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Experimental investigation of the response of precast concrete cladding panels with integrated connections under monotonic and cyclic loading

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A B S T R A C T

One major issue in the design of precast structures against earthquakes is the importance of cladding connections on the overall response. In the present work, an experimental investigation on the monotonic and cyclic behaviour of fixed panel connections, also referred as 'integrated' connections, is reported. The extensive experimental program was performed at the Laboratory for Earthquake Engineering of the National Technical University of Athens, Greece, within the framework of the FP7 European project SAFECLADDING, and aimed at the investigation of the behaviour of several types of connections materialized with vertical reinforcement bars, referred as 'rebar' connections, or steel mechanisms of two types: 'wall shoe' and 'steel plate'. The results show that rebar and wall shoe connections can attain large ductility and strength, but with significant pinching for large lateral displacements, due to the plastic deformation of the connections' rods that can lead even to residual joint opening. When this happens, apart from the horizontal slip that can occur, the energy dissipated decreases, as evident from the corresponding normalized energy dissipation capacity curves of the tested specimens. The damage to the panels observed during the tests was generally limited, except of large drifts combined with strong connections, and the overall failure was determined by the failure of the connectors.

1. Introduction

For over one century, precast concrete is widely used as an alternative to the common cast in situ practice. Its growth has been based on enhanced features that it possesses, such as construction speed, high quality control, large spans covered (in combination with prestressing) etc., which have enabled the designers to create economically competitive structures. The exterior façade of precast buildings is often covered by precast panels offering protection from the weather conditions and freedom of architectural expression. The type of the façades depends, to a great extent, on the main structural system of the building. The description and classification of common façade systems can be found in several reports [1–6].

Quite commonly, the panels are not designed to participate in the gravity or the lateral load bearing resistance of the building and their connections are dimensioned to support only the panels' self-weight, wind loads and local seismic loads corresponding solely to their mass. Based on this approach, the current design practice of precast buildings is based on a bare frame model where the cladding panels are considered only as masses, while the frame is assumed to behave similarly to cast-in-situ structures, possessing comparable energy dissipation capacity.

However, experimental research conducted in the last decades [7–13] has shown that, quite often, the panels become an integral part of the resisting system conditioning its seismic response. As a result, the overall stiffness is increased leading to forces significantly higher than those calculated from the frame model. Furthermore, one cannot rely on energy dissipation within plastic hinges expected to develop in the columns, as the capacity of the connections between the cladding walls and the structure is usually exhausted well before the development of the required drifts for the formation of such plastic hinges. This inadequacy of the design of cladding panel connections has been known since the Alaska (1964) earthquake where considerable damage to cladding systems was reported; however, the problem was profoundly pronounced in recent earthquake events, like the L'Aquila (2009) [14] and the Emilia (2012) [15] earthquakes in Italy.

An alternative design that could solve this problem is to design the precast concrete cladding walls as load-bearing members. In such a structural system, herein referred as 'integrated', the panel walls' connections are designed to sustain the required seismic loads assuming that the nonlinear response at the wall-to-structure interface follows a pre-determined mechanism of nonlinear deformation. Buildings with wall systems complying with this criterion can be classified as jointed wall systems according to fib Bulletin 27 [3]. It is noted that the

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research that has been conducted so far on such wall systems [16–20] points out that, under cyclic loading, the ductility and energy dissipation capacity are decreased by the gap opening and the shear slip that occur at the joints.

Recently, thorough investigation on the seismic response of precast structures with cladding panels has been complemented within the FP7 European project "SAFECLADDING: Improved fastening systems of cladding wall panels of precast buildings in seismic zones", GA No. 314122. Innovative panel-to-structure connections and novel design approaches for a correct conception and dimensioning of the fastening systems have been investigated. Part of this research concerned the experimental investigation of the behaviour of panels with 'fixed' connections, designed to resist large seismic forces [21], which was conducted at the Laboratory for Earthquake Engineering of the National Technical University of Athens (NTUA), Greece. The main results of this experimental campaign are reported herein.

2. Integrated panel walls

2.1. Panel arrangements

In the integrated frame-panels systems, the panel connections are arranged with a hyperstatic set of 'fixed' supports. The term 'fixed' is used here interchangeably with the term 'pinned' and denotes connections with restrained displacements, while rotations are allowed.

Typically, vertical panels are used, connected to the beams at four points (Fig. 1a), the lower two corresponding to the connections with the bottom beam and the upper two to the connections with the top beam. With this arrangement, each panel acts as a vertical wall clamped at both ends. However, and in order to accommodate possible thermal expansion of the panel, the two upper fixed fastenings can be replaced by two vertically sliding connections; with this arrangement, each panel acts as a vertical cantilever beam clamped at its bottom and pinned at its top (Fig. 1b). For this reason, this arrangement will be denoted in the ensuing as panels with 'three' connections.

