ENGINEERING
ETN-M-8-16

Technical Note

High-Strength Reinforcing Bars

Introduction

Grade 60 reinforcing steel, with a yield strength of 60,000 psi, is the most commonly used Grade in North America. Recent advances have enabled reinforcing steels of higher strengths to be commercially produced.

In ATC 115 (ATC 2014), high-strength reinforcing bars (HSRB) were considered any reinforcing bar with a yield strength greater than 60,000 psi. This Technical Note presents pertinent information on the following topics related to HSRB:

- Material properties
- ACI 318 requirements and limitations
- Main benefits
- Issues related to design and detailing of reinforced concrete members
- Availability

ACI 318 is periodically updated to include requirements for higher strength reinforcing bars as new reinforcing steel products appear in the marketplace. The following is a brief history of the appearance and adoption of the various Grades of reinforcing bars in ASTM specifications and ACI 318:

- Grades 33, 40, and 50 were in common use from the early 1900s through the early 1960s.
- Grades 60 and 75 reinforcing bars appeared in 1959 with publication of ASTM A432 (ASTM 1959a) and ASTM A431 (ASTM 1959b), respectively.
- The 1963 edition of ACI 318 allowed the use of reinforcing bars with a yield strength of 60,000 psi.
- In 1968, ASTM A615 first appeared, which included Grades 40, 60, and 75 deformed reinforcing bars.
- Grade 75 bars appeared in the 2001 edition of ASTM 955, and Grade 100 bars appeared in the inaugural 2004 edition of ASTM 1035[1]. The 2007 editions of these specifications first appeared in ACI 318-08, with ASTM 1035 containing requirements for both Grade 100 and Grade 120 bars.
- A yield strength of 100,000 psi was permitted for confinement reinforcement in the 2005 edition of ACI 318 for use in non-seismic applications and then in the 2008 edition of ACI 318 for use in seismic applications.
- The 2009 editions of ASTM A615 and ASTM A706 were the first to include requirements for Grade 80 reinforcing bars, which were adopted into the 2011 edition of ACI 318.

Tables 20.2.2.4a and 20.2.2.4b of the 2014 edition of ACI 318 (ACI 2014) contain the latest requirements and limitations for nonprestressed deformed reinforcement and nonprestressed plain spiral reinforcement, respectively. This document focuses on ASTM A615 and A706 reinforcing bars.

Currently available reinforcing bar grades, minimum yield strengths, and minimum tensile strengths are given in Table 1. The information in the table is taken from the respective ASTM specifications.

ASTM A706 requires that the actual tensile strength f_u shall not be less than 1.25 times the actual yield strength f_y (ASTM 2016b). Additional information on this requirement is given below. The other types of reinforcing steel are not subject to any similar requirement. ASTM A706 is also currently available only up to Grade 80 primarily due to the chemical composition restrictions in that specification related to weldability without preheating.

[1] Disclaimer: This CRSI document contains requirements that can, at the time of the document's adoption by CRSI, be satisfied only by use of a patented material, product, process, procedure, or technology. During the document preparation, the committee and Engineering Practice Committee (EPC) were informed in writing that the document under consideration involves the potential use of patented technology. The specific patented products being referenced include the following: reinforcing steel bar produced to ASTM A1035/A1035M and certain stainless steel alloys listed in Table 1 of ASTM A276.

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Table 1 – Currently Available Reinforcing Bar Grades

ASTM Designation and Type		Available Grades	Minimum Yield Strength, f_y (psi)	Minimum Tensile Strength, f_u (psi)
A615, Carbon-Steel		40	40,000	60,000
		60	60,000	90,000
		75	75,000	100,000
		80	80,000	105,000
		100	100,000	115,000
A706, Low-Alloy Steel*		60	60,000	80,000
		80	80,000	100,000
A955, Stainless-Steel		60	60,000	90,000
		75	75,000	100,000
A996	Rail-Steel	50	50,000	80,000
		60	60,000	90,000
	Axle-Steel	40	40,000	70,000
		60	60,000	90,000
A1035†, Low-Carbon, Chromium	CL	100	100,000	130,000
		120	120,000	150,000
	CM, CS	100	100,000	150,000
		120	120,000	150,000

** Maximum yield strength is 78,000 psi and 98,000 psi for Grades 60 and 80, respectively.*
† Chemical compositions for the different alloy types are given in Table 2 of ASTM A1035 (ASTM 2016e).

Bar designation numbers, nominal weights, nominal diameters, nominal cross-sectional areas, and nominal perimeters for currently available reinforcing bars can be found in Table 2. Specifications for #20 bars were first introduced in the 2015 edition of ASTM A615 (ASTM 2015b). Note that not all bar sizes are available in all Grades. Refer to the applicable ASTM specifications for more information.

In the following sections, information is provided on the material properties of HSRB and how those properties compare to Grade 60 reinforcing bars. Also discussed are ACI 318 requirements and limitations, main benefits of its use in structural members, design and detailing issues that need to be considered when specifying HSRB, and availability.

Material Properties

The design of any reinforced concrete member must satisfy the fundamental requirements for strength and serviceability as prescribed in ACI 318. With respect to reinforcing bars, the basic mechanical properties that are important in achieving safe and serviceable designs are the following:

- Yield strength, f_y
- Tensile-to-yield strength ratio, f_u / f_y
- Strain (elongation) at tensile strength, ε_u
- Length of yield plateau

Stress-strain Curves with a Well-defined Yield Strength

Figure 1 contains nomenclature for key points on the tensile stress-strain curve of reinforcing bars; these points represent important material properties[2]. Depicted is a generic stress-strain curve that has three distinct segments, which is characteristic for bars with a yield strength of 60,000 psi or less: (1) an initial linear-elastic segment up to a well-defined yield strength f_y; (2) a relatively flat yield plateau up to the onset of strain hardening, the strain at which is designated ε_{sh}; and (3) a rounded strain-hardening segment.

[2] The stress and strain values in the figures are for illustration purposes only; results obtained from tests may give different values. The same is true for the values in Figures 2 and 3..

