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THE EFFECT OF MASONRY CRACKS ON THE COMPOSITE ACTION BETWEEN STEEL LINTELS AND MASONRY WALLS (*)

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The paper discusses results of an analytical investigation into the effect of horizontal and vertical masonry cracks on the composite action between that masonry and the supporting steel lintel. The results confirm previous experimental data which suggest that the effect of any discontinuity in the masonry is highly position-dependent. Vertical cracks are shown to be particularly damaging. In addition, experimental tests are described which investigate the influence of the level of friction bonding at the lintel/masonry interface on the resulting structural behaviour.

1. Introduction

1.1. Background

A lintel is a steel or reinforced concrete beam used to support the brickwork or blockwork above an opening in a building, such as a window or door. Conventionally, lintels are designed using simple formulae for a beam subjected to a uniformly distributed load along the entire span. It is, however, well known from extensive experimental testing, that brick walls will "arch" and there is a transfer of load away from the centre of the lintels and towards the supports. This, in turn, reduces the bending moment on the lintel and both deflections and bending stresses are smaller than the predicted values. This effect is known as *Composite Action*. The function of the lintel is to act as a tie to prevent this arch from spreading outwards.

The first published work on composite action appeared in 1952, when Dr R.H Wood [1] of the Building Research Station, carried out a series of experimental tests on reinforced concrete beams supporting solid and cavity brick panel walls. From his test results it was seen that the stress levels in the beam reinforcement were much lower than anticipated. Similarly,

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beam deflections were of the order of one hundredth of the calibration values (based on the equivalent loading applied directly to the beam). Other papers published on this subject include those of ROSENHAUPT [2, 3], STAFFORD SMITH and RIDDINGTON [4, 5], WOOD and SIMMS [6], BURHOUSE [7], SAW [8], MALE and ARBON [9], YETTRAM and HIRST [10] and ROSENHAUPT and SOKAL [11]. A review of these papers is given elsewhere [12].

These previous experimental and analytical studies have generally concentrated on reinforced concrete beams. However, the current trend in the UK building industry is towards the use of steel lintels in preference to concrete (see Fig. 1). Steel lintels have the benefits of reduced weight, ease of installation and appearance. RIDDINGTON and STAFFORD SMITH [5] propose a simple design methodology which may be applied to steel beams since it does allow for the significant difference between the beam and wall stiffnesses. More recently, HARDY and AL-SALKA [12] have undertaken an analytical study, using finite element analysis, of the composite action specifically between steel lintels and masonry walls. The influence of some of the structural aspects of a wall-lintel structure were investigated:

i) the effect of the height of the wall above the lintel;

ii) the effect of the coefficient of friction at the interface between the top surface of the lintel and the base of the wall;

iii) the effect of the adjacent brickwork (i.e. extending the wall beyond the ends of the lintel).

In these analyses, the three-dimensional profile of an actual lintel was replaced by an equivalent beam with a rectangular solid cross-section, providing the opportunity to carry out a less complex but more extensive two-dimensional study. The predictions are, therefore, directly appropriate when considering the bending and shear deformation characteristics of a lintel. They do not, however, simulate the flange bending and warping torsion effects that are sometimes apparent in such structures. Nevertheless, they have provided some useful information and their findings can be summarised as follows:

- The study on the effect of wall height produced similar results to those previously given by STAFFORD SMITH and RIDDINGTON [4] and WOOD and SIMMS [6] for concrete lintels. Composite action is fully developed when the height of the wall is approximately equal to 60% of the free span. Further increases in wall height have no effect on the structural response.

- Whereas for concrete lintels there is a natural bond between the lintel and the wall which can limit the degree of horizontal spreading, the normal level of friction between a steel lintel and a masonry wall ($\mu \sim 0.3$) is insufficient to prevent spreading.

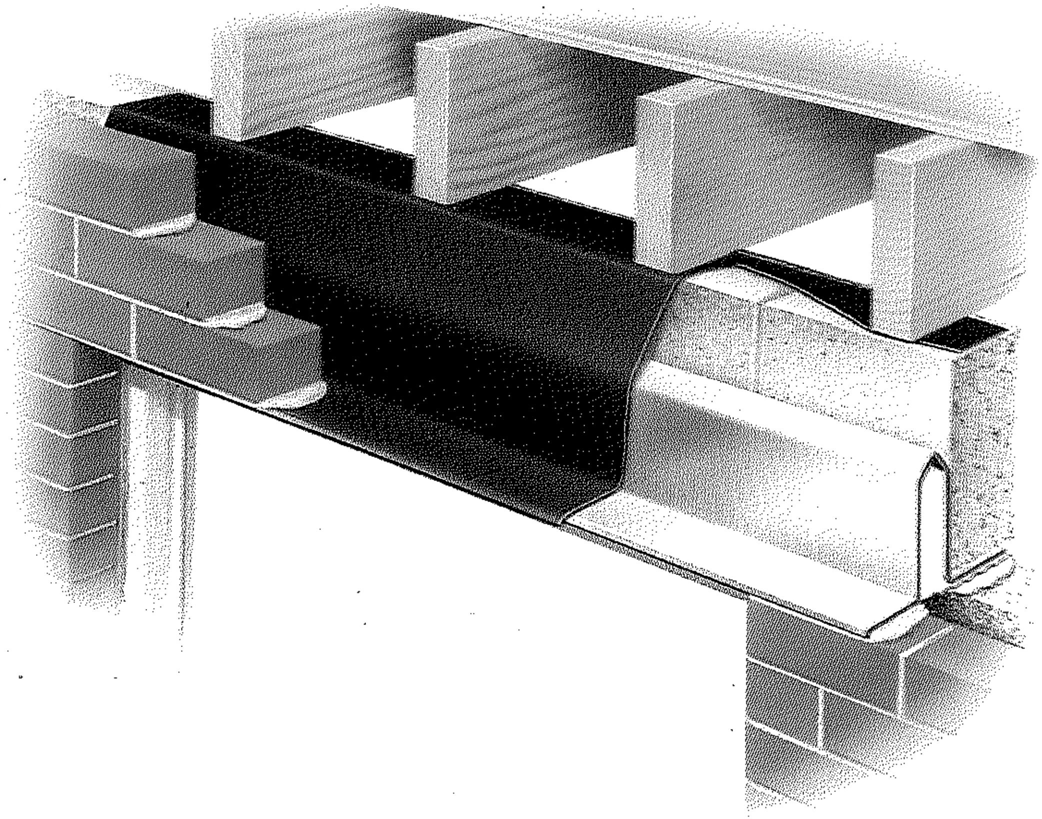

FIG. 1a. Open section steel lintel.

