AASHTO LRFD Bridge Design Specifications*:* *Strain Compatibility Analysis and Reinforcement Properties*

by Dr. Oguzhan Bayrak, University of Texas at Austin

This article provides an overview of three agenda items that update the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*:[1] agenda item 34 (working agenda item [WAI] 235): Strain Compatibility; agenda item 37 (WAI 238): Reinforcement Properties; and agenda item 38 (WAI 234): ASTM A615 Updates. While these agenda items were developed separately, it is logical to discuss them together because strain compatibility analyses involve the use of mechanical properties of reinforcement.

In estimating the flexural capacity of reinforced concrete elements, it is customary to assume that the rupture strain of typical ASTM A615[2] or ASTM A706[3] reinforcing bars is sufficiently large. That is to say, as crushing of concrete on the flexural compression side takes place, the reinforcement on the flexural tension side of a member yields but does not reach its rupture strain. This assumption can easily be verified by establishing the strain profile at strength limit strength. However, it can be problematic to extend the logic of the assumption to prestressed concrete components and members in which reinforcing materials with lower rupture strains, such as stainless steel or carbon-fiber reinforced polymers, are used. In such cases, rupture of reinforcement may take place before concrete on the flexural compression side of an element is crushed. In addition, the closed form equations of Article 5.6.3 of the AASHTO LRFD specifications can significantly underpredict the flexural resistance of flanged precast, prestressed concrete girders in cases when the neutral axis falls outside of the flange. (See articles on strain compatibility and girders with composite decks in the Fall 2024 and Winter 2025 issues of *ASPIRE*®.) In all of the cases described in this paragraph, strain compatibility analyses provide estimates of flexural capacity that are more accurate than the customary assumption. In this context, agenda item 34 offers guidance for performing strain compatibility analyses, and agenda item 37 provides detailed information on the mechanical properties of reinforcing steels. Since agenda item 34 relies on information provided in agenda item 37, let us start our discussion with agenda item 37.

Agenda Item 37

This agenda item adds a new table (**Table 5.4.3.1-1**) that provides a summary of steel reinforcement.

In addition to the table, this agenda item adds the following language after the second paragraph of C5.4.3.1, across from the new Table 5.4.3.1-1, as follows:

> *The values listed in Table 5.4.3.1-1 represent the minimum values that materials must achieve to meet the requirements of the ASTM specification for a given grade. Designers should use these minimum values in design equations unless material specific information is available.*
>
> *There is no value provided for elongation/tensile strain in ASTM A1064; therefore, it was not included in the table. Designers should review available research data should they need to find a minimum tensile strain for welded wire reinforcement that complies with ASTM A1064.*
>
> *Other materials that are not included in Table 5.4.3.1-1 may be used as reinforcement. For data on those materials, designers should consult applicable ASTM standards, available research, or material suppliers.*

Agenda item 37 also revises **Table 5.4.4.1-1** by adding the specified minimum tensile strains and including 0.7-in.-diameter strands.

Finally, this agenda item adds a new commentary article, C5.4.4.1, as follows:

> *The values for tensile strength and minimum tensile strain listed in Table 5.4.4.1-1 represent the minimum values that materials must achieve to meet the requirements of the ASTM specification for a given grade or type. Designers should use these minimum values in design equations unless material specific information is available.*

Agenda Item 34

This agenda item adds a new (15th) bullet point to Article 5.6.2.1, as follows:

- *The minimum strain limits of reinforcing steel specified in Table 5.4.3.1-1 and prestressing steel specified in Table 5.4.4.1-1 shall be considered.*

A new paragraph within the commentary (C5.6.2.1) and directly across from the new bullet point in Article 5.6.2.1 is added, as follows:

> *The values listed in Table 5.4.3.1-1 and Table 5.4.4.1-1 represent the minimum values that materials must achieve to meet the requirements of the ASTM specification for a given grade. Designs should not rely on values that exceed these minimums unless material specific information is available.*

In addition, this agenda item revises Article C5.6.3.2.2 by adding a new second paragraph to read as follows:

