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

Reported by ACI Innovation Task Group 6

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This guide provides recommendations on design provisions for the use of ASTM A1035/ASTM1035M Grade 100 (690) deformed steel bars for reinforced concrete members. The recommendations address only those requirements of ACI 318-08 that limit efficient use of such steel bars. Other code requirements are not affected.

This guide includes a discussion of the material characteristics of Grade 100 (690) ASTM A1035/A1035M 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 also for structural components not designated as part of the seismic-force-resisting system for SDC D, E, or F.

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

CONTENTS

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CHAPTER 1—INTRODUCTION

1.1—Objective

This guide provides design provisions for the use of ASTM A1035/A1035M Grade 100 (690) deformed steel bars for reinforced concrete structural members. This guide addresses only those requirements in ACI 318-08 that limit the more efficient use of such steel bars, and should not affect the application of other code requirements.

1.2—Scope

This guide includes a discussion of the material characteristics of ASTM A1035/A1035M steel bars and recommends design criteria for beams, columns, slab systems, walls, and footings for Seismic Design Category (SDC) A, B, or C. For a 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 yield strength, f_y, up to 100,000 psi (690 MPa) for special moment frames, special structural walls, and coupling beams as permitted by Section 21.1.5.4 of ACI 318-08. Refer to Section 10.1 of this guide for more information on seismic design considerations. Shells and folded plate members and prestressed concrete are beyond the scope of this guide. 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, the design of structural concrete was restricted to using specified yield strength, f_y, of 60,000 psi (410 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, the yield strength to be used in design shall be reduced to $0.85f_y$ or 60,000 psi, whichever is greater, unless it is shown by tension tests that at a proof stress equal to the specified 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. Design of tension reinforcement shall not be based on a yield strength, f_y, in excess of 60,000 psi 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 without test is to control cracking. The absolute maximum is specified as 75,000 psi 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, 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 but more design criteria for crack control and considerable American practical experience with 60,000 psi 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 yield strength, unless special full-scale tests are made. It was thought that 75,000 psi 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."

The most widely used deformed reinforcing bars conform to ASTM A615/A615M, which include Grade 40 (280), Grade 60 (420), and Grade 75 (520). The Grade 60 (420) reinforcement exhibits minimum yield strength of 60,000 psi (410 MPa) with a distinct yield plateau. ACI 318-08 permits use of reinforcing bars with a specified yield strength, f_y, exceeding 60,000 psi (410 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. Section 11.4.2 of ACI 318-08 limits the specified yield strength for deformed bars used as shear reinforcement to 60,000 psi (410 MPa). For deformed bars used as confinement reinforcement (ties or spirals) in compression members, Section 3.5.3.3 of ACI 318-08 permits the use of specified yield strength of up to 100,000 psi (690 MPa).

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 in the use of ASTM A1035/A1035M steel bars. El-Hacha and Rizkalla (2002) and DeJong et al. (2006) conducted studies on the fatigue behavior of ASTM A1035/A1035M 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 steel bars, as opposed to 23,700 psi (166 MPa) for Grade 60 (420) reinforcing bars. Thus, ASTM A1035/A1035M steel bars showed comparable fatigue resistance to Grade 60 (420) reinforcing bars because their stress at

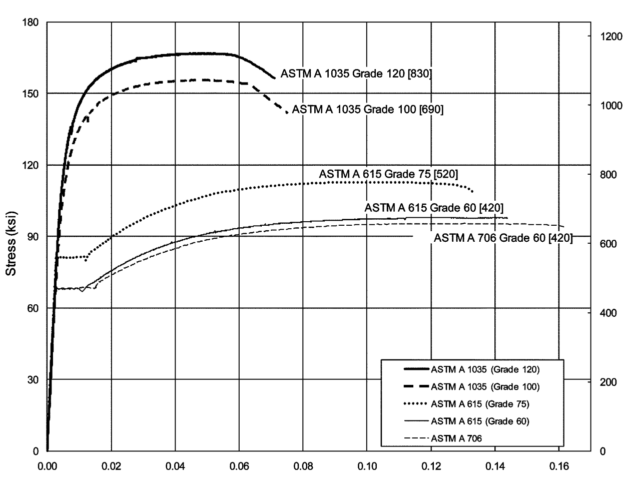

Fig. 1.1—Actual stress-strain curves for ASTM A615/A615M, ASTM A706/A706M, and ASTM A1035/A1035M reinforcing bars of different grades (WJE 2008).

