BEHAVIOR OF CENTRALLY LOADED HALF-SCALED REINFORCED BRICK SLABS

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ABSTRACT
Reinforced brick (RB) masonry slab is widely used for floor and roof diaphragms throughout northern India from 1920's to until recently. Currently such construction is still popular in rural areas because of its easily available materials, low cost and lesser skilled labour requirement. Increasing cases of deterioration of such existing slabs and the need for their retrofitting has renewed the interest in the study of its behavior. Four, half-scale one-way slabs of clear span of 1500 mm and 500 mm wide and two, two-way square slabs of 1500 mm clear span were casted and loaded up to failure. The one-way slabs were loaded as three-span (4-point) flexure loading, while, the two-way slabs were loaded centrally by a patch loading. The load carrying capacity of these slabs was compared with simple sectional analyses.

Working Stress and Limit State Methods were used to obtain the allowable and ultimate moment capacity of the RB slab section, respectively. The yield line theory was used to predict the load capacity of the two-way slabs based on their collapse mechanism. The working stress approach provided conservative estimates of moment and load capacities, which was about 0.42 times the experimental observed capacity. On the other hand, various formulations based on limit state approach provided estimates in the range of 62% to 89% of the experimental load capacity for one-way and two-way slabs.

KEYWORDS: reinforced brick slabs, masonry, flexural strength, FE analysis

INTRODUCTION
Reinforced brick (RB) slab construction is a classical construction style wherein the slab is made up of reinforced brick masonry. These are extensively adopted in typical roofs of most north-Indian houses since the 1920's. Similar to Reinforced Concrete (RC) slabs, these are also subjected to flexural stresses with compression being taken up by the brick masonry and tension by the steel. The thickness of the RB slabs is dependent on the dimension of bricks and layers of bricks being stacked together. The bricks and reinforcement arrangement is as shown in Figure 1.

The origin of such slabs can be traced back to the Chicago fire of the 1870's, where after, fireproof brick construction become very popular and started replacing the traditional timber construction. The first design guidelines for RB slabs came up in 1904 in the Steineisendecken-Runderlass, Prussia, based on the working stress method (WSM) adopted from the reinforced concrete guidelines [1].

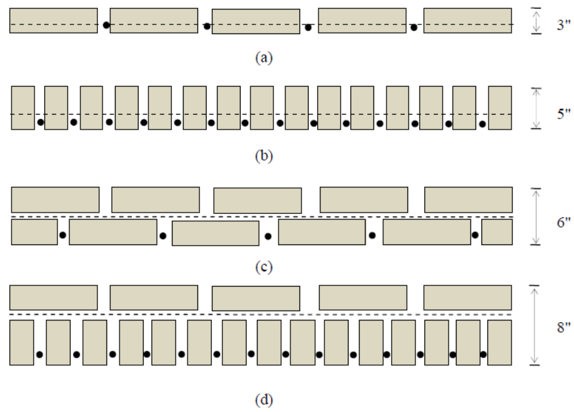


Figure 1: Brick Arrangement in slabs of variable thickness: a) 3 in. b) 5 in. c) 6 in. d) 8 in.

In 1922, the Central Public Works Department, India, carried out an extensive study on the behaviour of RB beams and slabs [2]. It stated that Reinforced Brickwork could substitute the RC structures on many fronts with some additional benefits like easily available materials (bricks), simpler and cheaper construction with lesser supervision, good workmanship and well insulated rooms. Another exhaustive study was done in 1932, in Virginia Polytechnic (USA), where thirty one-way RB slabs were tested by two-point loading at third points of the span [3]. It was observed that properties of brick units such as surface characteristics, water absorption, compressive strength, etc., greatly influence the load-deformation behaviour of the RB slabs along with the quality of workmanship.

