Proposed Simplification to the AASHTO LRFD Bridge Design Specification Tensile Stress Requirements for Precast-Prestress Girders

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ABSTRACT

Evaluating tensile stress limits for a precast-prestressed girder is a straightforward process for simple highway bridge structures. However, when applied to atypical and complex structures the tensile stress limitations specified by the AASHTO LRFD Bridge Design Specifications become unnecessarily complex, confusing, and in some cases undefined. This paper describes the shortcomings in the AASHTO LRFD Bridge Design Specification tensile stress limitations and provides proposed changes to fully define and simplify them for evaluation of tensile stresses in precast-prestress bridge girders.

Keywords: LRFD, Design, Pretension, Post-tension, Spliced Girders

INTRODUCTION

During the development of the PGSuper and PGSplice software programs for the design, analysis, and load rating of precast-prestressed girder and post-tensioned spliced girder bridges, the authors have uncovered complexities in the AASHTO LRFD Bridge Design Specifications[1] (LRFD) with regards to the allowable tension requirements for precast-prestressed elements. These complexities are confusing, unnecessary, and may have unintended consequences. This paper describes the current tensile stress requirements, illustrates the complexities, and offers solutions to correct the issues found in the LRFD specifications.

TENSION STRESS LIMITS FOR PRESTRESSED CONCRETE

The tensile stress limits for precast-prestressed concrete members are defined in LRFD 5.9.4 and its subsections. Limits are defined for temporary stress conditions prior to prestress losses and service stress conditions after losses. LRFD 5.14.1.3.2d and 5.14.1.3.3 further define requirements for evaluating tensile stress limits for spliced girder joints and precast-prestressed segments. LRFD 5.14.1.4.6 provides additional requirements for bridges composed of simple span precast girders made continuous with a cast-in-place continuity diaphragm.

The tensile stress limit in a precast-prestressed bridge girder depends on the position within the structure, reinforcement within the girder, and time when the stress is being evaluated. The applicability of tensile stress limitations is divided between locations that are “in the precompressed tensile zone” and “in areas other than the precompressed tensile zone”, in areas with and without sufficient bonded reinforcement, and before and after prestress losses have occurred. The tensile stress limits for temporary stresses before losses are in LRFD Table 5.9.4.1.2-1 and are summarized here in Table 1. The tensile stress limits for stresses at the service limit state after losses are in LRFD Table 5.9.4.2.2-1 and are summarized here in Table 2.

Table 1 - Temporary Tensile Stress Limits in Prestressed Concrete before Losses

Prestressed Element	Location	Stress Limit
Precast-pretensioned girder and spliced girder segments	In precompressed tensile zone without bonded reinforcement	N/A
	In areas other than the precompressed tensile zone and without bonded reinforcement	$0.0948\sqrt{f'_{ci}} \leq 0.2\ (ksi)$
	In areas with bonded reinforcement sufficient to resist the tensile force in the concrete computed assuming an uncracked section, where reinforcement is proportioned using a stress of $0.5f_y$ not to exceed 30 ksi	$0.24\sqrt{f'_{ci}}$
Spliced Girder Joints	Stresses in the precompressed tensile zone for joints without the minimum bonded auxiliary reinforcement through the joints	No tension
	Stresses in the precompressed tensile zone for joints with minimum bonded auxiliary reinforcement through the joints, which is sufficient to carry the calculated tensile force at a stress of $0.5f_y$; with internal tendons or external tendons	$0.0948\sqrt{f'_{ci}}$
	Stress in areas other than the precompressed tensile zone without the minimum bonded auxiliary reinforcement through the joint	No tension
	Stress in areas other than the precompressed tensile zone in areas with bonded reinforcement sufficient to resist the tensile force in the concrete computed assuming an uncracked section, where reinforcement is proportioned using a stress of $0.5f_y$, not to exceed 30 ksi.	$0.19\sqrt{f'_{ci}}$

Table 2 Tensile Stress Limits in Prestressed Concrete at Service Limit State after Losses

