REQUIREMENTS FOR STRENGTH AND DUCTILITY OF UNBONDED POST-TENSIONING TENDONS

TIME TO REVISIT THEM

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ABSTRACT

This paper summarizes published requirements for post-tensioning tendon strength and elongation which appear in four influential ACI and PTI codes and specifications. Differences between the requirements are cited and discussed, from historical and current perspectives. Recommendations are made for consistency and improvements.

KEYWORDS

Elongation; Tendons; Anchorages; Acceptance Criteria; Ductility; Strength Test

INTRODUCTION

Acceptance criteria for strength and ductility of unbonded single-strand post-tensioning tendons† appear in four influential documents, three published by the American Concrete Institute[1,2,3] (ACI) and one by the Post-Tensioning Institute (PTI)[4]. They contain significant differences.

ACI 318[1] is the most authoritative of these four documents because, when incorporated into a model code and then adopted as an ordinance by a municipality, it becomes a law. However the ACI 423[2] document is referenced by ACI 318, therefore it too has the force of law. ACI 301[3] is mentioned in the Commentary to ACI 318, which is non-mandatory. The PTI Guide Specification[4] has significant weight, since it was written by individuals most knowledgeable about tendon behavior, appears in many project specifications, and has influenced the ACI documents.

Following is a discussion of the relevant criteria in each of the four documents:

ACI 318-08[1]

Requirements for unbonded tendon anchorages are specified in 18.21, excerpted as follows:

> ***18.21*** *– Post-Tensioning anchorages and couplers*
>
> ***18.21.1*** *– Anchorages and couplers for bonded and unbonded tendons shall develop at least 95 percent of fpu when tested in an unbonded condition, without exceeding anticipated set….*

f_{pu} is defined in Chapter 2:

> f_{pu} *= specified tensile strength [emphasis by author] of prestressing steel, psi, Chapters 11, 18*

Commentary Section R18.21.1 addresses tendon elongation:

> ***R18.21.1*** *- …..Tendon assemblies should conform to the 2 percent elongation requirements in ACI 301[18.34] and industry recommendations.[18.29]….*

†*A "tendon" includes the anchorages, prestressing steel, sheathing and coating. While the discussion in this paper may apply to other types of tendons, it is primarily focused on tendons with ½-in. diameter, 270 ksi strand conforming to ASTM A 416. That type of tendon is prevalent in the USA and in many other parts of the world.*

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In the excerpt to Section R18.21.1 above Reference 18.34 is:

> **18.34**. ACI Committee 301, *Standard Specifications for Structural Concrete for Buildings (ACI 301-96)*,…[note that the current edition is ACI 301-05[3]]

and Reference 18.29 is:

> **18.29**. *Joint ACI-ASCE Committee 423, Specification for Unbonded Single-Strand Tendon Materials and Commentary (ACI 423.7-07[2]),…*

Additional relevant ACI 318 code sections include the following definition in Section 2.2:

> *Basic monostrand anchorage device – Anchorage device used with any single strand or a single 5/8 in. or smaller diameter bar that satisfies 18.21.1 and the anchorage device requirements of ACI 423.7.*

And the final relevant ACI 318 Section is 3.8.4:

> ***3.8.4** – "Specification for Unbonded Single Strand Tendon Materials (ACI 423.7-07) and Commentary[2]" is declared to be part of this code as if fully set forth herein.*

ACI 423.7-07[2]

Tendon strength and ductility are addressed in 2.6.4 and 2.6.5:

> ***2.6.4** – Strength test*
>
> *Anchorages and couplers of unbonded tendons shall be designed to develop at least 95% of the actual breaking strength [emphasis by author] of the prestressing steel. Actual strength of the prestressing steel shall not be less than specified by Section 2.1.1 [which requires that the prestressing steel conforms to ASTM A 416[5]], and shall be determined by tests of representative samples of the tendon material in conformance with ASTM A 370[6].*
>
> ***2.6.5** — Ductility test*
>
> *Total elongation under ultimate load shall not be less than 2% measured in a minimum gage length of 3 ft (915 mm) between two points at least 3 in. (75 mm) from each anchorage. Tendon couplers shall not reduce elongation at rupture below that required for anchorages.*

ACI 301-05[1]

Strength and ductility requirements for unbonded tendon anchorages are addressed in 9.2.1.6:

> ***9.2.1.6** Anchorages for unbonded tendons—Anchorages for unbonded tendons shall develop at least 95% of the actual breaking strength [emphasis by author] of the prestressed reinforcement without exceeding anticipated set. Total elongation of the tendon under ultimate load shall be not less than 2% when measured over a minimum gauge length of 10 ft.*

PTI SPECIFICATION FOR UNBONDED SINGLE STRAND TENDONS[4]

PTI requirements (found in Section 2.2) are similar to those of 423 and 301:

> ***2.2** Anchorages and Couplers*
>
> ***2.2.1** Anchorages*
>
> *Anchorages and couplers of unbonded tendons shall be designed to develop at least 95% of the actual breaking strength [emphasis by author] of the prestressing steel. Actual strength of the prestressing steel shall not be less than specified by Section 2.1.1.1 [which requires that the prestressing steel conforms to ASTM A 4165], and shall be determined by tests of representative samples of the tendon material in conformance with ASTM standards. Total elongation under ultimate load shall not be less than 2% measured in a minimum gauge length of 3 ft [915 mm] between two points at least 3 in. [75 mm] from each anchorage.*

ACTUAL OR SPECIFIED STRENGTH?

