THE EFFECT OF THE NUMBER OF MORTAR JOINTS ON THE STRENGTH OF MASONRY WALLS: AN ANALYTICAL INVESTIGATION

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A well-tested three-dimensional finite-element model for structural concrete is applied to the analysis of masonry walls by conducting a limited numerical parametric study in an attempt to establish the effect of the number of mortar joints on the load-carrying capacity of brick walls of constant height. It is observed, among other findings, that the strength of the brick wall increases with decreasing number of mortar joints, and this is explained with reference to the differing triaxiality of the various components of the wall.

INTRODUCTION

This paper describes the results of a numerical parametric study aimed at establishing the effect of the number of mortar joints on the load-carrying capacity of brick walls of constant height. The analytical model is based on a recently-developed fully three-dimensional (3-D) finite-element (FE) package for structural concrete [Ref. 1], its wide-ranging applicability having been proven on the basis of several case studies on plain-, reinforced- and prestressed-concrete members having varying geometric and reinforcement complexities, and concrete strengths [Refs. 2-5]. The FE package is based on a brittle constitutive relationship at the material level, and requires only the British Standard uniaxial cylinder strength (f_c) for material input. Its successful use in an investigation involving single brick units has recently been reported [Ref. 6], and its further extension to structural masonry is now illustrated by reference to the interaction between the brick and mortar units that make up a brick wall.

DETAILS OF THE WALLS STUDIED

In the present study, the masonry unit under consideration has dimensions 100 mm x 215 mm x 510 mm. The entire wall, of constant height h = 510 mm, has been analysed by setting the number of mortar joints equal to 25, 19, 13, 7 and 1 in turn. Denoting by N the number of mortar joints, the thickness of the various brick units is readily obtained as $t = (510 - 10\ N)/(N + 1)$. In all the cases studied, the thickness of each of the mortar joints was kept constant at a value of 10 mm. The mean crushing strength of a certain variety of clay brick "coupons" (69 MPa) tested and described elsewhere [Ref. 6] has been used as the f_c of the brick unit (with the corresponding constitutive relations) in the analysis. It may be mentioned here that the choice of the brick was simply dictated by the requirement that the brick strength should be considerably higher than that of the mortar, the latter's f_c being set originally at 20 MPa.

The ensuing mortar mix design was tested through four mortar cylinders (see [Ref. 7] for typical failure pattern), their average f_c being equal to 27.8 MPa, and, thus, quite close to the 20 MPa originally aimed at [Ref. 7]. One of the mortar cylinders was gauged (two gauges in the longitudinal direction and two gauges in the transverse direction) to record the stress-strain relationship (see [Ref. 7]); the resulting characteristic compared well with the corresponding case from among earlier constitutive data on mortars available from Imperial College [Refs. 8, 9]. (The constitutive relationship of the type of brick used in this study had been determined earlier [Ref. 6], and it also compared satisfactorily with the constitutive relationship of a concrete of similar strength.)

FINITE-ELEMENT MODELLING OF MASONRY WALL

In the FE discretization, symmetry was allowed for along the Y- and Z-axes (see Fig. 1). As such, the analysis of only one-fourth of the wall specimens was sufficient. The top loading plane of the wall was fixed in both X- and Y- directions, which mimicked full friction between the structure and its loading arrangement. (While freedom for the wall to slide horizontally along its ends would have been more amenable for the purposes of the present parametric study, as it would have eliminated end effects, an actual structural test of a wall is unlikely to involve attempts to minimize the unavoidable friction between wall specimen and loading plattens.) In all cases, a uniformly-distributed load of 10% of the mortar strength was applied vertically at each load step of the FE analysis. The main features of the 3-D FE model, and its related objectivity studies, have been described in sufficient detail elsewhere [Refs. 1-3] and, thus, it will be sufficient to simply recall the recommendations stemming from these references as regards the optimum strategies to be adopted for successful numerical analysis. In the discretization process, both brick (B) and mortar (M) units are represented by the HX20 "brick" element [Ref. 1]. The numerical integration of this element is carried out by means of the 2 x 2 x 2 Gaussian-integration rule. When cracking takes place, there is a reduction in shear moduli across the plane of the crack, and it is usual to define these by multiplying their uncracked values by the shear-retention factor (SRF), a parameter that is clearly associated with the concept of "aggregate interlock"; as argued elsewhere [Refs. 1-3, 10], however, the effect of aggregate interlock on the load-carrying capacity of a member is insignificant, and this is consistent with the chosen (constant) SRF (= 0.1), a value which, at the same time, is also sufficient to ensure the necessary numerical stability [Ref. 1]. (In the present context of brick and mortar, the exclusively-numerical nature of the SRF is even more evident, unless the brick itself is made of concrete.) Cracking is mimicked through smeared modelling, while "strong" nonlinearities are best accounted for through the iterative method known as the "Newton-Raphson plus" technique.