Prestressed Element	Location	Stress Limit
Precast-pretensioned girder and spliced girder segments	In the precompressed tensile zone for components with bonded prestressing tendons that are subjected to not worse than moderate corrosion conditions	$0.19\sqrt{f_c'}$
	In the precompressed tensile zone for components with bonded prestressing tendons that are subject to severe corrosive conditions	$0.0948\sqrt{f_c'}$
Spliced Girder Joints	Stresses in the precompressed tensile zone for joints without the minimum bonded auxiliary reinforcement through the joints	No tension
	Stresses in the precompressed tensile zone for joints with minimum bonded auxiliary reinforcement through the joints sufficient to carry the calculated longitudinal tensile force at a stress of $0.5f_y$; with internal tendons or external tendons	$0.0948\sqrt{f_c'}$
	Stress in areas other than the precompressed tensile zone without bonded reinforcement	No tension
	Stress in areas other than the precompressed tensile zone in areas with bonded reinforcement sufficient to resist the tensile force in the concrete computed assuming an uncracked section, where reinforcement is proportioned using a stress of $0.5f_y$, not to exceed 30 ksi.	$0.19\sqrt{f_c'}$

Additional tension limits are imposed on spliced girder bridges. The allowable tension limit for temporary stresses before losses, computed using the concrete strength at the time of stressing, must be evaluated for each stage of prestressing. Also, the allowable tension limit for service limit states, computed using the concrete strength at the time of loading, must be evaluated for each intermediate load stage.

Bridges composed of simple span precast girders made continuous with continuity diaphragms cast between the ends of girders at interior supports develop tensile stresses along the top face of the girder near the interior support. Harped strands can introduce compression into this region of the girder which satisfies the definition of precompressed tensile zone. However, LRFD commentary C5.14.1.4.6 explicitly states that this region is not a precompressed tensile zone and further, the tensile stress limits for service load stress after losses are to be evaluated using the limitations for temporary tensile stress before losses. The stress limits are to be computed using the concrete strength at the time of service loading in place of the initial concrete strength in the stress limit equations. Alternatively, the top of the precast girder at interior supports may be designed as reinforced concrete members at the strength limit state. In this case the service limit state stress limits do not apply.

For simple span bridges that are made continuous, LRFD 5.14.1.4.6 and C5.14.1.4.6 clearly state that the cast-in-place composite deck slab is not subjected to the tensile stress limits because the deck is not a prestressed element. In contrast, the LRFD specifications do not provide any tensile stress limitations or exceptions for a cast-in-place composite deck slab for a spliced girder bridge when post-tensioning is installed after deck placement. In our opinion, the deck slab satisfies the definition of prestressed concrete given in LRFD 5.2, and therefore should be subjected to tensile stress limitations. This conclusion is supported in the design examples found in NCHRP Report 517[2]. The strength limit state alternative for simple span bridges that are made continuous is not provided for spliced girder bridges.

PRECOMPRESSED TENSILE ZONE

An integral step in determining the applicability of the tensile stress limitations and the limit itself is locating the precompressed tensile zone. LRFD 5.2 defines the precompressed tensile zone as:

> *Any region of a prestressed component in which prestressing causes compressive stresses and service load effects cause tensile stresses.*

The term prestressing is not explicitly defined by the LRFD specifications however LRFD 5.2 gives the following definitions for post-tensioning and pretensioning:

> *Post-Tensioning – A method of prestressing in which the tendons are tensioned after the concrete has reached a predetermined strength.*

> *Pretensioning – A method of prestressing in which the strands are tensioned before the concrete is placed*

It can be inferred that prestressing is a general term meaning both post-tensioning and pretensioning and the exact meaning is disambiguated by the context of its usage.

The term service load is not well defined by the LRFD specifications. The term implies, and is generally taken to mean, the loading condition when the bridge is in service. LRFD 6.2 defines service load for steel structures as

> *Loads expected to be supported by the structure under normal usage.*

The definition of precompressed tensile zone does not make any distinct requirements regarding the sequence or timing of the prestressing. The definition only requires that prestressing induces compression. This apparently means any pretensioning or post-tensioning during any stage of construction. The definition also limits the tension stresses of concern to those caused by service loads and not any intermediate loading condition.

Two simple questions are presented to determine if a point in a precast-prestressed bridge girder is in the precompressed tensile zone:

1. Does the prestressing (pretensioning and post-tensioning) cause compression at this location?
2. Do the service loads cause tension at this location?

