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SEISMIC RESISTANCE OF REINFORCED MASONRY WALLS

Miha TOMAŽEVIČ and Marjana LUTMAN

Institute for Testing and Research in Materials and Structures
Dimičeva 12, 61109 Ljubljana, Yugoslavia

SUMMARY

Presented in this paper are the results of two series of tests of concrete-block reinforced masonry walls subjected to seismic loading. The walls were reinforced with vertical reinforcement, grouted in holes at vertical edges of walls and horizontal reinforcement in horizontal mortar joints. The experiments have indisputably shown the beneficial effect of reinforcement on lateral resistance and ductility of walls. On the basis of test results, the modifications of calculation procedures for evaluation of lateral resistance and deformability of reinforced masonry walls have been proposed.

INTRODUCTION

Load-bearing capacity of masonry walls for seismic actions is significantly improved with high quality mortar and masonry units. However, when subjected to seismic loading, unreinforced masonry walls behave as brittle structural elements with almost no energy absorbtion capaçity, especially if subjected to a high level of compression. In order to improve their lateral resistance, and taking care for their ductile behaviour, masonry walls should be also reinforced with steel reinforcement.

A considerable research in the behaviour of reinforced masonry walls subjected to cyclic lateral actions has been already carried out in different countries. On the basis of experimental results, analytical models have been proposed for prediction of fundamental parameters of seismic resistance of masonry walls, such as lateral resistance and deformability. However, not all investigators have come to the same conclusions as regards the reinforcement action: this is especially true in the case of shear failure of walls which most frequently occurs during earthquakes. Consequently, different procedures for calculation of lateral resistance and deformability of reinforced masonry walls have been proposed (see for example Refs. 1,2, and 3).

Systematic research in the behaviour of reinforced masonry walls subjected to seismic loading is still needed to study the effect of different parameters on seismic behaviour of reinforced masonry walls, which will also take into account the local conditions and typology of masonry construction. In this respect the reported work carried out at the Institute for Testing and Research in Materials and Structures (ZRMK) in Ljubljana, Yugoslavia, represents a small contribution.

DESCRIPTION OF TESTS AND TEST RESULTS

Description of Tests Two series of 16 walls with two different geometries (height/length ratio h/l= 1.25 and 2.30) have been tested. The walls were constructed in 1:2 scale reduced size with specially manufactured concrete blocks (Fig.1) in cement mortar which consisted of 0-2 mm sand and Portland cement in the proportion of 1:3.5. Deformed steel (grade 400) 10 mm diameter bars (1 bar in series C - 0.26% and 2 bars in series D - 0.52%) were used as vertical reinforcement, whereas smooth steel (grade 200) 6 mm diameter bars (0.14%) or burned wire, 4.2 (0.28%) and 3.1 mm (0.14%) in diameter, in the shape of closed stirrups have been used as horizontal reinforcement. Stirrups were placed around vertical reinforcement in each horizontal mortar joint (Fig.2). Two specimens of each type have been constructed. Mechanical properties of constituent materials are given in Table 1.

All specimens have been tested as simple vertical cantilevers by subjecting them to constant vertical load (V = 60 kN, σ_o = 0.98 MPa) and to cyclically acting lateral load, repeated three times at the same amplitude of lateral deformations. Typical instrumentation of specimens (strain-gauges to measure strains in masonry and reinforcement, LVDT-s and load cells to measure displacements of walls and lateral forces), is shown in Fig.3.

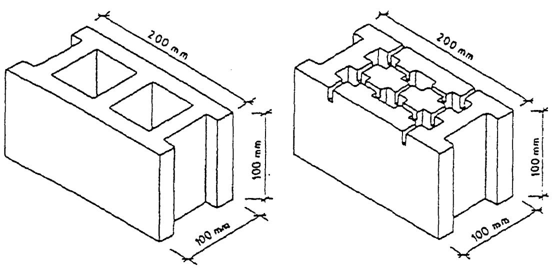


Fig. 1 Shape and Dimensions of Model Blocks

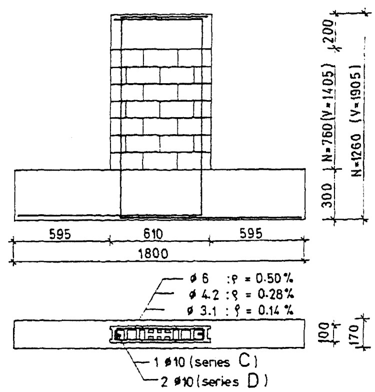


Fig. 2 Configuration and Dimensions of Test Specimens

Table 1 Mechanical Properties of Constituent Materials (MPa)

		Series C		Series D	
		Hollow	Load-Bearing	Hollow	Load-Bearing
Masonry blocks	Compressive strength	16.3	17.4	13.5	15.5
Mortar	Compressive strength	9.3		7.0	
	Bending strength	2.5		2.2	
Reinf. steel	Diameter	10 mm	6 mm	4.2 mm	3.1 mm
	Yield limit	522	253	391	323
	Tensile strength	733	382	448	443
	Yield strain (%)	2.54	1.21	1.86	1.54

Test Results If horizontally unreinforced, both squat and tall walls failed in shear, with typical single diagonally oriented cracks, passing through both mortar joints and masonry units.

