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Guide for the Use of ASTM A1035/A1035M Type CS Grade 100 (690) Steel Bars for Structural Concrete

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Reported by ACI Committee 439

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This guide provides recommendations on design provisions for the use of ASTM A1035/ASTM A1035M Type CS Grade 100 (690) deformed steel bars for reinforced concrete members. The recommendations address only those requirements of ACI 318-14 that limit efficient use of such steel bars. Other code requirements are not affected. Any other ACI 318 versions will be explicitly specified. Although there are limiting ACI 318 requirements, ACI 318-14 Section 1.10 would allow the use of high-strength reinforcement. "Sponsors...shall have the right to present the data on which their design is based to the building official or to a board of examiners appointed by the building official."

The International Building Code (IBC 2012) would allow the same under Section 104.11, "Alternative materials, design and methods of construction and equipment". To approve an alternative material under this section, a building department would typically require an ICC Evaluation Service (ICC-ES) Evaluation Report, which would be based on an ICC-ES Acceptance Criteria (AC) document. An AC document (ICC-ES AC429) and an Evaluation Report (ICC-ES ESR-2107) exist, permitting the use of ASTM A1035/A1035M Grade 100 reinforcement.

This guide includes a discussion of the material characteristics of Grade 100 (690) ASTM A1035/A1035M (CS) deformed steel bars and recommends design criteria for beams, columns, slab, systems, walls, and footings for Seismic Design Category (SDC) A, B, or C, and for structural components not designated as part of the seismic-force-resisting system for SDC D, E, or F.

A structure assigned to SDC A, B, or C is required to be designed for all applicable gravity and environmental loads. In the case of SDC A structures, seismic forces are notional structural integrity forces. This guide addresses all design required for SDC A, B, and C structures.

Because the modulus of elasticity for ASTM A1035/A1035M (CS) is similar to that of carbon steel (ASTM A615/A615M) using higher specified minimum yield strength f_y may result in higher steel stress at service load condition and potentially cause wider cracks and larger deflections, which may be objectionable if aesthetics and water-tightness are critical design requirements. Higher deflection can also contribute to serviceability issues. Also, with higher f_y, the required development length will be longer.

Keywords: bar; design; guide; high-strength steel; structural.

ACI 439.6R-19 supersedes ACI ITG-6R-10 and was adopted and published February 2019.

CONTENTS

CHAPTER 1—INTRODUCTION

1.1—Objective

This guide is based on ACI ITG-6R-10, "Design Guide for the Use of ASTM A1035/A1035M Grade 100 (690) Steel Bars for Structural Concrete," reported by ACI Innovation Task Group 6. The ACI ITG-6R guide provides design provisions for the use of ASTM A1035/A1035M Type CS Grade 100 (690) deformed steel bars in reinforced structural members. This guide, which is based on ACI ITG-6R-10, is a stand-alone document, references and addresses only those requirements in ACI 318-14 that limit the use of such steel bars, and should not affect the application of other code requirements. Any other ACI 318 version will be explicitly specified. This guide includes a discussion of the material characteristics of Grade 100 (690) ASTM A1035/A1035M Type CS (Chromium content 8.0 to 10.9 percent) deformed steel bars, and the design provisions are based on the specific material properties and stress-strain behavior of these bars.

Although there are limiting ACI 318 requirements, ACI 318-14 Section 1.10 would allow the use of high-strength reinforcement. "Sponsors...shall have the right to present the data on which their design is based to the building official or to a board of examiners appointed by the building official."

The IBC International Building Code (IBC 2012) would allow the same under Section 104.11, "Alternative materials, design and methods of construction and equipment". To approve an alternative material under this section, a building department would typically require an ICC Evaluation Service (ICC-ES) Evaluation Report that would be based on an ICC-ES Acceptance Criteria (AC) document. An AC document (ICC-ES AC429) and an Evaluation Report (ICC-ES ESR-2107) exist, permitting the use of ASTM A1035/A1035M Grade 100 reinforcement.

Since publication of ACI ITG-6R, additional Grade 100 (690) ASTM A1035/A1035M Types CM (Chromium content 4.0 percent to 7.9 percent) and CL (chromium content 2.0 percent to 3.9) were introduced to the market. The mechanical properties and stress-strain characteristics of these steels may affect the design criteria herein and limit the applicability of the guide. Additionally, ASTM A615/A615M Grade 100 (690) was introduced to the market. These bars will be addressed in future editions when research on concrete members reinforced with these bar types become available and the impact of the mechanical properties have been documented. Grade 120 (830) ASTM A1035/A1035M Type CS, CM and CL are available, but are not addressed under this guide.