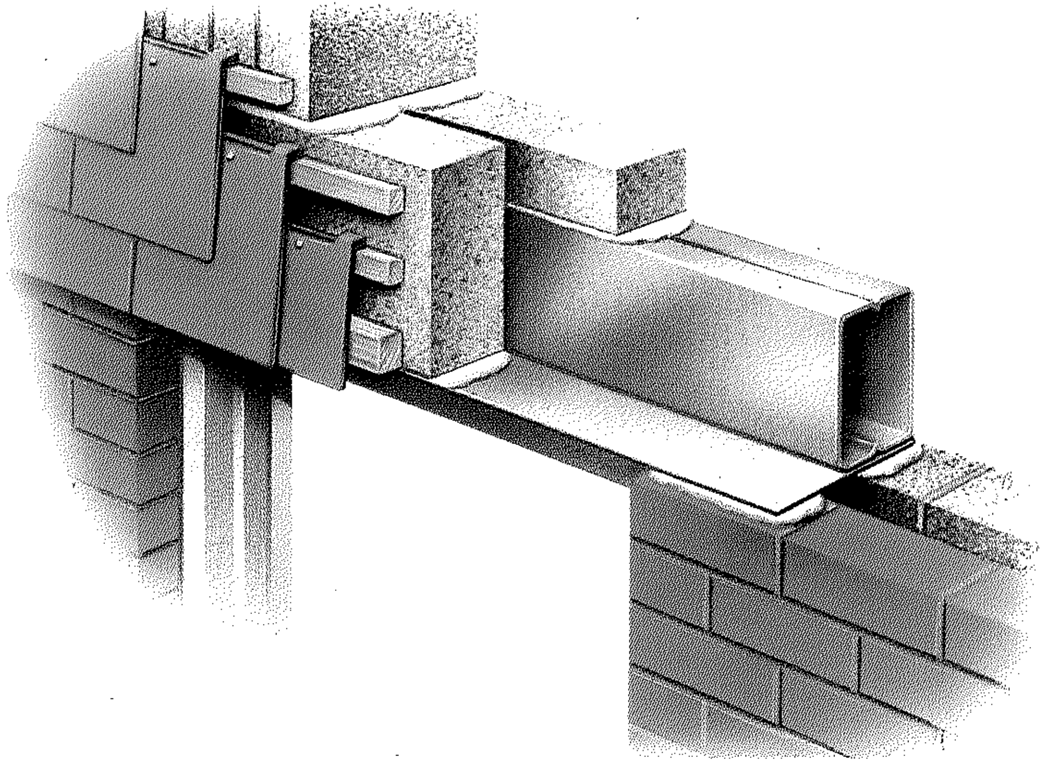

FIG. 1b. Box section steel lintel.

• Enhancing the friction bond between the lintel and the wall can produce a marked reduction in horizontal spreading and thus improve the composite action effect. This enhancing can be achieved by a variety of means.

• The effect of the adjacent wall is to prevent further this horizontal spreading. However, this contribution was found to be relatively small when compared to the interface friction effect.

The current design procedures used for steel lintels, to the relevant British Standard [13], take no account of composite action. If, however, the beneficial effects of composite action can be quantified and taken into consideration, then there are significant potential material savings to be made, with no loss of integrity of the lintel. In order to take full advantage of composite action, further detailed studies are necessary.

1.2. Scope of this paper

This paper is one of a series of publications which discuss the results of analytical and experimental investigations being carried out at University of Wales, Swansea, in conjunction with a major UK manufacturer, into the composite action between steel lintels and masonry walls. One area of concern to the designer who wishes to consider the benefits of composite action is the possibility of poor workmanship which can result in cracks in the masonry. Also, it should be noted that the transfer of load away from the centre of the lintel towards the supports will result in an increase in the compressive stresses in the masonry and may cause localised cracking in the region of the supports. This paper describes a recent analytical investigation into the effects of horizontal and vertical cracks in the masonry on displacements and stresses in the structures.

The paper also discusses further the effect of the level of interface friction, between the top surface of the lintel and the base of the wall, on the resulting structural response. Results from a series of experimental tests, with a range of interface conditions, are compared with finite element predictions for a three-dimensional model.

1.3. Nomenclature

b beam breadth,
d beam depth,
w uniformly distributed load (superimposed load and masonry),
E_b elastic modulus for the beam,
E_w elastic modulus for the masonry,

H height of the masonry wall,
I second moment of area of the beam cross-section,
L free span of the beam,
S length of the end bearing,
X width of masonry wall extending beyond the end of the lintel,
δ normalised midspan deflection,
μ coefficient of friction,
σ_b normalised midspan bending stress.

2. Geometries and loadings

2.1. Geometric and physical parameters

Steel lintels are usually made by folding flat sheet into the required open or box section (see Fig. 1). The open section is used for cavity walls and the box section is often used when there is a solid wall and produced by folding flat sheet into the required profile.

Figure 2 shows a typical lintel installation with parameters which affect the degree of composite action such as free span (L), the height of the wall above the lintel (H), the length of the supported or built-in portion of the lintel (S) (normally referred to as the "end bearing") and the width of brickwork which extends beyond the end of the lintel (X). These geometric parameters are normalised with respect to the free span (L), i.e. H/L, S/L and X/L. Other obviously important parameters are the lintel material and cross-section, the type of loading and the level of friction bond between

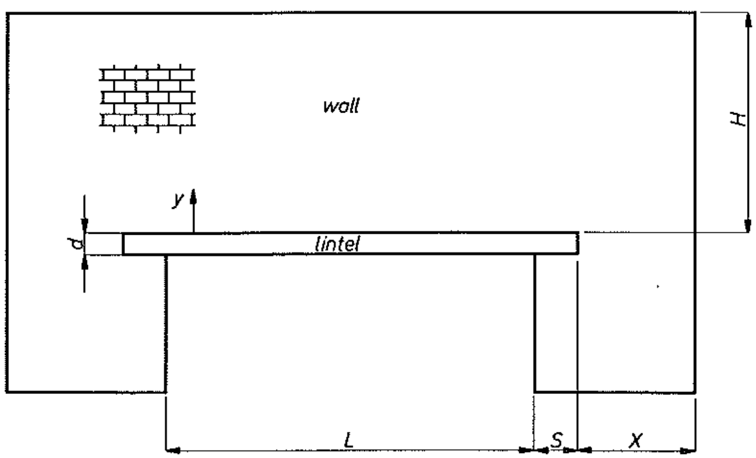

FIG. 2. Typical wall/lintel arrangement.

the top of the lintel and the bricks/blocks above, expressed in terms of the coefficient of friction (μ).

