CONCENTRATED LOADS ON BRICKWORK - A PRELIMINARY STUDY

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ABSTRACT Two dimensional elastic finite element analyses are used to carry out a preliminary study of stress distributions in masonry walls subjected to concentrated loads. One analysis assumes masonry to be a homogeneous continuum, the other treats bricks and joints separately. The influence of various parameters on stress distribution is studied. These parameters include the ratio of the loaded area to total area, the modular ratio of the bricks and joints, the location of the load along the top of the wall, and the interaction of parallel loading.

It is shown that the transverse tensile stresses (which would initiate cracking) increase with decreasing loaded area ratio, and with increasing brick/mortar modular ratio. Higher transverse tensile stresses are also obtained when the load is applied eccentrically along the wall. The nature of the load dispersion beneath the concentrated load is also studied, and compared with existing design assumptions.

1. INTRODUCTION

The dispersion of a concentrated force is a problem encountered in many structural applications (e.g. prestressed concrete end blocks, bridge bearings etc.). Stress distributions adjacent to concentrated loads for a homogeneous material are well documented. Normally two types of tensile stresses are produced, splitting stresses beneath the loading point, and bursting or spalling stresses away from the loaded area.

If masonry is assumed to be homogeneous, a concentrated load applied to the top of the wall will produce similar stress distributions. The problem is really three dimensional in nature, particularly if the load is applied by a beam spanning in a direction normal to the wall. For purposes of this investigation however, only the two dimensional problem is studied, with the wall assumed to be in a state of plane stress.

For masonry, the problem is complicated by the fact that the material is not strictly homogeneous, but consists of an assemblage of stiffer bricks set in a more flexible mortar matrix. Failure beneath concentrated loads therefore tends to occur by splitting in the vertical mortar joints (since the joints have low tensile bond strength), followed by the propagation of a vertical crack through brick and bed joint.

Existing design rules for predicting the capacity of walls subjected to concentrated loads are at best approximate, with various assumptions being made to allow for the restraining effect of the more lightly stressed material around the bulb of strain immediately below the loading point. For purposes of checking the stresses within the wall, a 45° angle of load dispersion is usual.

This paper describes a preliminary investigation of this problem using finite element techniques. Elastic finite element models have been used to study the nature of the stress distributions, rather than to predict failure of the wall. Two sets of analyses have been performed. One assumes masonry to be a continuum, the other considers masonry to be an assemblage of separate elastic bricks and joints. The study has investigated variations of stress distribution for different loaded areas, and different modular ratio of the brick and the mortar.

The investigation has also studied the stress distribution for eccentric loading as well as sets of symmetric parallel loads. In the comparisons, emphasis has been placed on variations in transverse tensile stress, as this will critically influence the failure of the wall.

This investigation forms part of an on-going study of the behaviour of walls subjected to concentrated loads, and will be extended to include material non-linearity, progressive failure and three-dimensional effects.

2. PREVIOUS RESEARCH

Most previous analytical studies of concentrated loads on structures have been concerned with stress distributions in the end zones of prestressed concrete beams. Smith and Carter (1) and Smith and Rahman (2) investigated the stresses in vertically loaded walls assuming the brickwork to be both a homogeneous continuum and also an assemblage of elastic bricks and joints. Probst (3) studied the internal distribution of horizontal stresses in masonry subjected to uniform loading around free edges and vertical and horizontal mortar joints. Recently Suter et al (4) investigated the stress distribution in masonry walls subjected to concentrated prestressing forces using a two-dimensional elastic finite element analysis.

The bulk of the experimental studies on concentrated loads has been concerned with the behaviour of concrete structures. Some masonry experiments have been carried out, but these have been limited in nature with no comprehensive design recommendations emerging (5-9).

3. METHOD OF ANALYSIS

3.1 Finite Element Model

Two types of linear elastic finite element models have been used in this investigation. One assumes masonry to be a homogeneous continuum, the other models bricks and joints separately with differing elastic properties. A typical finite element mesh is shown in Figure 1.

Four noded isoparametric elements have been used, with a finer mesh immediately below the point of load application where stress gradients are high. In the analysis it is assumed that there is full contact between the bearing plate and the wall and that no slip occurs at the plate-wall interface.

