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Cracking Behavior of High-Strength Spiral Steel Bars in Concrete Slabs

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Abstract

The performance of reinforced concrete structures depends on adequate bond strength between the concrete and reinforcing steel. Since the introduction of strength design in 1963, the use of concrete members reinforced with high-strength steel bars greater than 80 ksi (552 MPa) in earthquake-resistant structures has been restricted by U.S. building codes. This study investigates the mechanical properties and performance in concrete slabs of a new high-strength reinforcing steel bar designed with spiral patterns. Two sizes of the new high-strength spiral steel bar are tested using monotonic tension tests to quantify their mechanical properties. The bars are placed in concrete slab specimens geared to study flexure and anchorage properties. The final results demonstrate that spiral steel bars exhibit a stable load drift response in concrete members, thereby indicating the use of spiral steel bars are appropriate for gravity loaded reinforced concrete slabs.

Keywords: Cracking, High-Strength, Slabs, Spiral

1. Background and Introduction

The progressive demand for higher strength reinforcing steel bars in concrete construction is rapidly increasing in the U.S. and in many developed countries around the world. This demand is driven by the need to build immense and complex structures to solve population and societal needs. The environmental and economic benefits are key contributors to the demand for higher strength reinforcement[13]. The use of high-strength steel bars in reinforced concrete design has the potential to reduce significantly the overall quantity of steel that construction industry installed during constructions. A decrease in the amount of steel use would also reduce reinforcement congestion and bring down labor and construction costs. This reduction would translate into cutbacks in energy consumption related to fabricating, manufacturing, and transporting steel bars. The reduction in volume of steel bars in construction can help minimize the environmental impact and demand of primary resources and stabilize the efficiency in energy consumption.

In spite of the demand, current building codes in the U.S limit the use of high-strength reinforcing steel[5]. The reasons for these restrictions are mainly because of a lack of profound understanding and limited test data on the performance and effects of higher strength steel in concrete structures[10]. Today's limits on strength for concrete reinforced with steel bars have been enforced since the early 1950s. The yield strength limit on reinforcement was set in the 1956 version of the ACI (American Concrete Institute) 318 building code at 60 ksi. In 1971, the ACI 318 code raised the limit to 80 ksi for gravity systems[2, 4]. Recently, the ACI building code has allowed the use 100 ksi steel bars for confined reinforcement in earthquake design[5]. The behavioral aspect on the performance of high-strength steel bars is a major concern for U.S. building codes.

1.1 High-Strength Reinforcement and Production Methods

Increasing the yield strength of reinforcing bars often leads to reduction in fracture elongations, the length of yield plateau, and the tensile to yield strength ratio. The increase in carbon and manganese content was among the earliest efforts to increase the yield strength of reinforcing bars[8]. Although this process did increase the yield strength, there were great reduction in elongations of bars at fracture. Currently, there are three methods of increasing the yield strength of reinforcing steel bars. These methods are: *Cold working, micro-alloying, and quenching and tempering.* Known as strain hardening, work hardening, or cold rolling, cold working is long standing method of producing high-strength reinforcement. This process is carried out well below the recrystallization temperatures. Micro-alloying is the process of adding small amounts of titanium (Ti), niobium (Nb), or vanadium (V) to obtain high-strength steel. Quenching and tempering uses inexpensive carbon to produce high-strength steel by rapidly cooling the steel that has been heated in the austenitic phase. This is a phase in which solid steel recrystallizes and then quenched in oil or water in order to obtain a strong and very brittle steel[8]. The high-strength spiral bars used in this study were produced by using the cold working method.

1.2 Behavior of High-Strength Steel Bars

High-strength steel bars can resist large tensile forces, and increase the bond demands between the steel and concrete. In high-strength steel, a larger strain at yielding leads to larger strains at service loads which can cause wider cracks and increase deflections. For longitudinal reinforcement, larger strain concentrations can cause premature bar fracture. This is a problem because premature fracture and large cracks may allow water to penetrate inside concrete members. Through cracks, the presence of water inside reinforced concrete structures can gradually destroy and corrode the steel bars which ultimately can lead to unexpected burst outs in concrete. In addition, the presence of large cracks can lower the ductility of high-strength steel bars and weaken the concrete shear-transfer mechanisms by affecting the performance and deformation capacity of the system.

