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Effect of in-plane damage on out-of-plane strength of unreinforced masonry walls

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ABSTRACT

The out-of-plane capacity of unreinforced masonry (URM) walls is crucial for their overall stability and safety, especially after being damaged by in-plane forces. A nonlinear finite element model was developed to investigate the behavior of load bearing URM walls having different slenderness ratio and aspect ratio under combined in-plane and out-of-plane loading. The walls were subjected to sequence of cyclic in-plane drifts and monotonically increasing out-of-plane pressure and reduction in out-of-plane capacity due to in-plane damage was estimated. The reduction was larger for walls having slenderness ratio and aspect ratio greater than 20 and 2.0, respectively. Under severe in-plane damage, the out-of-plane capacity of cracked URM wall reduced to nearly one-third of its undamaged capacity. Fragility curves were generated to predict the probability of out-of-plane failure of URM walls with prior in-plane damage. These curves can be used to evaluate the vulnerability of URM walls in out-of-plane direction for expected in-plane damage corresponding to a specified performance level.

1. Introduction

Several reports of past earthquakes have identified the out-of-plane collapse of the URM wall as one of the predominant modes of failure [1,2]. During a seismic event, URM walls experience loading simultaneously in both in-plane and out-of-plane directions. However, the relative magnitude of loading depends on the type of diaphragm (rigid or flexible), its connection to walls, etc. Out-of-plane capacity of the URM wall panels may be significantly affected by the prior in-plane damage, which could be crucial to the stability of the walls as indicated in various past experimental and analytical studies [3–6]. Past studies mostly evaluated behavior of infill URM walls under combined loading; however, similar studies for load bearing URM walls are scarce.

A large inventory of URM walls are load bearing type and their behavior under combined in-plane and out-of-plane loading is crucial to the overall safety of the masonry buildings. Also, the behavior of URM walls under such extreme loading condition for a wide range of geometric properties like slenderness ratio (ratio of height and thickness of the wall, h/t) and aspect ratio (ratio of length and height of the wall, l/h) requires detailed investigation. Hence, damage assessment of URM walls under combined loading is important for any seismic risk mitigation program. Seismic mitigation methodologies employ fragility curves to estimate the probability of exceeding a certain damage level as function of hazard parameters like peak ground acceleration (PGA), spectral acceleration, etc. Fragility analysis also helps in making informed decisions while designing a new building or evaluating a damaged building.

This study focuses on further increasing the knowledge regarding the out-of-plane behavior of URM walls with prior in-plane damage. The main objectives of the study are:

- develop a simplified finite element model which can be used to study out-of-plane and in-plane force–deformation behavior of load bearing URM walls,
- generate interaction curves for the URM walls of different slenderness ratios and aspect ratios to evaluate their out-of-plane capacity for varying degree of in-plane damage, and
- integrate in-plane and out-of-plane damage to generate fragility curves for vulnerability assessment of URM walls.

Though the out-of-plane stability of URM walls under seismic loading is a dynamic problem, this study will treat the behavior in a simplistic manner by applying monotonically increasing out-of-plane pressure.

2. Finite element modeling

Many simplified analytical models for in-plane analysis of masonry walls were obtained by decomposing them into equivalent beams and columns with distributed elasticity [7,8]. Similarly, there are models to analyze the behavior of walls in the out-of-plane direction which use non-linear springs to represent the

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out-of-plane strength and stiffness [9]. However, these simplified models were not capable of simulating the effects of prior in-plane damage on out-of-plane capacity of URM walls. In finite element analysis, shell elements have been found sufficiently accurate in simulating the behavior of URM walls [10–12]. Hence, for this study masonry walls were represented using the 3D deformable shell element (Type S4R) available in finite element program Abaqus [13].

2.1. Material model

Masonry is an anisotropic and highly non-linear material and it exhibits complex behavior under combined action of forces due to the presence of mortar joints which act as planes of discontinuity. Thus, for exact simulation of its behavior sophisticated modeling techniques, such as, micro-modeling will be required [14]. Although micro-modeling can provide accurate simulation but it consumes plenty of resources and requires a detailed experimental study to define large number of material parameters such as friction angle, cohesive strength and joint stiffness. It has been observed from literature that simplified constitutive models, such as concrete smeared cracking and damaged plasticity model, developed for quasi-brittle materials were able to correctly predict the global behavior of masonry structural elements [15,16]. These constitutive models are based on simple yield surface with associated or non-associated flow rule and use scalar damaged elasticity to account for cracking. In the present study, macro-modeling strategy was employed to model the masonry

The Concrete Damaged Plasticity (CDP) model in Abaqus was used to simulate the inelastic behavior of masonry. The model uses the concepts of isotropic damaged elasticity in combination with isotropic tensile and compressive plasticity to represent the inelastic behavior. The CDP model is based on the non-associated flow rule and provides necessary control to dilatancy in modeling friction and quasi-brittle materials [17,18]. The dilatancy in this model is controlled by the parameter 'dilation angle' in the plastic potential function. The value of dilation angle as 30° was found to be appropriate and was able to generate masonry behavior close to experimental results.