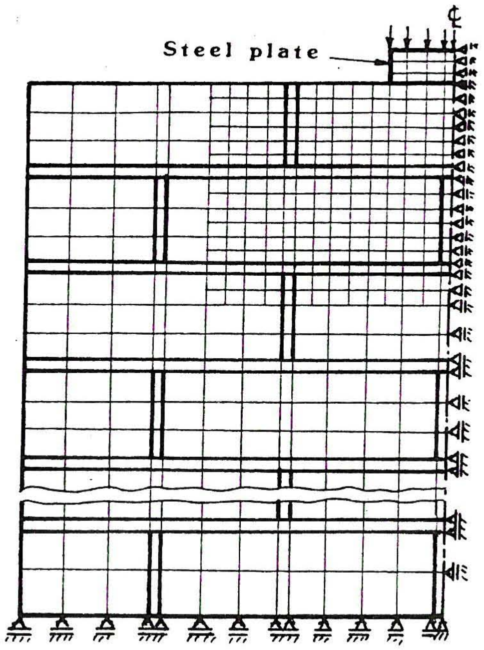


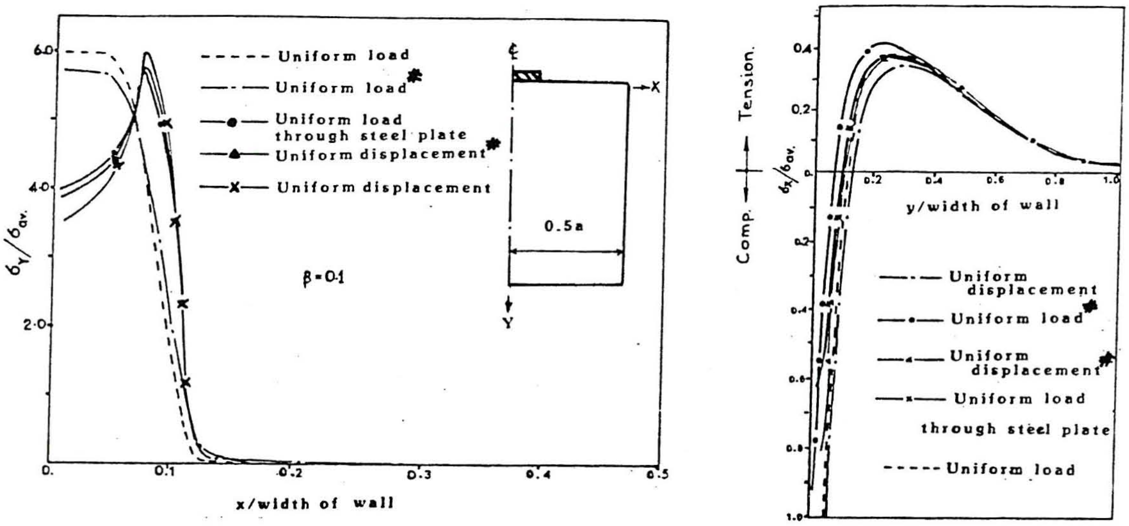
Fig 1 Typical Finite Element Mesh

3.2 Selection of Wall Size

For efficiency of computing, it is necessary to find the smallest wall size which will reproduce the behaviour of a complete wall. A series of analyses were carried out on homogeneous walls with height/width ratios ranging from 0.5 to 3.0 and with the base of the wall either laterally restrained or unrestrained. A study of the resulting stress distributions revealed that the behaviour of a full height wall could be satisfactorily reproduced by using a panel which had a height to width ratio of 1.25 and which was vertically constrained at the base. This confirmed the findings of Yettram et al (10) in studies of prestressed concrete. These dimensions were therefore adopted throughout the investigation except for the case of eccentric loading.

3.3 Method of Load Application

The method of load application significantly influences the stress distributions within the wall. Depending on the stiffness of the loading device, the stresses within the wall immediately beneath the load will be approximately uniform if the loading plate is flexible, and markedly non-uniform if the loading plate is stiff (in the limit the latter case would correspond to a prescribed displacement of the loading plate). In addition the loading plate can be either laterally restrained or unrestrained in relation to the loaded surface of the masonry (depending on the frictional characteristics of the interface). The influence of these parameters was investigated by using an isotropic elastic analysis. In each case the wall described in Section 3.2 was analysed with a loaded area ratio of 0.10. Limiting cases of prescribed load and prescribed displacement at the loaded boundary were considered, together with intermediate values of plate stiffness. The results are summarised in Figure 2.