If the answer to both questions is “yes”, the point under consideration is in the precompressed tensile zone. If the answer to either question is “no”, the point under consideration is in an area other than the precompressed tensile zone.

It is important to understand how the LRFD specifications define the precompressed tensile zone, since it is an integral component for determining the magnitude and applicability of tensile stress limitations. It will be shown that a strict application of this definition of precompressed tensile zone along with the specified allowable tensile stress limits can result in unintended consequences.

APPLYING TENSILE STRESS LIMITS TO COMPLEX STRUCTURES

Here we present an example of applying the allowable tension requirements to a complex spliced girder bridge structure. This example illustrates a case where strict application of the LRFD requirements for tensile stress limits results in unintended consequences.

Consider the typical two span spliced girder bridge structure shown in Figure 1. Each girder consists of six equal-length precast-prestressed beam segments. Each segment is constructed with straight pretensioned strands in the bottom flange. The segments are supported on erection towers as simple span elements during construction. Closure joints are cast between segments, and then the full length is post-tensioned with parabolic tendons to form a continuous girder. The low point of the tendons is near the center of each span and the high point is over the intermediate pier. Post-tensioning can be applied before or after the deck is placed. The sequence of post-tensioning is not important for purposes of determining the location of the precompressed tensile zone.

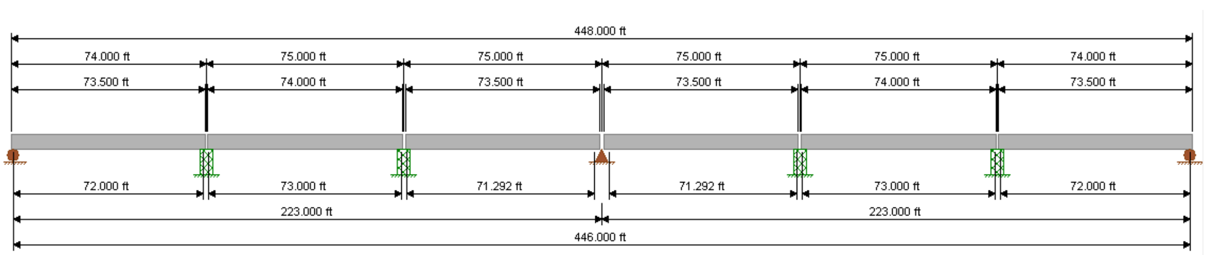

Figure 1 Example Spliced Girder Bridge

Figure 2 shows the stresses in the girder due to pre-tensioning and post-tensioning. The heavy red line drawn along the top and bottom of the girder indicates where the girder is precompressed. Figure 3 shows the stresses due to service loads. The heavy blue lines drawn along the top and bottom of the girder indicate where the girder is in tension due to service loads. The heavy green lines along the top and bottom of the girder in Figure 4 show the precompressed tensile zones.

