BANDED TENDONS IN POST-TENSIONED FLAT PLATES

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I appreciate very much the opportunity to speak tonight on a subject of major significance to those involved in the design and construction of post-tensioned concrete buildings, the use of what is known as the "banded" tendon distribution in post-tensioned flat plates.

Looking back over my 22-year career in prestressed concrete I would list 3 events as having had the most impact on the growth and development of post-tensioned concrete as a major framing system in US building construction:

1. The use of the equivalent load technique (load balancing) as a design and analysis tool.

2. The development of strand systems as the predominant post-tensioning method for monostrand tendons.

3. The development of the banded tendon distribution for post-tensioned flat plates.

So we can see how important the banded tendon technique has been to the growth of the US post-tensioning industry. Tonight we will address the following aspects of the banded tendon technique:

1. The history of banded flat plates

2. Testing of banded flat plates

3. The building codes and banded flat plates

4. Design recommendations for banded flat plates

Let's first get some definitions covered. A flat plate is a solid-thickness, two-way slab supported substantially on isolated columns. Sometimes the columns have small "shear caps" which supplement the punching shear capacity but are not used flexurally. A banded tendon distribution is one where ALL of the post-tensioning tendons in one direction are placed in a narrow (3-4') band over the columns, and ALL of the tendons in the perpendicular direction are spaced uniformly.

The first post-tensioned flat plates done in the US were in the early 1950's and were associated with the "lift-slab" construction technique. The early design methods were based upon average "beam-strips" in two perpendicular directions. Tendon distributions were influenced by concepts in use for non-prestressed slabs, i.e., arbitrary "column strip" (CS) and "middle strip" (MS) distributions where slab rebar would be distributed anywhere from 60 to 76% in column strips and 40 to 24% respectively in middle strips. Column strips and middle strips were defined as areas bounded by imaginary lines located at the quarter points of bays.

Leaning on these concepts, designers of early PT flat plates generally specified that tendons be distributed with similar percentages between the imaginary strips. One of the most popular tendon distributions for PT flat plates in the fifties and sixties was therefore 60/40, meaning that 60% of the tendons required in a full bay were placed in the column strip and the remaining 40% placed in the middle strip. Some engineers modified this to 67/33 (little easier to calculate) and certain radicals even went as far as 75/25!! No differences in slab behavior were noted with any of these distributions.

There is an interesting footnote to the various arbitrary CS and MS tendon distributions. In the load balancing method, the prevalent method for designing PT flat plates for over twenty years now, the designer assumes that the load "balanced" by the tendons is applied uniformly over the entire surface of the slab. If one follows the statics of applied tendon loads (those applied upwards and those applied downwards) around the various arbitrary areas of the slab (the "column strip/column strip area, the middle strip/middle strip area, the middle strip/column strip area, etc.) one quickly sees that only two tendon distributions actually accomplish this assumption: one is the banded distribution, the other is the 75/25 distribution. All other distributions of tendons balance more or less than the average selected balanced load in the various intersecting panels of the slab. The 60/40 distribution applies, for example, 160% of the average balanced load in the center of the bay (the middle strip/middle strip panel)! Run these numbers yourself for an informative exercise.

There are two significant disadvantages to the arbitrary "column strip/middle strip" method of distributing tendons in post-tensioned flat plates. First, to install the tendons in their correct parabolic profiles they must be "woven" in place like a basket. A particular tendon running in one direction may be ABOVE some of the tendons in the perpendicular direction, but BELOW others. The PT detailer must determine which tendon in the entire slab is below all others (it is placed first, tendon sequence #1), then the perpendicular tendon which is NOW the lowest (sequence

#2), and so on until he finds the tendon which is ABOVE all other tendons (the highest sequence number). This is a tedious and costly process both for the detailer and the ironworker who must follow the sequence perfectly in the field or end up with a birdsnest of tendons.

The second major disadvantage of "basket-weave" slabs is for the designer. Load paths, and framing in general, becomes very difficult when the slightest irregularity is introduced into the slab (i.e., as on every real building). What is a column strip when the columns don't line up or are offset in adjacent bays? How are loads carried around openings which interrupt columns strips and middle strips? Each designer of basket-weave PT flat plates struggles with these questions on virtually every job where these problems arise to some degree.