Table 2 – Deformed Reinforcing Bar Designation Numbers, Nominal Weights, and Nominal Dimensions

Bar Designation No.	Nominal Weight (lb/ft)	Nominal Diameter (in.)	Nominal Area (in.^{2})	Nominal Perimeter (in.)
#3	0.376	0.375	0.11	1.178
#4	0.668	0.500	0.20	1.571
#5	1.043	0.625	0.31	1.963
#6	1.502	0.750	0.44	2.356
#7	2.044	0.875	0.60	2.749
#8	2.670	1.000	0.79	3.142
#9	3.400	1.128	1.00	3.544
#10	4.303	1.270	1.27	3.990
#11	5.313	1.410	1.56	4.430
#14	7.65	1.693	2.25	5.32
#18	13.60	2.257	4.00	7.09
#20*	16.69	2.500	4.91	7.85

**Specifications for #20 bars are in ASTM A615 only.*

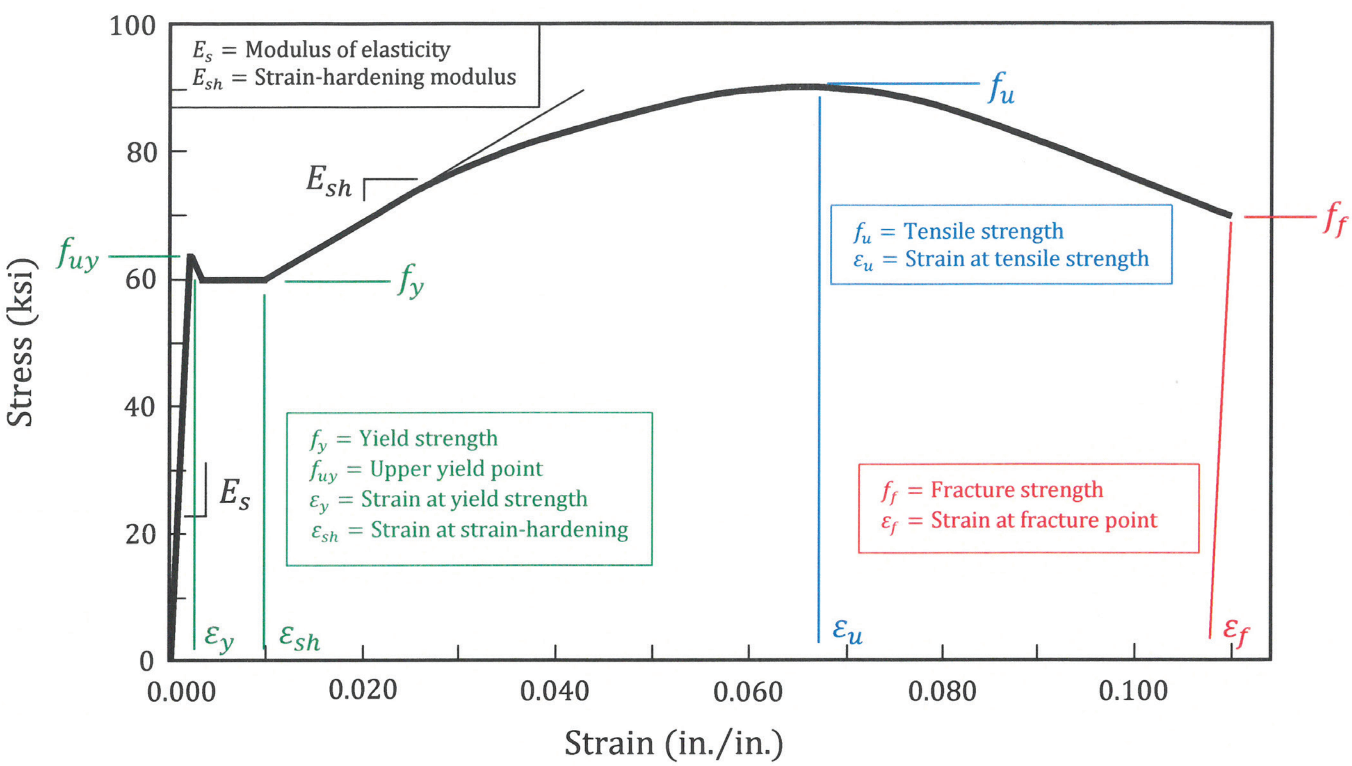

Figure 1 – Nomenclature for stress-strain curve of reinforcing bars.

ASTM A370 (ASTM 2015a) defines yield stress as the first stress in a material, less than the maximum obtainable stress, at which an increase in strain occurs without an increase in stress. Where the stress-strain diagram is characterized by a sharp-kneed or well-defined yield point, such as the one illustrated in Figure 1, the halt-of-force method can be used to determine the yield strength (see ACI 20.2.1.2[3]). In this method, an increasing force is applied to a tensile test specimen at a specified uniform rate. The load at which the force hesitates corresponds to the yield strength of the reinforcing bar.

[3] All references to ACI 318 (ACI 2014) are given as "ACI" followed by the appropriate section number.

