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SEISMIC BEHAVIOR OF REINFORCED MASONRY WALLS

Carl LUDERS Sch.[1] and Pedro HIDALGO O.[1]

[1]Department of Structural Engineering, Catholic University of Chile, Santiago, Chile

SUMMARY

This paper presents the analisys of the experimental results of thirty-four full scale reinforced masonry walls that have been tested in the past eight years at the Catholic University of Chile, by imposing displacement controlled cycles of monotonically increasing amplitude until failure was attained. The influence of the type of masonry units, aspect ratio of the walls, type of grouting and amount of horizontal reinforcement in the strength, ductility, and mode of failure of the wall was studied.

INTRODUCTION

The development of earthquake-resistant design codes for reinforced masonry structures in Chile has needed a number of both experimental and analytical studies. One of these experimental research programs was initiated in 1980 at the Catholic University of Chile, and has completed thirty-four in plane cyclic shear tests of both concrete block and clay brick reinforced masonry walls. Special emphasis has been placed in the shear mode of failure, since the behavior of walls that exhibit the flexural mode of failure can be predicted reasonably well using the same analytical model applicable to reinforced concrete elements (Ref. 1). This paper summarizes the characteristics of this research program and the main results that have been obtained so far.

A continuation of this research program, presently in progress at the Catholic University, has the main objective of obtaining a refined mathematical model of the seismic behavior of reinforced masonry walls, in order to represent the more important physical phenomena that control the post-cracking behavior. Another topic presently under study is the assessment of the degree of damage as a function of the cracking type and the effectiveness of different repair methods; the results of this study are important for post-earthquake inspection and repair studies of damaged structures.

METHODOLOGY

All the tests reported herein intended to represent the behavior of the masonry piers between window or door openings of perforated shear walls, as shown in Fig. 1. In-plane cyclic shear forces were applied through controlled lateral displacements of monotonically increasing amplitude, as shown in Fig. 2, until failure was attained. The first twelve piers were constructed using clay brick masonry units, and were tested using the cantilever setup shown in Fig. 3; all of them had a reinforced concrete beam on top of the pier, which influenced their crack pattern in the neighborhood of the top section. To elimitate this problem, a new test setup was devised (Fig. 4); the main characteristic of this setup (Ref. 2) is the accuracy to reproduce the real boundary conditions of the bottom half of a pier. The inflection point of the piers deformed shape is maintained at a fixed location. There is no restriction to the crack propagation through the section of zero bending moment and the forces are applied far enough from the zone under study to avoid any undesirable effects on the stress distribution. The stiffness of the reaction frame allows to study how cracks are initiated and propagated throughout the test. This setup, with 50 metric ton capacity, has been used to test twenty-two piers constructed using concrete block masonry units.

The parameters included in this study were the type of masonry unit, the aspect ratio of the wall (or M/Vd ratio), the type of grouting (full or partial), and the amount and mechanical characteristics of the horizontal reinforcement. All piers were constructed in series of six or seven specimens, with all specimens in each series being erected by the same mason at the same time. The comparison of results of different series was facilitated by the test of a reference specimen in each series, which has a M/Vd ratio of 1. The basic product obtained from the tests was the hysteresis loops diagram; Fig. 5 shows a diagram for a pier that failed in flexure, while Fig. 6 shows the diagram for a pier that exhibited the shear mode of failure. For each test, the initiation, prapagation, and size of cracks were recorded; Fig. 7 shows the crack pattern of a slender pier at the onset of the shear type of failure. Since the shear crack crosses the zero moment section it is apparent that the results from the cantilever setup test will overestimate the shear strength of the walls.

Moreover, the mechanical characteristics of masonry units, mortar, grout, masonry prisms, and both vertical and horizontal reinforcement for each of the specimens, were obtained from separate tests. The details of all the results have been published elsewhere (Refs. 1, 3, 4).

RESULTS AND CONCLUSIONS

Characteristics of the Hysteresis Loops Diagrams The curves obtained for the flexural and the shear mode of failure are reasonably close to the model proposed by Otani and Sozen (Ref. 5), but replacing the unloading branches by straight lines as shown in Fig. 8.