This investigation is divided into two distinct parts as far as the geometric modelling is concerned:

(i) a two-dimensional study on the effects of horizontal and vertical cracks in the masonry;

(ii) a three-dimensional study on the effect of varying the interface friction using a box lintel.

2.2. *Two-dimensional analysis of cracks*

The three-dimensional lintel profile has been replaced by an equivalent beam with a solid rectangular cross-section (breadth b, depth d) having the same second moment of area as that of the original open profile, as previously analyzed by Hardy and Al-Salka [12] and discussed in Sec. 1. A relatively short lintel, free span = 1.2 m (i.e. installed typically over a door opening), is used in the analysis with the other geometric parameters being:

$$H/L = 0.67, \quad S/L = 0.125, \quad X/L = 0, \quad b/L = 0.083, \quad d/L = 0.039.$$

A uniformly distributed load of 10 kN/m is applied to the top of the wall to represent the loads due to upper floors, roofing etc. This is the allowable load for the original profile, which is span-dependent and is taken from the respective manufacturer's handbook. The load supported by the lintel is therefore made up of the masonry load and this superimposed load.

2.3. *Three-dimensional analysis of box lintel*

The experimental tests and comparative finite element analyses have been performed on a 100 mm high by 75 mm wide box section lintel of the type shown in Fig. 1b. The free span was 600 mm with the other geometric parameters being

$$H/L = 0.5, \qquad S/L = 0.25, \qquad X/L = 0 \ \text{(no adjacent wall)}.$$

Due to height restrictions on the experimental test rig, only four courses of blockwork could be built above the lintel (see Sec. 5). Hence it was necessary to select a relatively short lintel in order to achieve a reasonable value of H/L. An increasing uniformly distributed load has been applied to the top of the wall.

3. Finite element analysis

3.1. Finite element program and material data

Finite element predictions have been obtained using the standard elastic facilities available in the PAFEC suite of programs [14]. Nonlinear GAP elements [14] are used to model the interface between the steel lintel and the masonry wall. The same GAP elements are used to model the horizontal and vertical cracks. The coefficient of friction between the contacting surfaces can be assigned any value between 0 and 1. Values for Young's modulus and Poisson's ratio of 209 GPa and 0.3, respectively, are used for the steel lintel. The masonry is assumed to be a homogeneous linear elastic material and corresponding values of 6.5 GPa and 0.15 are assumed for the wall [4]. The beam/wall stiffness ratio is ~ 30 and this is considered to be typical for a masonry wall on a steel beam application [5].

3.2. Two-dimensional model for the analysis of cracks

8-noded, plane stress, isoparametric elements are used. For the analysis of horizontal cracks it is only necessary to model one half of the structure because of the symmetry about the vertical middle axis, with suitable constraints applied along that axis of symmetry. For off-centre vertical cracks there is no such symmetry and it is necessary to use a full model. Values for the coefficient of friction of 0.3 and 0.6 are assumed for the wall-lintel and crack interfaces, respectively.

3.3. Three-dimensional analysis of box lintel

8-noded facet shell elements are used to model the steel lintel and 20-noded brick elements are used for the masonry wall. As for the two-dimensional analysis of cracks, the system is symmetrical about the central vertical axis and a one-half model, with appropriate boundary conditions, has been used.

4. Results from the analysis of cracks

4.1. Presentation of results

The parameter very often used to quantify the degree of composite action is the midspan vertical deflection of the lintel. The bending stresses in the lintel are also quoted.

In this paper, lintel deflections and stresses are generally normalised with respect to reference values based on simple bending theory, i.e.

normalised midspan deflection

$$\delta = \frac{\text{midspan deflection}}{wL^4/384E_bI}\,; \tag{4.1}$$

normalised bending stress

$$\sigma_b = \frac{\text{bending stress}}{wL^2d/48I}\,. \tag{4.2}$$

Compressive stresses in the masonry are normalised with respect to a reference value based on the average compressive stress, assuming continuity at the masonry/lintel interface, resulting from the uniformly distributed load of 10 kN/m. In practice, the weight of the masonry is less than 1% of this additional load and can therefore be ignored.

Normalised masonry compressive stress

$$\sigma_c = \frac{\text{compressive stress}}{w/b}\,. \tag{4.3}$$

Maximum values of masonry compressive stress occur in the region of the supports, as discussed in Sec. 4.3.

4.2. Horizontal cracks

Continuous horizontal cracks across the span have been introduced, using GAP elements, at heights of $y/L = 0.167, 0.33$ and 0.5, where y is the vertical distance above the lintel (see Fig. 2). The exaggerated deformed shape for a crack at $y/L = 0.167$ is shown in Fig. 3. Several features are noted in this figure:

i) the lintel has deflected away from the masonry, leaving a central gap. Hence the transfer of loading away from the centre towards the supports is clearly identifiable;

ii) there is considerable slippage at the interface between the lintel and the masonry. It should be noted that previous results [12] suggest that this horizontal slippage can be minimised if the coefficient of friction at the interface can be increased to ~ 0.6;

iii) some slippage and separation has also occurred at the crack interface.

The variation of predicted normalised midspan deflection with the position of the horizontal crack is presented in Table 1, together with the corresponding result for a wall without cracks. The first obvious feature of these

