THE EFFECT OF REPAIR AND STRENGTHENING METHODS FOR MASONRY WALLS

by

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SUMMARY

This paper contains the results of combined (vertical+horizontal) loading tests carried out on twenty walls of five different masonry types and on the same walls after repair by cement-grouting (ten walls) and strengthening by the application of steel-mesh reinforced cement plaster layers (ten walls). The results indicate that after cement-grouting walls built of blocks reattain or slightly increase their original shear strength; on the contrary stone-masonry walls increase their strength by a factor of 2-3 after grouting. In the case of strengthening of walls built of blocks with reinforced plaster layers their shear strength is increased to the extent that flexural failure consistently occurs first.

1.0 INTRODUCTION

Before repair works are carried out on the damaged buildings of an earthquake-hit area it is necessary to reproduce in the laboratory walls typical of these buildings, to determine their resistance to combined horizontal and vertical loading, and then to prove the effectiveness of the foreseen method of repair by retesting the same walls after repair.

In this paper only those methods of repair and strengthening are considered which lend themselves to mass use for the repair and strengthening of earthquake-damaged masonry buildings. The effect of cement-grouting is presented as a method of repair for walls built out of blocks, and as a method of strengthening for stone-masonry walls. As a method for strengthening walls built of bricks and other kinds of blocks has been chosen the application, on both sides of the wall, of a welded-mesh reinforced, 3 cm thick cement plaster layer, the two layers being held together by horizontal stirrups passing through predrilled holes in the wall.

Nearly all the wall tests were carried out under constant vertical load and cyclic horizontal load produced by programmed displacements at a frequency of 1 c.p.s. - Method "D" [1]. Because of their high shear strength some of the strengthened walls could be tested only using the simple diagonal compression test - Method "B".

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2.0 THE EFFECT OF REPAIRING WALLS BY CEMENT GROUTING

The repair of walls by cement-grouting was carried out as follows: sealing of cracked areas in the basic wall, fixing of injection tubes, pressure grouting of the cracked parts of the wall through each tube in succession. The grout consisted of 90% Portland Cement and 10% pozzolana, diluted with water to the ratio by weight of 1:1.

In Table 1 an analysis has been carried out on the experimentally-obtained results (horizontal and vertical loads at failure) for five different kinds of walls (2 basic and repaired walls of each type). In the Table are also given: block type and average compressive strength of blocks, mortar strength, wall thickness t and cross-section $F = d \cdot t$ (wall height "h" = 1,50 - 1,60 m). The tensile strength σ_n of the basic and repaired walls has been calculated from these results using the equation given in the Table, which is based on the assumption that the occurrence of X-cracks depends upon a maximum principal tensile stress. On the basis of the obtained values for σ_n and assuming a uniform comparative bearing stress σ_o - comp = 1.5, 5.0 or 8.0 kp/cm^2 (according to wall type), the corresponding comparative shear stresses at failure τ_o - comp. have been calculated from the equation given for τ_o - comp., which defines the influence of vertical loading [2].

The effect of repair by cement grouting on shear load capacity is given by the ratio τ_o comp. (repaired wall)/τ_o comp. (basic wall). From the calculated values of this ratio it can be seen that in the case of walls built out of blocks it is possible by means of cement-grouting to restore the wall at least to its original condition, or to improve somewhat upon it (up to 30%). In the case of stone-masonry walls, however, the latter's shear strength can be very substantially increased (by a factor of 2.5 approx.). This is easily understood, as by the cement-grouting of a relatively porous wall a kind of "prepacked" material is produced.

Comparisons of the deformational characteristics of the basic and repaired walls (see the two typical H - δ diagrams given in Figs 1 & 2) have shown that, in general, the walls' initial stiffness K_o, and with it the shear modulus G, does not change significantly after repairing, whereas the ductility or capacity of the wall to absorb energy increases significantly in the case of walls built of blocks. The failure of basic and repaired concrete-block wall 6A' is shown in Figs 3 & 4.

