High-Strength Steel in Bridge Applications

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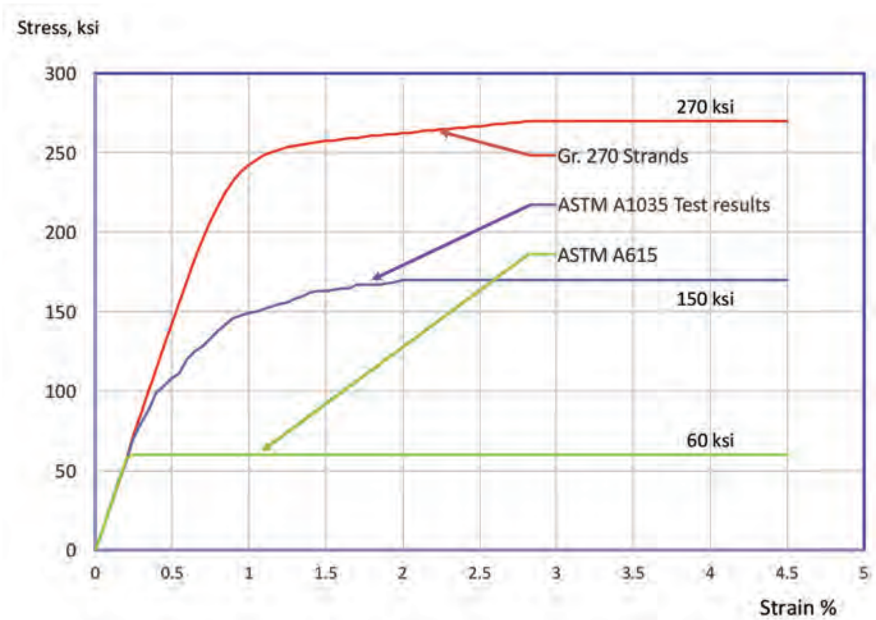

Figure 1. Comparison of stress-strain relationship for various steel types including ASTM A1035-CS alloy series with 100 ksi yield strength. All Photos and Figures: e.construct USA.LLC.

The most common type of reinforcing bars used for passive reinforcement of concrete in the United States is Grade 60 ksi steel conforming to ASTM A615/A615M, *Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement*. Grade 270 ksi, seven-wire prestressing strand, conforming to ASTM A416/A416M, *Standard Specification for Low-Relaxation, Seven-Wire Steel Strand for Prestressed Concrete*, has been used for prestressing, both pretensioning and post-tensioning. The strand grade has not changed for more than 40 years.

In the meantime, both concrete strengths and reinforcing bar strengths have experienced significant increases in the past 20 years. Concrete strength has nearly doubled from about 5 ksi to about 10 ksi in common practice. Concrete with strengths even as high as 22 ksi, which is known as ultra-high-performance concrete (UHPC), has been used in several projects.

A steel grade with a yield strength of 100 ksi was recently introduced into the ASTM A615 standard. Both the American Concrete Institute's *Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14)* and the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications* have recognized the higher strength reinforcing bars and have allowed use of 100 ksi steel in some applications and 75 to 80 ksi in others. Over the past 15 years, a new type of steel, which combines high strength with corrosion resistance and conforms to ASTM A1035/A1035M, *Standard Specification for Deformed and Plain, Low-Carbon, Chromium, Steel Bars for Concrete Reinforcement*, has been recognized in North American building codes. The introduction of this corrosion-resistant high-strength steel into the AASHTO LRFD specifications was based on recommendations from National Cooperative Highway Research Program (NCHRP) Project 12-77 by Shahrooz et al.[1] Figure 1 shows the stress-strain relationship for the various steel types.

It seems logical to try to combine high-strength concrete with high-strength steel to optimize structural members and systems; however, limitations exist. This article focuses on introducing corrosion-resistant high-strength steel conforming to ASTM A1035/A1035M. Examples of successful applications are also given.

What Is ASTM A1035 Steel?

The proprietary high-strength steel meeting ASTM A1035 specifications is manufactured in the United States and other countries under license from MMFX Technologies, Irvine, Calif. ASTM A1035 has three basic series: 2000, 4000, and 9000, representing a chromium content of 2, 4, and 9%, respectively. The highest chromium content is the 9000 series, also known as ASTM A1035-CS alloy. It is the most expensive and is used for the highest corrosion-resistance applications, for example bridge decks. The 4000 series is known as ASTM A1035-CM alloy. The 2000 series, also known as ASTM A1035-CL alloy, is the least expensive and can be used where low-corrosion resistance is acceptable, for example columns (generally where they are under axial loads and flexural strains remain small) and interiors of buildings.