In 1983, Bureau of Indian Standards drafted the code for the design and construction of reinforced brick floors and roofs utilizing the working stress method [4]. This code provides guidelines on materials, formwork, curing, laying of bricks and reinforcement and allowable stress for masonry. It recommends a minimum spacing of 60 mm between the bricks, an allowable stress in masonry equal to 0.23 f_m (where, f_m is the prism compressive strength) and placing the reinforcements embedded completely in the mortar joints in between the bricks.

Figure 2: Deterioration of RB slabs

RB slabs were popular during the first quarter of the last century in north India, where the quality of bricks produced was good. A large number of industrial, government and residential buildings were constructed in the following five to six decades with RB floors and roofs. Many of these slabs are now showing sign of distress and deterioration (Figure 2). A definite need to replace or strengthening such slabs is essential to prevent subsequent damages. An experimental study was conducted to understand the load deflection behaviour of the RB slabs and comparing the obtained results with the analytical methods using flexural strength analysis and finite element approach.

DETAILS OF SPECIMENS

The experimental study was conducted on half-scaled specimens of one-way and two-way RB slabs. The clear span of the prototype was 3000 mm × 3000 mm with a thickness of 220 mm, which reduces to 1500 mm × 1500 mm and 110 mm thick for the half-scaled test specimens. An additional 100 mm bearing length was provided on either side for positioning the RB slab specimens on the support system. To study the one-way action, slabs having length to width ratio 3:1, i.e., slab of dimensions 500 mm × 1500 mm were casted. The details of the geometry and reinforcement are given in Table 1 and Figures 3 and 4. The specimens are designated as 1WB, 1WT and 2W, where 1W and 2W signify one-way or two-way slab and the alphabets B and T denotes whether the slab had main reinforcement in the bottom or in the top mortar layer. For each type of RB slab two specimens were prepared and tested till failure.

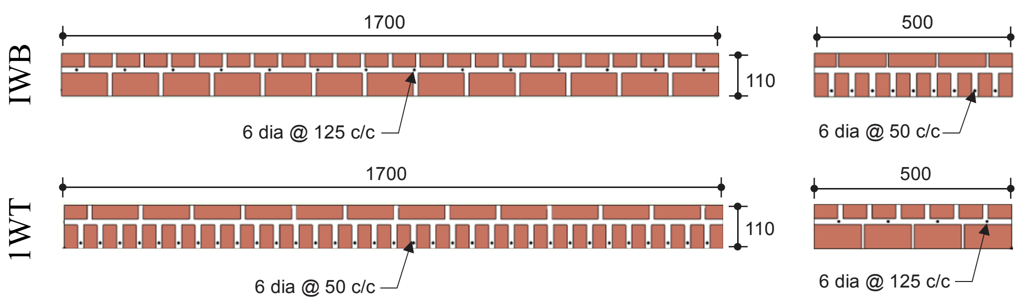
Table 1: Dimensions of various RB slab specimens

Specimen type	Nomenclature	Length# (mm)	Width (mm)	Thickness (mm)	Effective depth (mm)
One-way Slab	1WB	1700	500	110	95
	1WT	1700	500	110†	42.5
Two-way Slab	2WB	1700	1700	110	$d_b^* = 95.0$ $d_t^* = 42.5$

Length include the bearing length of 100 mm on both sides.

*d_b and d_t – Effective depth for the reinforcement at the bottom and top of the slab, respectively.

† Slight larger thickness of 130 mm was noted in one of the 1WT slab.



