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Review of the seismic performance of unreinforced masonry walls

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ABSTRACT: A comprehensive review of the existing literature on the seismic performance of unreinforced masonry walls was conducted to assess the state-of-the-art on this topic. A description of general modes of failure, current code requirements, constitutive models, experimental studies and modelling aspects of URM buildings are summarized. The proposed models for the study of URM structures are found to be numerous. Many of the newer theories remain controversial. Much research is needed to identify the reliability and range of applicability of each suggested model.

1. INTRODUCTION

A large proportion of North America's older building inventory is of unreinforced masonry (URM), constructed in the absence of mandatory earthquake design requirements. As URM is unquestionably recognized as a non-ductile type of construction most vulnerable to earthquakes, these older buildings tend to be at greater seismic risk than comparable new buildings. Not surprisingly, URM construction all but practically disappeared from seismic regions when earthquake-resistant design requirements where implemented. Since, little was done to improve the understanding on the seismic behavior of URM construction. Hence, the realistic assessment of the adequacy of existing URM buildings remains a complex task, particularly when subjected to small and moderate earthquakes.

The writers recently conducted a comprehensive review of the existing literature on the seismic performance of unreinforced masonry walls to assess the state-of-the-art on this topic, summarize the lessons to be learned from the reported performance, and identify the areas that require further research. Due to space constrains, only an abridged presentation of the findings is possible herein. A detailed report of this study is under preparation.

2. DESIGN CODE AND REQUIREMENTS

North American standards recognize two possible design methods for URM structures: (i) Empirical rules relying on assessments of compressive stresses and compliance with limits on wall slenderness ratios (which are proscribed for design against earthquake-induced forces), or (ii) Engineering Analysis based on simple elementary principles of elastic mechanics of materials coupled to some semi-empirical relationships to account for stability and load eccentricity effects. Essentially, the classical equations for shear stresses and combined axial and bending stresses are used. In both cases, the onset of cracking is defined as the failure criteria.

3. GENERAL MODES OF FAILURE

Lack of Anchorage: In the absence of positive anchorage, the exterior walls behave as cantilevers over the total building height. The risk of wall out-of-plane failure due to excessive flexural stresses at the base of the wall obviously increases with the wall's height and flexibility, but, more importantly, global structural failure can occur by the slippage of the joists/beams from their supports.

Anchor Failure: While the metal of the anchor may fail, rupture may also occur at the connection points, i.e. the anchor could shear loose from the framing member at one end, or be pulled off from the masonry itself at the other end.

In-plane Failures: Excessive bending or shear may produce in-plane failures, depending on the aspect ratios of the URM elements. In masonry facades having numerous window openings, spandrels and the short piers between those spandrels are highly shear-vulnerable. Flexural failure of those structural elements is also possible, particularly if slender.

Out-of-plane Failures: Joist-to-wall anchors provide out-of-plane support to the walls. If present in sufficient numbers and strength, these anchors will transform the out-of-plane behavior of the URM walls, from tall unrestrained cantilevers to shorter one-story high panels dynamically excited at each ends by the floor diaphragms. Parapet and gable failures fall in this category. Multi-wythe walls improperly bonded along their collar-joint are also extremely vulnerable, each wythe behaving independently as an individual thin wall.

Combined In-plane and Out-of-plane Effects: Earthquake forces are bi-directional in nature, and thus each URM element is solicited in both its in-plane and out-of-plane direction. The on-site identification of such a failure mode is nearly impossible, and observed such failures will generally be attributed uniquely and erroneously to the sole effect of out-of-plane forces. Pounding with adjacent structures can accelerate this combined failure mode.

Diaphragm-related Failures: Diaphragms are dynamically solicited in-plane, and their flexibility has a considerable impact on the seismic response of the URM walls. The failure of the diaphragm itself is rarely observed following earthquakes. However, since flexible floor diaphragms behave as deep beams spanning between URM walls, the in-plane rotation of the diaphragm's ends, and/or absence of a good shear transfer between diaphragms and reaction walls, can induce damage at the walls' corners.

4. CONSTITUTIVE MODELS

A comprehensive constitutive model capturing the seismic-behavior of masonry while considering its heterogeneous nature, with its inherent complex interaction of mortar, brick, layering patterns, and other distinctive features, remains elusive. Some attempts at the development of more advanced constitutive models for in-plane response were made by Mengi, Sucuoglu and McNiven (1982 and 1986 among many); They concluded that advanced mixture models are costly and impractical, and recommended an isotropic symmetric model. Instead of developing an hysteretic model to capture the observed non-linear behavior, Mengi and McNiven proposed an equivalent linear model that accounts for the non-linearity effect through variable secant shear modulus and secant damping coefficient.