Structurally, important considerations in the design of reinforced concrete structure are flexure tension crack formation, development, and control[9]. The flexure bond that transfers the forces across the interface between the concrete and steel is paramount in controlling the cracking behavior of reinforced concrete members[1]. In the early 1960s, limiting concrete allowable crack widths was a major concern[3]. Hognestad showed that the maximum and average crack widths are proportional to the reinforcing yield strength of steel bars[11, 12]. Based on Hognestad results, the American Concrete Institute decided that 60 ksi was a reasonable value for yield stress to control cracking. A decade after this implementation, maximum allowable crack widths were set in the ACI building code at 0.013 inch for exterior exposure members and 0.016 inch. for interior exposure members[4]. These restrictions were mainly for aesthetic and prevention purposes[6].

Figure 1. An image of the high-strength spiral steel bars.

It is evident that limited test data exists on the performance and behavior of high-strength steel in concrete structures. Therefore, in order to expand the current knowledge, new experimental research is needed to assess the cracking behavior, and other implications related with using high-strength steel bars in reinforced concrete structures. The experimental program developed in this study investigated the mechanical properties and performance of a new high-strength spiral steel bar in concrete slabs. The slab specimens were designed to have equivalent dimensions and concrete properties, but different reinforcement amounts. The new high-strength spiral steel bar is designed with spiral patterns as shown in Figure 1 above and geared to focus on flexure and anchorage behavior. The high-strength spiral steel bar is considered new because of its unique spiral geometric patterns to help increase the bond between the concrete and steel reinforcement.

2. Methods and Experimental Program

In order to investigate the mechanical properties and performance in concrete slabs of the new high-strength spiral steel bar, the experimental program developed in this study satisfied the ASTM A615M standards[7]. As a benchmark, the behaviors of concrete slabs reinforced with Grade 60 deformed bars were used to appropriately compare the difference in behavior between high-strength spiral bars and regular deformed bars. First, two sizes of the spiral bars were examined by conducting a monotonic tension test. A monotonic tension test is a type of test by which the load is directly applied at the center of a specimen. Specifically, a total of eight concrete slab specimens were designed to have a ductile behavior and experience yield flexure prior to any other failure mechanisms. The first series of tests consisted of four concrete slabs reinforced with Grade 60 deformed bars, and four specimens reinforced with high-strength spiral bars.

2.1 Reinforced Concrete Slab Design

With a cross sectional area of 18 inches (in.) by 6 in., the specimens were 120 in. long as shown in Figure 2. Also, the specimens were designed assuming a concrete compressive strength of 4000 psi and did not contain any splice[5]. By using a load cell, the specimens were loaded at their respective mid-spans. Additionally, a digital image correlation (DIC) system and strain gauges were installed and instrumented so that the deformations, deflection, applied load, stress-strain data, drift ratio, and crack widths could be measured and captured on the surface of each specimen[14]. For the scope of this research, drift ratio relates to the deflection of the slab divided by 48 in. or half of the slab longitudinal length and center to center span between the supports.

