Appendix M

2010 AASHTO Bridge Committee Agenda Item

2010 AASHTO BRIDGE COMMITTEE AGENDA ITEM:

SUBJECT: LRFD Bridge Design Specifications: Section 5, High-Strength Steel Reinforcement

TECHNICAL COMMITTEE: T-10 Concrete

☒ **REVISION**	☒ **ADDITION**	☐ **NEW DOCUMENT**
☒ **DESIGN SPEC**	☐ **CONSTRUCTION SPEC**	☐ **MOVABLE SPEC**
☐ **MANUAL FOR BRIDGE EVALUATION**	☐ **SEISMIC GUIDE SPEC**	☐ **COASTAL GUIDE SPEC**
	☐ **OTHER**	

DATE PREPARED:
DATE REVISED:

AGENDA ITEM:

Item #1

Revise or add the following definitions in Article 5.2:

Tension-Controlled Section—A cross-section in which the net tensile strain in the extreme tension steel at nominal resistance is greater than or equal to ~~0.005.~~ the tension-controlled strain limit.

Tension-Controlled Strain Limit—The net tensile strain in the extreme tension steel at nominal resistance that results in a tension-controlled section. See Article 5.7.2.1.

Item #2

Revise or add the following notations in Article 5.3:

f_y = specified minimum yield strength of reinforcing bars (ksi); specified yield strength of reinforcing bars ≤75 ksi (~~5.5.4.2.1)~~ (5.10.8) unless higher strength is permitted by a specific article (5.4.3.1)

ε_{cl} = compression-controlled strain limit in the extreme tension steel (in./in.) (5.7.2.1)

ε_{tl} = tension-controlled strain limit in the extreme tension steel (in./in.) (5.7.2.1)

Item #3A

Revise the third paragraph of Article 5.4.3.1 as follows:

The nominal yield strength shall be the minimum as specified for the grade of steel selected, except that yield strengths in excess of 75.0 ksi shall not be used for design purposes unless specified yield strengths up to 100.0 ksi are permitted by specific articles for Seismic Zone 1. The yield strength or grade of the bars or wires shall be shown in the contract documents. Bars with yield strengths less than 60.0 ksi shall be used only with the approval of the Owner.

Item #3B

Add the following paragraph at the beginning of Commentary C5.4.3.1:

Unlike reinforcing bars with yield strengths below 75.0 ksi, reinforcing bars with yield strengths exceeding

75.0 ksi usually do not have well-defined yield plateaus. Consequently, different methods are used in different standards to establish yield strengths. These include the 0.2% offset and the 0.35% or 0.50% extension methods. For design purposes, the value of f_y should be the same as the specified yield strength defined in the material standard. Based on research by Shahrooz et al. (2010), certain articles now allow the use of reinforcing steels with yield strengths up to 100.0 ksi for Seismic Zone 1.

Item #4

Revise Article 5.4.3.2 as follows:

The modulus of elasticity, E_s, of steel ~~reinforcing~~ reinforcement shall be assumed as 29,000 ksi for specified yield strengths up to 100.0 ksi.

Item #5A

Revise the second paragraph of Article 5.4.3.3 as follows:

The use of reinforcing steel with specified yield strengths of less than or equal to 100.0 ksi may be used for Seismic Zone 1 where permitted by specific articles. ~~Reinforcement conforming to ASTM A1035/A1035M may only be used as top and bottom flexural reinforcement in the longitudinal and transverse directions of bridge decks in Seismic Zones 1and 2.~~

Item #5B

Delete the second and third paragraphs of Commentary C5.4.3.3 as follows:

~~Epoxy-coated reinforcing steel provides a physical barrier to inhibit corrosion of the steel in the presence of chlorides. The handling, placement, and repair of epoxy-coated reinforcing steel requires significant care and attention.~~

~~Reinforcement conforming to ASTM A1035/A1035M has a specified minimum yield strength of 100 ksi determined by the 0.2 percent offset method, a specified minimum tensile strength of 150 ksi, and a specified minimum elongation of six or seven percent depending on bar size. There is also a requirement that the stress corresponding to a tensile strain of 0.0035 shall be a minimum of 80 ksi. The reinforcement has a non-linear stress-strain relationship. Article 5.4.3.1 of the Design Specifications states that yield strengths in excess of 75.0 ksi shall not be used for design purposes. Consequently, design is based on a stress of 75.0 ksi, but the actual strength is at least twice that value. This has lead to concerns about the applicability of the existing specifications with ASTM A1035 reinforcement. Consequently, it is proposed that initial usage of the reinforcement be restricted to top and bottom flexural reinforcement in the transverse and longitudinal directions of bridge decks in Seismic Zones 1 and 2.~~

Item #6A

Revise Article 5.5.3.2 as follows:

The constant-amplitude fatigue threshold, $(\Delta F)_{TH}$, for straight reinforcement and welded wire reinforcement without a cross weld in the high-stress region shall be taken as:

~~$(\Delta F)_{TH} = 24 - 0.33 f_{min}$~~

$$(\Delta F)_{TH} = 24 - 20 f_{\min} / f_y \qquad (5.5.3.2\text{-}1)$$

The constant-amplitude fatigue threshold, $(\Delta F)_{TH}$, for straight welded wire reinforcement with a cross weld in the high-stress region shall be taken as:

$$(\Delta F)_{TH} = 16 - 0.33 f_{min} \qquad (5.5.3.2\text{-}2)$$

where:

f_y = specified minimum yield strength, not to be taken less than 60.0 ksi nor greater than 100.0 ksi.