Horizontal panel arrangements can also be used, in which case the panels are connected to the columns. However, this arrangement is not recommended as the panels transfer large forces to the columns, capable to produce local damage. For this reason, the experimental campaign was limited to vertical panels only.

Several mechanisms can be used to materialize fixed panel-to-beam connections, such as simple connections made of protruding bars, which are referred as 'rebar' connections in the ensuing, or more sophisticated connections made of industrially produced or handmade steel mechanisms. The potential use of 'strong' connections to fasten cladding walls was the motive for the experimental investigation that was performed within the SAFECLADDING project, which included monotonic and cyclic tests on both types of connections and is presented in the following.

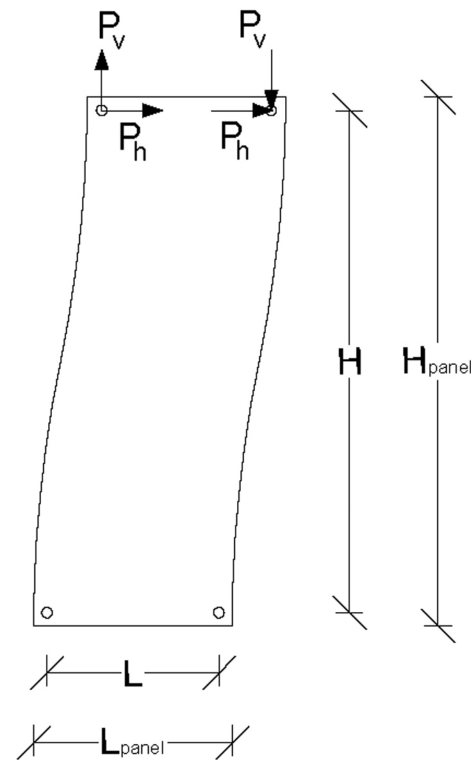

Fig. 2. Panels with four connections during seismic action.

2.2. Main features of seismic response

Good insight into the forces that develop at integrated connections during the seismic action can be gained from a simplified analysis, based on the assumption of fully fixed panels at their end edges, as the one presented in the following.

Let us assume that there are n vertical panels at each side of the building along the direction of the seismic action and that each panel is pinned to the top and the bottom beam by two connectors at each side. Each panel has dimensions $L_{panel} \times H_{panel}$, while L and H are the horizontal and the vertical distance, respectively, between the connections (Fig. 2). Then, one can define the coefficient C_1:

$$C_1 = L/L_{panel} \tag{1}$$

which accounts for the insertion length of the connections from the panel edges.

In general, the total length, L_{tot}, of the building sides is not fully covered with panels. The coverage of each side with panels can be described by a coefficient C_2 defined by:

$$C_2 = n{\cdot}L_{panel}/L_{tot} \tag{2}$$

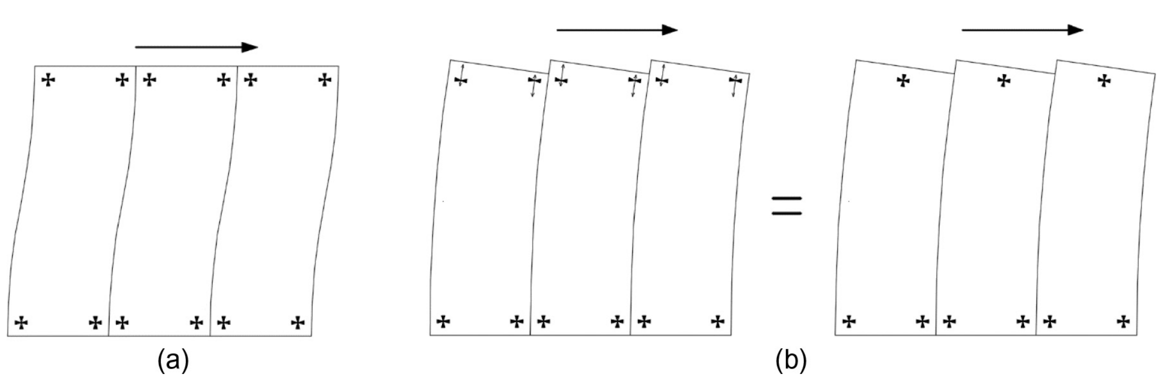

Fig. 1. Arrangement of vertical panels with: (a) Four connections; (b) 'Three' connections.

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