A Collaborative Evaluation of the BS 5628 "Wallette" Test for Measuring the Flexural Strength of Brickwork

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SUMMARY

The results are reported of a four-laboratory evaluation of the test method for the flexural strength of brickwork given in the British Code of Practice for the Structural Use of Masonry BS 5628.

The results indicate that the general level of variability is higher than would be desirable and that, despite the use of common materials and workmanship there were some differences between the laboratories. On the basis of the work improved specifications are suggested for equipment, calibration, specimen storage and test procedures.

1 INTRODUCTION

In the Code of Practice for the Structural Use of Masonry BS 5628 issued in 1978 a comprehensive method is given for the design of masonry subjected only, or principally, to lateral forces. This was a departure from CP 111 the previous Code which gave only rudimentary guidance. The principal design method given in BS 5628 is based on the masonry acting either as a cantilever springing from a foundation (free-standing wall), as a beam spanning vertically or horizontally between appropriate supports or as a plate spanning in two directions between three sided or four sided supports.

In order to calculate the design moment of resistance for such elements the following parameters are required:

(1) The flexural 'modulus of rupture' strength of the masonry (f_{kx}) in the two orthogonal directions.

(2) The materials safety factor γm.

(3) The section modulus Z.

Then the design moment of resistance $= \dfrac{f_{kx}}{\gamma m}$

where the f_{kx} appropriate to the principal direction of spanning is used.

Furthermore if, as has been proposed, the Code is amended in future to utilise a panel design method based on the elastic behaviour of plates, data would also be required on the Youngs modulus of various masonry materials.

In order to measure, economically, the flexural strength of masonry and also to eliminate as far as possible the additional effects of plate action most

workers, to date, have chosen to test relatively small rectangular pieces of masonry. These have then been analysed on the assumption that they behave as a simple beam.

In 1963 Ryder [1] reported the use of small panels of brickwork three bricks long, by four courses high tested horizontally in three point loading as a method of studying brick mortar bond and the influence of various factors, thereon following some earlier work reported by Youl and Coats [2].

Hendry [3] used a similar technique but with specimens four bricks long to measure flexural strength for horizontally spanning brickwork (strong direction tested <u>normal</u> to the bed plane) and six-brick-high prisms for vertically spanning brickwork (weak direction tested <u>parallel</u> to the bed plane).

In 1977 West, Hodgkinson and Hazeltine [4] reported the results of a large programme of tests carried out at the British Ceramic Research Association (BCRA) to establish flexural strength data for brickwork. In this programme the specimens used, termed wallettes, were four bricks long by four courses high for the strong direction and two bricks long by ten courses high for the weak direction.

Further departures from previous methods were the use of four point loading and testing the walls in a vertical attitude as built. This technique lowers the likelihood of damage during the setting up of the specimen and cuts down the chances of error arising from the failure away from the loading point in the three point configuration. Lawrence [5] also came to the conclusion that four point loading was more satisfactory.

This test is the basis of the one given in Appendix A3 of BS 5628: Part 1: 1978 which can be used to establish a value for f_{kx} for any particular combination of units and mortar.

During 1979/80 several more test rigs of the type described in BS 5628 were constructed and it was decided that an investigation of the repeatability of the test from laboratory to laboratory should be carried out.

In this initial experiment four laboratories were involved - British Ceramic Research Association (BCRA), Building Research Establishment (BRE), The London Brick Company (LBC) and The Polytechnic of the South Bank (PSB), and the experiment was designed with the intention that the variability due to workmanship, materials and curing should be minimised in order that the variability due to test apparatus and technique be examined.

In addition to the measurement of the strength of the wallettes (modulus of rupture) each laboratory also attempted to measure the deflection at mid-

span and from plots of the load and deflection values the secant and initial tangent modulus of elasticity were derived. This additional data is not currently required for the purposes of BS 5628 but was thought to give useful insight into the behaviour of the specimens and the apparatus and could be useful in future if any form of elastic design were contemplated.

