ENHANCEMENT OF SHEAR STRENGTH IN DEEP PRESTRESSED HOLLOW-CORE SLABS THROUGH THE USE OF STEEL FIBER REINFORCED CONCRETE

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ABSTRACT

Prestressed hollow-core slabs are commonly used in residential, industrial or commercial buildings, parking structures, and other civil structures throughout the world. The typical depths of the hollow core units in the United States vary from 6 to 12 inches. Current ACI Provisions allow no shear reinforcement in hollow-core units where total untopped depth is not greater than 12.5 inches. This height limitation was based on recent experimental results which indicated that prestressed hollow-core slabs with depth greater than 12.5 inches generally failed in shear strength at a point less than that predicted by the ACI V_{cw} *equation. However, the only effective practice is to increase the depth of the section when shear demand exceeds the calculated capacity as opposed to providing stirrups due to the obvious difficulties in placing shear reinforcement in the hollow-core slabs.*

Shear failure in plain concrete members is brittle in nature and consequently predisposes structures to sudden failure without any advance warning. One measure that is increasingly showing promise in protecting concrete members from brittle shear failure under excessive loads is the use of steel fiber reinforced concrete (SFRC). A growing body of research has been conducted on the shear behavior of SFRC beams over the past decades and results have shown that SFRC can considerably increase the shear strength and ductility of plain concrete. A pilot experimental research project was carried out for this particular study to investigate the shear behavior of SFRC deep hollow-core slabs with a height of 18-in. and a steel fiber fraction of 0.75% by volume. The average ultimate shear strength of the specimens fabricated and tested was more than two times the predicted V_{cw} *value according to ACI 318-11. SFRC specimens also demonstrated ductile behavior after the peak shear strength, as opposed to conventional prestressed hollow-core slabs in which an abrupt decrease in strength occurs immediately after the first crack. It is* *seen from the pilot test results that the shear strength and ductility of deep hollow-core slabs can be considerably enhanced by the addition of steel fibers.*

Keywords: Hollow-Core Slabs, Precast Concrete, Prestressed Concrete, Shear Strength, Steel Fiber Reinforced Concrete

INTRODUCTION

Prestressed hollow-core slabs have been used since 1950s. They are commonly used in residential, industrial or commercial buildings, parking structures, and other civil structures throughout the world. The typical thickness of the hollow core units in the United States is from 6 to 12 inches. Prestressed hollow-core slabs are widely known for their low maintenance, speed of construction, reduced weight and long economical spans, better control of deflection and flexural cracking, acoustical and heat transfer control, and fire resistance. The same shear design criteria given in ACI 318-11[1] are used for both hollow-core slabs and typical prestressed member. Current ACI Provisions allow no shear reinforcement for hollow core units with a total untopped depth not greater than 12.5 inches, where V_u is not greater than $0.5\varphi V_{cw}$ (φ = 0.75). The height and shear demand limitations were based on research results which indicated that prestressed hollow-core slabs with a depth greater than 12.5 inches generally showed web-shear cracking and failed in a shear strength much less than that predicted by the ACI equations[2]. The common practice is to increase the depth of the section when shear demand exceeds the calculated capacity rather than providing shear reinforcement due to difficulties in the production processes and the economic factors. As a consequence, the span or loading is generally limited due to the available shear strength. For instance, the allowed uniform load for shear capacity criterion will drop to about 20% for a typical 8-inch deep hollow core slab when the span is extended from 10 ft to 30 ft. In order to achieve the same shear capacity, the depth of the section needs to be five times deeper. But, due to the current ACI limitations, the depth of the section can be increased to only 12.5 inches without additional shear reinforcement. This means that the loading on a 30-ft slab can be increased to only 31% of that on a 10-ft slab. It is expected that the use of steel fiber reinforced concrete (SFRC) could significantly enhance the shear capacity of prestressed hollow-core slabs without much additional construction difficulty.