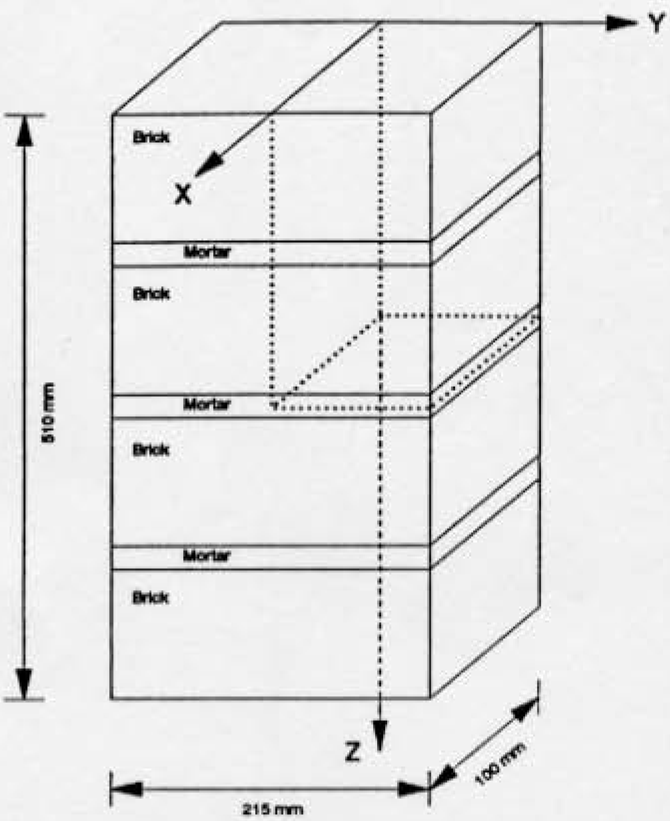

Fig.1 Typical case study (N = 3) prior to FE discretization (with dotted space denoting the one-quarter of the structure actually modelled)

OPTIMUM MESH-SIZE INVESTIGATION

In order to visualize the effect of mesh size on the FE predictions, and, also, to arrive at an optimum mesh configuration, the seven- and one-mortar joint case studies (i.e. N = 1, 7) were carried out initially using different mesh discretizations. The mortar strength was kept constant at 20 MPa. The present section contains the details of the optimum mesh-size investigation.

