COMPUTATIONAL MODELING OF LOW STRENGTH BRICKWORK WALL/BEAM PANELS WITH RETRO-FITTED REINFORCEMENT

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ABSTRACT

Retro-fitted stainless steel reinforcement is being used increasingly to strengthen the masonry cladding of low to medium rise buildings, particularly where cracking has occurred adjacent to a long-span window or similar opening. This paper describes the development of a computational model which was used to predict the behaviour of reinforced clay brick wall/beam panels subjected to vertical in-plane static loading. In practice, cracking in unreinforced walls of this type, particularly where low cement content mortar has been used, tends to occur along the brick/mortar interfaces and failure usually results from de-bonding of the bricks. As a result, software based on the Distinct Element Method (DEM) of analysis was used. The bricks were represented as an assemblage of stiff but deformable distinct blocks and the mortar joints were modelled as zero thickness interfaces. These interfaces could open or close depending on the magnitude and direction of the stresses applied to them. Reinforcement was modelled using spring connections attached to the masonry surface.

The masonry material parameters were obtained from the results of experimental tests carried out in the laboratory on full-scale unreinforced wall/beam panels. The computational model was then used to predict the behaviour of wall/beam panels containing bed joint reinforcement. Good correlation was achieved with the results obtained from the testing of full-scale reinforced panels in the laboratory, in particular, the load to cause first visible cracking, the propagation of cracks with increasing applied load, the mode of failure and the magnitude of the collapse load.

KEYWORDS: masonry, walls, reinforcement, distinct element modelling

INTRODUCTION

Unreinforced masonry structures can be strengthened in a variety of ways [1]. This paper is concerned with retrospectively fitted near-surface reinforcement also known as “retro-reinforcement”. In this case small diameter reinforcing bars are inserted into pre-cut grooves or pre-drilled holes in the outer (exposed) zones of the masonry and then encapsulated in a high strength, thixotropic, cementitious grout to create an under-reinforced masonry structure. The increasing use of retro-reinforcement as a means of strengthening more complex masonry structures has resulted in the need to develop a computational tool to help practising engineers to predict the pre- and post-cracking behaviour. Many of these structures in need of strengthening tend to be of masonry construction in which the bond at the masonry unit/mortar joint interface is

sufficiently low to have a dominant effect on the mechanical behaviour such as the formation of cracks, redistribution of stresses after cracking and the formation of the collapse mechanism.
This paper briefly describes the development of a computation tool for unreinforced masonry that is used to model the pre- and post-cracking behaviour of low bond strength clay brick single leaf (wythe) wall/beam panels that have been strengthened with retro-fitted small diameter stainless steel reinforcing bars. The computational results are compared with those obtained from the testing of full-scale unreinforced and reinforced clay brick wall/beam panels in the laboratory.

INITIAL CONSIDERATIONS – COMPUTATIONAL MODELLING

In the last few decades, many computational models have been used to simulate the behaviour of unreinforced and reinforced masonry [2]. With low strength masonry, given the important influence of the masonry unit/mortar interface on the structural behaviour, the authors decided to use a micro-modelling approach based on the Distinct Element Method of analysis. The software used was the Universal Distinct Element Code (UDEC) [3] which was developed initially to model sliding rock masses in which failure occurs along the joints [4]. This has similarities with the behaviour of low strength masonry. Typical examples of masonry structures that have been modelled using UDEC are described by Lemos [5], Toth et al. [6] and Zhuge [7]. An additional feature of UDEC is the capability to predict the onset of cracking; this is important when considering in-service as well as near-collapse behaviour. Strengthening by rock bolting, another feature of UDEC, allowed the authors to model masonry strengthened with reinforcing bars. As far as the authors are aware, the research described in this paper is the first in which UDEC has been used to model masonry structures that have been strengthened with retro-fitted reinforcement.

