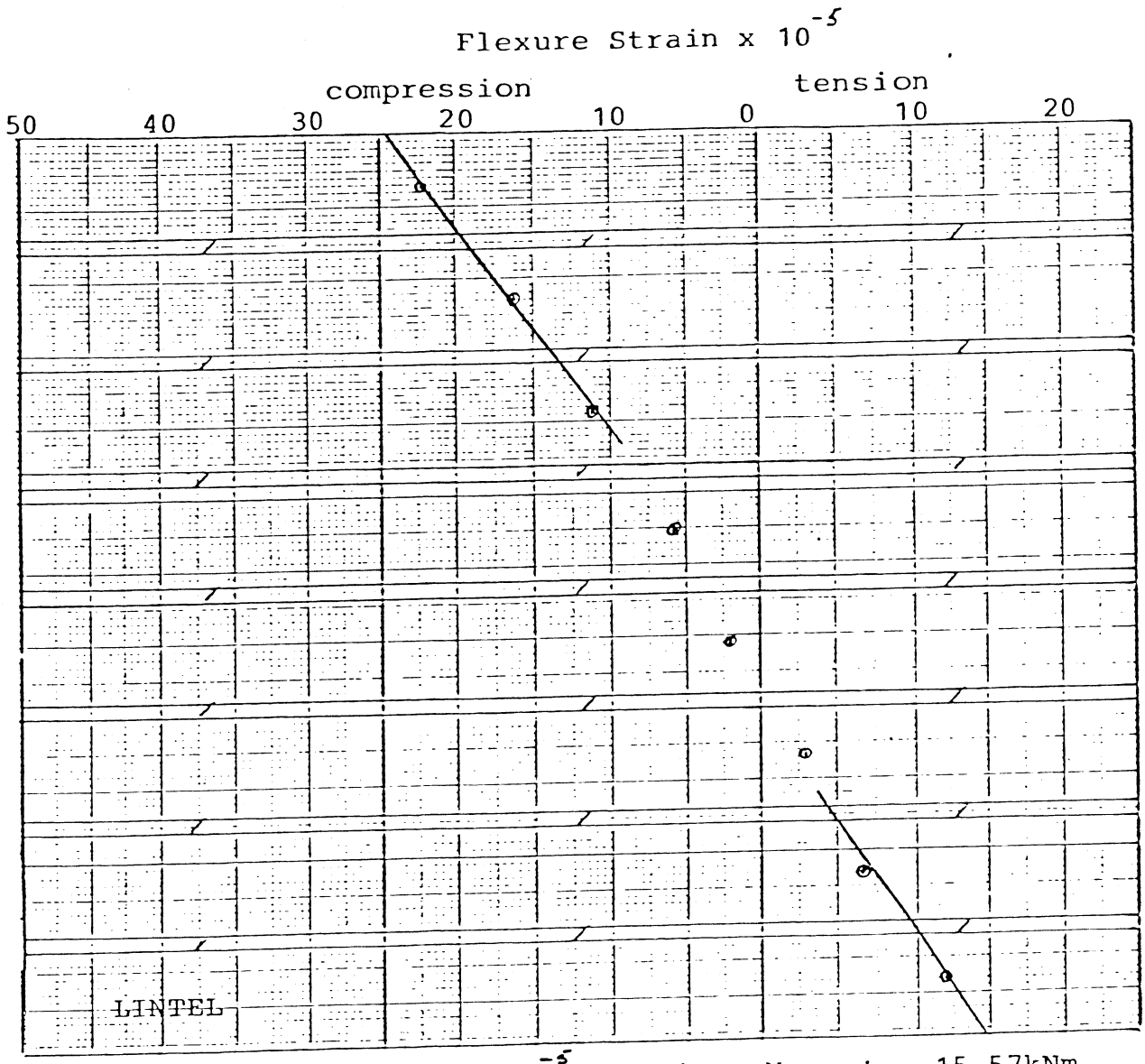


Top Edge Strain = 24,5 x 10^{-5} Maximum Moment = 15,57kNm

Bottom Edge Strain = 14,5 x 10^{-5}

Figure B.53

The measured top and bottom maximum edge flexure strains were determined by plotting to scale, the strains measured at the centre of each brick course and centre of lintel against wall height. The values being taken at the maximum moment recorded. For wall 8 this was determined as below.



Top Edge Strain = 24,5 x 10^{-5} Maximum Moment = 15,57kNm

Bottom Edge Strain = 14,5 x 10^{-5}

Figure B.53

WALL 8 - 6m x 7 Brick course

Comments were given on the following test results.

1. The load test values.
2. The calculated and measured stresses and strains in the wall.
3. The central wall deflection.
4. The failure crack pattern.
5. Further comments on the wall resistance to the loading during the test procedure.

The ultimate resistance moment of the wall produced a value of 15,8kNm, being 1,4 times the SHOFCO value of 11,2kNm. The ultimate resistance moment of the wall produced a value of 15,8kNm, being 1,4 times the SHOFCO value of 11,2kNm. The ultimate shear resistance of the wall produced a value of 15,8kN, being 1,8 times the empirical value of 8,75kN.

The maximum load test tensile flexure stress in the lintel of 6,45MPa was 22 per cent above the calculated result of 4,7MPa. The maximum load test compressive flexure stress in the brickwork of 1,91MPa was 22 per cent above the calculated result of 1,57MPa.

The graph of flexure strains (a) versus moment showed a fairly uniform strain increase with moment. The diagonal compressive strains 12,13,19 and 20 were grouped closely together in magnitude ranging from $4,5x10^{-5}$ to $5,5x10^{-5}$. The diagonal tensile strains also formed a group of nearly equal magnitudes.

The slip strains in this wall increased in magnitude from the outer ends of the wall inwards towards the centre

of the wall, the minimum values at 14 and 21 being $2,0x10^{-5}$ and $1,5x10^{-5}$ respectively, the maximum value at 16 and 23 being $8,7x10^{-5}$ and $7,0x10^{-5}$ respectively. The vertical strain at 9 running up the centre line of the wall, connecting the lintel to the brickwork produced a maximum value of $3,0x10^{-5}$.

The measured central wall deflection, taken at an end wall reaction of 11,3kN when the central deflection gauge was removed in case of wall failure gave a value of 2,05mm, being 1,2 times the calculated central deflection of 1,65mm. The measured results were not on a smooth curve but remained fairly close to the calculated results. As can be seen from the graphs depicting flexure strains, diagonal strains and slip strains there was no failure forecast in the wall. Hair line cracks were noted on both sides of the wall, travelling through the wall at approximately consistent rates.

The wall failed just after the last series of measurements had been taken through a sudden slip failure near the right hand support between the lintel and brickwork which combined with a diagonal failure starting approximately one metre in from the right hand support. The brickwork as a whole unit to the right of this diagonal was pushed out approximately 2cm to the right. The slip failure carried on throughout the length of the wall and irregular crack patterns formed running diagonally both ways up the wall near the centre line of the wall.

When the load was removed the wall remained in its failed collapsed position.

Wall No.9 - 6m x 9 brickcourses

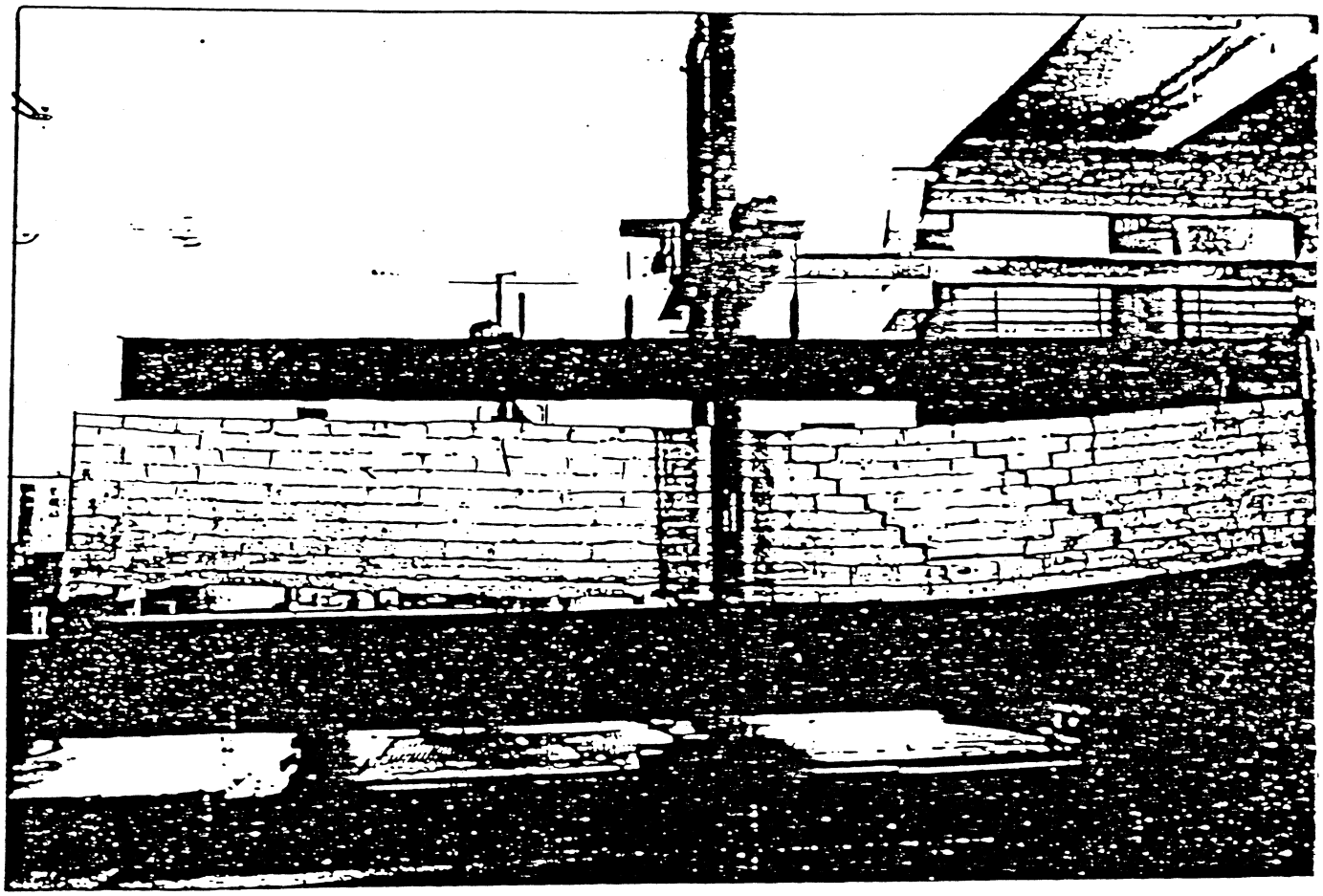
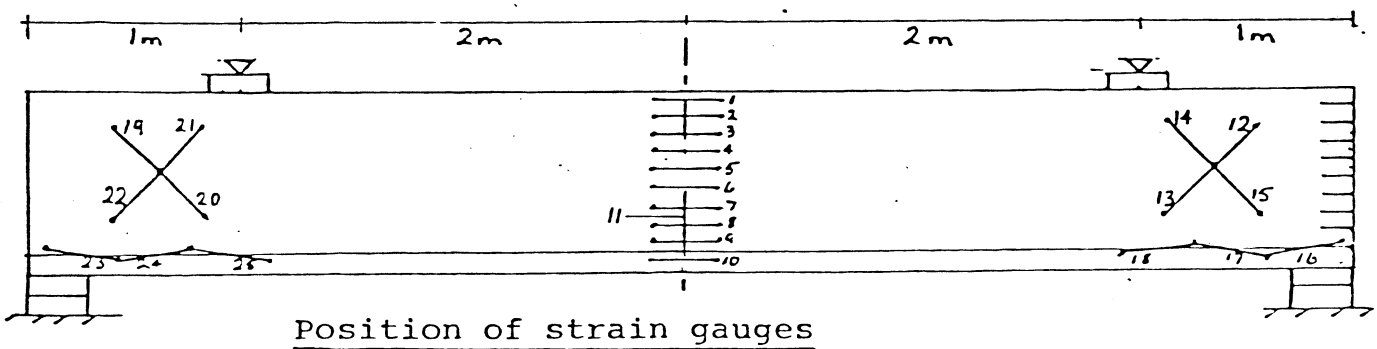