In 1968 an event occurred which forever changed the nature of PT flat plate construction. A building was built which may remain as the most famous post-tensioned building ever constructed...the Watergate Apartments in Washington, D.C. (yes, the very same Watergate you're thinking about). The column layout on this curved structure was horribly complex..basically nothing lined up in either direction. Columns were located architecturally where they could be...in closets, bathrooms, etc...with little regard to orthoganality. The building had no grid lines..all columns were located with a coordinate system. The columns were, however, located such that they were never more than about 22 feet away from another column. Thus, some type of rational framing MUST be possible. But certainly not with imaginary column strips and middle strips!!

The design team felt that the only rational way to frame the floors was to conceptualize the framing as if it were one-way...connecting the most logical columns with a "band" of tendons they could think of as a beam, and then using uniformly spaced tendons normal to the "bands" as if they were a one-way slab spanning to the "beams". Incredibly, with the use of this technique the apparently insurmountable framing problems vanished. With this "banded" concept the load paths became obvious and the framing of even this terribly complex layout became easy. The only problem was would such a radically different tendon distribution really work?

There were a number of indications that suggested it would. Some laboratory tests had already been published at that time on PT flat plates with various tendon distributions. Lin studied one and four-panel models in 1956 and 1959 at UC Berkeley; Gamble at the University of Illinois tested a six-panel specimen in 1964; Brotchie in Australia tested an 8-panel slab in 1967, and Odello again at UC Berkeley in 1967 tested another 4-panel slab. Although some of these slabs were freaks bearing little resemblance to practical PT flat plate construction, they all indicated that tendon distribution had no perceptible effect on slab behavior. This had been noted in the Commentary to ACI 318 since 1963, and that has remained unchanged through the current 83 version. The Commentary to Section 18.12.2 of 318-83 states:

> "Tests indicate that the moment and shear strength of prestressed slabs is controlled by the total tendon strength and by the amount and location of nonprestressed reinforcement, rather than by tendon distribution."

With this limited ammunition, and recognizing that the structure with all its complexity was still a relatively short-span flat plate, the Watergate design team went ahead with the first known "banded" flat plate. As you may suspect, the project was extremely successful, economically built, and exhibited completely acceptable serviceability behavior. Furthermore, the tendon placer received a pleasant surprise. With the banded tendon distribution ALL of the band tendons are placed first, and then ALL of the uniform tendons are placed on top of the bands. The complicated sequencing procedure unique to basket-weave slabs is eliminated. This resulted in a substantial savings in tendon placing costs. Placers generally estimate a 25% savings in labor costs with banded tendon distributions.

Since Watergate in 1968 the use of the banded tendon distribution grew dramatically throughout the country until by the mid 1970's it was the predominant method for constructing post-tensioned flat plates. Today it is almost exclusively used..it is becoming extremely rare to see a slab designed with the basket-weave method. Virtually all of our knowledge about the field and laboratory behavior of post tensioned flat plates for the last fifteen years has come from slabs with banded tendon distributions.

TESTS

Tests of banded PT flat plates are nicely summarized in the PTI publication "Design of Post-Tensioned Slabs", excerpts of which are attached as Appendix A. A brief description of each test follows:

1. Date - 1973
   In charge - Burns
   Location - University of Texas at Austin
   Description - Series of single panel tests
   Results - Studied the required amount of mild rebar required over columns and the punching shear capacity as a function of F/A.

2. Date - 1975
   In charge - Burns
   Location - University of Texas at Austin
   Description - 9-panel half scale model with two adjacent cantilevers providing an interior panel and edge and corner panels with and without cantilevers.
   Results - Confirmed classic two-way slab behavior (yield lines, transverse distributions of moment) for banded slabs. Confirmed applicability of equivalent frame method for predicting moments and accuracy of Eq. 11-42 (318-83) for predicting shear strength.

3. Date - 1975
   In charge - Hawkins
   Location - University of Washington, Seattle
   Description - Six FULL SCALE tests of interior and exterior slab column panels with emphasis on moment transfer and reversal of stress.
   Results - Verified current methods for calculating shear and moment transfer capacities. Demonstrated that rebar used for flexural moment transfer must be located within 1.5h from column faces.

4. Date - 1976
   In charge - Burns
   Location - University of Texas at Austin
   Description - 4 panels (2x2 symmetrical) with no cantilevers.
   Results - Symmetrical behavior of yield lines, deflection, and cracking patterns.
   At service load - no cracking.
   At factored load (181 psf) - some negative moment yield lines starting to develop. no positive moment cracking.
   At 210 psf - Full negative moment yield lines developed and first positive moment cracking becomes apparent. Catenary behavior starts above 210 psf.
   At 220 psf - Punching shear failure ends test.