Strength and Ductility

ASTM A1035 also specifies other chemical composition requirements, most notably carbon content. The 2000, 4000, and 9000 series have maximum carbon contents of 0.30%, 0.20% and 0.15%, respectively. The chemical composition allows all three series to have a yield strength of at least 100 ksi and a tensile strength of at least 150 ksi. There are actually six series of ASTM A1035

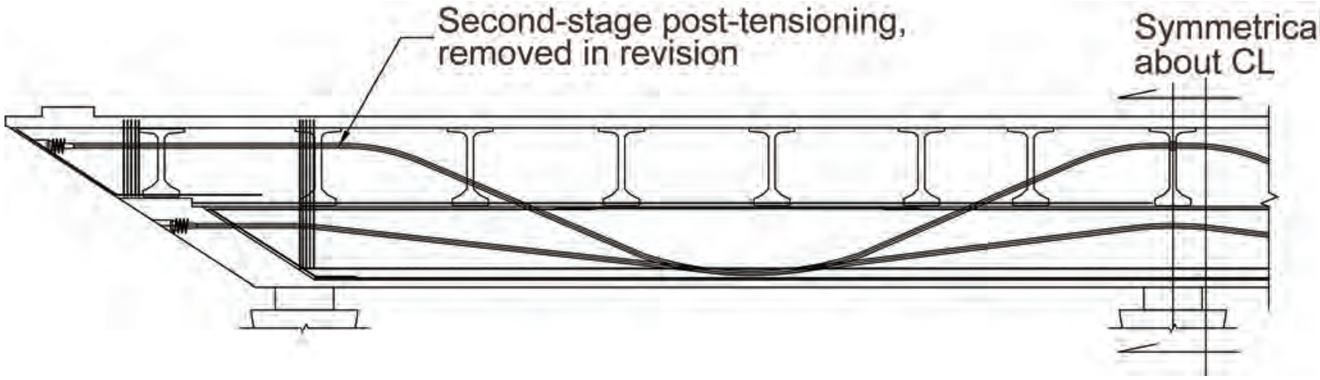

Figure 2. Partial view of pier crosshead showing two-stage post-tensioning.

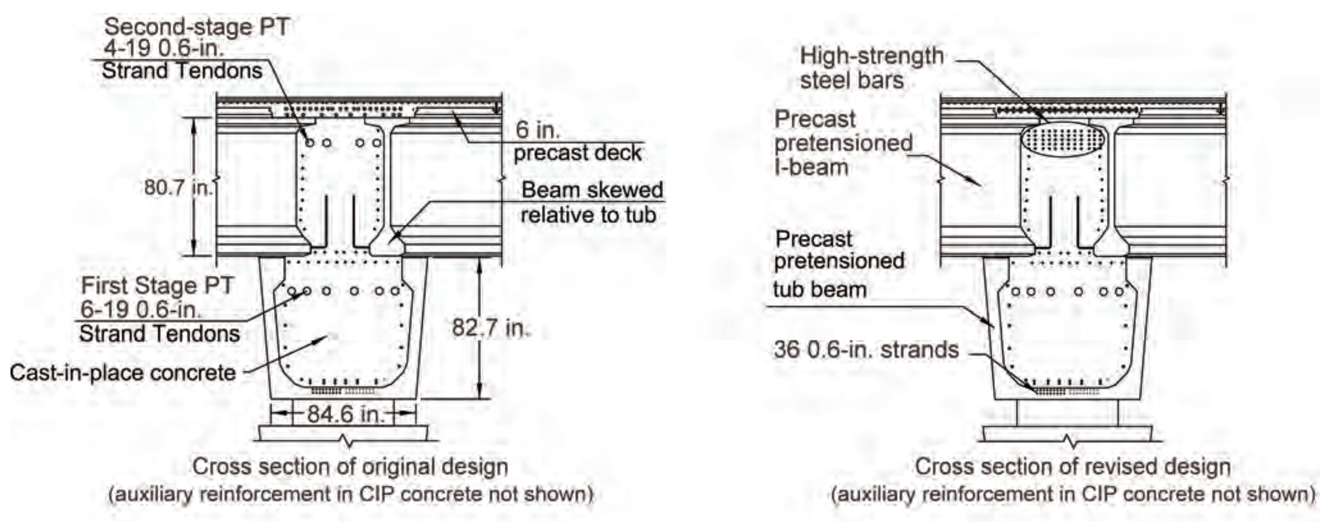

Figure 3. Typical cross sections of pier crosshead with revisions to replace post-tensioning with ASTM A1035-CS alloy steel.

steel: 2100, 2120, 4100, 4120, 9100, and 9120, ranked from the least yield strength and corrosion resistance to the highest strength and corrosion resistance.

