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Experimental assessment of the seismic performance of a prefabricated concrete structural wall system

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ABSTRACT

In this study the authors investigated experimentally the behaviour of prefabricated reinforced concrete sandwich panels (RCSPs) under simulated seismic loading through a large experimental campaign. Tests were carried out on single full-scale panels with or without openings, simulating the behaviour of lateral resisting cantilever and fixed-end walls. Tests were also carried out on a 2-storey full-scale H-shaped structure constructed by individual panels which were properly joined together. The performance and failure mode of all panels tested revealed strong coupling between flexure and shear due to the squat-type geometry of the panels. However due to their well-detailed reinforcement, all panels exhibited only a relatively gradual strength and stiffness degradation and in no case did any panel suffer from sudden shear failure. The prefabricated walls of the structural system investigated herein seem to meet all the requirements of Eurocode 8 for walls to be designed as "large lightly reinforced walls"; however this assumption should be supported with further experimental and analytical studies.

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1. Introduction and background

Most current design codes of concrete buildings for earthquake resistance give lower values of the behaviour factor q for wall systems than for frame systems. This is attributed to a couple of reasons; shear walls have large cross-sectional length ℓ_w and thus shear plays a superior role in their seismic response and also the seismic behaviour of the wall systems is not so well known and understood because experimental and analytical research on walls is practically difficult; so design codes tend to be on the safe side. To make matters worse, when the seismic performance of structures incorporating precast or prefabricated concrete walls as the main lateral force resisting system is considered, this conservativeness may become higher for designers in the seismic prone countries. This has advocated the bad behaviour of the poorly designed and constructed precast connections which caused the use of precast concrete structures to be regarded with suspicion by a part of the structural engineer's community.

In contrast, after the excellent seismic performance of buildings with structural walls [2,3], in very strong earthquakes (e.g. in Chile, 1985 and Kocaeli, Turkey 1999), there is presently a tendency to acknowledge similar q-factor values for frame and wall systems. In addition, during the 1988 Armenia earthquake poorly designed and constructed buildings that incorporated precast concrete walls as the main lateral force resisting system performed substantially better than buildings built with other structural systems [4]. Although the use of precast structural walls in seismic areas of the world has proved to be a cost-effective way for lateral resistance of buildings, the largest part of structures is based on cast in place reinforced concrete. This could be partly attributed to the fact that the majority of the research on wall systems has been focused on the seismic behaviour of cast in place walls (e.g. [5–9]).

During the past decade or so, however, the research community has increasingly focused on the use of precast concrete walls as the primary lateral load resisting system in seismic regions (e.g. [10–15]). The precast concrete structural wall systems, which have been investigated up to date, are generally arranged to provide lateral force resistance by cantilevering from the foundation structure, through coupling with beams or other special devices and by rocking about their foundation. Moreover structural wall systems showing strong nonlinear response can be grouped into either equivalent monolithic or jointed systems. An analytic review of the precast structural wall systems can be found in a relatively recent bulletin of fib [16].

In this paper the seismic performance of a prefabricated equivalent monolithic structural system comprising large reinforced concrete sandwich panels (RCSPs) is investigated. Despite the fact that the use of prefabricated RCSPs (described in detail below) has been introduced in the construction industry for more

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Notation

The following symbols are used in this paper:

A_h	Area included in a single hysteretic loop
A_{sh}	Area of transverse steel reinforcement parallel to the loading direction s_h
b_w	Width of compression zone (taken equal to thickness of concrete (not EPS core), namely 70 mm)
f_c	Compressive strength of concrete (MPa)
f_{yw}	Yield stress of the transverse steel
h	Cross-section side parallel to the loading direction
F_m	Average value of the maximum load in a loading cycle
L_s/h	Shear span ratio at the section of maximum moment
s_h	Spacing of the transverse steel
a	Effectiveness factor for confinement by transverse reinforcement (EC8 [1])
$a_{cy} = 1$	For cyclic loading
$a_{sl} = 1$	If there is slip of the longitudinal bars from their anchorage beyond the section of maximum moment
a_{st}	Coefficient for the steel type equal to 0.0185 for hot-rolled steel
$a_{w,nr} = 1$	For walls with T, H, U or hollow rectangular section
$a_{w,r} = 1$	For rectangular walls
δ_m	Average value of the maximum displacement in a loading cycle
ξ_{eq}	Equivalent viscous damping ratio
ν	Normalised axial force (compression taken as positive)
ρ_d	Geometric ratio of diagonal reinforcement, if any
ρ_s	Ratio of transverse steel parallel to the direction of loading
ω_1	Mechanical reinforcement ratio of tension and "web" longitudinal reinforcement
ω_2	Mechanical reinforcement ratio of compression longitudinal reinforcement