For a numerical model to represent the behaviour of a masonry structure with the required level of accuracy an appropriate constitutive model must be selected and parameters that are representative of the materials being modelled must be used. The elastic-perfectly plastic Coulomb slip-joint area contact model, available as an option within UDEC, was selected by the authors to represent the behaviour of low bond strength masonry. UDEC also provides a residual strength option to simulate tension softening effects. This was not selected as the bond strength of the masonry used in the research was much lower than that exhibited by modern masonry materials. As a result, any tension softening effects were likely to be an order of magnitude smaller than the bond strength and so were considered to be insignificant.

Conventionally, the material parameters for the constitutive models for masonry are based on the results from the testing of small assemblages or samples of material. Such tests do not usually reflect the more complex boundary conditions and the combinations of stress-state types that exist in real masonry structures. In addition, large numbers of tests are required to capture the inherent variations in the masonry and the results obtained from such tests are unlikely to include any variations in workmanship. Furthermore, the material parameters defined in UDEC to represent the characteristics of the zero thickness interfaces between the mortar joints and the bricks can be difficult to measure in practice. To address these difficulties, the authors used a method originally proposed by Toropov and Garrity [8] to determine the material parameters. Using the results from the laboratory testing of a series of unreinforced full-scale wall/beam panels constructed of low strength clay brick masonry, the authors were able to tune the UDEC parameters to best simulate pre- and post-cracking behaviour [9, 10]. The UDEC material parameters obtained using this approach are summarised in Table 1.

Table 1: Material Properties for Clay Brick Masonry used in UDEC

Joint normal stiffness (JKn) [GPa/m]	Joint shear stiffness (JKs) [GPa/m]	Angle of friction (Jfric) [degrees]	Joint cohesive strength (Jcoh) [MPa]	Joint tensile strength (Jten) [MPa]	Joint dilation angle (Jdil) [degrees]
13.5	5.87	40	0.06	0.10	40

MODELLING OF BRICKWORK WALL/BEAM PANELS WITH UDEC

Geometric models representing the clay brick wall/beam panels tested in the laboratory, described later in this paper, were created in UDEC. Each brick was represented by a deformable block separated by zero thickness interfaces at each mortar joint. To allow for the 10mm thick mortar joints in the real panels, each block was increased by 5mm in each face direction to give a UDEC block size of 225mm x 125mm x 75mm. Such an increase of the brick dimensions was found to have no significant effect on the accuracy of the model [10]. Also, each block was internally discretised into finite difference zone elements by UDEC, each assumed to behave in a linear elastic manner. As failure in low strength masonry is predominantly at the brick/mortar joint interfaces, the stresses in the bricks will be well below their strength limit and so no significant deformation of the block elements in UDEC would be expected. The zero thickness interfaces between adjacent blocks were modelled using UDEC's elastic perfectly plastic coulomb slip failure criterion with a tension cut-off. This means that, if in any of the numerical calculations the value of tensile bond strength or shear strength is exceeded at a certain location, then the tensile strength and cohesion are reduced to zero at that location.

The retro-fitted reinforcement (and the grout surrounding the reinforcing bars to ensure composite action) installed in some of the bed joints of the wall/beam panels was modelled using UDEC's structural beam elements. Using this approach, the reinforced bed joint is divided into segments with its disturbed mass "lumped" at nodal points along the length of the interface between the reinforced bed joint (inclusive of grout) and the rest of the brickwork. Forces generated in the reinforced bed joint are applied to the lumped masses which move in response to unbalanced forces and moments in accordance with the equations of motion. The reinforced bed joint is connected via the beam element nodes to the blocks by springs. Possible slip failure between the blocks and the reinforced bed joint is modelled in a manner similar to brick interaction along a discontinuity. Thus, displacements at such locations can be accommodated within the model. In the laboratory testing of the full-scale reinforced masonry wall/beam panels [1], it was noted that there was no premature de-bonding of the high strength cementitious grout from the stainless steel reinforcing bars. To replicate this lack of bond failure in the computational model, relatively high values were assigned to the material parameters defining the structural beam element. The properties used to represent the retrofitted reinforcement encapsulated in high strength grout and those used for the repaired diagonal mortar joints are shown in Tables 2 and 3, respectively.