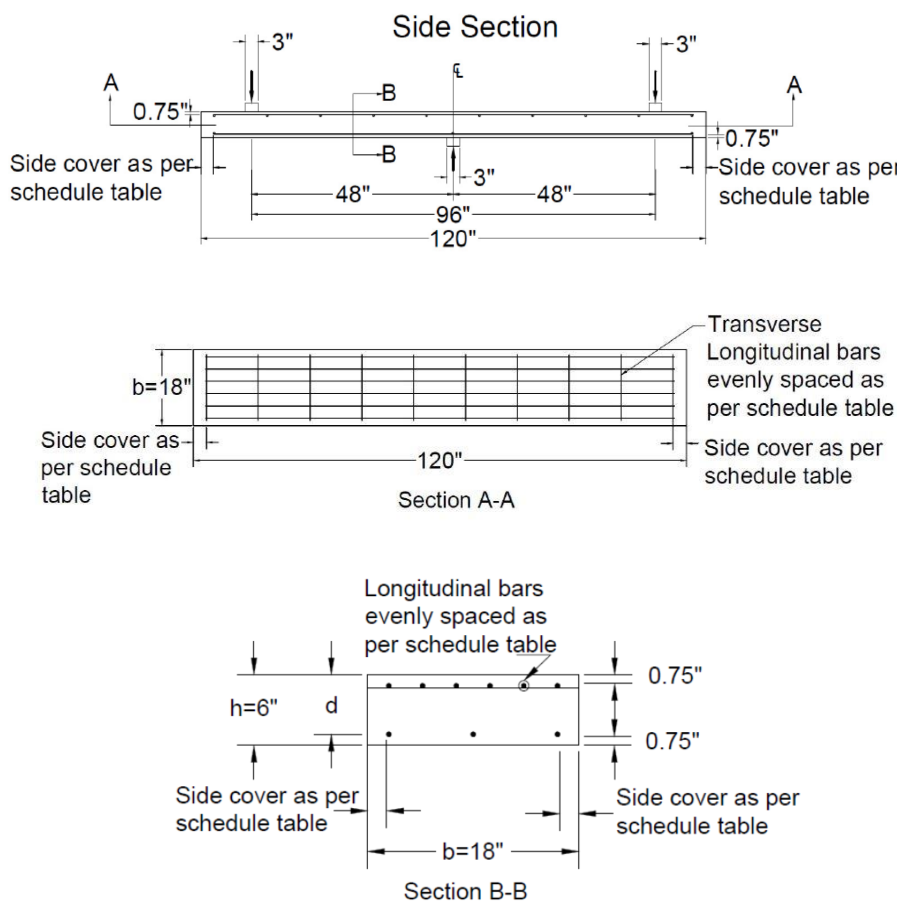

Figure 2: Representations of details about the specimens.

2.2 Reinforcing Bar

The spirally deformed bars had diameters of 5/16-in. and 3/8-in. Equation 1 below demonstrates how the equivalent cross-sectional areas and diameters were determined:

$$A_{sp} = \frac{\pi Dsp^2}{4} = \frac{W_b}{L_b \, \Delta_{steel}} \tag{1}$$

A_{sp} = equivalent area of spiral bar (ft^2); W_b = measured weight of bar coupon (lbs.); L_b = length of bar coupon (ft.); Δ_{steel} = density of steel (490 lb/ft^3); D_{sp} = diameter of spiral bar (ft.).

In order to satisfy ACI 318-14 minimum reinforcement requirements for the temperature and shrinkage longitudinal bars in the transverse directions were provided (see Table 1)[15].

To better organize the results, the following nomenclatures were used to specify the type of test, the number and type of bar, and the equivalent bar diameter:

Type of Test: *F1* ≈ flexure test of series 1
No. of bars: E.g. *6#3* ≈ six number three bars
Equivalent Diameter: *8-5/16* in. ≈ eight 5/16 in.
Type of bar: *DB* ≈ deformed bar or *SB* ≈ spiral bar

Table 1. Bar schedule and configurations.

Specimen	Number of longitudinal bars	Center-to center spacing of longitudinal bars (in.)	Number of transverse longitudinal bars	Center-to-center spacing of transverse longitudinal bars (in.)
F1-6#3 DB	6	2.8	10	12.6
F1-3#3 DB	3	7.3	10	12.6
F1-6#4 DB	6	2.5	6	18.5
F1-3#4 DB	3	7.3	6	18.5
F1-8-5/16 SB	8	1.8	14	8.63
F1-3-5/16 SB	3	7.3	14	8.63
F1-8-3/8 SB	8	2.0	8	16.5
F1-3-3/8 SB	3	7.3	8	16.5

Additionally, the following milestones labeling were utilized to unify and accurately identify the mechanical behavior and strength of the steel:

FFC – First flexure cracking
FY – First longitudinal reinforcement yield
PU – Peak or Ultimate load
FF – First longitudinal bar fracture
0.8PU – The point at which 20 % loss of strength occurred

For each test, the applied load, displacements, strains, and potentiometer readings were recorded. For the scope of this study, a special attention was placed on crack widths because of the preliminary design parameters.