(a) Longitudinal Section (b) Cross Section

Figure 3: Geometric and reinforcement details of 1WB and 1WT specimens

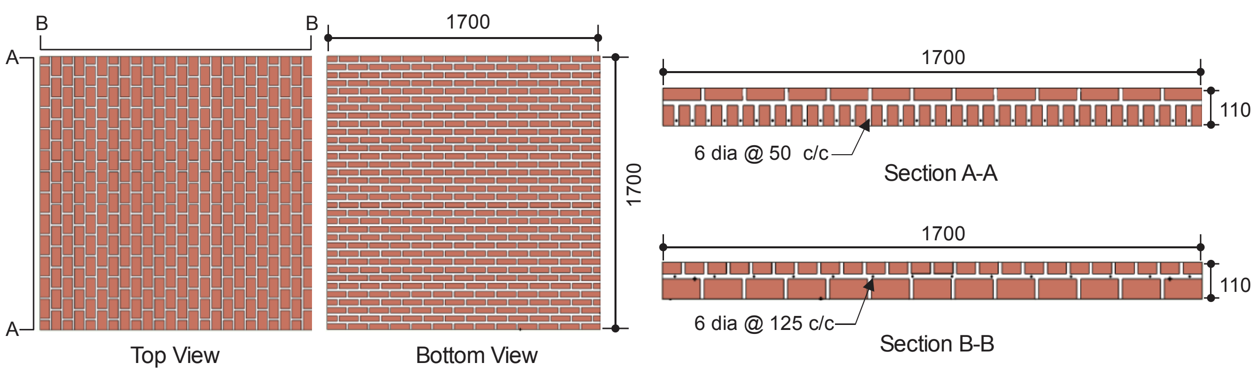
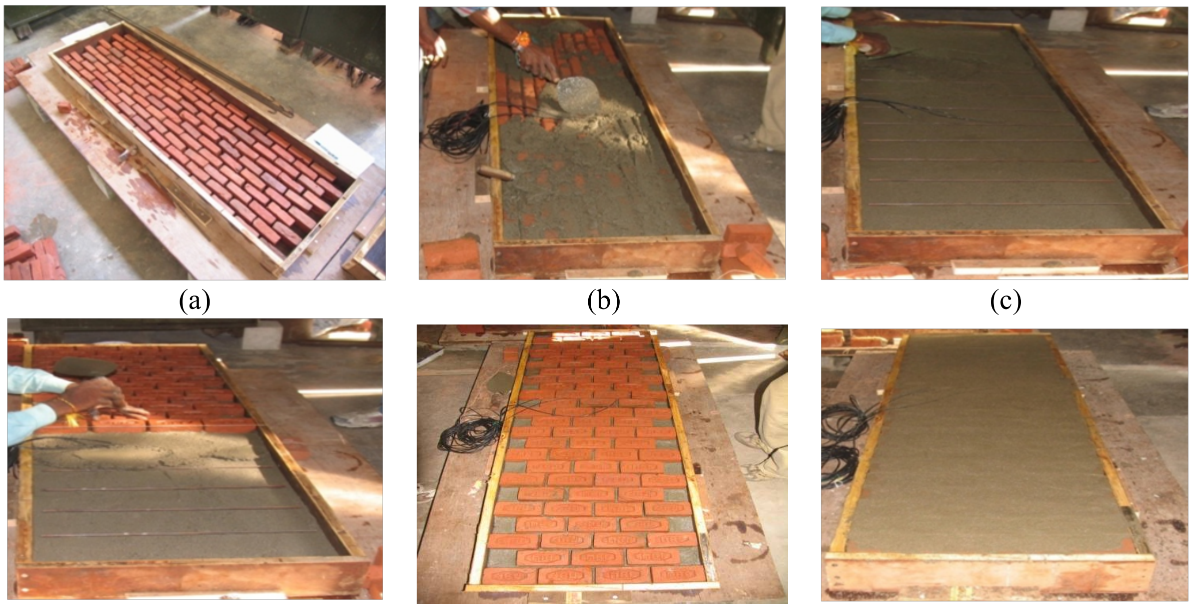


Figure 4: Geometric and reinforcement details of two-way RB slabs

The casting sequence of 1WB slabs are shown in Figure 5. Initially, the bottom brick layer was laid and the reinforcement bars were arranged in the brick joints (Figure 5a). The depth of the reinforcement was maintained throughout the casting. The joints were filled with mortar and vibrated for compaction (Figure 5b). A second layer of mortar was placed on bottom layer of bricks and the transverse reinforcement was then positioned in between two layers of bricks (Figure 5c). Finally, the top brick layer was placed and the gaps in between the bricks were filled with mortar (Figures 5d-5f). Prisms and mortar cubes were also casted to determine the compressive strength of masonry and mortar.