2 MATERIALS

All the materials used were drawn from common batches obtained by the BCRA at Stoke-on-Trent and dispatched to the other three laboratories over a period of about three weeks. Specifications are given in Table 1.

3 CONSTRUCTION

The aim of the experiment was to keep the constructional variables to a minimum in the hope that the laboratory-to-labatory test variability could be assessed. To this end all the mortar was mixed to the same nominal consistency using the dropping ball test as a control. Generally speaking consistency was reported in the specified range of 11-12 (see Table 2) but the feeling was that the test was not a very sensitive one.

The same bricklayer built all the walls using the same technique. Each wall was given a 'fair face' where the joints were struck off and tooled and a 'back face' where the joints were stuck off and then rubbed over with a piece of scrim.

3.1 Mortar strength

100 mm cubes were cast of all batches of mortar used and were cured and tested according to BS 4551 after 28 days storage in lime saturated water. Mean results are given in Table 2.

3.2 Storage conditions

By mutual agreement curing was carried out by covering the wallettes with polythene sheeting until the day of test. This technique does not produce a hermetic seal and there is some slow drying out of the brickwork.

4 APPARATUS

All the equipment used for the tests was constructed to meet the requirements of BS 5628 Appendix A3 Section 1. These requirements are essentially:

(1) The apparatus should enable the wallettes to be tested in the vertical attitude.

(2) One of the outer and one of the inner bearings should be pivotted to accommodate variations in the plane of the specimens.

(3) The loading and support knife edges should all be faced with some form of deformable 'bolster' such that contact is spread across the face of the wallette and not concentrated at high spots.

BS 5628 gives an example of hydraulic bolsters, ie water filled plastic tubes, which were used by BCRA and by BRE but PSB used a larger diameter water filled rubber tube and LBC used a rubber tube mounted on a steel

rod. Reasons given for not using the standard hydraulic bolster were that there is insufficient restoring tendency so the fluid could all collect at one end. This behaviour was not, however, observed at BRE.

(4) The outer bearings should be about 50 mm from the edge of the wallettes and the spacing of the inner bearings should be approximately 0.6 times the spacing of the outer bearings. The actual values used are given in Table 3. They are all almost identical except the BCRA rig which is a fixed compromise between the two wall formats. All the other apparati had adjustable bearer supports.

(5) The wallettes should be set on two layers of PTFE to obviate any frictional restraint. This requirement was met in the spirit of the Code but not to the letter at BRE and at PSB by using needle roller bearings in place of the PTFE layers.

There are no more specific requirements in BS 5628.

All the laboratories used a dual measuring system for failure load consisting of an oil pressure gauge attached to the hydraulic ram supply and an electrical output force transducer in series with the loading ram. Where the two measuring systems are not calibrated against each other there appears to be a likelihood of a disparity of up to 10% between the two measurements. A disparity in excess of this figure probably indicates that a fault has developed in one or other system.

Measurements of deflection were also made although this is not a requirement of BS 5628. BRE, BCRA and PSB employed a single electrical movement transducer bearing against the centre of the wall while LBC employed two transducers, one on either edge at centre span. All the deflections were measured with reference to the loaded face of the walls to avoid possible damage to the transducer. In each case a reference plane was attached with two points opposite one outer bearing and one point opposite the other in tripod layout.

It appears to be better to clamp the reference plane to the wallette rather than mount it on the loading frame with springs. Although the two techniques give apparently the same point of reference there appears to be sufficient variation in the stress conditions induced by the springs to cause minor deflections in the plane assembly on bedding in of the reference points, with consequent errors. On an earlier BRE frame of this type this behaviour led to apparently negative deflections being recorded in the first half of the test. The BCRA frames of this type have given results with very high variability.

There did not appear to be any particular advantage in using two transducers or any indication that the single central one gave the wrong results except the advantage of duplication should one unit fail. The LBC trial did, however, show that there was no particular bias to one side or other caused by the geometry of their apparatus.