There were several experimental research investigations carried out on the shear capacity of hollow-core slabs since the 1970s where most of the specimens had a depth of less than 12 in.[2] It was reported that the shear capacity of prestressed concrete provisions of the ACI Code is sufficient[3]; however the research was limited to a section depth of only up to 10 in. while the production trend for hollow-core slabs with depths greater than 12 in. has become a normal practice in Europe and has spread among the US manufacturers. While the flexure-shear capacity from ACI Code provisions agreed with test results, the web-shear capacity from test results appeared to be considerably scattered compared to code predictions[4]. There are concerns about the applicability of ACI 318 provisions for shear strength provided by concrete validity particularly with respect to the minimum shear reinforcement exception for lightly reinforced deep one-way slab made with high-strength concrete and steel[5]. For these reasons, ACI Committee 318 imposed a 50% reduction for the web-shear strength of hollow-core slabs with a total uptopped depth of not greater than 12.5 in.[6] More recent research in the US also indicates that, while the latest ACI 318 equations give conservative predictions for the web-shear strength of hollow-core slabs with depth greater than 12.5 in., the values from test results were substantially different from those predicted by the ACI equations[7]. European research results point out concerns for the validity of formulae to determine the shear strength of hollow core slabs on flexible supports for German and Finnish construction approvals which in turn control the application of prestressed hollow-core slabs[8]. It was suggested that the German construction approvals provide appropriate formulae to determine the shear strength of hollow-core slabs on rigid supports. However, the preset (or prequalified) approvals for flexible supports, which allow 50% of the strength from the rigid supports when the construction details are met, might be un-conservative. The Finnish design model was suggested with an appropriate adjustment to the mean value of the test results in order to correspond with the values from the model.

The minimum shear reinforcement exception in the current ACI 318 creates concerns for units deeper than 12.5 in. as shear reinforcement is virtually impracticable for hollow-core slabs. A practicable construction method to increase the shear capacity of hollow-core slabs was proposed by reducing the depth of the sections while simultaneously increasing the concrete topping thickness[9]. According to the test results done on 10.4-in. (26.5-cm.)-deep hollow-core slabs, reducing the section thickness by 2.75 in. (7 cm.) with 1.24-in. (3.15-cm.)-thick concrete topping, the shear capacity was increased by 30%. While this approach is practicable, it somewhat defeats the purpose and reduces the benefits of the hollow-core slab system as the overall weight on the unit increases while more time and labor associated costs increase as well. Hence, the use of steel fiber reinforced concrete (SFRC) to investigate the efficacy of steel fiber enhancement in the shear strength of deep hollow-core slabs is proposed. It is worth mentioning that fiber reinforcement adds a host of both tangible and intangible benefits to the performance of a concrete structure in addition to the increase in shear resistance. These benefits include prevention of cracking due to camber and release of strands at the end zones of prestressed members, ductility, and increased impact/energy absorption capacity with reduced crack widths resulting in marked improvement of durability of the structure[10]. However, to the best knowledge of the authors, there has been no experiment conducted to investigate such efficacy for hollow-core slabs with a depth greater than 10 in.

EXPERIMENTAL PROGRAM

The experimental program was designed to investigate the shear behavior of SFRC deep hollow-core slabs. Five full-scaled slabs with 18-in. height, 48- in. width, and 192-in. length, as shown in Fig. 1~~Fig. 1~~, were designed in accordance with ACI 318-11 and the Manual for the Design of Hollow Core Slabs[11] to withstand the ultimate flexural loads at the corresponding loading points. The voids were created through the use of shaped Styrofoam blocks. A total of six 0.5-in. diameter prestressing strands were used in each slab. An initial prestressing of 189 ksi was applied to each stand, which gave an average initial prestressing force of 544 psi in the slabs with the area of slab equal to 319 in^2. Six additional #4 conventional non-prestressed mild steel (ASTM A615 Grade 60) rebars were used to prevent premature flexural failure before the specimens failed in shear. Two plain concrete (PC) specimens were cast as a control using plain concrete with an average aggregate size of 3/8 in. and three SFRC specimens were cast with the same concrete mixture reinforced with 0.75%

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volume fraction (100 lbs of steel fibers per cubic yard of concrete) steel fiber. Fig. 2~~Fig. 2~~ shows the fabrication of the hollow-core slab specimens for this experimental program.