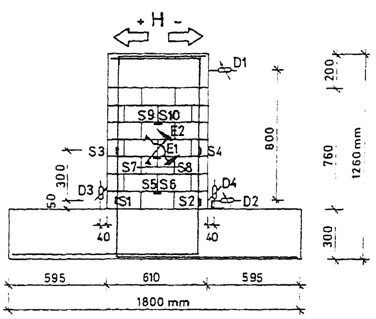


Fig. 3 Instrumentation of Test Specimens

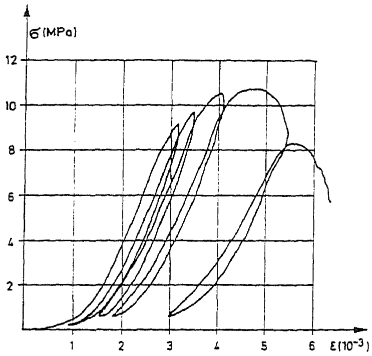
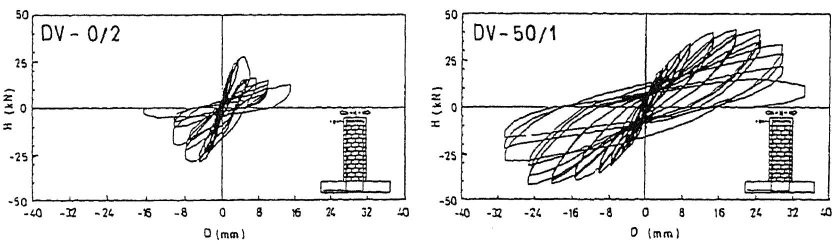


Fig. 4 Stress-Strain Diagram of Masonry at Compression

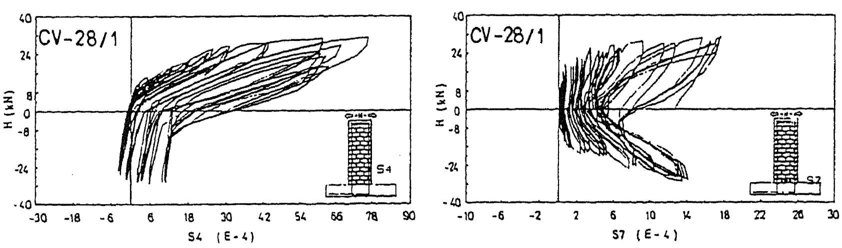
If horizontally reinforced, the behaviour depended on walls' height to length ratio. In the case of squat walls diagonally oriented and uniformly distributed cracks developed, partly passing through mortar joints and partly through masonry units. In most cases, failure mode was of classical shear type. In some cases, however, failure took place because of crushing of masonry blocks and grout in the compressed zone at the bottom section of wall, which resulted into horizontal shearing of walls in its lower part. In this respect, local quality of masonry units in critical zones plays a very important role. In the case of horizontally reinforced tall walls, uniformly distributed cracks developed, oriented at 45^{o} angle. Shear resistance of walls was improved, so that when lateral deformations were increased, walls failed in flexure due to buckling of reinforcement and crushing of masonry units and grout at the most compressed zone, with simultaneous yielding of reinforcement at the tensioned side.

Typical lateral load - lateral displacement hysteresis loops are presented for tall walls in Fig.5. It should be noted that the behaviour of squat walls was very similar. Typical lateral load - strain in vertical and horizontal rein-



a. Horizontally Unreinforced　　b. Horizontally Reinforced

Fig. 5 Typical Lateral Load - Deformation Hysteresis Loops - Tall Walls



a. Vertical Reinforcement　　b. Horizontal Reinforcement

Fig. 6 Typical Lateral Load - Strain in Reinforcement Hysteresis Loops forcement hysteresis loops, however, are presented in Figs.6a and 5b. Test results are summarized in Table 2.