Table 2: Material Properties for the combined Retro-fitted Reinforcement and Surrounding Grout used in UDEC

Young's Modulus E [GPa]	Poisson's Ratio v	Compressive Yield Strength St_ycomp [MPa]
27	0.2	55

Table 3: Material Properties for the Repair Mortar used in UDEC

Joint Normal Stiffness JK_n [GPa/m]	Joint Shear Stiffness JK_s [GPa/m]	Joint Tensile Strength J_{ten} [MPa]	Joint Friction Angle J_{fric} [degrees]	Joint Cohesion J_{coh} [MPa]	Joint Dilation J_{dil} [Degrees]
50	25	0.38	45	0.45	0

The bottom edges of the UDEC wall/beam panels were modelled as rigid supports in the vertical and horizontal directions, whilst the vertical edges were left free. Self-weight effects were assigned as a gravitational load. The analysis was carried out sequentially. First, the model was brought into equilibrium under its own self weight. Then, a velocity applied in the vertical downward direction to the load spreader plate on the top of the panel until collapse.

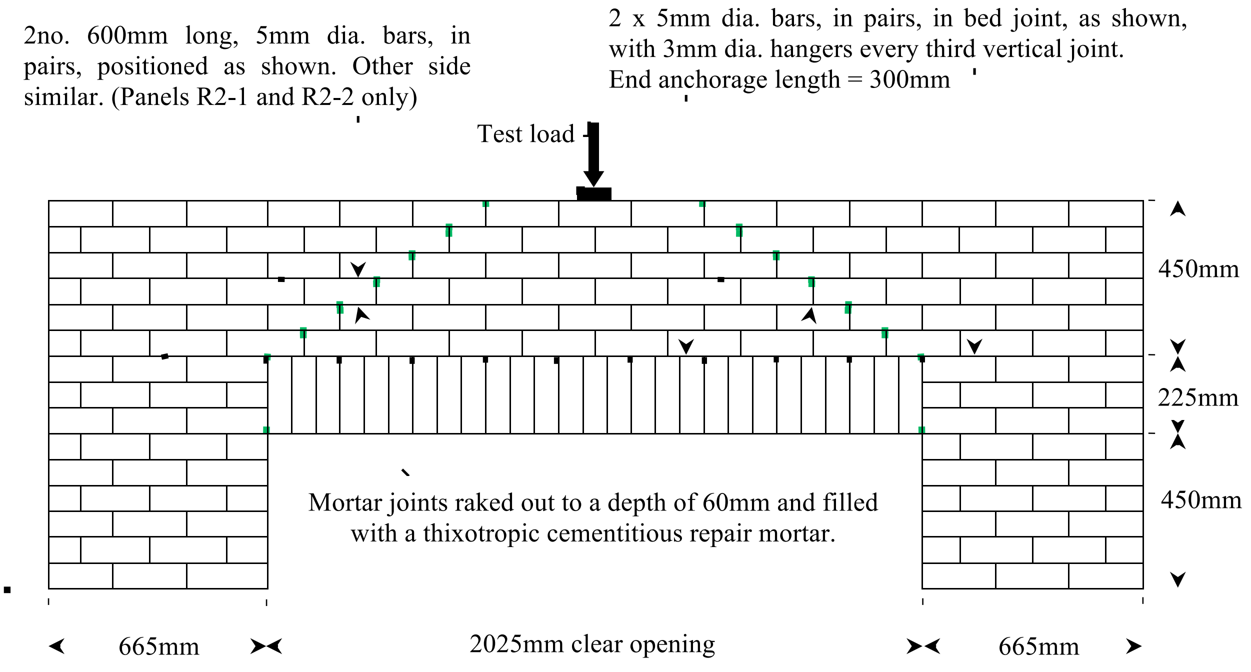
EXPERIMENTAL TESTING OF BRICKWORK WALL/BEAM PANELS