1.2—Scope

This guide presents the material characteristics of ASTM A1035/A1035M (CS) steel bars and recommends design criteria for beams, columns, slab systems, walls, and footings for Seismic Design Category (SDC) A, B, or C. A structure assigned to SDC A, B or C is required to be designed for all applicable gravity and environmental loads. In the case of SDC A structures, seismic forces are notional structural integrity forces. This guide addresses all design required for SDC A, B, and C structures. Due to lack of adequate data, the application of this guide for SDC D, E, or F is limited to slab systems, foundations, and structural components not designated as part of the seismic-force-resisting system, but explicitly checked for the induced effects of the design displacements. The only exception is the use of transverse reinforcement for concrete confinement with a specified minimum yield strength f_y up to 100,000 psi (690 MPa) in special moment frames, special structural walls, and all components of special structural walls including coupling beams and wall piers as permitted by ACI 318. Refer to 10.1 of this guide for more information on seismic design considerations. Shells, folded plate members, and prestressed concrete are beyond the scope of this guide. However, ASTM A1035/A1035M Type CS can be used as reinforcement in prestressed concrete but not as the prestressing strands. Design examples are included to illustrate design procedures and proper application of the design criteria. Modifications to these design criteria may be justified where the design adequacy within the scope of this guide is demonstrated by successful use, analysis, or test.

1.3—Historical perspective and background

For several decades prior to ACI 318-71, the design of structural concrete was restricted to using specified minimum yield strength f_y of 60,000 psi (420 MPa) or less for reinforcing bars. Section A603(e) of ACI 318-56 specified that "Stress in tensile and compressive reinforcement at ultimate load shall not be assumed greater than the yield point or 60,000 psi, whichever is smaller."

Section 1505 of ACI 318-63, specified two requirements:

"(a) When reinforcement is used that has a yield strength, f_y, in excess of 60,000 psi (420 MPa), the yield strength to be used in design shall be reduced to $0.85f_y$ or 60,000 psi (420 MPa), whichever is greater, unless it is shown by tension tests that at a proof stress equal to the specified minimum yield strength, f_y, the strain does not exceed 0.003;

(b) Designs shall not be based on a yield strength, f_y, in excess of 75,000 psi (520 MPa). Design of tension reinforcement shall not be based on a yield strength, f_y, in excess of 60,000 psi (420 MPa) unless tests are made in compliance with Section 1508(b)."

The Commentary on Section 1505 of ACI 318-63 states that:

> This section provides limitations on the use of high strength steels to assure safety and satisfactory performance. High strength steels frequently have a strain at yield strength or yield point in excess of the 0.003 assumed for the concrete at ultimate. The requirements of Section 1505(a) are to adjust to this condition.
>
> The maximum stress in tension of 60,000 psi (420 MPa) without test is to control cracking. The absolute maximum is specified as 75,000 psi (520 MPa) to agree with present ASTM specifications and as a safeguard until there is adequate experience with the high stresses.

Then, the Commentary on Section 1508 of ACI 318-63 states that:

> When the design yield point of tension reinforcement exceeds 60,000 psi (420 MPa), detailing for crack control becomes even more important. Entirely acceptable structures have been built, particularly in Sweden, with a design yield strength approaching 100,000 psi (690 MPa) but more design criteria for crack control and considerable American practical experience with 60,000 psi (420 MPa) yield strength tension reinforcement are needed before higher yield strengths are approved for general use. The Code, therefore limits *tension* reinforcement to 60,000 psi (420 MPa) yield strength, unless special full-scale tests are made. It was thought that 75,000 psi (520 MPa) yield strength tension reinforcement should be permitted where full-scale testing is economically feasible, such as in precast members. The crack width criteria are not too difficult to meet by proper attention to reinforcing details.

When the use of Grade 40 (280) reinforcing bars in the 1930s and 1940s was replaced by the use of Grade 60 (420) bars in the 1950s and 1960s, there were concerns about fatigue resistance of the higher-strength steel bars. Similar concerns were expressed about the use of ASTM A1035/A1035M (CS) steel bars when they were introduced. El-Hacha and Rizkalla (2002) and DeJong et al. (2006) conducted studies on the fatigue behavior of ASTM A1035/A1035M (CS) steel bars. Their results indicated that a fatigue life of 1×10^6 cycles was observed at a stress range of approximately 44,000 psi (310 MPa) for ASTM A1035/A1035M (CS) steel bars. The ASTM A1035/A1035M (CS) steel bars showed comparable fatigue resistance to Grade 60 (420) reinforcing bars even though their stress at service would be higher than that of Grade 60 (420) bars.