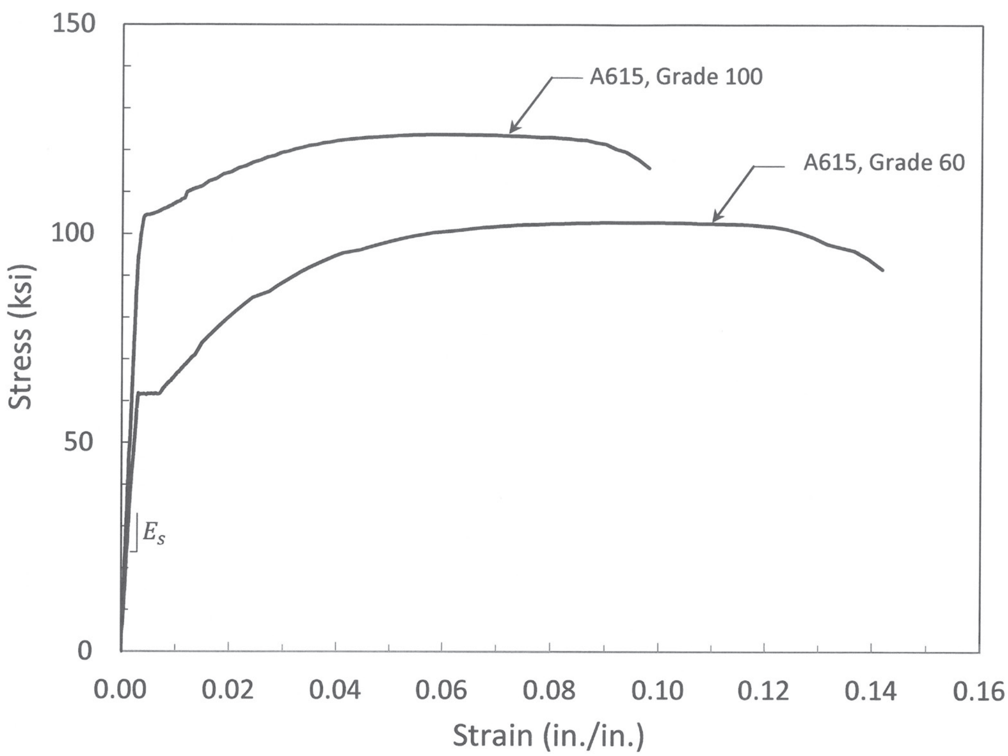

Figure 2 – Stress-strain curves for A615 reinforcing bars of Grades 60 and 100.

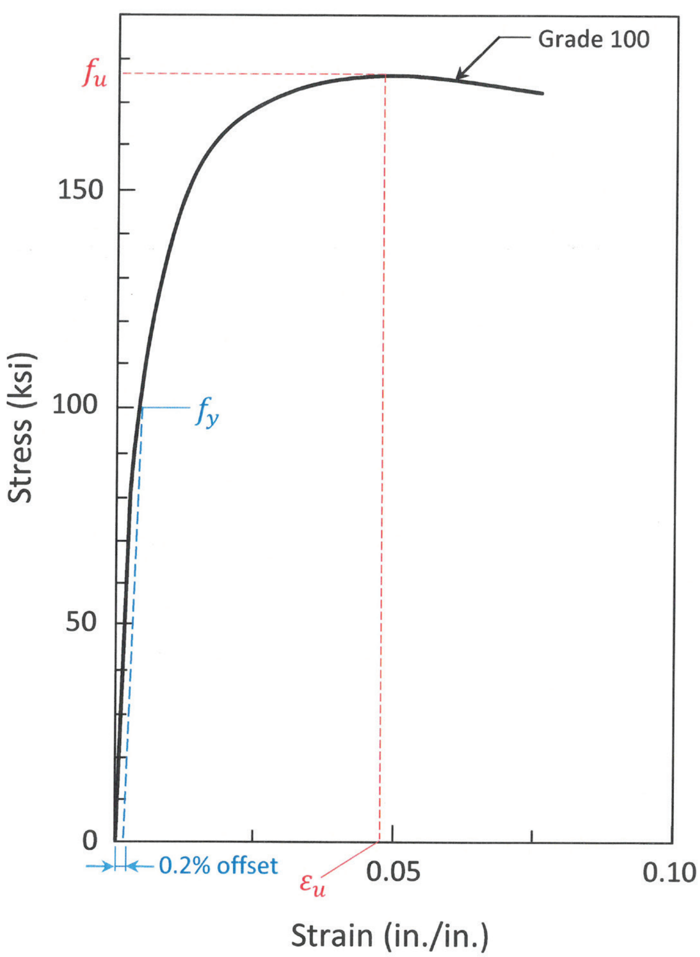

Figure 3 – Rounded stress-strain curve for Grade 100 reinforcing bars.

The slope of the initial linear segment of the stress-strain curve is the modulus of elasticity E_s. Note that test values of E_s may be of the order of 26,000,000 to 28,000,000 psi because the bar area is not constant due to transverse deformations. However, for design purposes, E_s is permitted to be taken as 29,000,000 psi as prescribed in ACI 20.2.2.2. The strain-hardening modulus E_{sh} is the slope that is tangent to the initial portion of the strain-hardening segment of the stress-strain curve. It is variable and not specified in any of the ASTM specifications nor described in ACI 318.

Most Grade 60 and lower reinforcing bars will have yield plateaus as depicted in Figure 1; the yield plateau is generally longer the lower the strength of the steel. Higher strength bars may or may not have yield plateaus, as discussed below.

The maximum tensile stress that a bar can be subjected to is defined as the tensile strength, f_u. The strain ε_u that occurs at the tensile strength f_u is commonly referred to as uniform elongation, which is the largest elongation in the bar for which the tensile strains are uniform throughout the length of the bar (see Figure 1). This generally occurs right before the onset of necking. For strains larger than ε_u, the strain becomes localized and the bar necks down; cross-sectional area of the reinforcing bar is different than the original cross-sectional area because of necking. This reduction in cross-sectional area makes the apparent stress in the bar decrease as no change is made to provide for this reduction in area in the calculation of stress. Portions of the bar sufficiently away from the necking zone cease to elongate. Although it is typically not reported, uniform elongation is useful in the design of structures subjected to seismic effects because this is the maximum strain that should be relied upon at a location where yielding of the reinforcing bar may occur (i.e., in an anticipated plastic hinge region in the member).

The strain at the fracture point ε_f is the total elongation over a prescribed gauge length that extends across the fracture of a reinforcing bar. According to Annex 9 in

ASTM A370 (ASTM 2015a), a reinforcing bar is marked with an initial 8-inch gauge length and is pulled to fracture. The ends of the fractured reinforcing bar are fit together and the distance between the gauge marks is re-measured. The total elongation is calculated as the percent increase in length relative to the original gauge length, that is,

$$\text{Total elongation (\%)} = \frac{\text{Distance between the gauge marks after fracture} - \text{Original gauge length}}{\text{Original gauge length}} \times 100$$

Stress-strain Curves and Yield Strength for HSRB

Depicted in Figure 2 are typical tensile stress-strain curves for ASTM A615 reinforcing bars of Grades 60 and 100. The initial elastic segments of the stress-strain curves are essentially the same for both Grades. Also, a well-defined yield plateau for the Grade 100 reinforcing bars is not evident.