A constitutive model proposed by Kaushik et al. (2006) was implemented to represent the compression behavior of masonry [19]. It was proposed that compression response can be broken down into two parts; the ascending parabolic part followed by the linear degrading part and each can be represented by an analytical formulation as given in Fig. 1a. A simplified tri-linear curve was used to define the tensile behavior of masonry and the strain corresponding to peak tensile strength was assumed as 0.0001 [20]. The post-peak behavior was approximated by a straight line up to the strain value of 0.008 and minimum stress of 0.02 MPa as shown in Fig. 1b. These values were chosen to provide smooth strength degradation necessary for convergence of finite element analysis [21].

Other material properties required for CDP model were taken as default values: flow potential eccentricity = 0.1, ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress = 1.16, ratio of second stress invariant = 0.667, and viscosity parameter = 0.0.

2.2. Damage parameter

Amongst the parameters required for modeling, a *damage parameter* should be carefully defined to simulate the post-peak behavior of URM walls. Damage parameter is required to simulate the loss of stiffness due to repeated loading. The stiffness degradation can be accurately modeled by the pivot rule proposed by Park et al. (1987) for beams and columns in terms of moment and curvature relationship [22]. The same rule can be extended to stress–strain regime to calculate damage parameter for tension, d_t and compression behavior, d_c. According to this rule all the unloading branches target a pivot point on the initial elastic branch at a distance of $\alpha_s\,\sigma_{peak}$ on the opposite side of the curve (Fig. 2).

On comparing the relation provided by Park et al. (1987) with the definition in Abaqus analysis manual, the following relation given by Eq. (1) was obtained for the damage parameters.

$$d_{t/c} = 1 - \frac{\sigma_{curr} + \alpha_s \sigma_{peak}}{E_o \varepsilon_{curr} + \alpha_s \sigma_{peak}} \tag{1}$$

where E_o is the initial elastic modulus, α_s = modulus degradation parameter, σ_{curr} = current stress, σ_{peak} = peak compressive stress and ε_{curr} = current strain. Kunnath et al. (1990) reported that for well-detailed RC masonry infilled frames the value of α_s ranges between 2 and 4 [23]. For URM no particular value of α_s is reported in the literature. However, after investigating the results for various values of α_s in the present study, it was found that $\alpha_s = 2$ suitably models stiffness degradation.

2.3. Stiffness recovery

Cyclic loading may involve formation of new cracks in each cycle as well as closing and opening of the previously formed cracks. It has been observed that stiffness recovery takes place as the load changes sign during a uniaxial cyclic test. Abaqus gives user the flexibility to define the amount of stiffness recovery by specifying the value of parameters, w_t and w_c which correspond to tension and compression stiffness recovery, respectively. Experimentally it has been found that in most quasi-brittle material, including

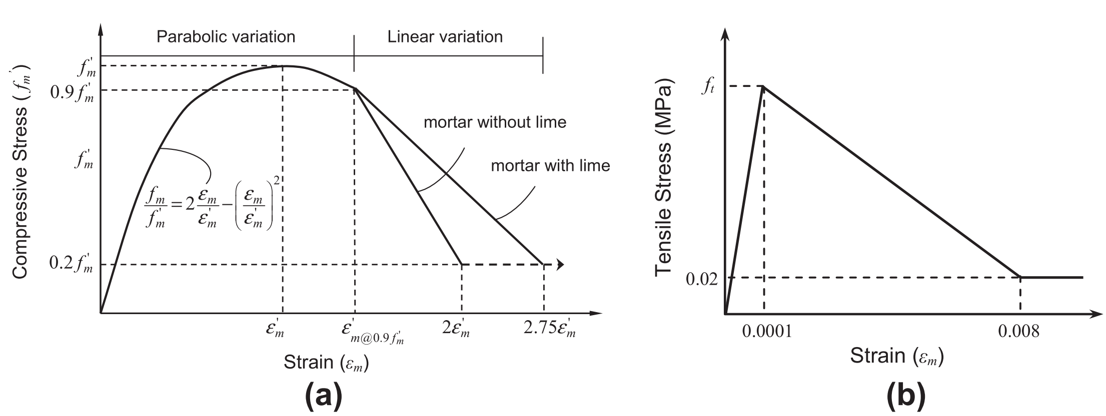

Fig. 1. Constitutive law used for masonry in (a) compression and (b) tension.