NO MORE POUR STRIPS

Shrinkage-compensating concrete eliminates need

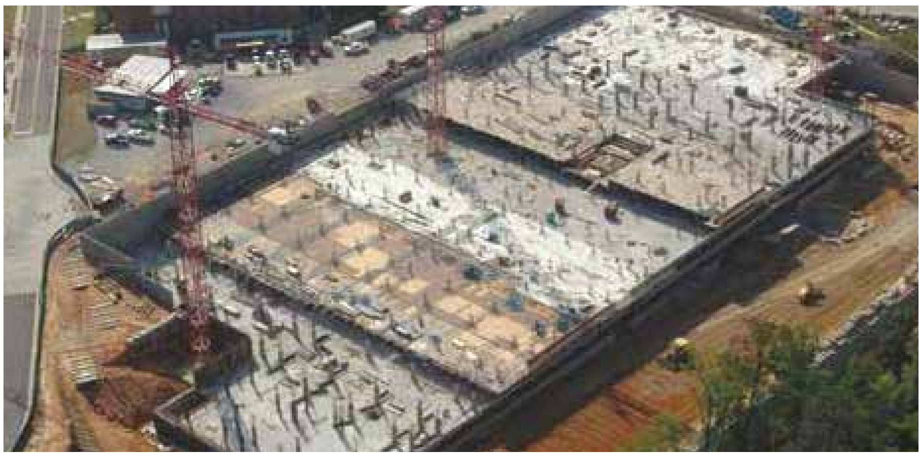

Fig. 1: Aerial view of Ridgecrest South under construction on May 20, 2008.
The slab-on-ground is complete, and more than half of Level 1 and one-third of Level 2 have been cast

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In 2004, the Board of Trustees at the University of Alabama embarked on a bold plan to provide on-campus housing to all freshmen starting in the fall of 2009. By 2007, with years of continuous construction behind them, the university was within reach of its goal. The final push was the construction of Ridgecrest South, a colossal five-story, 965-bedroom, 345,000 ft^2 (32,050 m^2) student housing facility built atop a sprawling three-level 600 x 270 ft (183 x 83 m), 1017-space parking structure. Separating the two structures is a spacious 68,000 ft^2 (6317 m^2) multi-purpose plaza level incorporating pavilions, sports courts, a running track, barbeque grills (mandatory in the deep South), and lush greenscapes (Fig. 1 and 2). The structural system is a post-tensioned flat plate concrete frame.

The Challenge

Adding to the challenge posed by the massive size of the project was a limited budget, a fast construction schedule with an absolute deadline, and a site located on the side of a slope created by years of dumping unwanted debris. With only 23 months remaining until students would be arriving, the original developer was unable to convince the university that the building would be completed on time and within budget. With time running out, our design team was asked by the university to find a way to build Ridgecrest even faster and still within budget. In fact, the redesign time had to come out of the original construction window, reducing time for construction even further.

Driven by the configuration of the student housing, we designed a parking structure layout with only one expansion joint. This resulted in a deck plate with unbroken dimensions of 325 x 270 ft (100 x 83 m). The original design addressed this challenge by incorporating pour strips (temporary joints), but the revised project schedule and budget could not accommodate pour strips because they:

- **Tie up significant quantities of costly material.** Reshores must be left in place for an extended period. Many specifications call for at least 12 weeks of open time, as it takes that long for the pour strips to be even partially effective;
- **Slow construction.** The presence of reshores in pour strip bays inhibits the completion of mechanical, electrical, and plumbing systems as well as delays the installation of final finishes;
- **Add material and labor costs.** Additional reinforcing bars and strands are often required in pour strip bays. The process of forming, placing, and finishing pour strips is labor intensive and expensive. In addition, joints are often caulked and sealed, adding yet more material and labor costs.
- **Introduce an irregularity.** In systems that must withstand exposed conditions, this increases the risk of long-term maintenance problems.