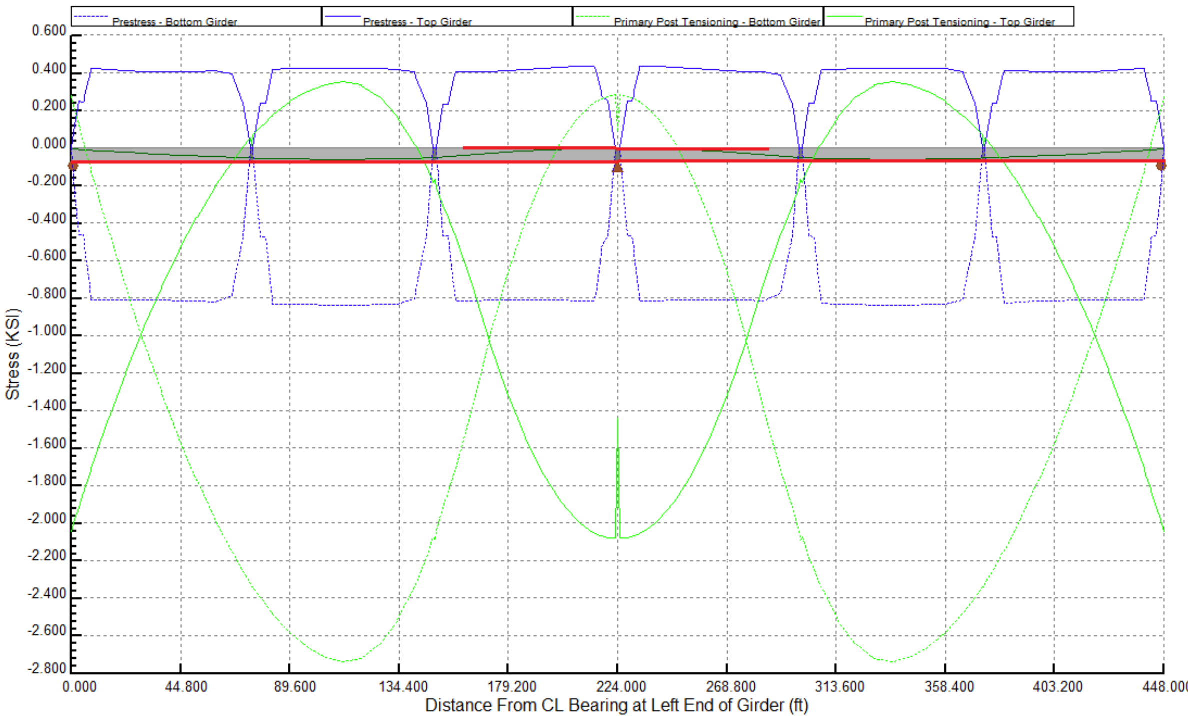

Figure 2 Stress in Girder due to Prestressing

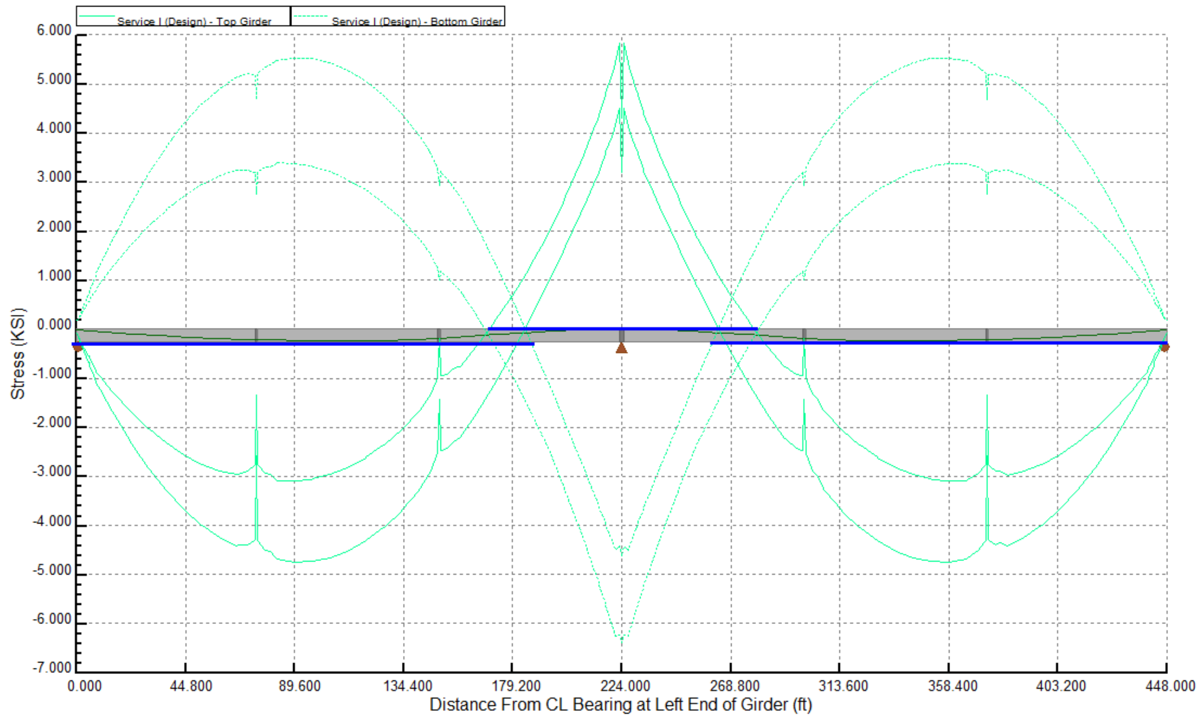

Figure 3 Stress in Girder Due to Service Loads

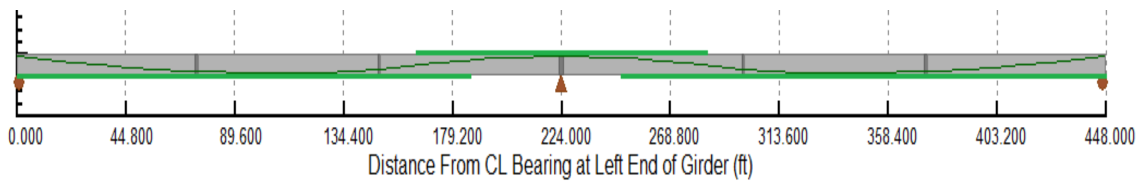

Figure 4 Precompressed Tensile Zone

Examining the segments adjacent to the intermediate pier, it is clear from Figure 4 that the precompressed tensile zone alternates between the top and bottom flanges. The temporary tensile stress limits before losses are not well defined for this case. If the segments do not have bonded reinforcement, the tensile stress limitations are not applicable, as explicitly stated in LRFD Table 5.9.4.1.2-1. However, if the segments have bonded reinforcement that is sufficient to resist the tensile force in the concrete, the tensile stress limits are applicable and the stress is limited to $0.24\sqrt{f'_{ci}}$. For segments with bonded reinforcement that is not sufficient to resist the tensile force in the concrete, stress limitations are not defined by the LRFD specifications and are assumed to be not applicable.

The top of pretensioned girder segments with strands in the bottom flange are subjected to tensile stresses at prestress release. This is typically a governing case. For the example structure, all of the segments are virtually identical at the time of prestress release. Some segments are subject to tensile stress limitations over the entire top flange, while other segments are subjected to the same limits over a small portion of the top flange. Even though permitted by the LRFD specifications, it does not make sense to exclude portions of these segments from the tensile stress limits.

It is problematic that the LRFD specifications explicitly state that the allowable tensile stress limit is not applicable in a case where it is most assuredly prudent to restrict the tensile stress. It is also problematic that reducing the amount of reinforcement on the tensile face, that for all intents and purposes is beneficial, also eliminates the requirement to limit tensile stresses. Excessive tensile stresses are detrimental to the structure. They can cause cracks which deter from aesthetics, lead to corrosion, create maintenance difficulties, and can shorten service life. As written, the LRFD specifications provide an incentive to reduce tension reinforcement. This clearly does not make sense.