service would be higher than that of Grade 60 (420) bars. When compared with ASTM A615/A615M steel, the ASTM A1035/A1035M steel (Grade 100 [690] and Grade 120 [830]) has low carbon content (maximum 0.15%) and high chromium content (8.0 to 10.9%). The carbon and chromium contents for ASTM A615/A615M steel are typically 0.30% and 0.50%, respectively, as reported by Trejo (2002). Being low in carbon and high in chromium, the ASTM A1035/A1035M steel is more corrosion-resistant and has higher tensile strength than conventional reinforcement (Rizkalla et al. 2005).

Figure 1.1 shows the comparison of typical stress-strain curves for ASTM A615/A615M, ASTM A706/A706M, and ASTM A1035/A1035M reinforcing bars (WJE 2008). The ASTM A1035/A1035M bar (Grade 100 [690] or Grade 120 [830]) exhibits a linear stress-strain relationship up to a proportional limit ranging from 60,000 psi (410 MPa) to 80,000 psi (550 MPa), without a well-defined yield plateau. (Refer to Appendix C 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% offset method, typically exceeds 115,000 psi (790 MPa) for Grade 100 (690) and 125,000 psi (860 MPa) for Grade 120 (830) bars. The tensile strength typically exceeds 155,000 psi (1070 MPa) for Grade 100 (690) bars and 160,000 psi (1100 MPa) for Grade 120 (830) bars. The corresponding strain at the peak of the stress-strain curve ranges from 0.04 to 0.06. Refer to Chapter 3 for more details on the material characteristics of ASTM A1035/A1035M reinforcing bars.

Using Grade 100 (690) reinforcing bars in structural concrete provides several advantages. With a higher specified yield strength, f_y, the designer can reduce the cross-sectional area of required reinforcement, and save cost on material, shipping, and placement. The reduced area of reinforcement results in fewer bars and reduces 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, and leads to better quality construction, improved durability of the structure, and a reduction in construction time and cost.

There are also disadvantages, however, in using Grade 100 (690) bars in structural concrete design. Using higher specified 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. Also, with higher f_y, the required development length will be longer and may not be economical and practical for large size bars. Finally, without a well-defined yield plateau, flexural members designed with ASTM A1035/A1035M bars may have less deformation capacity than members reinforced with Grade 60 (420) bars.

High-strength reinforcing bars conforming to ASTM A1035/A1035M are used with normal-strength concrete in many applications, but design may be more efficient in some cases when the bars are used with high-strength concrete, as illustrated in a few design examples in Appendix A.

1.4—Availability

As of this report writing, several mills located in North America and the Middle East are producing ASTM A1035/A1035M reinforcing bars based on a proprietary process. The mills are supported by a number of fabricating and warehousing facilities. Availability of Grade 100 (690) reinforcing bar will depend on the proximity of these facilities. The designer is advised to check the availability of this material.

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. (10-2) and Eq. (10-2M)

a = depth of equivalent rectangular stress block as defined in Section 10.2.7.1 of ACI 318-08, 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, lb (N)

C_c = clear cover to tension steel, in. (mm)

c = distance from extreme compression fiber to neutral axis, in. (mm)

c_b = $c_{min} + 0.5d_b$, in. (mm), refer to Eq. (10-1) and Eq. (10-1M)

c_{bb} = clear cover of reinforcement being developed or lap spliced, measured to tension face of member, 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 in lieu 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_y = specified yield strength of reinforcement, psi (MPa)

f_{yt} = specified 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. (10-2) and Eq. (10-2M)

ℓ_d = development length (also splice length), in. (mm)

M = applied moment at critical section, in.-lb (N·mm)