(a) Vertical Stress (σ_y) Immediately Below Loading Plate

(b) Transverse Stress (σ_x) Down Panel Centreline

#: Horizontal restraint across loaded area

Fig 2 Stress Distributions for Various Methods of Load Application

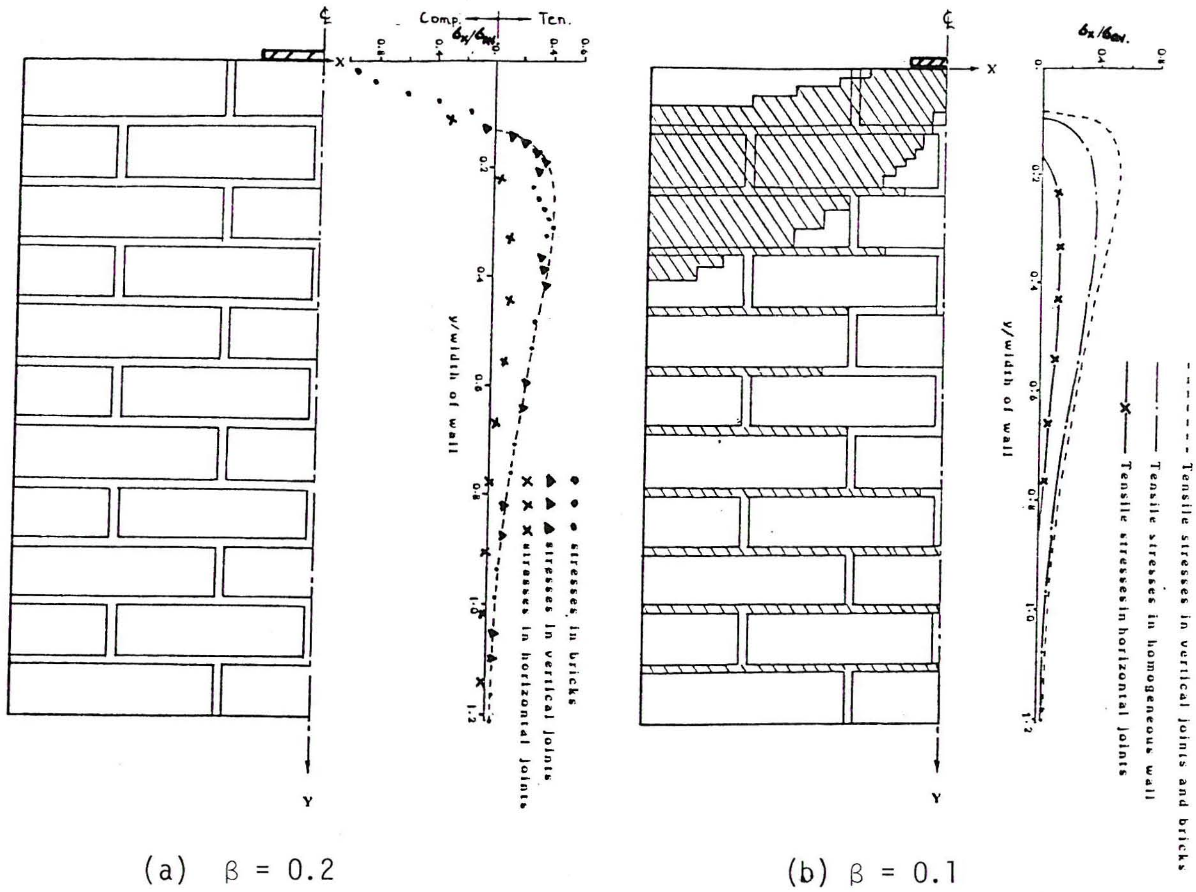
It can be seen that uniform load with horizontal restraint across the loaded surface, and uniform displacement represent the two extreme cases for both transverse and vertical stresses. Other loading methods lie between these two extremes. For all ensuing analyses the load has been applied through a 40 mm steel plate as this lies between the two bounds described above.

4. FACTORS INFLUENCING THE BEHAVIOUR OF MASONRY WALLS SUBJECTED TO CONCENTRATED LOADS

4.1 Loaded Area Ratio

A wall ten courses high and three bricks wide (height:width ratio 1.25) was used for this investigation. As previously described, two finite element analyses were carried out, one assuming masonry to be a homogeneous continuum, the other treating bricks and joints separately. For the homogeneous case (series 1) an elastic modulus (E) of 7000 MPa and a Poisson's ratio (ν) of 0.17 were assumed for the masonry. For the non-homogeneous case (series 2) values of E and ν of 7500 MPa and 0.17 were assumed for the brick and 3750 MPa and 0.2 for the mortar. A vertical uniformly distributed load was applied through a 40 mm steel plate with a loaded area/total area ratio (β) of 0.10, 0.20, 0.30 and 0.50.

4.1.1 Transverse Stresses. The distribution and magnitude of transverse stresses for the non-homogeneous case are summarised in Figure 3. Because of the non-homogeneity, the transverse stresses in the bricks and joints differ (see Fig.3(a)). For subsequent plots an envelope of the maximum transverse tensile stress in either the brick or the joint has been drawn.