3.0 THE EFFECT OF STRENGTHENING WALLS BY APPLYING TWO WELDED-MESH REINFORCED, 3 CM THICK CEMENT PLASTER LAYERS

The strengthening of walls, if necessary previously repaired by cement-grouting, was carried out as follows: application of a thin layer of cement plaster on both sides, placing of welded mesh reinforcement consisting of 6 mm dia. high-tensile wires at 15 cm centres in both directions, with mild-steel anchoring stirrups dia. 6 mm passing through predrilled holes in the wall (10 per m^2), and the application of plaster to a full thickness of 3cm. The nominal compressive strength of the concrete plaster was 200 kp/cm^2. Due to a 1 cm gap at the top and bottom of the wall the plaster layers were not loaded directly; in this way the conditions of strengthening approach those in actual buildings.

Walls strengthened in the above-described way were treated in the calculations as homogeneous walls, and it was assumed that the shear strength of such walls depends on a maximum principal tensile stress in the panel σ_n. The tensile strength of the walls σ_n was calculated in the same way as described in section 2.0. In the case of the diagonal compression tests with a failure load P and a wall aspect ratio of h/d= 1.5, σ_n was calculated as follows:

$$\sigma_o = 0.83\ \frac{P}{F};\ \tau_o = \frac{\sigma_o}{1.5} = 0.55\ \frac{P}{F};\ \sigma_n = \sigma_o \left[-\frac{1}{2} + \sqrt{\left(\frac{1,5\tau_o}{\sigma_o}\right)^2 + 0,25} \right] = 0,62\ \sigma_o.$$

Taking into account a factor of stress reduction due to the corner holding blocks (determined from finite element analysis) this gives σ_n = 0,49 P/F.

For a shear failure, the average shear stress at failure is given by the expression:

$$\tau_o^{(s)} = \frac{\sigma_n}{1.5} \sqrt{\frac{\sigma_o}{\sigma_n} + 1} \qquad \ldots (1)$$

Also possible, and more likely in the case of walls of narrow aspect and relatively high shear strength, is a flexural failure (see[3]). In this case the average shear stress at failure is given by the expression:

$$\tau_o^{(f)} = \sigma_n \cdot \left(\frac{\sigma_m}{\beta}\right)\left(\frac{\beta}{\sigma_n}\right) \frac{1}{3\ (h/d)} \qquad \ldots (2)$$

where β is the compressive strength of the wall under axial load and $\sigma_m = M_{ult.}/(td^2/6)$. The required value of (σ_m/β) is obtained from the dimensionless diagram of flexural failure (see[3]), for the known value of $\sigma_o/\beta = (\sigma_o/\sigma_n)\cdot(\sigma_n/\beta)$. The value of (σ_n/β), which is taken as a constant for an individual type of wall, is obtained from the results of axial vertical loading tests.

In Table 2 an analysis has been carried out on the experimentally-obtained results for four different kinds of walls. The results have been treated in a similar way to the results of Table 1, a uniform comparative bearing stress of σ_o - comp.= 8 kp/cm^2 having been taken into account. The horizontal loads $H_{comp.}$ and values of (σ_m/β) which correspond to a flexural failure are also given. The effect of strengthening by applying reinforced concrete plaster layers is given by the ratio H_{comp} (strengthened wall)/ $H_{comp.}$ (basic wall), where H_{comp} (strengthened wall) is the lower of the two values for shear and flexural failure. In the calculation of $H_{comp.}$ the actual cross-sectional areas of the basic and strengthened walls have been taken into account.

From Table 2 it can be seen that in the case of strengthened walls of high shear strength, the tensile strength σ_n cannot be determined except by using the simple diagonal compression test. The suitability of this test method was specially tested within this series of tests with a basic modular brick wall similar to walls 9A, 9A´, 9B, 11A, designated "wall 29", with mortar of compressive strength 100 kp/cm^2 (see Fig.5). The diagonal load producing failure was P = 14,3 Mp.This gives: σ_n = 0,49 P/F = 0,49 x 14300/2850= = 2,46 kp/cm^2. This value can be compared with the average value of σ_n for the four previously-cited walls, increased by an experimentally determined strength increase factor due to increase in mortar quality of 1,33: σ_n = = 1,77 x 1,33 = 2,36 kp/cm^2. This result also agrees with the results of other series of comparative tests (see [4]).

