# STRENGTH AND BEHAVIOR OF STRUCTURAL WALLS WITH SHEAR FAILURE

Oscar Hernández B. and Mario E. Zermeño de L. I

## SUMMARY

As a result of an experimental program the hysteretic behavior of concrete walls with shear failure is discussed and a method for the prediction of shear wall strength is proposed. The method takes into account several variables whose effect had not been sufficiently studied. Calculated strength is compared with the results of shear wall tests carried out in different research programs and an excellent approximation is found.

## INTRODUCTION

In the research program reported in ref. 1, 22 models at 1:8 scale and one full scale concrete wall were tested under alternating lateral loads studying the effect on the strength and inelastic behavior, when shear governs the failure, of several variables such as: shear span ratio (M/Vt, relationship of flexural moment to shear force and length of the wall), concrete strength, amount and distribution of reinforcement, axial load, the presence of intermediate slabs on wall heigth and of boundary elements, as columns or transverse walls. The main conclusions were: a) structural walls with shear failure have an inadequate hysteretic behavior by their progressive deterioration in strength under repetition of loads; b) the efficiency of boundary elements for improving behavior is low even if concrete of end columns is confined with high amounts of transverse reinforcement; c) it is convenient to place similar reinforcement ratios on both directions of web wall in order to prevent that yielding accelerates shear failure, it is proposed 3/2 as the relationship between largest and smallest reinforcement ratio; d) intermediate slabs behave as stiffeners, increasing initial rigidity of walls and improving deformation capacity at failure, but don't increase wall strength; e) the principal variables which influence deformation capacity at failure were shear span and reinforcement ratios, arrangements of web reinforcement and the amount and distribution reinforcement in boundary elements did not improve it; and f) the main variables affecting wall strength are: shear span ratio, concrete strength, web reinforcement, axial load and the presence of boundary elements. The aforementioned variables had not been sufficiently studied and different researchers (ref. 1 to 3) have mentioned that strength calculated by the ACI Code is conservative in the case of shear failure; based on results obtained in test of different research programs a method for predicting the shear wall strength has been proposed and its presentation is one of the objectives of this paper.

Another objective of the paper is to present equations that describe the hysteretic behavior of walls with shear failure; this subject is important because most of the design Codes assing higher seismic coefficients to buildings with shear walls than to those with frames without distinction of the type of failure. In walls with large shear spans flexural type of failure predominates and very ductile behavior can be obtained with few precaution in the reinforcement and same seismic coefficient than in frames must be used. In short walls shear usually predominates over flexure and behavior of walls gives rise to a much lower energy dissipation; mathematical models which describe such behavior must be formulated in order to perform inelastic step by step analysis wherefrom realistic seismic coefficients or ductility factors can ben obtained by comparing their results with those of

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.I Institute of Engineering, National Autonomous University of Mexico.

linear elastic systems.

## BEHAVIOR OF CONCRETE WALLS WITH SHEAR FAILURE

In fig. 1 the hysteresis loops under alternating loads of concrete walls with shear failure is shown. For low loads behavior is practically linear elastic. After cracking wall loses strength and rigidity; from laboratory test on microconcrete models it was observed that for a first cycle load paths similar to that shows by a continuous line in fig. 1 are obtained, under repetitions of lateral load for the same deformation level, wall strength deteriorates and after several cycles hysteresis loops stabilize (discontinuous path in fig. 1). This stabilized stress (on force) is named sustained stress and the largest as sustained strength, after maximum load this shear wall loses strength abruptly. Two stress (or force) envelopes can be defined, one for the stresses of the first cycle of each level of load and another for the sustained stresses. Expressions for these envelopes were deduced after drawing all experimental values on dimensionaless axes; equations obtained by mean square fitting are shown on fig. 1, where $v_u$ and $\gamma_u$ are the stress (or force) and distortion (displacement at the top to height of the wall) at failure. In the same way expressions for the hysteresis cycles were proposed in ref. 4 and are also shown on fig. 1, in these equations $v_c$ and $\gamma_c$ represent the limit stress (or force) and distortion of a given cycle. In ref. 1 additional expressions for internal paths in hysteresis loops are given, aforementioned equation were programmed in a computer and inelastic step by step analysis were carried out. By the shortness of this paper is not possible to make a detailed description of results; in general it was found that structures of low periods whose behavior is as described must be designed for higher shear forces and must be able to support large deformations than those whose behavior is linear elastic. The former outcome is due to the large strength deterioration and low energy dissipation in hysteresis loops.