5. Date - 1982
   In charge - Gamble
   Location - University of Illinois
   Description - Nine panels, no cantilevers. Main purpose to study shear at edge and corner columns.
   Results - Confirmed current methods for predicting shear and moment transfer capacity at edge and corner columns. Studied tendon stress at ultimate load resulting in change to ACI 318-83.

Test results on post-tensioned slabs with banded tendon distributions may be summarized as follows:

1. Banded flat plates are two-way slabs! They exhibit classic 2-way slab behaviour in all characteristics. While the development of yield lines can be influenced by the "d" dimension of the tendons, it appears to be unaffected by the orientation of the bands or uniform tendons.

2. Flexural and shear strengths are accurately predicted by the ACI code 318-83 using the equivalent frame method for slab and column moments and Equation 11-42 for shear capacities.

3. It is felt, based upon the tests summarized above, that our knowledge of the behaviour of post-tensioned flat plates with banded tendons is at a level exceeding or consistent with that of non-prestressed (rebar) flat plates.

<u>CODES</u>

The ACI code has never required any specific tendon distribution, nor has it prohibited any specific distribution from being used. Prior to 1983 the Commentary to the Code has implied the use of basket-weave slabs by mentioning "column strips" and "middle strips". Further, some of the tendon spacing recommendations in previous Commentaries could be interpreted as "de-facto" prohibitions of banded distributions, particularly when they were applied to the space between bands. To provide the backup for bringing the Code up to date with respect to banded tendons, the joint ACI/ASCE Committee 423 published in 1983 a report entitled "Recommendations for Concrete Members Prestressed with Unbonded Tendons". The entire Section 3.3 of this report, entitled "Two-way Systems", is attached as Appendix B. In Section 3.3.5, "Tendon Distribution and Spacing", Committee 423 states:

> "The predominant and recommended method of placing tendons in two-way slab systems is the banded distribution illustrated in Fig. 3.2. The use of banded tendon distribution(s) greatly simplifies the process of placing tendons, and therefore provides a significant reduction in field labor cost."

With this input from 423, ACI 318 modified Code and Commentary for 1983 to specifically recognize the banded tendon distribution. Code Section 18.12.4 reads (with the emphasis provided by me):

> "For normal live loads and loads uniformly distributed, spacing of prestressing tendons or groups of tendons IN ONE DIRECTION shall not exceed 8 times the slab thickness, nor 5 ft. Spacing of tendons also shall provide a minimum average prestress (after allowance for all prestress losses) of 125 psi on the slab section tributary to the tendon or tendon group. A minimum of two tendons shall be provided in each direction through the critical shear section over columns. Special consideration of tendon spacing shall be provided for slabs with concentrated loads."

Commentary Section 18.12.4 reads:

> "This section provides specific guidance concerning tendon distribution that will permit the use of banded tendon distributions in one direction. This method of tendon distribution has been shown to provide satisfactory performance by structural research."

To the best of my knowledge, the Los Angeles City Building Code was the only published ordinance to require a specific tendon distribution in PT flat plates. This was done in a rather awkwardly worded Section 91.2618.13 which said:

> "Slab Systems....Distribution of moments in a slab at a ratio of not less than 60 percent to the column strip and not more than 40 percent to the middle strip will be permitted in lieu of the distribution specified for conventionally reinforced slabs. Distribution other than as permitted herein may be permitted when substantiating data, satisfactory to the Department, is submitted."

This is kind of a "dinosaur" section which could be traced back to an origin in the early sixties. Obviously what it wants is a 60/40 distribution...that's generally what was being done then. However interpreting this in later years, particularly with the advent of banded tendon distributions, became a problem. Taken literally, the section is an interpretational disaster. First, it refers to "moments" rather than tendons, even though in your heart you know the writer meant tendons. Second, even though you suspect that the writer specifically wants a 60/40, the "not more than.." and "not less than..." stuff really only establishes the 60/40 distribution as a lower bound. Thus, 100% in the column strip is OK by this wording since it is greater than 60%, and no tendons in the middle strip is OK because that is less than 40%. So a 100/0 distribution apparently satisfies the requirement!

In spite of this fun with words, the requirement WAS in fact for many years interpreted by the City to require a 60/40 tendon distribution and prohibit all others, including banded distributions. Recognizing that the requirement was out of date, we challenged it with a variance for the first time in 1978 on a large office building complex known as "The Park" in downtown LA on Figueroa just east of the Harbor Freeway. The variance was approved and "The Park" became the first banded tendon job in the City of LA. Since then there have been many other banded jobs in the City and most have required a variance, however since the first job the approval of the variance has been very speedy and virtually automatic. We know of no case where the requested use of banded tendons has ever been refused by LA City. In recent years, since the adoption of UBC, there have been several banded jobs built which did not require variances. We would anticipate that future jobs using banded tendons in the City of LA will not require variances, because the City's attitude towards banded tendons is quite responsible and receptive. It's just that old Code requirements, no matter how outdated, die a long, hard death.