1.4—Reinforcing steel grades availability

The most widely used deformed reinforcing bars conform to ASTM A615/A615M, which include Grade 40 (280), Grade 60 (420), Grade 75 (520), and Grade 80 (550). The Grade 60 (420) reinforcement exhibits minimum yield strength of 60,000 psi (420 MPa) with a distinct yield plateau. ACI 318 permits use of reinforcing bars with a specified minimum yield strength f_y exceeding 60,000 psi (420 MPa), but f_y is limited to the lesser of 80,000 psi (550 MPa) or the stress corresponding to a strain of 0.0035, except as follows. ACI 318 limits the specified minimum yield strength for deformed bars used as shear reinforcement to 60,000 psi (420 MPa). For deformed bars used as confinement reinforcement (ties or spirals) in compression members, ACI 318 permits the use of specified minimum yield strength of up to 100,000 psi (690 MPa).

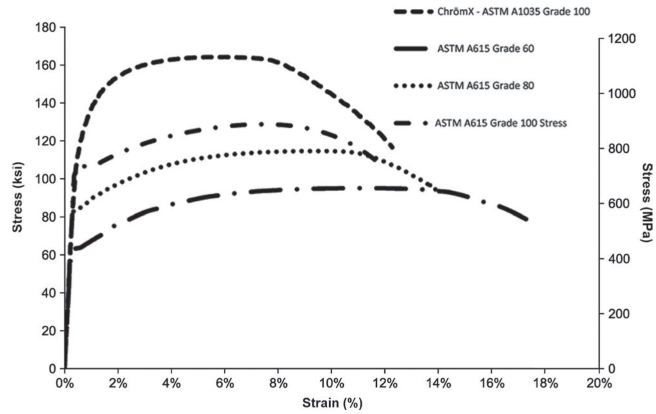

Fig. 1.5—Comparison of typical stress-strain curves for ASTM A615/A615M and ASTM A1035/A1035M (CS) reinforcing bars.

1.5—Introduction of ASTM A1035/A1035M Type CS Grade 100

The introduction of higher-strength steel reinforcing bars with a specified minimum yield strength, f_y = 100, the designers might be able to reduce the total cross-sectional area of required reinforcement. The reduced area of reinforcement could result in fewer bars and reduce reinforcement congestion often encountered in mat foundations, shear walls, beam-column joints, and many precast concrete elements. The reduction in reinforcement congestion facilitates concrete placement and consolidation.

The ASTM A1035/A1035M (CS) bar Grade 100 (690) (Fig. 1.5) exhibits a linear stress-strain relationship up to a proportional limit ranging from 60,000 to 80,000 psi (420 to 550 MPa), without a well-defined yield plateau. Refer to Appendix C of this guide for a discussion on how the lack of a well-defined yield plateau affects the flexural behavior of beams. Actual yield strength, determined by the 0.2 percent offset method, typically exceeds 115,000 psi (790 MPa) for Grade 100 (690) bars. The tensile strength typically exceeds 155,000 psi (1070 MPa) for Grade 100 (690) bars. The corresponding strain at the peak of the stress-strain curve ranges from 0.04 to 0.06. Refer to Chapter 3 of this guide for more details on the material characteristics of ASTM A1035/A1035M (CS) reinforcing bars.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A_s = area of nonprestressed longitudinal tension reinforcement, in.^{2} (mm^2)

A_s' = area of nonprestressed longitudinal compression reinforcement, in.^{2} (mm^2)

A_{tr} = total cross-sectional area of all transverse reinforcement that is within the spacing s and crosses the potential plane of splitting through the reinforcement being developed or lap spliced, in.^{2} (mm^2); refer to Eq. (10.2b)

a = depth of equivalent rectangular stress block as defined in ACI 318, in. (mm)