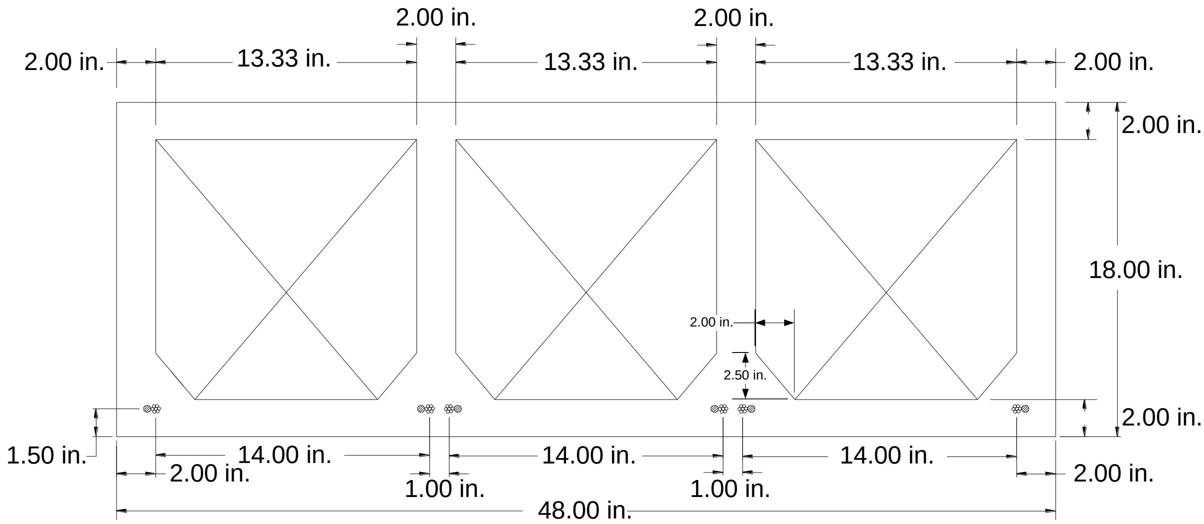

Fig. 1 Cross-section of the hollow-core slabs

(a) Concrete mixing with steel fiber

(b) Preparation of formwork

(c) Casting of specimens

(d) Finishing of specimens

Fig. 2 Specimen fabrication

MATERIALS

Concrete

The specified 28-day concrete compressive strength of 5 ksi with a target water-to-cementitious material ratio of 0.50 was prepared by professional workers at a local precast manufacturer for all of the specimens. The concrete mixture, as shown in Table 1~~Table 1~~, is the typical mixture used for their commercial precast concrete products (wet cast). The plain concrete was first mixed in a pan-type mixer for the controlled PC specimens. The second batch of concrete using the same mix proportion with the added steel fiber was mixed following the first batch for the SFRC specimens.

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Table 1 Concrete mixture

Material	Weights (lbs)
Type I Portland Cement	376 - 456
Fly Ash	94 - 114
ASTM 67 Crushed Lime Stone (3/8")	1600 - 1800
ASTM C-33 River Sand	1340 - 1540
Water	255 - 275

Material tests

Three compressive cylinder tests were performed on 4 in. × 8 in. cylinders in accordance with ASTM C39[12] for both plain concrete and SFRC at 28 days after casting of the specimens and also on the testing days of each specimen. The mean 28-day compressive strength for the cylinders was 5120 psi.

Prestressing strands

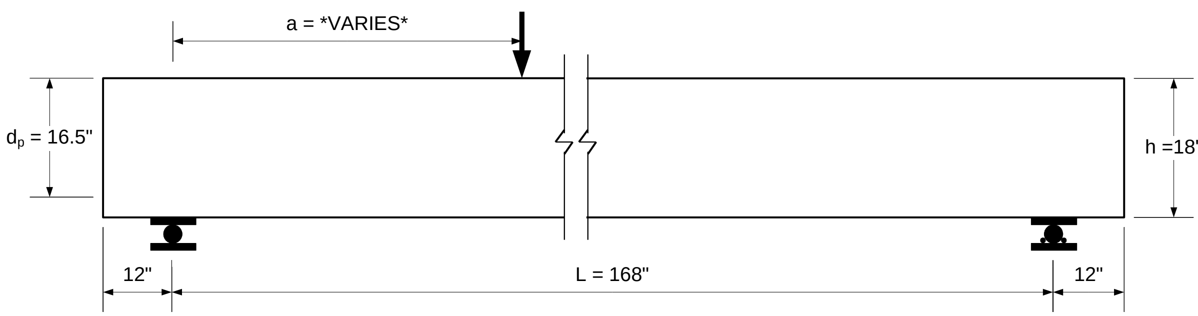
The conventional 0.5-in. diameter seven-wire, stress-relieved, ASTM A416 Grade 270 ksi prestressing strands were used for all of the specimens.

Steel fiber

Hooked-end steel fibers conforming to ASTM A820 with an aspect ratio of 66 (1.97-in. long with 0.03-in. diameter) and a tensile strength of 160 ksi were used for the three SFRC specimens.