5 RESULTS AND DISCUSSION

The results are summarised as means in Tables 4a and 4b for the two directions of test. Suspiciously high coefficients of variation (>30) are highlighted.

Observations and conclusions from these results and their subsequent analysis are as follows:

(1) Difference between the two faces of the specimens

There was no consistent difference between the two faces of the specimens, ie 'fair' and 'back' in respect of any of the properties measured. Differences in strength were apparent but these interacted with laboratory and were only just significant where observed. Subsequent analysis will ignore this factor.

(2) Oil pressure versus load cell load measurement

Apart from errors caused by a malfunctioning data logger on one BRE batch the two measuring methods for ultimate load gave sensibly similar results, although some differences are inevitable if the two methods are not deliberately cross calibrated. The use of the two methods simultaneously acts as a useful cross check. Analysis of the derived 95% confidence limits (f_{kx}) values without replication indicated no significant difference between the two methods.

(3) Laboratory-to-laboratory variation

Encouragingly there was no significance effect of laboratory-to-laboratory variability on the measured strength normal to the bedding plane after a full replicated analysis of all the oil pressure values and no effect on the calculated value for f_{kx} using an unreplicated analysis. Also apart from one normal and one parallel result, which were marginally under, all the mean strengths exceeded the values for f_{kx} in Table 3 of BS 5628 for the appropriate bricks and mortar.

Conversely, however, there was a laboratory-to-laboratory effect on the strength value for the more sensitive parallel direction observed for both the full analysis of strength and the unreplicated analysis of the calculated value of f_{kx}.

The values of f_{kx} determined using the log-normal distribution method given in BS 5628 ranged from -45% to +35% of the Code values but more often they tended to be lower than the Code figure.

Part of the reason for the lower than expected values for the normal direction may be the design of the bricks. The pattern of three large holes means that there are very thin walls in the centre of the brick at the point where the maximum stress is concentrated in a normal test. The results of this weakness was that the predominant mode of failure tended to be that of snapping of equal numbers of mortar joints and bricks instead of the more normal behaviour of shearing of the mortar joints. Even for the 1:2:9 mortar some of the failures were due to snapping of bricks.

Another problem appeared to be in the attainment of the Code mortar strengths. None of the mortar mixes actually achieved the preliminary laboratory test value prescribed in BS 5628 Table 1 and some did not achieve the 'site test' minimum. The possible explanation for this may be partly due to the higher plasticity used (dropping ball 11-12 instead of 10 as specified) and partly to the sand which only just fell within the grading requirements of BS 1200 as shown in Figure 1.

The deflection measurements highlight the inaccuracies resulting from equipment where the reference plane has any connection whatsoever with the loading system (used only by BCRA). Even taking the results from the other three laboratories alone there were differences in the mean measured deflection, the secant modulus and the tangent modulus. In all cases full statistical analysis of the replicates indicated that the differences were significant at the 99.9% level.

There also appeared to be some variation in the orthogonal ratio which was statistically signficiant at 95% probability on an unreplicated test. A full analysis is not possible because different specimens are used for the two test directions.

(4) Effect of mortar grade

The effect of the mortar grade was significant for nearly all the properties studied, especially on strength as would be expected.

It would not be unreasonable, however, if the ultimate deflection was somewhat less dependent on mortar grade than strength and elastic modulus are.

In fact the analysis of deflection for the normal wallettes tested at BRE, LBC and PSB showed it to be independent of mortar strength but dependent on laboratory, while in the parallel direction the deflection was very dependent on mortar strength and on laboratory.

There was also no statistically valid effect of mortar grade on the orthogonal ratio.

(5) Failure position in parallel test

Figure 3 shows the failure position distribution for all the specimens tested at all laboratories and Figures 2a-2d are the individual laboratory's distributions.