3. Results and Discussion

The stress and strain curves of the steel bars as shown in Figure 3 reveals that high-strength spiral steel bars do not exhibit a yield plateau when compared with regular Grade 60 deformed bars. Even though the yield strength of the spiral bars is higher by 20 ksi, the regular Grade 60 deformed bars experienced larger strains between their respective ultimate tensile strengths and yield points. The Spiral bars elongated uniformly up to 3.2% and 3.4% for fracture as expected due to the strain hardening process used during its production.

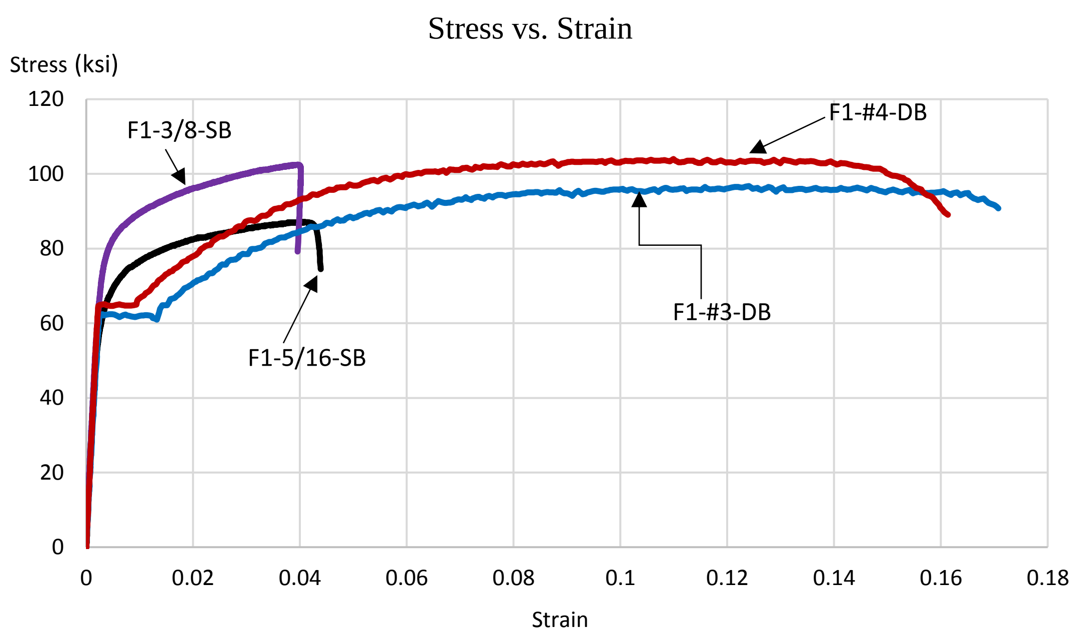

Figure 3. Stress and strain plots of spiral and deformed bars.

3.1 Deformed Bar Specimen: F1-6#3

The specimen reinforced with six #3 DB developed cracks that widened as the drift ratio increased. The slab reached a maximum load of 9.62 kips and a maximum moment of 231 k-in at a drift ratio of approximately 6.0% (see Table 2). Initially, the slab exhibited a linear force-drift behavior up to the first flexural crack at a drift ratio of 0.055% and a load of 3.04 kips. At a drift ratio of 6.98%, the specimen experienced 20% loss of its moment strength. The crack width distribution measurements at half yield, yield, and 2% drift ratio are shown in Figure 4. As expected at 2% drift ratio, large cracks were observed and measured.