(a) (b) (c) (d) (e) (f)

Figure 5: Casting of 1WB RB slab specimen

Custom-made half-scale burnt clay bricks and cement-mortar of mix proportion 1:3 (cement: sand) were used for the RB slabs. The bricks had an average dimension of 120 × 60 × 35 mm. Locally available 6 mm diameter reinforcement bars were used in all RB slab specimens. These reinforcement bars were of a sub-standard quality and had a large variation in their yield strength values, in the range of 305 MPa to 480 MPa. Five-brick tall standard stack-prism tests were conducted for each of the specimens. Moreover, flexural test on masonry wallets were performed to determine flexural strength for a plane of failure parallel and perpendicular to the bed joints as per BS EN 1052-2 [5]. Five specimens each for flexural strength parallel and perpendicular to the bed joint were casted following the similar construction procedure as RB slabs. These masonry wallets consist of single layer of bricks on edge and were approximately 660 mm in length, 390 mm wide and 60 mm thick. The average properties of material units, compressive and flexural strength of brick assemblages are shown in Table 2. It is interesting to note that only small difference was observed between the flexural strength of slabs for failure plane parallel and perpendicular to the bed joint. Typically the flexural strength of the brickwork in the direction at the right angle to bed joint is three times as great as across the bed joint [6]. However, due to the different construction procedure of RB slabs as compare to common brickwork the flexural strength for a plane of failure perpendicular to the bed joint was found to be only 1.3 times to the strength in bending across the bed joints.

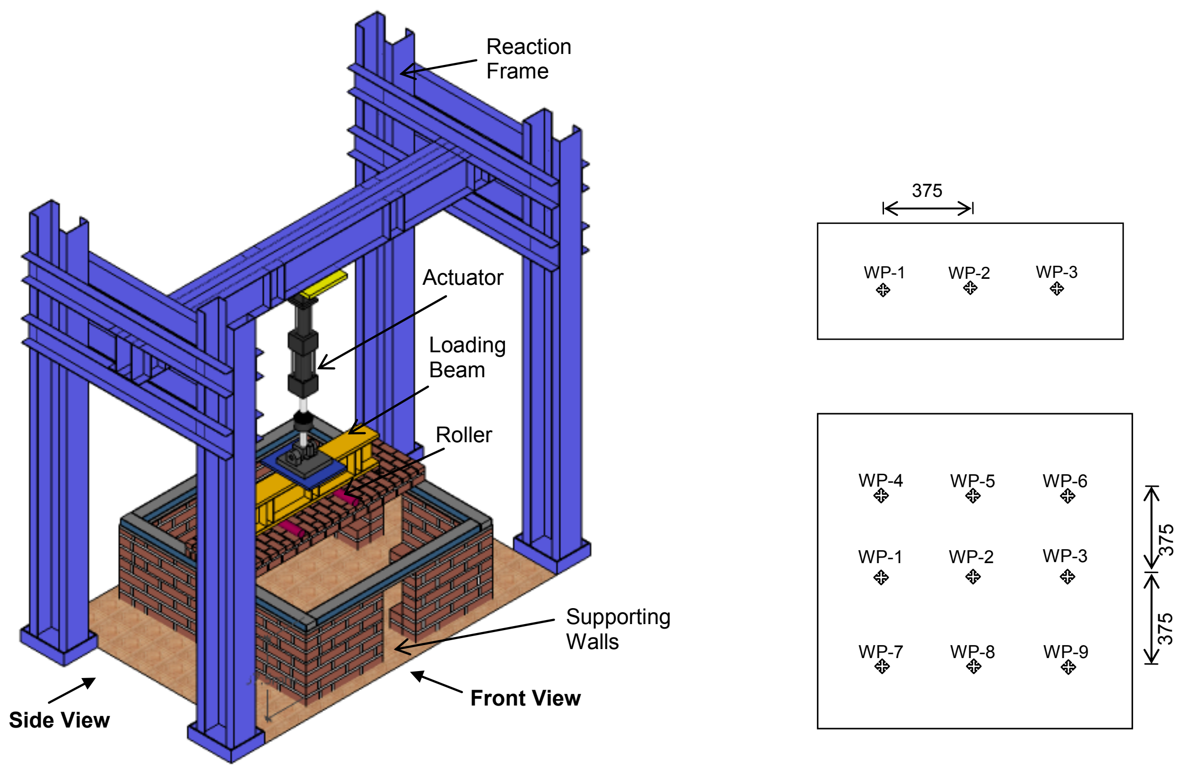
Table 2: Properties of material units and brick assemblages