## SHEAR STRENGTH PREDICTION

Maximum strength. Method was based on the usual criterion of concrete and steel stress superposition

$$v_u = v_c + v_s \tag{5}$$

where $v_c$ and $v_s$ are the concrete and the steel contribution to shear strength, the basic concrete contribution disregarding the effect of axial load is

$$v_c = v_o = (1.6 - 0.3\ (M/Vt)^2)\sqrt{f'_c} \geq 0.5\sqrt{f'_c} \tag{6}$$

in this equation $v_o$,concrete shear strength for a specific shear span M/Vt, in Kg/cm$^2$;M, flexural moment, kg-cm; V,shear force,kg; t, shear wall length, cm; and $f'_c$ concrete compressive strength, kg/cm$^2$.Concrete shear strength increase with axial load,its effect can be calculated as

$$v_c = v_o\sqrt{1+\sigma/v_o}\ ;\ \sigma/v_o \leq 5 \tag{7}$$

where $\sigma$ is the compressive stress,kg/cm$^2$.

As usual,steel contribution is expressed as

$$v_s = pf_y \tag{8}$$

where; $p = a_r\ /(sb)$,reinforced ratio in wall web; $f_y$ , yield steel stress , kg/cm$^2$; $a_r$ , reinforcement area,cm$^2$; s, horizontal or vertical steel separation, cm; and b, thickness of wall web, cm.

Expressions 5 to 8 were applied to several shear walls reported in ref.1 and results appear in table 1. The walls had the following general characteristics: axial load, different shear wall span ratios, rectangular cross sections, and reinforcement ratios lower than 0.007, all walls failed in shear. As can be seen correlation is very good, calculated to experimental strength ratio has a mean of 0.99 and a coefficient of variation of 0.06. It must be noticed that experimental stresses were calculated over total rectangular section and when $M/Vt<1$, vertical web reinforcement was used for calculations, otherwise horizontal reinforcement was considered; experimental results support last assumption. In addition, both vertical and horizontal reinforcement need to be almost in the same quantity as mentioned before.

Walls confined by boundary elements. When previous expressions were applied to walls confined by boundary elements calculated strength were lower than experimental results when stresses were calculated over web area. It was observed that boundary elements contributed to wall area with an effective width of twice the web thickness. Table 2 shows strength calculated with this criterion for walls reported in refs. 1 to 4. Mean calculated to experimental ratio is 0.99 and coefficient of variation is 0.06 .

Alternating loads. As mentioned, method was developed from shear wall model tests under alternating loads. When the equations are applied to shear walls tested under monotonic loads strength is underestimate in average by 15%, the same difference has been found by others authors between walls tested under monotonic and alternating loads.

Sustained Strength. The same method can be used to estimate sustained strength if eq. 6 is substituted by eq. 9

$$v_o = (1.2 - 0.23(M/Vt)^2)\sqrt{f'_c} \geq 0.3\sqrt{f'_c} \qquad (9)$$

Good correlation was found between experimental and calculated sustained strength, for walls tested in different research programs, even if in some cases sustained strength was inferred rather arbitrarily from experimental load-deformation curves. Calculated to experimental strength shown a mean of 1.02 and a coefficient of variation of 0.07 .

