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Internal slab-column connections under monotonic and cyclic imposed rotations

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ABSTRACT

Reinforced concrete flat slabs supported by slender columns are often used as gravity load resisting system for buildings in regions of moderate seismicity. Current codes of practice determine the displacement capacity of slab-column connections using empirical formulas which were calibrated against experimental studies. This article reviews and compares test configurations used in past experimental studies and presents the adopted configuration for an experimental investigation on 13 full-scale internal slab-column connections without transverse reinforcement. The objective of the test campaign was to assess the influence of the loading history (monotonic vs. reversed cyclic) for different gravity loads and reinforcement ratios. The study showed that cyclic loading led in particular for slabs subjected to low gravity loads to significant moment strength and deformation capacity reduction when compared to results obtained from monotonic loading tests. The effect of cyclic loading was more pronounced for slabs with low reinforcement content. The experimental results are compared to the predictions of ACI-318, Eurocode 2 and *fib*-Model Code 2010. All codes predict the moment strength on the safe side. For the deformation capacity of the cyclic tests, only ACI-318 provides estimates, which are, in average, accurate enough but unconservative for slabs subjected to high gravity loads.

1. Introduction

In many countries with moderate seismicity, reinforced concrete (RC) flat slabs supported on columns is one of the most commonly used structural systems for office and industrial buildings since it features several advantages (large open floor spaces, limited thickness). To increase the lateral stiffness and strength of the structure, RC walls are added which carry the largest portion of the horizontal loads generated during earthquakes. Therefore, the slab-column system does not contribute significantly to the lateral stiffness and strength of the structure, but each slab-column connection must follow the seismically induced drifts of the building while maintaining its capacity to transfer vertical loads from the slab to the columns. As a result of the seismically induced drift, the slab-column connection is subjected to a moment. Codes of practice determine the moment capacity of slab-column connections either using the eccentric shear transfer model [1,2] or by reducing the control perimeter [3]. The deformation capacity is estimated from empirical formulas [1] derived from past experimental works [4].

Past studies investigated the seismic response of slab-column connections subjected to monotonic loading or to cyclic loading with increasing rotation amplitudes. Until today, only three pairs of slabs were tested which investigated the impact of the loading history (monotonic vs. reversed cyclic). Understanding the effect of the loading history is important when developing mechanical models for the moment-rotation relationship of slab-column connections including their rotation capacity. To contribute to the understanding of the impact of the loading history on the response of slab-column connections, five pairs of slabs that were subjected to monotonic and cyclic loading respectively were tested and provided several important findings. These new pairs differed from the existing pairs mainly with regard to the slab thickness (new: 250 mm, existing: 76–90 mm).

This paper reviews the different experimental setup configurations adopted in past studies. The setup configuration that was adopted for this study is compared to previous configurations as well as demands obtained from the analysis of a prototype building. The main results of the experimental campaign (comprising in total 13 tests) are presented along with a discussion on the influence of the reinforcement ratio, gravity induced shear forces and

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loading history (monotonic vs. cyclic) on the deformation capacity and punching strength of slab-column connections without transverse reinforcement. The test results are also compared to the predictions of ACI-318 [1], Eurocode 2 [2] and *fib*-Model Code [3] in terms of moment resistance and deformation capacity.

2. Simulation of slab-column connections under seismically-induced drifts in the laboratory

Space limitations in the laboratory often determine the size of test units. For this reason, most experimental campaigns study the behaviour of isolated slab-column connections that comprise one column and the surrounding slab and only few research groups opted for testing subassemblies of one interior and two exterior slab-column connections [5] or large-scale tests on single-storey [6,7] and multi-storey buildings with slab-column connections [8]. Since there are only very few tests on subassemblies, mechanical models have to be validated mainly against tests on isolated slab-column connections. For this reason, it is important to understand the approximations related to the testing of such isolated connections. To do so, the slab-column connection of a prototype building is analysed and its moment-slab rotation relationship is used as benchmark for the curves obtained from different experimental setups. These comprise setup configurations of previous experimental campaigns and an adapted setup configuration that is used in the experimental study presented in this paper.