than 40 years [17], they have been used in practice primarily as gravity load bearing structural elements (e.g. [18,19]). More recently, in the last decade, many companies from the international precast construction industry have started manufacturing RCSPs commercially with the aim of developing a quick, permanent and cost-effective building system which is supplemented with a satisfactory earthquake resistance. According to the major companies involved in panel construction, it is estimated that the construction cost of a (low-rise) residential building with prefabricated RCSPs is about 2/3 of an equivalent (framed, walled or mix-type) RC structure. The seismic performance of this structural system, which can be possibly qualified as "Large Lightly Reinforced Walls" according to Eurocode 8 (as explained later), has not been addressed up to date. The investigation of the seismic performance of prefabricated RCSPs, which still remains a challenging task, is addressed in this study for the first time in a systematic way through full-scale seismic testing.

In the present study the authors investigate experimentally the behaviour of prefabricated RCSPs under simulated seismic loading through a large experimental campaign. Tests are carried out both on single full-scale walls with or without openings, reproducing the behaviour of lateral load resisting cantilever and fixed-end walls, and on a 2-storey full-scale H-shaped structure constructed by individual panels which were properly joined together. In the latter case the seismic performance of a complete prefabricated structure including the connections between RCSPs was addressed. Another innovative aspect is the experimental investigation of a full-scale H-shaped structure consisting of more than one rectangular part. Such types of structures have high stiffness and strength in both horizontal directions, and despite the fact that they appear to be more cost effective than the combination of their constituent parts as individual rectangular walls, our knowledge of their behaviour under cyclic bending and shear is very limited.

2. Description of the structural system

2.1. Reinforced concrete sandwich panel (RCSP)

A reinforced concrete sandwich panel (RCSP) is composed of an Expanded Polystyrene (EPS) foam core with prefabricated galvanised steel wire mesh reinforcement encased in two layers of sprayed concrete on both sides, as shown in Fig. 1(a). The steel wire mesh of reinforcement mounted on each face of the polystyrene foam is drawn with hot galvanisation and consists of 2.5 mm and 3.5 mm diameter horizontal and longitudinal reinforcement, respectively, spaced at 65 mm; this gives a longitudinal reinforcement ratio of 0.42%, which is more than the minimum longitudinal reinforcement of 0.2% of the Eurocode. The connection between the two concrete layers through the core of the wall panel is secured with 3 mm diameter steel connectors welded to the front and back wire meshes through the polystyrene. These connectors ($\sim 80/m^2$) could be straight or inclined depending on the manufacturing plan. The uniform connection between the parts of the sandwich panel is also favoured by the surfaces of the polystyrene which have been initially corrugated. The panels considered in this study have depth and length of corrugation equal to 10 mm and 70 mm, respectively (Fig. 1(a)). In this way the assembly develops nearly full composite behaviour in stiffness and shear transfer.

Each type of steel wire mesh used (horizontal, longitudinal, connector ties) has a nominal yield stress of 600 MPa. The shotcrete has typically a thickness of 35 mm (also greater values could be considered) and a characteristic 28 days cube compressive strength higher than 25 MPa. It should be noted that in order to control shrinkage a fiber reinforced concrete could be used. Connection between the panels and the foundation or floor is made by means of starter steel bars projecting from the foundation (or floor) as shown in Fig. 1(b). In the present study, the transfer of the tensile forces from the panels to the foundation was made by 8 mm diameter deformed bars which were placed at distances of 300 mm. These bars had a yield stress of 550 MPa.

2.2. Lateral load resisting system

In a large panel system composed of prefabricated RCSPs, the wall and slab panels are connected in the vertical and horizontal directions so that the walls enclose appropriate spaces for the rooms within a building. The height of the panels is equal to the storey height while horizontal floor and roof panels span either as one-way or two-way slabs. When properly joined together, these horizontal elements act as diaphragms that transfer the lateral loads to the walls. All the walls are continuous throughout the building height. Joint system is developed such that all structural elements work together as a box-type system.

Panel connections represent the key structural components in this system. Based on their location within a building, these connections can be classified into vertical and horizontal joints. Vertical joints connect the vertical faces of adjoining wall panels and primarily resist vertical seismic shear forces. Horizontal joints connect the horizontal faces of the adjoining wall and floor panels and resist both gravity and seismic loads. Vertical and horizontal connections are accomplished by means of dowels

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