# EARTHQUAKE DESIGN OF CONCRETE MASONRY WALLS

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This report presents the result of work performed as Phase I of a study program to determine the capacity of concrete masonry to resist lateral earthquake loads. Three structures are studied in order to compare, from an economic and structural integrity perspective, the present Uniform Building Code and a state-of-the-art design procedure.

## INTRODUCTION

Structures constructed of reinforced concrete masonry have a history of being economical and safe in earthquake regions. However, recently adopted or proposed modifications to U.S. building codes have posed a very serious threat to the economical use of concrete masonry as a construction material. These modifications, while being well intended, have failed to rationally view the concrete masonry problem from a balanced designer/researcher perspective. This study attempts such a view.

The view presented attempts to use technical research which exists on earthquake loading and concrete masonry resistance to compare structures designed using the loads and resistance estimated utilizing technical research with structures designed using the existing Uniform Building Code. Thus the recommendations presented are based upon a research review as well as actual design case studies. This paper summarizes a research effort undertaken for the Concrete Masonry Association of California and Nevada. Copies of the full report are available.

### State of the Art Procedure: Loading

Spectral techniques are commonly used by structural engineers to determine the probable forces to which a building might be subjected during an earthquake.

ATC-3(2) proposed a design response spectrum based upon a basic ground motion spectrum with an effective peak acceleration of 0.4g. This basic spectrum is used in this study to define anticipated earthquake loads.

The design response spectrum must be developed from the ground motion spectrum in a manner which is consistent with the analytical model of the structure. One model commonly used for structures with rigid diaphragms is the idealized lumped mass, close coupled multi-degree of freedom system. This model is not appropriate, however, for the analysis of low rise, flexible diaphragm, concrete masonry braced buildings. For such buildings the fundamental frequency of the bracing system (e.g. walls) is much higher than the fundamental frequency of the flexible diaphragm subsystems which they support. A more appropriate model is one which assumes that the shear wall serves as a rigid couple between the ground and the diaphragm(s). Therefore, the multi-degree of freedom system is equivalent to "n" single degree of freedom systems each excited by the same ground motion spectrum. Values for the modifiers applied to the ground motion (i.e. damping and ductility) must be associated with the characteristics of the diaphragms and not with the characteristics of the shear walls.[3]

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Damping characteristics and ductility of diaphragms depend on the diaphragm material. Wood diaphragm have high damping associates with plywood panel deformation and nail slippage. Metal deck and precast plank diaphragms topped with concrete have a significant number of shrinkage cracks and friction along these surfaces provides significantly higher levels of damping than that usually associated with concrete shear walls. Load tests of representative subassemblies exhibit a significant nonlinear behavior. Therefore, damping and ductility values used herein for the analysis of the one and two story buildings were 10% critical and 2, respectively. Now consider the six-story building example. Hysteresis loops and damping computations available [4] indicate that damping values of between 3 and 5% critical, and a ductility greater than 3.0, are reasonable. The test data developed by Mayes [5] and analyzed using the methodology of Chen indicate damping and ductilities in excess of 5% critical and 3, respectively. Masonry piers studied included those which were grouted solid and reinforced in various levels from minimum horizontal code steel to as great as 2.7 times the minimum code reinforcing. Typical horizontal wall reinforcing is usually between 1.5 and 2 times code minimum. Pier data used in establishing a ductility indicator of 3.7 contained minimum horizontal reinforcing (.0007). Other data developed in test programs indicates that energy absorption capabilities and ductility increase as the height to length ratio increases. Therefore, the selection of damping and ductility of 5% critical and 3, respectively, for the six story building is conservative.

## EVALUATION PROCEDURE

In order to evaluate current masonry design criteria as outlined in the Uniform Building Code, the conclusions generated by this criteria must be compared with the conclusions developed using realistic earthquake loads and ultimate material capacities. A consistent rational relationship between the load and the ultimate capacity of a concrete masonry subassembly must be developed in order to compare the two design criteria. More broadly stated, the amount of material required to support a load is determined by dividing the load by a measure of its resistance. Thus: $\text{AREA REQUIRED} = \frac{\text{LOAD}}{\text{RESISTANCE}}$

If required areas or material quantities are determined using the Uniform Building Code and state-of-the-art criteria then the ratio of the two defines the adequacy of the code criteria. Now define the ratio of code required area to state-of-the-art required area as an "Over Design Ratio" (ODR), i.e.:

$$\text{OVER DESIGN RATIO (ODR)} = \frac{A_{UBC}}{A_{SA}} = \frac{L_{UBC}}{R_{UBC}} \bigg/ \frac{L_{SA}}{R_{SA}}$$

If the Over Design Ratio (ODR) exceeds unity, the code criteria is conservative. However, if it is less than unity, the procedure is not adequate.