Item #6B

Add the following paragraph at the beginning of Commentary C5.5.3.2:

With the permitted use of steel reinforcement having yield stresses above 75.0 ksi, the value of f_{min} is expected to increase. In previous versions of Eq. 5.5.3.2-1, an increase in f_{min} would result in an decrease in $(\Delta F)_{TH}$, regardless of the yield strength of the bar. All available data indicates that steel with a higher yield strength actually has a higher fatigue limit (DeJong and MacDougall, 2006). Eq. 5.5.3.2-1 has been calibrated such that there is no change to the value of $(\Delta F)_{TH}$ from earlier versions of this equation for cases of f_y = 60.0 ksi, but it now provides more reasonable values of $(\Delta F)_{TH}$ for higher strength reinforcing bars.

Item #7A

Revise Article 5.5.4.2.1 as follows:

The provisions of Article 5.5.4.2.1 are applicable to nonprestressed reinforcing steels with specified yield strengths up to 100.0 ksi for Seismic Zone 1.

Resistance factor ϕ shall be taken as:

- For tension-controlled reinforced concrete sections as defined in Article 5.7.2.1 .... 0.90
- For tension-controlled prestressed concrete sections as defined in Article 5.7.2.1 .... 1.00
- For shear and torsion:
  - normal weight concrete........................ 0.90
  - lightweight concrete............................. 0.70
- For compression-controlled sections with spirals or ties, as defined in Article 5.7.2.1, except as specified in Articles 5.10.11.3 and 5.10.11.4.1b for Seismic Zones 2, 3, and 4 at the extreme event limit state 0.75
- For bearing on concrete...................................... 0.70
- For compression in strut-and-tie models............ 0.70
- For compression in anchorage zones:
  - normal weight concrete........................ 0.80
  - lightweight concrete............................. 0.65
- For tension in steel in anchorage zones.............. 1.00
- For resistance during pile driving 1.00

For sections in which the net tensile strain in the extreme tension steel at nominal resistance is between the limits for compression-controlled and tension-controlled sections, ϕ may be linearly increased from 0.75 to that for tension-controlled sections as the net tensile strain in the extreme tension steel increases from the compression-controlled strain limit, ε_{cl}, to ~~0.005~~the tension-controlled strain limit, ε_{tl}.

This variation ϕ may be computed for prestressed members such that:

~~$0.75 \le \phi = 0.583 + 0.25\left(\frac{d_t}{c} - 1\right) \le 1.0$~~

$$0.75 \le \phi = 0.75 + \frac{0.25(\varepsilon_t - \varepsilon_{cl})}{(\varepsilon_{tl} - \varepsilon_{cl})} \le 1.0 \qquad (5.5.4.2.1\text{-}1)$$

and for nonprestressed members such that:

~~$0.75 \le \phi = 0.65 + 0.15\left(\frac{d_t}{c} - 1\right) \le 0.9$~~

$$0.75 \le \phi = 0.75 + \frac{0.15(\varepsilon_t - \varepsilon_{cl})}{(\varepsilon_{tl} - \varepsilon_{cl})} \le 0.9 \qquad (5.5.4.2.1\text{-}2)$$

where:

~~c = distance from the extreme compression fiber to the neutral axis(in.)~~

~~d_t = distance from the extreme compression fiber to the centroid of the extreme tension steel element (in.)~~

ε_t = net tensile strain in the extreme tension steel at nominal resistance

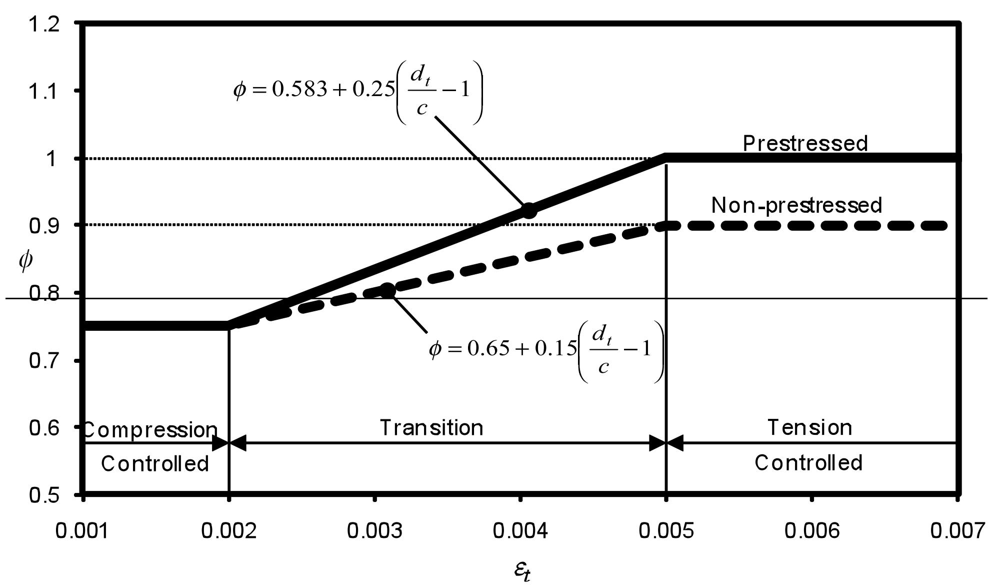
ε_{cl} = compression-controlled strain limit in the extreme tension steel (in./in.) (5.7.2.1)

ε_{tl} = tension-controlled strain limit in the extreme tension steel (in./in.) (5.7.2.1).

Item #7B

Revise the fourth paragraph of Commentary C5.5.4.2.1 and Figure C5.5.4.2.1-1 as follows:

For sections subjected to axial load with flexure, factored resistances are determined by multiplying both P_n and M_n by the appropriate single value of ϕ. Compression-controlled and tension-controlled sections are defined in Article 5.7.2.1 as those that have net tensile strain in the extreme tension steel at nominal strength less than or equal to the compression-controlled strain limit, and equal to or greater than ~~0.005~~the tension-controlled strain limit, respectively. For sections with net tensile strain ε_t in the extreme tension steel at nominal strength between the above limits, the value of ϕ may be determined by linear interpolation, as shown in Figure C5.5.4.2.1-1.



