Engineering Structures 142 (2017) 255–271

Contents lists available at ScienceDirect

Engineering Structures

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

Simplified approach to predict the flexural strength of self-centering masonry walls

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ARTICLE INFO

Article history:
Received 26 November 2016
Revised 9 January 2017
Accepted 23 March 2017
Available online 11 April 2017

Keywords:
Masonry
MSJC 2013
Shear strength
Flexural strength
Unbonded
In-plane
Post-tensioned wall

ABSTRACT

This paper develops a simplified design approach to predict the flexural strength of unbonded post-tensioned masonry walls. The accuracy of different flexural expressions was investigated according to experimental and finite element modelling results. Using an analytical model and considering the stress-strain relationships for unconfined and confined masonry, force displacement curves were developed for eleven tested walls, with and without confinement plates. The developed force–displacement procedure was able to predict the lateral strength, stiffness and post-peak degradation of the behavior of the tested walls. Using a similar analytical procedure, a parametric study was performed to obtain the force-displacement response of walls with different features and to investigate the effect of different parameters including axial stress ratio, length, height and thickness of the wall, on the compression zone length. Multivariate regression analysis was performed to develop an empirical equation to estimate the compression zone length in unbonded post-tensioned walls. According to the results, the wall length and axial stress ratio were found to be the most significant factors affecting the compression zone length. Depending on the configuration of the wall, the compression zone length varied between 6.7% to 28% of the wall length. The proposed equation for compression zone length was then incorporated into the flexural analysis of post-tensioned masonry walls and validated against experimental results and finite element results. Comparing the prediction from Masonry Standards Joint Committee, MSJC (2013), and the proposed method reveals that ignoring the elongation of PT bars in strength prediction resulted in a considerable underestimation of the strength. Using the non-iterative proposed approach significantly improved the prediction.

1. Introduction

Recent research has demonstrated that unbonded post-tensioned structural elements including concrete walls, concrete columns, and masonry walls can display high displacement levels while withstanding high levels of seismic loads. When an unbonded masonry wall (PT-MW) is subjected to a lateral in-plane load and the cracking moment is exceeded at the base of the wall, a single horizontal crack forms at the wall-foundation interface. The restoring nature of the post-tensioning (PT) force returns the wall back to its original vertical position and minimizes the residual displacement. This behavior is specifically favorable for structures which are designed for immediate occupancy performance levels. The rocking mechanism of PT-MWs results in plastic deformation concentrated at the toe of the wall which can be repaired with minimal cost [1–5].

To determine the in-plane flexural strength of an unbonded PT-MW, the level of stress developed in PT bars corresponding to the wall peak strength needs to be calculated. The stress developed in a PT bar is a function of the bar strain and hence the elongation of the bars. In bonded PT-MWs, the strain compatibility concept can be considered to determine the stress in the bars. For unbonded PT-MWs, the strain in the PT bar remains approximately constant along the length of the bar. Therefore, instead of the conventional strain compatibility equations used for strain calculations in structural elements having bonded reinforcement, displacement compatibility criteria need to be considered, in which the stress in the PT bars is a function of wall rotation and compression zone length. While the current approach of the Masonry Standards Joint Committee (MSJC 2013) [6] considers the stress increase in PT bars

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http://dx.doi.org/10.1016/j.engstruct.2017.03.050
0141-0296/

beyond initial post-tensioning for out-of-plane flexural strength prediction, it is not considered for in-plane flexural strength prediction. However, several experimental and finite element studies have shown that under lateral loads the post-tensioning force increased [3,4,7]. Recently, expressions have been proposed by different researchers for evaluating such post-tensioning force increases under in-plane loading [3] and out-of-plane loading [8]. The accuracy of the available expressions in predicting the in-plane strength of unbonded PT-MW needs to be examined before it can be adopted by the masonry codes.

The primary objectives of the research presented in this paper are:

- To investigate the accuracy of different expressions in predicting the in-plane flexural strength of unbonded PT-MWs based on experimental and finite element model results
- To elaborate on an existing procedure to obtain the lateral force-displacement response of unbonded PT-MWs.
- To develop simplified empirical equation to estimate the flexural strength of unbonded PT-MWs

2. Prediction of nominal flexural strength

This section reviews different expressions available in the literature to predict the flexural strength of PT-MWs. These expressions include MSJC 2013 [6] (no PT bar elongation assumed after initial post-tensioning) and methods A, B and C which are presented in the following.