Figure B53

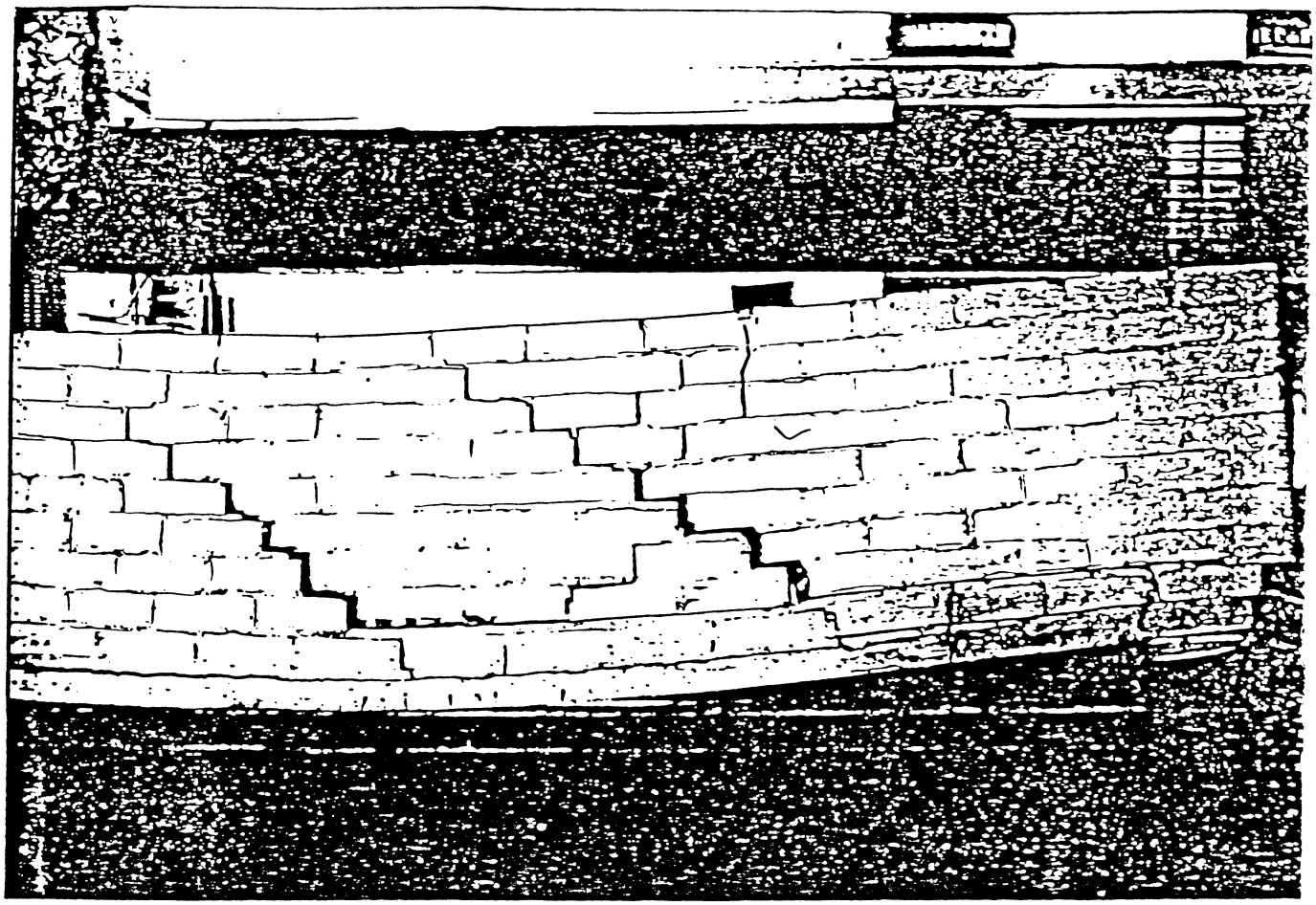
B54



Position of strain gauges

Figure B54 (a)

Wall No.9



Failure crack pattern

Figure B55

WALL NO 9 - 6m x 9brickcourse

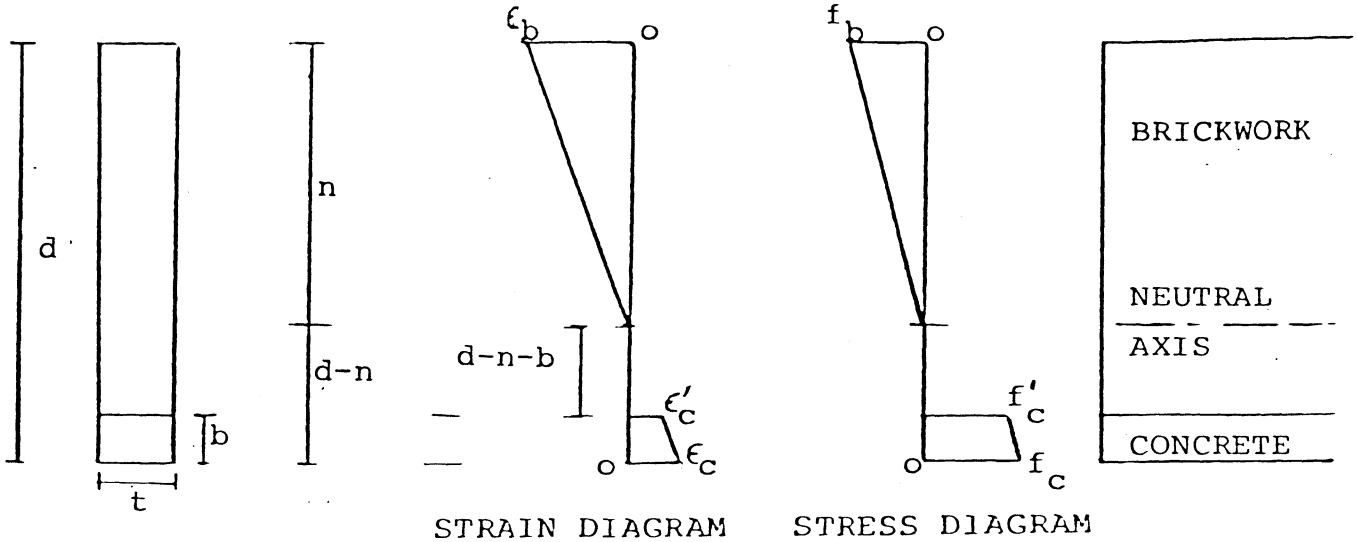


Figure B.56

E_b = 8,7GPa E_c = 44,5GPa b = 70mm t = 105mm d = 790mm

m = modular ratio = E_c/E_b = 44,5/8,7 = 5,1

$$n = \frac{-2mb \pm \sqrt{(2mb)^2 - 4mb(b-2d)}}{2} = 459,4mm$$

$$f_b = \frac{E_b nM}{E_b\frac{n}{3}t + E_c\frac{bt}{2}2(d-n) + 2b(n-d+\frac{b}{3})} = \underline{2,06MPa \text{ (calculated)}}$$

$f_b = E_b\epsilon_b = 8,7x10^3x26,5x10^{-5} = \underline{2,30MPa \text{ (measured)}}$

$$f_c \frac{E_c(d-n)M}{E_b\frac{n}{3}t + E_c\frac{bt}{2}2(d-n) + 2b(n-d+\frac{b}{3})} = \underline{7,6MPa \text{ (calculated)}}$$

$f_c = E_c\epsilon_c = 44,5x10^3x12,0x10^{-5} = \underline{5,34MPa \text{ (measured)}}$

Comparison of Load Test Results and Analytical Results

Table B.29

	Load Test Results	Analytical Results
Maximum stress in brickwork	2,3MPa	2,06MPa
Maximum stress in concrete	5,34	7,6MPa

