PREDICTIONS OF STABILITY FOR UNREINFORCED BRICK MASONRY WALLS SHAKEN BY EARTHQUAKES

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ABSTRACT

Full scale dynamic testing of unreinforced brick masonry walls shaken in the out-of-plane direction confirmed dynamic stability concepts. The dynamic stability prediction technique uses seismic spectral intensities as part of input into the selection of stable wall height-thickness ratios. Locations of walls in a lumped mass response model were also shown to be a determinant of probable stability. Earthquake response of horizontal elements such as floors and roofs was shown to be critical to the prediction of the dynamic stability of unreinforced walls. The results of the research program were introduced into earthquake hazard reduction ordinances that are now in effect in the Pacific Coast seismic hazard zone of the United States.

INTRODUCTION

Building construction using unreinforced masonry (URM) predates the development of seismic criteria that guide the design and construction of present-day buildings. A substantial number of these URM buildings are still being used in areas considered seismically active, even though investigations of earthquake damage have confirmed that this type of building has been a major contributor to personal injury or loss of life during relatively high intensity earthquakes.

In 1977, the National Science Foundation (NSF) initiated a multiphased program for the mitigation of seismic hazards, which resulted in a study to develop a methodology for the mitigation of seismic hazards in existing URM buildings. A key observation taken from these damage reports is that some structures sustained more damage than others, and the researchers were led to assume that the interaction among the building components was a vital issue in explaining and predicting URM building damage. Accordingly, a study of typical URM building response was conducted and three related component responses and their interactions were identified for further study; namely:

- Horizontal diaphragms
- URM walls subjected to out-of-plane motions
- Anchorage between the URM walls and the diaphragm

The topic of this paper, stability of URM walls shaken by earthquakes, has received little or no attention in prior research. In-plane strength of URM walls can be estimated by common design procedures, but survival of URM walls shaken out-of-plane, when anchored to floor and roof construction, cannot be rationalized by computations using strength concepts. Determination of the probability of stability of the anchored URM walls at the building exterior is the single most significant part of an earthquake hazard reduction program. Separation and collapse of the URM walls at the building exterior contribute the majority of threat to life during an earthquake. Anchorage of the URM walls is a straightforward partial solution. Determination of stability of the URM walls between anchorage levels needs analytical methods previously not known. As part of the overall research program, an analytical and experimental investigation into the response of URM walls shaken out-of-plane was undertaken.

CONCEPTS OF DYNAMIC STABILITY

Unreinforced masonry walls survive moderate to strong ground shaking by mechanisms not related to usual seismic design provisions. Masonry walls in seismic zones are typically designed for out-of-plane lateral forces by prescribing a minimum moment capacity. This moment capacity is provided by either reinforcement or the tensile capacity of the masonry assemblage. The analysis or design of unreinforced walls, without tensile capacity, for out-of-plane stability when shaken by earthquake motions, is termed in this paper as analysis of dynamic stability. Dynamic testing of URM walls confirmed that fully cracked URM walls will remain stable and continue to support superimposed loads during moderate to strong shaking. The intensity of shaking included motions that are appropriate for the highest hazard zone in the United States (2).

The stability of a fully-cracked URM wall, shaken by less than critical ground motion intensities, is maintained by gravity load moments applied at the cracked surfaces as shown in Figure 1. The approximated gravity load moments on the cracked surfaces, $(O + W_1)e_1$ and $(O + W_1 + W_2)e_2$, do not have to equal at any point in time the horizontal inertial moments caused by dynamic horizontal displacement of the URM wall. These moments limit the dynamic horizontal excursions of the two rotating blocks. When the center of gravity of the vertical loads above a cracked surface lies within the wall thickness dimension "t", the gravity load moments provide a restoring moment that closes the crack upon reversal of the earthquake displacement motions.