Although there are other minor differences between the four documents, the primary difference is whether the required minimum tendon strength is to be based upon the specified breaking strength or the actual breaking strength. ACI 318-08[1] requirements are based upon the specified breaking strength; the other three documents use the actual breaking strength. A further complication is the fact that ACI 318-08, in Section 18.21.1 bases its tendon strength criteria on specified strength, but in Section 3.8.4 it incorporates ACI 423.7-07[2] which bases its tendon strength criteria on actual strength.

SPECIFIED BREAKING STRENGTH

The specified breaking strength of prestressing steel is a straightforward, easily determined quantity; it is the minimum strength required by the appropriate ASTM standard under which the strand is manufactured. In the United States, and in many other parts of the world, the predominant standard is ASTM A 416[5], and of the two grades of steel addressed in that standard (250 and 270 ksi), the prevalent minimum strength in use today is 270 ksi. The user or specifier of prestressing steel manufactured, certified, and sold as conforming to ASTM A 416 Grade 270 has a very high degree of confidence that the steel will have a minimum breaking strength of 270 ksi, and can reliably base all structural decisions on that minimum strength.

ACTUAL BREAKING STRENGTH

The actual breaking strength of a specific length of prestressing steel can be determined by test, using anchorages that have negligible effect on the steel strength, such as notching, pinching, or other undesirable effects. The actual breaking strength of prestressing steel manufactured in accordance with ASTM A 416 Grade 270 is normally higher than 270 ksi. It is not unusual to see tensile tests of 270 ksi ASTM A 416 strand with breaking strengths of around

285 ksi (a breaking force of 43.5 kips for a ½-inch diameter strand.) The ACI 423.7-07[2] and PTI specifications[4] state that the actual breaking strength is to be determined by tests on "representative samples" of the tendon material, but provide no quantitative guidance on what this means (how many tests, sampling protocol, etc.) The ACI 301[3] specification provides no guidance whatsoever on how to determine the actual breaking strength. The "actual breaking strength" is in fact an unknown quantity. It is known (after the fact) only for the sample tested; it is unknown for steel not tested. It can only be guessed or extrapolated by assuming that the untested steel has at least the same strength as the tested sample.

HOW MUCH TENDON STRENGTH IS REQUIRED IN ACTUAL STRUCTURES?

The author first addressed this question almost 40 years ago[7]. In the referenced paper a required minimum strength was recommended by examining the ultimate tendon stress permitted by then-current building codes, and providing some factor of safety above that value. On that basis the author recommended that the anchorages of unbonded tendons be required to develop 95% of the "rated strength of the prestressing steel". "Rated strength" then was equivalent to "specified strength" today. Based upon code requirements in 1970 (ACI 318-63)[8] it was argued that an anchorage would be adequate for use in real concrete structures if it developed only 80% of the rated strength. While the code requirements have changed over the past four decades, this rationale is still valid. The analysis is easy.

For members with a span-to-depth ratio of 35 or less (most beams and girders), ACI 318-08 Section 18.7.2(b) limits the permissible steel stress at design (factored) loads f_{ps} to f_{se}+60,000 psi. For a typical high-end f_{se} value of 176 ksi, the maximum permissible design stress in a low-relaxation unbonded beam tendon is thus 176+60=236 ksi or 87% of the minimum specified strength of 270 ksi.

For members with a span-to-depth ratio greater than 35 (most slabs) ACI 318-08 Section 18.7.2(c) limits f_{ps} to f_{se}+30,000 psi. With f_{se} =176 ksi, the maximum permissible design stress in an unbonded slab tendon is thus 176+30=206 ksi or 76% of the minimum specified strength of 270 ksi.

Since the ACI code limits the usable design stress in unbonded tendons to 87% and 76% of 270 ksi for beam and slab tendons respectively, it seems that the requirement for anchorages to develop 95% of the specified strength of 270 ksi is still valid. This provides a reasonable margin beyond the maximum usable design stress and at the same time recognizes the notching effects present in all wedge anchorages.

TENDON ELONGATION CRITERIA

All four documents require a 2% minimum tendon elongation when the prestressing steel fails‡. ACI 301-05[3] requires that the elongation be measured in a 10-ft gauge length; the other three documents require a 3-ft gauge length.