Table B10 - Wall No.9 6m x 9 brickcourse

End reaction kN	Shear in shear span kN	Moment in flexure span kNm	Flexure strains x 10^{-5} at positions numbered on walls									
			1	2	3	4	5	6	7	8	9	10
0	0	0	0	0	0	0	0	0	0	0	0	0
2,23	2,23	2,23	-3,0	-1,0	-1,5	-1,0	-1,0	0	0	+0,5	+1,0	+2,5
4,45	4,45	4,45	-4,0	-3,0	-2,5	-2,0	-2,5	0	0	+0,5	+1,0	+2,5
6,67	6,67	6,67	-4,5	-3,0	-2,5	-2,5	-3,0	-1,0	-0,5	+0,5	+2,5	+3,0
8,9	8,9	8,9	-5,5	-3,0	-2,5	-2,5	-2,0	-1,0	-1,5	-1,5	+2,5	+3,0
11,13	11,13	11,13	-7,0	-5,0	-3,5	-3,0	-2,5	-0,5	-0,5	+1,0	+2,5	+3,0
13,35	13,35	13,35	-9,0	-5,0	-4,0	-4,0	-4,0	-3,5	-2,5	+0,5	+3,5	+4,0
15,58	15,58	15,58	-14,5	-9,5	-5,0	-5,0	-4,5	-3,5	-3,5	+1,0	+4,0	+6,5
17,8	17,8	17,8	-20,0	-14,0	-9,0	-8,0	-7,0	-5,0	-6,0	-0,5	+5,0	+7,5
20,03	20,03	20,03	-25,0	-22,0	-16,5	-9,0	-7,0	-5,0	-6,0	+2,5	+6,0	+10,0
22,25	22,25	22,25	F	A	I	L	U	R	E			

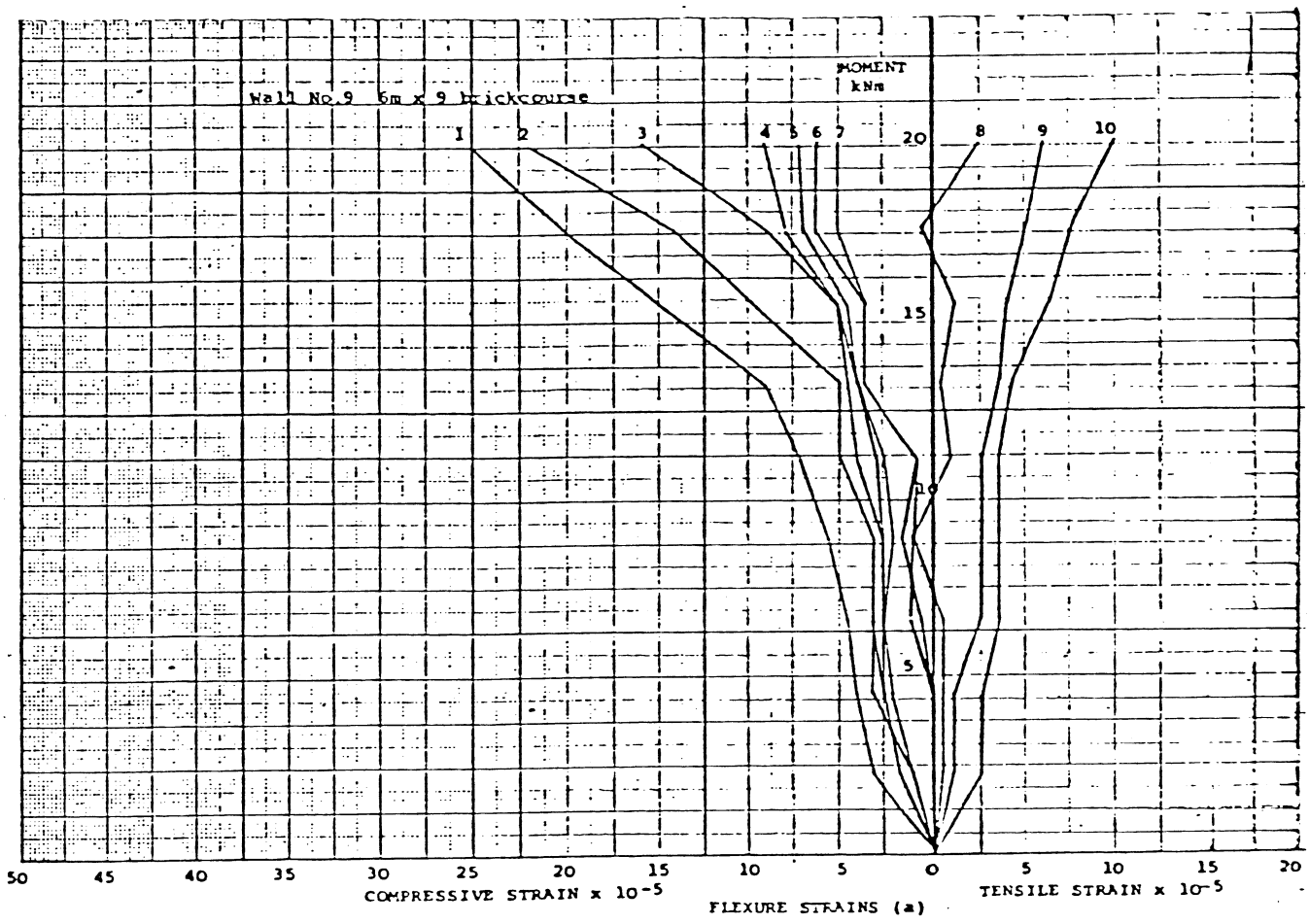


Figure B57

Table [illegible] Wall No. 9 (6m x 9 brickcourses)

End reaction kN	Shear in shear span kN	Moment in flexure span kNm	Diagonal strains x 10^{-5} at positions numbered on wall 12	13	14	15	19	20	21	22
0	0	0	0	0	0	0	0	0	0	0
2,23	2,23	2,23	−0,5	+2,0	0	0	0,5	0	0	−0,5
4.45	4.45	4.45	−1,0	+2,0	0	-1,0	1,0	0,5	−0,5	−1,0
6,67	6,67	6,67	−1,0	+2,5	−3,0	−1,0	1,0	0,5	−1,0	−1,5
8,9	8,9	8,9	−1,0	+4,0	−3,0	−2,0	1,0	1,5	−1,0	−2,0
11,13	11,13	11,13	−1,0	+3,0	−2,5	−3,0	1,5	2,0	−1,5	−3,5
13,35	13,35	13,35	−0,5	+4,0	−2,5	−3,0	1,5	2,5	−2,0	−4,5
15,58	15,58	15,58	−0,5	+3,0	−2,5	−4	1,5	2,5	−2,5	−5,0
17,8	17,8	17,8	−1,0	+2,0	−5,5	−5,5	2,0	5,5	−3,0	−8,5
20,03	20,03	20,03	−2,0	+1,5	−6,5	−8,5	2,0	13,0	−4,5	−9,0
22,25	22,25	22,25	F	A	I	L	U	R	E	