The stress-strain curves for some types of Grade 100 reinforcing bars can be more rounded in shape than the one shown in Figure 2; these are commonly referred to as round house or continuously yielding curves (see Figure 3). After an initial linear-elastic segment, a gradual reduction in stiffness occurs; behavior becomes nonlinear before reaching a yield strength f_y that is defined by the 0.2% offset method. This is followed by gradual softening until the tensile strength f_u is reached.

The 0.2% offset method of ASTM A370 (ASTM 2015a) is specified by ASTM A615 (ASTM 2016a), ASTM A706 (ASTM 2016b), ASTM A955 (ASTM 2016c), ASTM A996 (ASTM 2016d), and ASTM A1035 (ASTM 2016e) to determine f_y where a stress-strain curve does not have a well-defined yield point. ACI 20.2.1.2 also references this method[4]. First, a strain is located on the strain axis a distance of 0.002 in./in. from the origin (see Figure 3). A line emanating from this point is then drawn parallel to the initial linear portion of the stress-strain curve. The point where this line intersects the stress-strain curve is defined as f_y.

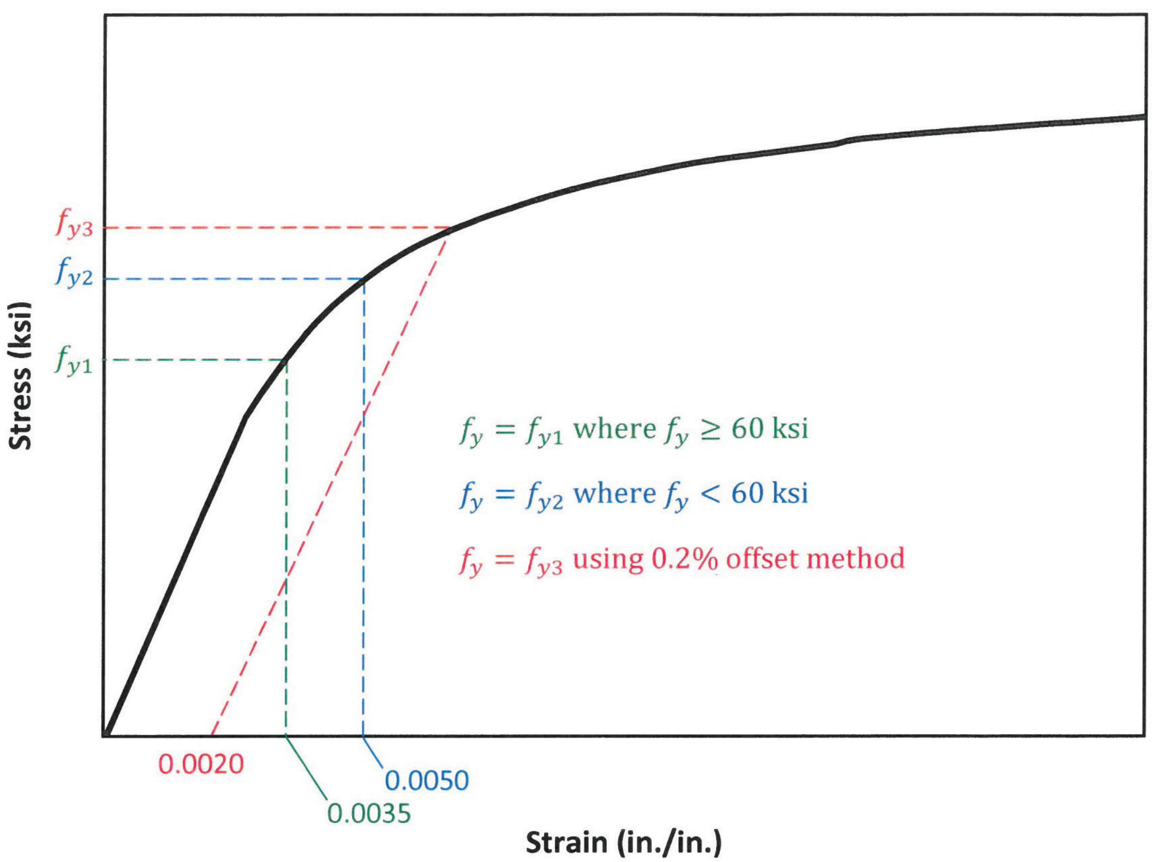

Figure 4 – Determination of yield strength using the extension under load (EUL) method and the 0.2% offset method.

[4] A recent study has demonstrated that for beams and columns with reinforcing bars up to and including a yield strength of 80,000 psi, the stress-strain curves based on the 0.2% offset method produce analytical strengths greater than or equal to those corresponding to the provisions of ACI 318 (Paulson et. al. 2016). As such, the results of the investigation justify the use of the 0.2% offset method to define the yield strength of reinforcing bars. A proposal based on these results was submitted for consideration by ACI Committee 318 and approved for adoption in ACI 318-14 (ACI 2014).

ASTM A370 (ASTM 2015a) also contains the extension under load (EUL) method to determine the yield strength in cases where a well-defined yield point is not evident on the stress-strain curve. This method was referenced in editions of ACI 318 prior to 2014 (but is not referenced in the 2014 edition) where yield strength is defined as follows (see Figure 4):

- For $f_y < 60{,}000$ psi: Yield strength shall be taken as the stress corresponding to a strain of 0.50 percent
- For $f_y \geq 60{,}000$ psi: Yield strength shall be taken as the stress corresponding to a strain of 0.35 percent

For comparison purposes, the yield strength determined by the 0.2% offset method is also indicated in Figure 4. It is evident that the EUL method reports a lower yield strength in this case.