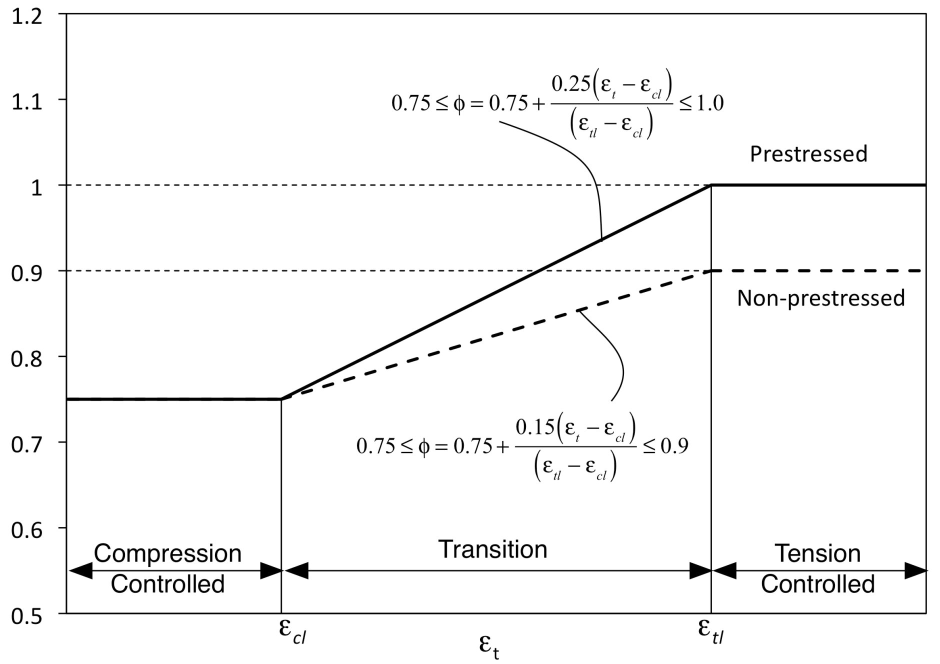


Figure C5.5.4.2.1-1—Variation of ϕ with Net Tensile Strain ε_t ~~and d_t/c~~ for ~~Grade 60~~ Nonprestressed Reinforcement and for Prestressing Steel

Item #8A

Add the following paragraph at the beginning of Article 5.7:

The provisions of this article are applicable to nonprestressed reinforcing steels with specified yield strengths up to 100.0 ksi for Seismic Zone 1.

Item #8B

Add the following paragraph at the beginning of Commentary C5.7:

The provisions for the use of reinforcing steel with specified yield strengths between 75.0 and 100.0 ksi are based on research by Shahrooz, et al. (2010), which did not consider seismic design.

Item #9A

Revise the 10th, 11th, and 13th bullets of Article 5.7.2.1 as follows:

- Sections are compression-controlled when the net tensile strain in the extreme tension steel is equal to or less than the compression-controlled strain limit, ε_{cl}, at the time the concrete in compression reaches its assumed strain limit of 0.003. The compression-controlled strain limit is the net tensile strain in the reinforcement at balanced strain conditions. For Grade 60 reinforcement, and for all prestressed reinforcement, the compression-controlled strain limit may be set equal to ~~0.002.~~ ε_{cl} = 0.002. For nonprestressed reinforcing steel with a specified yield strength of 100.0 ksi, the compression-controlled strain limit may be taken as ε_{cl} = 0.004. For nonprestressed reinforcing steel with a specified yield strength between 60.0 and 100.0 ksi, the compression controlled strain limit may be determined by linear interpolation based on specified yield strength.
- Sections are tension-controlled when the net tensile strain in the extreme tension steel is equal to or greater than ~~0.005~~the tension-controlled strain limit, ε_{tl} just as the concrete in compression reaches its assumed strain

limit of 0.003. Sections with net tensile strain in the extreme tension steel between the compression-controlled strain limit and ~~0.005 constitute a transition region between compression-controlled and tension-controlled sections~~ the tension-controlled strain limit constitute a transition region between compression-controlled and tension-controlled sections. The tension-controlled strain limit, ε_{tl}, shall be taken as 0.005 for nonprestressed reinforcing steel with a specified yield strength, $f_y \leq 75.0$ ksi and prestressed reinforcing steel. The tension-controlled strain limit, ε_{tl}, shall be taken as 0.008 for nonprestressed reinforcing steel with a specified yield strength, $f_y = 100.0$ ksi. For nonprestressed reinforcing steel with a specified yield strength between 75.0 and 100.0 ksi, the tension-controlled strain limit shall be determined by linear interpolation based on specified yield strength.

- In the approximate flexural resistance equations of Articles 5.7.3.1 and 5.7.3.2, f_y and f'_y may replace f_s and f'_s, respectively, subject to the following conditions:
  - f_y may replace f_s when, using f_y in the calculation, the resulting ratio c/d_s does not exceed ~~0.6.~~ :.

$$\frac{c}{d_s} \leq \frac{0.003}{0.003+\varepsilon_{cl}} \qquad (5.7.2.1\text{-}1)$$

where:

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

d_s = distance from extreme compression fiber to the centroid of the nonprestressed tensile reinforcement (in.)

ε_{cl} = compression-controlled strain limit as defined above.

If c/d_s exceeds ~~0.6~~this limit, strain compatibility shall be used to determine the stress in the mild steel tension reinforcement.