TEST SETUPS AND PROCEDURES

Two types of test setups, one for the web-shear failure mode and the other for flexure-shear failure mode, were used for the experimental program. Due to the lack of a standard test method in the US, the web-shear failure mode test setup was prepared according to the requirements described in the European Standard EN 1168:2005 "Precast concrete products – Hollow core slabs"[13], which recommends the applied load span across the whole width of the slab at a distance of 2.5*h* from the support, where *h* is the height of the slab. This translates to a/d_p ratio of 2.73 for the test specimens. For the flexure-shear failure mode, the load was applied at the mid-span of the specimen with an a/d_p ratio of 5.09. Steel supports were placed 12-in. from the ends of the specimens. Load was monotonically applied through a 600-kip hydraulic cylinder mounted on a steel reaction frame in 10-kip increments up to the failure point. In order to spread the applied load across the full width of the slab, a wide-flange steel section with reinforced web stiffeners was used as the load spreading beam.



(a) Geometry of the hollow-core slab specimens

(b) Web-shear test setup

(c) Flexure-shear test setup

Fig. 3 Experimental test setups

INSTRUMENTATION

Two Linear variable differential transformers (LVDTs) were used to measure the vertical displacement directly under the loading point, one at the middle of the slabs and the other 12-in. apart in the transverse direction as a backup. Two additional LVDTs were placed at the supports to measure the possible support settlement, one for each end, for each specimen. A 500-kip load cell was placed between the hydraulic cylinder and the load spreader beam.

TEST RESULTS

Two conventional PC and three SFRC specimens were tested in the research program. Both conventional specimens were tested under the web-shear failure mode test setup as controlled specimens. Two of the SFRC specimens were tested under the web-shear failure mode and the other one for the flexure-shear failure mode. Typical shear cracks upon failure are shown in Fig. 4~~Fig. 4~~(a) for the web-shear crack failure mode and Fig. 4~~Fig. 4~~(b) for the flexure-shear crack failure mode. The corresponding shear forces versus deflections underneath the loading point are shown in Fig. 5~~Fig. 5~~(a) and Fig. 5~~Fig. 5~~(b) for the web-shear crack and the flexure-shear crack failure mode, respectively.

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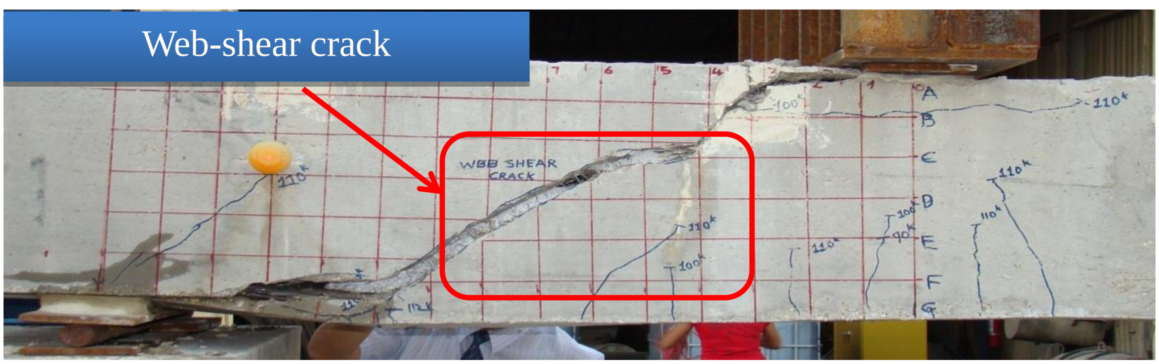
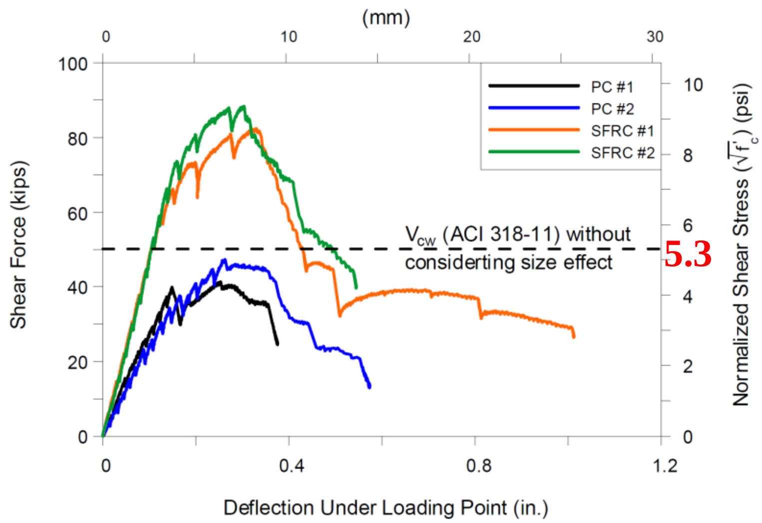