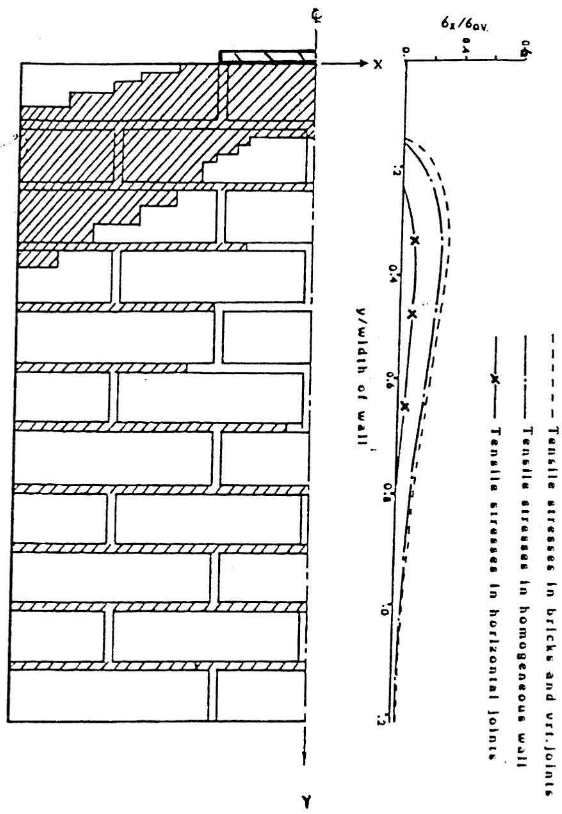


(a) $\beta = 0.2$

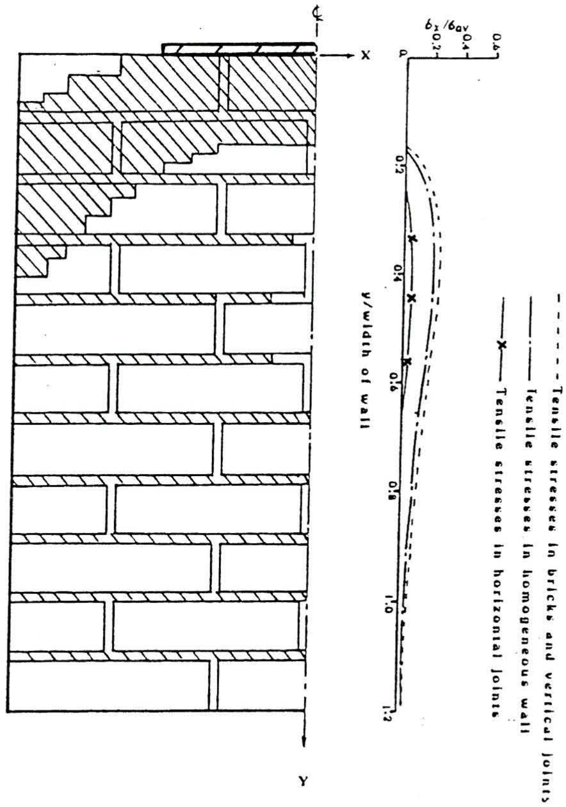
(b) $\beta = 0.1$

(Hatched area shows region of compressive σ_x)

Fig 3 Transverse Stress Distributions Down Panel Centreline for Different Loaded Area Ratios

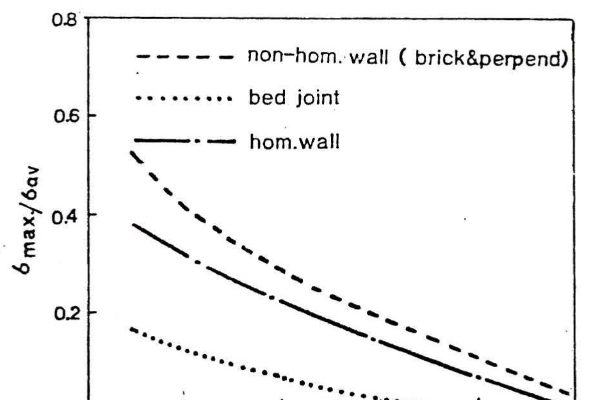


(c) β = 0.3

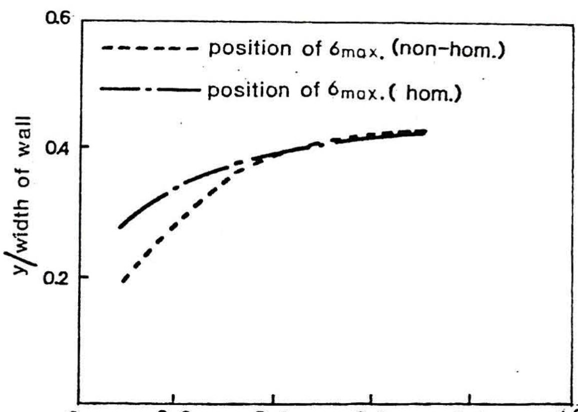


(d) β= 0.5

(Hatched areas show regions of compressive σ_x)



(e) Variation of σ_x(max) with loaded area ratio (β)



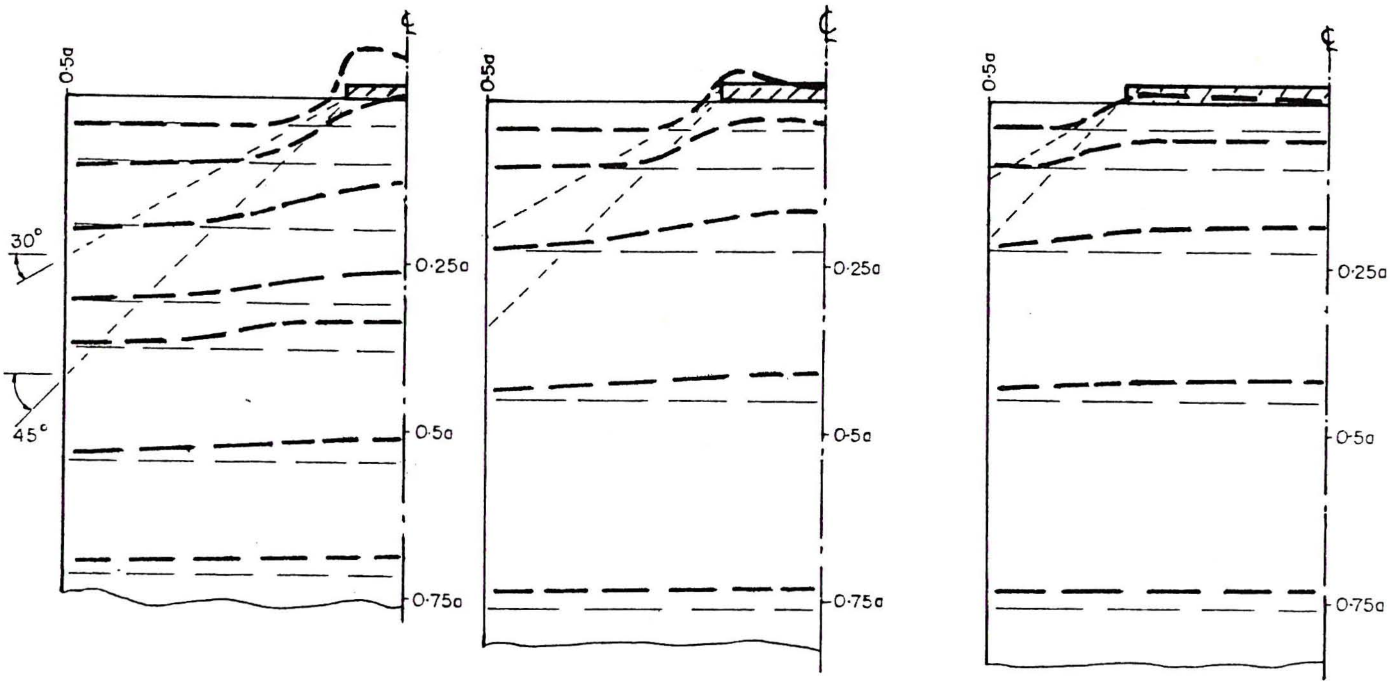
(f) Location of σ_x(max) for different loaded area ratios