Other spliced girder bridge configurations expose the same problem. In fact, this problem will be encountered in any bridge configuration where the inflection points fall within a segment. The closure joints are the weakest part of a spliced girder and the inflection points are the location of least bending moment, so ideally, closure joints should be located at the inflection points. However, the constraints of actual projects may force the location of closure joints to areas other than the inflection point.

TEMPORARY STRESSES DURING CONSTRUCTION STAGES

Many different construction sequences can be used for a precast-prestressed spliced girder bridge. Placement of a cast-in-place concrete bridge deck and stressing of post-tensioning tendons are two significant construction stages that add permanent stresses to the structure. The LRFD specification recognizes that a structure is in a temporary state of stresses immediately after tendons are stressed. The placement of the deck concrete before tendons are stressed also creates a temporary state of stresses. The dead load will, in general, increase the tensile stress in the bottom of the girder and the post-tensioning will compress the bottom of the girder reducing, and possibly eliminating, the tensile stress. When stressing tendons, the temporary tensile stress limits of LRFD 5.9.4.1.2 are applicable. Tensile stresses are limited to $0.0948\sqrt{f_c'}$ not to exceed 0.2 ksi, or $0.24\sqrt{f_c'}$ if there is sufficient bonded reinforcement. When the girder segments are loaded with the dead weight of the deck material, the tensile stress limits of LRFD 5.9.4.2.2 are applicable, and tensile stresses are limited to $0.19\sqrt{f_c'}$ or, $0.0948\sqrt{f_c'}$ depending on the exposure condition. The girder segments are subjected to tensile stresses in both cases which will later be reduced by the addition of load to the structure. The response of the material is independent of the source of loading. Hence, there does not appear to be a logical basis for imposing a different, and possibly more restrictive, tension stress limit to temporary stress conditions caused by gravity loads than those caused by post-tensioning.

