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Cyclic out-of-plane behaviour of tall reinforced masonry walls under $P-\Delta$ effects

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ABSTRACT

On the basis of experimental and numerical results, this paper discusses the out-of-plane behaviour of tall load-bearing reinforced masonry walls in a large-displacement regime, under the influence of vertical loads ($P-\Delta$ effects). Reinforced masonry systems can be advantageous for erecting one-storey commercial and industrial buildings 6–8 m high. These structures are often provided with deformable roofs and, as a consequence, in case of seismic actions out-of-plane forces can be significant in the wall behaviour and can lead to the onset of second order effects. For this structural configuration, a special set-up for out-of-plane cyclic tests was designed and built, to assess experimentally two reinforced masonry systems, gather information on their structural behaviour, and calibrate moment–curvature relationships to be implemented in numerical models. These models allowed the test results to be extended to different dead loads, degrees of wall slenderness, and quantities of reinforcement. The research validated the effectiveness of such systems and identified some limitations and procedures for modelling and design.

1. Introduction

Developments in structural masonry have been driven towards systems which have faster and cheaper construction processes and are based on new types of unit, mortar and/or grout, and ancillary components or reinforcement [1]. Improvements for unreinforced masonry have focused on replacing traditional head and bed joints with new types of joints with faster assemblage and better thermal performance [2–5]. Concurrently, developments for reinforced and confined masonry have focused on solving the lack of tensile strength in masonry while significantly improving resistance, ductility and energy dissipation capacity [6–8]. The general aim is improving the in-plane behaviour of walls, as the basic principles of conceptual design of structures for earthquake resistance are based on box-type behaviour. With this assumption, horizontal seismic actions are transferred to walls parallel to load direction (Fig. 1(a); see also [9]).

Reinforced and post-tensioned masonry solutions have recently been proposed also for one-storey buildings, such as those for commercial and industrial purposes, as they can fulfil several functions, including structure, fire protection, thermal and sound insulation, weather protection, and proper sub-division of space [10]. For these types of constructions, reinforced load-bearing masonry walls, compared with other solutions including framed structures, ensure that controlled thermo-hygrometric conditions are respected, with no use of insulating or coating materials [1]. However, for such slender walls, the effects of transverse loads, such as wind loading, earth pressure, and inertial forces from seismic excitations, have been recognised as significant. In addition, in such types of buildings, roofs are very often built with deformable structures. Deformable diaphragms hardly transfer horizontal loads to in-plane walls, and out-of-plane forces affect walls perpendicular to the earthquake direction. Concurrently, orthogonal walls, which could constitute good support to out-of-plane deformations, provided their adequate connection, become ineffective, as they are mostly located at very large distances [11]. Hence, during seismic events, roofs may be considered as elastic restraints, with variable stiffness along the wall extension, and this can significantly increase the local out-of-plane displacements of walls (Fig. 1(b)). The out-of-plane response of walls becomes critical, as the large displacements which may occur at the top of these structures during earthquakes, introduce second-order effects ($P-\Delta$ effects) and problems due to instability.

In case of cantilever walls, fixed at the bottom and free to rotate at the top, the out-of-plane behaviour is dominated by vertical flexure. Prior to cracking, reinforced masonry walls behave as unreinforced walls. After initial cracking, wall stiffness decreases, but at the same time, vertical reinforcement starts to work and the walls continue to carry loads up to and beyond steel yielding. These walls exhibit good deflection, ductile failure, and good values of earthquake damping [12]. The flexural capacity of the

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