The assumption that the probability of failure at one of the five mortar joints in the nominally constant bending moment region (joints 3-7) is constant is supported by the results of BCRA, LBC and BRE and the overall result but the PSB equipment had a pronounced tendency (confirmed by a Chi square test) to fail specimens in joint No 2. The statistical testing of the two remaining joints, Nos 2 and 8, is more difficult because the failure probability is not known but clearly it is lower especially for joint No 8.

Current practice is to assume a lower value for the bending moment at joints Nos 2 and 8 and to calculate the failure stress accordingly. This is a reasonable assumption provided the shear stress across this joint does not contribute in some way to the failure.

If all the results of specimens which failed at either joint Nos 2 or 8 are calculated in this way and then the mean of the group they are in is subtracted then the distribution is as given in Figure 4a compared to Figure 4b where no such correction has been made.

If the hypothesis that there is a reduced bending moment at joints Nos 2 and 8 is accepted then the result shown by Figure 4a would be expected,

ie that in these specimens the joint which failed was considerably weaker than the mean joint strength for that group.

Unfortunately if the other hypothesis that the combined action of bending and shear on joints Nos 2 and 8 is equivalent to the uniform bending moment on joints Nos 3 to 7 then the result illustrated by Figure 4b would also be expected.

(6) Mode of failure in a normal test

Failures were reported as one of three modes:

(1) Pure shear - no bricks broken
(2) Intermediate - one brick broken
(3) Failure of units - two bricks broken.

The overall results are probably illustrated most graphically by taking the total number of snapped units which were 59 for 1:1/4:3 mortar, 31 for 1:1:6 and 22 for 1:2:9. The distributions are shown in Figure 5. Although there is some laboratory-to-laboratory variation, this was not found to be significant by a 'Chi squared' test. With normal brickwork mortars the failure line always includes two or more perpend joints in tests on brick sized units.

6 CONCLUSIONS AND RECOMMENDATIONS

Apparatus

(1) Bolsters: Although it is not possible to prove it, the use of different bolsters may have been a contributory factor to the laboratory-to-laboratory differences. It would be useful if a specific investigation could be carried out to see if any one type is clearly better than the alternatives.

(2) Articulation of loading arms: The Code specifications call for only one of the inner loading arms to be articulated whereas all the machine users agreed that articulation of both inner arms was necessary. Three of the machines in fact achieved a degree of articulation by allowing the whole inner loading frame to articulate while the LBC machine was doubly articulated. Again this may have contributed to the laboratory-to-laboratory differences.

(3) Load measuring system: The two methods of measurement were equally valid but would give some discrepancy if not cross calibrated. From experience on the BRE machine it was evident that 'pressure lag' could occur if the oil pressure gauge was sited too far from the ram and this should be avoided if possible.

It was felt desirable that a portable Reference Standard should be developed which could be calibrated on a grade A test machine and such a device is now on trial.

(4) Affects of the loading points: possible differences arising from slight offsets of the loading points in setting up were concluded to be unimportant.

(5) Deflection measurement: It was concluded that a separate reference frame was essential on a vertical attitude machine. The portable Standard should also allow calibration of the deflection measuring system.

Specimen configuration

(6) Span/depth ratio: This was felt to be adequate for 100 mm thick specimens but not for anything thicker.

(7) Normal (strong) specimen: It is not possible to design a completely symmetrical specimen since odd numbers of courses are unrepresentative of the average structure while even numbers of courses always fail at a line of perpend joints. These are offset from the central axis and thus could give rise to torsional moments. Research should be carried out to establish whether the offset gives rise to any errors and whether additional courses would be desirable.

(8) Parallel (weak) specimens: The full statistical implications of testing five joints have not yet been resolved.

Further research would be desirable on the relationship between the behaviour of wallettes and full sizes walls and the predictive accuracy of the f_{kx} values derived from wallette tests.

In view of the ambiguity of the results derived from joints outside the region of constant bending moment it was suggested that, in future, these should be omitted from calculations pending a more thorough investigation.