In general, the tensile-to-yield strength ratio, the elongation at tensile strength, and the length of the yield plateau all decrease (or, in the case of the yield plateau, can become nonexistent) as the yield strength increases. Additional information on these quantities as they relate to design issues are discussed below.

Ductility

Ductility of reinforcing bars is evaluated by the magnitude of ε_u on the stress-strain curve. The bend test is one method for evaluating ductility; however, it cannot be considered as a quantitative means of predicting service performance in all bending operations. Requirements for bend tests are given in the ASTM specifications for the grade of reinforcing bar. Bars are bent around a pin (or, mandrel) of a specified diameter and to a degree of bending specified in the appropriate specification. The bend diameter varies with the bar diameter. The bar passes the bend test if no cracks appear on the outside radius of the bent portion of the bar. Typically, reinforcing bars are fabricated using the ACI 318 requirements for minimum inside bend diameters (ACI 25.3), which are independent of grade and are larger than those prescribed in the ASTM specifications. It is important to note that bar ductility and ductility of an entire structure are two separate issues that need to be addressed when designing and detailing a reinforced concrete structure, especially for those structures that are assigned to higher Seismic Design Categories (SDC).

ACI 318 Limitations and Requirements Related to HSRB

ACI Tables 20.2.4.4a and 20.2.2.4b contain limitations on the maximum value of yield strength of nonprestressed deformed reinforcement and nonprestressed plain spiral reinforcement, respectively, based on various usages and applications in reinforced concrete structures. Summaries of the limitations for deformed bars and plain spiral bars are given in Tables 3 and 4, respectively.

Compression Reinforcement. The yield strength of compression reinforcement is limited to 80,000 psi for use in applications other than special seismic systems. This limit is imposed because bars with yield strengths greater than approximately 80,000 psi will not contribute to increased compression capacity: at a strain of 0.003

Table 3 – ACI 318 Yield Strength Limitations for Deformed Reinforcing Bars

Usage	Application	Maximum f_y or f_{yt} Permitted for Design Calculations (psi)	Applicable ASTM Specifications
Flexure; Axial force; Shrinkage and temperature	Special seismic systems	60,000	Refer to ACI 20.2.2.5
	Other	80,000	A615, A706, A955, A996
Lateral support of longitudinal bars; Concrete confinement	Special seismic systems	100,000	A615, A706, A955, A996, A1035
	Spirals	100,000	A615, A706, A955, A996, A1035
	Other	80,000	A615, A706, A955, A996
Shear	Special seismic systems	60,000	A615, A706, A955, A996
	Spirals	60,000	A615, A706, A955, A996
	Shear friction	60,000	A615, A706, A955, A996
	Stirrups, ties, hoops	60,000	A615, A706, A955, A996
Torsion	Longitudinal and transverse	60,000	A615, A706, A955, A996

Table 4 – ACI 318 Yield Strength Limitations for Plain Spiral Reinforcing Bars

Usage	Application	Maximum f_y or f_{yt} Permitted for Design Calculations (psi)	Applicable ASTM Specifications
Lateral support of longitudinal bars; Concrete confinement	Spirals in special seismic systems	100,000	A615, A706, A955, A1035
	Spirals	100,000	A615, A706, A955, A1035
Shear	Spirals	60,000	A615, A706, A955, A1035
Torsion in nonpre-stressed beams	Spirals	60,000	A615, A706, A955, A1035

at the extreme concrete compression fiber of a reinforced concrete section (the strain assumed at crushing of the concrete), the maximum usable stress in the reinforcing steel would be 87,000 psi based on linear-elastic behavior (ACI 22.2.2.1). Note that Grade 100 longitudinal reinforcement may be used in columns provided the aforementioned limit of 80,000 psi is used in the calculations in accordance with ACI 318. Recent tests revealed that longitudinal reinforcement with a yield strength greater than 100,000 psi yielded in columns subjected to uniaxial loads where high-strength concrete with a compressive strength of 29,000 psi was used (Shin et. al. 2016). The compressive strain in the concrete was found to be greater than 0.004 under short-term loading; this enabled the high-strength longitudinal reinforcement to contribute to increased compression capacity.

Shear and Torsion Reinforcement. The limit of 60,000 psi for shear and torsion reinforcement is intended to control the width of inclined cracks that tend to form in reinforced concrete members subjected to these types of forces. References to research that supports the use of 100,000 psi reinforcing bars for lateral support of longitudinal bars and concrete confinement, including special seismic systems, can be found in ACI R20.2.2.4.

Longitudinal Bars in Special Seismic Systems. Only deformed longitudinal bars conforming to (a) and (b) below are permitted by ACI 318-14 in special seismic systems (special moment frames, special structural walls, and all components of special structural walls, including coupling beams and wall piers) to resist the effects caused by flexure, axial force, and shrinkage and temperature. Higher grades of reinforcement were not included because at that time, there was insufficient data to confirm applicability of existing ACI 318 provisions for members with higher Grades of reinforcement[5]. These special systems are required in structures assigned to SDC D and higher.

Deformed longitudinal reinforcing bars used in structures assigned to SDC D or higher must conform to the following provisions (ACI 20.2.2.5):

(a) ASTM A706, Grade 60

(b) ASTM A615, Grade 40 provided the requirements in (i) and (ii) are satisfied; and ASTM A615, Grade 60 provided the requirements in (i) through (iii) are satisfied.

(i) Actual yield strength based on mill tests does not exceed f_y by more than 18,000 psi.

(ii) Ratio of the actual tensile strength to the actual yield strength is at least 1.25.

(iii) Minimum elongation in an 8 in. gauge length shall be at least 14% for bar sizes #3 through #6, at least 12% for bar sizes #7 through #11, and at least 10% for bar sizes #14 and #18.

In (i), the upper limit is placed on the actual yield strength of the longitudinal reinforcement in special seismic systems because brittle failures in shear or bond could occur if the strength of the reinforcement is substantially higher than that assumed in the design (higher strength reinforcement leads to higher shear and bond stresses).

