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Behavior of high-strength fibrous concrete slab–column connections under gravity and lateral loads

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Abstract

Ten slab–column connections were tested under combinations of gravity and lateral loads to investigate the effect of adding steel fibers to concrete mix on the structural behavior of normal- and high-strength slab–column connections. The variables selected for this study were the strength of concrete, volumetric ratio of steel fibers, type of steel fibers, and moment to shear ratio. The test specimens consisted of two identical series. The first series constructed with normal-strength concrete with a cube compressive strength of about 28 MPa, and designated as NSC. The second series constructed with high-strength concrete with cube compressive strength of about 75 MPa were designated as HSC. Each series consisted of three specimens with steel fibers and were tested under gravity load and unbalanced moment, and two control specimens; one was tested under gravity load only, while the other was tested under pure moment. The addition of steel fibers does significantly enhance the performance of the tested slab; it improves the shear strength, increases the ductility due to deflection and rotation, yields greater stiffness, and smaller cracks widths. Further improvement was also obtained when larger aspect ratio was used. Test results showed that the high-strength concrete specimens had larger shear strength, displacement and rotation ductility ratios, and corresponding energy absorption, than the normal-strength specimens by about 7–21%, 11–64%, 106–123%, 48–150%, and 93–246%, respectively. Incorporating steel fibers with high-strength concrete improved the overall deformation characteristics of the tested specimens and resulted in less sudden and more gradual failure mode.

Keywords: Flat slab; High moment; High-strength concrete; Ductility; Energy absorption; Stiffness; Steel strain; Concrete strain; Punching shear; Slab–column connections

1. Introduction

In recent years, the use of high-strength concrete in various structural elements including slabs has become popular worldwide. Flat plate slab systems, which have no beams, column capitals or drop panels, are competitive and attractive structural system in buildings. Such system has some disadvantages, however, because of the risk of a punching shear failure at the slab–column joint. A slab–column connection in a flat plate structure is subjected to high shear force which can produce a sudden and brittle punching failure. Such failure generally occurs due to transfer of vertical shearing force and unbalanced bending moment between the slab and the column. Gravity loads mainly cause the vertical shearing force, while non-uniform gravity loads or any lateral loads due to wind or earthquake forces can produce the unbalanced bending moment.

The ultimate strength of flat slab systems is governed frequently by the punching shear capacity of the connection between the slab and column. One solution that may be used to increase the flat plate shear strength is to increase the concrete strength. Although the use of high-strength concrete would improve the shear resistance and allow higher forces to be transferred through the slab–column connections, in addition to other over all benefits, the brittleness of the system may be enhanced. The additional

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use of steel fibers is likely to improve the ductility of the connection, and may further increase the slab punching shear strength.

The behavior of normal-strength concrete slab–column connections with or without steel fibers has been widely investigated under gravity shear forces alone [1–10], and under shear forces and moments or lateral static loading [11,12]. However, few numbers of studies have been carried out on connections made of high-strength concrete under vertical shear forces [13–16], and very few studies are available under combination of shear forces and bending moments with or without steel fibers [17]. This study represents part of a competent research program on the behavior of various slab systems conducted to investigate the performance of high-strength concrete slab–column connections incorporating steel fibers under gravity and lateral loads, at service as well at ultimate stages [18].

2. Experimental program

2.1. Introduction

A total of five normal-strength (N1–N5) and five high-strength slab specimens (H1–H5), with and without steel fibers, were fabricated and tested under combinations of gravity and lateral loads. All specimens were cast using a full-scale interior column connected to a slab part bound by the assumed lines of contra-flexure around the column. Loading setup and applications were implemented using the actuators and steel strong floor of the structural laboratory at JUST. Deformation measurements were made using electrical strain gages and LVDTs.

Preceding the experimentation on slab specimens, the engineering properties of fresh and hardened concrete at various ages including slump, compressive strength, split cylinder strength, and modulus of rupture were obtained. Also, different volumetric percentages of steel fibers were examined. At least three specimens were tested for each property. For each slab parameter, one or two slab models were cast and tested.

2.2. Materials

Locally available crushed coarse and medium limestone aggregates and silica sand fine aggregate were used for normal-strength concrete specimens. For high-strength concrete specimens, crushed basalt coarse, medium and fine aggregates, and silica sand were used. Jordanian Portland cement, similar to ASTM Type I was used in this experimental program. To enhance some properties of high-strength concrete, silica fume was used in the mixing process. To improve the workability of normal- and high-strength concrete mixes, to prevent balling and segregation of steel fibers mixes, and to ensure suitable dispersion of hooked steel fibers in the concrete mixes, Conplast SP 430 superplasticizer was added. The material quantities of cement, coarse aggregate, medium aggregate, silica sand, water, and superplasticizer per one cubic meter of concrete were 300 kg, 667 kg, 628 kg, 610 kg, 157 L, and 3.45 L for normal-strength mixes, and 472 kg, 378 kg, 661 kg, 708 kg, 165 L, and 11.8 L for high-strength mixes, respectively.

Two types of Dramix hooked steel fibers, with volumetric percentages of 0.5% and 1.0% were used in this experimental program. The first type of fiber designated as F1, has an aspect ratio of 60 (30 mm in length and 0.5 mm diameter). The second type is designated as F2 with an aspect ratio of 75 (60 mm in length and 0.8 mm diameter). The yield strength (F_y) of F1 and F2 fibers were 1172 MPa and 1100 MPa, respectively. Two sizes of reinforcing bars having diameters of 10 mm and 14 mm were used. Steel reinforcing bars with yield strength of 468 MPa and yield strain of about 2240 microstrain, were used in the experimental program.

2.3. Test specimens

Ten slab–column connections, simply supported 150 mm thick and 1.5 m × 1.5 m square slabs; with 250 mm × 250 mm column cross-sections and 650 mm height both above and below the slab were used. The specimen configuration is based on the assumption that, under lateral loading, points of contra-flexure in a multistory frame are located at the midheight of the columns and the midspan of the slab. The layout of the tested connection and its reinforcement details, which were identical in both NSC and HSC series, are shown in Fig. 1.

2.4. Test setup

The test setup was designed to test the slab in horizontal position, as in real life, since it was difficult to test the slab in vertical position in which it would be easier to mark and detect cracks. The specimens were simply supported at the perimeters and the column movement was free in the perpendicular direction to the slab. In addition to the laboratory main steel frame and steel strong floor, the test setup consists of four (400 × 400 × 15 mm) I-columns, four (200 × 200 × 10 mm) I-edge beams, roller bars placed in special groove on top of the I beams, another beam and bar placed on top of one slab end and braced with a lower beam to prevent specimen from tilting up during lateral loading. Two lateral steel reaction frames were fabricated to support two servo-hydraulic actuators, which apply the lateral loads. The gravity load was applied through a vertical actuator perpendicular to slab. Schematic diagram and photograph of test setup assembly is shown in Fig. 2.

2.5. Strains and deflection instrumentations

Different devices were used to record deformations. Electrical strain gages known as (LY41-6/120) and (LY41-50/120) were used to measure strains in the steel and concrete, respectively. For each specimen, three steel strain gages (S1, S2, and S3) were placed on the tension