> *Seguirant, Brice, and Khaleghi (2004)*[8] *demonstrate that the*

Table 5.4.3.1-1. Material Standards for Reinforcing Steel

Standard	Grade of Reinforcement	Specified Minimum Yield Strength (ksi)	Specified Minimum Tensile Strength (ksi)	Specified Minimum Tensile Strain
ASTM A615	Grade 60	60	80	0.07
	Grade 80	80	100	0.06
	Grade 100	100	115	0.06
ASTM A706	Grade 60	60	80	0.10
	Grade 80	80	100	0.10
	Grade 100	100	117	0.10
ASTM A955[4]	Grade 60	60	90	0.20
	Grade 75	75	100	0.20
	Grade 80	80	100	0.16
ASTM A1035[5]	Grade 100	100	150	0.06
ASTM A1064[6]	Grade 56	56	70	Not included in ASTM
	Grade 65	65	75	
	Grade 70	70	80	
	Grade 72.5	72.5	82.5	
	Grade 75	75	85	
	Grade 77.5	77.5	87.5	
	Grade 80	80	90	

Note: Minimum tensile strain for each grade is shown. Value is dependent on bar size within grade. See ASTM standard for more details. For components designed using the *AASHTO Guide Specifications for LRFD Seismic Bridge Design*,[7] the reduced ultimate tensile strain values shall be used in lieu of the values in the table above.

Table 5.4.4.1-1. Limits on Prestressed Steel

Material	Grade or Type	Diameter (in.)	Tensile Strength, f_{pu} (ksi)	Yield Strength, f_{py} (ksi)	Specified Minimum Tensile Strain
Strand	270 ksi	0.375 to 0.7	270	90% of f_{pu} = 243	0.035
Bar	Type 1, Plain	0.75 to 1.375	150	85% of f_{pu} = 127.5	0.04
	Type 2, Deformed	0.625 to 2.5	150	80% of f_{pu} = 120	

Note: For components designed using the *AASHTO Guide Specifications for LRFD Seismic Bridge Design*, the reduced ultimate tensile strain values in the Guide Specifications shall be used in lieu of the values in the table above.

> *flexural resistance predicted by Eq. 5.6.3.2.2-1 becomes increasingly conservative relative to strain compatibility analysis when the neutral axis is below the reinforced concrete deck. The degree of conservatism magnifies with increasing girder concrete strength. Neglecting the compression force contribution of beam flanges and large chamfers at box section web-flange intersections also contributes to the conservatism. The higher strength concrete in the prestressed concrete girder is not considered due to limitations of the approximation flexural resistance equations. As the depth of the compression block increases to balance the tension force in the reinforcement, the internal moment arm decreases leading to a lower predicted capacity. This in turn leads to sections that are predicted by Eq. 5.5.4.2-1 and Eq. 5.5.4.2-2 to be in the compression-controlled or transition region with reduced resistance factors. In these cases, strain compatibility analysis can provide a more accurate estimate of flexural resistance.*

Article 5.6.3.2.5 is also revised as follows:

> *The strain compatibility approach is recommended when more precise calculations are required especially for flanged prestressed concrete sections. The appropriate provisions of Article 5.6.2.1 shall apply.*
>
> *The stress and corresponding strain in any given layer of the*

section is taken from any appropriate stress-strain formula or graph of the material in the layer. Minimum specified properties shall be used in the stress-strain formula or graph for non-prestressed reinforcement with yield strengths between 75.0 and 100 ksi.

A new commentary article, C5.6.3.2.5, is added, as follows:

> *Strain compatibility analysis is a method of analysis that often involves subdividing the cross section into discrete layers or fiber elements, estimating the strain in each element based on the assumption of plane sections, evaluating the stress using stress-strain relationships, and integrating the stress field to determine the flexural strength of the section. This analysis is typically iterative by varying the curvature of the section until conditions of equilibrium are satisfied.*
>
> *Strain compatibility analysis uses stress-strain relationships for the reinforcement and the concrete elements. Composite girder sections with different concrete compressive strengths in the deck and girder are more accurately modeled with this approach. Non-rectangular sections and multiple layered reinforcing with limited ductility can also be accurately analyzed. The analysis can account for reinforcement at any position in the cross section.*
>
> *Stress-strain relationships for concrete compression are typically non-linear or bilinear curves. Several stress-strain concrete curves have been developed and may be used to determine the stress-strain relationship to model the behavior of the concrete in compression. See Hognestad (1951)*[9] *and Desayi and Krishnan (1964).*[10] *Seguirant, Brice, and Khaleghi (2004)*[8] *use a non-linear stress-strain curve based on Collins and Mitchell (1991).*[11] *Figure C5.6.3.2.5-1 shows a bilinear concrete compression stress-strain relationship based on French specifications (2016)*[12] *and used by El-Helou (2022)*[13] *and Tadros (2021).*[14] *The bilinear stress-strain relationship is expressed in Eqn. C5.6.3.2.5-1 and produces results similar to nonlinear models.*
>
> $$f_c(\varepsilon_c) = \begin{Bmatrix} E_c\varepsilon_c \text{ for } \varepsilon_c < \dfrac{0.85f'_c}{E_c} \\ 0.85f'_c \text{ for } \varepsilon_c \geq \dfrac{0.85f'_c}{E_c} \end{Bmatrix}$$
>
> *(C5.6.3.2.5-1)*
>
> *where:*
>
> ε_c = *compressive strain in concrete (in./in.)*
>
> f_c = *compressive stress corresponding to the strain* ε_c *(ksi)*
>
> E_c = *modulus of elasticity of concrete (ksi)*
>
> f'_c = *compressive strength of concrete for use in design (ksi)*
>
> *The Menegotto-Pinto model (Menegotto, 1973),*[15] *also known as the "power formula" (Mattock 1979,*[16] *Skogman 1988,*[17] *Devalapura 1992*[18]*), is often used to idealize the tensile stress-strain behavior of steel reinforcement. The power formula is expressed by Equation C5.6.3.2.5-2. Figure C5.6.3.2.5-2 shows the stress-strain curve for different reinforcement types.*

