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Cyclic lateral load behavior of squat reinforced concrete walls

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ABSTRACT

The level of existing research, as well as current code provisions and modeling approaches, are not adequate to characterize the behavior of squat reinforced concrete walls with shear – controlled responses. In this study, an experimental program was conducted to investigate the shear-dominated response attributes of eleven squat wall specimens; including their failure mode, lateral load capacity, ductility, hysteretic response characteristics, and deformation characteristics. Test parameters included the wall aspect ratio, the amounts of vertical and horizontal web reinforcement and longitudinal boundary reinforcement, and the level of axial load. The experimental findings are presented and discussed in this paper, with emphasis on the observed failure mode, shear strength, deformation capacity, and strength degradation characteristics of the walls tested, as well as the contribution of shear, flexural, and sliding deformations to wall lateral displacements. Comparison of the test results with backbone curves specified in performance assessment guidelines is also provided.

1. Introduction

Structural walls are widely used for improved seismic performance of reinforced concrete building structures, and are commonly designed to experience ductile flexural yielding under severe earthquakes [1]. Properly designed and detailed structural walls possess the necessary strength, stiffness, and ductility characteristics to ensure life-safety performance in a building subjected to a design-level earthquake, and to minimize damage on the structure during a service-level earthquake. An adequate design of a slender reinforced concrete structural wall requires that wall shear failure does not occur and the wall experiences a ductile flexural response under seismic excitations. However, this may not be achieved when the structural wall is relatively short, and its response is governed by shear deformations. Such walls with aspect ratios smaller than 1.5 can be used in the seismic design of low-rise buildings such as parking structures, or buildings with perimeter walls where the perimeter wall has large window openings which results in formation of squat horizontal and vertical wall segments between the openings [2].

The targeted behavior and failure mode of a well-detailed structural wall is, as aforementioned, usually flexure-controlled. However, depending on different attributes including wall geometry and aspect ratio, web and boundary reinforcement characteristics, and loading conditions, squat walls generally experience one of the three typical mode of failures: diagonal tension, diagonal compression or sliding shear [1]. Fig. 1 shows representative damage patterns for the three failure modes observed in squat walls. The diagonal tension failure mode (Fig. 1(a)) will occur whenever the transverse reinforcement amount is insufficient to carry the shear forces, or is inadequately anchored. When adequate transverse reinforcement is provided, but the wall is subjected to a high shear stress, concrete may crush under diagonal compression (Fig. 1(b)). Finally, for walls with adequate transverse reinforcement but low quantities of longitudinal reinforcement in the web, failure can be due to yielding of longitudinal reinforcement followed by growth and widening of interface cracks, leading to a sliding deformation along the base of the wall (Fig. 1(c)). This last failure mode is particularly important for walls subjected to cyclic displacement reversals.

Most of the early research on squat walls has focused on their stiffness and lateral load capacity, without characterizing other important response attributes such as shear ductility or strength degradation after capacity is reached. Some researchers [3–5] have developed empirical equations for design parameters of squat walls using test data, and others [6] have developed behavioral models that use basic principles of mechanics in order to estimate their lateral load capacity. Benjamin and Williams [7] conducted one of the pioneering experimental research studies on monotonic testing of low-rise walls with openings, for characterizing their lateral load capacity and different failure modes. Cardenas et al. [3] investigated the strength and load–deformation characteristics of walls in both high- and low-rise

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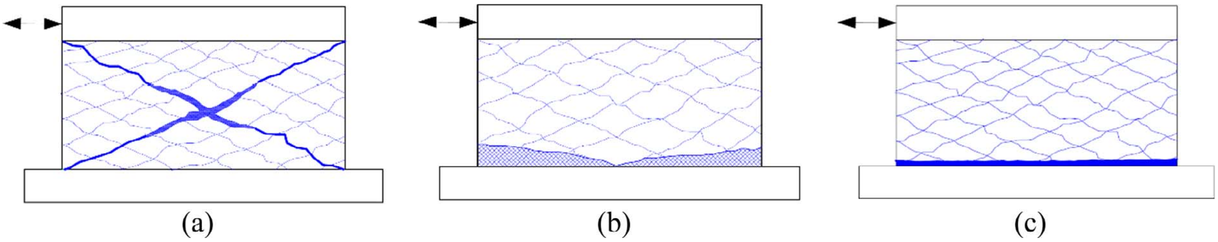

Fig. 1. Failure modes of squat walls: (a) Diagonal tension, (b) Diagonal compression, and (c) Sliding shear.

buildings. Another experimental study by Cardenas et al. [8] on low-rise walls with 1.0 aspect ratio and no boundary elements showed that the amount and distribution of web reinforcement were the major parameters affecting their lateral strength. Barda et al. [4] showed that boundary elements enhanced the post–ultimate load carrying characteristics of squat walls, and also suggested that the specimens with aspect ratios of 1/2 and less, the horizontal reinforcement did not increase the shear strength, whereas horizontal reinforcement was effective for producing a distributed cracking pattern. Based on test results, Hidalgo et al. [9] drew conclusions on the shear strength and energy dissipation capacity of squat walls.