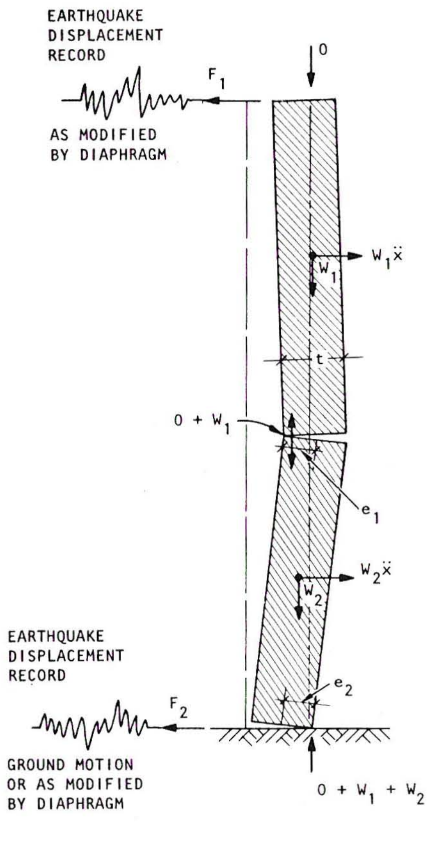

FIGURE 1. DYNAMIC STABILITY FORCE MODEL

Figure 1 presents a simplified force system to indicate the principles of dynamic stability. Shear forces transferring horizontal forces between the rotating blocks may occur at the center crack. Gravity loads W_1, W_2 and 0 are modified by vertical accelerations caused by a component of the ground motion as well as vertical accelerations resulting from the upward displacement of the wall segments, relative to the base. These upward displacements are caused by geometric relationships of the displaced and rotated wall segments. The test apparatus did not include input of vertical time histories that would be appropriate in combination with horizontal time histories. The probability of modification of dynamic stability predictions by vertical ground motions is discussed in the recommendations of this paper.

The concept of control of structural displacements of yielding elements is inherent in all seismic design provisions. A yield capacity of the lateral load resisting system is prescribed by design provisions. This prescribed capacity is less than calculated elastic structural response, but can effectively limit the magnitude of relative inelastic displacement.

DYNAMIC TESTING PROGRAM

URM wall specimens were fabricated adjacent to the test apparatus using common masonry material and mortars. The specimens were 1.8 m wide and 3.0 to 4.9 m high. The height-to-thickness ratios (H/T) ranged from 14 to 25. The material included three wythe common brick and grouted and ungrouted clay and concrete blocks. Four specimens were reinforced by a retrofit technique that consisted of application of a reinforced mesh and brick wall surfaces by hand plastering techniques.

The URM wall specimens were installed in a test fixture that allowed the base and top of the wall to be moved independently in the out-of-plane direction by servocontrolled hydraulic actuators. The walls were fabricated on a concrete filled, metal base with two attachment lugs for the hydraulic actuators. When the wall was installed in the test fixture the base rested on a low-friction roller-supported base plate that allowed the base of the wall to be displaced without rotation by the two hydraulic servoactuators. A mechanical header with one attachment lug was installed on the top of the wall that allowed the top of the wall to be displaced by one hydraulic servoactuator; however, the top of the wall was free to rotate. The mechnical header was guided by a pantograph linkage system that allowed the top of the wall to move in the vertical direction without restraint. In addition, the mechanical header was fitted with two vertical rods that supported an overburden mass to simulate additional wall or parapet mass above the wall section being tested. The overburden mass was suspended from the header a few inches above the laboratory floor so that its fall at the time of wall collapse would be controlled.

The basic instrumentation for the measurement of the dynamic responses and forcing functions consisted of load cells, accelerometers, and displacement sensors. The displacements were measured using string potentiometers. The displacement sensors, including feedback deflection sensors, were mounted to a stable reference frame that was independent of the frame for the forcing system. The data from each instrument was recorded on magnetic tape in digital form. The raw source data tapes were interpreted and written on new tapes, using a standard format with some data compression, for use in data presentation and interpretation. Additional data recording was taken in the form of still and motion pictures as well as observer notes and test logs. The detailed data, photographic coverage and observer notes are given in reference (1).

The kinematic motions used in the test program were based on actual earthquake ground motion records that correspond to seven major geographical regions of the United States (2). The ground motion records were scaled so as to cover the full range of seismicity from an Effective Peak Acceleration (EPA) of 0.1 g to 0.4 g. These ground motions were input to the nonlinear, dynamic analysis model of a typical URM building described earlier to obtain diaphragm/wall response motions. The model accounted for the nonlinear response of the diaphragm, including both stiff and flexible diaphragms, and the dynamic inertial effect of the URM walls. The motion sets were assembled in pairs from these dynamic motions to simulate the kinematic environment at the base and top of the URM walls for both ground level wall elements and elevated level wall elements.

The pairs of motions were selected to include the following parameters:

- Paired motions with small phase shift.
- Paired motions with substantial phase shift.
- Paired identical input motions.

The selected motions represented the full range of ground shaking intensities (EPA) that corresponds to the contours of current hazard zoning maps (3). The paired motion with small phase shift can represent, with increasing spectral intensity, single story walls supported at the top by stiff roof diaphragms, walls at the mid-height of buildings with similar stiffness floor diaphragms, or walls at the uppermost story of building with diaphragms constructed of modern materials. The paired motions with substantial phase shift represent URM walls in single story buildings with undesigned and flexible roof diaphragms, or walls at the uppermost story of a building with undesigned diaphragms. The paired identical input motions represent URM walls that are attached to diaphragms coupled by crosswalls that control relative diaphragm displacement.