Three replicate pairs of single leaf thick clay brick masonry wall/beam panels were tested in the laboratory as part of a larger series of tests. Two of the panels (designated in this paper as U-1 and U-2) were unreinforced and the other four (R1-1, R1-2, R2-1 and R2-2) were retro-fitted with stainless steel bed joint reinforcement. Such panels were constructed to represent the outer leaf of an external cavity wall containing a 2.025m wide opening for a window; see Figure 1. All panels were built with a soldier course immediately above the opening, with the reminder of the brickwork being constructed in stretcher bond. This form of construction is in common use in the UK for low-rise buildings. The bricks were UK standard size (215mm x 102.5mm x 65mm) with a sand-faced finish and a compressive strength of the order of 35MPa. The mortar joints were all 10mm thick 1:12 (PC:sand), weigh-batched mortar. The compressive strength of the mortar varied from 0.6 to 0.9MPa. The bricks and mortar were selected deliberately to produce brickwork with low bond strength. Four of the panels were reinforced with bed joint reinforcement consisting of two 5mm diameter stainless steel reinforcing bars installed in the lowest bed joint immediately above the soldier course. Every third vertical joint of the soldier course was connected to the bed joint reinforcement using a 3mm diameter stainless steel L-shaped hanger bar. Two of the test panels (R2-1 & R2-2) were constructed with additional reinforcing bars in the fourth bed joint above the opening. All the reinforcement was encapsulated in a high strength thixotropic cementitious grout to ensure that the reinforcement acted compositely with the existing brickwork. The reinforcing details are summarised in Table 4 and the reinforcement layout is shown in Figure 1. A more detailed description of the construction is provided elsewhere [1].

Table 4: Test Panel Details

Test panel and Description U = Unreinforced R1 = One layer of steel R2 = Two layers of steel	Mortar compressive strength [MPa]	Grout compressive strength [MPa]	Reinforcing details
U-1	0.9	49.8	None
U-2	0.8	49.8	None
R1-1	0.9	55.0	2 no. 5mm dia. bars in bottom bed joint
R1-2	0.7	55.0	2 no. 5mm dia. bars in bottom bed joint
R2-1	0.6	54.7	2 no. 5mm dia. bars in bottom bed joint +2 pairs of 600mm long 5mm dia. bars above
R2-2	0.6	54.7	2 no. 5mm dia. bars in bottom bed joint +2 pairs of 600mm long 5mm dia. bars above

It is common practice to install reinforcement into walls that are already cracked and deformed. Typically, in walls with openings, cracking tends to propagate diagonally from the corners of the opening. Such cracks are often repaired by raking out the cracked mortar and re-pointing with a stronger repair mortar. To replicate this form of repair, in all the test panels referred to in this paper, some of the mortar in the joints shown in Figure 1 were raked out to a depth of 60mm whilst the mortar was still relatively fresh. This was replaced by the same high strength cementitious repair grout that was used with the retro-fitted reinforcement.



2no. 600mm long, 5mm dia. bars, in pairs, positioned as shown. Other side similar. (Panels R2-1 and R2-2 only)

2 x 5mm dia. bars, in pairs, in bed joint, as shown, with 3mm dia. hangers every third vertical joint. End anchorage length = 300mm

Mortar joints raked out to a depth of 60mm and filled with a thixotropic cementitious repair mortar.

Figure 1: Typical Test Panel Details showing the Test Load Position, Reinforcement Layout and Simulated Diagonal Cracking Damage

After a minimum grout curing period of 28 days had elapsed, each wall panel was subjected to an externally applied vertical mid-span point load using a hydraulic ram via a 100mm x 100mm x 50mm thick steel spreader plate which was placed on top of the wall; see Figure 1. The load was applied in approximately equal increments, in each case the vertical mid-span deflection was measured and recorded.