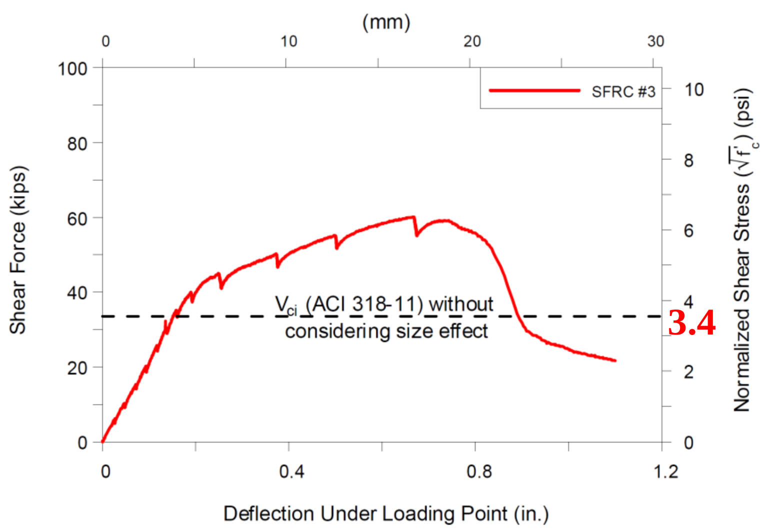
(a) Web-shear crack failure mode

(b) Flexure-shear crack failure mode

Fig. 4 Failure modes at ultimate



(a) Web-shear crack failure mode



(b) Flexure-shear crack failure mode

Fig. 5 Shear vs. deflection responses

For the controlled PC specimens tested under the web-shear crack failure mode, no flexure-shear crack was observed throughout the tests. The average shear stress at failure (4.7 $\sqrt{f_c'}$) is 11% less than the predicted V_{cw} value (5.3 $\sqrt{f_c'}$), as calculated according to ACI 318-11, if no size effect is considered.

For the SFRC specimens, the first flexure- and web-shear cracks occurred at shear stresses approximately 7.0 $\sqrt{f_c'}$ and 7.7 $\sqrt{f_c'}$, respectively for the specimens that failed in the web-shear crack mode, and 4.2 $\sqrt{f_c'}$ and 5.3 $\sqrt{f_c'}$, respectively for the specimens that failed in the flexure-shear crack mode. The average ultimate shear strength of $9.0\sqrt{f_c'}$ for the web-shear crack failure mode in the SFRC specimens is 71% larger than that of the predicted V_{cw} and is approximately two times greater than the conventional PC specimens.

For the SFRC specimen tested in the flexure-shear failure mode setup, the actual ultimate shear strength of $6.4\sqrt{f_c'}$ is 89% larger than the predicted V_{ci} value ($3.4\sqrt{f_c'}$).

Table 2 Summary of test results

Specimen	a/d_p	Load at first flexure-shear crack (kips)	Load at first web-shear crack (kips)	Ultimate load (kips)	Corresponding shear force at ultimate (kips)	Normalized shear stress*
PC #1	2.73	-	55	56	41	4.38
PC #2	2.73	-	35	65	47	5.01
SFRC #2	2.73	90	100	113	82	8.72
SFRC #3	2.73	110	90	121	88	9.36
SFRC #4	5.09	80	100	120	60	6.36

*Normalized shear stress = $\dfrac{v}{\sqrt{f_c'}b_w d}$, where f_c' = 5120 psi

All SFRC specimens exhibited similar performance. They showed higher strength, stiffness, and more ductile behavior, as opposed to conventional prestressed hollow-core slabs.

CONCLUSION

Shear failure in plain concrete members is brittle in nature and consequently predisposes structures to sudden failure without any advance warning. One measure to protect concrete members from brittle shear failure under excessive loads is to use steel fiber reinforced concrete (SFRC). Numerous research investigations have been conducted on the shear behavior of SFRC beams over the past decades and results have shown that SFRC can considerably increase shear strength and ductility of plain concrete[14]. Due to the mounting body of evidence from research results, ACI 318-08 has allowed SFRC as an alternative for conventional shear reinforcement (i.e. steel stirrups) to be used in prestressed and non-prestressed beams. For the same reason, it is expected that the use of SFRC could significantly enhance the shear capacity of prestressed hollow-core slabs with little additional construction difficulty. It is noted that the efficiency of steel fibers is greater when fibers are used in hollow-core slabs as compared to beams. This is due to the thin webs of the hollow-core sections which lead to the preferable fiber orientation along the axis of the slabs during concrete casting. It can be seen from the test results that the shear strength and ductility of deep hollow–core slabs is considerably enhanced by the addition of steel fibers.

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