2.1. Prototype building

A five-storey office building typical for Central European construction served as reference for the design of the test specimens of the performed experimental campaign. The slabs had a thickness of 250 mm and internal spans of 6.8 m. The storey height was 3.0 m. The primary lateral load-resisting system comprised two RC C-shaped cores providing lateral strength and stiffness in both directions (Fig. 1), whereas slab-column connections were designed to carry only vertical loads. The design was performed according to the *fib*-Model Code [3] for moderate seismic zone. The columns were square and cast-in-place with a size of 390 mm. The top reinforcement ratio in each direction was equal to 0.75% in the zone of the slab near the column (grey zones) and 0.5% in the middle strip (white zones), as shown in Fig. 1. Bottom reinforcement was provided in both directions over the whole slab, with a ratio equal to 0.375% around the column (dark grey zones) and 0.5% elsewhere. The provided bottom flexural reinforcement was continuous over the slab-column connections, complying with the integrity rules of ACI-318 [1]. The quasi-permanent vertical loads consisted of 6.25 kN/m^2 of self-weight of the slab, 1.00 kN/m^2 superimposed load and 0.60 kN/m^2 quasi-permanent live load. Under this load combination, the unfactored vertical load acting on an interior slab-column connection was approximately 40% of the punching strength according to ACI-318 [1] and Eurocode 2 [2] and 50% of the punching strength according to *fib*-Model Code [3] using mean strength values without applying any safety factors. The assumed concrete compressive strength was 32 MPa and the yield and maximum tensile stress of the reinforcing steel were 550 MPa and 680 MPa, respectively.

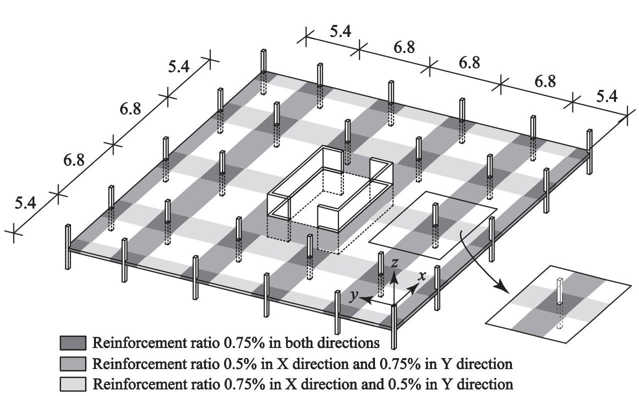

Fig. 1. Typical storey of the building that served as reference for the experimental campaign and top reinforcement ratios (dimensions in m).

2.2. Setup configurations of previous experimental research

Most test programmes on the behaviour of slab-column connections subjected to an unbalanced moment considered test specimens representing a single interior column and the surrounding slab. The dimensions of the specimens for the monotonic tests were typically chosen as $0.44L \times 0.44L$ where L is the distance between column axes [9–11]. The distance $0.22L$ corresponds for an elastic slab with constant stiffness and equal spans subjected to an evenly distributed vertical load to the distance of the point of contraflexure to the column axis. Most experimental campaigns focusing on the seismic response of slab-column connections used slab elements of the size $1.0L$x$1.0L$, i.e., from midspan to midspan of adjacent bays (e.g. [4,12,13] with few exceptions where larger elements were tested [14,15]).

All past tests used one of the following test setups, which differed with regard to the kinematic boundary conditions and the way the vertical load was applied:

- Setup (a): the unbalanced moment is introduced by an eccentric vertical load and by restraining the vertical displacement of the slab ends [16–18,21] (Fig. 2).
- Setup (b): the unbalanced moment is introduced by applying additional vertical loads to the edges of the slab and by fixing the column stub ends [14,11,20] (Fig. 2).
- Setup (c): the unbalanced moment is introduced by applying a horizontal force to the top column stub and by restraining the vertical displacement of either the slab edges [9,10,4,12,21,13,22–25] (Fig. 2) or specific locations on the slab surface [26] determined through finite element analysis to reproduce the internal actions of the prototype building [27]. The vertical load is applied either by jacks underneath the column stub [24,26] or by weights on the slab surface [12,13], with several campaigns combining both aforementioned ways of vertical load introduction [4,23].

Setup (a) is predominantly adopted to simulate unbalanced moments due to unequal spans. The test setup is simple and easy to implement but when applied to simulate seismic loading, it is somewhat unrealistic as the ratio of inserted moment to applied vertical load on the slab-column connection (subsequently referred to as eccentricity) remains constant. As a result, the applied vertical load changes throughout the test.

Depending on the control of the actuators inducing the forces at the slab edges, setup (b) can be used to simulate constant eccentricity [11], constant vertical load [14] or equal but opposite slab deflections at the two opposite edges [20]. No additional reinforcement was provided to the slab edges perpendicular to the unbalanced moment to account for the slab part between $0.22L$ and $0.5L$.

Setup (c) is predominantly used for cyclic tests on slab-column connections. It is based on the assumption that for seismic actions the contraflexure points are located at midspan of the slab. The test unit size and the reaction structure for the lateral load application impose significant space requirements for laboratories and there-