The most straightforward method of evaluating Over Design Ratios (ODR) is to analyze several representative types of structures. Three structures were selected as being most representative of typical concrete masonry construction:

1. A one story warehouse type building with perimeter load bearing concrete masonry walls.
2. A two story department store type structure with perimeter concrete masonry walls.
3. A six story residential type structure with load bearing interior concrete masonry walls and a concrete floor.

Uniform Building Code Procedure

The Uniform Building Code, 1976 Edition, is used herein to determine required Code areas. The applied loads were generated using the force generating equation:

$$V = ZIKCSW$$

Zone 4, an importance factor of 1.0, and K = 1.33 were assumed for this report. Allowable shear stresses used are from Table 24-H of the UBC, 1976 Edition.

State of the Art Procedure: Resistance

A variety of test data is available on ultimate stress capacity of masonry walls. Most tests focus on a distinct set of variables and hence, require extrapolation in order to develop approximations to the ultimate strength values of concrete masonry. Of the many potential variables associated with concrete masonry construction, three have a significant impact on this study; nature of loading (static versus cyclic), wall geometry (height to length ratio) and steel reinforcing (horizontal and vertical).

Static and dynamic tests conducted at the University of California, Berkeley[4] provide insight into the performance of concrete masonry walls. Ultimate shear strengths used in this study were extrapolated from these various reports (see Table 2).

For a variety of reasons, tests performed to date do not indicate that the shear strength of a masonry panel is significantly or consistently increased by the addition of reinforcing steel. Therefore, no increase in shear strength is assumed for reinforcing in this study. Reinforcing, undoubtedly, contributes significantly to the shear strength of a masonry panel with an h/d ratio greater than 2. As a result, a significant over-conservatism must be anticipated in the six-story example building.

CONCLUSIONS

A summary of "Over Design Ratios" developed from the example buildings is presented in Table 1. The average of the Over Design Ratios exceeds 2. This clearly indicates that the code design criteria is not appropriate. The spread in values of the ODR's is large. A simple adjustment in code permitted stresses is not an acceptable answer.

TABLE 1 - OVER DESIGN RATIO (ODR)

| SHEAR REINFORCING | UNREINFORCED | REINFORCED |
|---|---|---|
| ONE STORY | 2.1 | - |
| TWO STORY | 2.2 | 1.4 |
| SIX STORY | 3.2 | 1.3 |

Several basic UBC provisions severely penalize concrete masonry construction:

A) Ultimate stresses permitted by the UBC for reinforced concrete assume that a reconciliation between loads and stresses requires an ultimate load factor of 2. Concrete masonry requires an ultimate load factor of 4 unless reinforcement is provided to take the entire shear in which case the load factor is 2.4. This is for shear walls with an aspect ratio of one. Load factors increase significantly for lower aspect ratios.

B) The UBC requires that reinforcing steel be provided which is capable of carrying the entire shear force if load factors less than four are to be used. This requires that between 3 and 4 times code minimum reinforcing is required in order to reduce this load factor from 4 to 2.4 since no shear capacity is allowed for the masonry when a load factor of less than 4 is used. Since test programs have not been able to establish a clear indication of increased shear strength associated with reinforcing a masonry panel this concept does not seem justified.

Further reconciliation of masonry over-design ratios requires a revision of the loading criteria contained in the code as it applies to intermediate range structures (six-story buildings). This can be accomplished within the scope of the code if spectral design procedures are accepted and code values treated as an upper-bounds.

## RECOMMENDATIONS

Revising the format of the masonry code as it relates to seismic design would produce a more orderly evolution of seismic design procedures. Allowable shear stresses in masonry should be based on ultimate shear strengths and load factors which are compatible with other building products. The ultimate shear stresses presented in Table 2 are easily justified by test data developed to date[(4) (5)].

TABLE 2 - PROPOSED CONCRETE MASONRY SHEAR STRESSES

| Shear Reinforcing | | h/d | $v_m$ | Max. |
|---|---|---|---|---|
| a) | minimum (UBC 2418 (j)3) | 1 | $1.7\sqrt{f'_m}$ | 100 psi |
| b) | minimum (UBC 2418 (j)3) | 0 | $4.0\sqrt{f'_m}$ | 250 " |
| c) | carries excess shear | 1 | $2.5\sqrt{f'_m}$ | 135 " |
| d) | carries excess shear | 0 | $6.0\sqrt{f'_m}$ | 300 " |

Long range research objectives should:

- focus on the effect of reinforcing (quantity and didrection), on the shear strength of Concrete Masonry Shear Walls.
- provide a better relationship between shear strength and aspect ratio so that current Over Design Ratio(ODR) which exist in buildings braced by long low walls can be reduced.
- define a consistent set of damping, ductility and ultimate strength values for concrete masonry which can be used in the spectral analysis of structures.

Developing a safe yet realistic building code which is not so complex as to detract from its purpose is a difficult task. Such a code can only evolve gradually. Recent research activity in concrete masonry will certainly accelerate the process if this research is presented in a form which can be readily brought to bear on design procedures and the Building Code.

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