Properties		Average values*
Water absorption capacity of bricks		12.6 (11)
Crushing strength of bricks, f_b (MPa)		22.0 (21)
Compressive strength of mortar cubes, f_j (MPa)		29.6 (9)
Compressive strength of masonry prism, f_m (MPa)		13.3 (18)
Flexural strength for failure plane (MPa)	Parallel to the bed joint	1.8 (8)
	Perpendicular to the bed joint	2.4 (5)
Yield strength of reinforcing bars, f_y (MPa)		370.0 (14)

*Values in bracket () denote coefficient of variation

TEST SET-UP

The schematic of the test setup is shown in Figure 6(a). Support systems for the slabs were made by creating a wall of height 630 mm on four sides with the opening of 300 mm on each side of the wall for operations under the slab. Slab deflections were recorded by using a square grid of nine wire potentiometers for two-way slabs and three for the one-way slabs as shown in Figure 6(b). One-way slabs were loaded as three-span loading whereas the two-way slabs were loaded by a centrally-applied patch load on an area of 300 mm × 300 mm (Figure 7). Leather pads were provided in between the slab and the plate to ensure a uniform distribution of the load.



(a) (b)

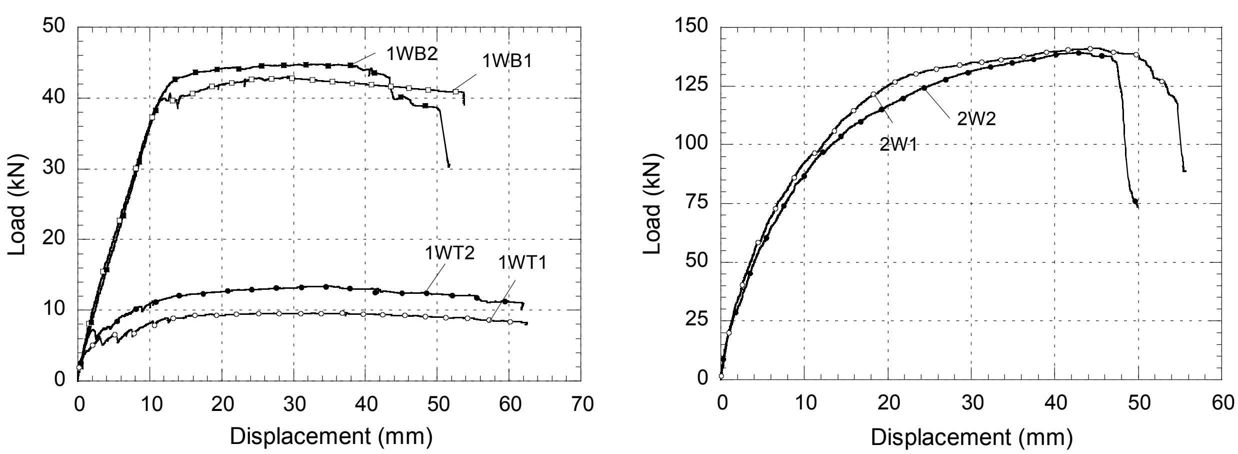
Figure 6: (a) Isometric view of the test set-up (b) Schematic of the location of potentiometers in one-way and two-way slabs