The results of various initial exploratory runs concerning the optimum mesh-size investigation are given in Table 1. It is apparent from this table that, with the number of mortar joints remaining unchanged at N = 1, the FE model predicts higher failure loads for analyses consisting of very large-sized finite elements for the high-strength brick units when these are combined with elements of smaller dimensions representing low-strength mortar units. This can be seen by reference to the case of one mortar joint of 10 mm thickness and two bricks of 250 mm height, for which three FE runs were made. In the first of these runs (CS5a), each brick unit was represented by only one HX20 brick element of 250 mm height. Consequently, the masonry wall sustained a load equivalent to 58 MPa. For the same brick unit, when modelled using five HX20 elements of 50 mm height (CS5b), the maximum sustained load (MSL) attained by the wall was 46 MPa. The MSL predicted by the FE model becomes 28 MPa when each brick unit is discretized using 25 HX20 elements each having 10 mm thickness (CS5c). A careful appraisal of the principal stresses in the various elements and the displacements of the nodes of these three investigations uncovered the fact that, when the size of the elements adopted for representing the brick unit becomes very large in comparison to the adjacent element representing the mortar joint, the effect of the dilation of the weak mortar becomes less prominent and, as a result, the structural member sustains more load as the tensile stresses caused by the mortar are localized. In such cases, the Gauss points of the large-sized brick elements remain outside the zone of influence of the element(s) representing the mortar. However, when the size of the two adjacent elements is comparable, the dilation in the low-strength mortar and its induced tension reach the Gauss points in the neighbouring high-strength brick elements representing part of the whole brick unit, and the brick fails in tension at a load much lower than its own failure load, as it should. This seems to be a rational explanation of the presently-observed numerical phenomenon. Thus, the excessive increase in the load-carrying capacity of the brick wall as observed in the first two FE runs (CS5a, CS5b) is due to numerical rather than factual reasons, stemming from the use of coarse meshes for the brick units. In the latter instances, the mortar at loads near to failure was subjected to a lateral confining stress equal to more than 50% of its ultimate capacity and this enabled the mortar to sustain loads in excess of twice its actual failure load. It is obvious that, in reality, the failure load is dictated by the incapacity of the high-strength brick elements to undergo expansion of similar magnitude to ths readily-expanding mortar. This observation points to the need, in FE modelling, to use elements of consistent size, since the adoption of incompatibly-sized elements, especially in conjunction with structural elements consisting of highly-different material properies, can lead to results which may not portray the real behaviour of the structure. It can also be seen from Table 1 that, for the case studies with 7-mortar joints (CS4a and CS4b), the effect of mesh size on the load-carrying capacity was much less significant (in fact, the discrepancy is of the order of the load-step increment, i.e. of the order of magnitude of the uncertainty inherent in the analysis). This

Case No.	No. of mortar joints	Mesh configuration (X x Y x Z)	Configuration of elements along z-axis	Maximum sustained failure stress, MPa
CS4a	7	1 x 1 x 8	4 B + 4 M	26
CS4b	7	1 x 1 x 24	20 B + 4 M	28
CS5a	1	1 x 1 x 2	1 B + 1 M	58
CS5b	1	1 x 1 x 6	5 B + 1 M	46
CS5c	1	1 x 1 x 26	25 B + 1 M	28

Table 1 Case studies to determine the optimum mesh configuration (mortar strength constant at 20 MPa).

suggests that only the presence of an isolated low-strength element in a FE mesh consisting of predominantly high-strength elements (for example, case studies CS5a, CS5b and CS5c) demands more care in the discretization process. Only the case studies which are not affected by the size of the elements will henceforth be reported and discussed.

RESULTS AND DISCUSSION

The results obtained from various FE runs, with mortar strength constant at 20 MPa, are shown in Table 2. It is evident from the table that, with the decrease in the number of mortar joints, the load-carrying capacity of the brick wall increases. When the number of joints is large, mortar strength practically determines the strength of the wall. The contents of Table 2 show that, for walls with 25, 19 or 13 mortar joints, the MSL was 10% above the ultimate strength of mortar. On the other hand, in walls with 7 or 1 mortar joints, the MSL was 40% above the mortar strength. The explanation for this effect is quite simple. Keeping the size of the wall fixed, the increase in the number of mortar joints results in a corresponding increase in the lateral expansion and thereby lateral tension in the abutting bricks, which eventually give in. However, for walls with a smaller number of mortar joints, the total amount of dilation undergone by all the weak mortar is relatively less. This results in a reduced amount of lateral expansion in the "constraining" bricks. As a result, the wall sustains more load. What is interesting is that the reduction in structural strength with the number of mortar joints does not appear to be a continuous process; instead, there appear to be two distinct types of behaviour (one above N = 13 and the other below N = 7).