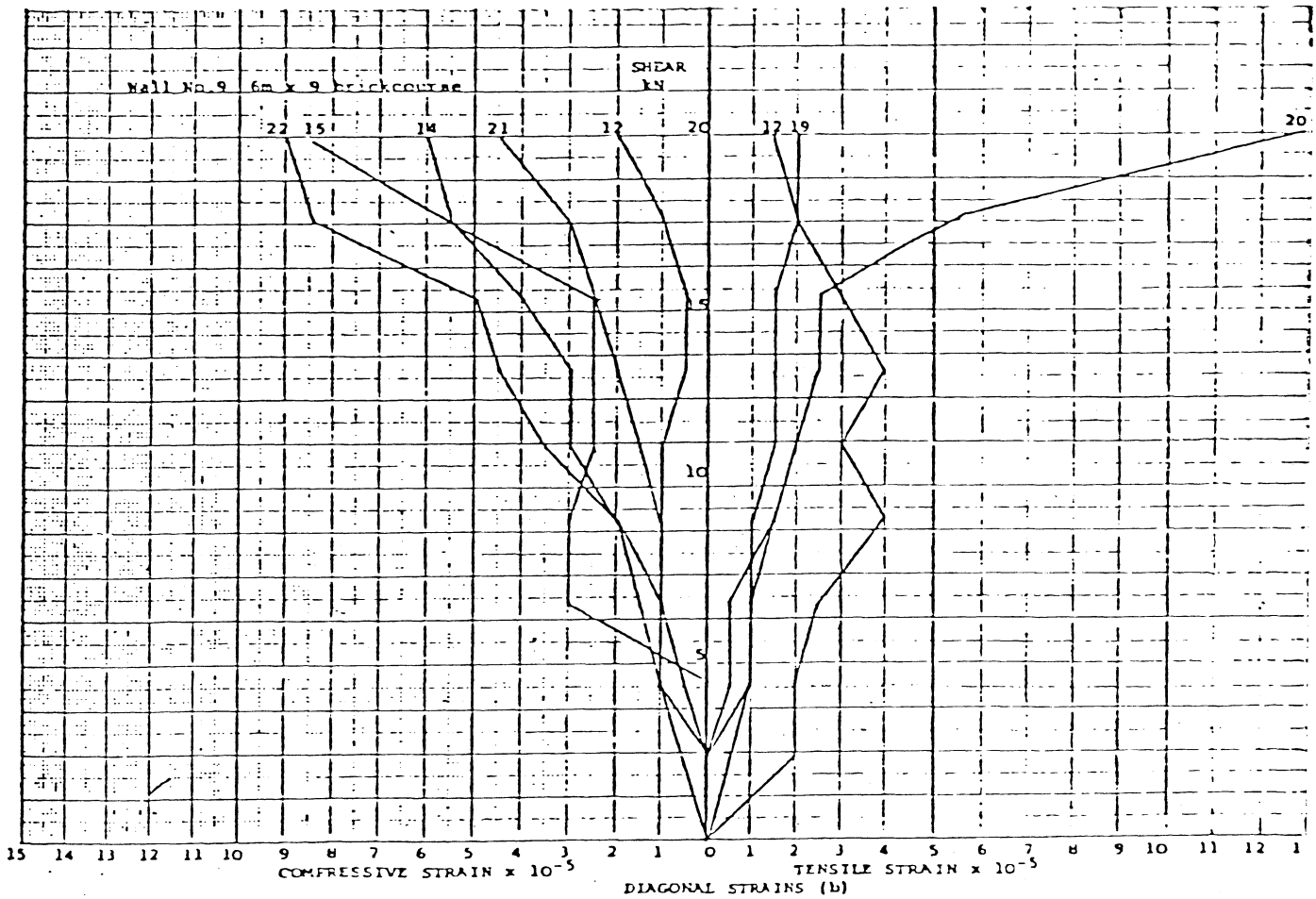
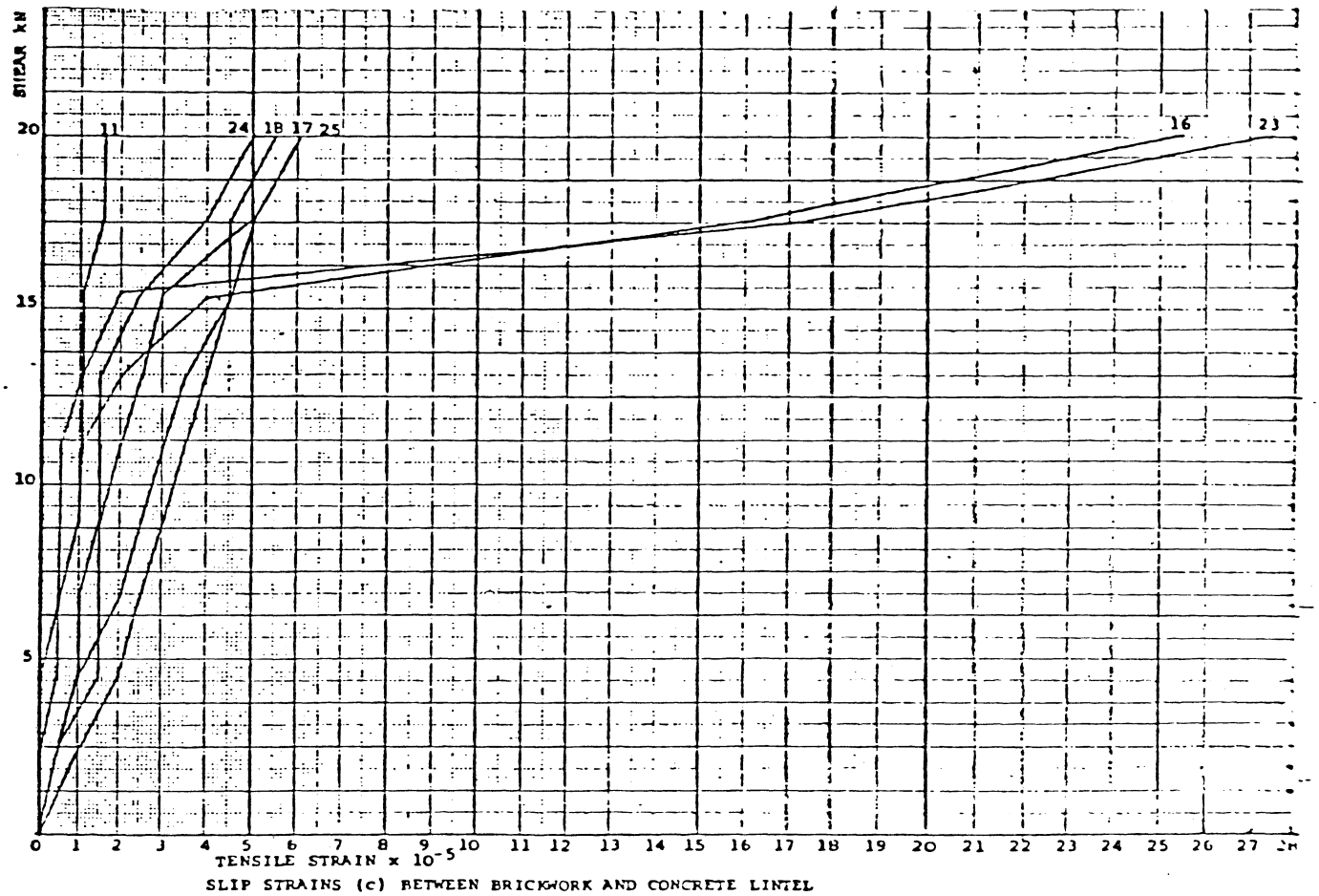


Figure P5B

Table B32 - Wall No.9 6m x 9 brickcourse

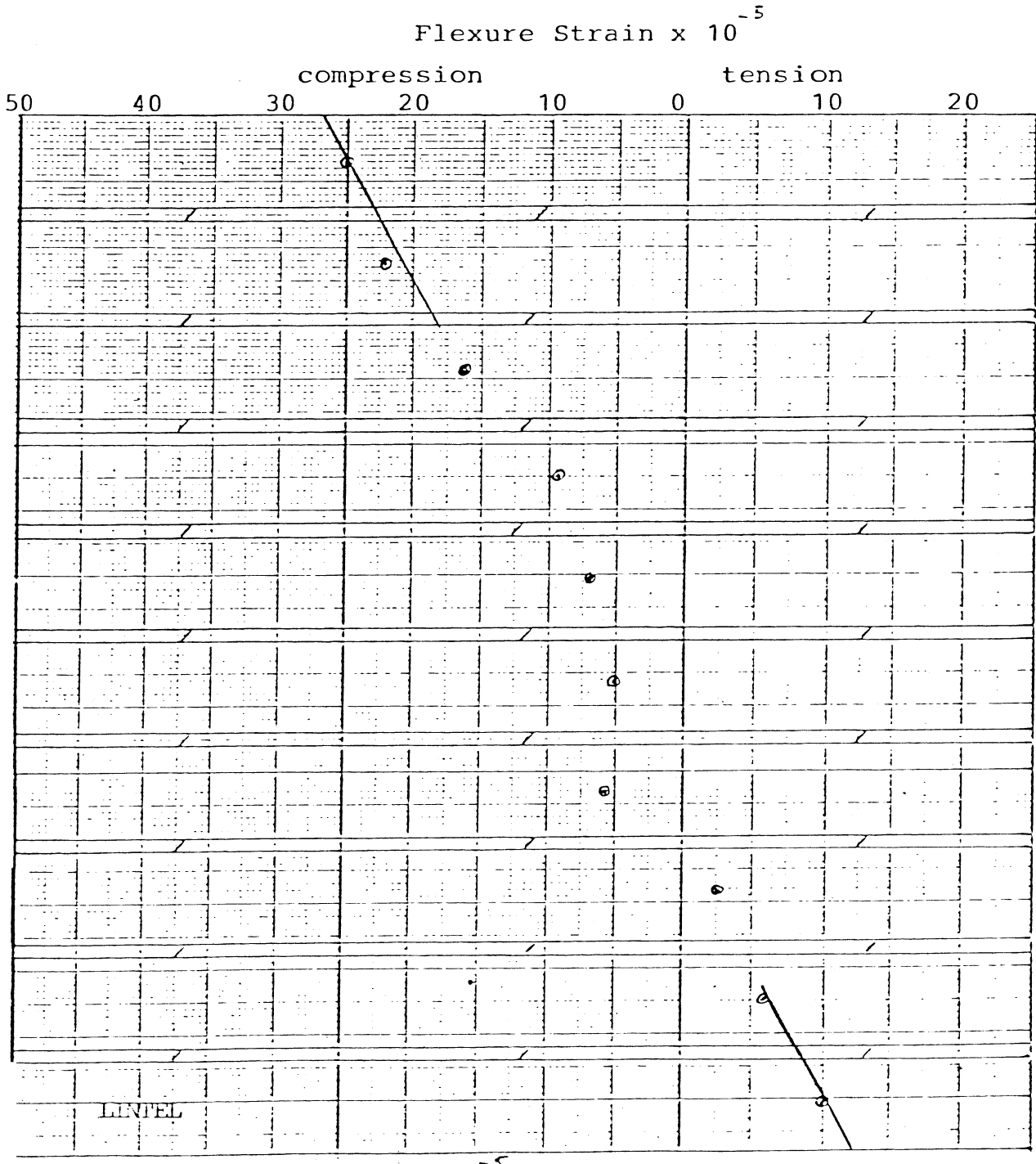
End reaction kN	Shear in shear span kN	Moment in flexure span kNm	Slip strains x 10^{-5} between brickwork and lintel at positions numbered on wall							Central wall deflection mm
			16	17	18	23	24	25	11	
0	0	0	0	0	0	0	0	0	0	0
2,23	2,23	2,23	0	0	1,0	0	0,5	0,5	0	0,21
4,45	4,45	4,45	0,5	1,0	2,0	0,5	1,5	1,0	0	0,42
6,67	6,67	6,67	0,5	1,0	2,5	0,5	1,5	2,0	0,5	0,68
8,9	8,9	8,9	1,0	1,5	3,0	1,0	1,5	2,5	0,5	0,77
11,13	11,13	11,13	1,0	2,0	3,5	1,0	1,5	3,0	0,5	0,96
13,35	13,35	13,35	2	2,5	4,0	1,0	1,5	3,5	1,0	1,24
15,58	15,58	15,58	4	3,0	4,5	2,0	2,5	4,5	1,0	
17,8	17,8	17,8	16,5	5,0	4,5	17,5	4,0	5,0	1,5	
20,02	20,03	20,03	25,5	6,0	5,5	27,5	5,0	6,0	1,5	
22,25,	22,25	22,25	F	A	I	L	U	R	E	



SLIP STRAINS (c) BETWEEN BRICKWORK AND CONCRETE LINTEL

Figure B59

The measured top and bottom maximum edge flexure strains were determined by plotting to scale, the strains measured at the centre of each brick course and centre of lintel against wall height. The values being taken at the maximum moment recorded. For wall 9 this was determined as below.