(9) Joint finish: It was concluded that minor differences were unimportant but that raked joints should either be tested for under Appendix A3 or should be allowed for in calculations.

Specimen preparation

(10) Mortar consistency: The mortar testing clauses in BS 5628 Appendix A1.1 specify a consistency of 10 mm penetration of the dropping ball. It should be made clear in the relevant sections (Appendices A2 and A3) that mortar for bricklaying will usually be of a different consistency and preferably a range of consistency should be stated.

(11) Dropping ball test: This was felt to be a very inconsistent and insensitive measure of plasticity especially in the hands of unfamiliar operators.

(12) Preparation of mortar specimens: Specimens prepared by non-experienced staff should be regarded as 'site prepared' for the purposes of these tests.

(13) Size of mortar specimens: BS 5628 allows three specimen sizes and the current BS 4551 four sizes and there is no indication in either document as to whether these different specimens can give different results or on which specimen size the Table of Mortar Strengths is based. In some recent tests, differences of up to 2:1 have been observed between the

early strength of 70.71 mm and 100 mm cubes. Additionally BS 5628 specifies a non-standard cube size of 75 mm. Codes such as BS 5628 should specify a single standard specimen size unless it can be stated explicitly that all the allowed variations give the same results.

(14) Curing conditions: standard curing regimes for both the wallettes and the mortar cubes should be stated explicitly in all Codes.

7 GENERAL

Both the internal variability and that between one laboratory and another was felt to be too high and research should be continued in an attempt to improve the test along the lines discussed.

8 ACKNOWLEDGEMENT

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9 REFERENCES

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TABLE 1 MATERIALS DATA

Bricks	Ibstock 3-hole perforated wirecuts Crushing strength 57.2 N/mm^2 Initial rate of absorption 0,90 kg/m^2/min Total water absorption 8.3%
Cement	Ordinary Portland cement to BS 12
Lime	Standard hydrated lime to BS 890
Sand	Local building sand complying with BS 1200, 1976 Sieve analysis as Figure 1

TABLE 2 MEAN MORTAR STRENGTH AND CONSISTENCE

LABORATORY	STRENGTH (N/mm^2)				CONSISTENCE (DB mm)			
	BCRA	BRE	LBC	PSB	BCRA	BRE	LBC	PSB
1:$\frac{1}{4}$:3 (i)	11.5	9.5	13.2	13.5	11.4	11.4	11.3	11.3
1:1:6 (iii)	4.2	1.8	2.7	2.7	11.4	11.5	11.3	11.2
1:2:9 (iv)	0.93	0.80	0.97	1.10	11.5	11.5	11.5	11.3

TABLE 3 GEOMETRY OF THE TEST APPARATUS

		BCRA	BRE	LBC	PSB
Normal	Overall span – mm	712	800	790	800
	Span of inner points – mm	400	480	474	480
	Ratio of inner/overall	0.56	0.60	0.60	0.60
Parallel	Overall span – mm	712	650	640	650
	Span of inner points – mm	400	390	384	390
	Ratio of inner/overall	0.56	0.60	0.60	0.60