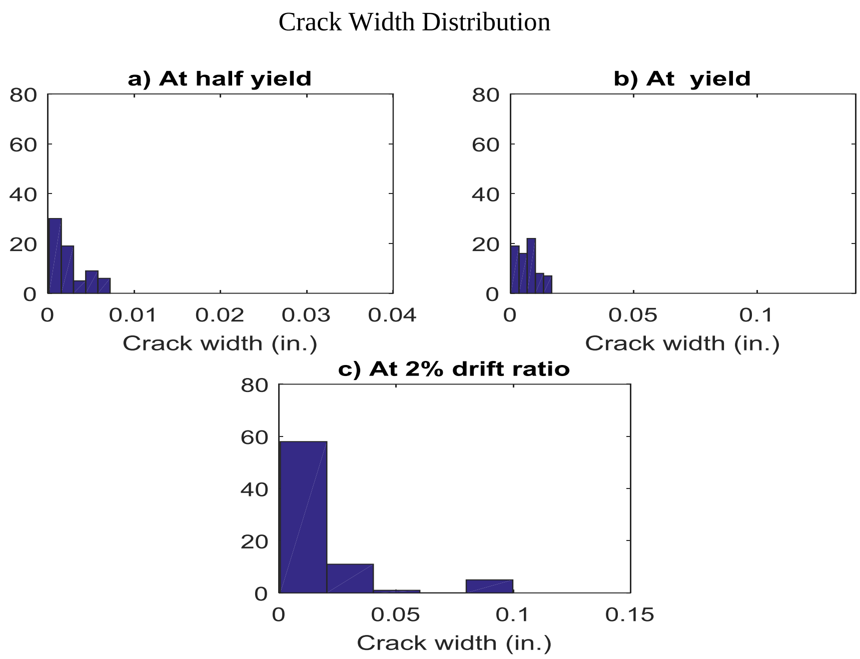

Figure 4. F1-6#3 DB – Crack widths at half yield, yield, and 2% drift ratio.

There was no longitudinal bar fracture, however due to an increase in crushing and spalling of the concrete, a rapid increase in the load was observed (see Figure 5). The first longitudinal reinforcement yield occurred at a drift ratio of 0.71% with a load of 6.50 kips.

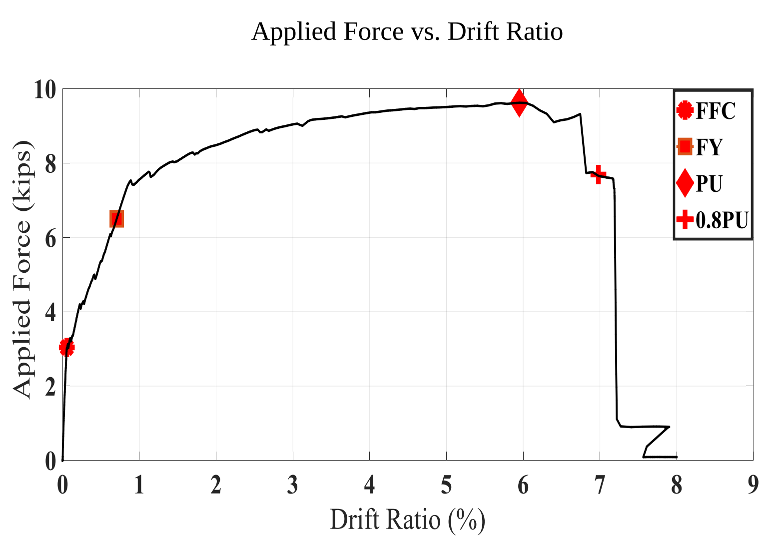

Figure 5. F1-6#3 DB – Applied force vs drift ratio.