The order of dynamic test motions was first based on the assumption that the collapse of the URM test specimen would be related to:

- Increasing spectral intensity (EPA).
- Large relative displacement of the wall ends.
- Increasing spectral velicity of input motions.

The order of dynamic motions were revised after the first tests established that input velocities, simultaneous in time, were the critical dynamic input factors.

The URM specimens were installed in the test apparatus with a test overburden. Three tests overburden weights were used for each group of test specimens. The ratio of overburden weight to test specimen weight (O/W) varied from 0.13 to 5.1. The specimens were shaken by increasing intensity paired motions until collapse occurred or the excitation capacity of the apparatus was reached. Specimens with O/W ratios above 3.8 and H/T ratio of 15.7 and 21.3 survived input velocities of 1 m/sec and 0.7 m/sec respectively. All specimens were fully cracked at several bed joints by prior test sequences. The bed joints that opened appeared to be related to the input end motions and were not always the previously cracked bed joints.

The observations and interpretation of the test program confirmed that understanding of the complete response model of the URM building is necessary for prediction of stability of URM walls. The amplification of ground motions by the in-plane URM walls and the floor and roofs, both in their elastic capacity and inelastic response range, must be considered and categorized for each seismic hazard zone.

PREDICTION OF DYNAMIC STABILITY

Experimental studies of in-plane dynamic stability of URM wall piers have indicated that the stability moments caused by dynamic displacements on cracked surfaces have a linear relationship to the rotation on the cracked surface for small rotations. The relationship is nonlinear for moderate to large rotations. The restoring gravity moment shown in Figure 1 has a declining branch due to rotational geometry that is similar to a degrading hysteretic moment-rotation plot. However, unloading moment-rotation plots trace the loading moment-rotation plot. Kinetic energy is lost from the system by loss of momentum on cracking closing. Mathematical duplication of this behavior is difficult and can be done only for a generalized masonry model. For this reason, statistical studies are extensively used. Statistical studies are used for parametic studies in many phases of earthquake hazard reduction research. Earthquake input motions are described on the basis of probability. Modification of the input earthquake motions by horizontal elements is based on probability values of the stiffness properties and the yield capacities of diaphragms. Apparent damping (energy adsorption) of URM walls is generalized and presently can only be given a probable value for the variety of masonry assemblages that may be subjected to dynamic motions. The recommendations for acceptable risk of collapse of URM walls need to consider probability combinations that are equivalent to those incorporated into current seismic design recommendations.

Statistical studies and analyses of the test data concluded that the key parameters that determined dynamic stability of the URM walls were:

- The square root of the sum of the squared (SRSS) input velocities to the ends of the URM wall.
- The overburden to wall weight (O/W) ratio of the wall.
- The wall height to wall thickness (H/T) ratio of the wall.

Plots of these parameters are presented in Figure 2 for a 98% probability of survival of the URM wall. For interpretation of the test data, the parameters were plotted for 50% and 86% probability of survival. A few "wrong-side" test results were discovered and the relative displacement-time plots of the cracked wall specimens were examined. The plotting of the instrumentation data indicated that the theoretical upper bound of displacement of the center of the wall relative to its ends can be momentarily exceeded. The exceedance can be explained by recognition that dynamic displacement of the ends of the wall can reduce the relative center displacement before the center of the wall drifts into instability. The observed collapse of the unstable URM wall specimens was not sudden but can be characterized as a slow drift into instability during reversal of the dynamic motions of the ends of the walls. The collapse was generally related to single pulses of input velocity. Cyclic input of velocities of less than critical would cause large cyclic cracked excursions of the center of the wall without instability.