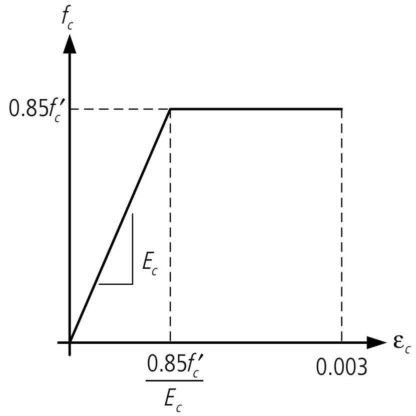

Figure C5.6.3.2.5-1. Bilinear concrete compression stress-strain relationship.

> $$f(\varepsilon_s) = E\varepsilon_s\left\{Q + \frac{1-Q}{\left[1+\left(\dfrac{E\varepsilon_s}{Kf_y}\right)^R\right]^{\frac{1}{R}}}\right\} \leq f_u$$
>
> *(C5.6.3.2.5-2)*
>
> *where:*
>
> ε_s = *strain in reinforcement (in./in.)*
>
> E = *reinforcement modulus of elasticity;* E_s *for steel reinforcing,* E_{ps} *for prestressing steel (ksi)*
>
> f_y = *reinforcement yield stress;* f_y *for steel reinforcing,* f_{py} *for prestressing steel (ksi)*
>
> f_u = *minimum tensile strength of reinforcement;* f_{pu} *for prestressing steel (ksi)*
>
> *K, Q, and* R = *curve fitting parameters*
>
> *Power formula curve fitting parameters for prestressing strand and reinforcing bars are given in Table C5.6.3.2.5-1. Common properties of reinforcement are listed in Table 5.4.3.1-1 and Table 5.4.4.1-1. Steel reinforcement stress-strain curves using the curve fitting parameters are shown in Figure C5.6.3.2.5-2.*

Table C5.6.3.2.5-1. Power Formula Curve Fitting Parameters

Reinforcement Type	K	Q	R
ASTM A416[19] Grade 270 Strand	1.040	0.031	7.36
ASTM A615, A706 Grade 60	1.096	0.000	100.0
ASTM A615, A706 Grade 80	0.980	0.028	100.0
ASTM A615 Grade 100	0.980	0.022	4.50
ASTM A1035 Grade 100	1.140	0.050	1.71

> *Stress-strain relationships for steel reinforcement by Thompson and Park (1980)*[20] *and prestressing steel according to PCI Design Aid 15.2.3 (PCI, 2017)*[21] *may be used.*

Agenda Item 38

This agenda item corrects the ratios of minimum yield strength to ultimate tensile strength for AASHTO M 31 (ASTM A615) Grade 60 and Grade 80 reinforcing bars. The correction will increase the cracking moment M_{cr}, which would increase the minimum amount of flexural reinforcement required in cases where M_{cr} is less than 1.33 times the ultimate moment M_u.