b = width of compression face of member, in. (mm)
b_w = web width, in. (mm)
C = force in the compression zone of a beam, lbf (N)
c = distance from extreme compression fiber to neutral axis, in. (mm)
c_b = $c_{min} + 0.5d_b$, in. (mm); refer to Eq. (10.2a)
c_{bb} = clear cover of reinforcement being developed or lap spliced, measured to tension face of member, in. (mm)
c_c = clear cover to tension steel, in. (mm)
c_{max} = maximum value of c_s or c_{bb}, in. (mm)
c_{min} = minimum value of c_s or c_{bb}, in. (mm)
c_s = minimum value of c_{si} + 0.25 in. (6.35 mm) or c_{so}, in. (mm); c_{si} may be used instead of c_{si} + 0.25 in. (6.35 mm)
c_{si} = one-half of average clear spacing between bars or lap splices in a single layer, in. (mm)
c_{so} = clear cover of reinforcement being developed or lap spliced, measured to side face of member, in. (mm)
d = distance from extreme compression fiber to centroid of longitudinal tension reinforcement, in. (mm)
d' = distance from extreme compression fiber to centroid of longitudinal compression reinforcement, in. (mm)
d_b = bar diameter, in. (mm)
d_t = distance from extreme compression fiber to centroid of extreme layer of longitudinal tension reinforcement, in. (mm)
E_c = modulus of elasticity of concrete, psi (MPa)
E_s = modulus of elasticity of reinforcement, psi (MPa)
f_c' = specified compressive strength of concrete, psi (MPa)
f_s = calculated tensile stress in reinforcement, psi (MPa)
f_u = specified ultimate strength of reinforcement, psi (MPa)
f_y = specified minimum yield strength of reinforcement, psi (MPa)
f_{yt} = specified minimum yield strength of transverse reinforcement, psi (MPa)
h = overall height or thickness of member, in. (mm)
h_f = flange thickness of T-beam, in. (mm)
I_{cr} = moment of inertia of cracked section transformed to concrete, in.^{4} (mm^4)
I_e = effective moment of inertia for computation of deflection, in.^{4} (mm^4)
I_g = moment of inertia of gross concrete section about centroidal axis, neglecting reinforcement, in.^{4} (mm^4)
K_{tr} = transverse reinforcement index; refer to Eq. (10.2b)
ℓ_d = development length (also splice length), in. (mm)
M = applied moment at critical section, in.-lbf (N·mm)
M_a = maximum moment in member due to service loads at stage deflection is computed, in.-lbf (N·mm)
M_{cr} = cracking moment, in.-lbf (N·mm)
M_n = nominal flexural strength at section, in.-lbf (N·mm)
n = number of bars being developed or lap spliced along plane of splitting; refer to Eq. (10.2b)
P_n = nominal axial strength of cross section, lbf (N)
R_r = relative rib area of the reinforcement = ratio of projected rib area normal to bar axis to the product of the nominal bar diameter and the center-to-center rib spacing, may be taken conservatively as 0.07 for design
s = spacing of transverse (shear) reinforcement, in. (mm)
T = force in tension reinforcement of a beam, lbf (N)
T_s = additional bond strength provided by the transverse steel, lbf (N)
t_d = bar diameter factor = $0.78d_b + 0.22$ in. (mm); refer to Eq. (10.2d)
t_r = term representing the effect of relative rib area on T_s = $9.6R_r + 0.28 \leq 1.72$; refer to Eq. (10.2c)
V = applied shear at critical section, lbf (N)
V_c = nominal shear strength provided by concrete, lbf (N)
w_u = factored load per unit length of beam or one-way slab, lb/ft^3 (kg/m^3)
α = reinforcement location factor
β = ratio of the distance from the neutral axis to the extreme tension face to the distance from the neutral axis to the center of the tension reinforcement factor relating depth of equivalent rectangular compressive stress block to neutral axis depth, as defined in ACI 318
β_c = coating factor; refer to Eq. (10.2a)
Δ = deflection, in. (mm)
ε_s = strain in reinforcement
ε_t = net tensile strain in extreme layer of longitudinal tension steel at nominal strength, excluding strains due to creep, shrinkage, and temperature
ϕ = strength reduction factor
λ = lightweight aggregate concrete factor
ρ_b = bias factor = ratio of the average actual value to the specified minimum value of a property being analyzed
ρ = reinforcement ratio = A_s/bd
ρ_b = reinforcement ratio producing balanced strain conditions as defined in ACI 318
ρ_s = volumetric spiral reinforcement ratio
ψ = curvature
ω = factor reflecting benefit of large cover/spacing perpendicular to controlling cover/spacing = $0.1(c_{max}/c_{min}) + 0.9 \leq 1.25$; refer to Eq. (10.2a)

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, ACI Concrete Terminology. Definitions provided herein complement that resource.

0.2% offset method—method for determining a yield strength value for a material that does not exhibit a distinct yield plateau. The yield strength is the stress on the engineering stress-strain curve at its intersection with a line having a slope equal to the initial modulus of elasticity and offset from the linear elastic portion of the engineering stress-strain curve by a strain of 0.2%.

bias factor—ratio of the average actual value to the specified minimum value of a property being considered in risk analysis.

coefficient of variation (COV)—the standard deviation divided by the mean value of a variable.

cumulative distribution function (CDF)—a function or graph describing the probability distribution of a real-valued random variable taking on a value less than or equal to a particular value.