Turning a Challenge into Opportunity

Concrete floor systems shorten over time, and this shortening is resisted by foundations, structural walls, and other fixed elements. The restraint to floor shortening creates tension in the field of the slab, which can cause cracking. The longer the

Fig. 2: Artist's rendering of completed Ridgecrest South facility

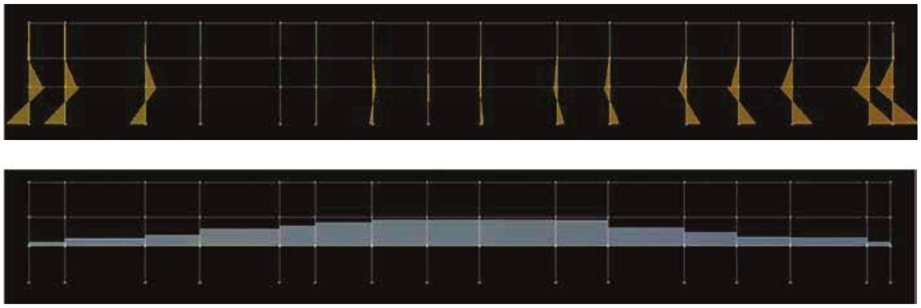

Fig. 3: Graphical output from structural model of parking garage levels: (a) column bending moments due to contraction of first framed level slab; (b) associated axial forces in the first level slab. The cumulative effect of restraint due to the columns causes maximum slab forces to be in the central bays

dimensions of the floor plate, the more pronounced these forces become as the incremental strains along the length of the slab add up. In a post-tensioned slab, 66% of the incremental strains come from concrete shrinkage.[1] The balance of strains is caused by elastic (7%) and creep (11%) shortening due to the compression action of the post-tensioning and shortening due to temperature drops (16%).[1]

Pour strips allow for a portion of the concrete shortening to dissipate before tying the full length of the slab together. If most of the shortening can be eliminated, the strips can be eliminated as well. Shrinkage-compensating concrete (SCC, not to be confused with self-consolidating concrete) can help eliminate this shortening.

SCC is often interchangeably called Type K concrete. In the U.S., however, SCC is not typically produced using Type K cement. Instead, one of several powder additives is incorporated into the mixture, causing the concrete to behave as if it included Type K cement. In this case, we added Komponent®, manufactured by CTS Cement Manufacturing Corp.

For the first 3 days or so after casting, SCC expands. Once the expansion stops, SCC shrinks much like ordinary concrete except that the ultimate magnitude of this shrinkage is reduced. Say a normal mixture shrinks 0.05% over the long run. A similar SCC mixture designed for 0.05% expansion would expand the 0.05% and then shrinkage would begin, but this shrinkage would be less than the baseline 0.05% – perhaps only 0.03%. Thus, in the long run, the concrete would have an overall expansion of 0.02%.

We decided that SCC would allow us to improve on the performance of pour strips. Why? Because it takes a long time for all the shrinkage to occur in normal concrete – a pour strip left open 12 weeks might address only half the potential shrinkage. In contrast, SCC provided the potential to offset 100% of the shrinkage strain.

The Design: Loading

In evaluating restraint forces, it's necessary to develop an adequate approach for incorporating slab shortening effects. In a post-tensioned slab system, restraint forces and strains arise due to shrinkage, elastic shortening, creep shortening, and temperature changes. The magnitudes of the strains are established using procedures outlined in References 2 and 3. Typically, we convert the sum of the shrinkage, elastic, and creep strain values into an equivalent temperature change and add it to the design temperature change. The resulting equivalent temperature change is used as a load case in the structural model to evaluate the effects of concrete shortening.