RESULTS

Ultimate and first crack loads

Results from the computational analysis using UDEC are compared with those obtained from the testing of the wall/beam panels in the laboratory in Table 5. The load at which cracking was first detected visually in the laboratory testing, in Table 5, is compared for each panel with that predicted using UDEC when the applied load in the computational model corresponded to a separation of the blocks of 0.2mm. Apart from the load at first cracking predicted for wall/beam panel R2-2, there is good correlation between the results predicted using UDEC and those observed in the laboratory. The reason for this large single discrepancy is likely to be due to a particularly weak joint in the soldier course of panel R2-2 which caused initial cracking to occur at an applied load of 1.6kN; it is interesting to note that both unreinforced panels showed signs of initial cracking at the same load.

Table 5: Comparison of Experimental and Computational Results

Test panel	Experimental Results	Computational Results	Difference between experimental and computational results	Experimental Results	Computational Results	Difference between experimental and computational results
	Load at first visible crack [kN]	Load at first crack [kN]		Ultimate Load [kN]	Ultimate load [kN]	
U-1	1.6	1.6	0	5.1	4.3	16%
U-2	1.6		0	4.6		7%
R1-1	6.6	4.1	23%	13.6	14.6	7%
R1-2	4.6		11%	13.6		7%
R2-1	4.6	4.1	11%	14.6	15.0	3%
R2-2	1.6		156%	15.1		1%

Load vs. Displacement Behaviour

Figure 2 shows the applied load versus mid-span displacement responses predicted using UDEC for a plain (U), singly reinforced (R1) and doubly reinforced (R2) wall/beam panel. These responses match those observed in the laboratory quite well. Of particular interest are the small peaks in the UDEC-predicted responses after first cracking and the resulting reduction in stiffness. Similar variations were observed in the laboratory, particularly as the load was increased close to the peak value. Typically, under a constant applied load, changes in the vertical deflection were observed over a period of about 15 to 30 minutes. This coincided with the formation and propagation of cracks and the resulting redistribution of stress.