  - f'_y may replace f'_s when, using f'_y in the calculation, if $c \geq 3d'_s$~~.~~, and $f_y \leq 60.0$ ksi. If $c < 3d'_s$~~,~~ or $f_y > 60.0$ ksi, strain compatibility shall be used to determine the stress in the mild steel compression reinforcement. ~~The~~ Alternatively, the compression reinforcement ~~shall~~ may be conservatively ignored, i.e., $A'_s = 0$.

When using strain compatibility, the calculated stress in the nonprestressed reinforcing steel may not be taken as greater than the specified yield strength.

Item #9B

Revise the fourth and subsequent paragraphs of Commentary C5.7.2.1 as follows:

When the net tensile strain in the extreme tension steel is sufficiently large (equal to or greater than ~~0.005~~the tension-controlled strain limit), the section is defined as tension-controlled where ample warning of failure with excessive deflection and cracking may be expected. When the net tensile strain in the extreme tension steel is small (less than or equal to the compression-controlled strain limit), a brittle failure condition may be expected, with little warning of impending failure. Flexural members are usually tension-controlled, while compression members are usually compression-controlled. Some sections, such as those with small axial load and large bending moment, will have net tensile strain in the extreme tension steel between the above limits. These sections are in a transition region between compression- and tension-controlled sections. Article 5.5.4.2.1 specifies the appropriate resistance factors for tension-controlled and compression-controlled sections, and for intermediate cases in the transition region.

Before the development of these provisions, the limiting tensile strain for flexural members was not stated, but was implicit in the maximum reinforcement limit that was given as $c/d_e \leq 0.42$, which corresponded to a net tensile strain at the centroid of the tension reinforcement of 0.00414. The net tensile strain limit of 0.005 for tension-controlled sections was chosen to be a single value that applies to ~~all types of steel (prestressed and nonprestressed)~~

~~permitted by this Specification.~~ nonprestressed reinforcing steel with a specified yield strength of 75.0 ksi or less and prestressed reinforcing steel. Research by Shahrooz, et al. (2010) and Mast (2008) supports the values stated for compression- and tension-controlled strain limits for steel with higher specified yield strengths.

Unless unusual amounts of ductility are required, the ~~0.005~~tension-controlled strain limit will provide ductile behavior for most designs. One condition where greater ductile behavior is required is in design for redistribution of moments in continuous members and frames. Article 5.7.3.5 permits redistribution of negative moments. Since moment redistribution is dependent on adequate ductility in hinge regions, moment redistribution is limited to sections that have a net tensile strain of at least ~~0.0075~~$1.5\varepsilon_{cl}$.

For beams with compression reinforcement, or T-beams, the effects of compression reinforcement and flanges are automatically accounted for in the computation of net tensile strain ε_t.

When using the approximate flexural resistance equations in Articles 5.7.3.1 and 5.7.3.2, it is important to assure that both the tension and compression mild steel reinforcement are yielding to obtain accurate results. In previous editions of the *AASHTO LRFD Bridge Design Specifications*, the maximum reinforcement limit of $c/d_e \leq 0.42$ assured that the mild tension steel would yield at nominal flexural resistance, but this limit was eliminated in the 2006 interim revisions. The current limit ~~of~~ on c/d_s ~~≤ 0.6~~ assures that the mild tension steel will be at or near yield~~, while~~. The ratio $c \geq 3d'_s$ assures that ~~the~~ mild compression steel with $f_y \leq 60.0$ ksi will yield. For yield strengths above 60.0 ksi, the yield strain is close to or exceeds 0.003, so the compression steel may not yield. It is conservative to ignore the compression steel when calculating flexural resistance. In cases where either the tension or compression steel does not yield, it is more accurate to use a method based on the conditions of equilibrium and strain compatibility to determine the flexural resistance.

Item #10

Add the following paragraph at the end of Article 5.7.3.2.5:

When using strain compatibility, the calculated stress in the nonprestressed reinforcing steel shall not exceed the specified yield strength.

Item #11

Revise the second paragraph of Commentary C5.7.3.3.1 as follows:

The current provisions of LRFD eliminate this limit and unify the design of prestressed and nonprestressed tension- and compression-controlled members. The background and basis for these provisions are given in Mast (1992). ~~Below a~~ When the net tensile strain in the extreme tension steel ~~of 0.005~~is below the tension-controlled strain limit, as the tension reinforcement quantity increases, the factored resistance of prestressed and nonprestressed sections is reduced in accordance with Article 5.5.4.2.1. This reduction compensates for decreasing ductility with increasing overstrength. Only the addition of compression reinforcement in conjunction with additional tension reinforcement can result in an increase in the factored flexural resistance of the section.

Item #12A

Revise the definition of f_{ss} in Article 5.7.3.4 as follows:

f_{ss} = tensile stress in steel reinforcement at the service limit state (ksi) not to exceed 60.0 ksi

Item #12B

Add the following paragraph after the ninth paragraph in Commentary C5.7.3.4:

Research by Shahrooz et al. (2010) indicated that Eq. 5.7.3.4-1 can be applied to reinforcement with specified yield strengths up to 100.0 ksi but the tensile stress in the steel reinforcement at the service limit state, f_{ss}, cannot exceed 60.0 ksi. Moreover, when using reinforcing steel acknowledged to have greater resistance to corrosion (i.e., ASTM A955 and A1035), only Class 1 requirement needs to be satisfied.

Item #13A

Revise the first paragraph of Article 5.7.3.5 as follows:

In lieu of more refined analysis, where bonded reinforcement that satisfies the provisions of Article 5.11 is provided at the internal supports of continuous reinforced concrete beams, negative moments determined by elastic theory at strength limit states may be increased or decreased by not more than $1000\varepsilon_t$ percent, with a maximum of 20 percent. Redistribution of negative moments shall be made only when ε_t is equal to or greater than ~~0.0075~~$1.5\varepsilon_{tl}$ at the section at which moment is reduced, where ε_{tl} is the tension-controlled strain limit defined in Article 5.7.2.1.