Initial Shear Cracking The nominal shear stress corresponding to the onset of diagonal cracking is independent of the amount of horizontal reinforcement (Ref. 6). Fig. 9 shows the experimental values obtained in this program, which fall in the range $0.08\sqrt{f'm}$ to $0.20\sqrt{f'm}$ (MPa).

Ductility of Reinforced Masonry Walls The influence of the mode of failure in the ductility factors of the piers is quite significant. Piers that exhibited the flexural mode of failure under low values of axial compression stresses show ductility factors of over 10 (Ref. 7). For the shear mode of failure, ductility factors are significantly smaller, with a limiting value of 1 for piers without horizontal reinforcement. The minimum horizontal reinforcement ratio required by the Chilean Code NCh 1928 is enough to increase the ductility factor of walls that failed in shear up to values that vary between 1.5 and 5. However, no clear relationship between amount of horizontal reinforcement and ductility factor is apparent from the tests. Nevertheless, ranges of ductility factors for walls with different types of masonry units and different type of grouting have been determined (Ref. 7).

Influence of Horizontal Reinforcement in Pier Strength Interesting results have been obtained as to the influence that horizontal reinforcement has in the strength of walls. Due to the fact that the shear crack that develops across the wall varies greatly in width along its length the horizontal bars are subjected, from one another, to very different elongations. If the steel used is brittle, and bond does not deteriorate, some bars break before the rest of them start to yield. This triggers a chain of local failures that negates the possibility of developing the sum of the strengths of all the bars available. Fig. 10, reflecting these results, allows the derivation of the following formula for the additional strength provided by horizontal reinforcement:

$$V_s = A_v f_y \tan\phi \tag{1}$$

where A is the lesser of horizontal or vertical gross cross section of the walls, ρ_v is the horizontal reinforcement ratio, f_y is the yield strength of this reinforcement, and $\tan\phi$ the effectiveness factor of the horizontal reinforcement.

The effectiveness of horizontal reinforcement depends on the ductility and on the bonding properties of the reinforcing steel. For spot welded ladders of A56-50 steel, a value for $\tan\phi$ of 0.55 was obtained (Ref. 6).

Failure Modes The tests exhibited in addition to the classical failure modes: bending, shear, and slipping other failure modes, including combinations of the former, that are important for the prediction of the seismic behavior of a wall. One such mode is a vertical crack that appeared in a number of cases next to the column formed by the vertical reinforcing steel and the grout surrounding it. This form of failure was associated to a specific type of block and partial filling of the holes (Ref. 8). Another very interesting case is that of a failure mode consisting of a combination of diagonal shear cracking with slipping (Ref. 6). After the March 3, 1985 earthquake in central Chile, this mode was observed in walls having a broad aspect ratio, with base dimension larger than its story height. In contrast with what happens in reinforced concrete walls, in which shear is associated with a number of parallel diagonal cracks, squat reinforced masonry walls tend to show a single diagonal crack that continues in a slipping failure.

Consequently, in Eq. (1) the variable A must be understood as either the area of the horizontal cross-section of the wall, or the area of a vertical cross-section between the wall base and the first story slab.

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REFERENCES

1. Lüders, C., Hidalgo, P., "Comportamiento Sísmico de Muros de Albañilería Armada de Ladrillos Cerámicos," Primeras Jornadas Chilenas de Hormigón Estructural. Vol. 1, pp. D1-26, Santiago, Chile, (1982).
2. Lüders, C., "Marco de Carga para el Ensayo de Muros Sometidos a Esfuerzo de Corte Cíclicos Alternados," Colloquia 88. Vol. V, pp. 189-207, Madrid, Spain, (1988).