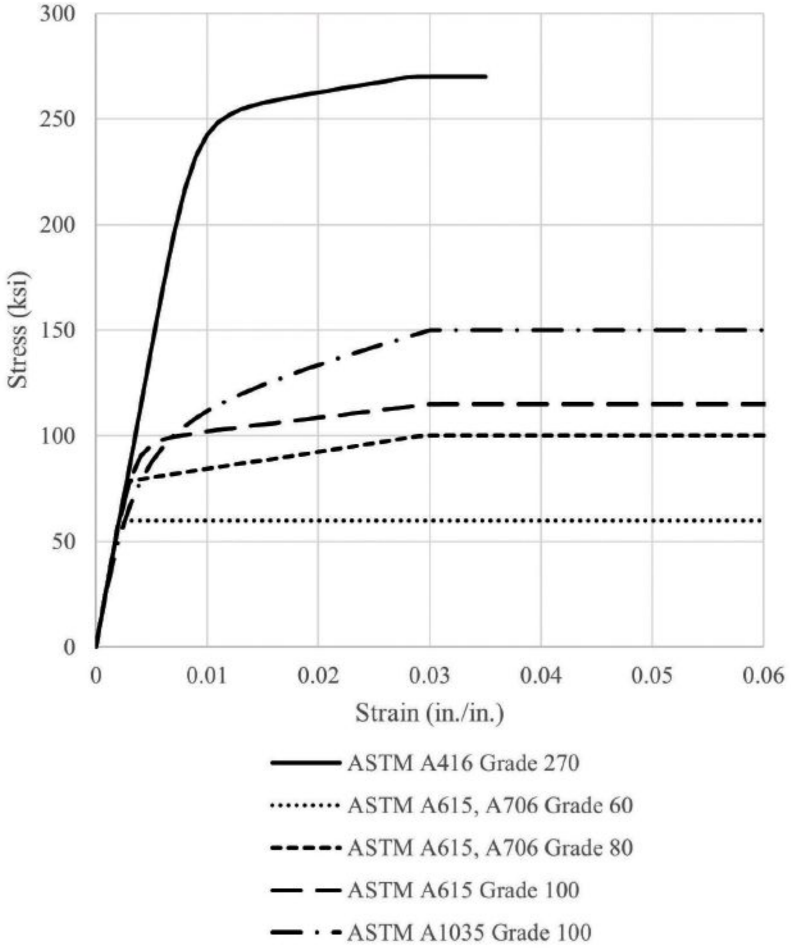

Figure C5.6.3.2.5-2. Stress-strain curves for several types of steel reinforcement.

Additionally, agenda item 38 adds the ratios for AASHTO M 31 (ASTM A615) Grade 100 reinforcing bar, ASTM A706 Grade 100 reinforcing bar, and ASTM A955 Grades 60, 75, and 80 reinforcing bars. It also provides values for minimum tensile strength of reinforcing bars to use when determining spacing of noncontact lap splices of longitudinal reinforcement that go from columns and anchors in oversized shafts.

This agenda item also refers users to the new Table 5.4.3.1-1 that is being developed under WAI 238.

Furthermore, this agenda item revises the notation $f_{u\ell}$ in Article 5.3 as follows:

$f_{u\ell}$ = *specified minimum tensile strength of column longitudinal reinforcement (ksi), (5.10.8.4.2a)*

The third paragraph of Article 5.6.3.3 is revised as follows:

γ_3 = *ratio of specified minimum yield strength to minimum tensile strength of the non-prestressed reinforcement*

= *0.75 for AASHTO M 31 (ASTM A615), Grade 60 reinforcement*

= *0.80 for AASHTO M 31 (ASTM A615), Grade 80 reinforcement*

= *0.87 for AASHTO M 31 (ASTM A615), Grade 100 reinforcement*

= *0.75 for ASTM A706, Grade 60 reinforcement*

= *0.80 for ASTM A706, Grade 80 reinforcement*

= *0.85 for ASTM A706, Grade 100 reinforcement*

= *0.67 for ASTM A955, Grade 60 reinforcement*

= *0.75 for ASTM A955, Grade 75 reinforcement*

= *0.80 for ASTM A955, Grade 80 reinforcement*

= *0.67 for AASHTO M 334 (ASTM A1035), Grade 100 reinforcement*

Finally, this agenda item revises the definition of $f_{u\ell}$ in Article 5.10.8.4.2a as follows:

$f_{u\ell}$ = *specified minimum tensile strength of column longitudinal reinforcement (ksi) from Table 5.4.3.1-1*

Fundamentally, the three agenda items covered in this article provide the much-needed clarification on calculating flexural capacity of prestressed concrete elements in bridges, by taking into account all potential failure modes such as strand rupture and crushing of concrete on the flexural compression side of an element. In addition, the inclusion of minimum specified tensile strain values in Chapter 5 of the AASHTO LRFD specifications, will prove to be useful in design.