Item #13B

Revise Commentary C5.7.3.5 as follows:

In editions and interims to the LRFD Specifications prior to 2005, Article 5.7.3.5 specified the permissible redistribution percentage in terms of the c/d_e ratio. The current specification specifies the permissible redistribution percentage in terms of net tensile strain ε_t. ~~The background and basis for these provisions are given in Mast (1992).~~

Mast (1992) provides an equation for the minimum strain in the tensile steel required for moment redistribution, which is based on the yield strain of the reinforcing steel and the assumption that $\rho/\rho_{bal} = 0.5$. Using reasonable values of yield strain for reinforcing steel with $f_y = 100.0$ ksi, the minimum tensile strain for moment redistribution can be found as 0.0012, which is $1.5\varepsilon_{tl}$ (Shahrooz, et al. 2010) Previous versions of this article set the minimum tensile strain at 0.0075 when the tension-controlled strain limit was set to 0.005. Thus, $1.5\varepsilon_{tl}$ gives the same value of minimum tensile strain for moment redistribution for reinforcing steel with $f_y \leq 75.0$ ksi as in previous editions, but also provides a reasonable value of minimum tensile strain for moment redistribution for higher strength reinforcing steels.

Item #14

Add the following paragraph at the end of Commentary C5.7.4.2:

When using high strength reinforcing steel in axially loaded members, designers should account for the fact that these members may have smaller areas of steel and/or smaller gross dimensions for the same resistance. These reductions may affect axial deformations, slenderness effects, and/or the effects of creep and shrinkage.

Item #15

Add the following paragraph at the end of Commentary C5.7.4.4:

Research by Shahrooz, et al. (2010) and Ward (2008) showed that these provisions are applicable to columns using reinforcing steel with specified yield strengths up to 100.0 ksi. Designers should account for the fact that columns using high strength reinforcing steel may have smaller areas of steel and/or smaller gross dimensions for the same resistance. These reductions may affect axial deformations and/or slenderness effects.

Item #16

Revise the definition of f_{yh} in Article 5.7.4.6 as follows:

f_{yh} = specified yield strength of spiral reinforcement (ksi) $\leq$ 100.0 ksi for Seismic Zone 1; $\leq$ 75.0 ksi for Seismic Zones 2, 3, and 4)

Item #17A

Add the following paragraph at the end of Article 5.8.2.4:

For members subjected to flexural shear without torsion, reinforcing steel with specified yield strengths up to 100.0 ksi may be used for transverse reinforcement for Seismic Zone 1.

Item #17B

Add the following paragraph at the end of Commentary C5.8.2.4:

Testing by Shahrooz, et al. (2010) has verified the use of transverse reinforcement with specified yield strengths up to 100.0 ksi for both prestressed and nonprestressed members subjected to flexural shear without torsion for nonseismic applications. No torsional or combined torsion/flexure tests of members using transverse reinforcement with specified yield strengths between 75.0 and 100.0 ksi have been conducted.

Item #18A

Revise the definition of f_y in Article 5.8.2.5 as follows:

f_y = yield strength of transverse reinforcement (ksi) $\leq$ 100.0 ksi

Item #18B

Add the following paragraph at the end of Commentary C5.8.2.5:

Testing by Shahrooz, et al. (2010) has verified these minimum values of transverse reinforcement for reinforcing steel with specified yield strengths up to 100.0 ksi for both prestressed and nonprestressed members subjected to flexural shear without torsion for nonseismic applications.

Item #19

Add the following paragraph at the end of Commentary C5.8.2.7:

These spacing requirements were verified by Shahrooz, et al. (2010) for transverse reinforcement with specified yield strengths up to 100.0 ksi for prestressed and nonprestressed members subjected to flexural shear without torsion for nonseismic applications.

Item #20A

Insert a new second paragraph and revise the existing second paragraph in Article 5.8.2.8 as follows:

For members in Seismic Zone 1 subjected to flexural shear without torsion, the design yield strength of nonprestressed transverse reinforcement shall be taken as the specified yield strength, but not to exceed 100.0 ksi.

In all other cases, the ~~The~~ design yield strength of nonprestressed transverse reinforcement shall be taken equal to the specified yield strength when the latter does not exceed 60.0 ksi. For nonprestressed transverse reinforcement with yield strength in excess of 60.0 ksi the design yield strength shall be taken as the stress corresponding to a strain of 0.0035, but not to exceed 75.0 ksi.

Item #20B

Revise the second paragraph of Commentary C5.8.2.8 as follows:

Some of the provisions of Article 5.8.3 are based on the assumption that the strain in the transverse reinforcement has to attain a value of 0.002 to develop its yield strength. For prestressed tendons, it is the additional strain required to increase the stress above the effective stress caused by the prestress that is of concern. ~~Limiting~~ Previous versions limited the design yield strength of nonprestressed transverse reinforcement to 75.0 ksi or a stress corresponding to a strain of 0.0035 ~~provides~~ to provide control of crack widths at service limit state. ~~For~~ Shahrooz et al. (2010) compared the performance of transverse reinforcement ~~without a well-defined~~ with specified yield

~~point, the yield strength is determined~~ strengths of 60.0 ksi and 100.0 ksi in prestressed and nonprestressed members subjected to flexural shear only, under nonseismic conditions. The results do not show any discernable difference between the performance of the two types of transverse reinforcing steel at ~~a strain of 0.0035 at~~ either service or strength limit states. Research . . .

