Engineering Structures 173 (2018) 960–978

Contents lists available at ScienceDirect

Engineering Structures

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

Experimental assessment of the in-plane/out-of-plane interaction in unreinforced masonry infill walls

Paolo Ricci, Mariano Di Domenico*, Gerardo M. Verderame

Department of Structures for Engineering and Architecture, University of Naples Federico II, Via Claudio, 21 – 80125 – Naples, Italy

ARTICLE INFO

Keywords:
URM infill wall
Out-of-plane
Experimental
In-plane/out-of-plane interaction
Out-of-plane strength
Out-of-plane response

ABSTRACT

During earthquakes, unreinforced masonry (URM) infills are subjected to in-plane (IP) and out-of-plane (OOP) actions. Displacement demands in the IP direction affect the OOP response to seismic accelerations and vice versa: this phenomenon is called IP/OOP interaction. In this study, experimental tests aimed at investigating the IP action effects on the OOP response of thin URM infills are presented. Three URM infills in reinforced concrete frames are first cyclically loaded in-plane up to three different drift levels. Then, on each test specimen, monotonic OOP tests are performed. Tests' results are compared to the pure OOP response of an IP-undamaged reference specimen. For each specimen, the evolution of cracking pattern during the IP and the successive OOP test is presented and discussed. Data concerning the variation of secant stiffness and force at first OOP macro-cracking and at peak load due to the increasing IP damage are presented. Based also on experimental tests presented in the literature, empirical relationships relating the reduction of force and secant stiffness at first macro-cracking and peak load due to the IP damage to the maximum interstorey drift ratio attained during IP tests are proposed. Finally, some considerations concerning the different post-peak behaviour, up to collapse displacement, of IP-undamaged and IP-damaged infills are reported.

1. Introduction

Past and recent earthquakes showed the negative consequences of the out-of-plane (OOP) collapse of unreinforced masonry (URM) infill walls in terms of both economic losses and human life safety protection [1–4]. For these reasons, a growing interest on the OOP behaviour of URM infills is currently arising in the seismic and structural engineering community. In fact, even if less studied than the in-plane (IP) behaviour, an increasing number of numerical and experimental studies focused on the pure OOP behaviour of URM infills is proposed in recent literature. Even less studied in the past than the pure OOP behaviour of infills is the IP/OOP interaction, i.e., the effects of previous damage due to IP displacement demands on the OOP response of infills and vice versa. This is a crucial issue, given that infills are subjected, during earthquakes, to combined IP and OOP actions and that IP damage promotes and facilitates their OOP collapse.

In this research paper, experimental tests carried out at the Department of Structures for Engineering and Architecture of the University of Naples Federico II aimed at investigating the IP damage effects on the OOP response of thin URM infills are presented. A reference specimen, named OOP_4E, was tested only in the OOP direction. In addition, three specimens, nominally identical to the reference one for geometric and mechanical properties, are first cyclically tested in the IP direction up to three different nominal drift levels (0.20% for test specimen IP + OOP_L, 0.40% for test specimen IP + OOP_M and 0.60% for test specimen IP + OOP_H) and then monotonically tested in the OOP direction. An IP cyclic test on the bare RC frame is also performed.

The IP and the OOP response of each test specimen is herein described with the support of cracking patterns evolution during IP and OOP tests. Then, the OOP response of the IP-damaged test specimens is compared to that exhibited by the IP-undamaged reference specimen OOP_4E in terms of secant stiffness and force variation at first OOP macro-cracking and peak load. Stiffness and strength degradation due to IP/OOP interaction observed in this study is compared with the results of similar experimental tests presented in the literature.

Empirical formulations for the prediction of secant stiffness and strength degradation at first macro-cracking and at peak load are proposed. Moreover, some considerations concerning the variation of the OOP post-peak behaviour and collapse displacement due to the IP damage are presented and discussed.

* Corresponding author.
E-mail addresses: paolo.ricci@unina.it (P. Ricci), mariano.didomenico@unina.it (M. Di Domenico), verderam@unina.it (G.M. Verderame).

https://doi.org/10.1016/j.engstruct.2018.07.033
Received 4 August 2017; Received in revised form 7 June 2018; Accepted 11 July 2018

Nomenclature

d_{IP}	IP displacement of test specimens at the upper beam end opposite to the loaded end
d_{OOP}	OOP displacement of the infill centre
E_m	masonry elastic modulus
F_{crack}	force at first OOP macro-cracking of the infill wall
F_{IP}	IP force
F_{max}	OOP strength of the infill wall
F_{OOP}	OOP force
f_b	brick compressive strength
f_{cm}	concrete mean compressive strength
f_j	mortar mean compressive strength
f_m	masonry mean compressive strength
f_t	masonry mean tensile strength
f_{ym}	reinforcement steel mean yielding stress
G	masonry mean shear modulus
h	infill height
IDR	interstorey drift ratio
IDR_u	interstorey drift ratio at the complete IP resistance loss of the infill
K_{crack}	OOP secant stiffness at first infill macro-cracking
K_{deg}	absolute value of the OOP softening stiffness
K_{max}	OOP secant stiffness at the infill peak load
R	OOP strength reduction factor due to IP damage
R_1	OOP strength reduction factor due to IP damage according to Angel et al.
t	infill thickness
w	infill width