ASTM A 416[5] requires that the prestressing steel elongate 3.5% at the minimum specified breaking strength of 270 ksi. In Ref. 7 the author conservatively recommended a minimum elongation at failure of 1.5%. It is not clear how and why the 2% value was selected in all of the published specifications. An examination of typical stress-strain curves for ASTM A 416 prestressing steel suggests that the 2% value is difficult, if not impossible to achieve even with tendon anchorages which have no effect on strand strength.

The *PCI Design Handbook*[9], *5th Edition*, p. 11-22, presents a very useful mathematical expression which closely matches the typical stress-strain curve for ASTM A 416 (270 ksi) prestressing steel. The expression is:

For $\varepsilon_{ps} \le 0.0086$ $\quad f_{ps}=28500\ \varepsilon_{ps}$

For $\varepsilon_{ps} > 0.0086$ $\quad f_{ps}=270-(0.04/(\varepsilon_{ps}-0.007))$

Based upon the PCI expression, the strain at a stress of 0.95x270=257 ksi is only slightly greater than 1% (0.01008). The stress-strain curve is very flat in this inelastic region and a small increase in stress results in a large increase in strain. A 10 ksi increase in stress from 257 ksi ($0.95f_{pu}$) to 267 ksi ($0.989f_{pu}$) doubles the calculated strain to 2%, and another increase in stress of only 3 ksi increases the strain to 3.5%. But it is clearly seen that achieving a strain of 2% at a stress of 257 ksi is highly problematic.

It is of interest to determine the tendon elongation which would exist at the maximum tendon stress permitted by the ACI code. Since the maximum stress fps permitted under any circumstance by ACI 318 is 236 ksi, the strain associated with that stress (conservatively assuming that the strain is constant throughout the entire length of the tendon) using the PCI expression is 236/28500=0.0083 or 0.83%. Since the author has shown in Ref: 7 that it is impossible to achieve an unbonded tendon strain substantially in excess of 1% in a real concrete structure under design loads, and the strain at the maximum permissible ACI code tendon stress is only 0.83%, the elongation requirement of 2% at $0.95f_{pu}$ appears to be unnecessarily restrictive, and should be critically re-evaluated.

‡ *There is no specific elongation requirement in the actual text of 318-08, however by incorporating ACI 423.7-07 (in Section 3.8.4) the 2% elongation requirement in the 423 document becomes a part of 318.*

SUMMARY AND RECOMMENDATIONS

The use of actual breaking strength as a basis for required tendon strength should be abandoned with all due haste. All requirements for minimum required tendon strength should be based upon specified breaking strength, (f_{pu} in ACI terminology.) It makes no sense to base tendon strength criteria on an unknown quantity, or at best a quantity determined only after testing is performed on some undefined sampling of tendon material and then extrapolated to untested material. Since the maximum permissible ACI code tendon stress for design is only $0.87f_{pu}$, tendon strength beyond f_{pu} is irrelevant.

The required tendon elongation at the minimum required breaking strength of $0.95f_{pu}$ should be 0.9%. The present requirement of 2% is unrealistically high, unnecessary, and probably unachievable with most prestressing steels and anchorages. The lower value of 0.9% approximates the maximum strain possible in an unbonded tendon in a real structure under design loading, is 8% larger than the strain required to develop the maximum permissible ACI code tendon design stress, and is achievable considering typical stress-strain relationships at a breaking stress of $0.95f_{pu}$.

Several other less significant differences in these specifications should be resolved by their authors. ACI 318[1] and ACI 301[3] each contain the term "without exceeding anticipated set" when referring to the minimum tendon breaking strength. This term was abandoned by ACI Committee 423 when developing ACI 423.7-07[2], because none of the current members of the committee knew precisely what the term meant or could remember its origins. It was also felt that the term added little or nothing of value to the specification. The term should be abandoned by Committees 318 and 301 for the same reasons. Finally, the differences in minimum gauge length over which the tendon elongation is measured (10 ft in ACI 301, 3 ft within a distance at least 3 in. from each anchorage in the 423 and PTI documents) should be resolved in favor of the 3 ft criterion, which is more practical and addresses wedge movement.

A final recommendation is that ACI and PTI should find some method to maintain a single specification, approved by both organizations, for unbonded tendons. That would eliminate the necessity to maintain four different documents and the inherent potential for conflict among them.

REFERENCES

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3. *Specifications for Structural Concrete, ACI 301-05*, American Concrete Institute, Farmington Hills, MI, 2005.

4. *Specification for Unbonded Single Strand Tendons, 2nd Edition*, Post-Tensioning Institute, Phoenix, AZ, 2000.

5. *Standard Specification for Steel Strand, Uncoated Seven-Wire for Prestressed Concrete, ASTM A416/A416M-06*, ASTM International, West Conshohocken, PA, www.astm.org.

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