TABLE 4a MEAN RESULTS FOR PARALLEL (WEAK) WALLETTES

MORTAR (BS 5628 f_{kx} N/mm²)	LAB	STRENGTH N/mm² AND VARIABILITY						DEFLECTION AT FAILURE mm		YOUNGS MODULUS kN/mm²			
		From load cell			From oil pressure					Secant		Tangent	
		Mean	CV%	f_{kx}	Mean	CV%	f_{kx}	Mean	CV%	Mean	CV%	Mean	CV%
1:¼:3 (0.5)	BCRA	0.57	20.4	0.37	0.56	20.3	0.37	0.096	64.1	8.7	55.2	-	-
	BRE	1.05	24.2	0.65	0.88	13.4	0.67	0.058	16.8	18.6	11.9	20.1	10.1
	LBC	0.69	18.8	0.47	0.75	24.2	0.43	0.063	29.7	11.45	25.1	15.9	8.6
	PSB	0.81	18.1	0.54	0.83	17.3	0.56	0.065	21.2	14.0	21.6	18.9	13.9
1:1:6 (0.4)	BCRA	0.39	29.1	0.24	0.39	30.1	0.23	0.05	11.0	19.3	88.5	-	-
	BRE	0.69	14.0	0.52	0.65	16.7	0.47	0.046	18.6	15.7	16.4	17.3	13.4
	LBC	0.54	18.5	0.37	0.59	20.8	0.38	0.042	22.1	13.05	17.2	15.7	13.0
	PSB	0.56	18.2	0.38	0.57	17.3	0.40	0.041	10.3	15.7	22.8	16.6	17.6
1:2:9 (0.35)	BCRA	0.36	25.8	0.19	0.35	26.1	0.19	1.03	98.7	3.8	140	-	-
	BRE	0.50	21.3	0.33	0.52	18.4	0.36	0.034	18.6	15.8	15.4	16.8	11.9
	LBC	0.40	15.0	0.30	0.44	19.9	0.28	0.040	21.6	10.31	13.7	11.7	10.9
	PSB	0.45	9.8	0.37	0.46	9.6	0.38	0.041	15.2	11.4	6.2	12.5	11.8

TABLE 4b MEAN RESULTS FOR NORMAL (STRONG) WALLETTES

MORTAR (BS 5628 f_{kx} N/mm²)	LAB	STRENGTH N/mm² AND VARIABILITY						DEFLECTION AT FAILURE mm		YOUNGS MODULUS kN/mm²				ORTHOGONAL RATIO	
		From load cell			From oil pressure					Secant		Tangent			
		Mean	CV%	f_{kx}	Mean	CV%	f_{kx}	Mean	CV%	Mean	CV%	Mean	CV%	Means	f_{kx}
1:¼:3 (1.5)	BCRA	2.02	19.3	1.33	2.02	19.1	1.30	0.55	30.0	4.3	28.9	-	-	0.28	0.28
	BRE	1.58	30.1	0.87	1.71	25.3	1.05	0.25	24.7	10.1	22.5	15.7	29.1	0.51	0.64
	LBC	1.89	28.5	1.06	2.06	27.4	1.19	0.31	19.4	9.39	16.8	14.1	8.2	0.36	0.36
	PSB	2.02	22.7	1.20	2.03	22.3	1.25	0.31	25.1	10.1	8.4	13.8	10.1	0.41	0.45
1:1:6 (1.1)	BCRA	1.51	22.4	0.93	1.51	22.4	0.94	1.02	83.3	3.5	109	-	-	0.26	0.25
	BRE	0.84	40.6	0.31	1.59	18.4	1.07	0.24	25.5	10.8	21.3	-	-	0.41	0.44
	LBC	1.61	12.4	1.24	1.78	11.5	1.39	0.34	15.9	7.1	10.7	12.9	5.5	0.33	0.27
	PSB	1.56	17.4	1.11	1.56	17.6	1.11	0.34	22.0	7.2	19.8	12.7	10.4	0.37	0.36
1:2:9 (1.0)	BCRA	0.96	18.8	0.69	0.96	18.5	0.69	0.23	50.4	5.4	37.7	-	-	0.36	0.28
	BRE	1.33	23.2	0.79	1.34	19.4	0.86	0.32	18.5	6.3	12.8	7.2	13.6	0.39	0.42
	LBC	1.12	23.2	0.69	1.23	23.0	0.76	0.30	23.4	5.73	16.6	12.9	7.3	0.36	0.37
	PSB	1.15	29.5	0.55	1.18	29.8	0.55	0.30	21.7	5.9	17.9	11.1	14.4	0.39	0.69