Subscripts

dam	referred to the IP-damaged infill
undam	referred to the IP-undamaged infill
h	referred to the horizontal direction in the infill plane
v	referred to the vertical direction in the infill plane

2. Literature formulations for IP/OOP interaction effects modelling

An OOP strength model accounting for IP/OOP interaction was proposed by Angel et al. [5,6] based on experimental data. In this case, the pure OOP resistance of the undamaged infill is reduced using an R_1 factor that will be called R in this paper. R is expressed as a function of the infill height (h) over thickness (t), h/t, slenderness ratio and of the maximum IP interstorey drift ratio (IDR) attained normalized with respect to the IP drift corresponding to the infill IP first visible cracking (IDR_{crack}), as reported in Eq. (1).

$$R=\begin{cases} 1 & \frac{IDR}{2IDR_{crack}}<0.5 \\ [1.08+(h/t)(-0.015+(h/t)(-0.00049+0.000013(h/t)))]^{\frac{IDR}{2IDR_{crack}}} & \frac{IDR}{2IDR_{crack}}\geqslant 0.5 \end{cases} \quad (1)$$

OOP strength reduces at increasing IP displacement and reduces faster for higher slenderness values, as intuitively expected. Angel et al.'s complete formulation [5,6] was included in FEMA306 U.S. standard [7], while FEMA356 [8] and ASCE SEI 41-13 [9] provided a simplified OOP strength formulation assuming a "flat" OOP strength degradation due to IP damage equal to 24% (Flanagan and Bennett, [10]), independently of the effective IP demand and the infill slenderness. A similar approach is adopted in the new guidelines to the seismic assessment of existing buildings currently applied in New Zealand [11]. In that code, an OOP strength reduction factor named γ, that will be called R in this paper, obtained through the linearization of Angel et al.'s R factor [5,6] depending only on the infill slenderness and calculated for an IP displacement equal to two times the IP displacement at first cracking is proposed, as reported in Eq. (2).

$$R=\min\left(1.1\left(1-\frac{h/t}{55}\right);1\right) \quad (2)$$

Morandi et al. [12], based on Calvi and Bolognini's tests [13], proposed empirical stepwise (Eq. (3)) and linear (Eq. (4)) formulations for the calculation of the OOP strength reduction factor due to IP damage. In the stepwise formulation, the onset of IP/OOP interaction effects on the OOP strength for thin infills is set corresponding to an IDR equal to 0.30%, which is the threshold IDR for infilled RC buildings at the attainment of Damage Limitation Limit State according to the Italian building code NTC2008 [14].

$$R=\begin{bmatrix} 1.00 & IDR\leqslant 0.30\% \\ 0.20 & 0.30\%<IDR\leqslant 1.00\% \\ 0 & IDR>1.00\% \end{bmatrix} \quad (3)$$

$$R=\begin{bmatrix} 1-2.67IDR & IDR\leqslant 0.30\% \\ 0.20 & 0.30\%<IDR\leqslant 1.00\% \\ 0 & IDR>1.00\% \end{bmatrix} \quad (4)$$

Based on Guidi et al.'s tests [15] on unreinforced masonry strong and thick infills, Verlato et al. [16] proposed an empirical relationship for the evaluation of the R factor. Such relationship is reported in Eq. (5).

$$R=\begin{bmatrix} 1-0.86IDR & IDR\leqslant 0.70\% \\ 0.40 & 0.70\%<IDR\leqslant 1.20\% \\ 0 & IDR>1.20\% \end{bmatrix} \quad (5)$$

Ricci et al. [17], based on experimental data, proposed empirical relationships aimed at predicting the OOP secant stiffness and force at first macro-cracking and at peak load variation due to the IP displacement demand. The IP displacement demand is represented by the maximum interstorey drift ratio normalized to the IDR corresponding to the complete loss of IP load-bearing capacity, IDR_u, as reported in Eq. (6), which is dedicated to the prediction of the OOP strength reduction factor R.

$$R=0.27\left(\frac{IDR}{IDR_u}\right)^{-0.37} \quad (6)$$

Specific indications relating the OOP collapse displacement variation due to IP damage to the maximum IP displacement normalized with respect to the IP collapse displacement are provided by Kadysiewki and Mosalam [18], Furtado et al. [19] and Ricci et al. [17]. URM infill wall models accounting for the infill OOP behaviour and for the IP/OOP interaction were proposed by Hashemi and Mosalam [20], Kadysiewski and Mosalam [18], Mosalam and Günay [21], Furtado et al. [19], Shing et al. [22], Oliaee and Magenes [23], Asteris et al. [24], Ricci et al. [17], Di Trapani et al. [25].

3. Experimental state-of-the-art

In this section, previous experimental tests carried out to investigate the IP/OOP interaction in URM infill walls are described.

Angel et al. [5] tested 1:2 scaled 22 infilled RC frames. All tests were performed in displacement control up to the attainment of an OOP central displacement equal to the 3% of the infill height by applying an uniformly distributed load on the infill surface. Solid clay bricks and concrete masonry units infills were tested. The experimental program was aimed at evaluating the IP/OOP interaction effects on URM infills and on infills repaired or reinforced by using different strengthening techniques. With reference to URM infills made with solid clay bricks,