M_a = maximum moment in member due to service loads at stage deflection is computed, in.-lb (N·mm)

M_{cr} = cracking moment, in.-lb (N·mm)

M_n = nominal flexural strength at section, in.-lb (N·mm)

n = number of bars being developed or lap spliced along plane of splitting, refer to Eq. (10-2) and Eq. (10-2M)

P_n = nominal axial strength of cross section, lb (N)

R_r = relative rib area of the reinforcement = projected rib area normal to bar axis/(nominal bar perimeter × 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, lb (N)

T_s = additional bond strength provided by the transverse steel, lb (N)

t_d = bar diameter factor = $0.78d_b + 0.22$ in. (mm), refer to Eq. (10-4) and Eq. (10-4M)

t_r = term representing the effect of relative rib area on T_s = $9.6R_r + 0.28 \leq 1.72$, refer to Eq. (10-3) and Eq. (10-3M)

V = applied shear at critical section, lb (N)

V_c = nominal shear strength provided by concrete, lb (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

β_1 = factor relating depth of equivalent rectangular compressive stress block to neutral axis depth, as defined in Section 10.2.7.3 of ACI 318-08

β_c = coating factor, refer to Eq. (10-1) and Eq. (10-1M)

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

λ_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 Section 10.3.2 of ACI 318-08

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. (10-1) and Eq. (10-1M)

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, "ACI Concrete Terminology," at http://terminology.concrete.org. Definitions provided herein complement that resource.

0.2% offset method—a 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 portion of the engineering stress-strain curve by a strain of 0.2%.

bias factor—the 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.

CHAPTER 3—MATERIAL PROPERTIES

3.1—Introduction

This guide addresses high-strength deformed reinforcing bars that conform to 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.

Before 2004, universities and commercial laboratories conducted tensile and compressive tests on low-carbon and high-chromium Grade 100 (690) high-strength reinforcing bars produced according to the proposed standards of ASTM A1035/A1035M. When ASTM A1035/A1035M was issued in 2004, it was a modified version of the proposed standards, and the manufacturing process for the bar was modified, resulting in changes of the material properties. For this reason, the results of prestandardization tests should be used only if the test specimens were produced by the modified manufacturing process.

Data in this design guide are based primarily on tests of reinforcing bars that conform to ASTM A1035/A1035M. This chapter discusses the properties of both Grade 100 (690) and Grade 120 (830) steel bars to show their differences. It is important to note that this design guide is applicable only to Grade 100 (690) steel bars and Grade 120 (830) bars cannot be used to substitute for Grade 100 (690) bars.

3.2—Weights, dimensions, and deformations

ASTM A1035/A1035M 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 3.1 and 3.2 contain a summary of the specified tensile properties for ASTM A1035/A1035M and other reinforcing bars. Table 3.1 shows that the specified strength-related tensile properties for ASTM A1035/A1035M bars are significantly greater than those for ASTM A615/A615M Grade 60 (420) bars, which are the most commonly used reinforcing bars in the U.S. The requirements for elongation in 8 in. (200 mm) across the fracture, as shown in Table 3.2, are comparable to those for ASTM A615/A615M Grade 75 (520) reinforcing bars, and slightly lower than those for ASTM A615/A615M Grade 60 (420) reinforcement.

As described in Section 1.3 of this design guide, ASTM A1035/A1035M reinforcing steel does not exhibit a distinct yield plateau. Consequently, ASTM A1035/A1035M specifies minimum yield strength according to the 0.2% offset method. However, with ASTM A1035/A1035M reinforcement, the tensile strains corresponding to 0.2% offset are relatively high, approximately 0.006, as indicated in Fig. 3.1. Therefore, ASTM A1035/A1035M also specifies a minimum stress of 80,000 psi (550 MPa) corresponding to a strain of 0.0035. The reason for this requirement is explained in Note 3 of ASTM A1035/A1035M-07 as follows:

Table 3.1—Specified tensile and yield strengths

Bar type	Tensile strength, minimum, psi (MPa)	Yield strength*		Stress corresponding to prescribed strain	
		Minimum, psi (MPa)	Maximum, psi (MPa)	Minimum stress, psi (MPa)	Strain, %
ASTM A615/A615M Grade 60	90,000 (620)	60,000 (420)	—	60,000† (420)†	0.35†
ASTM A615/A615M Grade 75	100,000 (690)	75,000 (520)	—	75,000† (520)†	0.35†
ASTM A615/A615M Grade 80	105,000 (725)	80,000 (550)	—	80,000† (550)†	0.35†
ASTM A706/A706M Grade 60	80,000‡ (550)‡	60,000 (420)	78,000 (540)	60,000† (420)†	0.35†
ASTM A706/A706M Grade 80	100,000‡ (690)‡	80,000 (550)	98,000 (675)	80,000† (550)†	0.35†
ASTM A1035/A1035M Grade 100	150,000 (1030)	100,000 (690)	—	80,000 (550)	0.35
ASTM A1035/A1035M Grade 120	150,000 (1030)	120,000 (830)	—	90,000 (620)	0.35

*Observed yield point for ASTM A615/A615M and ASTM A706/A706M bars, and yield strength according to 0.2% offset method for ASTM A1035/A1035M bars.
†Applicable to ASTM A615/A615M and ASTM A706/A706M bars only when steel bar tested does not exhibit a well-defined yield point.
‡Tensile strength for ASTM A706/A706M bars should also be not less than 1.25 times actual yield strength.

> "The stress-strain curves for bars meeting this specification do not have a well-defined yield point (that is, yield is not characterized by a sharp knee or discontinuity similarly to stainless steel bars). The provisions of 9.2 [of this specification] require that the yield strength (minimum 100,000 psi [690 MPa] for Grade 100 [690] and minimum 120,000 psi [830 MPa] for Grade 120 [830], respectively) be measured by the 0.2% offset method and that the stress corresponding to a strain of 0.0035 be a minimum of 80,000 psi (550 MPa) for Grade 100 and 90,000 psi (620 MPa) for Grade 120 (830). Experimental results for concrete beams reinforced with bars meeting this specification show that the flexural strength of under-reinforced members is conservatively predicted based on the yield strength measured using the 0.2% offset method. The minimum stress corresponding to a tensile strain of 0.0035 is required to ensure that the specified steel is at least as stiff at lower strains as lower-strength reinforcing bars."

3.4—Actual tensile properties

Knowledge of actual tensile properties of reinforcing bars, whether ASTM A1035/A1035M bars or other reinforcement, is important for understanding the behavior of reinforced concrete structural members. Tensile properties are necessary in the probabilistic studies that establish the strength reduction factors used in reinforced concrete design.

Figure 1.1 shows comparisons of stress-strain curves recorded for samples of ASTM A1035/A1035M bars in Grades 100 (690) and 120 (830) to similar curves for samples of ASTM A615/A615M bars in Grades 60 (420) and 75 (520), and ASTM A706/A706M bars. ASTM A1035/A1035M bars have a greater tensile strength and lack a well-defined yield point. ASTM A1035/A1035M bars reach a proportional limit at a stress from 60,000 to 80,000 psi (410 to 550 MPa), which is similar to the yield stress of ASTM A615/A615M Grade 60 (420) and ASTM A706/A706M bars (WJE 2008). The stress corresponding to the strain of 0.0035 is approximately 90,000 psi (620 MPa) for both grades of ASTM A1035/A1035M bars. 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 bars range from 0.10 to 0.14.

For ASTM A1035/A1035M 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 bars range from 0.09 to 0.12 and 0.14 to 0.20, respectively. The measured modulus of elasticity for both grades of ASTM A1035/A1035M bars was 29,000,000 psi (200,000 MPa), which is the same as the value specified by ACI 318. The use of 29,000,000 psi (200,000 MPa) for modulus of elasticity in design computations is recommended.