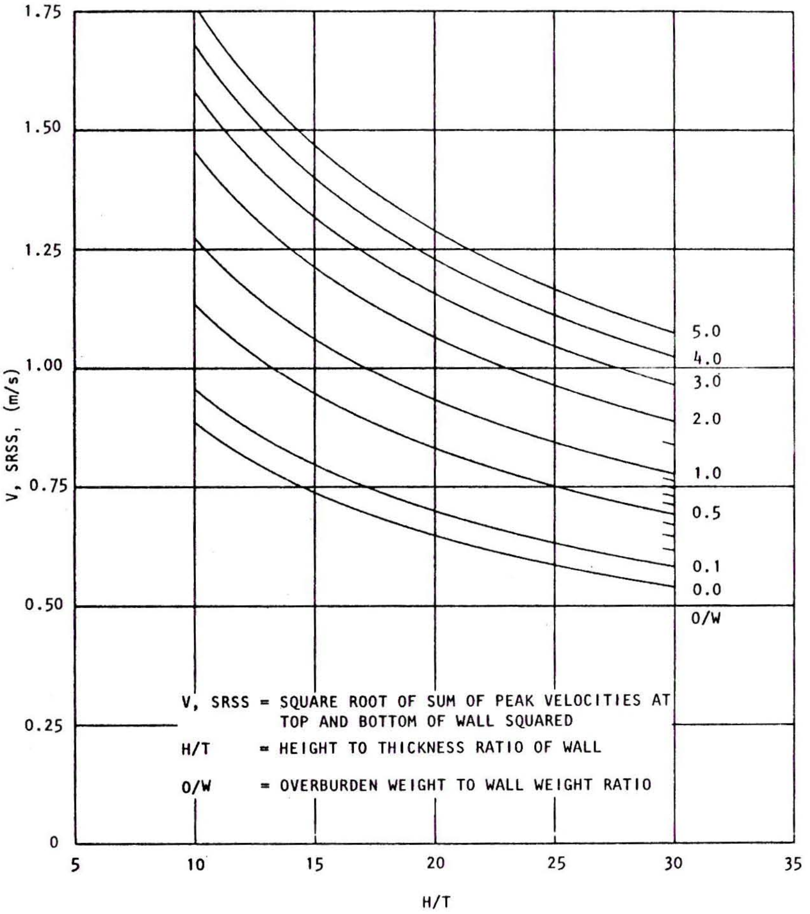

FIGURE 2. UNREINFORCED MASONRY WALL STABILITY CRITERIA

The prediction of input velocity to the ends of the wall is the single parameter that depends on the URM building response model. A parallel dynamic test program for typical diaphragms was conducted to provide data for this parameter (4). Interpretation of this data (5) and integration of this data into the developed methodology (6) recognized the influence of crosswalls on the modification of input motions by the diaphragm. A crosswall is defined as an element with elasto-plastic load-displacement characteristics that interconnects the diaphragm with the ground between the diaphragm ends. These crosswalls are generally interior partitions that extend between diaphragm levels.

Development of mathematical models for time-history studies of the elastic and inelastic responses of diaphragms indicated that the hazard analysis of the diaphragm response should not utilize usual demand-capacity relationships based on probable elastic response and elastic load capacities. A plot of acceptable relative displacement control parameters (Figure 3) was developed for seismic hazard zones of EPA = 0.4 g. This recommendation recognizes that crosswalls may be used for displacement control by use of the calculation of the demand-capacity ratio as $W_D/(2v_u D + \Sigma V_c)$.

Where: W_D = Total weight tributary to the diaphragm

v_u = Yield capacity of the diaphragm

D = Diaphragm depth

V_c = Total yield capacity of crosswalls.

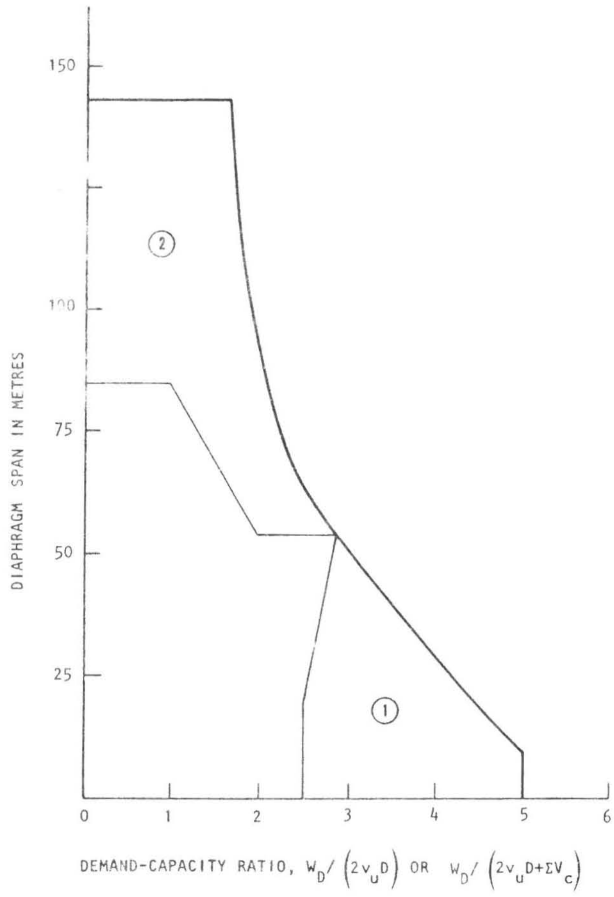

FIGURE 3. ACCEPTABLE SPAN FOR DIAPHRAGMS
(BASED ON DISPLACEMENT CONTROL CONCEPTS)