Fig. 4: For the elevated slabs in the garage levels, fogging was started immediately after concrete placement

Fig. 5: Vibrating wire strain gauges (black) were welded to epoxy-coated reinforcing bars (green) and connected to a data logger via cables (dark blue). Also visible: post-tensioning strand sheathing (light blue) and headed stud shear reinforcement

The Design: Structural Model

A three-dimensional model of the concrete frame was constructed using RAM™ Elements (formerly RAM Advanse) and the following parameters:

Foundation fixity – At Ridgecrest, columns are supported by drilled shaft foundations (piers) extending through soft soil and socketed into rock. Rotational springs were used to model the restraint provided by the drilled piers, using spring stiffness values developed in consultation with TTL Inc., the geotechnical consultant on the project. Prior to the placement of the slab-onground, elastic and creep strain and significant shrinkage can occur. So at this stage, the lateral restraint at ground level could have been modeled using elastic springs. After the slab-on-ground is in place, however, it can provide significant lateral restraint. As a conservative simplifying assumption, we assigned full lateral fixity at the ground level in the model.

Section properties – For analysis during service conditions, full section properties were used. For strength design, gross section properties were factored by 50% to account for cracking. Slabs were modeled as beam elements with stiffness based on half the bay width (tributary width) and an area based on the full width of the bay. Modeling the stiffness provided by flat plate slab systems as half the bay width is a good approximation for post-tensioned slabs, while modeling the area based on the full width of the bay is necessary to correctly represent reaction to the temperature load case.

The Design: Serviceability Considerations

Applying the equivalent temperature change to the structural model results in significant restraint forces at the first framed level. The typical pattern has large moments at exterior columns and a large axial force at the center of stiffness on the first framed level.

In Fig. 3(a), a typical distribution of column moments is shown (slab moments are generally small and are not shown). Figure 3(b) illustrates a typical distribution of axial forces in the level closest to the foundation restraint. Axial forces on the second framed level are about a third of those on the first framed level and are of opposite sign (not shown). Axial forces are negligible on the third framed level.

The moments and axial forces from the model were converted into equivalent stresses. For the axial load, the cross-sectional area of the bay was used. In computing stress due to any slab moments of non-negligible magnitude, a width equal to a “column strip” was used to calculate a moment of inertia. These stresses were combined (though they were generally not located such that they simultaneously occur in large magnitudes at any given location) and then converted to a multiple of $\sqrt{f'_c}$.

For example, the sum of a 25 psi extreme fiber stress due to moment and 125 psi due to axial load is 150 psi. This is 2.12 $\sqrt{f'_c}$ for 5000 psi concrete (in SI units, 170 kPa bending stress and 860 kPa axial stress sum to about 0.17 $\sqrt{f'_c}$ for 35 MPa concrete).

When designing two-way post-tensioned slabs for serviceability, ACI 318 requires that the computed extreme fiber stress in tension is limited to 6 $\sqrt{f'_c}$ (in SI units, this limit is 0.50 $\sqrt{f'_c}$). Incorporating the exact results from the model would be impractical for design purposes. Our fairly conservative approach was to reduce the code-limited extreme fiber stress by an amount equal to the sum of the maximum bending stress and maximum axial stress obtained from the shrinkage model, thereby creating an allowance for the restraint forces. Using the example stresses, the allowable design stress under dead and live loading would be (6 – 2.12) $\sqrt{f'_c}$ = 3.88 $\sqrt{f'_c}$ (in SI units, [0.50 – .17] $\sqrt{f'_c}$ = 0.33 $\sqrt{f'_c}$).This method is conservative for the center span and can be extremely conservative for spans other than center spans. A refinement is to use a second and possibly third design value for other spans.

Two-way post-tensioned slabs are also designed to provide a minimum P/A compressive stress. An approach similar to that outlined above is used to address this design constraint. The maximum tensile stress caused by restraint is added to the target P/A value. For example, if the maximum tensile stress resulting from restraint is found to be 100 psi (0.69 MPa) and the target compressive stress is 200 psi (1.38 MPa), the design compressive stress used is 300 psi (2.07 MPa). In this way, the system would have 200 psi (1.38 MPa) compression after 100 psi (0.69 MPa) is taken away by restraint forces.