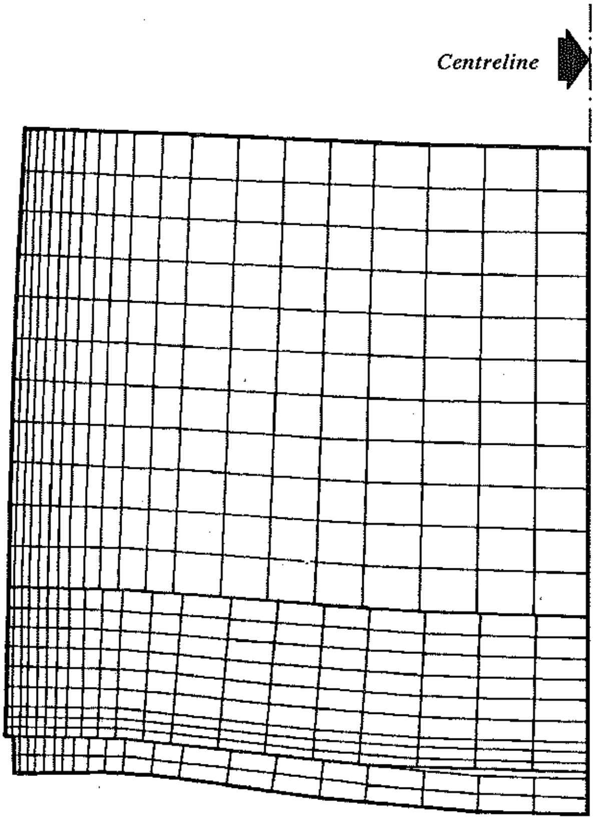

FIG. 3. Horizontal crack at $y/l = 0.167$.

results is the fact that the normalised deflections are well below unity. This itself provides evidence that composite action is taking place and that the simple bending equations over-predict the structural response by a factor of ~ 7. The presence of cracks at $y/L = 0.167$ and 0.33 has only a small effect on the midspan deflection. Nevertheless it does show that the existence of a horizontal crack in this region does have an adverse effect on the composite action. The crack at $y/L = 0.5$ resulted in the same midspan deflection as for the case with no crack.

STAFFORD SMITH and RIDDINGTON [4] observed that "*if composite action is to develop with the wall acting as an arch, holes cannot be allowed in the arching region of the wall. A restriction must therefore be placed on the locations and sizes of holes in the wall*". This arching region has been shown to spread to wall heights of $y/L =\sim 0.5 - 0.6$ (see Fig. 4) and the results in Table 1 suggest that their observations can be extended to include any discontinuities, including cracks.

Table 1. The effect of horizontal masonry cracks on normalised midspan deflection.

Crack Position (y/L)	Normalised Midspan Vertical Deflection
No Crack	0.136
0.167	0.150
0.333	0.151
0.500	0.136

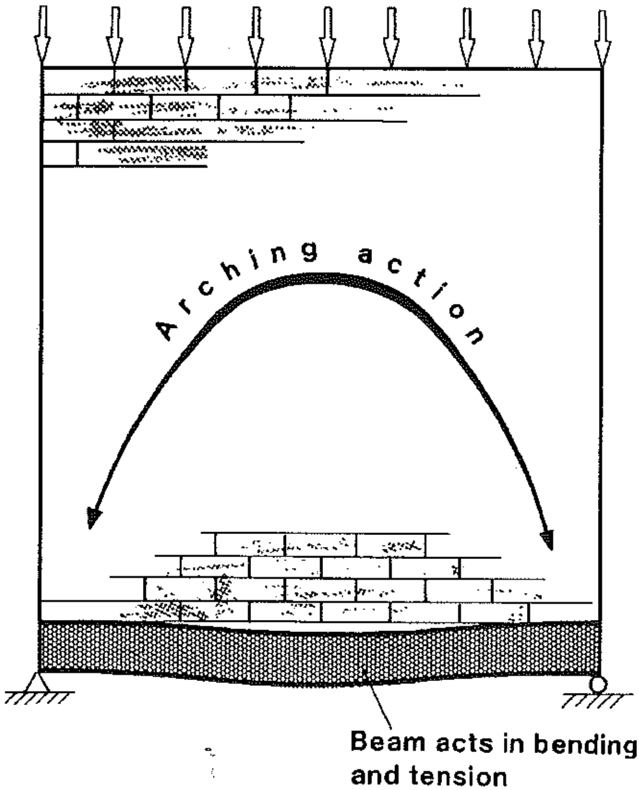

FIG. 4. Arching region [4].

4.3. Vertical cracks

The effect of continuous vertical cracks, of the full height of the wall, on the composite action between the lintel and the masonry has been investigated. Cracks have been introduced, again using GAP elements at the $L/8$, $L/4$, $3L/8$ and $L/2$ positions.

The exaggerated deformed shape for a crack at $3L/8$ is shown in Fig. 5. There is a distinct separation of the two crack faces and the right-hand edge of the crack has "slipped down" and resumed contact with the lintel. This renewed contact has a detrimental effect on the lintel bending moments and results in an increase in the normalised midspan deflection to 0.532 (from 0.136 for the "no crack" condition).

Table 2. The effect of vertical masonry cracks on normalised midspan deflection.

Crack Position	Normalised Midspan Vertical Deflection
No Crack	0.136
$L/2$	0.115
$3L/8$	0.532
$L/4$	0.426
$L/8$	0.165

The variation of predicted normalised midspan deflection with the position of the vertical crack is shown in Table 2, which includes the corresponding result for the "no crack" situation. The following observations are made:

i) As with horizontal cracks, the normalised deflections are below unity, again indicating that the simple bending equations over-predict the structural response.

ii) In contrast to horizontal cracks, the position of the vertical crack is very important when considering the degree to which that crack has an adverse effect on the composite action. A crack along the centreline has very small effect. In fact, the results suggest that a central crack may have a minor beneficial effect on composite action. This may be because the separation of the crack faces causes a further transfer of load away from the centre of the lintel. Similarly, a crack close to a support ($L/8$) has only limited effect since the composite action occurs over 88% of the total span. The most significant effects are noted for the crack positions of $3L/8$ and, to a lesser extent, $L/4$. In both cases, slippage of the crack faces and renewed contact with the lintel away from the ends has caused an increase in bending moments and subsequent midspan deflections. These results are, again, generally consistent with the limitations on holes in the arching region proposed by STAFFORD SMITH and RIDDINGTON [4], as shown in Fig. 4. The cracks at $3L/8$ and $L/4$ clearly pass through the arching region whereas the $L/8$ crack may be outside this region. The exception to this rule is the central crack, for reasons previously explained. The midspan deflection is increased by a factor ~ 4 when a vertical crack is introduced at the $3L/8$ position.