Studies of the amplification of the seismic hazard design velocities determined that diaphragms with large demand-capacity ratios (in excess of 2.5 for spans of [illegible] meters or more and 3.0 for a span of 54 meters maximum) have a limited amplification of input velocities. For region (1) of Figure 3, the predicted amplification of the diaphragm may be taken as not greater than 1-3/4 times the design ground motion velocities. Time-history studies based on recorded ground motion scaled to an EPA of 0.4 g determined that crosswalls with a yield capacity of not less than 30% of the diaphragm capacity, $v_u \cdot D$, and spaced not more than 12 meters along the diaphragm length can also limit the diaphragm amplification factor to 1-3/4. These recommendations are fully described in the commentary in references (6) and (7).

Figure 3 and the described crosswall criteria for limiting amplification of design ground motions is only applicable to a seismic hazard zone of EPA = 0.4 g. The dynamic testing and its interpretation indicates that dynamic instability of anchored URM walls with H/T ratios that are common to existing buildings is improbable in lesser EPA hazard zones. An exception to this is described for the seismic hazard zone of EPA = 0.2 g in reference (6), which describes a method of determination of acceptable H/T ratios.

RECOMMENDATIONS FOR USE OF DYNAMIC STABILITY CONCEPTS

The methodology, reference (6), recommends an upper limit of acceptable H/T ratios for URM walls in the seismic hazard zone of EPA = 0.4 g. Table 1 uses descriptive terms to define the relationship of the wall to the parameters that affect the prediction of dynamic stability. These parameters are:

- Overburden-Wall Weight (O/W) ratios
- SRSS of the input velocities to the top and bottom of the wall
- Height-thickness (H/T) ratio.

TABLE 1. ALLOWABLE HEIGHT/THICKNESS RATIOS OF URM WALLS WITH MINIMUM QUALITY MORTAR

	Building with Crosswalls	All Other Buildings
Walls of one-story building	20	14
First story walls of multi-story buildings	20	20
Walls in top story of multistory buildings	14	9
All other walls	20	15

The recommended allowable H/T ratios are related to Figure 2 by categorization of stability parameters as:

- O/W = 0 for single and top story walls.
- O/W = 0.5 for all other walls.
- Design ground motion for EPA = 0.4 g is 0.3 m/sec.
- Amplification of design ground motions at the upper (roof) level is 2.
- Amplification of design ground motion at floor levels is 2-1/4.
- Peak velocities are assumed to be in phase.
- Plots of dynamic stability using a 98% probability of survival were used to determine allowable H/T ratios.

The effects of vertical ground motion were not considered to have a significant influence on the dynamic stability predictions for URM walls. If the soils under a URM building are modeled as an elasto-plastic medium, the recorded free field vertical ground motions are modified and acceleration peaks are attenuated. The frequency band of vertical motions is not in the critical frequency band of horizontal ground motions. The effect of high frequency vertical motions on the restoring moments, Figure 1, does not result in a bias of increasing or reducing the restoring moments, due to the significantly lower frequency of instability excursions, especially as the relative excursion of the center part of the wall approaches instability. The design diaphragm

excitation also assumed the URM shear walls were rigid bodies to transmit ground excitation to the diaphragm ends. For solid URM walls on property lines this assumption is valid, but modification of peak value horizontal ground motions by inelastic shear coupling in the soil medium is probable. The probability of vertical ground motion influencing the prediction of dynamic stability of URM walls shaken in their out-of-plane dimension is smaller than the probability introduced by categorization of the critical parameters that were used for preparation of Table 1.

ACKNOWLEDGEMENT

This research was conducted by ABK, A Joint Venture, for the National Science Foundation under Contract No. NSF-C-PFR-78-19200 and Grant No. CEE-8100532. The Joint Venture, ABK, consists of three firms, Agbabian Associates, S.B. Barnes & Associates, and Kariotis & Associates, all in the Los Angeles area. The principal investigators for the three firms are R.D. Ewing, A.W. Johnson, and J.C. Kariotis. Dr. J.B. Scalzi served as Technical Director of this project for the National Science Foundation and maintained scientific and technical liaison with the joint venture throughout all phases of the research program. His contributions and support are greatly appreciated.

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