3. Lüders, C., Hidalgo, P., and Gavilán C., "Comportamiento Sísmico de Muros de Albañilería Armada," School of Engineering. Catholic University of Chile, 90 pp, Santiago, Chile, (1985).
4. Lüders, C., Hidalgo, P., "Ensayos Cíclicos de Muros de Albañilería Armada de Bloques de Hormigón," Report to the Research Division of the Catholic University of Chile, 77 pp., Santiago, Chile, (1987).
5. Otani, S., Sozen, M.A., "Behavior of Multistory Reinforced Concrete Frames During Earthquakes," Civil Engineering Studies, Structural Research Series N° 392, University of Illinois, Urbana, U.S.A., (1972).
6. Lüders, C., Hidalgo, P., "Influencia del Refuerzo Horizontal en el Comportamiento Sísmico de Muros de Albañilería Armada," 4th. Chilean Conference on Seismology and Earthquake Engineering, Viña del Mar, Vol. 3, pp. H134-158, Santiago, Chile, (1986).
7. Lüders, C., Hidalgo, P., "Ductilidad y Degradación de Rigidez de Muros de Albañilería Armada," XXIV Jornadas Sudamericanas de Ingeniería Estructural, Vol. 1, pp. 33-47, Porto Alegre, Brasil, (1987).
8. Lüders, C., Hidalgo, P., "Modos de Fallas en Muros de Albañilería Sometidos a Cargas Horizontales Cíclicas," 3ra. Conferencia Latinoamericana en Ingeniería Sismorresistente, Guayaquil, Ecuador, (1984).