Figure 3.1 shows actual stress-strain curves recorded for samples of ASTM A1035/A1035M reinforcing bars (WJE 2008). Yield strength of ASTM A1035/A1035M bars, determined by the 0.2% offset method, exceeds 115,000 psi (790 MPa) for Grade100 bar and 125,000 psi (860 MPa) for Grade 120 (830) bar. The tensile strength for ASTM A1035/A1035M Grade 100 (690) bar exceeds 155,000 psi (1070 MPa) and for Grade 120 (830) bar exceeds 160,000 psi (1100 MPa). The stress-strain curves for Grade 120 (830) bar are slightly above the stress-strain curves for Grade 100 (690) bar, and the tensile properties of both grades of bars are greater than the corresponding specified minimum values, which is common for most types of steel bar reinforcement.

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. 3.2.

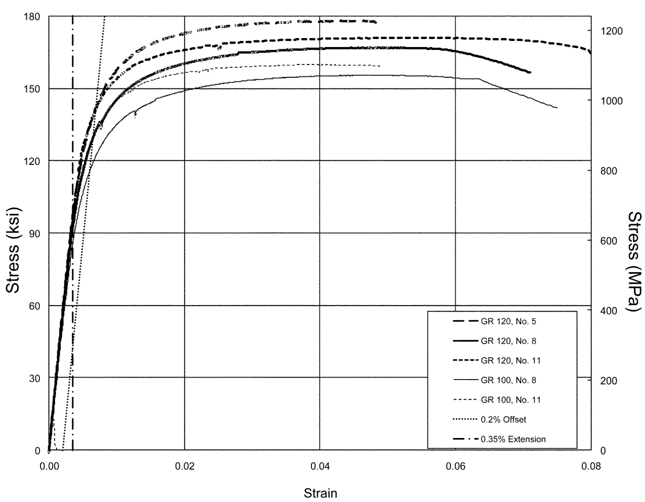

Fig. 3.1—Actual stress-strain curves for ASTM A1035/A1035M reinforcing bars of different grades and sizes (WJE 2008).

Table 3.2—Specified elongation in 8 in. (200 mm) across fracture

	Bar size no.				
	3, 4, 5 (10, 13, 16)	6 (19)	7, 8 (22, 25)	9, 10, 11 (29, 32, 36)	14, 18 (43, 57)
Bar type	Elongation in 8 in. (200 mm) across fracture, minimum, %				
ASTM A615/A615M Grade 60 (420)	9	9	8	7	7
ASTM A615/A615M Grade 75 (520)	7	7	7	6	6
ASTM A615/A615M Grade 80 (550)	7	7	7	6	6
ASTM A706/A706M Grade 60 (420)	14	14	12	12	10
ASTM A706/A706M Grade 80 (550)	12	12	12	12	10
ASTM A1035/A1035M Grade 100 (690)	7	7	7	7	6
ASTMA1035/A1035M Grade 120 (830)	7	7	7	7	Not produced

$$f_s = 29{,}000\varepsilon_s \text{ (ksi) for } \varepsilon_s \leq 0.0024 \quad (3\text{-}1)$$

$$f_s = 170 - \frac{0.43}{\varepsilon_s + 0.0019} \text{ (ksi) for } 0.0024 < \varepsilon_s \leq 0.02 \quad (3\text{-}2)$$

$$f_s = 150 \text{ (ksi) for } 0.02 < \varepsilon_s \leq 0.06 \quad (3\text{-}3)$$

The aforementioned equations expressed in SI units are as follows

$$f_s = 200{,}000\varepsilon_s \text{ (MPa) for } \varepsilon_s \leq 0.0024 \quad (3\text{-}1M)$$

$$f_s = 1170 - \frac{2.96}{\varepsilon_s + 0.0019} \text{ (MPa) for } 0.0024 < \varepsilon_s \leq 0.02 \quad (3\text{-}2M)$$

$$f_s = 1040 \text{ (MPa) for } 0.02 < \varepsilon_s \leq 0.06 \quad (3\text{-}3M)$$

Actual yield strength is an important property used in the statistical determination of strength reduction factors ϕ (Nowak and Szerszen 2003; Szerszen and Nowak 2003). Accordingly, an analysis was performed on the results of 137 mill tests on ASTM A1035/A1035M 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. (3-2) and (3-3) 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 Grade 100 (690) bars such that at least 95% of the data lie above the corresponding values calculated by these equations with a confidence level of 90%.