In (ii), the requirement that the tensile strength of the reinforcement be at least 1.25 times the yield strength is based on the assumption that the capability of a structural member to develop inelastic rotation capacity is a function of the length of the yield region along the axis of the member. It has been shown that the length of the yield region is related to the relative magnitudes of nominal and yield moments: the greater the ratio of nominal to yield moment, the longer the yield region. Inelastic rotation can be developed in reinforced concrete members that do not satisfy this condition, but they behave in a manner significantly different than members that conform to this provision.

[5] Test results for HSRB in seismic applications were subsequently referenced in NIST GCR 14-917-30 (NIST 2014). Based primarily on these test results, it is anticipated that the use of ASTM A706 deformed reinforcing bars with a yield strength of 80,000 psi will be permitted in the 2019 edition of ACI 318 for use in special seismic systems.

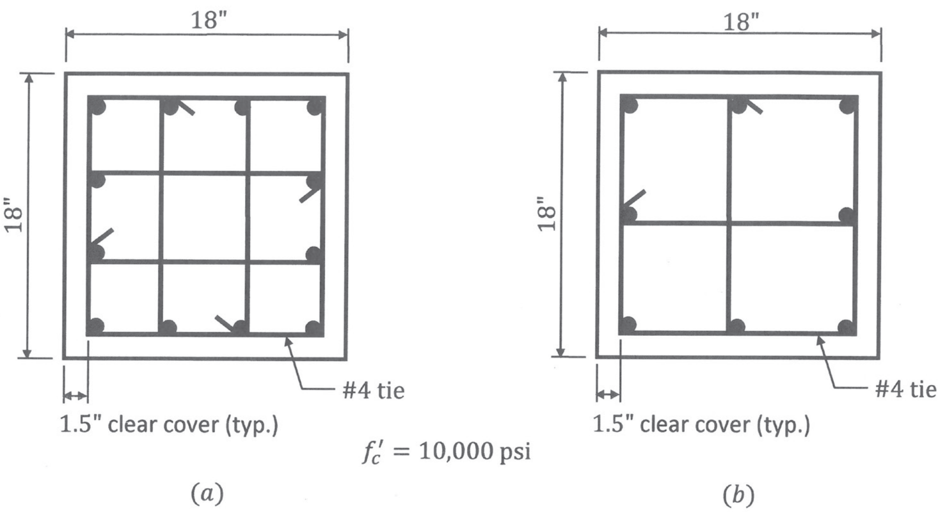

Figure 5 – Reinforced concrete column. (a) Grade 60 reinforcement (b) Grade 80 reinforcement.

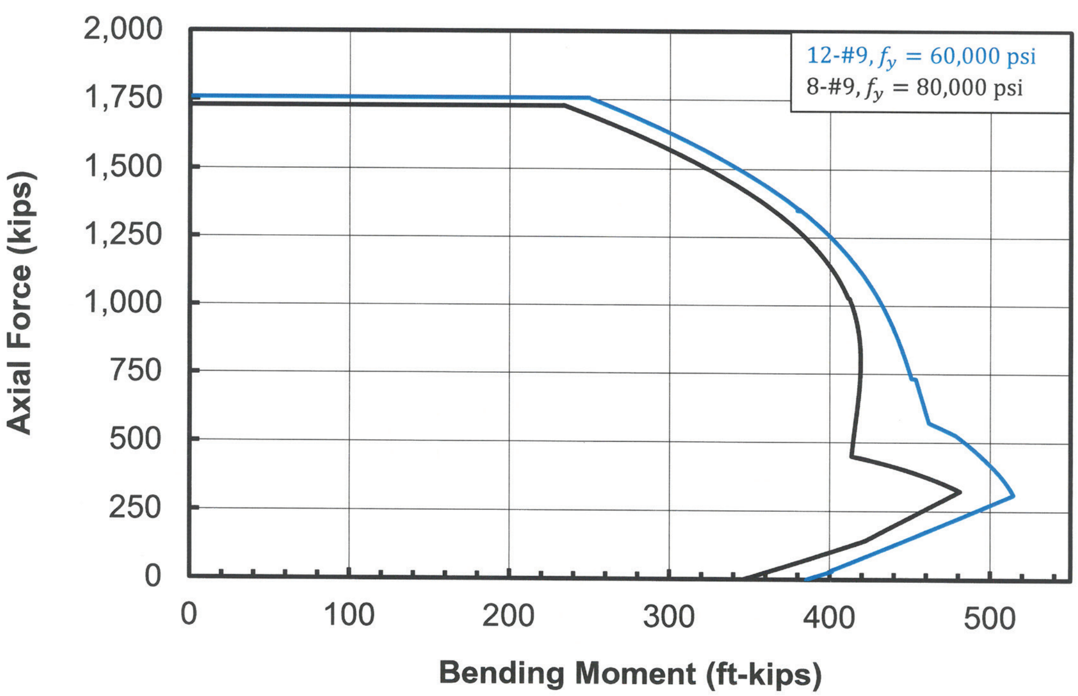

Figure 6 – Interaction diagrams of the columns in Figure 5 with 12-#9 bars (Grade 60) and 8-#9 bars (Grade 80).

In (iii), the required minimum elongations for ASTM A615, Grade 60 reinforcement were added in ACI 318 (ACI 2014) and are the same as those required for ASTM A706, Grade 60 reinforcement.

Additional information on the use of HSRB in reinforced concrete structures subjected to the effects from earthquakes can be found in NIST GCR 14-917-30 (NIST 2014).