## REFERENCES

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TABLE 1 RECTANGULAR CROSS SECTION WALLS. LAB AND CALCULATED STRENGTH UNDER ALTERNATING LOADS

| IDENT. | REF.* | H/L 6 M/LV | $f'_c$ ** | $p_h$ | $f_y$ ** | $p_v$ | $f_y$ ** | $\sigma$ ** | $v_o$ ** | $v_c$ ** | $v_s$ ** | $v_{calc}$ ** | $v_m$ ** | $\frac{v_{calc}}{v_m}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 1 | 1.95 | 306 | 0.0035 | 3100 | 0.0035 | 3100 | 22 | 8.7+ | 16.4 | 10.9 | 27.3 | 26.2 | 1.04 |
| 5 | 1 | 1.95 | 305 | 0.0035 | 3100 | 0.0035 | 3100 | 22 | 8.7+ | 16.4 | 10.9 | 27.3 | 29.2 | 0.93 |
| 7 | 1 | 1.95 | 296 | 0.0035 | 3100 | 0.0035 | 3100 | 22 | 8.6+ | 16.2 | 10.9 | 27.1 | 26.5 | 1.02 |
| 8 | 1 | 1.95 | 292 | 0.0035 | 3100 | 0.0035 | 3100 | 22 | 8.5+ | 16.2 | 10.9 | 27.1 | 27.0 | 1.00 |
| 10 | 1 | 0.67 | 378 | 0.0035 | 3100 | 0.0035 | 3100 | 22 | 28.5 | 37.9 | 10.9 | 48.8 | 55.1 | 0.89 |
| 12 | 1 | 0.67 | 280 | 0.0035 | 3100 | 0.0035 | 3100 | 22 | 24.5 | 33.8 | 10.9 | 44.7 | 44.0 | 1.02 |
| 13 | 1 | 2.00 | 293 | 0.0035 | 3350 | 0.0035 | 3350 | 22 | 8.6+ | 16.2 | 11.7 | 27.9 | 27.7 | 1.01 |
| 21 | 1 | 2.00 | 250 | 0.0035 | 3630 | 0.0035 | 3630 | 22 | 8.6+ | 15.4 | 12.7 | 28.1 | 29.0 | 0.97 |