From the above study, therefore, it becomes clear that the effect of a reduced number of mortar joints is to increase the overall load-carrying capacity of a brick-wall unit, the cause of this finding having been explained with reference to the differing triaxiality of the various components of the wall. A more extensive parametric study was subsequently conducted to validate further such observations. All the case studies have been repeated using different values of mortar strengths. Thus, in Table 3, the load-carrying capacities of brick walls with mortar strengths of 20, 15, 10, 5 and 1 MPa have been reported. In all the runs listed in Table 3, 10% of the relevant mortar strength has been used in the input as the uniformly-distributed load step.

It is evident from Table 3 that the basic trend showing the effect of the number of mortar joints in a brick wall remains unchanged with variation in the strength of mortar (i.e. two basic "wall" strength values for each mortar strength are apparent, on either side of the intermediate range $7 < N < 13$). A quantitative difference is, however, apparent. While for case studies with mortar strength of 20 MPa, the wall strength in CS5 is 27.27% higher than that for CS1, for brick walls with 15, 10, 5 and 1 MPa mortar strengths this gain becomes 9.09%, 33.33%, 83.33% and 500%, respectively. Except for the case of 15 MPa mortar strength (had there been a further two load steps - a possible margin of error - for this case, the gain would have been 27.27%, as for the case N = 20), the influence of mortar strength on the load gain, due to a decrease in the number of mortar joints, of a brick wall has been found to be more pronounced with a decrease in the strength of the mortar material. Now, it is well known that low-strength concrete and mortar materials dilate more, at loads near failure, than their normal- or higher-strength counterparts. Also, as pointed out above, due to the reduced tendency to overall lateral expansion (thereby reduced tension in the brick) of the mortar material, brick walls with a smaller number of mortar joints sustain higher loads. This effect, therefore, is, understandably, proportionally higher in brick walls having lower-strength mortar joints. Consequently, the percentage gain in the load-carrying capacity of the masonry unit as N decreases becomes higher with a lowering of mortar strength.

The preceding explanation for the increase in the overall load-carrying capacity of the brick walls with a corresponding decrease in the number of mortar joints has been argued for on the basis of the differing degrees of triaxiality of the various components of the wall. This can be further clarified with reference to Figs. 2(a) and 2(b), where the analytical crack patterns at the onset of cracking (load step 9) and at the maximum sustained load (MSL) level (load step 12), respectively, of CS1 (with mortar strength equal to 10 MPa) are shown (by reference to the one-fourth of the structure that was analysed). The top element refers to the mortar joint of half thickness located at the mid-height of the masonry unit. It is evident from Fig. 2(a) that the cracking process started at this central mortar joint, there being no further cracks in the next two load steps. Further cracking occurred at the MSL level but, still, only the elements representing mortar underwent cracking. The cracks formed at the mortar Gauss points were nearly vertical (as, in accordance to the sign convention of the 3-D package [Ref. 1] used in the analyses, cracks denoted by a circle represent fracture directions making an angle less than 45° with the plotting plane). Vertical cracks portray the presence of triaxial stresses perpendicular to the direction of loading, which subject the abutting brick elements to tensile forces. As a result, in the subsequent load step, these vertical cracks propagated suddenly into the adjacent elements representing brick units and the structure failed so abruptly that a suitable plotting file (of load step 777 - representing the MSL step plus one) could not be recovered. With a decrease in the number of

Case No.	No. of mortar joints	Mesh configuration (X x Y x Z)	Configuration of elements along z-axis	Maximum sustained failure stress, MPa
CS1	25	1 x 1 x 26	13 B + 13 M	22
CS2	19	1 x 1 x 20	10 B + 10 M	22
CS3	13	1 x 1 x 14	7B + 7 M	22
CS4	7	1 x 1 x 24	20 B + 4 M	28
CS5	1	1 x 1 x 26	25 B + 1 M	28

Table 2 Case studies with mortar strength constant at 20 MPa. (Note : the mesh configuration refers to one-quarter of the structure, so that the number of brick elements is (N+1)/2, while the number of full mortar joints is (N-1)/2 with an additional mortar joint with half the thickness.)