An hysteretic model applicable to URM shear panels has been proposed by Benedetti and Benzoni (1984). Developed to replicate experimentally obtained shear stress-strain hysteretic curves, it is constructed from three superimposed bilinear hysteretic shear sub-elements, failing brittly at prescribed strain intensities. Parameters shaping this phenomenological hysteretic envelope are calibrated from available experimental results. This model has been derived from tests on stone masonry; its applicability to general URM structures is only inferred.

5. RECENT EXPERIMENTAL STUDIES

In-plane Shear Cracking: A large number of static tests have been carried-out on URM shear walls in the past to establish or verify analytical failure equations. The important interaction of shear and axial stresses is well recognized in the existing literature. Yet most of the past investigations were concerned with the behavior of these walls under static monotonically applied loads, more representative of winds than earthquake loadings.

Recent tests (Konig et al. 1988) investigated the post-cracking dynamic cyclic behavior of URM shear walls to understand the effect of axial loads on the failure type and ductility of URM walls subjected to seismically-induced in-plane shear forces. They demonstrated that, under low axial load, cracking passes by the bed joints, in a diagonal jagged pattern across the wall, and the individual separated portions of the wall can slide on each other, resulting in large relative deformations (with ductilities of up to 4) and little strength degradation before failure. Under higher axial loads, the friction resistance of the bed joints is proportionally increased, and cracking occurs instead through the masonry units if the principal stresses locally exceed the tensile strength of the units; as a result, the individual separated portions of the walls tend to slide downwards along the more regular diagonal cracks, with little apparent ductility.

In-Plane Flexural Cracking: In the absence of axial compressive forces, URM piers of large height to width aspect ratios behave linear elastically as brittle beams, i.e. first cracking coincides with complete failure. URM spandrels would behave similarly. The presence of an axial compression force plays a determinant role on the performance of URM walls in this case; It contributes to the overall stability beyond flexural first cracking. ABK (1984) were apparently the first to investigate this behavior. In static tests, a stable rigid-body rocking motion that attempt to develop following first flexural cracking is restrained if a sufficient axial compressive load is present. The pier's lateral load resistance is greatly enhanced by this effect, and the compression capacity of the masonry in the uncracked bearing area becomes the limiting factor, unless overturning occurs. This is confirmed by other researchers.

Out-of-plane Seismic Dynamic Stability: The concept of dynamic stability is relatively new. It was formulated following observations that URM walls properly anchored to floors and roof diaphragms can resist earthquakes more severe than otherwise predicted by traditional static analysis methods. After cracking, portions of walls behave as rigid-body members rocking on the wall's through-cracks; if gravity forces are sufficient to prevent overturning of these individual bodies through the entire earthquake, a condition of dynamic stability exists. The ABK testing program established that the margin between the seismic intensities needed to initiate cracking and produce dynamic instability was large enough to have a major impact on engineering decisions. Other researchers have since experimentally corroborated the validity of the dynamic stability concept.

6. MODELIZATION ASPECTS

Out-of-plane Modelling: Out-of-plane models, suitable for use in a design office, are few. While the dynamic stability concepts exposed previously are simple, the formulation of an analytical model extending beyond purely static stability considerations remain elusive. One approach based on energy considerations has been proposed by Priestley (1985). Also, at this time, the natural "vertical-anchorage" provided by continuity with the other perpendicular walls is conservatively neglected. This continuity could possibly enhance significantly the out-of-plane resistance in the case of narrow walls. It is noteworthy that such a consideration of the effect of various boundary conditions on the ultimate out-of-plane strength of URM panels, in a non-seismic context, has received some attention: a fracture-line model applicable to orthotropic brickwork panels of low tensile strength, proposed by Sinha (1978) has shown excellent correlation with experimental results for URM panels tested free of concurrent in-plane axial loads.

In-plane Modelling - Solid-pier/Cracked-spandrel Model: A legitimate, yet conservative, model is to assume that the spandrel beams will crack under a very low lateral load, leaving the piers alone to resist the lateral loads. This approach is not unlike that recommended by some researchers for the analysis of reinforced masonry walls having numerous opening, where the masonry above and below the openings is neglected. Although this models the structure at its ultimate state if the spandrels are shallow or not well connected to the piers, it immediately assumes a structure in its degraded condition, neglecting the potentially larger capacity of the structure before cracking.