Other research has focused on developing rational design criteria for squat walls, via investigating the effect of different parameters on their behavior and failure modes. Lefas et al. [10] investigated the cause of wall failure and suggested that shear resistance of structural walls is associated with the compression zone rather than the tensile zone of the section. Later Salonikios et al. [11] explored the applicability of ACI 318 requirements for squat walls and reported that even walls with 1.0 aspect ratio can experience flexural failure when detailed properly.

In terms of characterization of the nonlinear response characteristics of squat walls for performance assessment, in the pioneering FEMA 356 Prestandard and Commentary for the Seismic Rehabilitation of Buildings [12], particular emphasis was placed on the estimation of the shear strength of squat structural walls or wall segments in existing buildings. Orakcal et al. [13] showed that the recommendations of FEMA 356 [12] incorporate deficiencies related to consideration of the influence of axial load, the number of curtains of web reinforcement, and the amount of longitudinal boundary reinforcement on assessment of the shear strength of lightly-reinforced squat wall segments. As well, very limited information was provided in FEMA 356 [12] on the lateral load versus deformation backbone relationships for shear-controlled walls or wall segments (e.g., wall piers and spandrels), to be used in the seismic performance evaluation (e.g., pushover analysis) of existing buildings. The FEMA 356 [12] methodology to determine the envelope curve from a cyclic experimental data was shown to potentially result in underestimation of the lateral load versus displacement response characteristics for squat walls. Massone [14] showed that the backbone relationships defined in FEMA 356 [12] incorporate deficiencies related to the initial stiffness and ductility of squat wall segments, as well as their shear strength under axial load. An alternative procedure was introduced by Massone [14], which provides better estimation of stiffness and ductility of squat structural walls, as well as better representation of their lateral load–displacement response attributes. Based on the experimental research conducted by Massone [14], modified backbone curves for shear-controlled walls were first introduced as part of ASCE 41/SEI – Supplement 1 and later adopted in ASCE 41-13 [15].

Recent building codes and performance assessment guidelines (e.g. ACI 318-14 [16], ASCE 41-13 [15]) place considerable emphasis on understanding the lateral strength, stiffness, and ductility characteristics of the individual structural members, as well as their nonlinear response attributes and the modeling parameters to be used in nonlinear analysis. Most of the limited amount of existing research on analytical modeling of the nonlinear behavior of shear-controlled walls approaches the problem using one of three alternative methodologies. The first approach is the estimation of wall shear strength using the strut-and-tie modeling approach [17,18], the second is modeling of the wall response using fiber-based or multiple-spring models [2,19] that consider shear-flexure interaction, and the third is utilizing the finite element modeling approach [20,21]. While all of these modeling approaches incorporate advantages as well as limitations of their own, they are not commonly used in design or performance assessment of buildings incorporating squat walls or shear-controlled wall segments, and are not available in widely-used commercial software for nonlinear analysis. Use of the backbone curves specified in ASCE 41-13 [15], together with the shear strength calculation prescribed in ACI 318-14 [16] is therefore the more common approach used in nonlinear analysis for performance assessment.

Overall, although extensive research has been conducted on the behavior and design of slender walls, available information on the behavior of squat walls with shear-controlled responses is limited. Also, strength calculations specified in design codes and backbone curves recommended in assessment/rehabilitation guidelines may not always provide realistic estimations of shear-controlled wall response. Based on these shortcomings, this experimental study was conducted for further investigating the shear-dominated lateral load behavior and failure modes of squat walls. Test observations on important wall response characteristics are presented in this paper. Comparison of test results with backbone curves specified in performance assessment guidelines is also provided.

2. Test program

2.1. Specimen properties

Six types of squat wall specimens, comprising a total of eleven specimens (Type 1: four specimens, Type 2: three specimens, Type 3: one specimen, Type 4: one specimen, Type 5: one specimen, and Type 6: one specimen) were tested at the Bogazici University Structural Engineering Laboratory, as part of a research project initiated at the University of Chile (BU/UCH test program). Three wall aspect ratios were considered: 0.33, 0.5 and 1.0. All wall specimens had 1500 mm (59 in.) length and 120 mm (4.7 in.) thickness, with varying heights to attain different aspect ratios. The specimens were differentiated by their web reinforcement ratio, aspect ratio, the amount of boundary reinforcement, and the compressive strength of concrete. Properties of the test specimens are presented in Table 1, along with their notation. The specimens are grouped in six types (T component of the name), where each specimen type has a specific aspect ratio and specific web and boundary reinforcement amounts. For each specimen of a specific type, there is a specimen number (S component of the name). The final number in the specimen name is only related to the sequence of testing, and will be dropped in further discussion. Two of the specimens of Type 1 were tested under constant axial load, and an additional code is incorporated in their name (N component of the name): Specimen T1-N5-S1 was tested under an axial load of approximately 5% of its axial load capacity ($5\%A_gf_c'$), whereas Specimen T1-N10-S1 was subjected to an axial load of approximately $10\%A_gf_c'$.