ASTM A1035-CS alloy steel has excellent ductility with a minimum ASTM required ultimate elongation of 7% for bar sizes No. 3 through No. 11 and 6% for No. 14 and No. 18. These are the same limits specified in ASTM A615 for Grade 75/80 steel, but are slightly less than the limits for Grade 60 steel.

Corrosion Resistance

Reinforcing bar corrosion begins when the chloride concentration at the steel surface reaches the critical chloride threshold (CT) of the steel. The CT of ASTM A1035 Grade 9100 is four times that of ASTM A615 steel bar and twice that of ASTM A1035 Series 4100.[2-4]

The AASHTO Standard Specification MP 18M/MP 18[5] covers two types of steel that should be investigated by owners and their consultants for applications requiring uncoated corrosion-resistant bars: ASTM A1035 Series 9100 and stainless steel conforming to ASTM A955/A955M, *Standard Specification for Deformed and Plain Stainless-Steel Bars for Concrete Reinforcement*. The minimum chromium content in stainless steel is 12% and is 9.2% for ASTM A1035 Series 9100. Thus, stainless steel is more corrosion resistant. However, stainless steel is significantly more expensive and has a yield strength of only 75 ksi.

Structural Design Considerations

The biggest reduction in the amount of steel, when A1035 steel is used, is realized for flexural-tension reinforcement controlled by strength limit state. To take full advantage of high-strength steel, the compressive strength of the concrete should be high enough to drive the neutral axis towards the compression face of the section, achieving so-called tension-controlled behavior. This is not difficult to achieve in practical applications. Other limits to be aware of are

- minimum reinforcement to avoid sudden tension-initiated failure, and
- crack and deflection controls, which limit the amount of reduction of steel that can be realized.

A recent study[4] showed that when the bar size is reduced by one size and cover is reduced by 1/2 in., high-strength bar resulted in less cracking than black Grade 60 reinforcing bar. In cases where crack width at the concrete face is an important design criterion, designers should be aware that reducing the steel area alone could result in an increase in crack width. The designer should consider reducing the bar size, bar spacing, and concrete cover over reinforcement.

Members subjected to combined flexure and axial load could be optimized to by replacing Grade 60 with ASTM A1035 steel with a yield

Figure 4. ASTM A1035-CS alloy reinforcement cage being placed in a segment form for the Lesner Bridge in Virginia Beach, Va.

strength of 100 ksi. However, using conventional assumptions for flexural strength analysis, the maximum usable concrete strain at the strength limit state is 0.003 (see the seventh edition AASHTO LRFD specifications article 5.7.2.1 or the eighth edition AASHTO LRFD specifications article 5.6.2.1).[6] With the modulus of elasticity of steel assumed to be equal to 29,000 ksi, the maximum stress that can be achieved in compression reinforcement is 87 ksi. This is why ACI 318-14 limits the strength of steel in the compression zone to 80 ksi. The designer may be able to overcome this restriction by providing confinement (lateral) steel that increases the extreme fiber concrete strain to 0.0035, which incidentally is the ultimate strain used in some Canadian and European codes.

The maximum yield strength of steel that can be used when designing for shear is 80 ksi in ACI 318-14, but the seventh edition of the AASHTO LRFD specifications allows the use of 100 ksi in Seismic Zone 1. The reason for limiting the use of the higher strength to Seismic Zone 1 in AASHTO is that tests are only available for non-seismic applications.[1] However, the AASHTO LRFD specifications do allow use of 100 ksi in seismic applications with owner approval. The designer must be careful to make sure there is no diagonal tension cracking in prestressed concrete thin-web members at the service limit state because such cracking could create fatigue conditions (see article 5.8.5 of the seventh edition AASHTO LRFD specifications or article 5.9.2.3.3 of the eighth edition AASHTO LRFD specifications).

There are many other applications where corrosion-resistant Grade 100 steel can be used. They include bridge decks, retaining walls, piles and columns in salt water, foundations, columns and walls in high-rise buildings and bridges, auxiliary steel in segmental box-girder bridges, and continuously reinforced concrete pavements.