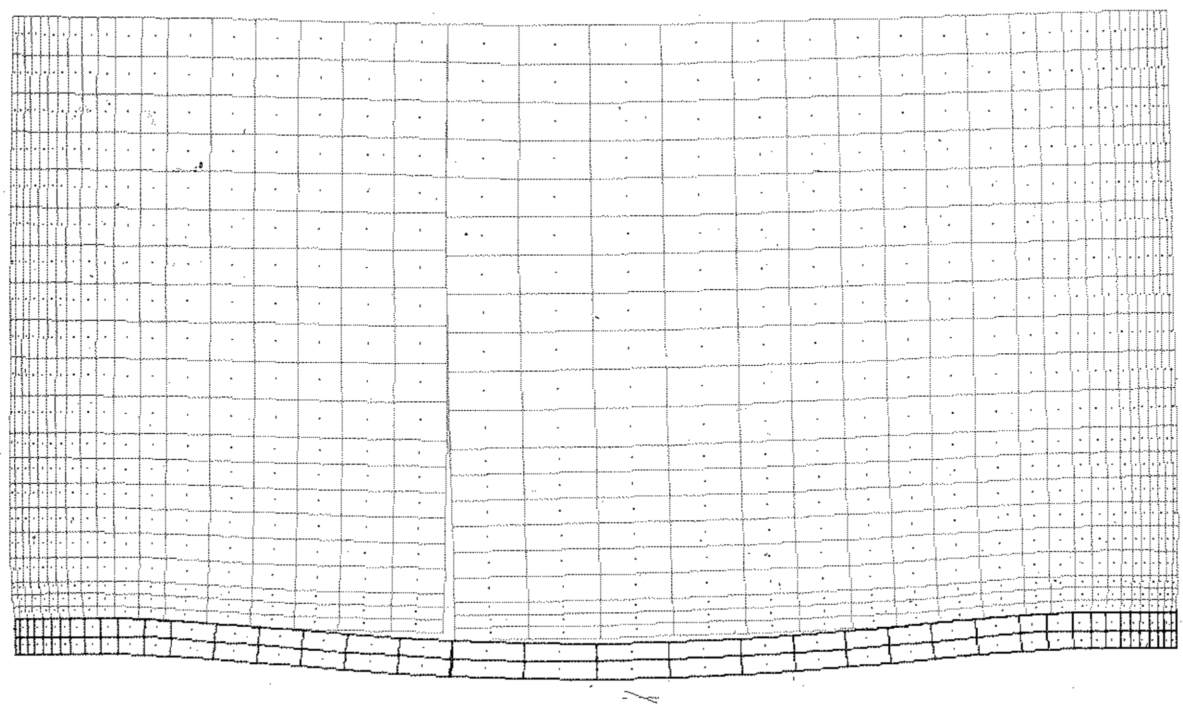

FIG. 5. Vertical crack at $3L/8$. Exaggerated deformed shape.

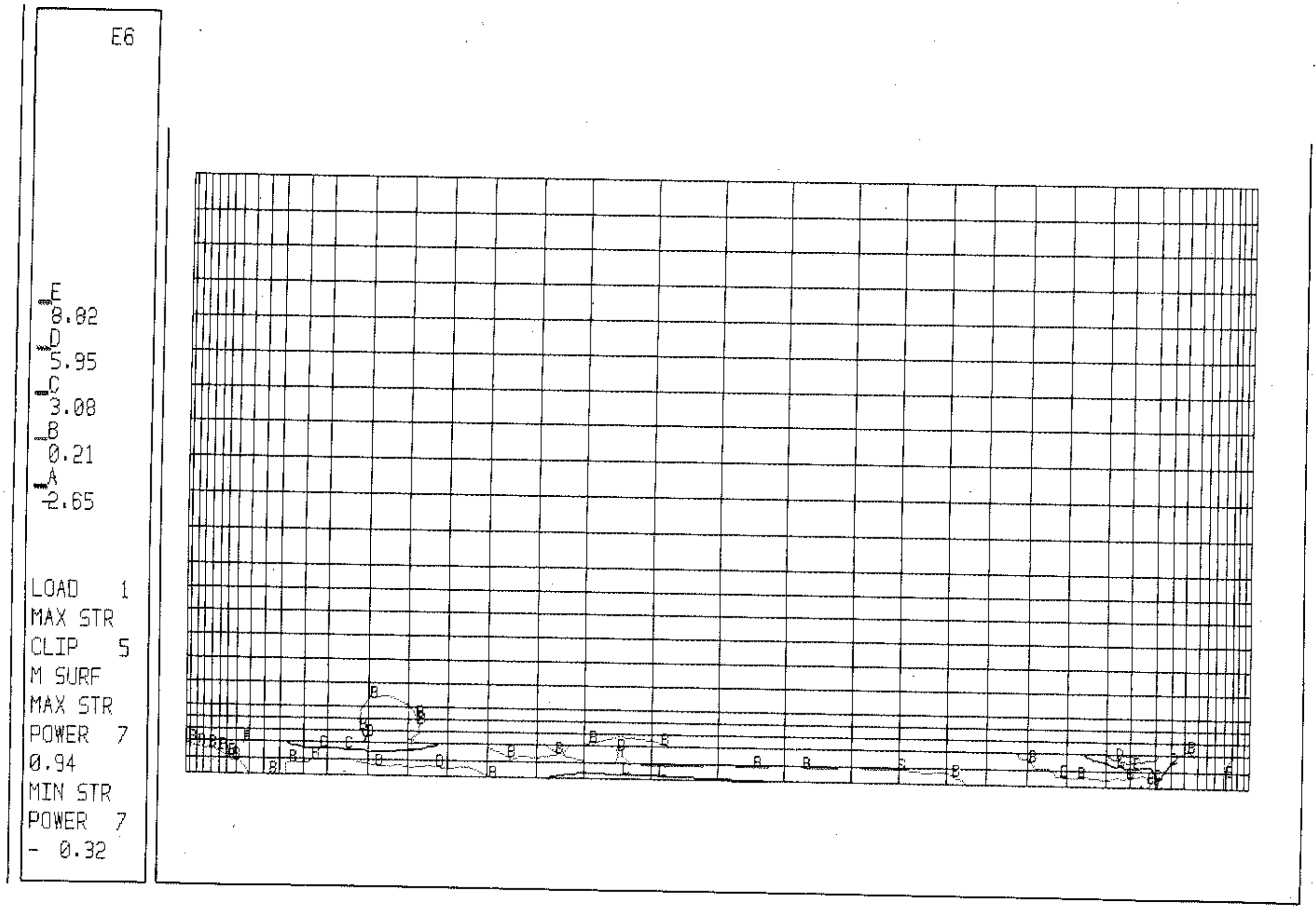

FIG. 6. Vertical crack at $3L/8$. Stress distribution in wall and lintel.