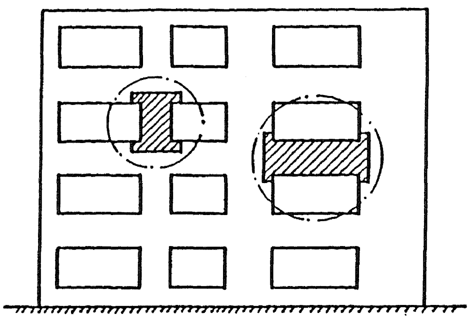

FIG. 1 PERFORATED SHEAR WALL

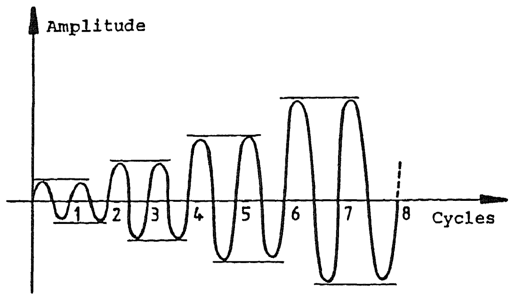

FIG. 2 SEQUENCE OF INDUCED SHEAR DISPLACEMENTS

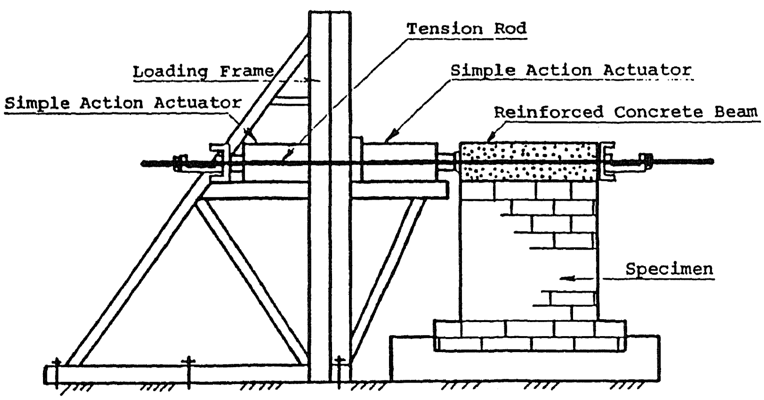

FIG. 3 CANTILEVER TEST SET-UP

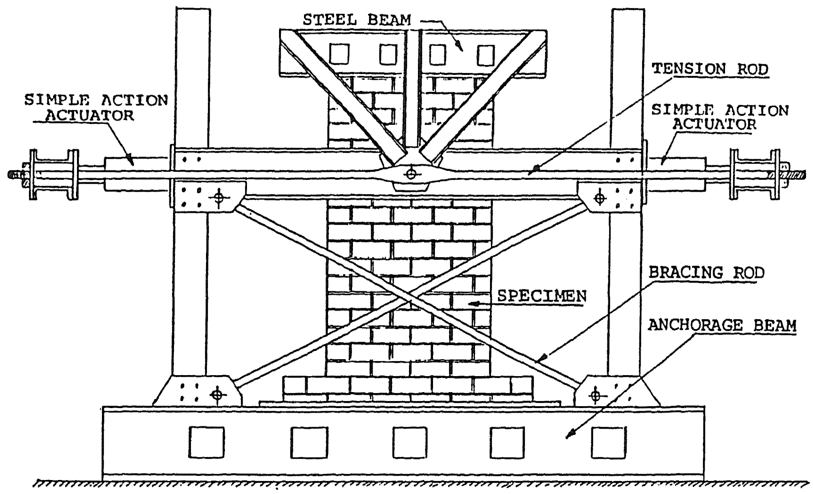

FIG. 4 CATHOLIC UNIVERISTY LOADING FRAME

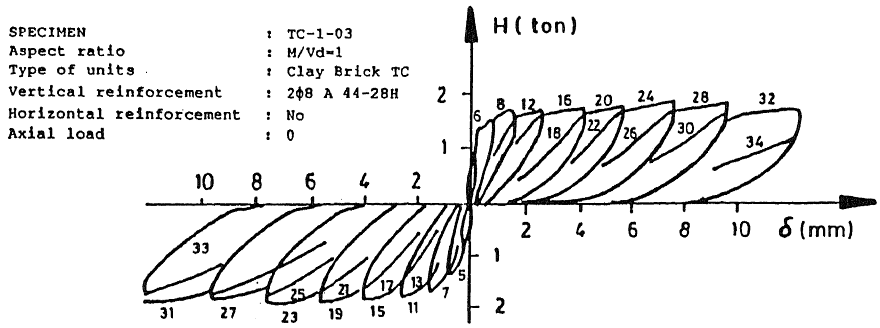

FIG. 5 TYPICAL LOAD-DISPLACEMENT CURVES OF PIERS THAT FAILED IN A FLEXURAL MODE

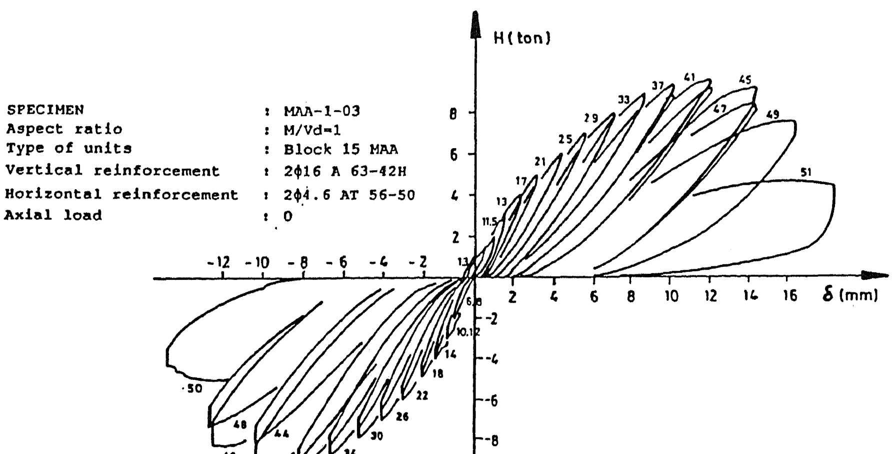

