Engineering Structures 33 (2011) 3329–3340

Contents lists available at SciVerse ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

# Effect of openings and shear bolt pattern in seismic retrofit of reinforced concrete slab–column connections

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ARTICLE INFO

*Article history:*
Received 26 September 2008
Received in revised form
28 May 2011
Accepted 30 May 2011
Available online 1 July 2011

*Keywords:*
Flat reinforced concrete slab
Opening
Column
Seismic
Punching
Shear bolt
Ductility

ABSTRACT

This study addresses seismic retrofit of reinforced concrete flat slab–column connections against punching shear failure. The tested slabs are retrofitted using shear bolts. These bolts were developed for installation in existing slabs by drilling holes around columns or concentrated load application points and then tightening against the slab surfaces. Slabs with and without openings are investigated. The effect of the pattern of shear reinforcing elements around the column area, namely orthogonal and radial is also investigated. This paper describes tests on six flat slab–column specimens; three with two openings at the column and three without openings. Among each of the three specimens in a group, one has no shear reinforcement; one is retrofitted in the orthogonal pattern; and one in the radial pattern. The test results, comparisons of the behavior of the specimens, and comparisons with the current code formulas are presented and discussed. The results indicate that shear bolts increase lateral drift capacity and ductility of the slab–column connections.



## 1. Introduction

Reinforced concrete flat slab–column structural systems are economical and easy to construct. However, especially when used in seismic zones, they can be susceptible to a brittle punching shear failure. Flat slabs supported on columns are usually constructed together with additional lateral load supporting system, but they still need to be able to sustain seismic lateral movements without abrupt, local failures.

Many of the flat reinforced concrete slabs, especially the older ones, were constructed without any shear reinforcement. Their punching shear capacity depends on concrete strength only. Although concrete might be able to provide adequate shear strength, it will not provide ductility at large deformations. Under seismic loads slabs are subject to large imposed deformations, which cause cracking, and thus weaken the concrete shear strength, and therefore can result in punching failure. One way to avoid such failure is to retrofit the original unreinforced slabs using externally inserted shear bolts.

Shear bolts, a punching shear strengthening method for concrete flat slabs were developed at the University of Waterloo [1–3] (Fig. 1), where they were proven effective under both static and reversed cyclic lateral loads. They increase punching shear capacity and ductility of existing slab–column connections in a similar way as normal, properly anchored shear reinforcement does in newly constructed slabs. Shear bolts are installed in existing slabs in the column area. Small holes are drilled through the slab thickness first. Then the bolts are inserted through the holes and tightened against the slab surfaces. The process is straightforward and no prestressing is needed.

In practical situations, it is often necessary to create openings in slabs to allow electrical, water or air conditioning ducts to go through floors. These openings, located next to columns for practical and aesthetic reasons, reduce the punching shear capacity of the connection. Strengthening a slab with openings with shear bolts is one way of preventing punching failure. This has been shown in previous research on slabs with openings under static loads, [2,3].

The focus of research presented herein is the understanding of the behavior of retrofitted flat concrete slabs with and without openings next to columns, under gravity and reversed cyclic horizontal loads. Current codes of practice, e.g., [4–7], consider different shear reinforcement patterns. The two most popular patterns, orthogonal and radial, are investigated in this work. This study is part of the larger testing research program, which examines the behavior of slabs with and without openings and with and without shear bolts [8,1]. Six tests described in this paper address the following parameters: openings next to the column,

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doi:10.1016/j.engstruct.2011.05.025

**Notations**

| | |
|---|---|
| $V$ | Vertical applied gravity load |
| $V_n$ | Nominal concentric punching shear strength of a slab without shear reinforcement according to ACI [4] |
| $f'_c$ | Concrete compressive strength |
| $f'_t$ | Concrete tensile strength |
| $\mu_{\max}$ | Ductility at maximum lateral load |
| $\mu_{\%}$ | Ductility at percentage of maximum lateral load |
| $\delta_{\max}$ | Lateral displacement at maximum lateral load |
| $\delta_{\%}$ | Lateral displacement at percentage of maximum lateral load |
| $\delta_y$ | Lateral displacement at first yield of flexural reinforcement |

shear bolt reinforcement and shear bolt reinforcement pattern in the slabs.

## 2. Experimental investigation

### *2.1. Test specimens*

Six isolated slab–column specimens were tested. The specimens can be regarded as taken from a prototype structure in which the flat slab spans 3.75 m between columns. This resulted in full scale slabs with 120 mm thickness. The specimens were subjected to a vertical constant load of 160 kN (simulating gravity loading) and cyclic reversed lateral displacements (simulating seismic loading), which increased during the testing. The slabs were supported on the bottom surfaces at the lines of contraflexure under static gravity loads, located at 1500 × 1500 mm perimeter. To prevent lifting, the slabs were also supported on top along the lines perpendicular to the lateral load application. The slabs were square in plan, 1800 × 1800 mm, to allow for proper anchorage of the flexural bars past the simple supports. Under lateral loading (plus gravity loads) the locations of lines of contraflexure change depending on the direction of lateral loading. Therefore, to allow for rotation, the simple supports were simulated by adding thick neoprene pads (25 mm thick and 50 mm wide) on top and on the bottom supports of the slabs (Fig. 3).