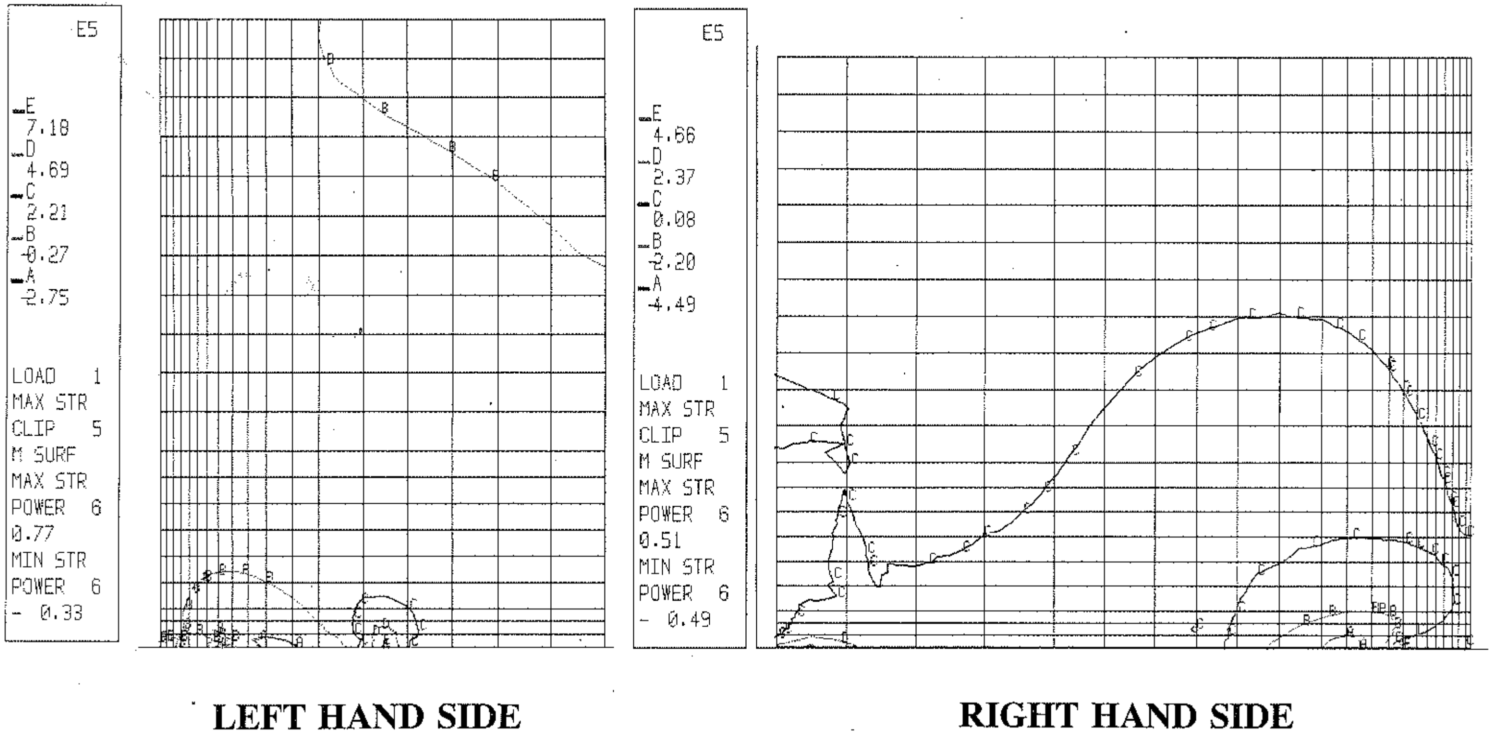

FIG. 7. Vertical crack at $3L/8$. Stress distribution in wall.

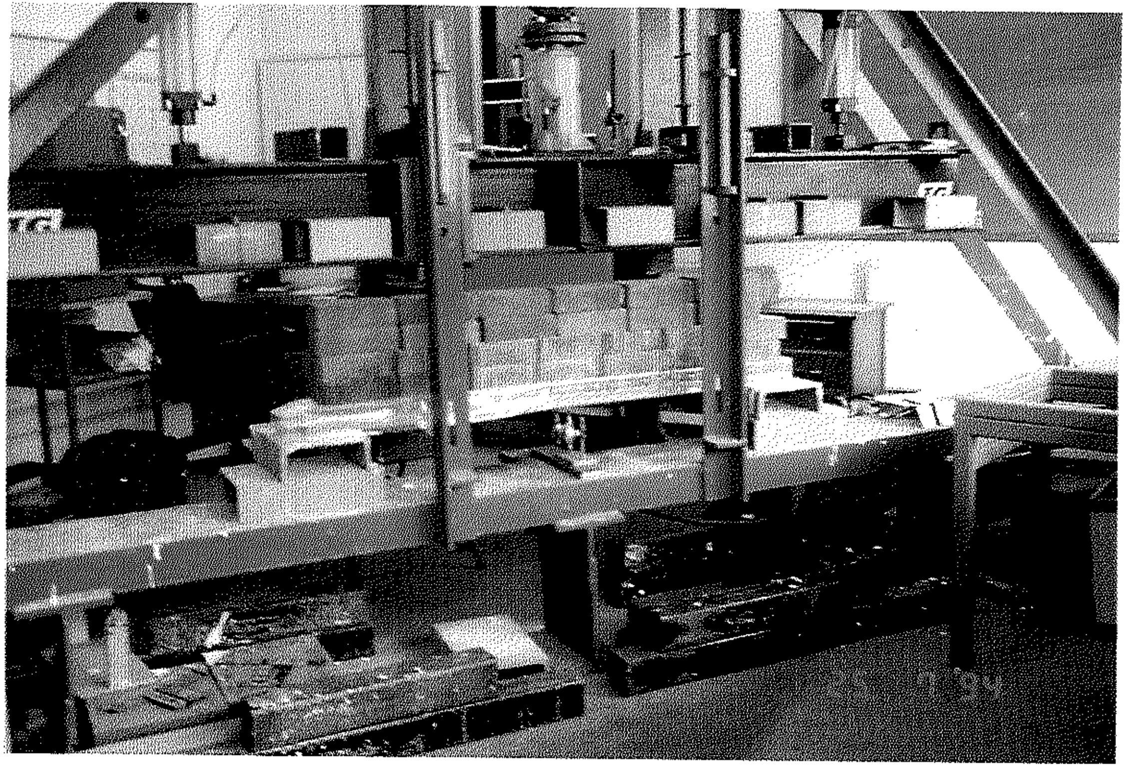

FIG. 8. Experimental test rig.