(a) (b)

Figure 7: (a) Three span loading for the one-way slabs (b) Patch loading for the two-way slabs

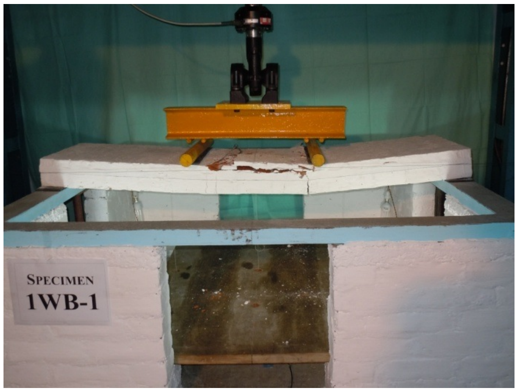
TEST RESULTS

The load-deformation behaviour of the one-way RB slabs with the main reinforcement at the bottom (1WB) and at the top (1WT) mortar layers are compared in Figure 8a. The observed behaviour in the two 1WB specimens was nearly the same. The load was resisted almost linearly by the slabs for up to 40 kN for 1WB1 and 43 kN for 1WB2, which was then followed by a pronounced non-linear behaviour. On the other hand, the specimen 1WT-1 and 1WT-2 exhibited different ultimate loads of 9 kN and 13 kN, respectively. This variation was due to the larger thickness 1WT-2 specimen (about 130 mm) which leads to a higher effective depth as compared to 1WT-1 specimen. For both 1WT specimens, the elastic behaviour was observed until the masonry cracked at a load of 3 kN, following which the tensile forces were taken up by the reinforcing bars and the load being resisted non-linearly. It can be observed that the 1WB specimens have significantly higher strength as compared to the 1WT specimens. This is primarily due to the larger effective depth of about 95 mm in 1WB slabs as compared to 42.5 mm in 1WT slabs. The ultimate failure of these slabs was marked by the compressive failure of masonry as shown in Figures 9(a) & 9(b).

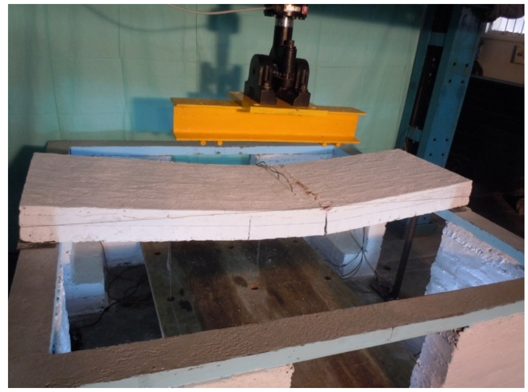


(a) (b)

Figure 8: Load-deformation behavior of (a) one-way and (b) two-way slabs



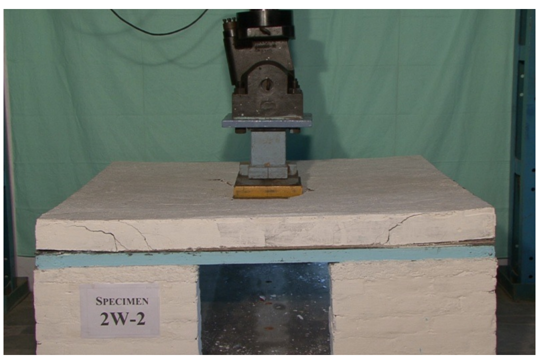
(a)



(b)

Figure 9: Ultimate failure of the slab specimens (a) 1WB (b) 1WT

The load-deformation plot for the 2W RB slabs is shown in Figure 8b. For both specimens, the behaviour was found to be nearly identical. These slabs under patch load exhibited non-linear behaviour even at small deflection levels. The major flexural cracks were observed at a load of 90 kN. The ultimate loads for these were found to be about 140 kN, which was followed by a brittle failure in the punching shear mode. Figure 10(a) shows the specimen 2W-2, failed in the punching shear mode and the crack patterns at the bottom of the slab are shown in Figure 10(b).