Item #21

Add the following paragraph after Eq. C5.8.3.3-1 in Commentary C5.8.3.3:

As noted in Article 5.8.2.4 for members subjected to flexural shear without torsion, transverse reinforcement with specified yield strengths up to 100.0 ksi is permitted for Seismic Zone 1.

Item #22A

Add the following paragraph at the end of Article 5.8.3.5:

The use of longitudinal and/or transverse reinforcing steel with specified yield strengths up to 100.0 ksi is permitted for Seismic Zone 1.

Item #22B

Add the following paragraph at the end of Commentary C5.8.3.5:

This provision allows the use of longitudinal and transverse reinforcing steel with specified yield strengths up to 100.0 ksi for Seismic Zone 1; however, the use of higher strength longitudinal reinforcing steel may not be practical due to longer required development lengths.

Item #23

Add the following paragraph at the end of Article 5.8.4.1:

If a member has transverse reinforcing steel with a specified yield strength greater than 60.0 ksi for flexural shear resistance, interface reinforcement may be provided by extending the transverse reinforcement across the interface zone. In this case, the value of f_y in Equation 5.8.4.1-3 shall not be taken as greater than 60.0 ksi.

Item #24A

Add the following paragraph at the end of Article 5.10.2.1

Standard hooks may be used with reinforcing steel having a specified yield strength up to 100.0 ksi.

Item #24B

Add the following paragraph at the end of Commentary C5.10.2.1:

Tests by Shahrooz et al. (2010) showed that standard hooks are adequate for reinforcing steel with specified yield strengths up to 100.0 ksi if transverse, confining reinforcement is provided.

Item #25A

Add the following sentence at the end of the paragraph in Article 5.10.2.2:

For seismic hooks, f_y shall not be taken greater than 75.0 ksi.

Item #25B

Add the following new Commentary C5.10.2.2:

Detailing of seismic hooks has not been verified for reinforcing steels with yield strengths exceeding 75.0 ksi.

Item #26A

Add the following paragraph at the end of Article 5.10.6.1:

In Seismic Zone 1, spirals and ties may be designed for specified yield strengths up to 100.0 ksi.

Item #26B

Add the following paragraph at the end of Commentary C5.10.6.1:

Spirals and ties with specified yield strengths of up to 100.0 ksi are permitted based on research by Shahrooz et al. (2010). Since this research did not consider seismic design, the use of high strength spirals and ties is limited to Seismic Zone 1.

Item #27

Add the following paragraph at the end of Article 5.10.11.1:

The use of reinforcing steel with specified yield strengths of less than or equal to 100.0 ksi may be used in Seismic Zone 1, where permitted by specific articles.

Item #28

Revise the definition of f_y at two locations in Article 5.10.11.4.1d as follows:

f_y = yield strength of reinforcing bars (ksi) $\leq$ 75.0 ksi

f_y = yield strength of tie or spiral reinforcement (ksi) $\leq$ 75.0 ksi

Item #29A

Revise Article 5.11.1.1 as follows:

The calculated force effects in the reinforcement at each section shall be developed on each side of that section by embedment length, hook, mechanical device, or a combination thereof. Hooks and mechanical anchorages may be used in developing bars in tension only. This article is applicable to nonprestressed reinforcing steel having a specified yield strength up to 100.0 ksi for Seismic Zone 1.

Item #29B

Revise Commentary C5.11.1.1 as follows:

Most of the provisions in this Article are based on ACI 318-89 and its attendant commentary. Shahrooz et al. (2010) verified that development length equations for reinforcing bars, splice lengths, and hooks in tension are applicable for specified yield strengths up to 100.0 ksi in nonseismic applications.

Item #30A

Revise Article 5.11.2 as follows:

~~For reinforcement conforming to the requirements of ASTM A1035/A1035M, the value of f_y used in this Article shall be taken as 100 ksi.~~

Development lengths shall be calculated using the specified yield strength of the reinforcing steel. Use of nonprestressed reinforcing steel with a specified yield strength up to 100.0 ksi is permitted for Seismic Zone 1.

Item #30B

Revise Commentary C5.11.2 as follows:

~~Although the specified yield strength of reinforcing bars used in design shall not exceed 75.0 ksi, tests have shown that a longer development length is needed with reinforcement conforming to ASTM A1035/A1035M to achieve a ductility comparable to that achieved with reinforcement conforming to AASHTO M 31. Limited tests have shown a lack of ductility in tension splices of reinforcement conforming to ASTM A1035 when compared to the behavior of splices with reinforcement conforming to AASHTO M 31, when the splice length is calculated using the maximum design yield strength of 75.0 ksi. However, when the splice length of the ASTM A1035/A1035M reinforcement is determined using its specified minimum yield strength of 100 ksi, more ductility is achieved. Consequently, it is proposed to use 100 ksi until additional research indicates an alternative value.~~

Research by Shahrooz et al. (2010) showed that calculated tensile splice lengths and calculated tensile development lengths for both straight bars and standard hooks are adequate in nonseismic applications for reinforcing steels with yield strengths up to 100.0 ksi combined with concrete strengths up to 15.0 ksi.

Item #31

Add the following paragraph at the beginning of Article 5.11.2.1:

For straight bars having a specified yield strength greater than 75.0 ksi, transverse reinforcement satisfying the requirements of Article 5.8.2.5 in beams and Article 5.10.6.3 in columns shall be provided over the required development length.

Item #32

Add the following paragraph at the beginning of Article 5.11.2.4:

For hooks in reinforcing bars having a specified yield strength greater than 60.0 ksi, ties satisfying the requirements of Article 5.11.2.4.3 shall be provided. For hooks not located at the discontinuous end a member, the modification factors of Article 5.11.2.4.2 may be applied.