In-Plane Modelling - Solid-spandrel/Cracked-piers Model: If the spandrels are deep and/or of short span, the piers may fail first, in flexural cracking, shear cracking (diagonal tension), or compression crushing. A number of models of this behavior are suggested in the existing literature. Elementary equations of mechanics of materials are often used to define a shear failure criteria directly related to the diagonal tension capacity by principal stresses relationships. Some researchers have recommended that, in addition, the usual Coulomb friction shear strength equation (i.e. the one generally present in codes) be checked: The latter reflects that bond and friction between the mortar joints could potentially govern at low axial compressions, whereas for high bond mortar and/or higher axial loads, only the former would be applicable.

The above strategies implicitly postulate that shear strength is exhausted at the onset of first cracking. This need not be the limiting condition under flexural cracking, considering, even statically, the stabilizing effect of axial loads. Equations have been proposed to assess the ultimate strength of flexurally cracked piers having reserve shear strength capacity (ABK 1984 and Priestley 1985).

Finally, others suggested that the compressive strength at the toe of URM walls flexurally cracked at their base could be reached before overturning and diagonal tension (shear) failures, and recommended that this limiting condition be also checked.

Finite Element Models: Linear elastic finite element analyses are becoming popular, particularly in Europe, to establish the state-of-stress in complex URM heritage structures, often built of stone. However, only a few of the reported studies are concerned with seismic resistance (Vestroni et. al. 1991). These linear elastic analyses may be worthwhile to provide some guidance as to the governing failure mode, ultimate elastic capacity, natural frequencies, mode shapes and modal participation factors of uncracked URM buildings, but they provide little insight into the ultimate strength and seismic behavior of such structures. Recognizing these limitations, some researchers have investigated the adequacy of special non-linear and cracking finite elements for studying the ultimate seismic behavior of structures. Both discrete-crack and smeared-crack formulations have been tried (Chiostrini and Vignoli 1991). However, more research is needed to fully assess the potential of these finite element strategies.

7. THE ABK METHODOLOGY

The ABK methodology is based on the results of a comprehensive static and dynamic testing program of standard structural components often found in URM buildings (diaphragms and walls). It first assumes that the ground motion is directly transmitted unmodified to each floor by the end-walls parallel to the direction of earthquake excitation. Thus, each floor diaphragm is seismically excited at its end-attachment points to the URM walls by the original unamplified ground motion. These diaphragms, in turn, push on the head walls, (i.e. the walls perpendicular to the ground motion direction) which are excited in their out-of-plane direction. Therefore, the dynamic characteristic of the diaphragms directly influence the severity of the out-of-plane excitation of head-walls and the required strength of walls-to-diaphragms anchors. Limits on diaphragms spans are set as a measure to control the severity of the diaphragm-amplified seismic excitations imparted to the URM head-walls and limits on slenderness ratios derived from dynamic stability concepts are imposed to protect these head-walls against out-of-plane failure. Clearly, out-of-plane stability and structural integrity are the primary goals of this methodology. Structural integrity (adequate ties between walls and diaphragms) must be present or added for the methodology to be applicable.

Other researchers have since essentially endorsed the ABK work with the following recommendations: the full dynamic in-plane response of the URM end-walls should be considered and engineering judgement should be exercised for buildings having rigid diaphragms and/or irregular plan shapes.

8. CONCLUSIONS

The various failure modes of URM buildings or components subjected to earthquake excitation have been described. It was found that while some constitutive models have attempted to consider the non-homogeneous characteristics of URM, this proved too complex for seismic-adequacy evaluation analyses. Experimental testing has been extensive, and addressed a broad spectrum of issues. Numerous static and dynamic tests of URM walls for out-of-plane and in-plane motions were conducted, and a few studies have addressed the effect of floor diaphragms on seismic response. The proposed models for the study of URM structures are numerous, ranging from simple hand calculation methods to finite-element analyses using specialized elements. While a rational basis underlies all models, many of the newer theories remain controversial. Much research is needed to identify the reliability and range of applicability of each suggested model.

9. REFERENCES

Over 100 references were consulted for this work. Obviously, their unabridged presentation is impossible herein. The few sources following proved key in formulating the above conclusions. The writers would most welcome any submission from researchers whose work is pertinent.

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