Top Edge Strain = 26,5 x 10^{-5} Maximum Moment = 20,03kNm

Bottom Edge Strain = 12,0 x 10^{-5}

Figure B.60

WALL 9 - 6m x 9 Brick course

Comments were given on the following test results.

1. The load test values.
2. The calculated and measured stresses and strains in the wall.
3. The central wall deflection.
4. The failure crack pattern.
5. Further comments on the wall resistance to the loading during the test procedure.

The ultimate resistance moment of the wall produced a value of 22,25kNm, being 1,3 times the SHOFCO value of 17kNm. The ultimate shear resistance of the wall produced a value of 22,25kN, being 1,9 times the SHOFCO value of 11,5kN.

The maximum load test tensile flexure stress in the lintel of 5,34MPa was 42 per cent below the calculated result of 7,60MPa. The maximum load test compressive flexure stress in the brickwork of 2,30MPa was 12 per cent above the calculated result of 2,06MPa.

The graph of the flexure strains (a) versus moment showed a non-uniform increase throughout the total loading range. The diagonal strains (b) also produced very irregular and varying values throughout the total loading range, with several of the strains increasing and then decreasing and overlapping one another.

The diagonal strains at 22 and 15 produced maximum compressive values of $9,0 \times 10^{-5}$ and $8,5 \times 10^{-5}$ respectively. The diagonal strains at 13 and 20 produced maximum tensile values of $1,5 \times 10^{-5}$ and $13,0 \times 10^{-5}$ respectively.

The slip strains (c) at 16 and 23, between the lintel and brickwork at the outer ends of the wall produced maximum tensile values of $25,5x10^{-5}$ and $27,5x10^{-5}$ respectively.

The slip strains at 17, 18, 24 and 25 further in to the centre of the wall produced a maximum value of $6,0x10^{-5}$ about 25 per cent of the outer slip strains. The vertical strain at 11, running up the centre line of the wall produced a maximum value of $1,5x10^{-5}$.

The measured central wall deflection taken at an end reaction of 13,35kN when the central deflection gauge was removed in case of wall failure gave a value of 1,24mm, being 1,3 times the calculated value of 0,96mm. The measured values did not produce a smooth curve, but remained fairly close to the calculated values.

As can be seen from the photographic reproduction, the final wall failure was produced by a slip failure between the lintel and brickwork at the right hand support and also between the lowest layer of bricks and the one above it which continued on into a diagonal shear failure. The brickwork as a whole unit between this diagonal failure and the right hand end of the wall was displaced approximately three centimetres to the right. A second diagonal failure in the brickwork was produced in the flexure span under the ultimate load when the slip failure between the lintel and the brickwork spread across the whole length of the wall. The wall remained in its collapsed position when the load was removed.

Hair line cracks were noted running through the left hand side of the wall at the lower load of approximately ·9kN, the right hand side of the wall remaining uncracked. Again,

this wall as in wall 4, (the 4m×5 brick course) showed a pattern of energy conservation as energy dissipated itself in the flexing left hand half, the right hand half storing the strain energy and releasing it in a sudden failure.

APPENDIX C

RESULTS OF STRESS/STRAIN RELATIONSHIP FOR CONCRETE CUBE TESTS

Stress/strain relationship for each of the two cubes tested in compression to determine the E value of concrete, referred to on p.

Table

CUBE 1		CUBE 2	
Stress N/mm^2	Strain x 10^{-5}	Stress N/mm^2	Strain x 10^{-5}
0	0	0	0
2,42	3,0	2,42	4,5
4,84	6,25	4,84	8,75
7,26	9,75	7,26	14,5
9,68	15,5	9,68	17,5
12,10	18,25	12,10	22,75
14,53	23,0	14,53	29,75
16,95	30,50	16,95	34,25
19,30	36,50	19,30	40,25
21,72	43,25	21,72	29,75
24,20	53,50	24,20	59,75
26,62	63,25	26,62	67,50
29,04	71,75	29,04	75,75

Table C,1

APPENDIX D

DERIVATION OF THEORETICAL FORMULAE USED

Theoretical derivation of composite wall action formulae neglecting tensile strength in brickwork

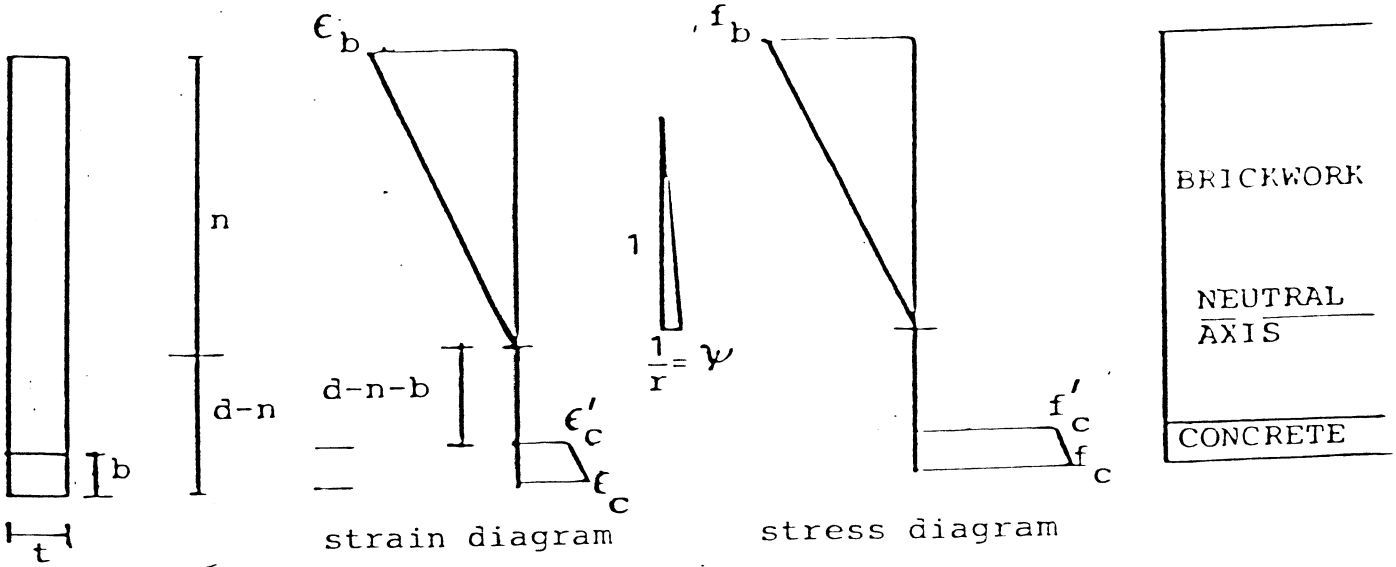


Figure D.1

$\epsilon_b = n.\psi$ $\quad f_b = E_b.n.\psi$ $\quad \frac{E_c}{E_b} = m$

$\epsilon'_c = (d-n-b)\psi$ $\quad f'_c = E_c(d-n-b)\psi$

$\epsilon_c = (d-n)\psi$ $\quad f_c = E_c(d-n)\psi$

Using subscript 'b' for brickwork and subscript 'c' for concrete.

Equating Forces

$$b.\frac{n.\psi.t.n}{2} = E_c\left[(d-n-b) + (d-n)\right]\frac{\psi}{2}.t.b$$

$$= m(2.d-2.n-b)b$$

$$+ 2.m.b.n + m.b^2 - 2.m.b.d = 0$$

$$+ 2.m.b.n + m.b(b-2.d) = 0$$

$$= \frac{-2.m.b \pm \sqrt{\left[(2.m.b)^2 - 4.m.b(b-2.d)\right]}}{2}$$

MOMENT M = FORCE LEVER ARM

$$M = f_b.\frac{n.t}{2}.\frac{2}{3}.n + f'_c.\frac{b.t}{2}(d-n-\frac{2}{3}.b) + f_c.\frac{b.t}{2}(d-n-\frac{b}{3})$$

$$\chi = \frac{f_b}{E_b.n} = \frac{f'_c}{E_c(d-n-b)} = \frac{f_c}{E_c(d-n)}$$

$$\frac{M}{\chi} = E_b.\frac{n^3.t}{3} + E_c(d-n-b)\frac{b.t}{2}(d-n-\frac{2}{3}.b) + E_c(d-n)\frac{b.t}{2}(d-n-\frac{b}{3})$$

$$\frac{M}{\chi} = E_b.\frac{n^3.t}{3} + E_c.\frac{b.t}{2}\left[2(d-n)^2 + 2b(n-d+\frac{b}{3})\right]$$

$$\chi = \frac{M}{E_b.\frac{n^3.t}{3} + E_c.\frac{b.t}{2}\left[2(d-n)^2 + 2b(n-d+\frac{b}{3})\right]}$$

$$f_b = E_b.n.\chi = \frac{E_b.n.M}{E_b.\frac{n^3.t}{3} + E_c.\frac{b.t}{2}\left[2(d-n)^2 + 2b(n-d+\frac{b}{3})\right]}$$

$$f_c = E_c(d-n).\chi = \frac{E_c(d-n).M}{E_b.\frac{n^3.t}{3} + E_c.\frac{b.t}{2}\left[2(d-n)^2 + 2b(n-d+\frac{b}{3})\right]}$$

APPENDIX E

SHOFCO VALUES FOR THE WALLS

The SHOFCO values for Moment and Shear for the walls were taken from SHOFCO (Structural Hollow Floor Co.) Prestressed Concrete Products recommended strength values of brickwork without reinforcement supported on lintels. The SHOFCO curves are related to the moment and shear resistance curves obtained from stresses given in accordance with SABS 029-1962.

The stresses and related factors taken from this reference were used to produce curves of moment and shear resistance of walls composed of lintels supporting five, seven and nine brickcourses. A full calculation of moment and shear resistance for a seven brickcourse wall is given, the lintel used, being for spans greater than 4m.