The factor of increase of horizontal load-carrying capacity, given in Table 2, is in all cases limited by flexural strength, and has a value of 2 for normal-strength masonry walls and of 1.25 for walls of high initial tensile strength $\sigma_n > 3.0$ kp/cm^2. In Fig.6 the failure of the strengthened modular-brick wall 9A in the diagonal compression test is shown.

4.0 CONCLUSIONS FROM THE TESTS

The following conclusions have been drawn from the tests:

1) Concerning the repair of damaged brick or block-masonry walls of all kinds: if the cracked areas are well cement-grouted the shear resistance of the original, undamaged walls can be reattained.

2) Concerning the repair and strengthening of stone-masonry walls: a very significant increase in the original shear strength of the walls - by a factor of 2 to 3 - can be achieved by cement-grouting. Thus cement--grouting is an efficient way of revitalizing stone-masonry buildings.

3) Concerning the strengthening of brick or block-masonry walls of all kinds: by the application to both sides of such walls of welded-mesh reinforced, 3 cm thick, stirrup-tied cement plaster layers a large increase in the wall structure's tensile strength is achieved, and the horizontal load-carrying capacity of normal strength masonry walls is increased by a factor of 2. In the case of walls of high initial tensile strength $\sigma_n > 3$ kp/cm^2 it is increased by a factor of 1.25.

5.0 REFERENCES

1. "The Influence of Frequency on the Shear Strength and Ductility of Masonry Walls in Dynamic Loading Tests", Terčelj S., Sheppard P., Turnšek V., Paper 11-1, 6 WCEE, New Delhi, 1977.

2. "Some Experimental Results on the Strength of Brick Masonry Walls", V.Turnšek & F.Čačovič; "Sibmac" Session IV (Structural Design) Proceedings, British Ceramic Research Association, London 1971.

3. "The Flexural Resistance of Masonry Walls to Combined Horizontal and Vertical Loads", Sheppard P., Terčelj S., Turnšek V., Paper 3-35, 6 ECEE, Dubrovnik, Yugoslavia, 1978.

4. "A Comparison of Three Laboratory Test Methods Used to Determine the Shear Resistance of Masonry Walls", Bernadini A., Modena C., Turnšek V. and Vescovi U., 7 WCEE, Istanbul, 1980.

TABLE 1: SHEAR RESISTANCE OF BASIC WALLS AND THE SAME WALLS REPAIRED BY GROUTING

$$\sigma_n = \sigma_o \left[-\frac{1}{2} + \sqrt{\left(1{\cdot}5\ \frac{H}{V}\right)^2 + 0{\cdot}25} \right]; \quad \tau_o\text{-comp} = \frac{\sigma_n}{1{\cdot}5} \cdot \sqrt{\frac{\sigma_o\text{-comp.}}{\sigma_n} + 1}$$

$$\sigma_o = V/F \quad ; \quad \tau_o = H/F \ .$$

σ_o-comp	BLOCK TYPE & NOM. STRGTH (kp/cm²) WALL THICKNESS & CROSS-SECTION	WALL DESIGNATION	AV. MORTAR STRENGTH kp/cm²	BASIC WALL σ_n kp/cm²	BASIC WALL τ_o-comp. kp/cm²	WALL REPAIRED BY GROUTING σ_n kp/cm²	WALL REPAIRED BY GROUTING τ_o-comp. kp/cm²	FACTOR OF INCREASE OF τ_o-comp.
1.5 kp/cm²	STONE-MASONRY t = 60 cm F = 6000 cm²	C	5	0·20	0·39			
		D	5	0·24	0·43	1·01	1·06	2·47
5.0 kp/cm²	NORMAL-FORMAT SOLID BRICKS (200) t = 25 cm F = 2375 cm²	B1	5	0·69	1·32	1·08	1·71	1·30
		B2	30	1·98	2·48	2·48	2·87	1·16
8.0 kp/cm²	PULV. FUEL ASH. BLOCKS (150) t = 29 cm F = 2930 cm²	E1	13	1·44	2·46	1·39	2·41	0·98
		E2	13	1·56	2·57	2·20	3·16	1·23
	MODULAR BRICK BLOCKS (200) t = 28,5 cm F = 2850 cm²	9B	48	1·52	2·54	2·60	3·50	1·38
		11A	61	1·86	2·85	1·80	2·80	0·98
	EXP. CLAY AGG. BLOCKS (75) t = 29 cm F = 2900 cm² — ORD'Y MASRY	7B	29	1·91	2·90	2·81	3·67	1·27
	COMPACT MASRY	6A'	58	4·22	4·79	4·65	5·11	1·07