(a)

(b)

Figure 10: (a) Ultimate failure of 2W-2 in the punching mode of the 2W slab (b) Flexural cracks at the bottom of the slab post-failure

SECTIONAL ANALYSIS OF THE RB SLABS

The RB slabs were analysed for allowable loads by various approaches such as the Working Stress and the Limit State Method. The Working Stress Method (WSM) predicts the load carrying capacity of the RB slab on the basis of elastic stresses in masonry and steel. The values of permissible stresses used for the design of RB slab was taken from Brebner [2]. The results were obtained in terms of the moment capacity and the load capacity calculated along the direction of main reinforcement.

In the Limit State Method (LSM), the limit states of collapse and serviceability were considered for estimating the design strength. The limit state method for the analysis and design of RB slabs was implemented by Dayaratnam [7], Dasgupta [8], and Chakrabarti et al. [9]. Dayaratnam utilized a design method similar to RC slabs given in IS 456 [10] and proposed a reduction factor of 0.85 to incorporate for the direct compressive strength of prisms in the analysis while the slabs were actually subjected to flexural stresses [7]. Further, partial safety factors were also incorporated in design for both the brickwork and the reinforcement. Dasgupta [8] carried out laboratory tests on RB slabs which were designed according to the design guidelines for RC slabs as per ACI 318 [11]. It was proposed that the stress distribution at the ultimate load can be replaced by an equivalent, rectangular stress block of 0.85 f_m to predict the flexural strength of the RB slabs. Similarly, Chakrabarti et al. (1988) based on the experimental results proposed semi-empirical relations to predict flexural strength of RB slabs [9].

The strength of the two-way slabs based on working stress and limit state method was calculated using the yield line approach. The yield line theory is an upper-bound approach which estimates the ultimate load of the slab by postulating a collapse mechanism compatible with the boundary conditions. The collapse mechanisms are well known for almost all practical cases and assuming the correct mechanism can ensure the proper estimation of the capacity of slabs. The capacity of the two-way RB slab was estimated by considering the yield-line pattern for centrally loaded slabs with simply supported boundary conditions as shown in Figure 11. The yield line divide the slab in five segments one at the centre equal to the area of the loading plate and other four equal segments making 45° angle with the edges. Applying the virtual work principle, the total collapse load F_u can be estimated using following equation:

$$F_u = 5 \times \left(m_{ux} + m_{uy} \right) \tag{1}$$

where, m_{ux} and m_{uy} are the ultimate moment of resistance per unit width (kNm/m) of slab along x- and y-direction, respectively. For two-way RB slabs as shown in Figure 4, m_{ux} and m_{uy} will be moment of resistance per unit width provided by reinforcement at the bottom and top brick layer. Moreover, the section analysis of both 1W and 2W RB slabs were also performed in SAP 2000 [12] to estimate the moment carrying capacity. The moment-curvature relationship for the 2W slab was obtained along two orthogonal directions and the minimum was taken as the ultimate load carrying capacity.