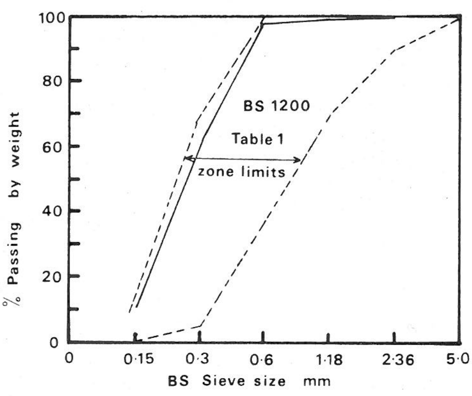

FIGURE 1 SAND GRADING

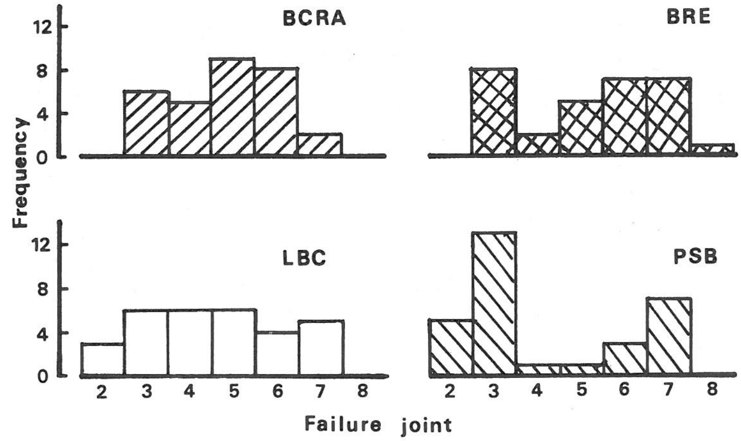

FIGURE 2 DISTRIBUTION OF JOINT FAILURE POSITIONS FOR PARALLEL SPECIMENS

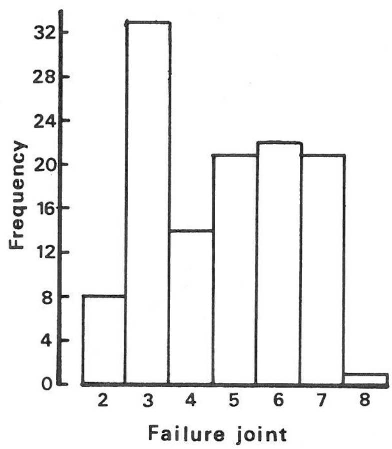

FIGURE 3 TOTAL DISTRIBUTION OF JOINT FAILURE POSITIONS

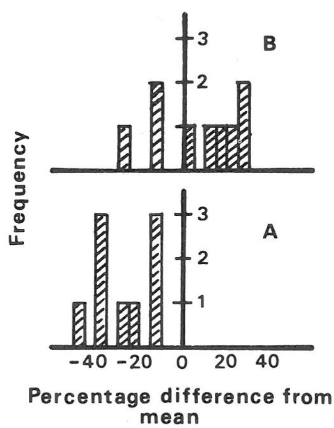

FIGURE 4 FAILURES IN JOINTS 2 AND 8 CALCULATED
(A) BY REDUCING BENDING MOMENT
(B) WITH NO CORRECTION

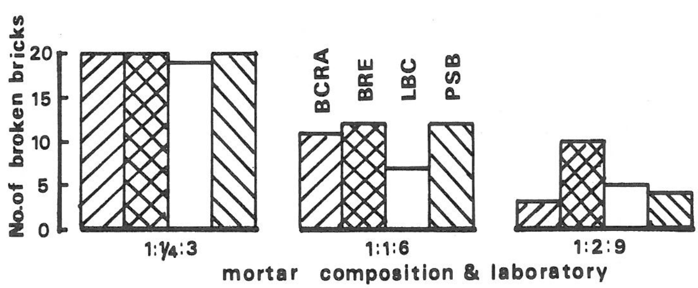

FIGURE 5 NO.OF BROKEN BRICKS IN THE NORMAL TEST SPECIMENS