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Theoretical and experimental study on precast reinforced concrete wall panels subjected to shear force

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ABSTRACT

The paper presents the results of the first part of an experimental program developed to study the seismic performance of precast reinforced concrete wall panels with and without openings. The specimen characteristics and reinforcement configuration were taken from a typical Romanian project used widely since 1981 and scaled 1:1.2 due to the constraints imposed by the laboratory facilities. This type of precast wall panels was used mostly for residential buildings with multiple flats built from 1981 to 1989. The performance and failure mode of all of the panels tested revealed a shear type of failure that is influenced by the opening type, and critical areas and lack of reinforcement were observed in certain regions. A numerical analysis was performed to create a model that could predict the behaviour of the precast reinforced concrete shear walls of different parameters. The performed experimental tests stopped when the panels lost 20% of their load bearing capacity to be further repaired, strengthened post-damage and subsequently tested again. The precast reinforced concrete walls investigated in this study meet the requirements of Eurocode 8 for walls designed to DCM (medium ductility) as large, lightly reinforced walls.
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1. Introduction

A structural system composed of precast reinforced concrete shear walls can provide a good seismic performance of buildings. Because of both the 50 years of existence and the actual comfort requirements of buildings, the use of such a structural system requires upgrading. Because a significant number of buildings use such a system built in Romania and Eastern Europe, research studies on this type of structural system is strongly encouraged and required to evaluate the seismic performance, to investigate the cut-out effects produced in structural walls due to architectural changes in buildings and finally to improve the ductile behaviour of the walls and provide solutions for improved seismic performance of buildings. The design of the shear walls for buildings placed in seismic regions was made according to the design code of concrete structures, as well as by the design guidelines of buildings for earthquake resistance. Pavese and Bournas [1] investigated experimentally the behaviour of prefabricated reinforced concrete sandwich panels (RCSPs) under simulated seismic loading, with the tests being performed on single full-scale panels with or without openings. These researchers concluded that the presence of the openings on panels substantially reduced their lateral resistance and stiffness. In the presence of openings, the cumulative dissipated energy was lower than for those panels without openings, while substantial increases in the deformation capacity was recorded. Jiang and Kurama [2] performed an analytical investigation on the lateral load behaviour and retrofit of medium-rise RC shear walls. Among the conclusions, the researchers stated that providing confinement for walls that initially did not have concrete confinement in combination with the added transverse web reinforcement can result in a much higher lateral displacement capacity. Fragomeni et al. [3] tested forty-seven reinforced concrete walls with various opening configurations, with the tests being performed in both one-way and two-way action. The results of the tests indicated that the failure loads of two-way panels with openings were approximately two to four times those of similar one-way panels with openings. Wang et al. [4] performed two experimental tests of three-storied reinforced concrete structural walls having large openings. The results of the strength, stiffness, lateral load–drift angle relationship indicate that the proposed macro-model was more adequate. Orakcal et al. [5] conducted an experimental program to assess the shear strength requirements for lightly reinforced wall piers and spandrels used in mid-1900s building construction. Antoniades et al. [6] performed cyclic tests on seismically damaged low-slenderness reinforced concrete walls strengthened using Fibre-Reinforced Polymer Reinforcement. The testing of a pilot specimen that was only repaired in a conventional

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Nomenclature

PRCWP	precast reinforced concrete wall panel
α_s	aspect ratio
h_w	wall height
l_w	wall length
DCM	medium ductility class
7,8,10,11,12	number of specimens
E1	narrow door opening
E3	wide door opening
L1	narrow window opening
L1/L3	narrow window opening enlarged to a wide window opening
T	unstrengthened
A_s	cross sectional area of reinforcement
A_c	cross sectional area of concrete
$f_{cm,cube}$	mean concrete cubic strength
f_{ck}	characteristic cylinder strength of concrete
f_{cm}	mean value of concrete cylinder compressive strength
f_y	yield strength of reinforcement
f_u	ultimate strength of reinforcement
E_s	modulus of elasticity of steel reinforcement
M	bending resisting moment
V	lateral load
V_{exp}	experimental shear force
V_{th}	theoretical shear force
N	axial load
N_c	constant axial force
N_v	variable axial force
P	pressure transducer
D	displacement transducer
G	strain gauge
μ	displacement ductility coefficient
Δ_y	drift at yielding
Δ_u	drift at failure
CED	cumulative dissipated energy
ε	strain
$K_{sec,Ri}$	secant stiffness corresponding to the δ_i displacement amplitude (R_i drift ratio) on the monotonic load–displacement envelope
K_{nn}	normal stiffness
K_{tt}	tangential stiffness
f_t	tensile strength
c	cohesion
φ	friction coefficient
z	lever arm of internal forces
b_w	width of the cross section
x	neutral axis depth
d_N	distance between the axial force position and the centroid of the compressed reinforcement
$d_{1,2}$	distance between the reinforcement centroid position and the tensioned/compressed fibre of the section (on x-axis)
H_P	height of the wall pier
L_P	length of the wall pier