Seismic Design Category (SDC)—classification assigned to a structure based on its occupancy category, and the severity of the design earthquake ground motion. The category assignment can range from A to F.

CHAPTER 3—MATERIAL PROPERTIES

3.1—Introduction

This guide addresses high-strength deformed reinforcing bars of Type CS as defined by ASTM A1035/A1035M, "Standard Specification for Deformed and Plain, Low-Carbon, Chromium, Steel Bars for Concrete Reinforcement." As with other specifications for steel reinforcing bars, this standard includes requirements for nominal weights and dimensions, tensile properties, chemical composition, and deformations. This chapter reviews properties of primary interest to the structural designer who may specify the use of ASTM A1035/A1035M bars.

Since the publication of ACI ITG-6R, additional Grade 100 (690) reinforcing steels were introduced to the market, including ASTM A1035/A1035M Types CM and CL and ASTM A615/A615M Grade 100 (690). The mechanical properties and stress-strain characteristics of these steels may impact the applicability of this design guide. These bars will be addressed in future editions when research on concrete members reinforced with these bar types become available and the impact of the mechanical properties have been documented.

3.2—Weights, dimensions, and deformations

ASTM A1035/A1035M (CS) specifies nominal weights (mass), areas, and dimensions. Deformation requirements are the same as those specified by ASTM A615/A615M for carbon-steel bars and ASTM A706/A706M for low-alloy steel bars. Consequently, this section does not discuss bar deformations and related aspects.

3.3—Specified tensile properties

Tensile properties are paramount for structural design. Tables 3.3a and 3.3b contain a summary of the specified tensile properties for ASTM A1035/A1035M (CS) and other reinforcement (ACI 439.4R). Table 3.3a shows that the tensile strength properties for ASTM A1035/A1035M (CS) bars are significantly greater than those for ASTM A615/A615M Grade 60 (420), Grade 80 (550), and Grade 100 (690) bars. The requirements for elongation in 8 in. (200 mm) across the fracture, as shown in Table 3.3b, are comparable to those for ASTM A615/A615M Grade 80 (550) and Grade 100 (690) reinforcement, and in some cases lower than those for ASTM A615/A615M Grade 60 (420) reinforcement. As described in 1.3 of this guide, ASTM A1035/A1035M (CS) reinforcing steel does not exhibit a distinct yield plateau (Fig. 1.5). Consequently, ASTM A1035/A1035M (CS) specifies minimum yield strength according to the 0.2 percent offset method.

Table 3.3a—Specified tensile and yield strength

Bar type	Tensile strength, minimum, psi (MPa)	Yield strength*	
		Minimum, psi (MPa)	Maximum, psi (MPa)
ASTM A615/A615M Grade 60 (420)	90,000 (620)	60,000 (420)	—
ASTM A615/A615M Grade 80 (550)	105,000 (725)	80,000 (550)	—
ASTM A615/A615M Grade 100 (690)	115,000 (790)†	100,000 (690)	—
ASTM A706/A706M Grade 60 (520)	80,000‡ (550)‡	60,000 (420)	78,000 (540)
ASTM A706/A706M Grade 80 (520)	100,000‡ (690)‡	80,000 (550)	98,000 (675)
ASTM A1035/A1035M (CS, CM, and CL) Grade 100 (690)	150,000 (1030)	100,000 (690)	—

*Observed yield point for ASTM A615/A615M and ASTM A706/A706M bars, and yield strength according to 0.2 percent offset method for ASTM A1035/A1035M bars, which is applicable to ASTM A615/A615M and ASTM A706/A706M bars only when steel bar tested does not exhibit a well-defined yield point.

†Grade 100 (690) reinforcing bars have a ratio of specified tensile strength to specified yield strength of 1.15. Designers should be aware that there will, therefore, be a lower margin of safety and reduced warning of failure following yielding when Grade 100 (690) bars are used in structural members.

‡Tensile strength for ASTM A706/A706M bars should also be not less than 1.25 times measured yield strength.