The five and nine brickcourse wall results were obtained in the same way and the results used to obtain the curves shown in Fig.E.3

In obtaining these curves a low compressive strength brick was used (20,1 MPa-28,1MPa) set in a 1:4 cement/sand mortar with lintel size 105 x 70 with 4, 4,5mm diameter wires. This steel area being used for the longest spans made, greater than 4m.

Moment and Shear Resistance Curves obtained for composite wall of lintel and seven brickcourses.

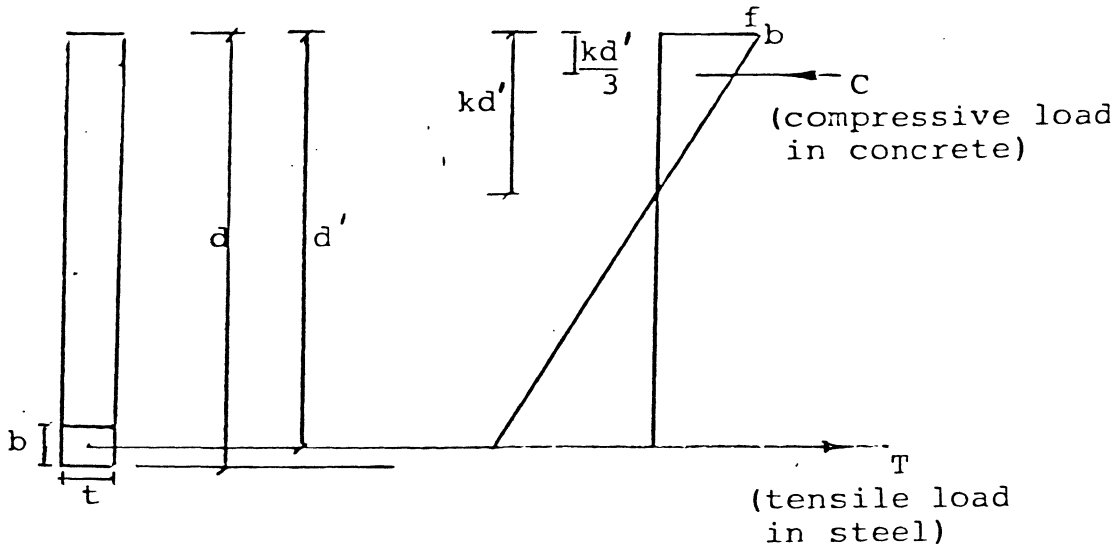


Figure E.1

Extract from SABS 029 1962

Quality of Brick f_b(ult) = 20,1 - 28,1MPa

Allowable working bending stress (f_b) = 1,8MPa

Allowable shear stress v = 0,20MPa

$E_s/E_b = m'$ = 27

$E_s/E_c = m''$ = 10

Allowable Shear Force = $V = v.t(d-kd'/3)$

T_w = Allowable working tension per wire = 16kN (4,5mm dia)

$C/f_b = t.kd'/2 = 105.kd'/2 = 52,5kd'$

$T/f_b = \frac{(d'-kd')}{kd'} \cdot \frac{m'}{m''}(A_l + m''.A_s)$

A_l = Lintel area A_s = Steel area

$T = f_b \frac{(d-kd')}{kd'} (\beta)$

k and β are constants

For balanced design C = T

$t.\frac{(kd')}{2} = \beta \frac{(d'-kd')}{kd'}$

$$t.\frac{(kd')^2}{2\beta} + kd' = d'$$

$\beta = \frac{m'}{m''}(A_1 + m''A_s)$ is solved for the values of $m' = 27$ and $m'' = 10$ and for a lintel size of 105×76 and a steel area of four wires of 4,5mm diameter.

$\beta = 23,26\times10^3 mm^2$

$$\frac{105(kd')^2}{2.23,26.10^3} + kd' = d'$$

for $kd' = 100mm$ $d' = 122,57mm$

for $kd' = 200mm$ $d' = 290,26mm$

for $kd' = 300mm$ $d' = 503,13mm$

for $kd' = 400mm$ $d' = 761,1mm$

for $kd' = 500mm$ $d' = 1064,3mm$

for $kd' = 600mm$ $d' = 1414,5mm$

A graph of $kd' - d'$ is shown plotted in Figure E.2

For a seven brickcourse wall

$d = 630mm$ $d' = 630-70/2 = 595mm$

from FIGURE E.2 $kd' = 337mm$

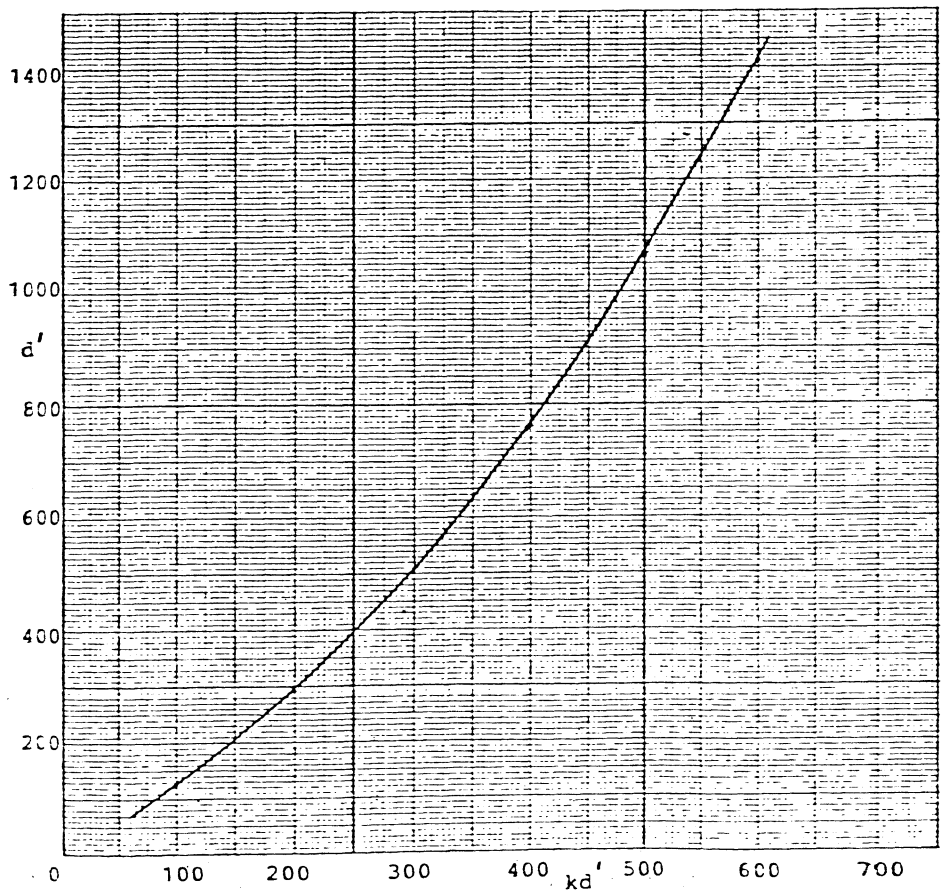


FIGURE E.2

$$C = f_b \cdot \frac{t.kd'}{2} = \frac{1,8.105.337.10^{-3}}{2} = 31,85kN$$

Resistance moment (brickwork) $= C(d'-\frac{kd'}{3}) = 31,85(595-\frac{337}{3})10^{-3}$

$= \underline{15,37kNm}$

$T_{max.} = 4T_w = 4.16kN = 64kN$

Resistance moment (steel) $= T_{max.}(d'-\frac{kd'}{3}) = 64(595-\frac{337}{3})$

$= \underline{30,9kNm}$

C governs resistance

Allowable Shear Force for seven brickcourse wall

$$V = v.t(d-kd'/3) = 0,20.105(630-337/3)10^{-3}kN$$

$\underline{10,8kN}$

Values of Moment Resistance and Shear Resistance were found for the five and nine brickcourse walls and tabulated below.

Number of Brickcourses	Moment Resistance	Shear Resistance
5	9,15 kNm	8,0 kN
7	15,37 kNm	10,8 kN
9	23,5 kNm	13,8 kN

Table E.1

The above results are shown plotted in FIGURE E.3 together with the SHOFCO curves