3.2. Spiral Bar Specimen: F1-8-5/16

The F1-8-5/16 SB specimen also exhibited a linear force-drift behavior up to the first flexural crack at a load of 2.36 kips, a drift ratio of 0.096% with a moment of 56.6 k-in at mid-span. Yielding in the longitudinal reinforcement occurred when the applied load reached 5.92 kips and a drift ratio of 1.32% (see Table 2). As the load increased at mid-span, the main flexure cracks became wider and more cracks were formed near the mid-span region of the specimen. Beyond its ultimate load capacity, 20% of the strength was lost when the specimen attained a load of 5.36

kips, a drift ratio of 4.21% with a moment of 129 k-in. With an ultimate moment of 161 k-in., the relationship between the applied force and drift ratio in Figure 6 shows the behavior of the reinforced specimen. Concerning this slab specimen, the crack width distribution data is not shown nor discussed because the specimen portrays similar crack width distributions identical to the F1-8-3/8 SB specimen shown in Figure 7.

Applied Force vs. Drift Ratio

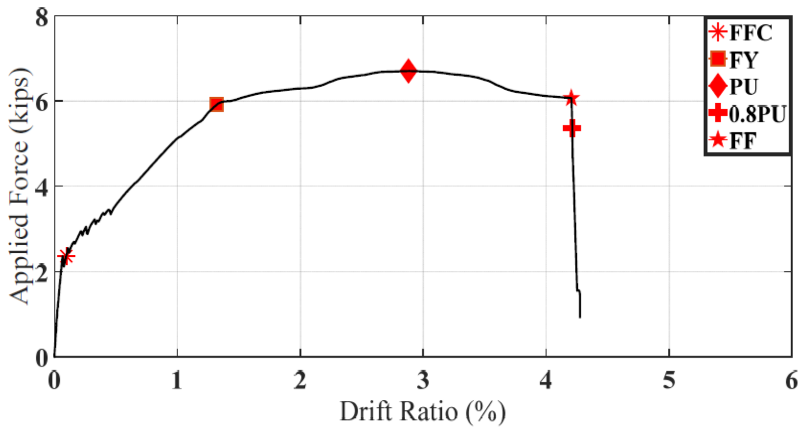

Figure 6. F1-8-5/16 SB – Applied force vs drift ratio.

3.3. Spiral Bar Specimen: F1-8-3/8

With a higher yield strength and large diameter, the cracking behavior observed for this specimen occurred at very high moment capacity starting at 93 k-in to 331 k-in (see Table 2). This particular slab reached an ultimate load of 13.8 kips at a drift ratio of approximately 3.25%. At half yield and yield, the crack widths were relatively larger than the widths obtained when the element reached a 2% drift ratio (see Figure 7). The first longitudinal reinforcement yield occurred at a load of 12.7 kips and a drift ratio of 1.74% with a moment capacity of 331 k-in. At a drift ratio of 3.25%, the ultimate load capacity reached 13.8 kips as shown in Figure 8.

Crack Width Distribution

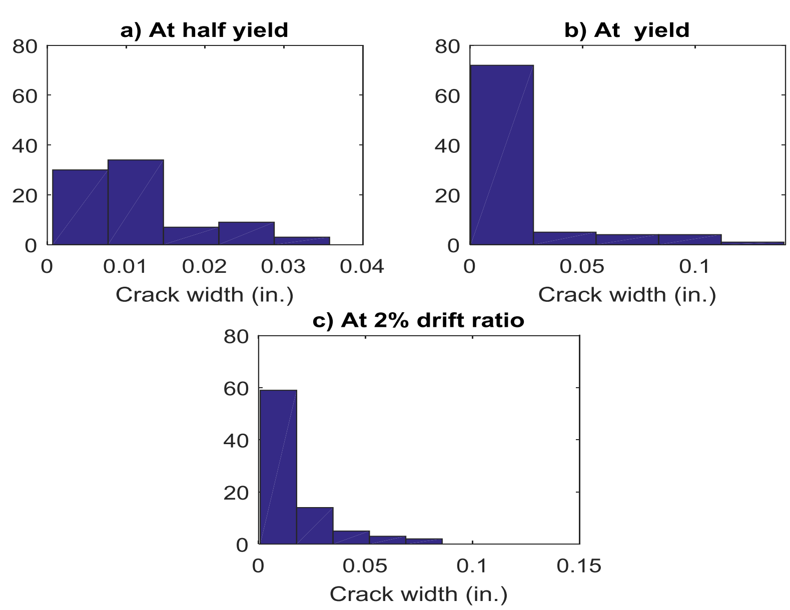

Figure 7. F1-8-3/8 SB – Crack widths at half yield, yield, and 2% drift ratio.

