Engineering Structures 136 (2017) 511–522

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Scoring models for reinforced masonry shear wall maximum displacement prediction under seismic loads

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ARTICLE INFO

Article history:
Received 21 December 2015
Revised 15 December 2016
Accepted 20 December 2016

Keywords:
Shear wall
Multivariate analysis
Scoring model
Displacement-based design
Projection to latent structure

ABSTRACT

In the past decade, there has been an increased shift towards performance-based seismic design (PBSD) approaches to meet the requirements for the next generation of seismic codes worldwide. Displacement-based seismic design (DBSD) is key for implementing PBSD approaches as structural performance is typically linked to damage which in turn is associated with component displacements and deformations. Available reinforced masonry shear wall (RMSW) displacement prediction models in the literature are found to be unreliable when compared with published experimental results. This study outlines the use of a statistical multivariate analysis technique and applying it to develop a reliable model for the maximum displacement capacity prediction of RMSW systems. This approach is subsequently used to build scoring models based on an experimental database of 81 flexurally dominated RMSW tested under simulated seismic loads. The models are further utilized to investigate the influence of altering the wall design characteristics on their maximum displacement capacities. The developed models are considered a major step to facilitate DBSD codification of RMSW systems for the next generation of PBSD codes.

1. Introduction

Performance-based seismic design (PBSD) approaches attempt to quantify how components or systems are likely to preform, given a potential seismic hazard that they are likely to experience, considering uncertainties inherent in quantifying both the hazard and the component/system responses. A typical PBSD process starts with the selection of performance objectives [1,2]. Each performance objective indicates the acceptable risk of incurring specific damage levels, and the consequent losses as a result of this damage, conditional on a specified level of seismic hazard. Each level of damage, as a performance indicator, is typically predefined by the lateral drifts either at the top floor-level and/or inter-story drifts. Linkage between damage and displacement has been the motivation for the development of displacement-based seismic design methodologies [3–5].

Masonry systems are among the most common forms of construction in urban areas for low- and mid-rise buildings. In terms of potential seismic risk, there is a perception that masonry buildings in general possess low level of ductility and are particularly vulnerable under seismic events. This perception is attributed to the observed brittle nature of unreinforced masonry components and systems worldwide during seismic events. However, over the past decades, a large number of experimental studies has demonstrated the seismic performance capabilities enhancements of reinforced masonry shear walls in terms of displacement ductility and energy dissipation capabilities [6,7].

Displacement-based seismic design (DBSD) approaches focus on identifying target design displacement as such a displacement typically correspond to a specific damage/performance level. As such, displacement is the main design input in any DBSD procedure. DBSD also requires quantifying the secant stiffness corresponding to that target displacement as well as hysteretic damping and ductility level. Although outside the scope of the current study, predictive models for such parameters are also needed. Regardless of the procedure adopted for DBSD [8], it is necessary to develop and calibrate a displacement capacity model for the structural component and system under consideration. In this respect, several analytical models are proposed to predict the displacement capacity for RMSW with opening, squat wall, or confined masonry governed by shear failure [9–12]. Unlike available models for predicting reinforced *concrete* shear wall (RCSW) displacements, models to predict the displacements of reinforced *masonry* shear walls (RMSW) are scarce in literature. For flexurally-dominated rectangular cantilever RCSW where a plastic region is expected to formed at the interface region between the wall and the foundation, seven different models (Paulay and Priestly [13], Priestly et al. [14], Pangiotakos and Fradis [15], Euro Code 8 [16], Priestly et al. [17], Bohl

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http://dx.doi.org/10.1016/j.engstruct.2016.12.036
0141-0296/© 2016 Published by Elsevier Ltd.