Item #33A

Revise the first paragraph of Article 5.11.5 as follows:

Use of reinforcing steel with specified yield strengths up to 100.0 ksi is permitted in this article for Seismic Zone 1. For spliced bars having a specified yield strength greater than 75.0 ksi, transverse reinforcement ~~conforming to~~ satisfying the requirements of ~~ASTM A1035/A1035M, the value of f_y used in this~~ Article 5.8.2.5 in beams and Article 5.10.6.3 in columns shall be ~~taken as 100 ksi.~~ provided over the required splice length.

Item #33B

Add a new Commentary C5.11.5 as follows:

C 5.11.5

Research by Shahrooz et al. (2010) verified the use of these provisions for tensile splices for reinforcing steels with specified yield strengths up to 100.0 ksi in nonseismic applications.

Item #34A

Add the following paragraph at the end of Article 5.11.5.3.1:

For splices having f_y > 75.0 ksi, transverse reinforcement satisfying the requirements of Article 5.8.2.5 in beams and Article 5.10.6.3 in columns shall be provided over the required development length.

Item #34B

Add the following paragraph at the end of Commentary C5.11.5.3:

Research by Shahrooz et al. (2010) verified these provisions for nonseismic applications for reinforcing steels with specified yield strengths up to 100.0 ksi combined with concrete strengths up to 15.0 ksi.

Item #35

Add the following references to Article 5.15:

DeJong, S. J. and C. MacDougall, 2006. "Fatigue Behaviour of MMFX Corrosion-Resistant Reinforcing Steel," Proceedings of the 7th International Conference on Short and Medium Span Bridges, Montreal, Canada 2006.

Shahrooz, B. M., R. A. Miller, K. A. Harries, and H. G. Russell. To be published. *Structural Concrete Design with High-Strength Steel Reinforcement*, NCHRP Report _____. Transportation Research Board, National Research Council, Washington, DC.

Item # 36

Add a new appendix D5 as follows:

APPENDIX D5—ARTICLES MODIFIED TO ALLOW THE USE OF REINFORCING STEEL WITH A SPECIFIED YIELD STRENGTH UP TO 100 KSI

Article	Brief summary of changes
5.2 DEFINITIONS	Modified the definition of tension-controlled section by changing "0.005" to "tension-controlled strain limit". Added definition of tension-controlled strain limit.
5.3 NOTATION	Modified the definition of f_y to allow higher yield strengths. Added definitions of ε_{cl} and ε_{tl}; compression- and tension-controlled strain limits, respectively.
5.4.3.1 and C5.4.3.1 Reinforcing Steel, General	Permits the use of reinforcing steel with specified yield strengths up to 100.0 ksi when allowed by specific articles.
5.4.3.2 Reinforcing Steel, Modulus of Elasticity	E_s=29,000 may be used for specified yield strengths up to 100.0 ksi.
5.4.3.3 and C5.4.3.3 Reinforcing Steel, Special Applications	Permits the use of reinforcing steel with specified yield strengths up to 100.0 ksi in Seismic Zone 1.
5.5.3.2 and C5.5.3.2 Fatigue Limit State, Reinforcing Bars	Modifies the fatigue equation for reinforcing bars to allow the equation to be used for specified yield strengths up to 100.0 ksi.
5.5.4.2.1 and C5.5.4.2.1 Resistance factors, Conventional Construction	Allows the use of reinforcing steel with specified yield strengths up to 100.0 ksi in Seismic Zone 1. Modifies the equation, figure, and commentary for ϕ. These now use ε_{cl} and ε_{tl}, (compression- and tension-controlled strain limits) in place of 0.002 and 0.005.

5.7 and adds C5.7 DESIGN FOR FLEXURAL AND AXIAL FORCE EFFECTS	Allows the use of reinforcing steel with specified yield strengths up to 100.0 ksi in Seismic Zone 1.
5.7.2.1 and C5.7.2.1 Assumptions for Strength and Extreme Event Limit States	Keeps compression- and tension- controlled strain limits of 0.002 and 0.005 for reinforcing steels with specified yield strengths up to 60.0 and 75.0 ksi, respectively. Provides compression- and tension-controlled strain limits of 0.004 and 0.008 for reinforcing steel with a specified yield strength equal to 100.0 ksi. Linear interpolation is used for reinforcing steels with specified yield strengths between 60.0 or 75.0 ksi and 100.0 ksi. Equations are provided for when f_y may replace f_s or f_s' in 5.7.3.1 and 5.7.3.2.
5.7.3.2.5 Strain Compatibility Approach	Limits the steel stress in a strain compatibility calculation to the specified yield strength.
C5.7.3.3.1 Maximum Reinforcement	Replaces 0.005 with “tension-controlled strain limit”.
5.7.3.5 and C5.7.3.5 Moment Redistribution	Adjusts strain limit to allow moment redistribution in structures using reinforcing steel with specified yield strengths up to 100.0 ksi.
C5.7.4.2 and C5.7.4.4. Limits for Reinforcement	Warns that designs should consider that columns using higher strength reinforcing steel may be smaller and have lower axial stiffness.
5.7.4.6 Spirals and Ties	Permits spirals and ties made of reinforcing steel with specified yield strengths up to 100.0 ksi in Seismic Zone 1.
5.8.2.4 and C5.8.2.4 Regions Requiring Transverse Reinforcement 5.8.2.5 and C5.8.2.5 Minimum Transverse Reinforcement	Permits transverse reinforcement with specified yield strengths up to 100.0 ksi in applications with flexural shear without torsion.
C5.8.2.7 Maximum Spacing of Transverse Reinforcement	Indicates that spacing requirements have been verified for transverse reinforcement with specified yield strengths up to 100.0 ksi in applications of shear without torsion.
5.8.2.8 and C5.8.2.8 Design and Detailing Requirements.	Permits transverse reinforcement with specified yield strengths up to 100.0 ksi in applications with flexural shear without torsion.
C5.8.3.3 Nominal Shear Resistance	Identifies that transverse reinforcement with specified yield strengths up to 100.0 ksi may be used in applications with flexural shear without torsion.
5.8.3.5 Longitudinal Reinforcement	Permits longitudinal reinforcing steel with specified yield strengths up to 100.0 ksi.
5.8.4.1 Interface Shear Transfer, General	Clarifies that f_y is limited to 60.0 ksi in Eq. 5.8.4.1.3.
5.10.2 and C5.10.2 Hooks and Bends	Permits hooks with specified yield strengths up to 100.0 ksi with transverse confining steel in Seismic Zone 1.
5.10.6.1 and C5.10.6.1 Transverse Reinforcement for Compression Members, General	Permits spirals with specified yield strengths up to 100.0 ksi in Seismic Zone 1.
5.10.11.1 Provisions for Seismic Design, General	Permits the use of reinforcing steel with specified yield strengths up to 100.0 ksi in Seismic Zone 1.
5.11.1.1 and C5.11.1.1 DEVELOPMENT AND SPLICES OF REINFORCEMENT, Basic Requirements 5.11.2 and C5.11.2 Development of Reinforcement	Permits the development length equations to be used for reinforcing steel with specified yield strengths up to 100.0 ksi.
5.11.2.1 Deformed Bar and Wire in Tension	Requires transverse confining steel for development of reinforcing steel with specified yield strengths greater