(y measured from top of wall)

Fig 3 (Cont) Transverse Stress Distributions Down Panel Centreline for Different Loaded Area Ratios

The magnitude of the transverse tensile stress increases markedly with decreasing loaded area ratio (see Figure 3(c)). For example, $\sigma_x \max/\sigma_{av.}$ increases from 0.04 to 0.4 for the homogeneous case and from 0.05 to 0.52 for the non-homogeneous case as the loaded area ratios reduce from 1.0 to 0.1. ($\sigma_{av.}$ = load/total area of the wall.) The location of the maximum transverse stress also changes with loaded area ratio (see Figure 3(f)). Note that the location and values of the maximum stresses are different for the homogeneous and non-homogeneous cases.

4.1.2 Vertical Stresses. Typical distributions of vertical stresses (and hence an indication of the nature of the load dispersion) is shown in Figure 4. These have been derived from the homogeneous material model (series 1). Series 2 results were similar except for the vertical joints.



(a) $\beta = 0.2$ (b) $\beta = 0.3$ (c) $\beta = 0.6$

Fig 4 Vertical Stress Distributions for Different Loaded Area Ratios

The vertical stress is compressive except for a small area at the corner of the wall. The stress increases beneath the loading point as the loaded area ratio decreases. The distribution of stress becomes uniform at a depth below the top of the wall approximately equal to its width. The vertical stress in the vertical joints is always less than in the brick and the bed joints.

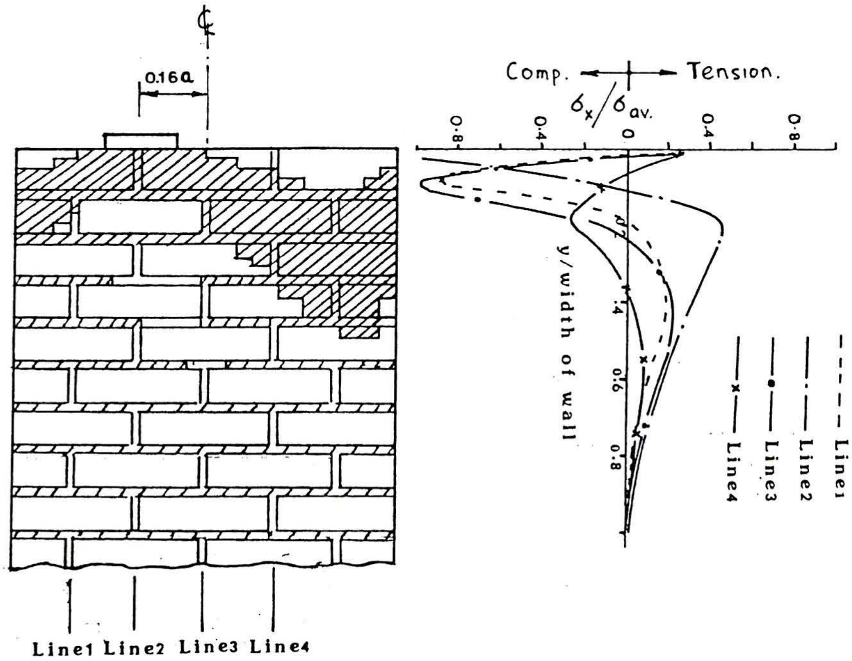
Most design rules suggest that the load can be assumed to disperse at an angle of 45° beneath the loaded area. This dispersion is shown in Figures 4(a), 4(b) and 4(c). It can be seen that the influence of the concentrated load extends beyond this dispersion line particularly in the regions immediately beneath the concentrated load (the line of influence is at approximately 30°). However, an average stress calculated at each level assuming a 45° dispersion gives a reasonable approximation of the stress distribution, although underestimating the peak stress (by up to 30% for $\beta = 0.2$).