OTHER INCONSISTENCIES

Several other inconsistencies in the LRFD tensile stress limitations have been uncovered. Each is presented below.

Nomenclature

Tension stress limits, which are contingent on a minimum amount of reinforcement to carry the tensile forces in the concrete, use different terms to describe the reinforcement. This can lead to confusion as to whether or not particular reinforcement can be considered when evaluating the tensile stress limit, and can result in inconsistent designs. The various tensile stress limits for precast prestressed girders, and cast in place closure joints, use the terms; "minimum bonded auxiliary reinforcement", "bonded reinforcement", and "bonded nonprestressed reinforcement". It may be common practice to assume these terms all have the same meaning; but this is not a certainty. One could make a case that minimum bonded auxiliary reinforcement is different than bonded reinforcement. By its very definition, auxiliary reinforcement is reinforcement that supplements other reinforcement. Therefore, these requirements could be construed to mean that only a portion of the total reinforcement on the tensile side of a segment can be considered when evaluating the sufficiency of the reinforcement.

Type of Reinforcement

For precast girders and spliced girder segments, the type of reinforcement used to carry the tensile forces in the concrete can be reinforcing bars or prestressing steel. In spliced girder joints, the reinforcement is to be "bonded auxiliary reinforcement" in the precompressed tensile zone, and "nonprestressed reinforcement" in areas other than the precompressed tensile zone. There does not appear to be any logical rational for the distinction of reinforcement type. Also, the use of prestressing steel as reinforcement is permitted in all areas of a precast segment, but only in areas other than the precompressed tensile zone for closure joints. Extension of prestressing steel from the end of a precast segment into the closure joint is a common detail, and should be addressed for determining tensile stress requirements.

Stress in Reinforcement

For precast girders and spliced girder segments, the force in the reinforcement is limited to $0.5f_y$ not to exceed 30 ksi. For spliced girder joints, the force in the reinforcement is also limited to $0.5f_y$, not to exceed 30 ksi, except when the location under consideration is in an area other than the precompressed tensile zone before losses, or in the precompressed tensile zone after losses. There does not appear to any logical rational to exclude the 30 ksi limit for some cases.

Inconsistencies such as these generally do not have a detrimental effect on bridge structures. However, they do create confusion and add unnecessary complexity to the LRFD specifications.

BONDED TENSILE REINFORCEMENT

The magnitude of several tensile stress limits depend on the presence of reinforcement in girders. If there is bonded reinforcement sufficient to resist the tensile force in the concrete computed assuming an uncracked section; a higher tensile stress limit is specified than for cases where the reinforcement is insufficient, or has not been provided.

LRFD commentary C5.9.4.1.2 provides a procedure for computing the required amount of reinforcement to utilize the higher tensile stress limit. The procedure is as follows with the variables defined in Figure 5:

1. Using the extreme fiber stresses $f_{ci\ bot}$ and $f_{ci\ top}$, determine the depth of the tensile zone, x
2. Compute the area of the tensile zone, A_t
3. Compute the tensile force in the concrete, T, as the product of the average tensile stress and the area of the tensile zone. $T = \frac{1}{2} f_{ci\ top} A_t$
4. The required area of reinforcement is computed by dividing the tensile force by the permitted stress in the reinforcement. $A_s = \frac{T}{f_s}\ where f_s = 0.5 f_y \leq 30ksi$

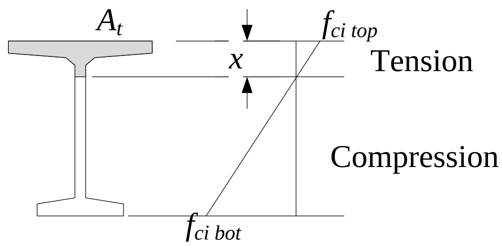

Figure 5 Calculation of Tensile Force and Required Area of Reinforcement

The guidance provided in the LRFD commentary can lead to the conclusion that bonded reinforcement is sufficient if the cross sectional area is at least equal to the computed required area of reinforcement. This is misleading as additional analysis is required to ensure static equilibrium.