FIG. 6 TYPICAL LOAD-DISPLACEMENT CURVES OF PIERS THAT FAILED IN A SHEAR MODE

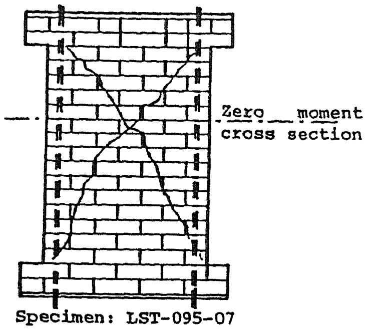

FIG. 7 TYPICAL SHEAR CRACKS OF A SLENDER PIER THAT FAILS IN A SHEAR MODE

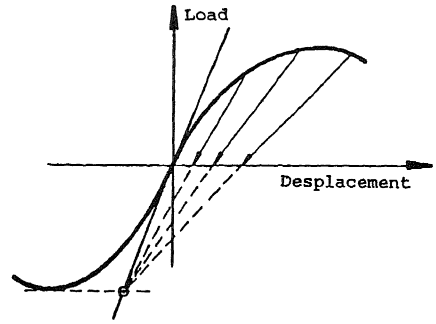

FIG. 8 MODEL FOR THE UNLOADING BRANCHES OF THE LOAD DISPLACEMENT CURVES

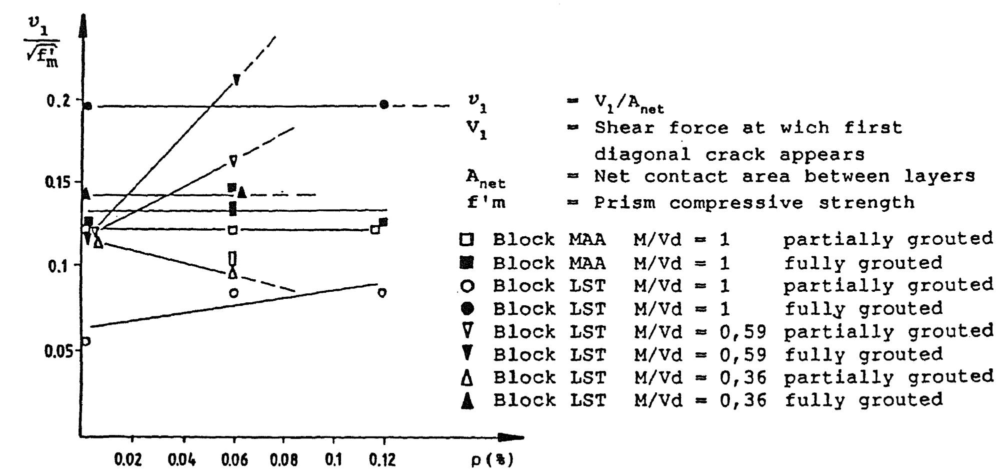

FIG. 9 INFLUENCE OF THE HORIZONTAL REINFORCEMENT ON THE INITIAL SHEAR CRACKING

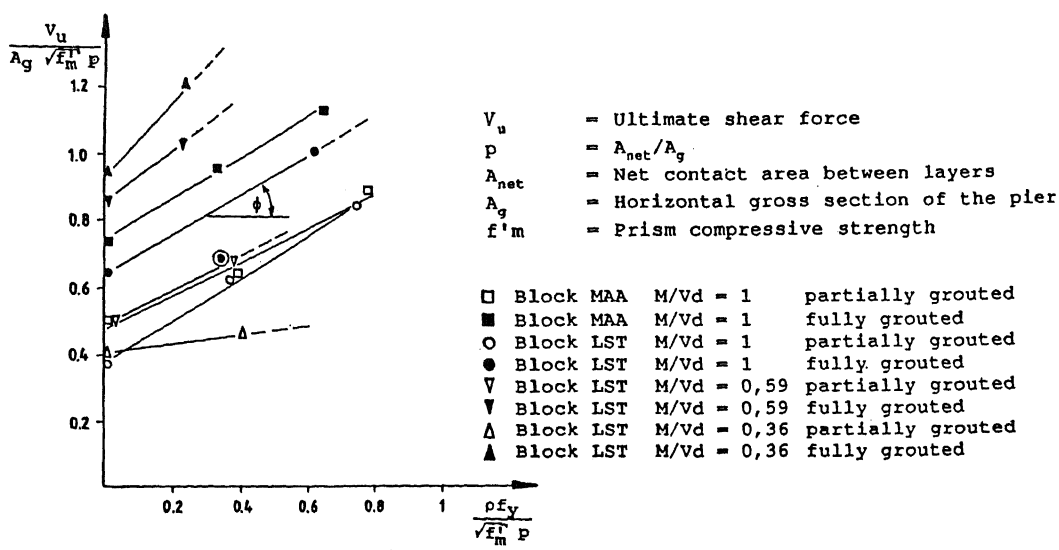

FIG. 10 INFLUENCE IN STRENGTH OF HORIZONTAL REINFORCEMENT