4.2 Loading Position

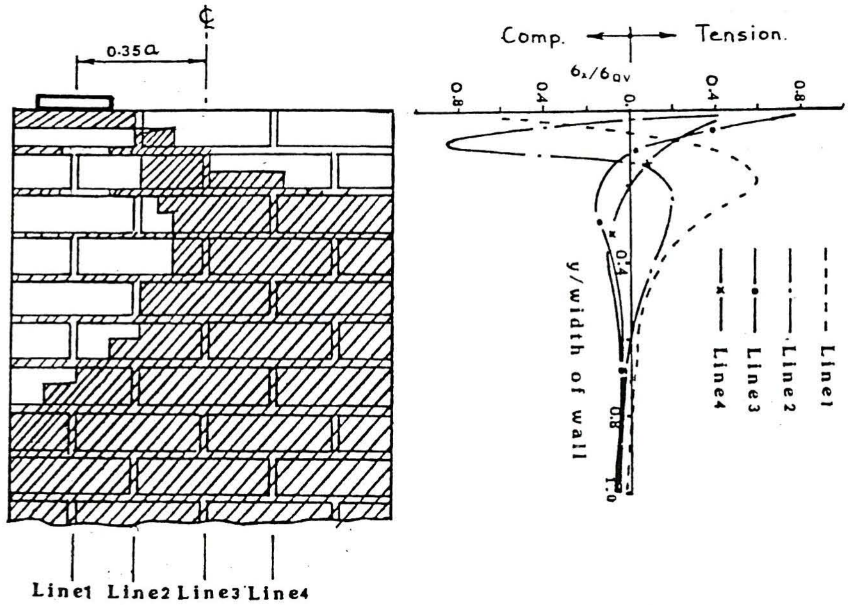
In this investigation, a wall with height/width ratio of 1.25 with complete restraint

at the base was used. The loaded area ratio was held constant, but the location of the load was varied across the wall. The same elastic properties described in Section 4.1 were assigned to the masonry.

4.2.1 Transverse Stresses. Typical distributions of the transverse stresses in bricks and vertical joints are shown in Figure 5. Since greater transverse stresses are attained in the non-homogeneous case (series 2), these stress envelopes are shown.



5(a) e = 0.16a



5(b) e = 0.35a

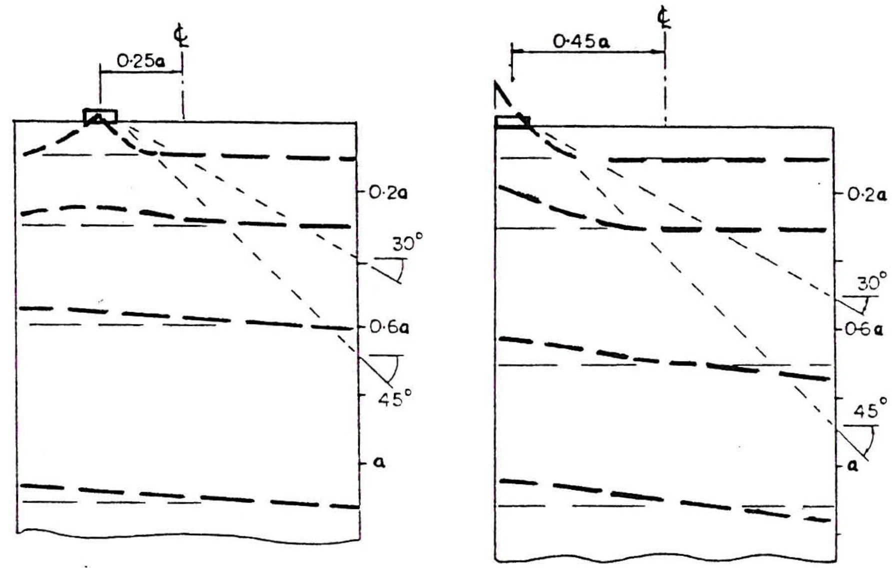
Fig 5 Transverse Stress Distributions Down the Panel for Different Load Locations ($\beta = 0.2$)

(Hatched areas show regions of compressive σ_x)

It can be seen that the transverse tensile stresses increase as the distance of the loading point from the centre of the wall e increases. Depending on the magnitude of the eccentricity, this increase can be very significant. When the load is

located near the edge of the wall ($e = 0.35a$), the maximum transverse tensile stress is more than twice the maximum stress obtained for the corresponding wall subjected to concentric loading. This vindicates code provisions which reduce the allowable stresses when concentrated loads are applied towards the edge of a wall.

4.2.2 Vertical Stresses. Typical distributions of vertical stress are shown in Figure 6.



(a) $e = 0.25a$ (b) $e = 0.45a$

Fig 6 Vertical Stress Distributions for Different Load Locations ($\beta = 0.2$)

The vertical stresses increase with increasing eccentricity. Vertical compressive stresses are a maximum under the loading plate whereas vertical tensile stresses are a maximum near the base of the wall. Depending on the amount of eccentricity, vertical tensile stresses can also develop at the unloaded end of the wall panel.

4.3 Modular Ratio (E_b/E_m)

This effect was studied by varying the elastic modulus of the mortar while holding the brick elastic modulus constant (the equivalent of the varying the mortar strength). The wall described in Section 4.1 was analysed, holding the loaded area ratio constant at 0.2. The values of E_m were taken as 3750, 2500 and 1250 MPa corresponding to E_b/E_m ratios of 2, 3 and 6 respectively.