EXPERIMENTAL RESULTS FROM COMBINED HORIZ./VERT. LOADING TESTS (LOADS GIVEN IN "MP")

WALL DESIG.	BASIC WALL H	BASIC WALL V	REP'D WALL H	REP'D WALL V	WALL DESIG.	BASIC WALL H	BASIC WALL V	REP'D WALL H	REP'D WALL V
C	2·2	8·0			E1	5·6	12·5	6·8	21·5
D	2·45	8·0	6·9	11·5	E2	5·9	12·5	8·85	20·9
B1	3·2	12·5	4·15	12·5	9B	6·1	15·0	10·7	27·3
B2	6·0	12·5	7·40	15·0	11A	6·2	11·0	8·3	25·0
					7B	7·1	15·0	10·1	20·0
					6A'	14·8	28·0	18·4	43·0

TABLE 2 : RESISTANCE OF BASIC WALLS AND OF THE SAME WALLS STRENGTHENED BY APPLYING TWO 3 cm THICK WIRE-MESH REINFORCED PLASTER LAYERS

σ_0 - comp. = 8 kp/cm^2

BLOCK TYPE & NOM. STRGTH(kp/cm^2) WALL THICKNESS & CROSS-SECTION (BASIC/STRGTHD.)	WALL DE-SIGNATION	AV. MORTAR STRENGTH.	BASIC WALL SHEAR		STRENGTHENED WALL SHEAR		STRENGTHENED WALL FLEXURE		FACTOR OF INCREASE OF $H_{comp.}$
		kp/cm^2	σ_n kp/cm^2	H_{comp} Mp	σ_n kp/cm^2	H_{comp} Mp	σ_w/β /	$H_{comp.}$ Mp	
MODULAR BRICK BLOCKS (200) t = 28·5 / 34·5 cm	9A	52	1·86	8·1	14·1	40·6	0·35	[15·4]	1·9
F = 2850 / 3450 cm^2 $(\sigma_n/\beta)_{rep.}$ = 0·25	9A'	50	1·85	8·1	18·6	51·2	0·29	[16·3]	2·0
PULV. FUEL ASH. BLOCKS (200) t = 29 / 35 cm	E3	13	1·59	7·6	4·35	17·8	0·45	[15·5]	2·0
F = 2930/3640 cm^2 $(\sigma_n/\beta)_{rep.}$ = 0·10	E4	13	1·71	7·95	4·15	17·2	0·45	[15·5]	2·0
NORMAL-FORMAT SOLID BRICKS (200) t = 25 / 31 cm F = 2375 / 2950 cm^2 $(\sigma_n/\beta)_{rep.}$ = 0.10	D2	4	0·54	3·4	3·45	[12.3]	0.52	[11.8]	3·5
CONCRETE BLOCKS (LIGHT AGG.(75)) $(\sigma_n/\beta)_{rep.}$ = 0.15	1A'	51	4·52	*12.5	11·5	35·0	0·28	[16·7]	1·3
t = 29/ 35cm F = 2900/3500 cm^2 (LIGHT AGG.(75))	5A'	63	3·80	12·9	10·4	32·3	0·30	[16·2]	1·25
t = 19/ 25 cm F = 1900/2500 cm^2 (ORD'Y (50))	B3	34	3·30	7·7	4·7	12·9	0·56	[9·8]	1·25

