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Review

Out-of-plane behavior of masonry infilled RC frames based on the experimental tests available: A systematic review

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HIGHLIGHTS

- A systematic review of out-of-plane behavior of infill walls out-of-plane is presented.
- Comparisons were drawn between the specimens to assess the impact on the panel response.
- Empirical relationships were proposed to predict the infill panels OOP capacity.

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ABSTRACT

The primary objective of this manuscript is to present a systematic review of experimental studies regarding infill masonry walls out-of-plane (OOP) behaviour. An extended database was built containing information from each experimental campaign and specimen tested. Parameters such as geometric dimensions, material and mechanical properties, test setups and loading protocols and test results were collected. A systematic review methodology s conducted with the aim of filter the more relevant work in this field. For the analysis of each parameter in the infill wall OOP performance, three different groups were defined: as built specimens, specimens with previous in-plane damage and retrofitted specimens. Comparisons were drawn between the specimens of each group to assess the impact of those parameters on the panel response. Empirical relationships were proposed to predict the infill panels OOP capacity according to the aspect ratio, panel slenderness, percentage of masonry units' voids, masonry properties and previous in-plane drift. The results demonstrated that previous damage caused by in-plane tests that reached a maximum drift until 1.25% can reduce about 70% the OOP capacity of the panel, changing the failure mode of the panel that can result in fragile collapses. It was also observed that the parallel flexural strength parallel to the horizontal bed joints can increase the panel OOP maximum strength until 5 times.

Contents

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Nomenclature

$F_{0.15Fmax}$	Strength during the increasing phase corresponding to 15% of the maximum strength
$F_{0.30Fmax}$	Strength during the increasing phase corresponding to 15% of the maximum strength
F_{max}	Maximum strength
$F_{0.80Fmax}$	Strength during the decreasing phase corresponding to 80% of the maximum strength
F_{ult}	Ultimate strength reached by the panel
F_{crack}	Strength reached by the panel at the formation of the first visible crack
$K_{crack,sec}$	Secant cracking stiffness
K_{sec}	Secant stiffness
$K_{ult,sec}$	Secant ultimate stiffness
H_p	Panel Height
W_p	Panel Width
t	Panel thickness
f_{mo}	Mortar compressive strength
$f_{t,mo}$	Mortar flexural strength
$f_{b,parallel}$	Masonry unit compressive strength parallel to the holes direction
$f_{b,perpendicular}$	Masonry unit compressive strength perpendicular to the holes direction
f_m	Masonry compressive strength
E_m	Masonry elasticity modulus
$f_{b,para}$	Masonry flexural strength parallel to the horizontal bed joints
$f_{b,perp}$	Masonry flexural strength perpendicular to the horizontal bed joints
f_t	Masonry diagonal tensile strength

1. Introduction

The infill masonry walls are widely used for partition purposes and to provide also thermic and acoustic insulation to the reinforced concrete (RC) structures. Usually, the infill walls are considered non-structural elements and no special attention is given to them during the design process of new buildings and safety assessment of existing ones [34]. However, its poor performance was observed in recent earthquakes [18,19,35,41,77] and in particular their out-of-plane (OOP) vulnerability when subjected to transversal loadings resulted in innumerous of collapses/extensive damages that in general increased significantly the risk to the population and the rehabilitation' costs of the buildings. The risk associated to this type of failure can be greatly increased due to constructive details aspects commonly adopted in the Southern countries of the Europe, such for example no connection between the panel and the surrounding RC elements, no connection between the leafs (in the case of double-leaf infill masonry walls) and insufficient width support condition of the panel.

Some *in-situ* survey reports after the Lorca (Spain) earthquake in 2011 emphasyzed the deficient infill masonry seismic performance [64]. Some OOP collapses were reported, associated to insufficient support of the panels (Fig. 1). Many authors pointed that the abcense of proper connection between the frame structure and the infill masonry wall increase their OOP vulnerability, and not prevent their collapse . Recently, in 2016 after the Central Italy Earthquake similar damages were observed. Cracking and/or collapse of the facade masonry infill panels (usually at the lower stories). Reports of local damage in column members adjacent to the damage panels were also presented [26,51]. Some earthquake evidences described by several authors, which enanced the high number of infill masonry walls damaged and/or collapsed in other events such as the L'Aquila (Italy) earthquake in 2009 [76], the Gorkha (Nepal) earthquake in 2015 [10,35,75] for example.

Over the literature, it can be found test campaigns that were carried to study and characterize the infill panel OOP behaviour that fill steel and RC frames considering and not the interaction with the in-plane (IP) loading demand [4,11,13,16,17,27,32,31,36,38,37,40,52,56,58,61,60,66,73]. Some of the test campaigns were carried out through shaking table tests of simple IM panels or scaled infilled RC structures [15,21,45,46,48,69,71,78]. Some other numerical works were carried out during the last years with the goal of simulate the infill masonry walls non-linear seismic behaviour, such as IP and OOP [6–8,30,34,43,63,68].

The main aim of this manuscript is to present a systematic review of experimental tests that were performed to study the infill walls OOP behaviour. It will be pointed out the open challenges that are still lacking a deeper research and discussion. A systematic review methodology will be detailed and the list from the final group of works that will be studied within the framework of this manuscript will be presented. Similar databases were developed by different authors in the field mechanical modelling of existing masonry assemblages and earthquake performance of infilled frames, among others [9,44]. With this systematic review it was collected the following information from each parameter: panel geometries, slenderness, aspect ratio, masonry