The envelopes of transverse tensile stress down the centre of the wall for different modular ratios is shown in Figure 7. It can be seen that as E_b/E_m increases, the transverse tensile stresses in the brick and vertical mortar joints increase, and the stresses in the bed joints decrease. For the variation of E_b/E_m from 1.0 to 6.0, the transverse tensile stresses increase by approximately 75%. The failure of masonry subjected to concentrated loads could therefore be expected to be sensitive to this parameter.

4.4 Parallel Loading

In this investigation the loaded area was held constant and the distance between the two symmetrically placed loading plates was varied. The wall described in Section 4.1 was again used in the analysis.

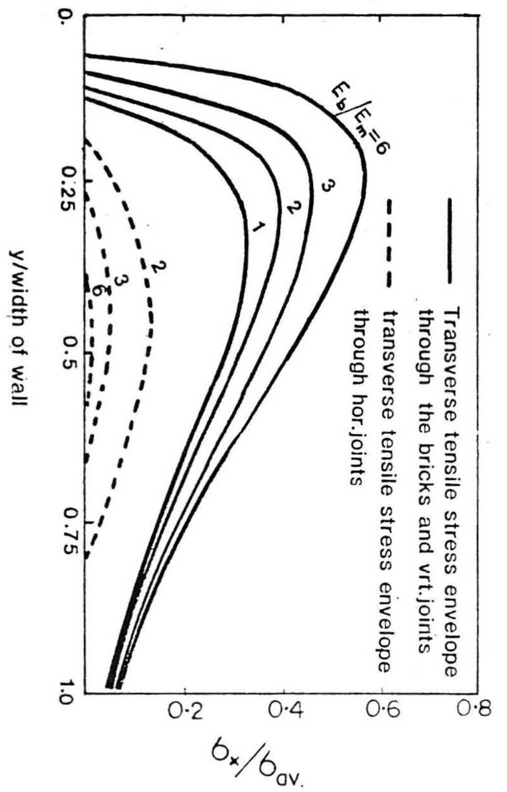
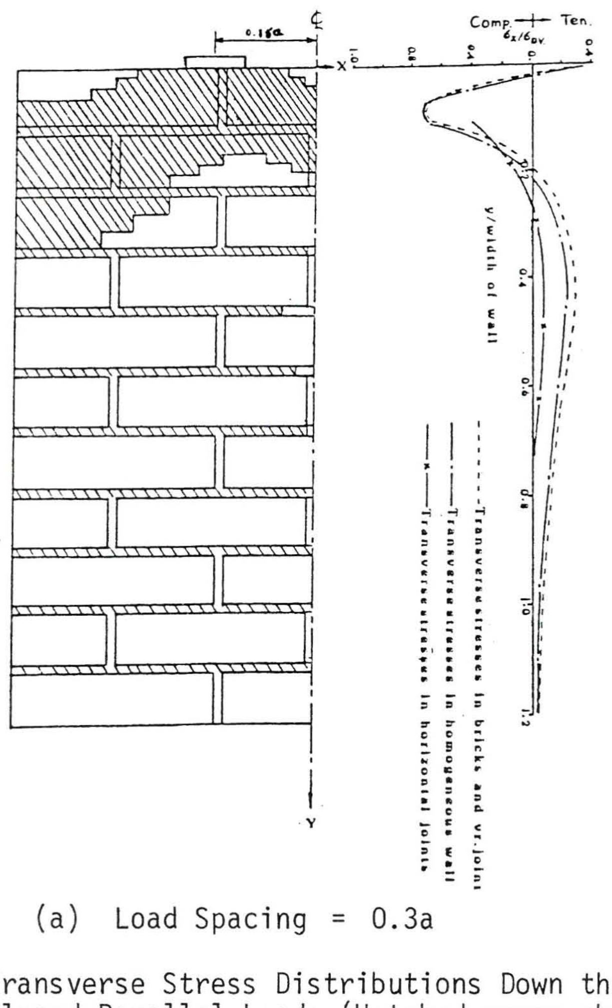
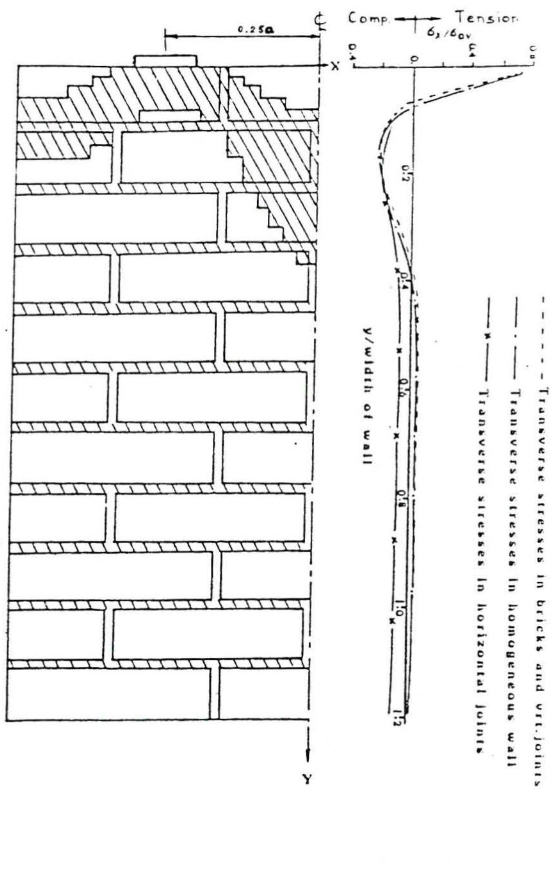