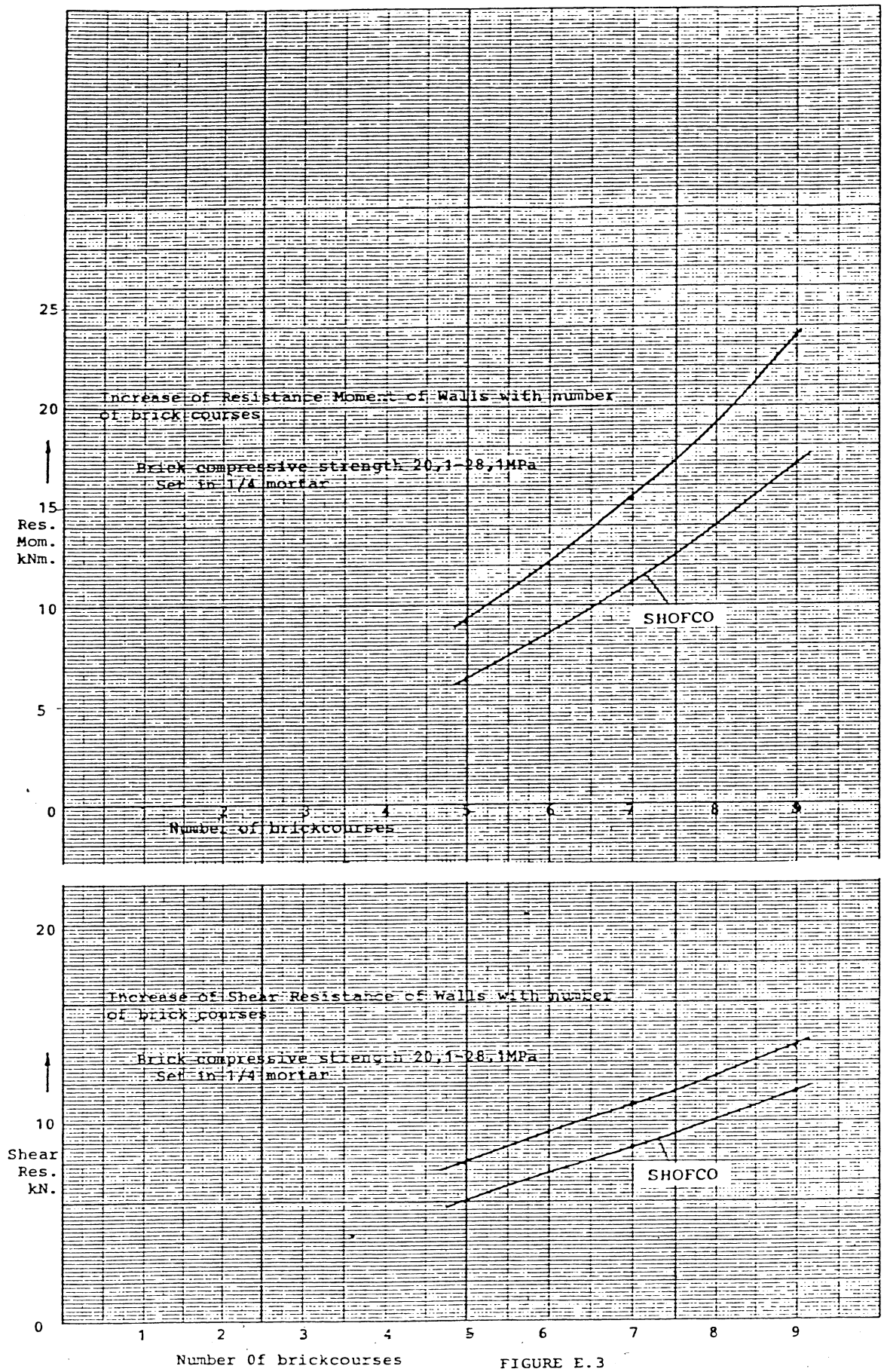

Increase of Resistance Moment of Walls with number of brick courses
Brick compressive strength 20,1-28,1MPa
Set in 1/4 mortar
Res. Mom. kNm.
SHOFCO
Number of brickcourses
Increase of Shear Resistance of Walls with number of brick courses
Brick compressive strength 20,1-28,1MPa
Set in 1/4 mortar
Shear Res. kN.
SHOFCO
Number Of brickcourses

FIGURE E.3

Figure E.4 shows a comparison of the Ultimate Resistance Moment of the walls determined experimentally with the calculated values derived from the formula shown in Appendix E and using the lintels given in Appendix G.

The above two values are within approximately the same range. The calculated values are very high and allow for no factor of safety.

Figure E.5 shows a comparison of the Ultimate Shear Resistance of the walls determined experimentally with the calculated values derived from the formula shown in Appendix E and using the lintels given in Appendix G.

The 4m and 6m spans carrying 5 brick courses gave calculated values close to the ultimate values. The 4m and 6m spans carrying the 7 brick courses gave calculated values of approximately half the ultimate values. The 4m and 6m spans carrying the 9 brick courses gave caculated values of less than the ultimate values.

The 2m spans produced the only big difference in comparison, giving calculated values of approximately one third of the ultimate values.

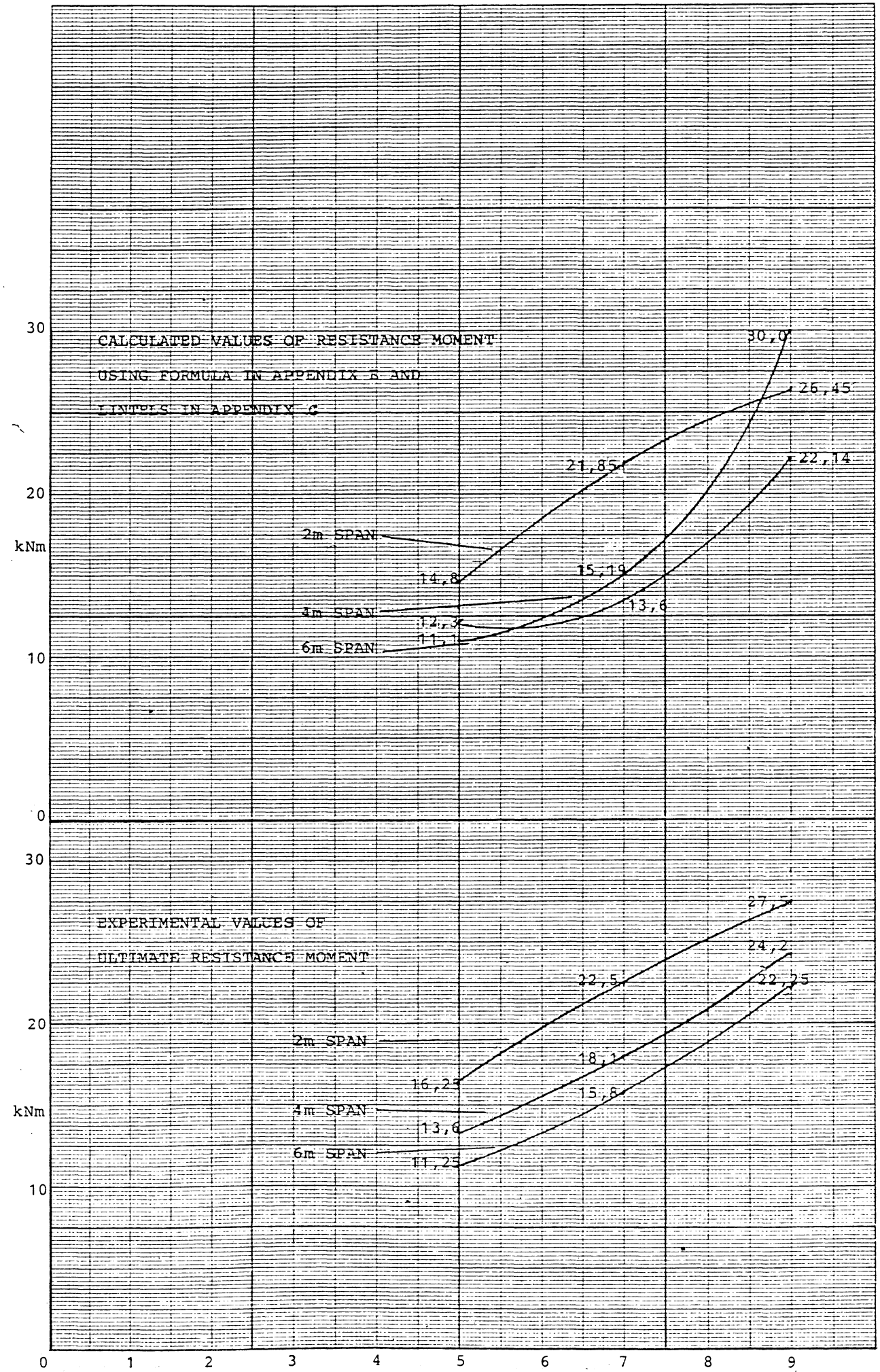

CALCULATED VALUES OF RESISTANCE MOMENT
USING FORMULA IN APPENDIX B AND
LINTELS IN APPENDIX C
30,0
26,45
22,14
21,85
15,19
14,8
13,6
12,3
11,1
2m SPAN
4m SPAN
6m SPAN
EXPERIMENTAL VALUES OF
ULTIMATE RESISTANCE MOMENT
27,7
24,2
22,5
22,25
18,1
16,25
15,8
13,6
11,25
2m SPAN
4m SPAN
6m SPAN
kNm
kNm
30
20
10
0
30
20
10
0
1
2
3
4
5
6
7
8
9
NUMBER OF BRICKWORK COURSES