Composite action has also a major effect on the stress distributions in both the lintel and the masonry. In particular, high concentrations of stress are generated in the contact region. This is illustrated in Figs. 6 and 7 which show the predicted wall/lintel and wall stress distributions, respectively, for the case of a vertical crack at the $3L/8$ position. Maximum values of both lintel bending stress and masonry compressive stress are predicted in the contact region.

Table 3. The effect of vertical crack position on maximum lintel and masonry stresses.

Crack Position	Maximum Normalised Bending Stress	Maximum Normalised Masonry Compressive Stress (Left side)	Maximum Normalised Masonry Compressive Stress (Right side)
No Crack	0.305	3.5	3.5
$L/2$	0.328	3.7	3.7
$3L/8$	0.551	3.3	4.9
$L/4$	1.007	1.0	5.2
$L/8$	0.515	2.3	4.4

Maximum predicted values of lintel bending stress and masonry compressive stress are quoted in Table 3. A crack at the centre appears to produce a small increase in both lintel and masonry stress levels, compared with the "no crack" condition. There is a significant increase in lintel bending stress, particularly for a crack at the $L/4$ position which induces an approximate threefold increase. In this case, any conservatism introduced by the presence of composite action (i.e. a factor of $1/0.305$ $\{= 3.3\}$ with no crack) is lost due to the crack. The contact stresses induced in the masonry show a similar trend. As the crack is moved to the left away from the centre, there is a progressive increase in load carried over the right-hand contact region, and a corresponding reduction over the left hand contact region. The highest contact stress is predicted for the $L/4$ crack position, followed by a more balanced stress distribution for the $L/8$ crack position. As previously identified, this latter case is less significant because the crack may be outside the arching region.

5. Results from the analysis of the box lintel

The experimental test results have been obtained using the test rig shown in Fig. 8. The superimposed load is applied by means of a hydraulic jack and uniformly distributed through an I section loading beam and steel plates. Due to height restrictions on this test rig, it was only possible to insert up to four courses of brickwork between the lintel and the loading beam in its highest position, hence the requirement for a relatively short span lintel (see Sec. 2.3).

The aim of the experimental test programme was to study the influence of the lintel/masonry interface friction bond on structural response and three tests were undertaken, as outlined in Table 4. For Test 1, a layer of polythene was inserted at the interface to represent low friction conditions. Test 2 was the normal case where any mortar key provides the bond and for Test 3, a wire mesh was welded to the top of the lintel to provide an increase in the mortar bonding. In all three cases, the four courses of brickwork were bonded with 1 : 1 : 6 mortar and left to cure for three days before testing. Deflections were measured at the midspan using two dial gauges, on either side of the loading beam.

Table 4. Experimental test programme.

Test	Experimental arrangement	Assumed value of μ for FEA
1	Layer of polythene at lintel/wait interface	0.1
2	Normal mortar key at lintel/wall interface	0.6
3	Wire mesh welded to top of lintel	0.8

The load-deflection characteristic for Test 1, low friction, is shown in Fig. 9. There is reasonable agreement between the readings for the two gauges suggesting that the load was being applied as symmetrically as could be expected under the experimental test conditions. The curves are reasonably linear for loads up to ~ 18 kN. At this point, cracks began to appear in the mortar close to the supports, and discontinuities in the characteristic are evident. Similar cracking was observed by ROSENHAUPT [2]. Further increases in load were applied and at ~ 26 kN it was observed that the mortar was beginning to crumble. Finally, "failure" occurred at a load of 34 kN. It was noted that there were cracks between all courses. For this particular lintel, the specified Safe Working Load corresponds to a maximum midspan deflection of 3.2 mm under normal test conditions (i.e. load applied directly to the top of the lintel). Clearly, this has not been achieved under these loading and interface conditions.

The corresponding results for Test 2, normal friction, are shown in Fig. 10. The two dial gauge readings are in close agreement. Some "bedding in" of the lintel (i.e. settlement of the mortar joint as the load is gradually applied) over the end bearings, is apparent in the region ~ 15 – 23 kN. The first signs

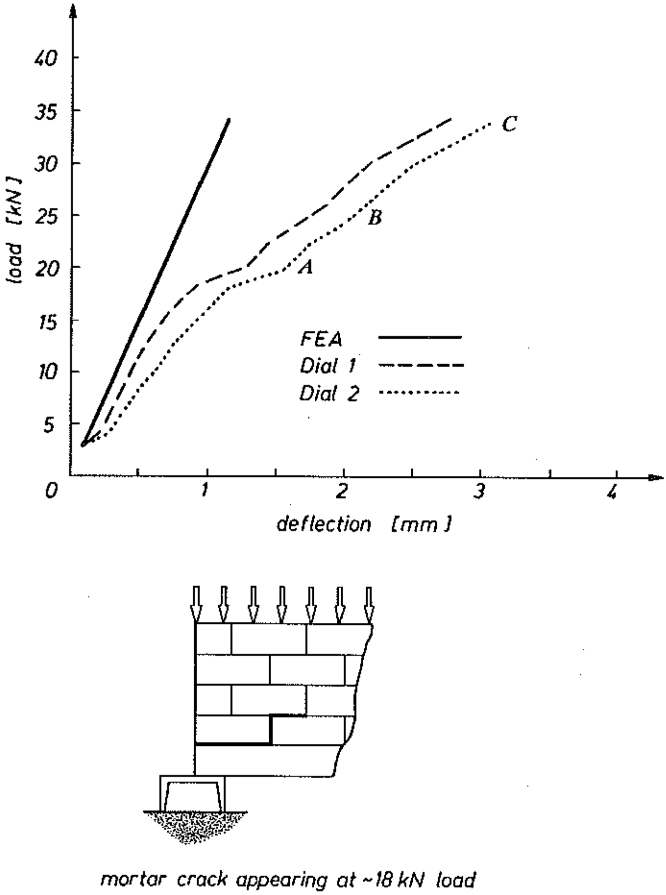

FIG. 9. Box lintel – midspan deflection. Test 1 – Low interface friction. A – cracks appearing in mortar; B – mortar starting to crumble; C – loading failure, cracks in all courses.

of failure were at ~ 36 kN, when mortar in the regions above the supports began to crumble. At ~ 46 kN, some of the bricks in these regions had started to crack. In this test, final collapse occurred at a load of ~ 52 kN and this was due to buckling of the lintel end bearing webs. The maximum midspan deflection was ~ 3.7 mm.