Fig 7 Transverse Stress Distributions Down the Panel Centreline for Different Modular Ratios ($\beta = 0.2$)

4.4.1 Transverse Stresses. Transverse stress envelopes down the panel centreline from the non-homogeneous analysis are shown in Figure 8. The transverse tensile stresses increase as the distance between the two plates increases. The maximum transverse tensile stress was located at the centre of the wall in each case (although this may not always be true for other plate widths).



(a) Load Spacing = 0.3a

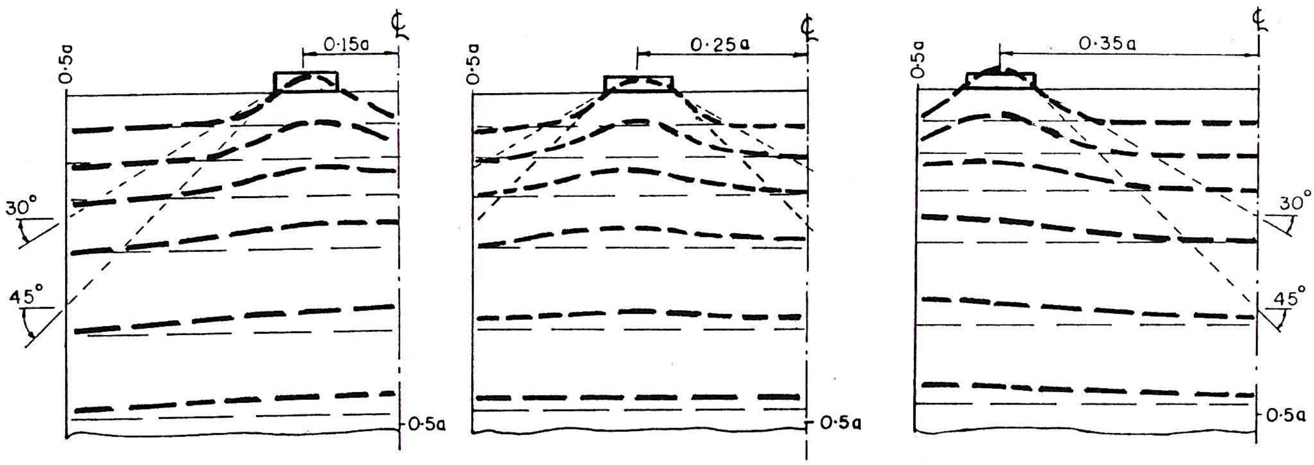


(b) Load Spacing = 0.5a

Fig 8 Transverse Stress Distributions Down the Panel Centreline for Symmetrically Placed Parallel Loads (Hatched areas show regions of compressive σ_x)

4.4.2 Vertical Stresses: The distribution of vertical stresses is shown in Figure 9. These have been derived from the homogeneous material model (series 1).

As for Section 4.1.2, the vertical stress is mainly compressive except at the corner of the wall with the maximum stresses being located beneath the loading plates.



(a) Load Spacing = 0.3a (b) Load Spacing = 0.5a (c) Load Spacing = 0.7a

Fig 9 Vertical Stress Distributions for Symmetrically Placed Parallel Loads

5. CONCLUSIONS

This paper has described a preliminary analytical study of the behaviour of brickwork walls subjected to concentrated loads. Two-dimensional elastic finite element analyses have been used. One analysis assumed masonry to be a homogeneous continuum, the other modelled bricks and joints separately. The following conclusions can be drawn from the study:

1) An elastic finite element model which treats bricks and joints separately is more effective, since it reflects the influence of the varying stiffness of its constituents. This was particularly important in the study of transverse tensile stresses, where peak stresses were always greater than those predicted in the homogeneous wall.

2) The transverse tensile stresses (which would initiate cracking and failure) significantly increase with decreasing loaded area ratio.

3) The concentration of vertical stress beneath the loaded area increases as the loaded area decreases. The dispersion of concentrated load occurs at an angle of approximately 30°. An average stress at any level calculated on the basis of a 45° dispersion gives a reasonable approximation of the stress distribution, although underestimating the peak stress.

4) As the ratio of brick/mortar stiffness increases, the transverse tensile stresses increase in the bricks and the vertical joints, and decrease in the bed joints.

5) As the concentrated load is applied closer to the edge of the wall, transverse tensile stresses markedly increase.

6) The maximum transverse tensile stress for parallel loading occurs on the centreline and failure could be expected to initiate in this region.

To more accurately assess the behaviour and load capacity of masonry walls subjected to concentrated loads, non-linear material characteristics, progressive local failure and possible three dimensional effects need to be considered.

6. REFERENCES

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