5.11.2.4 Standard Hooks in Tension	Requires the use of modification factors or ties for hooks of reinforcing steel with specified yield strengths exceeding 60 ksi.
5.11.5 and adds C5.11.5 Splices of Bar Reinforcement 5.11.5.3 and C5.11.5.3 Splices of Reinforcement in Tension	Permits splices in reinforcing steel with specified yield strengths up to 100.0 ksi and requires transverse confining steel.
Table 5.11.5.3.1-1 Classes of Tension Lap Splices	Requires transverse confining steel in splices of reinforcing steel with specified yield strengths exceeding 75.0 ksi.

OTHER AFFECTED ARTICLES:

None

BACKGROUND:

The *AASHTO LRFD Bridge Construction Specifications* permits the specification of ASTM A1035 reinforcing bars. These bars contain low carbon, chromium steel and are characterized by a high tensile strength of 100.0 or 120.0 ksi and a stress-strain relationship having no yield plateau. Because of their high chromium content, A1035 bars are reported to have superior corrosion resistance when compared to conventional reinforcing steel grades. For this reason, designers have specified A1035 bars as a direct, one-to-one, replacement for conventional reinforcing bars as an alternative to stainless steel or epoxy-coated bars. The *AASHTO LRFD Bridge Design Specifications*, however, currently limit the design yield strength of reinforcing steel to 75.0 ksi for most applications. Therefore, although A1035 steel is being specified for its corrosion resistance, its higher yield strength cannot be utilized.

NCHRP Project 12-77 was initiated to provide an evaluation of existing *AASHTO LRFD Bridge Design Specifications* relevant to the use of high-strength reinforcing steel and other grades of reinforcing steel having no discernable yield plateau. An integrated experimental and analytical program to develop the data required to permit the integration of high-strength reinforcement into the *LRFD Specification* was performed. In addition, a number of 'proof tests' intended to validate the existing provisions of the *LRFD Specifications* to higher strength reinforcing steel were made. The focus of the experimental phase of the study was the use of ASTM A1035 reinforcing steel since it captures both behavioral aspects of interest i.e., it has a very high strength and has no discernable yield plateau. In addition, the research specifically considered the use of higher strength concrete. The experimental and analytical studies included concrete having compressive strengths of 5.0, 10.0, and 15.0 ksi.

The research included evaluations of reinforcement yield strengths, flexural design, fatigue strength, shear strength, shear friction, compressive strength, bond and development, and serviceability criteria for deflections and crack widths. In some cases, the affected articles could simply be modified to allow the use of high strength reinforcing steel. In other cases, additional modifications or requirements were necessary. The study did not address seismic applications, and no such increase in permitted yield strength is allowed for Seismic Zones 2 through 4.

A critical objective of the work was to identify an appropriate steel strength and/or behavior model to adequately capture the behavior of high-strength reinforcing steel while respecting the tenets of design and the needs of the designer. A value of yield strength, f_y, not exceeding 100.0 ksi was found to be permissible without requiring significant changes to the *LRFD Specifications* or, more critically, to the design philosophy and methodology prescribed therein. Some limitations to this increase were identified.

The important conclusion of NCHRP Project 12-77 was that reinforcing steel with specified yield strengths of up to 100.0ksi can be successfully used in non-seismic bridge applications for both its increased corrosion resistance and its higher yield strength.

ANTICIPATED EFFECT ON BRIDGES:

A number of grades of steel reinforcement with yield strengths exceeding 75.0 ksi are commercially available in the United States. The use of steel with this higher capacity could provide benefits to concrete bridge construction by reducing member cross sections and reinforcement quantities, leading to savings in material, shipping, and placement costs. Reducing reinforcement quantities will also reduce congestion problems leading to better quality of construction. Since many of these reinforcing steels have better corrosion resistance, enhanced durability will be achieved. Finally, the use of high-strength steel reinforcement with high-strength concrete should result in more efficient use of both materials.

REFERENCES:

Shahrooz, B. M., R. A. Miller, K. A. Harries, and H. G. Russell. To be published. *Structural Concrete Design with High-Strength Steel Reinforcement*, NCHRP Report _____. Transportation Research Board, National Research Council, Washington, DC.

OTHER:

None