DESIGN AND DETAILING RECOMMENDATIONS

It is relatively easy these days to arrive at the correct amount of post-tensioning tendons and mild reinforcing steel required by code and standard practice to be provided in a flat plate. Sophisticated and friendly computer programs are readily available which will do this for you accurately and efficiently. The key to quality performance for these structures, however, lies not in the number-crunching, but in the detailing of this reinforcing and the joinery. For that reason, I would like to highlight a number of important detailing recommendations which apply specifically to post-tensioned flat plates.

Before getting to the details, I feel it is important to emphasize that virtually ALL significant PT flat plate problems (those which result in real structural failures or those which end up in court) can be lumped into two categories:

1. Shear...a deficiency in punching shear capacity generally caused by simply ignoring the shear strength calculation.

2. Restraint to Shortening...excessive cracking in slabs, columns, or walls caused by inadequate detailing and joinery to alleviate such distress.

Solving the shear problem is ridiculously simple...just DO the calculations in accordance with the code or buy a program that does it for you. Rarely if ever have shear problems arisen due to errors in the shear calculations..they are relatively straight=forward. The problem is typically that they are ignored. This is terribly significant and ironic when one recognizes that this is really the only area of flat plate behavior that presents any real danger to human life.

Solving the shortening problem is much more complicated and it is here that we really separate the men from the boys in designing good PT buildings. Years of experience have shown us that numbers are of little help in solving shortening problems. Good judgment, details, and joinery are everything! While each PT building presents its own set of unique problems and has its own unique set of solutions, some generalities can be made. In my opinion the two most important tools available to the designer for solving shortening problems are the pourstrip and the addition of carefully located crack distribution rebar.

The pourstrip, or delay strip, is a temporary separation in the slab which 1) disconnects the slab from stiff restraining elements (like walls) until a big percentage of the early drying shrinkage has occurred, and/or 2) divides the post-tensioned slab temporarily into smaller pieces and minimizes overall shortening. Pourstrips are generally left open for from one to two months depending on the severity of the restraint condition. Typical pourstrip details are presented in Appendix C, Details 1 and 2. The pourstrip is by far the most effective weapon available to the engineer in the fight against restraint to shortening cracks.

Another effective tool available to minimize shortening cracks is the careful detailing of mild rebar at "hot spots", points where shortening or shrinkage cracks are known to start. This would include slab edge corners (inside and outside corners), corners of slab openings, and at other obvious irregularities in slab shape which would produce stress concentrations. In addition to these "hot spot" bars, we recommend and use in our own designs, a continuous mat of developed rebar in both directions, throughout the slab, which is in addition to all other bars required for any other reason. Typically this will be #4 bars at 36" o/c each way as a minimum. This steel provides a multitude of benefits including:

1. It stops or distributes early cracks which start before the tendons are stressed.

2. It distributes and minimizes cracks which try to start at "hot-spot" locations you didn't think of.

3. It will minimize all forms of tendon "breakouts".

4. It will make you feel a lot better for very little additional cost.

Every banded flat plate needs attention to detail at two important locations, the column and at the band anchorages. The detailing of stressed and unstressed reinforcement at the columns is critical. We recommend details similar to 9-12 in Appendix C which clearly show the layering of the tendons and rebar over the column in both directions. It is only with the inclusion of a detail such as this which will ensure that the installation conforms to the assumptions for effective depths assumed in the calcs, and also which will ensure that the mild rebar is placed within the area prescribed by the Code (i.e., within distances of 1.5h from the column faces).

To prevent or minimize breakouts at heavily concentrated band anchorages, build a containment cage around them at the slab edge as in detail 15 in Appendix C. The standard 2-#4 "backup bars" are quite adequate for relatively widely spaced anchors for uniform tendons, but very inadequate for the concentrations at band stressing (or deadend) points. The band anchor containment detail shown has virtually eliminated serious breakouts at the stressing points of our banded jobs.

Obviously the above discourse doesn't solve everything but it does highlight on several very important items which are crucial to the behavior of every flat plate. Now let's take a few moments and see some slides of banded flat plates under construction.