The results for Test 3, enhanced friction, are shown in Fig. 11. At a load of ~ 46 kN, the lintel webs were starting to bow at the end bearings. Ultimate failure occurred at ~ 62 kN, again due to buckling of the lintel end bearing webs. Up to this point, there had been no signs of any mortar or masonry cracking. The maximum midspan deflection achieved in this test was of the order of 4.6 mm which is well in excess of the 3.2 mm obtained under "normal test conditions".

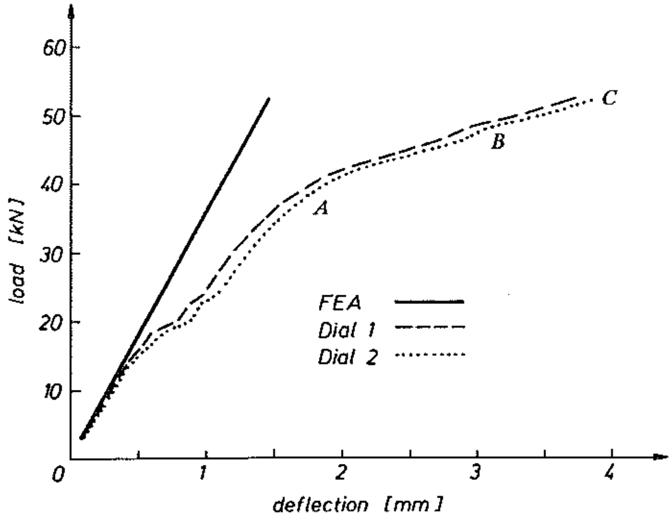

FIG. 10. Box lintel – midspan deflection. Test 2 – Normal interface friction. *A* – mortar starting to crumble; *B* – bricks starting to crack; *C* – webb buckling close to supports. Collapse.

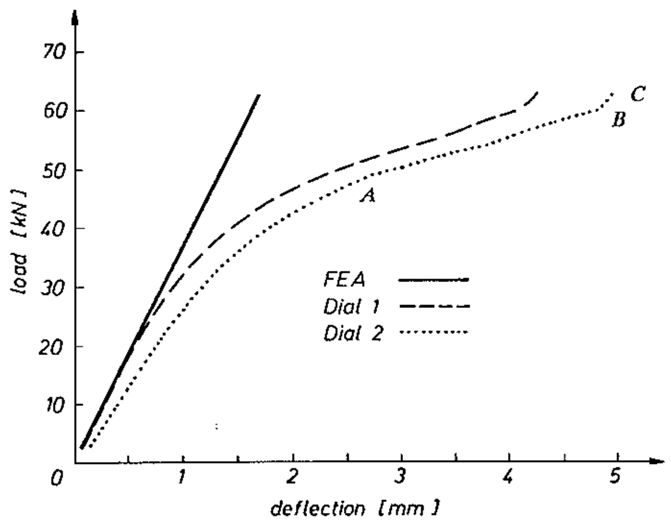

FIG. 11. Box lintel – midspan deflection. Test 3 – High interface friction. *A* – signs of bowing at end bearings; *B* – no cracking; *C* – webb buckling. Collapse.

Figures 9 to 11 also include the corresponding finite element predictions of midspan deflection. If the effects of "bedding in" in Tests 1 and 2 are ignored, then there is apparent good agreement between predictions and test results over a significant load range. For the low and normal interface friction comparisons, again ignoring the "bedding in" effects, the experimental and predicted load/deflection slopes are very similar up to the point where mortar cracking begins. Clearly this effect is not modelled in the finite element analysis and deviations between experiment and model predictions above this load are to be expected. Similarly, for Test 3, the experimental and predicted load/deflection slopes are comparable up to a load of ~ 30 kN. Above this, the experimental curve becomes nonlinear. This is probably due to the onset of web bowing, although not clearly visible at this stage. If this is so, then it also suggests that the finite element model does not adequately represent this bowing behaviour and that further refinement is necessary.

6. Discussion

Although the existence of composite action has been acknowledged for many years, little attempt has been made to quantify the effect in order that it may be taken into account in the design process. Furthermore, it is clear that current lintel design procedures are conservative and that composite action can have a major beneficial effect on the structural requirements of a lintel. However, these benefits are subject to certain criteria, one being continuity of the masonry. Poor workmanship, leading to cracks in the mortar, will inevitably result in a lessening of the extent to which composite action takes place. The first part of this paper has addressed this problem by way of a two-dimensional analysis of horizontal and vertical masonry cracks. The following conclusions are drawn from the results:

1) horizontal cracks cause only a minor reduction in the composite action effect;

2) vertical cracks are of major concern and their presence can outweigh the benefits to be gained from composite action;

3) the position of the vertical crack is important;

4) cracks in the "arching region" cannot be allowed if composite action is to be accounted for;

5) arching has a localised detrimental effect on the masonry due to high compressive stresses, which can be as much as ~ 5 times greater than the nominal value. Consequently, masonry cracking can occur.

In practice, diagonal cracks very often occur. Furthermore, several cracks may appear simultaneously. This part of the study is now being extended to include the analysis of diagonal cracks and the results will be compared with those presented here.

The second part of the paper has presented further evidence of the degree to which structural behaviour of an actual lintel is affected by the level of horizontal slip at the lintel/masonry interface. Previous results [12] suggested that significant improvements in overall stiffness could be achieved by increasing the friction contact at this interface. This has been supported by the experimental and analytical results presented here. Furthermore, the experimental results show that the mode of ultimate failure is also dependent on the level of interface slippage. The following conclusions are drawn from the results:

1) for normal, low friction conditions, masonry spreading occurs and this ultimately leads to failure due to cracks in the mortar;

2) with enhanced interface friction, this spreading is resisted and failure occurs due to buckling of the lintel itself, with little signs of any mortar damage;

3) a significant increase in collapse load, from 34 kN (for $\mu \sim 0.1$) to 62 kN (for $\mu \sim 0.8$), has been achieved. It should also be noted that these loads are well in excess of the recommended limit load (15 kN) for this particular lintel;

4) good comparison between experimental results and finite element predictions is achieved over a limited range of loading. The comparison suggests that further refinement of the finite element models is necessary, particularly when lintel buckling is the dominant mode of failure.

This part of the study is now being extended to examine in-service structural behaviour. This involves on-site instrumentation and investigation during the building stage and subsequent occupation.

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