Case No.	No. of mortar joints	Mesh Configuration	Configuration of elements along Z-axis	Maximum sustained failure stress, MPa	Maximum sustained failure stress, MPa	Maximum sustained failure stress, MPa	Maximum sustained failure stress, MPa	Maximum sustained failure stress, MPa
				20 MPa mortar load @ 2.0 MPa	15 MPa mortar load @ 1.5 MPa	10 MPa mortar load @ 1.0 MPa	5 MPa mortar load @ 0.5 MPa	1 MPa mortar load @ 0.1 MPa
CS1	25	1 x 1 x 26	13 B + 13 M	22	16.5	12	6	1.2
CS2	19	1 x 1 x 20	10 B + 10 M	22	16.5	12	6	1.2
CS3	13	1 x 1 x 14	7 B + 7 M	22	16.5	12	6	1.2
CS4	7	1 x 1 x 24	20 B + 4 M	28	18	16	11	6
CS5	1	1 x 1 x 26	25 B + 1 M	28	18	16	11	6

Table 3 Case studies with varying mortar strength.

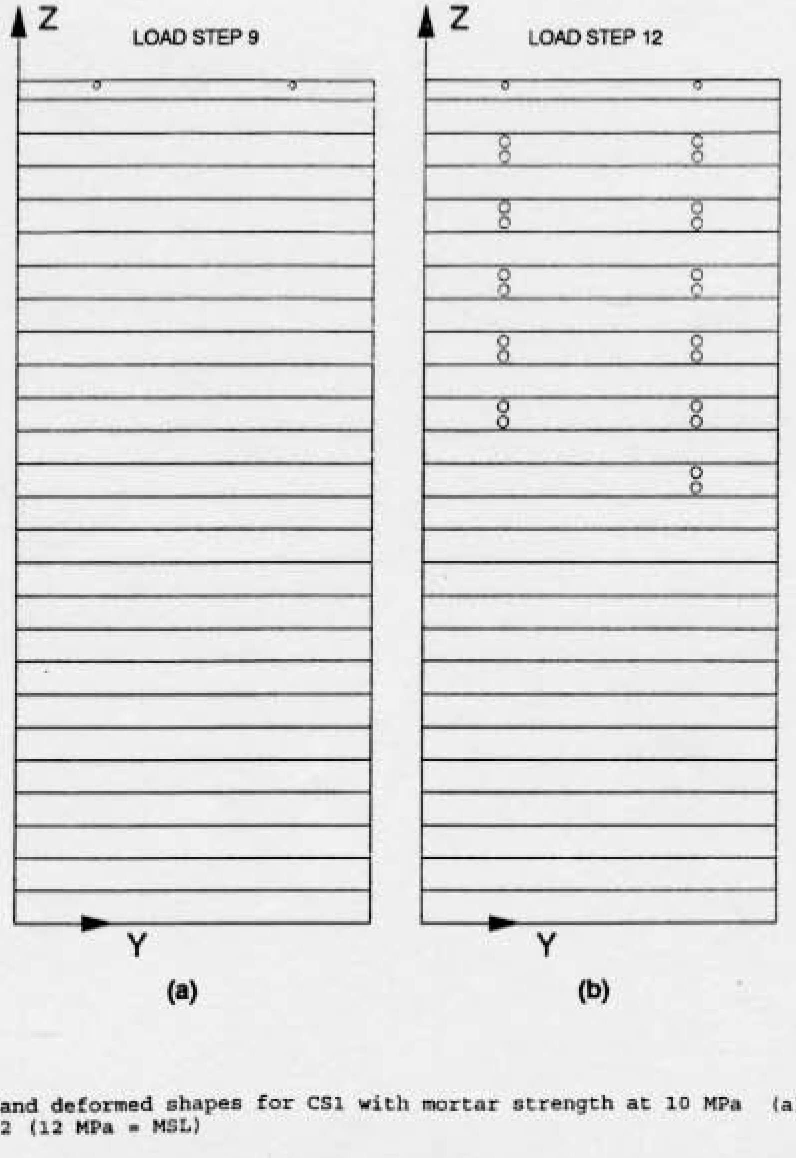

Fig.2 Crack patterns and deformed shapes for CS1 with mortar strength at 10 MPa (a) Load step 9 (9 MPa); (b) Load step 12 (12 MPa = MSL)

mortar joints, the resultant pull exerted by the expanding mortar on the structure also decreases. Thus, for example, in CS5, the brick wall (with only one mortar joint) sustained a load up to the MSL step of 16 MPa, after which the brick wall suffered sudden fracture and collapse without any early warning of cracking.