FIGURE E.4

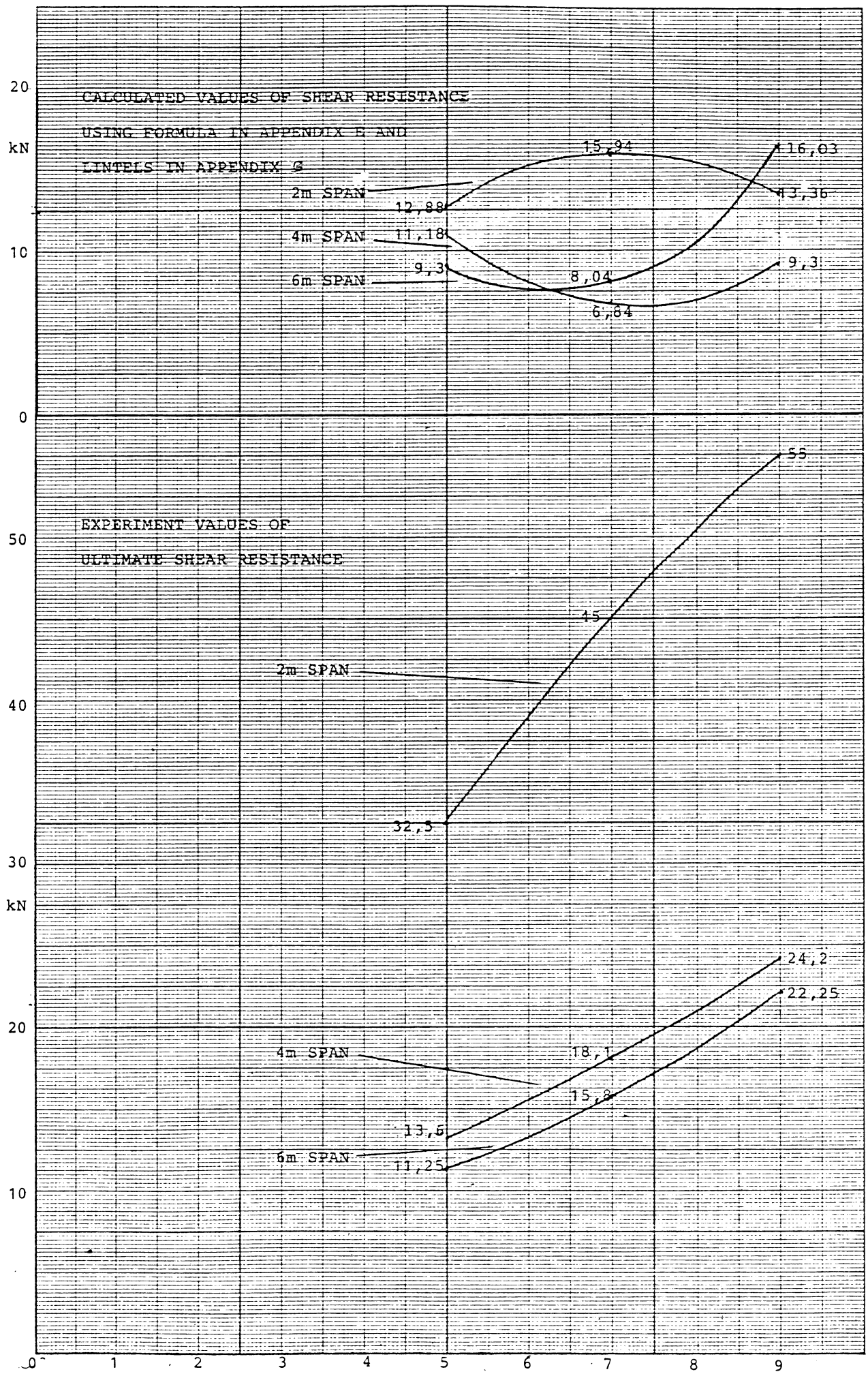


FIGURE E.5 NUMBER OF BRICKWORK COURSES

APPENDIX F

Theoretical Derivation of Central Wall Deflection

Obtaining an equivalent EI in terms of brickwork only, neglecting brickwork on tension side of neutral axis

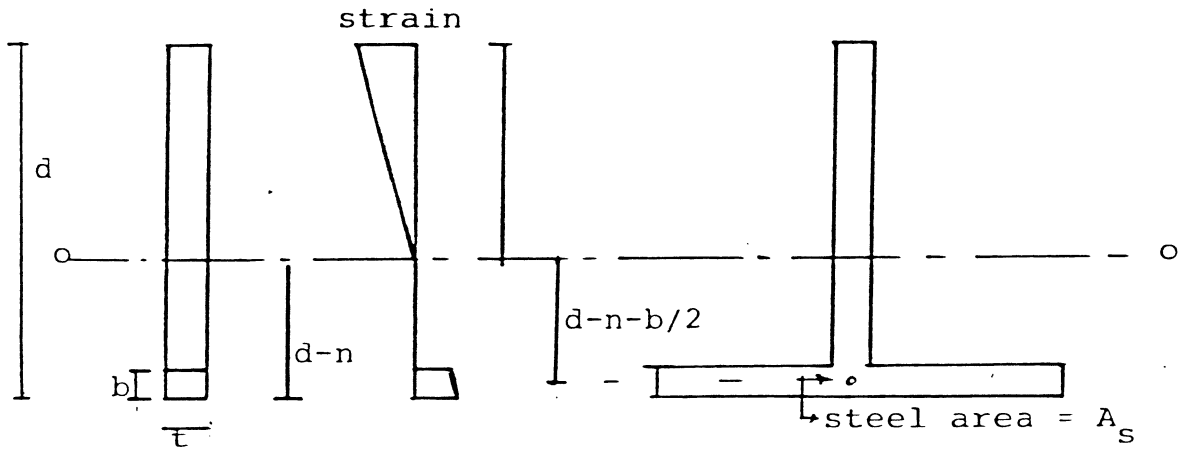


Figure F.1

$E_c/E_b = m$ $\quad E_s/E_b = m'$ $\quad A_s$ = area of steel

Total $I_{oo} = tn^3/3 + tb^3/12 + tb(d-n-b/2)^2 + A_s(d-n-b/2)^2$

Equivalent EI in terms of brickwork only =

$E_b[tn^3/3 + m(tb^3/12 + tb(d-n-b/2)^2) + m'(A_s(d-n-b/2)^2)]$ --

Calculation of Central Wall Deflection

Considering the 4m×7brickcourse wall

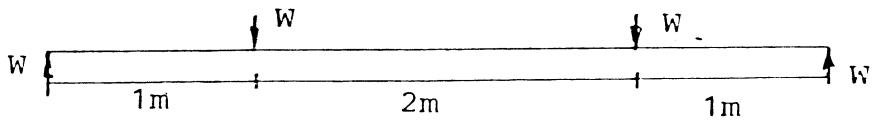


Figure F.2

$EId^2y/dx^2 = Wx - W(x-1) - W(x-3)$

$EIdy/dx = Wx^2/2 - W/2(x-1)^2 - W/2(x-3)^2 + A$

$EIy = Wx^3/6 - W/6(x-1)^3 - W/6(x-3)^3 + Ax + B$

$y = 0 \quad x = 0 \quad B = 0 \;, \quad y = 0 \quad x = 4 \quad A = -1,5W$

Deflection at centre of wall $y = 1,833W/EI$

The equivalent EI in equation 1 is obtained for the 4m×7brickcourse wall by substituting the following terms.

E_b = 8,8GPa E_c = 44,5GPa E_s = 200GPa

$m = E_c/E_b$ = 44,5/8,8 = 5,05 $m = E_s/E_b$ = 200/8,8 = 22,73

t = 105mm n = 385,15mm b = 70mm d = 630mm

A_s = area of five wires of 2,64mm diameter = 27,37mm^2

Equivalent EI = 36,2 10^3 kNm^2

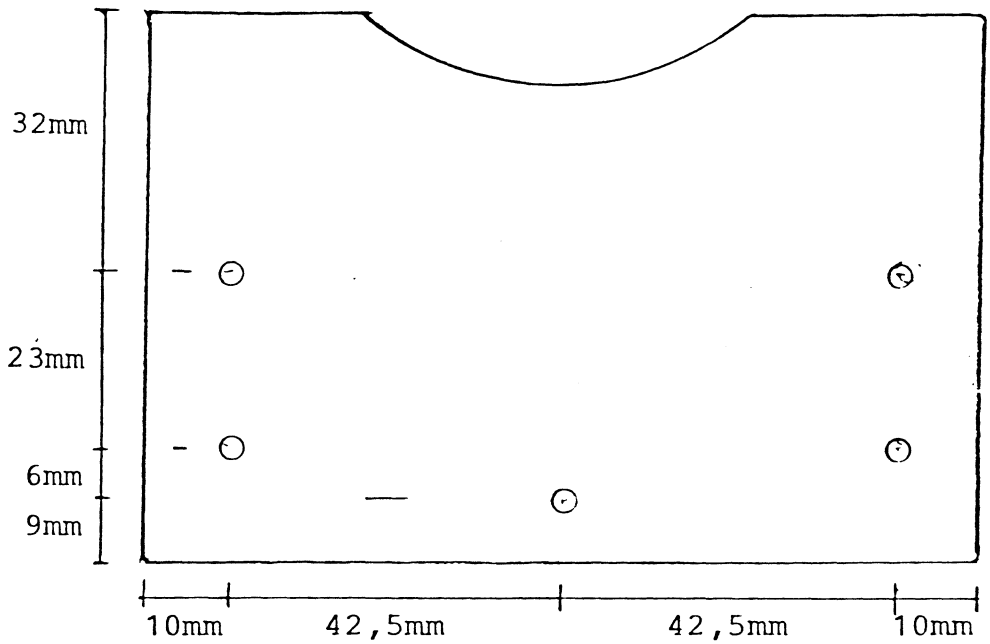
Central wall deflection under loads of 8,9kN is obtained from

$$y = \frac{1,833\ 8,9}{36,2\ 10^3} = 0,45\ 10^3 m = \underline{0,45mm}$$

APPENDIX G

Lintel Specifications

The lintels used in the tests, contained five tendons, each of 2,64mm diameter, placed as shown in Figure



A load of 6kN was initially applied to each tendon , being 70% Of the breaking load of 8,6kN. A 20% loss of load was allowed for giving a final load in each tendon of 4,8kN. The five tendons produce a total prestressing force of 24kN resulting in a maximum prestess of 5MPa

REFERENCES

1. Studies in Composite Construction. Tests on New Government Offices, Whitehall Gardens. National Building Studies. Research Paper No.28. Building Research Station, Watford, England, 1951.

2. Studies in Composite Construction. The Composite Action of Brickpanel Walls Supported on Reinforced Concrete Beams by R.H. Wood, National Building Studies, Research Paper No.13 1952.

3. Elastic Analysis of Composite Walls by S. Rosenhaupt. Structural Division, Bulletin Research Station, Technion - Israel Institute of Technology, Haifa. Vol.10c. 1961, pp.62-67.

4. Experimental Studies of Masonry Walls on Beams by S. Rosenhaupt. Proceedings of the American Society of Civil Engineers. Journal of the Structural Division, June 1962.

5. Small Scale Specimen Testing by Structural Clay Products Research Foundation. Progress Report No.1, Geneva, Illinois, October, 1964.

6. Crushing Tests on Storey-Height Walls 4½ inches thick by S. Prasan, A.W. Hendry and R.E. Bradshaw. Proceedings of the British Ceramic Society, No.4, July 1965.

7. Composite Action of Walls Supported on Beams by A. Coull. Building Science Vol.1, 1966, pp.259-270.

8. Composite Action between Brick Panel Walls and their Supporting Beams by P. Burnhouse. Proceedings of the Institute of Civil Engineers, Vol.43, June 1969, pp.175-194.

9. Studies in Composite Construction; an Elastic Analysis of Wall-Beam Structure by J.R. Colbourne. Paper CP 15/69. Building Research Station, Watford, England, May 1969.

10. A Finite Element Study of Composite Action in Walls Supported on Simple Beams by D.J. Male and P.F. Arbon, Proceedings of Second Australian Conference on Mechanics of Structures and Materials, Paper No.14, August, 1969.

11. A Tentative Design for the Composite action of Heavily Loaded Brick Panel Walls upported on Reinforced Concrete Beams by R.H. Wood and L.G. Simms. Paper CP26/69, Building Research Station, Watford, England, July 1969.