Notation

A_g	gross cross sectional area of the wall (mm^2)
a_i	proposed model coefficient
d_b	diameter of flexural (vertical) reinforcement (mm)
E	error matrix for X data
F	error matrix for Y data
f'_c	concrete compressive strength (MPa)
f'_m	masonry compressive strength (MPa)
f_u	ultimate strength for reinforcement steel bars (MPa)
f_y	yield strength for reinforcement steel bars (MPa)
H_w	wall height (mm)
k	number of variables
L_p	equivalent plastic hinge length (mm)
L_w	wall length (mm)
P	axial compressive load (kN)
p_k	loading value for k variable associated with X data
Q^2	predictability/goodness of prediction measure
q_k	loading value for k variable associated with Y data
R^2X	goodness of fit associated with X data
R^2Y	goodness of fit associated with Y data
t_k	principal component score for k variable associated with X data
t_w	wall thickness (mm)
X	input data matrix
x'	standardized data matrix
u_k	principal component score for k variable associated with Y data
Y	output data matrix
α	$\left(1-\frac{P}{A_g f'_m}\right)$ axial load effect parameter
β	$\left(1-\frac{f_y \rho_{sh}}{f'_m}\right)$ shear reinforcement effect parameter
β_m	cracking angle outside the plastic hinge zone
β_k	regression coefficient
γ_n	shear strain at maximum strength
Δ_{fl}	flexural displacement (mm)
Δ_p	plastic displacement (mm)
Δ_{sh}	shear displacement (mm)
Δ_m	maximum lateral displacement (mm)
Δ_y	yield lateral displacement (mm)
ε_k	prediction error
ε_m	average axial strain
θ_p	plastic rotation
ρ_{sh}	ratio of horizontal wall reinforcement to A_g
ρ_v	ratio of vertical wall reinforcement to A_g
ϕ	curvature of the wall section (1/mm)
ϕ_p	plastic curvature of the wall section (1/mm)
ϕ_y	yield curvature of the wall section (1/mm)
ϕ_u	ultimate curvature of the wall section (1/mm)

and Adebar [18], and Kazaz [19]) have been proposed to predict wall displacement capacities. In addition to the above models, Siam et al. [20] considered also the model developed for RMSW by Shedid and El-Dakhakhni [21] and demonstrated that the maximum displacement predictions of all eight models were unreliable compared to available RMSW experimental database results. It was also found that current models do not account for the shear deformation component for flexurally dominated walls.

Therefore, it was deemed necessary to develop a model that can accurately predict wall displacement capacity taking into account its shear deformations. As such, the focus of the current study is to propose a wall displacement prediction model that accounts for both flexural and shear deformation mechanistic parameters with coefficient calibrated using Multivariate Data Analysis (MVDA) statistical tools. Subsequently, two approaches were used in MVDA: 1) principal component analysis (PCA); and 2) projection to latent structure (PLS) [22] using a database of RMSW containing 81 walls from different published studies as will be explained later.

2. Model parameters

As the level of seismic demand increases, RMSW experience increased deflections that might force the wall to respond in an inelastic manner. Because of the complex anisotropic nature of RMSW systems, four distinct failure modes or a combination thereof can occur: flexural, rocking, sliding, and diagonal shear. These four failure modes depend on the wall design parameters such as its cross-section configuration, reinforcement details and ratios, material characteristics, and boundary conditions. Rocking and sliding can be prevented with adequate detailing at the wall-foundation interface zone leaving the flexural and the diagonal shear as the two most common failure mechanisms.

2.1. Flexural deformation

For seismic design, RMSW are typically designed to fail in flexural to ensure a ductile response and effective energy dissipation during seismic events [23]. Flexural failure is typically characterized by tensile yielding of the vertical reinforcement, the formation of a plastic hinge zone and crushing of masonry units, grout, and mortar at wall toes [24]. Crushing is often accompanied by web splitting of the concrete masonry units [25]. At increased displacements, masonry unit face shell spalling and eventual crushing of grout column also occur in the toe regions followed by a possible buckling of the vertical reinforcement at the toe region [26]. Flexural wall behavior is typically negatively influenced by high vertical reinforcement ratios which correspond to decreased levels of drifts and ductility and can result in brittle failures [27]. In addition, flexural strength is enhanced with increased axial forces [28]. Other research studies have also indicated that walls with aspect ratio greater than 1.0 exhibit more flexural- than shear-dominated behavior [29]. In the event of vertical bar(s) pullout, additional wall lateral deformation may occur. Modern design codes however, do account for such undesirable effects by providing adequate anchorage and development length for seismic reinforcement within the foundation. In addition the effect of reinforcement strain penetration into the foundation [17] was shown to have a minimal influence on the overall wall deformation as compared to other contributing factors [18,30].

Under seismic loading, RMSW are typically assumed to act as cantilevers. In this configuration, top wall displacement corresponding to first yield of the outermost vertical reinforcement is defined as yield displacement which can be calculated by double integration of the curvature profile distribution along the wall height. To simplify the process, and in lieu of the double integration of the wall curvature profile, an equivalent idealized plastic hinge length is typically assumed using Eq. (1) [23]. Where curvature is assumed to be constant and equal to ultimate curvature ϕ_u along the equivalent plastic hinge length L_p.

$$\Delta_{fl} = \Delta_y + \Delta_p = \frac{H_w^2 \phi_y}{3} + (\phi_u - \phi_y) L_p (H_w - 0.5 L_p) \qquad (1)$$

where Δ_{fl} is the flexural displacement (which is equal to the summation of the yield displacement, Δ_y, and the plastic displacement, Δ_p); H_w is the wall height; and ϕ_y is the yield curvature.