Table 3.3b—Specified elongation in 8 in. (200 mm) across fracture

Bar type	Bar size no.			
	3, 4, 5, 6 (10, 13, 16, 19)	7, 8 (22, 25)	9, 10, 11 (29, 32, 36)	14, 18 (43, 57)
	Elongation in 8 in. (200 mm) across fracture, minimum, percent			
ASTM A615/A615M Grade 60 (420)	9	8	7	7
ASTM A615/A615M Grade 80 (550), 100 (690)	7	7	6	6
ASTM A706/A706M Grade 60 (420)	14	12	12	10
ASTM A706/A706M Grade 80 (550)	12	12	12	10
ASTM A1035/A1035M (CS, CM, and CL) Grade 100 (690)	7	7	7	6

3.4—Measured tensile properties

Understanding the differences in tensile behavior of higher strength steels is essential for the safe and serviceable design

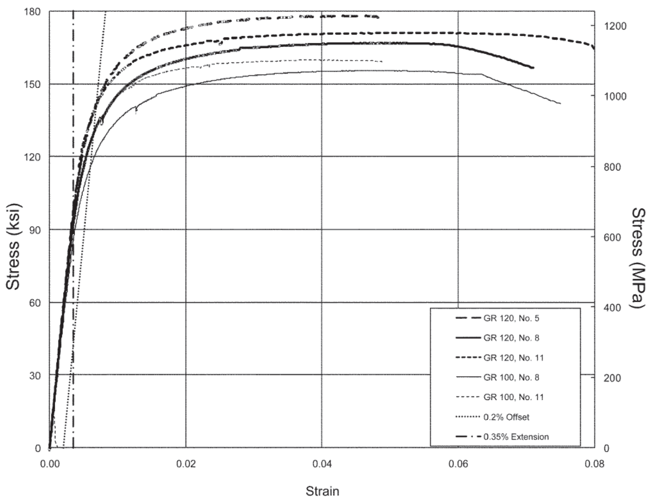

Fig. 3.4a—Actual stress-strain curves for ASTM A1035/A1035M Type CS reinforcing bars of different grades and sizes (WJE 2008).

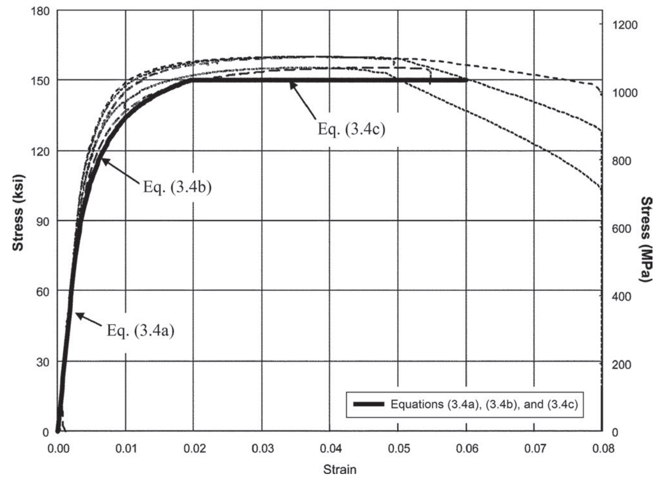

Fig. 3.4b—Equations (3.4a), (3.4b), and (3.4c) compared with actual stress-strain curves from samples of No. 8 (25) and No. 11 (36) bars of ASTM A1035/A1035M Grade 100 (690) Type CS.

of concrete members. Tensile properties are necessary in the probabilistic studies that establish the strength reduction factors used in reinforced concrete design.

Figure 1.5 shows comparisons of stress-strain curves recorded for samples of ASTM A1035/A1035M (CS) Grade 100 (690) bars to similar curves for samples of ASTM A615/A615M bars in Grades 60 (420) and 80 (550). ASTM A1035/A1035M (CS) bars have a greater tensile strength and lack a well-defined yield point and yield plateau. ASTM A1035/A1035M (CS) bars reach a proportional limit at a stress from 60,000 to 80,000 psi (420 to 550 MPa), which is similar to the yield stress of ASTM A615/A615M Grade 60 (420) and ASTM A706/A706M Grade 60 (420) bars (WJE 2008) and the strain at the peak tensile stress in the bar ranges from 0.04 to 0.06. By comparison, strains at peak tensile stress for ASTM A615/A615M Grade 60 (420) bars range from 0.07 to 0.10, and those of ASTM A706/A706M Grade 60 (420) bars range from 0.10 to 0.14.

For ASTM A1035/A1035M (CS) bars, the elongation in 8 in. (200 mm) across the fracture ranges from 0.08 to 0.13, whereas the elongation in 8 in. (200 mm) across the fracture for ASTM A615/A615M Grade 60 (420) and ASTM A706/A706M Grade 60 (420) bars range from 0.09 to 0.12 and 0.14 to 0.20, respectively. The modulus of elasticity value of 29,000,000 psi (200,000 MPa) as defined in ACI 318 is applicable to define the elastic modulus for ASTM A1035/A1035M (CS) Grade 100 (690) bars.