It is interesting to note that the general finding of the present analytical exercise is very much in line with the limited experimental evidence available. For example, in [Ref. 11] the effect of the number of mortar joints has been observed experimentally by reference to tests on 9-inch (225 mm) cubes of brickwork consisting of zero (by placing one upon another properly-ground bricks to form the brickwork) to four mortar joints. It was concluded that the compressive strength of brickwork cubes decreased gradually as the number of mortar joints increased - a trend also observed in the present study, but not in the range of the number of mortar joints tested (1 to 4) where analysis predicts constant strength. However, a careful study of the data reported in [Ref. 11] provides a timely reminder that experimental scatter in brickwork tests may well make it impossible to correlate experiments with analytically-predicted trends: nevertheless, excluding the single-cube test result ("ground bricks") in [Ref. 11], a plot of constant compressive strength throughout the range of 1 to 4 mortar joints can readily be proposed from the test data in view of such scatter, which is more compatible with present numerical findings. (A quantitative comparison between the experimental findings of [Ref. 11] and observations made in the present analytical study cannot, of course, be accomplished because of the difference in strength and dimension parameters of the wall units investigated.)

Another correlation of the test results of [Ref. 11] with the analytical trends presently reported refers to the relative values of brick and mortar strengths: thus, the ratio of the wall-to-mortar strength attains small values for high-strength mortars and, conversely, large values for low-strength mortars. Finally, other workers [Ref. 12] have found that, with an increase in the thickness of conventional mortar joints, brickwork strength is lowered. The effect of mortar thickness, although not studied in this paper, can also be explained by reference to triaxial stress conditions - a phenomenon which is central to the present analytical study -in the mortar joint in the proximity of failure. The effect of a thicker mortar joint should, indeed, be very much similar to the effect of additional mortar joints in the brickwork. Thus, an increase in the thickness of the mortar joint means a corresponding increase in the amount of lateral expansion (i.e. lateral tension in the neighbouring brick units) due to an increased amount of dilation in the weak mortar, as already explained earlier.

TENTATIVE CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

It is, of course, unwise to draw all-embracing conclusions on the basis of the above single wall example despite the parametric variation in both number of mortar joints and mortar strength. Nevertheless, the following remarks, specific to the case studies covered, might, tentatively, point to more general conclusions:

(a) The load-carrying capacity of the brick wall increases with the decrease in the number of mortar joints. Mortar (uniaxial) strength practically determines the strength of the wall when the number of joints is large.

(b) The basic trend showing the effect of the number of mortar joints in a brick wall remains unchanged with variation in the strength of mortar. Two basic strength values of the brick wall are apparent for each mortar strength, on either side of the intermediate range, or "regime", $7 < N < 13$.

(c) The rate of increase in the load-carrying capacity of a masonry unit of constant dimensions with respect to the strength of the mortar, as the number of mortar joint decreases, becomes higher with a lowering of mortar strength.

The present investigation was limited to the effect of the number of mortar joints on the strength of a masonry wall of fixed height. Although this work did enable certain trends to be identified, a fuller insight into the phenomenon would require the following additional studies:

(a) Further studies of the effect of the number of joints so as to determine whether the "transition" region defined by $7 < N < 13$ consists of a smooth transition or of a sudden jump; and whether such transition range for N varies with wall type.

(b) A study to investigate the effect of keeping the size of the brick unit constant for a fixed mortar thickness. It is felt that this parameter might be of particular relevance in providing a fuller understanding of the overall phenomenon, as the proposed additional work separates the effects of varying N and varying brick size (these were varied simultaneously in the present work). This could be carried out by allowing the height of the wall to vary.

(c) The effect of vertical as well as horizontal mortar joints (the former could be either straight or zig-zagging). Such a study would provide a more realistic description of a masonry wall.

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