Applied Force vs. Drift Ratio

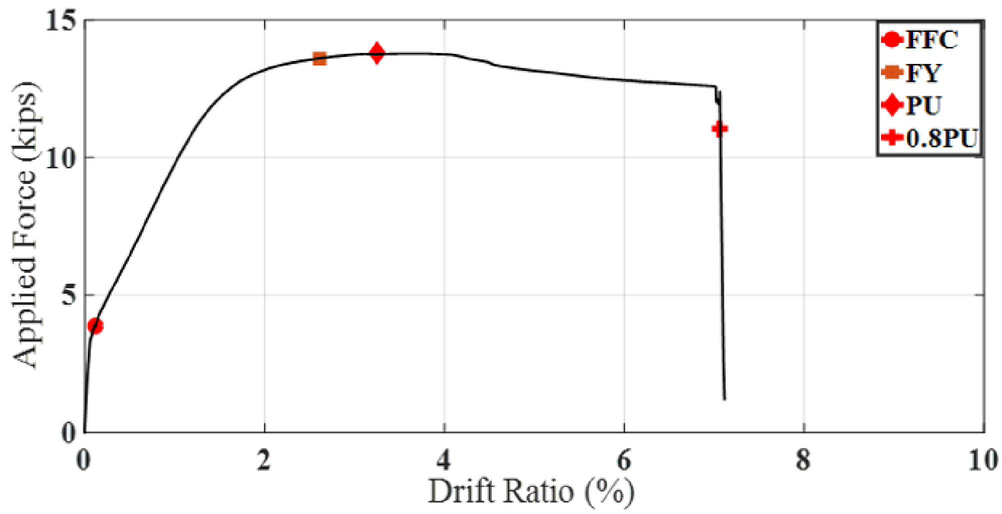

Figure 8. F1-8-3/8 SB – Applied force vs drift ratio.

Table 2. Behavioral summary of milestones.

Specimen	Behavioral Milestones				
	FFC - First flexure cracking **(kips)**	**FY -** First longitudinal reinforcement yield **(kips)**	**PU -**Ultimate load **(kips)**	**0.8 PU -** 20 % loss of strength **(kips)**	**M_u –** Ultimate moment at mid-span **(kip-in.)**
F1-6#3 DB	3.04	6.50	9.62	7.69	231
F1-3#3 DB	3.30	4.77	7.77	6.22	187
F1-6#4 DB	3.62	13.6	17.7	14.1	424
F1-3#4 DB	3.44	8.87	11.2	8.96	269
F1-8-5/16 SB	2.36	5.92	6.70	5.36	161
F1-3-5/16 SB	3.37	3.77	5.39	4.31	129
F1-8-3/8 SB	3.87	13.6	13.8	11.0	331
F1-3-3/8 SB	4.23	6.11	7.64	6.11	183

4. Conclusion

By investigating of the mechanical behavior and performance of high-strength spiral bars in concrete slabs, this study demonstrated that concrete slabs reinforced with high-strength spiral bars can attain its first flexural cracking around the same load as slabs reinforced with regular deformed Grade 60 bars. Aware of the direct relationship between the crack width and the yield strength, at half yield and up to 2% drift ratio, concrete slabs reinforced with high-strength spiral bars exhibit large crack widths. Since Grade 60 deformed bars have higher tensile-to-yield strength ratios than high-strength spiral bars, concrete slabs reinforced with high-strength spiral bars experienced lower strength gains at the ultimate strength capacity. However, high-strength spiral bars showed higher drift ratios at yield when compared with deformed bar specimens. Overall, the high-strength spiral bars examined in this study exhibited a stable drift ratio up to 3% and some transcending 7%. This observation perhaps might be an indicator that high-strength spiral steel bars are suitable for concrete members supporting gravity loads. Additionally, depending on the type of construction, high-strength spiral bars can minimize reinforcement congestion for heavily reinforced concrete elements. Considering the engineering applications associated with the usage of high-strength bars, it is imperative for future research to analyze the relationship and effects of tensile-to-yield strength ratio of high-strength spiral bars.