In an effort to accelerate the construction process, 3000 psi (21 MPa) concrete at 48 hours was specified to allow for early post-tensioning and form removal. SCC was specified at the parking levels, with an expansion between 0.05% and 0.07% per ASTM C878. This was expected to be more than sufficient to offset the full expected shrinkage value. As part of the preconstruction process, we placed several test slabs with the SCC mixture and conducted a full battery of strength and expansion tests.

An interesting effect of the high-early-strength mixture was that it gained strength so fast that it partially restrained the expansion of the SCC. We could have adjusted the mixture but decided to move forward with the existing one as our design did not require a complete offset of the concrete shrinkage. We only needed to match the 50% or so shrinkage reduction that would have been provided by pour strips.

Implementation

SCC must be wet cured for 7 days to be fully effective. We specified soaker hoses covered with a burlene-type covering (burlap with a white polyethylene covering). We found that periodic wetting of the slab was insufficient as the SCC dried out the burlene quickly. We were able to achieve a wet cure condition only when the soaker hoses were left running continuously.

The SCC’s propensity to dry quickly was also evident during placement. An application of a monomolecular film evaporation retarder was specified for use during the finishing operations. We found, however, that even with a thorough application of the evaporation retarder, the exposed surface of initial placements dried and light surface crazing was evident the next day. Use of several true fogging devices was deemed impractical, but the use of high-pressure sprayers with fogger nozzles proved adequate (Fig. 4).

An additional consideration was the sequence and shape of slab placements. Each slab placement was a strip cast against the previous pour such that only one side of the placement was cast against the existing slab. This allowed for uniform expansion.

Testing and Instrumentation

An extensive instrumentation program was incorporated into the project. Vibrating wire strain gauges were installed along one frame line (Fig. 5) and in two freestanding reference blocks, with dimensions of 6 x 1 x 1 ft (1.8 x 0.3 x 0.3 m), which were cast on the ground floor next to the data logger. In addition to the instrumentation, a set of three expansion prisms (per ASTM C878) was made from every 100 yd^3 (76 m^3) of SCC placed.

How did it perform?

Strain data taken from the two reference blocks are shown in Fig 6. Figure 6(a) shows data for Test Block 1, with two 5 ft (1.5 m) long No. 4 bars, while Fig. 6(b) shows data for Test Block 2, with three 5 ft (1.5 m) long No. 4 bars. One bar in each block was instrumented. The blue line shows the actual strain data, corrected to eliminate local ambient temperature strain effects. Let’s compare the results to the expected behavior of SCC. First, we expect expansion. This is present with almost 150 microstrain in Test Block 1 and almost 100 microstrain in Test Block 2. Once the expansion is complete, we expect shrinkage – specifically, less shrinkage than normal concrete. Both test blocks exhibit shrinkage after the period of expansion. The red line is the shrinkage predicted using ACI 209R-92 procedures for normal concrete. We clearly see that the SCC exhibits less shrinkage than normal concrete.

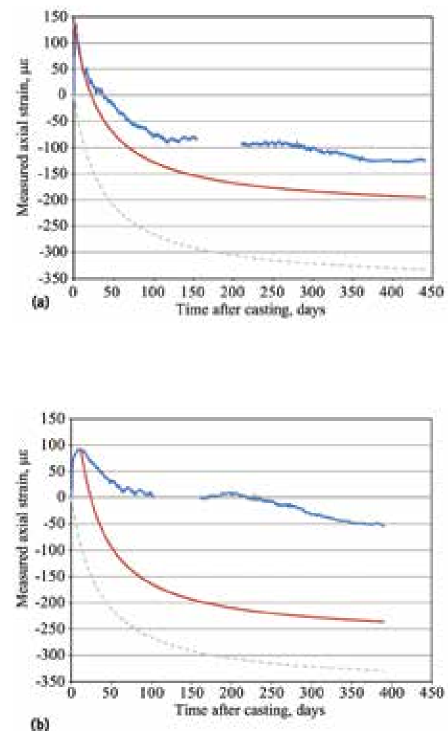

Fig. 6: Axial strain data for reference blocks: (a) Test Block 1, with two No. 4 (12 mm) bars; and (b) Test Block 2, with three No. 4 (12 mm) bars. The blue line shows the measured data, the red line indicates the shrinkage predicted per Reference 2, and the gray line indicates the predicted shrinkage if no initial expansion had occurred.