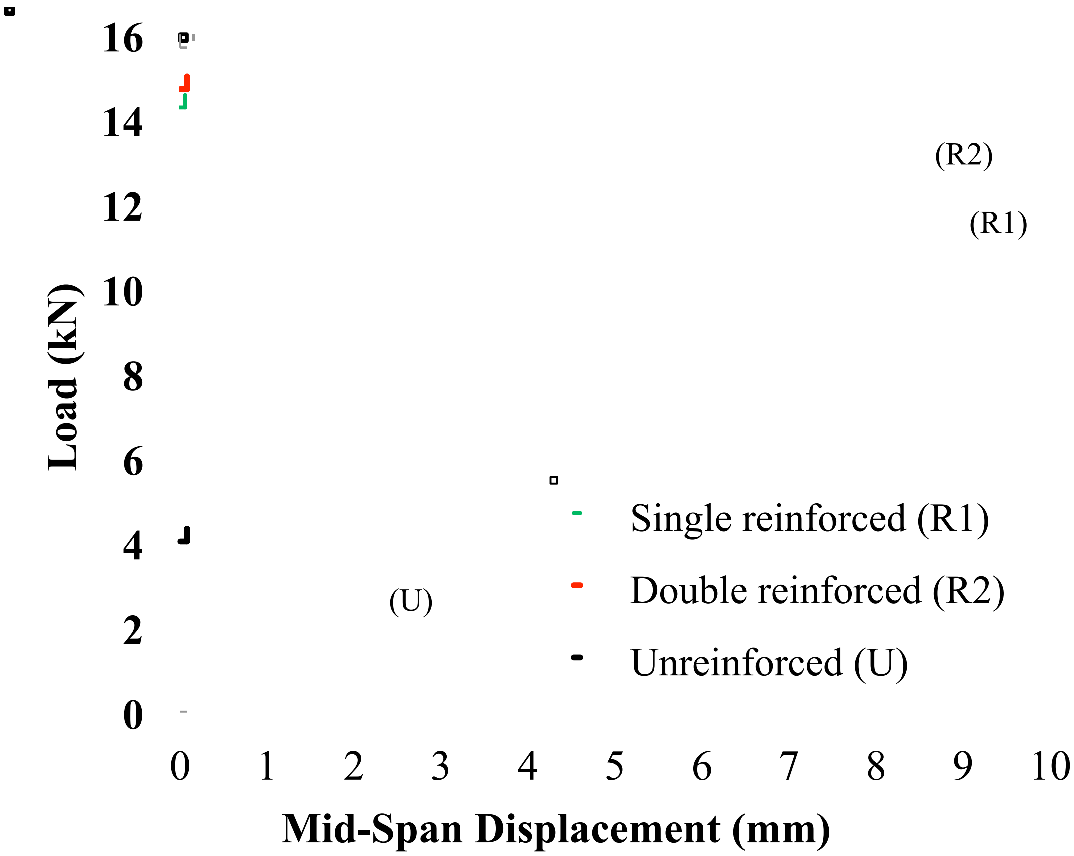


Figure 2: Load-Displacement Responses predicted using UDEC

Cracking

The formation and propagation of cracks under increasing applied load predicted using UDEC were found to be very similar to that observed in the laboratory. In particular, the behaviour predicted using UDEC coincided with four notable aspects of behaviour observed in the laboratory namely: a) initial flexural cracking in the soffit of the panel; followed by b) the development of flexural cracks in the bed joint of each support; followed by the development and propagation of diagonal cracks c) then collapse. Figure 3 summarises the development of cracks at different stages of loading for the wall/beam panels with one layer of reinforcement (R1) predicted using UDEC. This compares well with the crack pattern observed in the laboratory testing of panels R1-1 and R1-2 which is summarised in Figure 4. A similar crack pattern was obtained for a panel with two layers of reinforcement (R2).

In the laboratory testing of the reinforced panels there was a marked difference in behaviour between the reinforced and unreinforced panels. In particular, the addition of retro-fitted bed joint reinforcement was found to increase the load at which first visible cracking occurred; the load carrying capacity and the ductility to avoid sudden brittle failure mechanisms and to enhance the load carrying capacity after first cracking. These important features were all successfully replicated in the UDEC model which, with increasing applied load, showed what appeared to be the formation of hinges, in-plane arching action and the interlocking of bricks. UDEC was also found to be capable of predicting behaviour at or close to collapse including the mode of failure.

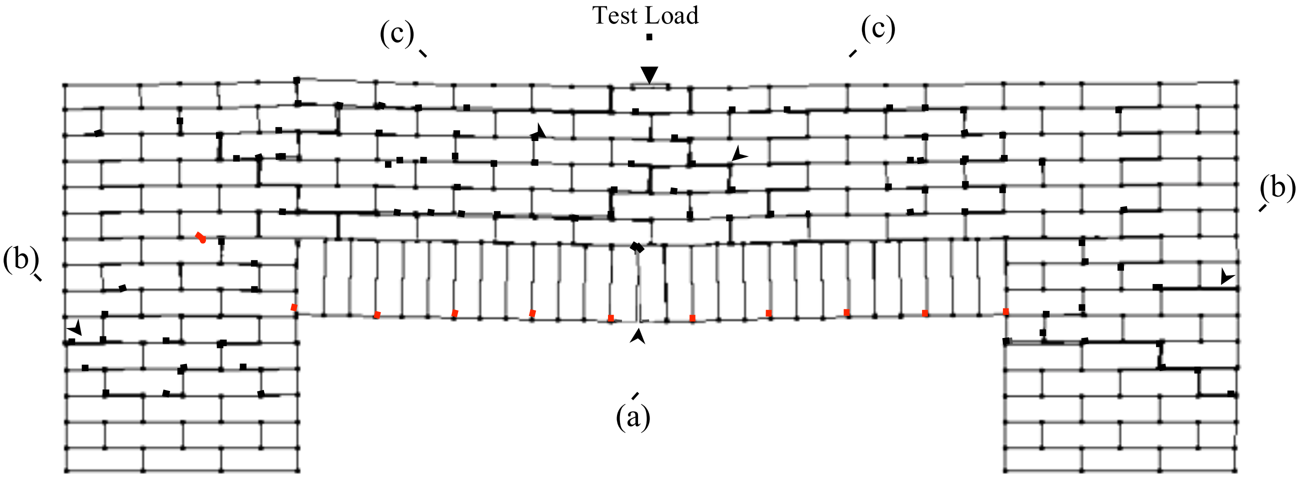


Figure 3: Crack pattern predicted using UDEC for reinforced panel (R1) at collapse