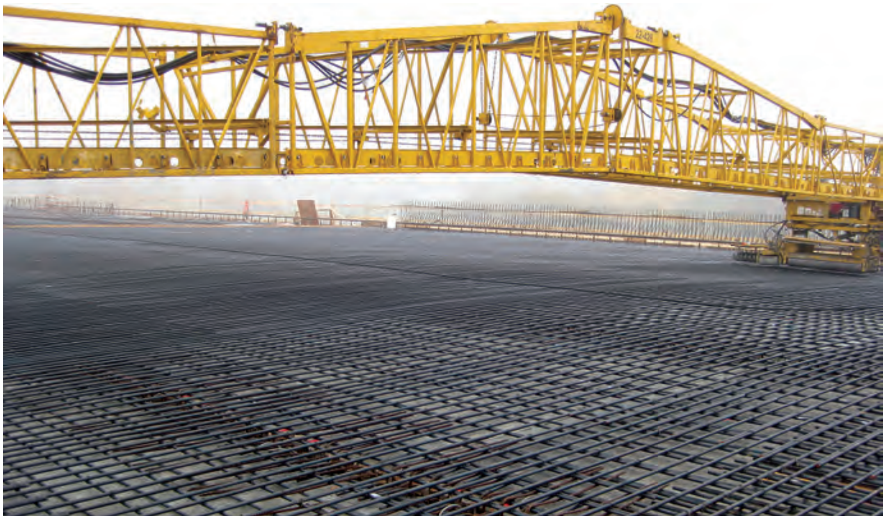

Figure 5. Deck for Circle Drive Bridge in Saskatoon, Canada, with conventional Grade 60 reinforcement replaced with ASTM A1035 CS Series 9100.

Cost of ASTM A1035 Reinforcing Steel

It is hard to give an accurate cost comparison based on increased strength alone without considering the benefit of corrosion resistance. Using high-strength steel has more benefits than just reducing steel quantities, such as reduced fabrication costs and steel congestion. As a general guide for initial estimates, one can assume that ASTM A1035 Series 9100 costs slightly less than $1.00 per pound, with lower grade materials costing less. ASTM A1035 Series 4100 costs about the same as epoxy-coated ASTM A615 steel.

Projects Using High-Strength Reinforcement

The following section are some recent applications of ASTM A1035 reinforcement in bridges.

The Abu Dhabi International Airport Departure Bridge

The Abu Dhabi International Airport Departure Bridge had a challenging pier crosshead. The bridge was curved in plan and had unusually heavy design loads and sharply skewed pier crossheads (caps) with very few column supports. Figure 2 shows the elevation of one of the crossheads. The nearly 16 ft superstructure depth had to be constructed in two stages.

Figure 3 shows a typical cross section before and after revisions were made to replace the second-stage post-tensioning with ASTM A1035-CS alloy steel. The revisions allowed for simpler, faster construction with reduced congestion. The first-stage post-tensioning ensured adequate precompression of the positive moment zone. The passive ASTM A1035-CS alloy reinforcement for negative moment was only placed where needed, rather than full length, and its installation did not require the presence of a specialty subcontractor. It also reduced the need for anchors in the slanted crosshead end. The bridge construction was completed in 2016.

A similar study was performed for a precast concrete pier cap of a curved bridge in the United States. It was shown that the weight of the cap could be reduced from 123 tons to 89 tons and the amount of post-tensioning could be reduced. The pier cap was changed from a 60-in.-wide rectangle to a 24-in.-wide inverted tee with bottom flange ledges that could be used to eliminate independent shoring of the main girders at the piers.

Lesner Bridge in Virginia Beach, Virginia

The first half of the Lesner Bridge in Virginia Beach, Va., was opened in late 2016. ASTM A1035-CS reinforcement was substituted for stainless steel (Fig. 4). The design utilizes a yield strength of 75 ksi rather than the 60 ksi proposed for the stainless steel. Using the higher strength of ASTM A1035-CS alloy in the deck and substructure, significant savings due to simplified details and construction requirements were achieved.

Bridge Decks

ASTM A1035-CS alloy has been used for the deck reinforcement for the Circle Drive Bridge in Saskatoon, Canada, (Fig. 5) and for several bridges in Virginia. Research for the Virginia Department of Transportation[4] found that a deck constructed using ASTM A1035-CS alloy reinforcement with a ½ in. reduction in concrete cover and one bar size smaller than a conventional deck using Grade 60 reinforcement will perform similarly. A demonstration project is planned.

Conclusion

High-strength steel reinforcing bars with high resistance to corrosion are available on the market and have been used on bridge structures to reduce congestion, speed up construction, and improve service life.

References

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