Benefits and Limitations of HSRB

Utilizing HSRB in concrete members may result in smaller bar sizes and/or a fewer number of bars compared to members reinforced with Grade 60 or lower bars. It may also permit smaller member sizes. By specifying HSRB, the following may be attained:

- Lower placement costs
- Less congestion, especially at joints
- Improved concrete placement and consolidation
- Smaller member sizes
- More useable space

Consider the reinforced concrete column illustrated in Figure 5a. For architectural reasons, the cross-sectional

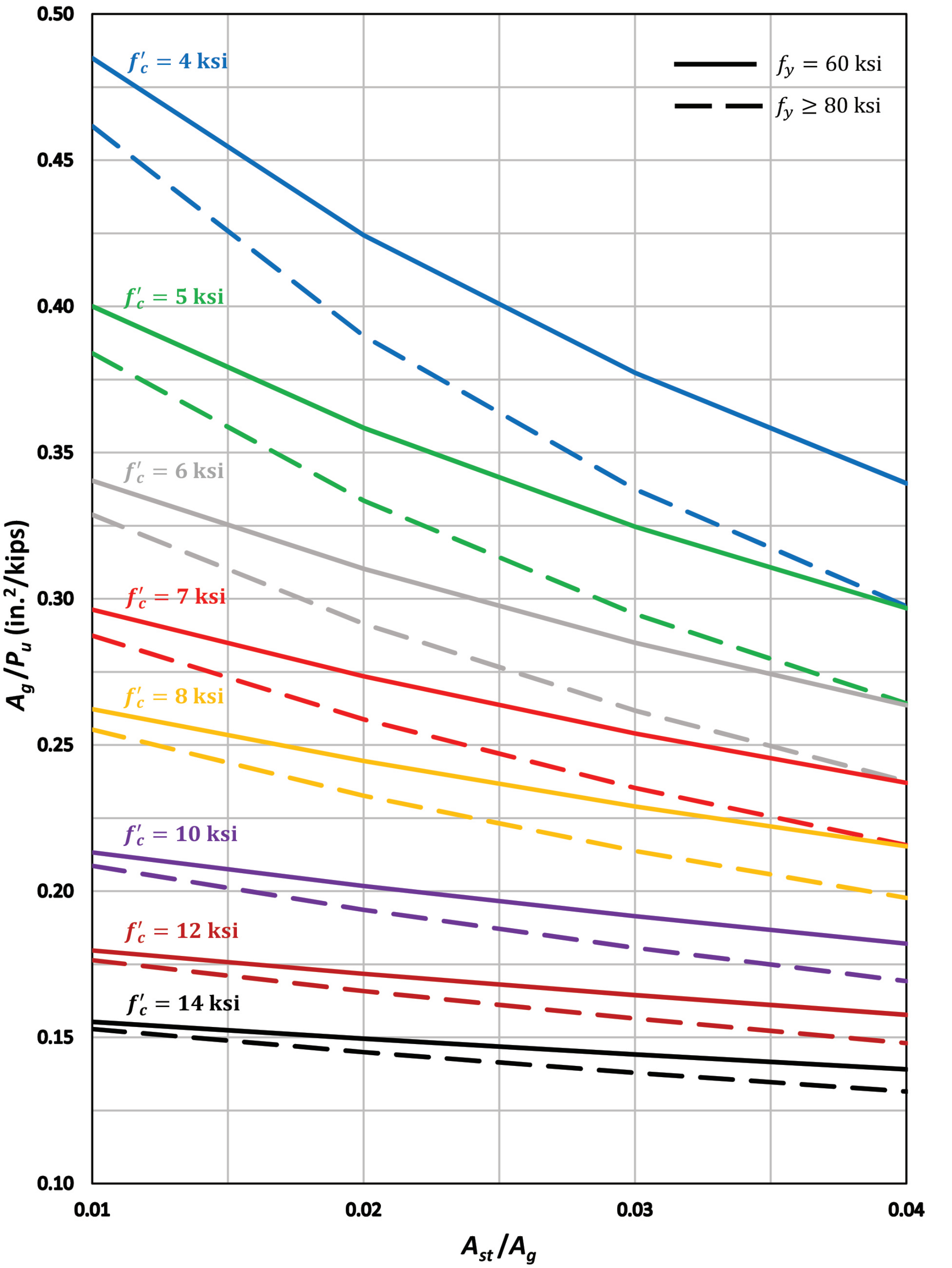

Figure 7 – Required column area A_g as a function of reinforcing bar yield strength f_y, concrete compressive strength f'_c, and amount of longitudinal reinforcement A_{st}.

dimensions are limited to 18 in. Assuming that the column is nonslender and that it is subjected to a concentric factored axial load P_u = 1,700 kips, the required longitudinal reinforcement using Grade 60 reinforcement is 12 #9 bars (ρ_g=3.7%) with f'_c = 10,000 psi. This is a relatively large reinforcement ratio and at locations of lap splices, ρ_g= 7.4%, which is slightly less than the code-prescribed maximum value of 8%. Additionally, the clear spacing between the longitudinal bars is about 3 in. The combination of large reinforcement ratio and relatively small clear spacing could cause considerable congestion issues at the joints.

If Grade 80 bars were utilized instead (see Figure 5b), 8 #9 bars would be required (ρ_g= 2.5%). Not only is the reinforcement ratio more reasonable, the likelihood of congestion at the joints is also significantly reduced (the clear space between the bars is almost 5.5 in.). A comparison of the interaction diagrams of the column with different bar grades is given in Figure 6.

The cross-sectional area of a column with high-strength longitudinal bars may be smaller compared to one with Grade 60 bars, which could translate into more useable space. Figure 7 illustrates how the gross area of a column A_g decreases as a function of the yield strength f_y for various concrete compressive strengths f'_c and amounts of longitudinal reinforcement A_{st}. It is clear from the Figure that combining high-strength reinforcement and high-strength concrete has the greatest impact on decreasing the required column area for a given percentage of longitudinal reinforcement A_{st}/A_g. When reinforced concrete members are reduced in cross-section, it is always important to keep in mind the possibility of congestion issues that may accompany the size reduction.

Design Issues Related to HSRB

Design professionals can design reinforced concrete structures with HSRB using the requirements and limits prescribed in ACI 318-14, which are summarized in Table 3 for deformed bars. It is important to note that some provisions of ACI 318 may need adjustment before HSRB can be used in applications where the yield strength is greater than the limits prescribed in Table 3 (for example, using longitudinal tension reinforcement with a yield strength of 100,000 psi in beams). As new research and/or new analytical studies becomes available related to the use of HSRB, it is anticipated that ACI 318 will be updated accordingly. For example, as discussed previously, ACI Committee 318 will be considering the general use of Grade 80 reinforcement in special seismic systems as well as some other possible modifications related to HSRB in the next edition of ACI 318 based on some recent research.