way revealed that strength was almost fully restored, but the stiffness and energy dissipation capacity were not restored. Li and Lim [7] investigated the results of an experimental study on the seismic performance of axially loaded reinforced concrete walls with boundary elements confined by limited transverse reinforcement. The results indicated the increased drift capacities of the strengthened walls. Greifenhagen and Lestuzzi [8] analysed four specimens with a focus on the shear dominated response of walls that are not designed for earthquake resistance. Compared to other tests from the literature for squat walls, the drift capacity depends on the axial force ratio, vertical reinforcement arrangement, and the degree of restraining at the top of the wall. Dazio et al. [9] performed quasi-static cyclic tests on six reinforced concrete (RC) walls and investigated the effect of different vertical reinforcement contents and different reinforcement ductility properties on the deformation behaviour of slender RC walls. The specimens exhibited a reduced deformation capacity of RC structural walls with low longitudinal reinforcement content. Thomson et al. [10] developed a simplified model for simulating the damage of squat RC shear walls under lateral loads based on damage and fracture mechanics, describing the reduction in stiffness and strength due to diagonal cracking, permanent deformations due to yielding of transverse reinforcement and sliding across shear cracks. Li and Chen [11] performed an analytical approach to determine the stiffness of six RC shear walls with irregular openings and validated the approach by comparing theoretical and experimental results. Simple equations were proposed to assess the initial stiffness of RC structural walls with irregular openings based on parametric case studies. Gebreyohaness et al. [12] developed a model to study the behaviour of non-ductile reinforced concrete walls subjected to earthquake-induced lateral forces. Dan et al. [13] performed a theoretical study and experimental tests on composite steel–concrete shear walls with steel encased profiles. The results indicated a more ductile behaviour in terms of displacement ductility than for the common reinforced concrete walls. Mosoarca [14] conducted a theoretical and experimental study on three types of walls with and without openings, investigating the failure mechanisms and explaining their failure modes based on the latest recordings of seismic wave characteristics. The behaviour of squat reinforced concrete structural walls is known to be controlled by shear, and their typical failure modes were also investigated by Paulay et al. [15], Sánchez-Alejandre and Alcocer [16] and others. “Reported failure modes of squat walls are associated with inclined web cracking, sliding along the wall base and crushing of web concrete” [16]. In addition to these failure modes, walls with openings also develop concrete crushing in the corners of the opening. The shear strength assessment of lightly reinforced wall pier and spandrels using code provisions was also evaluated by Orakcal et al. [5] according to ACI 318-05 [17] and FEMA 356 [18].

To investigate the behaviour of precast reinforced concrete walls, a theoretical and experimental program was developed in the Civil Engineering Department at the Politehnica University of Timisoara, Romania. In Eurocode 8, Part 1 [20], section 5, the walls with an aspect ratio ($\alpha_s = h_w/l_w$) of less than 1.5 are designated as large lightly reinforced walls, which should be designed to DCM (medium ductility). For this type of structural wall, the precast reinforced concrete wall panel (PRCWP) notation will be used in the following. In this paper, five specimens with openings, known as precast reinforced concrete wall panels, PRCWP (7–8 and 10–12), are proposed and tested. This phase of the experimental research program continued the previous phase, where six specimens, known as PRCWP (1–6), were investigated and presented by Demeter [19]. All of the specimens were designed with an initial opening. Specimen PRCWP 10 simulates an opening enlargement to investigate the cut-out effect. The variation of the wall parameters, such as concrete compressive strength, reinforcement ratio and opening type, allowed for the identification of the relevant failure modes and consideration of the shear strength and ultimate

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