Cumulative distribution functions (CDF) for the stress corresponding to a strain of 0.0035, the yield strength by the 0.2% offset method, and the tensile strength were developed from the ASTM A1035/A1035M Grade 100 (690) bar mill test data. The results are summarized in Table 3.3 and Fig. 3.3 through 3.5. The summarized statistical data include the bias factor, λ_b, and the coefficient of variation (COV). The bias factor for pooled mill test data for all sizes of ASTM Grade 100 (690) bars was 1.221 for stress at a strain of 0.0035, 1.305 for yielding according to the 0.2% offset method, and 1.106 for tensile strength. The corresponding COVs were 0.057 for stress at a strain of 0.0035, 0.051 for yield according to the 0.2% offset method, and 0.040 for tensile strength.

Nowak and Szerszen (2003) reported the comparable statistical analysis for yield strength of ASTM A615/A615M Grade 60 (420) bars. They recommended using a bias factor of 1.145 and a COV of 0.055 in the development of strength reduction factors for ACI 318. The values of the bias factors for ASTM A1035/A1035M Grade 100 (690) bars are larger than 1.145 for ASTM A615/A615M Grade 60 (420) bars, whereas the values for COV are comparable to the recommended value of 0.055 for ASTM A615/A615M Grade 60 (420) bars. Use of the same strength reduction factors with ASTM A1035/A1035M Grade 100 (690) bars as used for ASTM A615/A615M Grade 60 (420) bars is

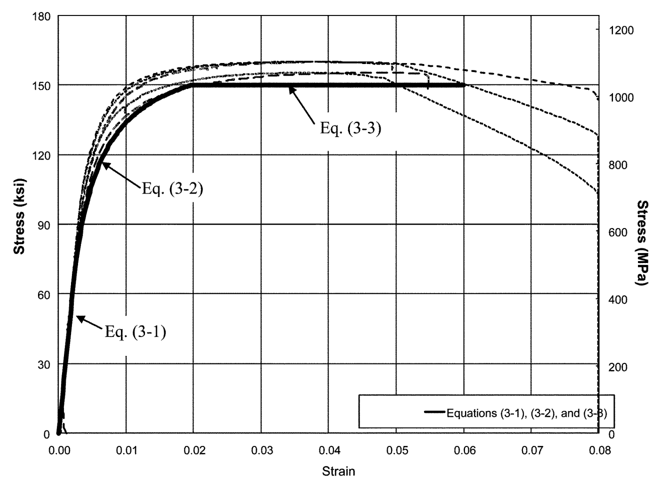

Fig. 3.2—Equations (3-1), (3-2), and (3-3) compared with actual stress-strain curves from samples of No. 8 (25) and No. 11 (36) bars of ASTM A1035/A1035M Grade 100 (690).

Table 3.3—Statistical analysis of mill test data for ASTM A1035/A1035M, Grade 100 (690) steel reinforcing bars

Bar size	No. of samples	Stress at 0.35% extension under load			0.2% offset yield strength			Tensile strength		
		Mean, ksi (MPa)	Bias factor† λ_b	COV	Mean, ksi (MPa)	Bias factor† λ_b	COV	Mean, ksi (MPa)	Bias factor† λ_b	COV
No. 3 (10)	10	105.8 (730)	1.327	0.085	139.8 (964)	1.397	0.044	174.3 (1202)	1.167	0.046
No. 4 (13)	20	96.5 (665)	1.209	0.025	129.9 (895)	1.298	0.026	162.1 (1118)	1.085	0.027
No. 5 (16)	28	96.8 (668)	1.214	0.030	130.9 (903)	1.308	0.036	164.7 (1135)	1.102	0.035
No. 6 (19)	16	94.6 (652)	1.185	0.038	129.9 (895)	1.298	0.067	164.1 (1132)	1.099	0.045
No. 7 (22)	15	94.2 (650)	1.181	0.032	124.2 (857)	1.241	0.061	162.5 (1120)	1.088	0.028
No. 8 (25)	9	96.9 (668)	1.215	0.068	128.4 (886)	1.283	0.032	161.6 (1114)	1.082	0.019
No. 9 (29)	8	93.2 (643)	1.169	0.036	127.1 (877)	1.270	0.029	161.7 (1115)	1.083	0.039
No. 10 (32)	3	102.5 (707)	1.285	0.127	133.7 (922)	1.336	0.050	169.5 (1169)	1.135	0.051
No. 11 (36)	28	99.7 (688)	1.250	0.052	132.8 (916)	1.327	0.040	168.5 (1162)	1.128	0.031
All Sizes	137	97.4 (672)	1.221	0.057	130.6 (901)	1.305	0.051	165.2 (1139)	1.106	0.040
ASTM A615/A615M Grade 60 (420)*	—	—	—	—	—	1.145	0.055	—	—	—