* FLEXURAL FAILURE

EXPERIMENTAL RESULTS (LOADS GIVEN IN "MP")

WALL DESIG.	BASIC WALL - METHOD "D" H	BASIC WALL - METHOD "D" V	STRGTHD. WALL - METHOD "D" H	STRGTHD. WALL - METHOD "D" V	WALL DESIG.	BASIC WALL - METHOD "D" H	BASIC WALL - METHOD "D" V	STRGTHD. WALL - METHOD "B" P
E3	5.95	12.5	20.2	42.2	9A	6.2	11.0	99.2
E4	6.25	12·5	19·6	41·8	9A'	6.9	15.0	131·0
D2	2.8	12·5	10·65	15·0	1A'	17.25	38·0	82·5
B3	7.7	15.0	12·85	20·0	5A'	13·65	27·0	74·5

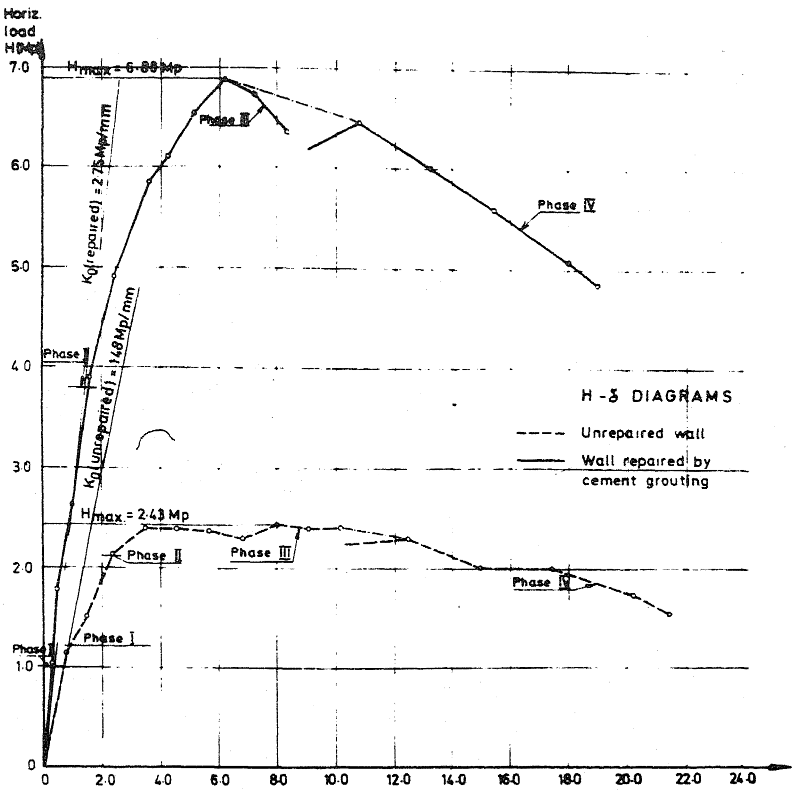

FIG.1: H-δ DIAGRAMS FOR STONE-MASONRY WALL D

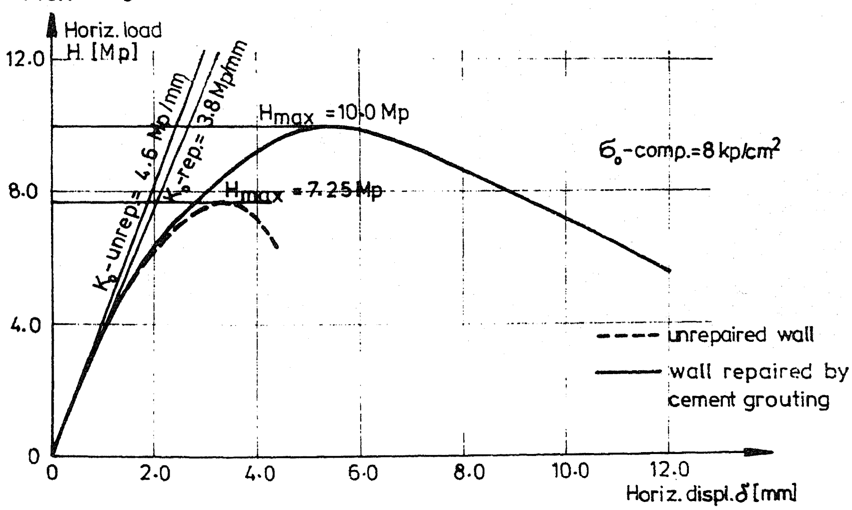

FIG.2 : H - δ DIAGRAMS FOR MODULAR BRICK WALL 9B

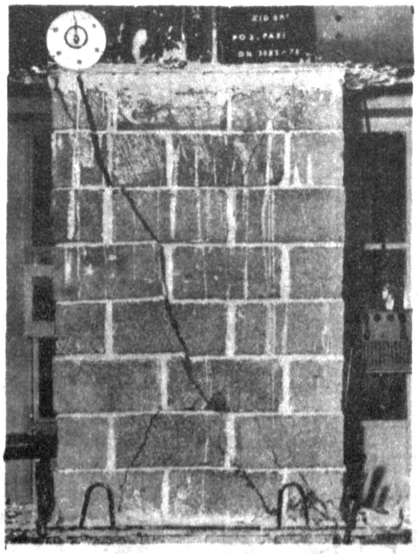

Fig.3: Failure of basic wall 6A´

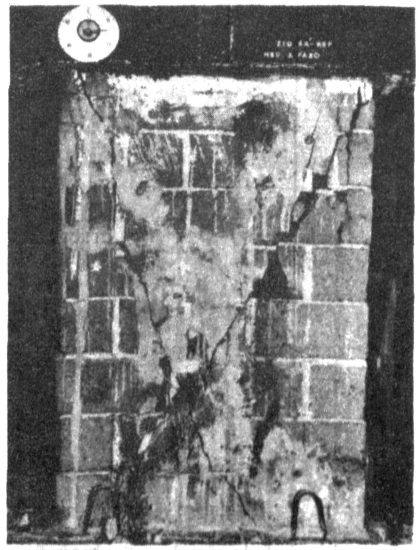

Fig.4: Failure of repaired wall 6A´

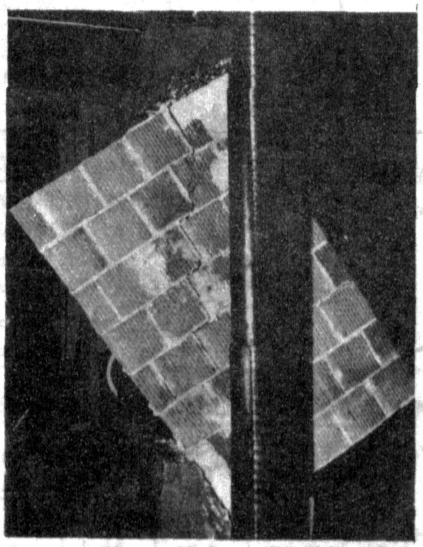

Fig.5: Failure of wall 29

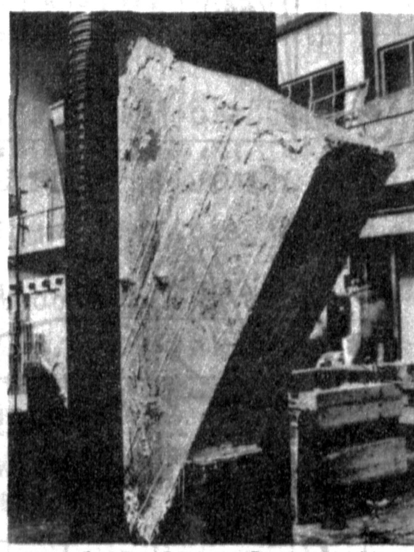

Fig.6. Failure of strengthened wall 9A