2.1. Masonry standard joint committee (MSJC 2013)

MSJC 2013 uses Eqs. (1) and (2) to predict the flexural strength of PT-MWs,

$$M_n = (f_{se}A_{ps} + f_yA_s + N)\left(d - \frac{a}{2}\right) \tag{1}$$

$$a = \frac{f_{se}A_{ps} + f_yA_s + N}{0.8f'_m b} \tag{2}$$

where a is the depth of the equivalent compression zone, A_s is the area of conventional flexural reinforcement, f_y is the yield strength, f_{se} is the effective stress in the PT bar after immediate stress losses, A_{ps} is the area of the PT bar, N is the gravity load including the self-weight of the wall, f'_m is the compressive strength of masonry, b is the cross section width and d is the effective depth of the wall. The predicted lateral strength of PT-MWs using this flexural expression is equal to the nominal moment capacity, M_n, divided by the effective height, h_n.

The base shear capacity is the minimum strength obtained from the shear expression and the flexural expression. The shear capacity, according to MSJC 2013, of PT-MWs having no bonded steel can be calculated as follows:

$$V_n = min\begin{cases} 0.315A_n\sqrt{f'_m} & (a) \\ 2.07A_n & (b) \\ 0.621A_n + 0.45N & (c) \end{cases} \tag{3}$$

where A_n is the net cross sectional area of the wall.

In the flexural expression presented by MSJC 2013 (Eq. (1)), different locations of PT bars along the length of the wall are not considered. The equation was originally developed for out-of-plane loading in which the PT bars are usually located at the center of the wall, resulting in a single value of d. While acceptable for out-of-plane bending, for in-plane loading the equation is not able to account for the distribution of multiple PT bars along the length of the wall. Hence, Eqs. (1) and (2) need to be re-written as following:

$$M_n = \sum f_{psi}A_{psi}\left(d_i - \frac{a}{2}\right) + \sum f_yA_{sj}\left(d_j - \frac{a}{2}\right) + N\left(\frac{L_w}{2} - \frac{a}{2}\right) \tag{4}$$

$$a = \frac{\sum f_{psi}A_{psi} + \sum f_yA_{si} + N}{0.8f'_m b} \tag{5}$$

where L_w is the length of the wall in m, A_{sj}, d_j and f_y are the cross sectional area, the distance from the extreme compression fiber to the jth vertical bar, and the yield strength of conventional flexural reinforcement, respectively.

As mentioned, MSJC 2013 conservatively ignores the effect of the stress increment due to the elongation of PT bars, hence, $f_{ps} = f_{se}$. However, for out-of-plane bending of PT-MWs, Eq. (6) is considered by the MSJC 2013 to evaluate f_{ps},

$$f_{ps} = f_{se} + 0.03\left(\frac{E_{ps}d}{L_{ps}}\right)\left(1 - 1.56\frac{A_{ps}f_{ps} + N}{f'_m L_w d}\right) \quad \text{(Out-of-plane bending)} \tag{6}$$

where L_{ps} is the unbonded length and E_{ps} is the elastic modulus of PT bar.

2.2. Method A: out of plane expression

Ryu et al.[4] indicated that the out-of-plane expression of MSJC 2008 [9] can be also used to determine the flexural strength of walls loaded in-plane. The equation was proposed by Bean Popehn et al. [8] as a result of a series of test results and finite element models of PT-MWs loaded out-of-plane. However, the equation has been updated in the latest version of MSJC [6] (Eq. (6)). Moreover, to determine the in-plane flexural strength of PT-MWs having multiple post-tensioning bars, the ultimate stress in each PT bar needs to be calculated. Hence, to account for different locations of PT bars along the length of the wall, Eq. (6) can be re-written as follows,

$$f_{psi} = f_{se} + 0.03\left(\frac{E_{ps}d_i}{L_{ps}}\right)\left(1 - 1.56\frac{\sum A_{psi}f_{psi} + N}{f'_m L_w d_i}\right) \tag{7}$$

Eq. (7) can be solved iteratively for f_{psi}.

2.3. Method B: wight and Ingham's approach

Eq. (7) assumed constant rotation of PT-MWs of 0.03 rad (or drift of 0.03). However, it has been reported that rotations of walls at the peak strength is not constant and is a function of the configuration of the wall, aspect ratio, and axial stress ratio, f_m/f'_m, where f_m is defined using Eq. (9).Using experimental results and finite element models, Wight and Ingham [3] proposed Eq. (8) to estimate the peak tendon force:

$$f_{ps} = f_{se} + \frac{E_{ps}}{L_{ps}}\theta\left(d_i - \frac{f_m L_w}{\alpha\beta f'_m}\right) \tag{8}$$

where

$$f_m = \frac{f_{se}A_{ps} + N}{L_w t_w} \tag{9}$$

$$\theta = \frac{\left(\frac{h_w}{L_w}\right)\varepsilon_{mu}}{30\left(\frac{f_m}{f'_m}\right)} \tag{10}$$