The slabs had top and bottom 200×200 column stubs extending 700 mm from the center of the slab. The vertical load was applied to the top column through a roller that allowed simultaneous lateral movement. Horizontal loads were applied at 565 mm from the slab's surfaces. The "top" of the slab in this project was defined as the slab's compression surface. This is opposite to the situation in a real slab–column system where compression is on the bottom, near the columns. Table 1 and Figs. 2 and 3 provide information on the six specimens.

The flexural reinforcement ratio of all slabs in one direction was 1.3% (the lower tension mat) and 1.1% (the transverse upper tension mat), to maintain the same moment capacities in the two orthogonal directions. The rebars that were cut due to construction of the openings were placed on the side of the openings along the direction perpendicular to the lateral load. The rebars cut along the load application (which is also in-line with opening locations) were not added to the sides of the openings due to the lack of space. The reinforcing of the columns consisted of 3 × 25M bars on the two faces of the column width, and 10M closed stirrups in order to make the column strong enough to transfer shear force and cyclic moments to the slab. Figs. 4 and 5 show the reinforcement of the specimens.

The specimens are divided into two groups. Group 1 includes slabs without openings, SW4, SW5 and SW9. Group 2 is with openings; specimens SW6, SW7 and SW8 had two 150 mm × 150 mm openings, in the slab next to the column, and in the direction of the horizontal load application. In each group one specimen has no shear reinforcement, one specimen has shear reinforcing in a orthogonal pattern, and one in a radial pattern (Table 1).

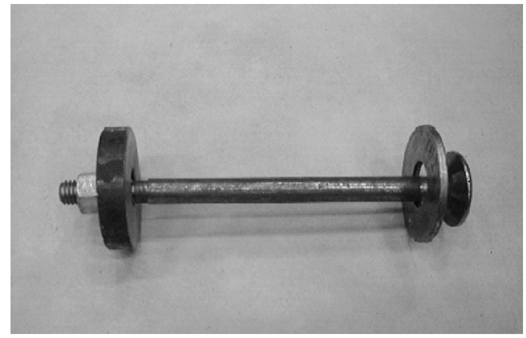

**Fig. 1.** Shear bolt.

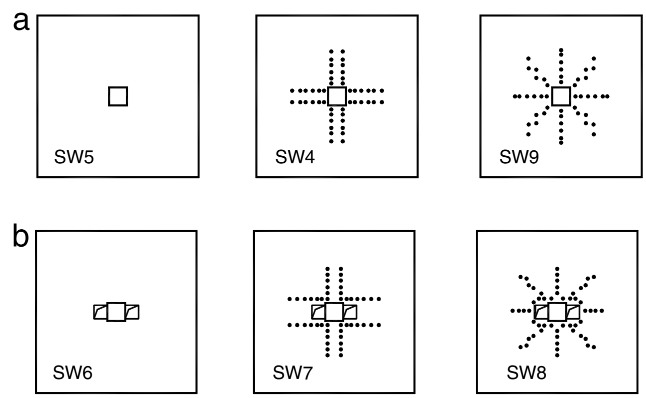


**Fig. 2.** Specimens (a) without openings, (b) with openings.

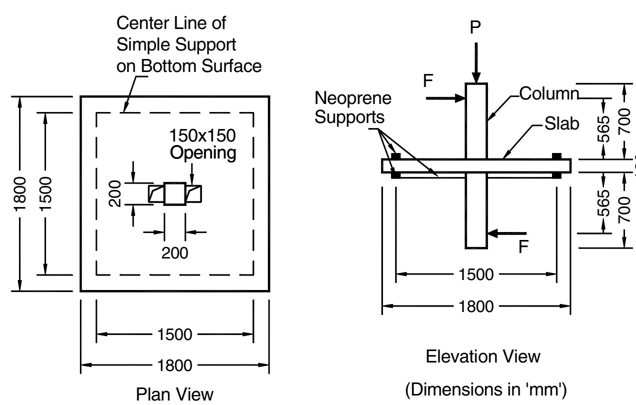


**Fig. 3.** Plan and elevation views of the specimens.

### *2.2. Material properties*

The specimens were cast using ready-mixed commercial concrete in two batches. Concrete cylinder (100 × 150 mm) compressive strength was tested right after each column–slab specimen test. All slabs were cast at least 3 months before the time of testing. Split cylinder tests were also carried out for concrete tensile strength. Yield and ultimate strength for reinforcing bars and shear bolts were obtained by tension tests. Material properties for all specimens are shown in Table 2.