A brief summary is given below on some design issues related to the use of HSRB and the potential impact on ACI 318 provisions. The following list of issues and observations is not meant to be comprehensive nor is it meant to discourage the use of HSRB. Rather, it is provided so that design professionals have a clearer understanding of what ACI 318 provisions may need adjustment and what additional information is required for general use of HSRB beyond the limitations in Table 3. In-depth information on these and other issues can be found in ATC 115 (ATC 2014).

Strength

1. Flexure and axial load strength

(a) Compression-controlled sections are defined as those where the net tensile strain ε_t does not exceed the compression controlled strain limit ε_{ty}, which is defined in ACI 21.2.2.1 as f_y/E_s. The current definition of ε_{ty} is based on a stress-strain curve that is linear-elastic to the yield plateau. For HSRB with a rounded stress-strain curve (see Figure 3) where f_y must be determined by the 0.2% offset method, the definition of ε_{ty} may need to be revised from f_y/E_s. In lieu of revising the definition, specific values of ε_{ty} can be provided for different grades, similar to prestressed reinforcement (see ACI 21.2.2.2).

(b) Tension-controlled sections are defined as those where the net tensile strain ε_t is equal to or greater than the tension-controlled strain limit of 0.005. The limiting value of 0.005 is approximately 2.5 times the yield strain of 0.002 for ASTM A615 Grade 60 reinforcement. The yield strain will typically be larger for HSRB, so it may be appropriate to increase the tension-controlled strain limit of 0.005 to provide levels of ductility consistent with the current provisions.

(c) For nonprestressed one-way slabs, two-way slabs, and beams, the net tensile strain ε_t must be equal to or greater than 0.004 to mitigate brittle flexural behavior in case of an overload (see ACI 7.3.3.1, 8.3.3.1, and 9.3.3.1, respectively). For HSRB, the elongation capacity ε_u is generally less than that for Grade 60 reinforcing bars, so the limit may need to be revised accordingly.

(d) Current methods for calculating the flexural strength of one-way slabs, two-way slabs, and beams assumes that the stress-strain curve of the reinforcement includes a yield plateau. For members reinforced with HSRB without a yield plateau, the current methods to determine flexural strength must be validated analytically and/or experimentally.

2. Shear strength

(a) Research has shown that one-way and two-way shear strength of the concrete is influenced by the longitudinal reinforcement ratio: the larger the ratio, the larger the concrete shear strength. Using HSRB may result in a smaller required longitudinal reinforcement ratio, which may lead to reduced concrete shear strength.

(b) For HSRB that are utilized as shear reinforcement, crack control needs to be addressed in cases where the yield strength exceeds 60,000 psi.

Serviceability

1. Deflections

(a) The minimum member thicknesses in ACI 7.3.1, 8.3.1, and 9.3.1 for one-way slabs, two-way slabs, and beams, respectively, need to be verified for members utilizing HSRB.

(b) The equation for the effective moment of inertia I_e of nonprestressed members in ACI 24.2.3.5, which is used in calculating deflections of reinforced concrete members, needs to be verified for members utilizing HSRB.

(c) The time-dependent deflection factor λ_Δ in ACI 24.2.4.1.1 that is used in calculating long-term deflections is independent of the yield strength of the reinforcement in the member. This factor needs to be verified for HSRB.

2. Drift

(a) Depending on a number of factors, there is a potential for increased flexural cracking to occur in reinforced concrete flexural members with HSRB. As such, a reduction in the flexural stiffness is anticipated, resulting in possible larger drift.

(b) Increased cracking is not anticipated in columns with HSRB. However, the amount of longitudinal reinforcement and/or the size of the column may be decreased, which would have an impact on stiffness and drift.

Other Design Considerations

1. Because development and lap splice lengths are proportional to the yield strength, f_y, these lengths for HSRB are longer, with a percentage increase of 25%, 33%, 67% and 100% for Grades 75, 80, 100 and 120, respectively, over Grade 60 bars. The use of mechanical splices and headed bars should be considered where appropriate. Headed bar and coupler options are available to anchor and connect HSRB, including large bar sizes.
2. ACI 25.4.4.1(b) limits headed bars to a yield strength no greater than 60,000 psi. With the inordinately longer development and lap splice lengths of HSRB, a greater emphasis will be placed on utilizing headed bars. Thus, further research is required in order to justify using headed bars to develop HSRB.
3. As noted previously, the use of HSRB in seismic-force-resisting systems is covered in NIST GCR 14-917-30 (2014). Pertinent design issues are covered in detail in that document.

Availability

Just like any other type of reinforcement, it is recommended to check with a local concrete contractor or reinforcing bar supplier to ensure that the grade and/or bar size of HSRB is available prior to design and production of the construction documents.

Summary

Provisions for the use of higher strength reinforcing bars have been incorporated into ACI 318 as new reinforcing steel products have become available. It is anticipated that this trend will continue as additional research and analytical studies validate the performance of HSRB in reinforced concrete members.

Designers can specify and utilize HSRB (with yield strengths greater than 60,000 psi) based on the current provisions and limitations in ACI 318-14 (see Table 3 for deformed reinforcing bars). Proposed modifications to the next edition of ACI 318 with respect to HSRB are currently under consideration. A number of jurisdictions in the U.S. permit the use of HSRB above and beyond the limitations set forth in the current ACI 318.

Cost-effective reinforced concrete structures may be realized by taking advantage of the benefits of HSRB, which include smaller required bar sizes and/or a smaller number of required bars, less congestion, lower placement costs, and smaller member sizes.

CRSI can assist designers and building authorities in all aspects on the use of HSRB. Contact CRSI for additional design information or questions about local code approval procedures.

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