TABLE 2 WALLS WITH BOUNDARY ELEMENTS. LAB AND CALCULATED STRENGTH UNDER ALTERNATING LOADS

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 1 | 1.95 | 280 | 0.0035 | 3100 | 0.0035 | 3100 | 22 | 8.4+ | 16.0 | 10.9 | 26.9 | 26.4 | 1.02 |
| 4 | 1 | 1.95 | 290 | 0.0035 | 3100 | 0.0035 | 3100 | 22 | 8.5+ | 16.1 | 10.9 | 27.0 | 26.0 | 1.01 |
| 6 | 1 | 1.95 | 345 | 0.0035 | 3100 | 0.0035 | 3100 | 22 | 9.3+ | 17.1 | 10.9 | 28.0 | 26.8 | 1.04 |
| 9 | 1 | 0.50 | 360 | 0.0035 | 3100 | 0.0035 | 3100 | 22 | 28.9 | 38.4 | 10.9 | 49.3 | 46.1 | 1.07 |
| 11 | 1 | 0.50 | 300 | 0.0035 | 3100 | 0.0035 | 3100 | 22 | 26.4 | 35.8 | 10.9 | 46.7 | 44.5 | 1.05 |
| 14 | 1 | 2.00 | 247 | 0.0035 | 3800 | 0.0035 | 3800 | 22 | 7.9+ | 15.4 | 13.3 | 28.7 | 26.9 | 1.07 |
| 15 | 1 | 2.00 | 320 | 0.0035 | 3575 | 0.0035 | 3575 | 22 | 8.9+ | 16.6 | 12.5 | 29.1 | 29.2 | 1.00 |
| 16 | 1 | 2.00 | 209 | 0.0070 | 3100 | 0.0070 | 3100 | 22 | 7.2+ | 14.5 | 21.7 | 36.2 | 38.2 | 0.95 |
| 17 | 1 | 2.00 | 175 | 0.0070 | 3100 | 0.0035 | 3100 | 22 | 6.6+ | 13.7 | 21.7 | 35.4 | 33.0 | 1.06 |
| 18 | 1 | 0.50 | 230 | 0.0035 | 3100 | 0.0070 | 3100 | 22 | 23.1 | 32.3 | 21.7 | 54.0 | 55.6 | 0.97 |
| 19 | 1 | 2.00 | 187 | 0.0070 | 3500 | 0.0070 | 3500 | 22 | 6.9+ | 14.2 | 24.6 | 38.8 | 38.2 | 1.01 |
| 20 | 1 | 2.00 | 258 | 0.0070 | 2650 | 0.0070 | 2650 | 22 | 8.0+ | 15.5 | 18.6 | 34.1 | 33.5 | 1.02 |
| WB-1 | 4 | 0.54 | 160++ | 0.0025 | 3000 | 0.0025 | 3000 | 0 | 19.1 | 19.1 | 7.5 | 26.6 | 26.0 | 1.02 |
| WB-2 | 4 | 0.54 | 160++ | 0.0025 | 3000 | 0.0025 | 3000 | 0 | 19.1 | 19.1 | 7.5 | 26.6 | 27.6 | 0.97 |
| WB-3 | 4 | 0.54 | 160++ | 0.0025 | 3000 | 0.0025 | 3000 | 0 | 19.1 | 19.1 | 7.5 | 26.6 | 31.0 | 0.86 |
| WB-6 | 4 | 0.54 | 160++ | 0.0050 | 3000 | 0.0050 | 3000 | 0 | 19.1 | 19.1 | 15.0 | 34.1 | 35.3 | 0.97 |
| WB-7 | 4 | 0.54 | 160++ | 0.0050 | 3000 | 0.0050 | 3000 | 25 | 19.1 | 29.1 | 15.0 | 44.1 | 45.6 | 0.97 |
| 2 | 3 | 2.05 | 373 | 0.0033 | 5160 | 0.0033 | 5160 | 27 | 9.6+ | 19.6 | 17.1 | 36.7 | 37.3 | 0.98 |
| 1 | 3 | 2.05 | 378 | 0.0033 | 5160 | 0.0033 | 5160 | 27 | 9.7+ | 19.6 | 17.1 | 36.7 | 37.8 | 0.97 |
| B3-2 | 2 | 0.50 | 276 | 0.0050 | 5230 | 0.0050 | 5554 | 0 | 25.3 | 25.3 | 27.8 | 53.1 | 52.8 | 1.00 |
| B6-4 | 2 | 0.50 | 216 | 0.0050 | 5062 | 0.0025 | 5062 | 0 | 22.4 | 22.4 | 12.7 | 35.1 | 41.7 | 0.84 |
| B7-5 | 2 | 0.25 | 262 | 0.0050 | 5111 | 0.0050 | 5413 | 0 | 25.6 | 25.6 | 27.1 | 52.7 | 52.3 | 1.00 |
| B8-5 | 2 | 1.00 | 240 | 0.0050 | 5050 | 0.0050 | 5378 | 0 | 20.1 | 20.1 | 25.2 | 45.4 | 42.2 | 1.08 |

** in kg/cm$^2$; +, $0.5\sqrt{f'_c}$; ++ General datum of the reference

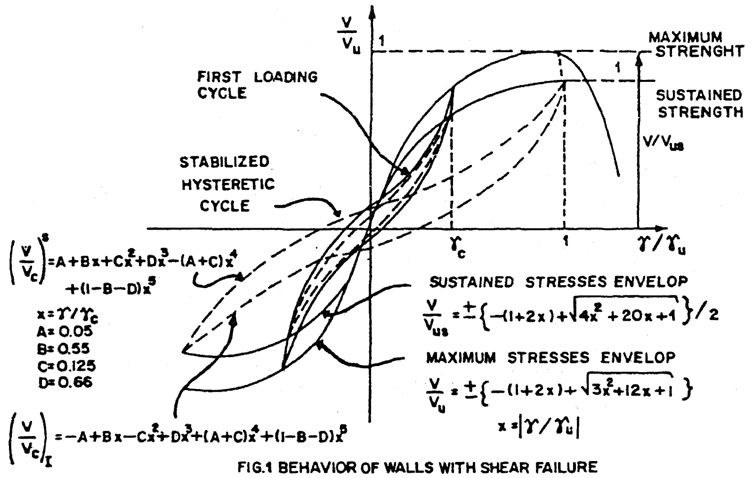

FIG.1 BEHAVIOR OF WALLS WITH SHEAR FAILURE