Table 2 Lateral Resistance and Deformability of Tested Walls

	Series C (ρ_v = 0.26%)					Series D (ρ_v = 0.52%)				
ρ_h (%)	Wall	H_{max} (kN)	M_{max} (kNm)	δ_{cr} (mm)	δ_{max} (mm)	Wall	H_{max} (kN)	M_{max} (kNm)	δ_{cr} (mm)	δ_{max} (mm)
0.0	CN-0	32.89	29.77	1.08	5.78	DN-0	30.06	25.08	0.76	5.45
0.14	CN-14	40.68	36.81	0.98	11.65	DN-14	34.92	29.14	0.77	10.50
0.28	CN-28	35.34	31.98	0.99	22.57	DN-28	43.22	37.14	1.02	10.56
0.50	CN-50	40.28	36.45	1.05	14.99	DN-50	46.84	39.58	1.01	10.86
0.0	CV-0	26.01	40.32	2.66	10.38	DV-0	29.05	41.97	0.99	11.17
0.14	CV-14	30.15	46.74	2.26	30.36	DV-14	42.23	61.66	2.39	19.99
0.28	CV-28	31.53	48.87	1.59	33.89	DV-28	38.11	56.96	2.14	25.69
0.50	CV-50	29.22	45.29	2.59	31.43	DV-50	39.29	61.00	2.60	26.67

CALCULATION OF LATERAL RESISTANCE OF REINFORCED MASONRY WALLS

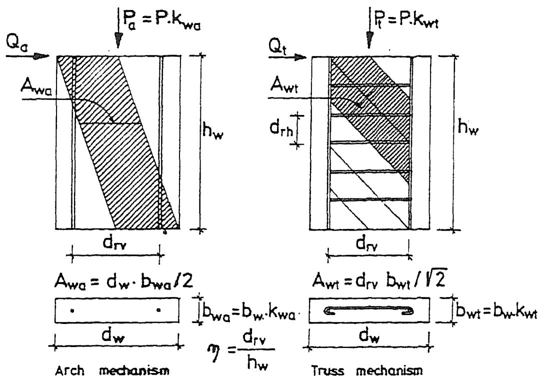
Shear Resistance Horizontal reinforcement acts in tension when subjected to lateral loading (see Fig.6b): after cracking, wall tends to expand laterally because of vertical load. Although not yielded, strain of horizontal reinforcement accumulates when preventing the separation of wall's cracked parts at repeated lateral load reversals by prestressing. However, loss of bond between mortar and reinforcement, or crushing of concrete masonry blocks did not allow for the development of full tension capacity ($H_{rh,y}$) of horizontal reinforcement. Effectiveness of horizontal reinforcement at maximum attained lateral load H_{max} and before collapse of the wall (at maximum attained lateral displacement δ_{max}) is evaluated in Table 3.

Table 3 Effectiveness of Horizontal Reinforcement at Shear Failure of Squat Walls

Wall	$H_{rh,y}$	Effectiveness at H_{max}	Effectiveness at δ_{max}	C_R
CN-14	14.63 kN	0.66	0.83	0.53
CN-28	32.50 kN	0.41	0.65	0.08
CN-50	42.92 kN	0.41	0.65	0.17
DN-14	14.63 kN	0.46	0.79	0.33
DN-28	32.50 kN	0.52	0.78	0.40
DN-50	42.92 kN	0.53	0.61	0.39

In order to model the behaviour of wall at shear failure, the idea proposed in Ref.3 has been followed. The modification of the model, proposed in Ref.3 can be seen in Fig.7 and in equations (1) to (6) which represent the compatibility and equilibrium conditions of the two parts of mathematical model. Fig.8 shows the comparison between the measured and the calculated lateral load - lateral deformation hysteresis envelopes. In Fig.8 the measured values of forces in horizontal reinforcement are also compared to the theoretical values. Fig. 9 shows the relationships between the measured and theoretical values of the contribution of horizontal reinforcement to the lateral resistance of wall at the maximum attained lateral load ($H_{rh,seg}/H_{max}$) in dependence on the parameter of horizontal reinforcement $\mu_{rh} = (A_{rh}/A_{wv})(f_y/f_c)$.

However, since the test results have shown that masonry is carrying an important part of lateral load acting on the wall until the wall's final collapse (see Tables 2 and 3), it is proposed that shear resistance of horizontally reinforced masonry walls be practically calculated as the sum of the shear



Arch mechanism:

$$\varepsilon_{wa} = (\varepsilon_{rva} + \eta R)/(1 + \eta^2) \qquad (1)$$

$$(A_{wa}\sigma_{wa} + 2A_{rva}\sigma_{rva})/(1 + \eta^2) = P_a \qquad (2)$$

$$Q_a = \eta\,(A_{wa}\sigma_{wa})/(1 + \eta^2) - P_a R \qquad (3)$$

Truss mechanism:

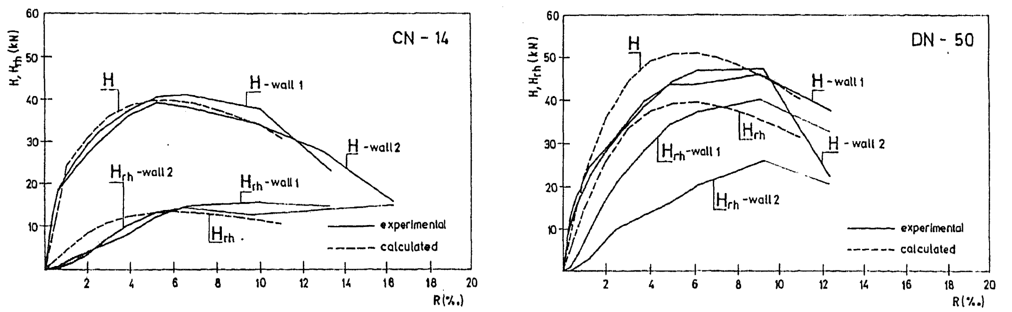
$$R = 2\,\varepsilon_{wt} - \varepsilon_{rht} \qquad (4)$$

$$\sigma_{wt}A_{wt}/\sqrt{2} + \sigma_{rht}A_{rh}d_{rv}/d_{rh} = 0 \qquad (5)$$

$$Q_t = \sigma_{wt}A_{wt}/\sqrt{2} - P_t R \qquad (6)$$

k_{wa}, k_{wt} - determined from experiments

Fig.7 Shear Mechanism (Modification of Model in Ref.3)



a. Horizontal Reinforcement: 0.14%　　　b. Horizontal Reinforcement: 0.50%

Fig. 8 Comparison Between Experimental and Theoretical Results

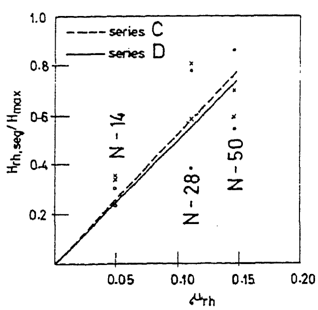


Fig.9 Contribution of Horizontal Reinforcement to Lateral Resistance

Table 4 Comparison Between Experimental and Calculated Flexural Capacity

	σ_o (MPa)	f_c (MPa)	$A_{rv,y}$ (mm^2)	$M_{u,exp}$ (kNm)	$M_{u,calc}$ (kNm)	Exp / Calc
Series C	1.01	10.7	78.54	46.97	37.10	0.79
Series D	1.01	9.5	157.08	59.87	56.98	0.95

resistance of the basic, unreinforced masonry wall (Ref.4) which depends on the wall's section A_w, normal stress in the wall σ_o and tensile strength of masonry f_t, and the tension capacity of horizontal reinforcement, reduced by a capacity reduction factor C_R (experimental values are given in Table 3):

$$H_{u,s} = A_w\,(f_t/b)\,(\sigma_o/f_t + 1)^{0.5} + C_R A_{r,h} f_y . \qquad (7)$$

<u>Flexural Resistance</u> As indicated by analysis of measured strains in vertical reinforcement in dependence on lateral loading (see Fig.6a), as well as by taking into account the stress-strain relationships of masonry in compression (Fig.4), reinforced concrete analogy can be used to calculate the flexural

capacity of a vertically reinforced masonry wall. The following expression for flexural capacity of a wall's section hase been derived for the case of symmetrically reinforced wall:

$$M_u = (0.5\sigma_o\ t\ l^2)\ (1 - (\sigma_o/f_c)) + (1 - 2l')\ (A_{r,v} f_y). \qquad (8)$$

In equation (8), t and l are thickness and length of the wall, l' is distance of vertical reinforcing bar from the vertical edge of the wall, and f_c is compressive strength of masonry. The calculated results for tall walls of both tested series of walls are presented in Table 4. As can be seen, sufficiently good correlation between experimental and calculated results has been obtained, especially in the case of walls of series D. Although the calculated values seem to be a little conservative, euqation (8) provides a reasonably good tool for quick estimation of flexural capacity of a reinforced masonry section.

CONCLUSIONS

By reinforcing the masonry with vertical and horizontal reinforcement, the improved seismic behaviour of walls can be expected. In this respect, horizontal reinforcement in mortar joints plays the most important role: by reinforcing the walls horizontally, shear capacity and ductility are improved which may result into yielding of vertical reinforcement and into the development of full flexural capacity of the wall's section.

Simple formulae can be used to calculate the shear and flexural capacity of reinforced masonry walls. However, masonry units and mortar should be of adequate quality in order to carry the internal forces developed in the wall, by compression and shear. Also, adequate bond and anchorage conditions should be provided in order to fully activate the reinforcement.

It has been found that requirements for optimum design, i.e. the quantity of minimum or maximum reinforcement to be used in reinforced masonry walls strongly depend on the type and quality of masonry units.

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