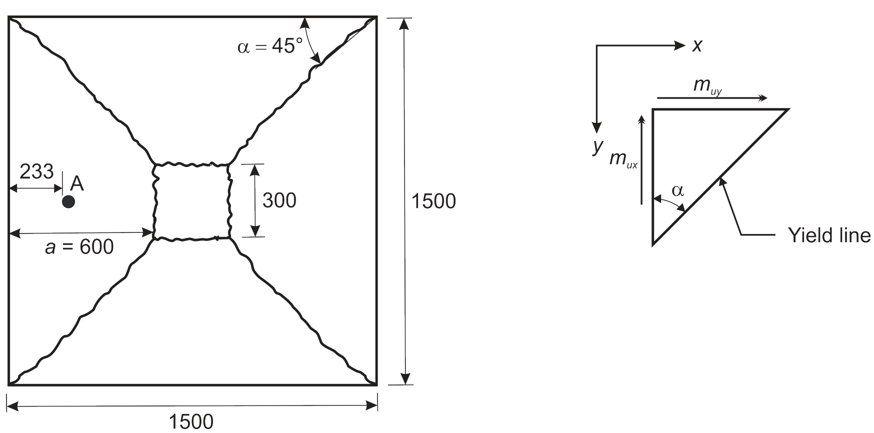


Figure 11: Yield line pattern and dimensions of the two-way slabs (*A* is the centroid of each trapezoidal segment from the edges)

In Table 3, the flexural strength predicted using various approaches were compared with the experimental results. The strength estimates for the slabs using WSM were found to be conservative (~ 0.4 times the experimental load) and can be attributed to the assumed low permissible stresses. However, the various limit state methods predicted the flexural strength of RB slabs reasonably close to experimental values. The design method proposed by Dayaratnam (1987), slightly under-predicts the capacities for both 1W and 2W slabs because the safety factors used for the materials were higher than those adopted in the other approaches. The average results using methods proposed by Dasgupta (1981) and Chakrabarti (1988) were 80 – 90% of experimental values and were found to be appropriate for design purposes. The section analysis in SAP 2000 gave reasonably good prediction for the 1W slabs but the 2W slabs results were slightly over predicted.

Table 3: Comparison of capacity (kN) of RB slabs estimated using different approaches with experimental results

Slab type	Exp. load	Working stress method	Dayaratnam (1987)	Dasgupta (1981)	Chakrabarti et al. (1988)	SAP 2000 (Sec. analysis)
1WB	41.0	18.7 (0.46)	33.0 (0.81)	39.5 (0.94)	39.8 (0.95)	30.4 (0.74)
1WT	9.6	3.7 (0.39)	6.6 (0.73)	7.9 (0.82)	7.9 (0.83)	7.2 (0.75)
2W#	141.0	-	88.0† (0.62)	124.8 (0.89)	105.5 (0.75)	159.5 (1.13)

*Figure the bracket () indicates the ratio of predicted load by experimental load
Strength calculations are based on yield line approach
† includes partial safety factors for materials

CONCLUSIONS

Reinforced Brick (RB) slabs has been popular alternatives to RC slabs and are commonly used in the load bearing masonry buildings in northern India where good quality bricks are available. Experiments on half-scaled models of one-way and two-way slabs are carried out to understand their load-deformation behaviour upto failure and to verify the accuracy of various analytical estimates of their load carrying capacity. It was observed from the experimental tests that the behavior of the RB slabs closely resembles with that of the RC slabs. In the case of the one-way with main reinforcement in the bottom layer mortar (1WB) specimens, the nearly elastic behavior was observed until the yielding of the rebars (indicated by formation of the flexural cracks) and followed by pronounced non-linear behaviour. However, for the one-way slab with main reinforcement in the top layer (1WT) slabs, the cracking of the masonry began even before the yielding of the rebars, but continued to resist increasingly higher loads till the yielding of the rebars. As expected the capacity of the 1WB specimens were more - about four times of the 1WT specimens. The load-deformation behavior of the two-way slabs (2W) was rather nonlinear from the initial stages of the loading with a gradually decreasing stiffness. After the occurrence of the first flexural cracks there was a drastic deterioration in stiffness until the slab reached the maximum load. The experimentally observed cracking pattern was similar to that assumed for the yield line analysis of centrally loaded RC slabs and the final failure was in the punching mode.

Available working stress and limit state design methods (WSM and LSM) were utilized to predict the capacity of the slabs. The WSM provided rather conservative estimates of about 0.40 times of the experimentally observed values for both one-way and two-way slabs, indicating somewhat lower values of permissible stresses. On the contrary, the LSM approach gave a fairly good estimate of flexural strength of RB slabs and can be used in design purposes.

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