Figure 3.4a shows actual stress-strain curves recorded for samples of ASTM A1035/A1035M reinforcing bars (WJE 2008). Yield strength of ASTM A1035/A1035M (CS) bars, determined by the 0.2 percent offset method, exceeds 115,000 psi (790 MPa). The tensile strength for ASTM A1035/A1035M (CS) Grade 100 (690) bar exceeds 155,000 psi (1070 MPa).

An approximate lower bound for the stress-strain curves of Grade 100 (690) bars can be represented by the following three equations, as shown in Fig. 3.4b.

Equations (3.4a) through (3.4c) represent a lower bound to the stress-strain behavior of ASTM A1035/A1035M (CS) Grade 100 (690) bar. The equations are based on an assumed proportional limit of 70,000 psi (480 MPa) and an assumed tensile strength of 150,000 psi (1030 MPa), which is reached at the strain of 0.02, the upper limit for Eq. (3.4b).

$$f_s = 29{,}000\varepsilon_s \text{ (ksi) for } \varepsilon_s \leq 0.0024 \text{ (in.-lb)}$$
$$f_s = 200{,}000\varepsilon_s \text{ (MPa) for } \varepsilon_s \leq 0.0024 \text{ (SI)} \quad (3.4a)$$

$$f_s = 170 - \frac{0.4317}{\varepsilon_s + 0.0019} \text{ (ksi) for } 0.0024 < \varepsilon_s \leq 0.02 \text{ (in.-lb)}$$

$$f_s = 1170 - \frac{2.9670}{\varepsilon_s + 0.0019} \text{ (MPa) for } 0.0024 < \varepsilon_s \leq 0.02 \text{ (SI)}$$

(3.4b)

$$f_s = 150 \text{ (ksi) for } 0.02 < \varepsilon_s \leq 0.06 \text{ (in.-lb)}$$
$$f_s = 1040 \text{ (MPa) for } 0.02 < \varepsilon_s \leq 0.06 \text{ (SI)} \quad (3.4c)$$

Accordingly, an analysis was performed on the results of 137 mill tests on ASTM A1035/A1035M (CS) Grade 100 (690) bars produced after 2004 that were provided by a manufacturer. Based on the analysis of the mill test data, it was shown that Eq. (3.4b) and (3.4c) would provide a lower tolerance limit on actual stress corresponding to a strain of 0.0035, actual yield strength, and actual tensile strength for ASTM A1035/A1035M (CS) Grade 100 (690) bars such that at least 95 percent of the data are greater than the corresponding values calculated by these equations with a confidence level of 90 percent.

Cumulative distribution functions (CDFs) for the yield strength by the 0.2 percent offset method and the tensile strength were developed from the ASTM A1035/A1035M

Table 3.4—Statistical analysis of mill test data for ASTM A1035/A1035M (CS) Grade 100 (690) steel reinforcing bars*

Bar designation	No. of samples	0.2% offset yield strength			Tensile strength	
		Mean, ksi (MPa)	Bias factor λ_b	COV	Mean, ksi (MPa)	COV
No. 3 (10)	10	139.8 (964)		0.044	174.3 (1202)	0.046
No. 4 (13)	20	129.9 (895)		0.026	162.1 (1118)	0.027
No. 5 (16)	28	130.9 (903)		0.036	164.7 (1135)	0.035
No. 6 (19)	16	129.9 (895)		0.067	164.1 (1132)	0.045
No. 7 (22)	15	124.2 (857)		0.061	162.5 (1120)	0.028
No. 8 (25)	9	128.4 (886)		0.032	161.6 (1114)	0.019
No. 9 (29)	8	127.1 (877)		0.029	161.7 (1115)	0.039
No. 10 (32)	3	133.7 (922)		0.050	169.5 (1169)	0.051
No. 11 (36)	28	132.8 (916)		0.040	168.5 (1162)	0.031
All sizes	137	130.6 (901)		0.051	165.2 (1139)	0.040
Lower tail of data for all sizes	—	—	1.159	0.043	—	—
Lower tail of data for ASTM A615/A615M Grade 60 (420)*	—	—	1.145	0.055	—	—

*Statistical determination used for establishing strength reduction factors ϕ as reported by Nowak and Szerszen (2003).