5. Appendix

K-in. – Kilopound inch
Kips – Kilopounds
Ksi – Kilopound per square inch
Spiral reinforcement – Continuously wound reinforcement in the form of a cylindrical l helix.

6. Acknowledgements

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7. References

1. ACI, 2003, *Bond and Development of Straight Reinforcing Bars in Tension*, ACI 408R 03, American Concrete Institute, Farmington Hills, Michigan.
2. American Concrete Institute (ACI) Committee 318, 1956. “Building code requirement for structural concrete (ACI 318-56)”, Detroit, MI: American Concrete Institute.
3. American Concrete Institute (ACI) Committee 318, 1963. “Building code requirement for structural concrete (ACI 318-63)”, Detroit, MI: American Concrete Institute.
4. American Concrete Institute (ACI) Committee 318, 1971. “Building code requirement for structural concrete (ACI 318-71)”, Detroit, MI: American Concrete Institute.
5. American Concrete Institute (ACI) Committee 318, 2014. “Building code requirement for structural concrete (ACI 318-14) and commentary”, Farmington Hills, MI: American Concrete Institute.
6. American Concrete Institute (ACI) Committee (ACI) Committee 439, 1973. “Use and limitations of high strength reinforcement (ACI 439-73)”, ACI Structural Journal, Vol, 70, No. 2, pp. 77-104.
7. ASTM Standard A615/A615M-13, 2013. "Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement." ASTM International, West Conshohocken, PA.
8. Caifu, Y., 2010, “Development of High Strength Construction Rebars,” Proceedings, International Seminar on Production and Application of High Strength Seismic Grade Rebar Containing Vanadium, Central Iron & Steel Research Institute, Beijing, China.
9. Frosch, R.J., 1999, “Another look at cracking and crack control in reinforced concrete”, ACI Structural Journal, Vo. 96, No. 3, 437-442.
10. Gergely, P., and Lutz, L. A., 1968, "Maximum Crack Width in Reinforced Concrete Flexural Members," Causes, Mechanism, and Control of Cracking in Concrete, SP-20, American Concrete Institute, Farmington Hills, Mich., pp. 87–117.
11. Hognestad, E., 1961, “High strength bars as concrete reinforcement, Part 1—Introduction to a series of experimental reports,” Journal of the PCA Research and Development Laboratories, Vol. 3, No. 3, pp. 23-29.
12. Hognestad, E., 1962, “High strength bars as concrete reinforcement, Part 2—Control of flexural cracking,” Journal of the PCA Research and Development Laboratories, Vol. 4, No. 1, pp. 46-63.
13. National Institute of Standards and Technology, 2014. *Use of High Strength Reinforcement in Earthquake-Resistant Concrete Structure,* NIST GCR 14-917-30 Report prepared by the NEHRP Consultants Joint Venture, a partnership of the applied Technology Council and the Consortium of the Universities for Research in Earthquake Engineering for the National Institute of Standards and Technology, Gaithersburg, Maryland.
14. Sokoli, D., Shekarchi, W., Buenrostro, E., Ghannoum, M. W., (2014). "Advancing behavioral understanding and damage evaluation of concrete members using high-resolution digital image correlation data." Earthquakes and Structures, Vol.**7** No. 5, pp. 609-626.
15. Winter, G., & Nilson, A. H., 1986. *Design of concrete structures* (10th ed.). New York: McGraw-Hill.