In addition to providing a sufficient area of reinforcement, the reinforcement must also be adequately developed and located in a position to carry the tensile force. Excessive tensile stresses often occur near the ends of pretensioned girders. However, the capacity of the reinforcement in this region is reduced due to the lack of full development and cannot be fully utilized. Theoretically, at the instant of rupture, the tensile force in the concrete is immediately transferred to the reinforcement. The reinforcement must be positioned in the cross section so that it generates a force couple equivalent to the one created by the tension and compression stress resultants in the concrete. If the reinforcement is between the tensile stress resultant of the uncracked section, and the neutral axis, the lever arm of the force couple will be reduced from its pre-rupture state and a force in excess of that computed by the procedure in C5.9.4.1.2 must be carried by the reinforcement. Thus, an area of reinforcement larger than that computed by the procedure given above would be required to keep the stresses at the permitted value. The LRFD specification does not provide guidance with regards to this concern. The calculation procedure in the commentary omits these details and can lead to the accidental use of a higher allowable tension limit than is permissible.

Fortunately, the limiting stress in the reinforcement has a factor of safety of 2 against yielding, so it is unlikely that undesirable consequences will result.

PROPOSED REVISIONS TO THE LRFD SPECIFICATIONS

Revisions to the LRFD specifications are needed to address the issues discussed in this paper. The objective of these proposed revisions is to simplify the requirements for evaluating tensile stress limits, and eliminate cases that might result in unintended consequences.

The origin of the term “precompressed tensile zone” is unknown to the authors. It is suspected that its purpose is to reduce the number of tensile stress limit evaluations by eliminating locations that will not govern. It is interesting to note that the LRFD specification does not have similar requirements for compression stress limits. All locations in a precast-prestressed girder must satisfy the compression stress limitations. Experienced designers use their knowledge and experience to eliminate unnecessary stress evaluations. There is no concept of a “pretensioned compression zone” or “other than in the pretensioned compression zone” for compression stress limits. It is unnecessary for the tensile stress limitations to be significantly more complex than the compression stress limitations.

The notion of the precompressed tensile zone should be eliminated from the LRFD specification. The example presented illustrates how the LRFD specifications exclude certain locations from meeting tensile stress limitations when it is clear that the limitations should apply. Imposing tensile stress limitations to all locations in a girder will remedy this situation. This will not create additional work for designers as they can easily use their judgment to eliminate non-governing cases, just as is done for compression.

LRFD 5.14.1.3.3 should be revised to state that the limits for temporary concrete stresses shall apply to all intermediate load stages. This will resolve the inconsistency with the allowable tension limits for prestressing and gravity loading at intermediate construction stages for spliced girder bridges.

A subsection should be added to LRFD 5.14.1.3 that states cast-in-place composite decks are prestressed elements if post-tensioning is applied after the deck is cast. The stress limits specified in LRFD 5.9.4.2.1 and 5.9.4.2.2 shall apply.

Even though the calculation procedure given in LRFD C5.9.4.1.2 is not theoretically correct, the factor of safety against yielding of the reinforcement is likely sufficient to make any errors inconsequential. The commentary should provide an explanation that the sufficiency of the reinforcement depends not only on the quantity of the reinforcement but also its degree of development, and its location with respect to the neutral axis. It is conservative to require that reinforcement be fully developed, in addition to satisfying a minimum cross sectional area, as a condition of sufficiency.

LRFD Table 5.9.4.1.2-1 should be revised so the term “bonded reinforcement” is used consistently throughout to describe the reinforcement required for certain tension stress limits. Also, all of the bonded reinforcement stress limits should consistently limit the stress in the reinforcement to $0.5f_y$, not to exceed 30 ksi in LRFD Tables 5.9.4.1.2-1 and 5.9.4.2.2-1.

CONCLUSION

Engineers have successfully avoided serious issues with the inconsistencies and complexities of the LRFD tensile stress limitations. However, the limitations remain open to misinterpretation and the resulting unintended consequences. Complex spliced girder bridges are becoming more common, and more engineers will be applying the LRFD specifications to this type of structure, possibly for their first time. It is important to resolve these issues so that the LRFD specifications are clear and consistent. The recommendations presented in this paper will improve the LRFD specification and help remedy unintended consequences that may result from the current specifications.

REFERENCES

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