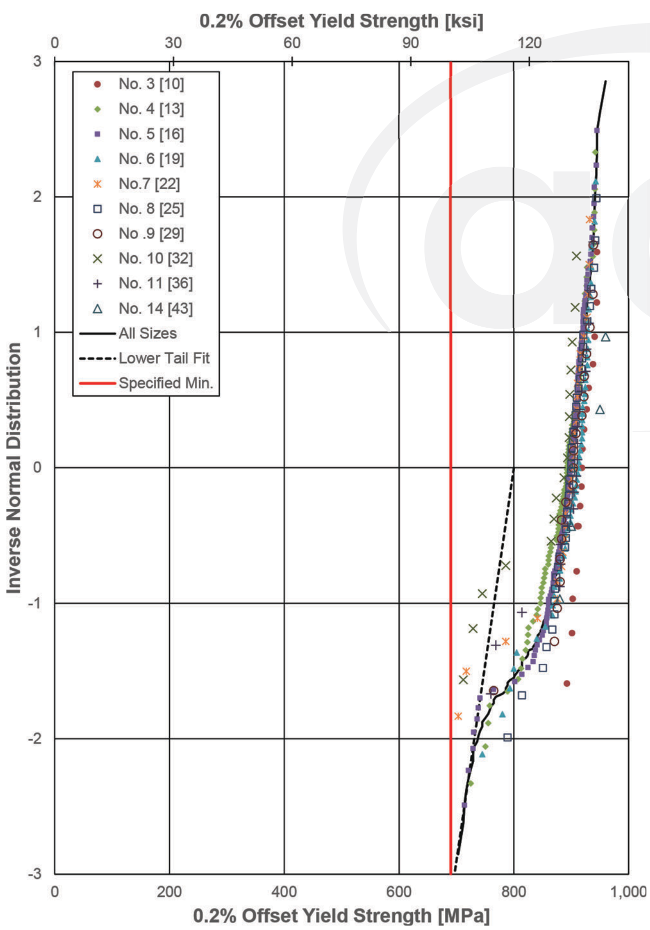

Fig. 3.4c—Cumulative distribution function for yield strength of ASTM A1035/A1035M (CS) Grade 100 (690) bars by 0.2 percent offset method. (Note: 1 MPa = 145 psi.)

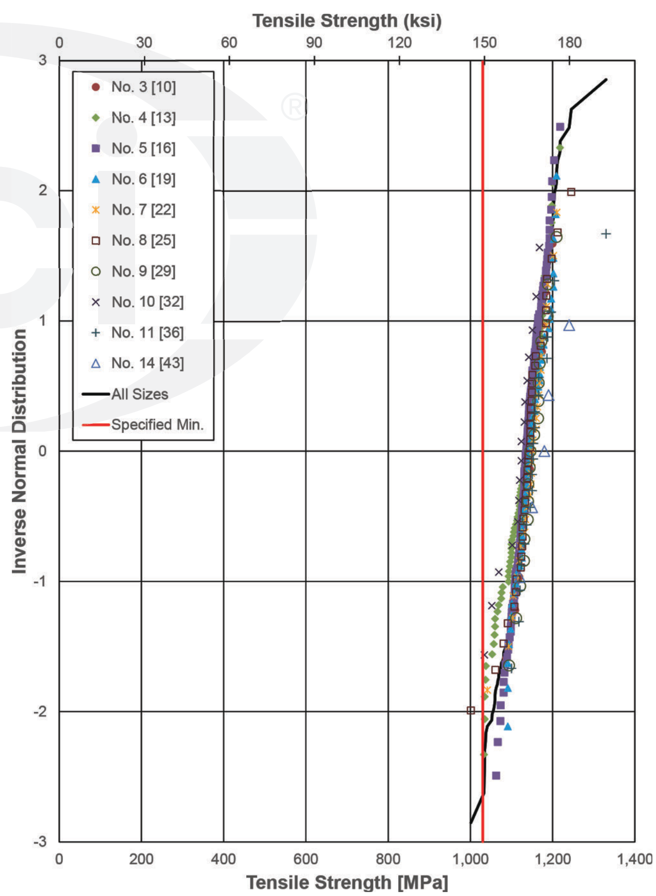

Fig. 3.4d—Cumulative distribution function for tensile strength of ASTM A1035/A1035M (CS) Grade 100 (690) bars. (Note: 1 MPa = 145 psi.)

(CS) Grade 100 (690) bar mill test data. The results are summarized in Table 3.4, Fig. 3.4c, and Fig. 3.4d. The summarized statistical data include the bias factor λ_b and the coefficient of variation (COV).

Nowak and Szerszen (2003) reported the comparable statistical analysis for yield strength of ASTM A615/A615M Grade 60 (420) bars as used for code-calibration reliability analysis. They recommended using a bias factor λ_b of 1.145