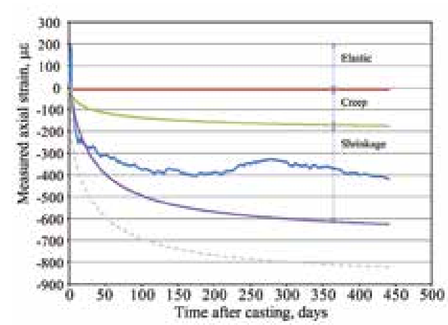

Fig. 7: Axial strain data for the first framed level slab, measured near the expansion joint. The blue line shows the measured data. The red, green, and purple lines show the elastic, creep, and shrinkage components of the strain that would be expected for an SCC that expanded and then exhibited shrinkage comparable to normal concrete.

And how did we do overall? The gray line represents the predicted strain if there had been no initial expansion. In the case of Test Block 1, the expected shrinkage strain of almost 350 microstrain for normal concrete goes to a value of just under 125 microstrain for the SCC.

Next, consider data taken directly from the structure itself (Fig. 7). These data were measured near the expansion joint, near the outermost edge of the slab. The effects of restraint forces are significantly reduced at this location, but they are not completely eliminated. The red, green, and purple lines represent components of expected strains that would occur after the expansion phase if the SCC's only behavior was expansion during the first few days. Again, the contrast between predicted and measured behaviors indicates SCC not only expands and thereby offsets shrinkage, but also shrinks less than normal concrete. The dashed gray line represents what the slab strain would be if the building was constructed of normal concrete, with no expansion and normal shrinkage. As can be seen, the measured results are less than half what would be expected with normal concrete. The key takeaway is that this is significantly better than what would be achieved with a pour strip left open 12 weeks.

The real proof is the slab itself – there are virtually no cracks in more than 420,000 ft² (39,000 m²) of slab. Further, the concrete frame was bid and constructed under budget and completed 42 days ahead of (a very aggressive) schedule. Best of all, because the slab was originally bid with pour strips and then re-bid with SCC in place of the pour strips, we know that the high quality and fast schedule were obtained with a net cost savings – even after paying a premium for SCC.

Additional Research

The instrumentation and testing program undertaken for this project is not just about validating the use of SCC in place of pour strips. Data accumulated over the next few years will be used to investigate other important topics, including measured versus predicted reaction to ambient and seasonal temperature changes and development of a simple design approach for estimating the restraint provided by drilled piers.

We believe the information will be of wide interest because of its relevance to such topics as prestress loss, creep and shrinkage effects, actual versus theoretical stiffness of flat plates, and comparisons of predicted and measured column and slab moments for two-way flat plates.

Looking Forward

Our experience shows that SCC is a viable, costsaving, and schedule-shortening alternative to the use of pour strips. It also shows that in buildings with no structural walls, the major restraint is limited to the foundation level. Thus, only the first two framed floors are truly impacted by restrained shrinkage. In fact, above the second elevated slab, restraint forces drop below meaningful magnitudes, with most of the forces concentrated at the first framed level.

Yet, we frequently see pour strips used many levels past the first two elevated slabs, even though they may not be needed. Even Reference 3 includes an example of the use of pour strips throughout a six-level structure. While we understand the trepidation that may come with using SCC in place of pour strips, we hope that, at the very least, this article reminds us why we have pour strips, what they do, and why their presence past the second framed level may be unnecessary.

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