*From Nowak and Szerszen (2003).

†Bars manufactured according to SI units of ASTM A1035/A1035M. Bias factors are established relative to specified SI units.

Note: Available pool of mill test data for ASTM A1035/A1035M, Grade 120 (830) reinforcing bar is too small to provide for meaningful analysis of test data.

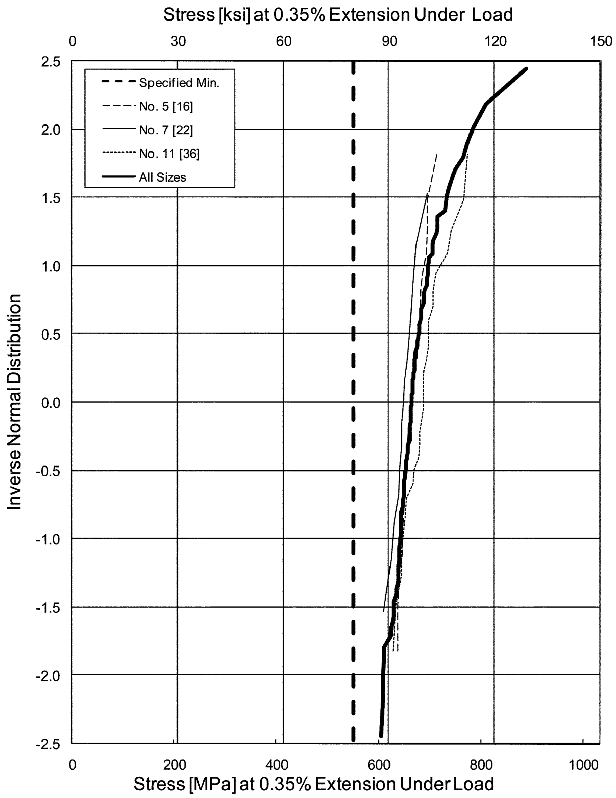

Fig. 3.3—Cumulative distribution function for stress in ASTM A1035/A1035M Grade 100 (690) bars at 0.35% strain under load. (Note: 1 MPa = 145 psi.)