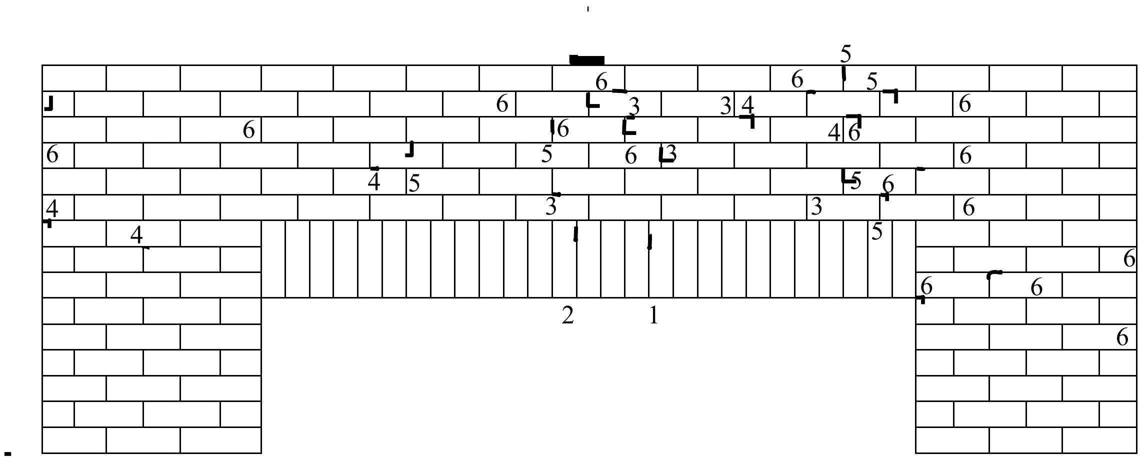


Figure 4. Observed sequence of cracking in reinforced panels R1-1 and R1-2
(1 = 1st crack formed; 2 = 2nd crack formed, etc.)

CONCLUSIONS

The development and suitability of the two dimensional discrete element software, UDEC, to predict the behaviour of a series of reinforced clay brick masonry wall/beam panels tested in the laboratory have been described. In this case the masonry consisted of a brick and mortar combination producing low strength masonry in which the bond at the masonry unit/mortar joint interface is sufficiently low to have a dominant effect on the mechanical behaviour.

The results of a programme of laboratory testing of full-scale wall panels reported at this conference [1] has shown that retro-fitted bed joint reinforcement can increase the load carrying capacity and the load at which first visible cracking occurs. In addition, such reinforcement was also found to improve the ductility sufficiently to avoid sudden brittle failure mechanisms and to enhance the load carrying capacity after first cracking. The research reported in this paper, which is limited to wall panels containing openings subjected to static in-plane vertical loading, shows that UDEC can be used to:

a). Predict the onset of initial cracking and the load at which this occurs in unreinforced and reinforced masonry wall/beam panels. This should prove to be useful for serviceability limit state considerations.

b). Model the formation and propagation of cracking beyond initial cracking up to near-collapse conditions.

c). Predict the load carrying capacity of unreinforced and retro-reinforced masonry wall/beam panels.

d). Predict the improvements in ductility and increases in the reserve of strength beyond first cracking that were found in the laboratory testing of full-scale wall/beam panels.

The authors are also applying UDEC and the three dimensional version, 3-DEC, to model the behaviour of masonry arches that have been strengthened using near-surface reinforcement.

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