References

1. American Association of State Highway and Transportation Officials (AASHTO). 2024. *AASHTO LRFD Bridge Design Specifications*. 10th ed. Washington, DC: AASHTO.
2. ASTM International. 2022. *Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement*. ASTM A615/A615M-22. West Conshohocken, PA: ASTM International.
3. ASTM International. 2025. *Standard Specification for Deformed and Plain Low-Alloy Steel Bars for Concrete Reinforcement*. ASTM A706/A706M-25. West Conshohocken, PA: ASTM International.
4. ASTM International. 2020. *Standard Specification for Deformed and Plain Stainless Steel Bars for Concrete Reinforcement*. ASTM A955/A995M-20c. West Conshohocken, PA: ASTM International.
5. ASTM International. 2024. *Standard Specification for Deformed and Plain, Low-Carbon, Chromium, Steel Bars for Concrete Reinforcement*. ASTM A1035/A1035M-24. West Conshohocken, PA: ASTM International.
6. ASTM International. 2024. *Standard Specification for Carbon-Steel Wire and Welded Wire Reinforcement, Plain and Deformed, for Concrete*. ASTM A1064/A1064M-24. West Conshohocken, PA: ASTM International.

7. AASHTO. 2023. *AASHTO Guide Specifications for LRFD Seismic Bridge Design*. 3rd ed. Washington, DC: AASHTO.

8. Seguirant, S. J., R. Brice, and B. Khaleghi. 2005. "Flexural Strength of Reinforced and Prestressed Concrete T-Beams." *PCI Journal* 50 (1): 44–73. https://doi.org/10.15554/PCIJ.01012005.44.73.

9. Hognestad, E. 1951. *A Study of Combined Bending Axial Load in Reinforced Concrete Members.* Bulletin Series no. 399 (vol. 49), Urbana: Engineering Experimental Station, University of Illinois.

10. Desayi, P., and S. Krishnan. 1964. "Equation for the Stress-Strain Curve of Concrete." *ACI Journal Proceedings* 61 (3): 345–350.

11. Collins, M. P., and D. Mitchell. 1991. *Prestressed Concrete Structures*. Englewood Cliffs, NJ: Prentice Hall.

12. Association Française de Normalisation (AFNOR). 2016. *National Addition to the* Eurocode 2—Design of Concrete Structures: *Specific Rules for Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC)*. NF P18-710. Paris, France: AFNOR.

13. El-Helou, R. G., and B. A. Graybeal. 2022. "Flexural Behavior and Design of Ultrahigh-Performance Concrete Beams." *Journal of Structural Engineering* 148 (4). https://doi.org/10.1061/(ASCE)ST.1943-541X.0003246.

14. Tadros, M., J. Lawler, M. Abo El-Khier, D. Gee, A. Kurt, G. Lucier, and E. Wagner. 2021. *Implementation of Ultra-High-Performance Concrete in Long-Span Precast Pretensioned Elements for Concrete Buildings and Bridges*. Chicago, IL: Precast/Prestressed Concrete Institute. https://doi.org/10.15554/pci.rr.mat-012.

15. Menegotto, M., and P. Pinto. 1973. *Method of Analysis for Cyclically Loaded R.C. Plane Frames Including Changes in Geometry and Non-Elastic Behaviour of Elements under Combined Normal Force and Bending*. Rome, Italy: Istituto di Scienza e Tecnica delle Costruzioni. https://doi.org/10.5169/seals-13741.

16. Mattock, A. H.1979. "Flexural Strength of Prestressed Concrete Sections by Programmable Calculator." *PCI Journal* 24 (1): 32–54. https://doi.org/10.15554/pcij.01011979.32.54.

17. Skogman, B., M. K. Tadros, and R. Grasmick. 1988. "Flexural Strength of Prestressed Concrete Members." *PCI Journal* 33 (5): 96–123. https://doi.org/10.15554/pcij.09011988.96.123.

18. Devalapura, R., and M. Tadros. 1992. "Stress-Strain Modeling of 270 ksi Low-Relaxation Prestressing Strands." *PCI Journal* 37 (2): 100–106. https://doi.org/10.15554/pcij.03011992.100.106.

19. ASTM International. 2024. *Standard Specification for Low-Relaxation, Seven-Wire Steel Strand for Prestressed Concrete.* ASTM A416/A416M-24. West Conshohocken, PA: ASTM International.

20. Thompson, K. J., and R. Park. 1980. "Ductility of Prestressed and Partially Prestressed Concrete Beam Sections." *PCI Journal* 25 (2): 46–70. https://doi.org/10.15554/pcij.03011980.46.70.

21. Precast/Prestressed Concrete Institute (PCI). 2017. Design Aid 15.2.3. In *PCI Design Handbook: Precast and Prestressed Concrete.* 8th ed. Chicago, IL: PCI.