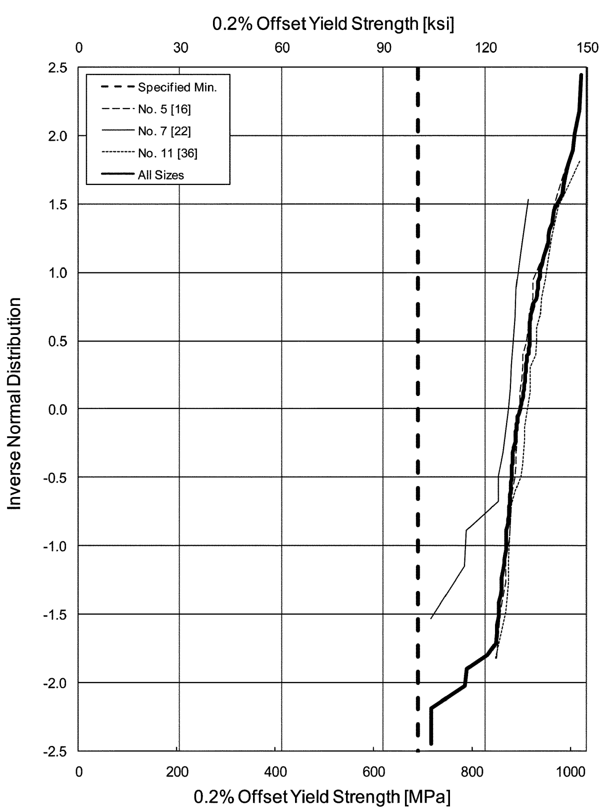

Fig. 3.4—Cumulative distribution function for yield strength of ASTM A1035/A1035M Grade 100 (690) bars by 0.2% offset method. (Note: 1 MPa = 145 psi.)

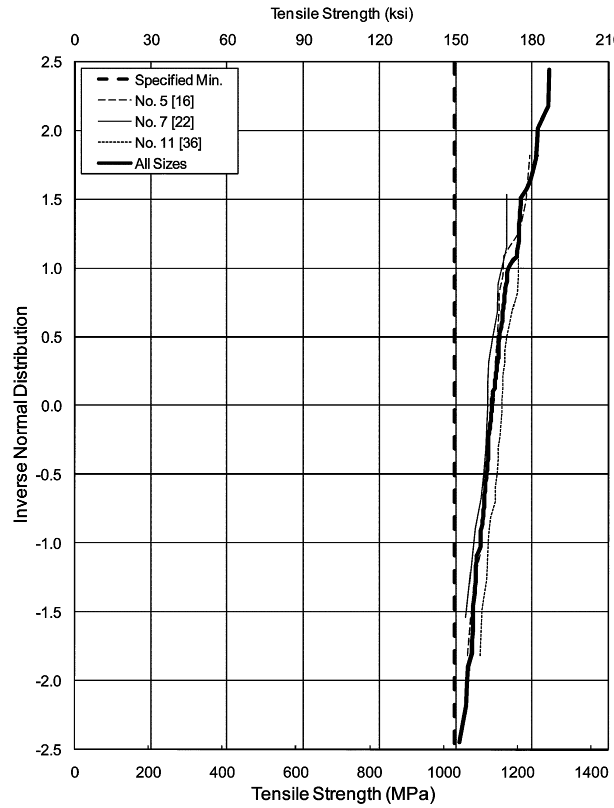

Fig. 3.5—Cumulative distribution function for tensile strength of ASTM A1035/A1035M Grade 100 (690) bars. (Note: 1 MPa = 145 psi.)

recommended. With respect to ASTM A1035/A1035M Grade 120 (830) bars, the pool of available mill test data is too small to provide statistical analysis.

3.5—Actual compressive properties

WJE (2008) studied the stress-strain behavior in compression of representative samples of ASTM A1035/A1035M bars in size No. 5 (16), 8 (25), and 11 (36) in both Grades 100 (690) and 120 (830). The typical length of a compression test specimen was twice its nominal diameter. Figure 3.6 shows recorded compressive stress-strain curves. The proportional limit ranges from 60,000 to 80,000 psi (410 to 550 MPa) for both grades. The stress corresponding to a strain of 0.0035 is approximately 90,000 psi (620 MPa) for both grades. Yield strength in compression by the 0.2% offset method is approximately 130,000 psi (900 MPa) for Grade 100 (690) bars and ranges from 135,000 to 140,000 psi (930 to 970 MPa) for Grade 120 (830) bars. The initial slopes of the stress-strain curves in compression are consistent with 29,000,000 psi (200,000 MPa) for modulus of elasticity.

3.6—Chemical composition

Table 3.4 shows the comparison of the specified chemical composition for ASTM A1035/A1035M low-carbon, chromium-steel bars with that of ASTM A615/A615M carbon-steel bars and ASTM A706/A706M low-alloy steel bars. The specified chemical content of ASTM A1035/A1035M bars differs from the other two primarily in that there is a required amount of chromium (8.0 to 10.9%). In