Closure Strip Strategies

Available design approaches are summarized and evaluated against field data

by Andre Brault, Neil Hoult, Tom Greenough, Ian Trudeau, and Barry Charnish

The construction industry in the United States accounts for 4% (about $720 billion) of the country's Gross Domestic Product.[1] Thus, the elimination of any construction inefficiencies could lead to significant economic benefits. Currently, reinforced concrete (RC) buildings with floor plans larger than 60 to 76 m (200 to 250 ft) commonly include closure strips to mitigate the formation of shrinkage cracks. Closure strips, also referred to as "pour" strips or shrinkage strips, add to the cost and timelines of a project,[2] and yet the industry lacks detailed guidance regarding their design and need for implementation. Further, it has been hypothesized that closure strips are often used when they are not needed, especially in the upper levels of multi-story buildings.[3,4]

Closure strips are temporary gaps that allow sections of floors on either side to undergo shrinkage independently (Fig. 1). This reduces the maximum-induced shrinkage stresses and mitigates the formation of cracks that can form when shrinkage is restrained by vertical structural elements such as columns, shear walls, and shear cores.[4,5]

Typically, closure strips are filled anywhere from 2 to 12 weeks following the placement of the main slab. This results in a number of challenges:

- Primary shoring and formwork must be kept in place at the location of the closure strip and at all the adjacent bays until the strip is closed and the concrete has reached the desired design strength;
- The presence of shores/reshores in these bays adds to the project timeline by delaying mechanical, electrical, and other contractors; and
- The presence of shoring leads to additional material and labor costs.[3]

While modern technologies such as lockable dowels can eliminate the need for shoring at closure strips, the spacing of the joints, the size of concrete slab that truly requires them, and the time at which the joints can be locked are design questions that remain unanswered.

In short, only limited guidance is available for RC closure strip design. Most available design methods are primarily based on industry experience,[2,5] and only a few include considerations of many building specific characteristics that affect slab shrinkage. A design method that takes these effects into consideration was developed by Kim and Cho.[4] Although this method looks promising, we are aware of no field data validating its predictions. We also know of no published reports on monitoring of closure strips in RC buildings. This article summarizes design approaches that are currently available, presents a case study of closure strip monitoring, and compares the obtained field measurements with predictions from two available design approaches.

Available Design Approaches

For post-tensioned slabs, strip placement requirements are summarized in some detail in the literature.[5,6] Guidelines for expansion joint design are also readily available,[5,7] and it is common for engineers to use these, paired with engineering judgment, for RC closure strip design.

We know of only a few guidelines that apply directly to the design of RC slab closure strips. While Commentary Sections R4.4.5 and R5.3.6 of ACI 318-14[8] mention the use of closure strips as a method to control shrinkage cracking in RC buildings, they do not provide design guidance. Fintel[5] suggests that concrete slabs greater than 60 m in length

Fig. 1: A 1 m (3.28 ft) wide closure strip before concrete placement
(photo courtesy of A. Brault)

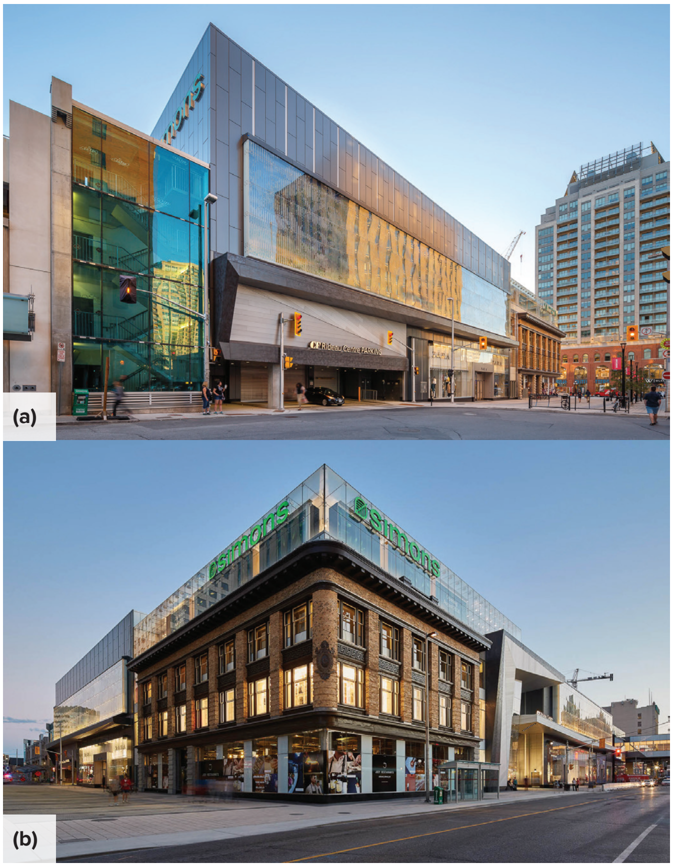

Fig. 2: The Rideau Centre Expansion construction project, Ottawa, ON, Canada, served as field monitoring site *(photos courtesy of doublespace photography)*

require a closure strip (denoted as shrinkage strips in Fintel's handbook). The handbook's recommendations include:

- The spacing between strips should be 30 to 45 m (100 to 150 ft), but should be less if the slab has very stiff supports (no guidance is given on stiffness levels or spacing reductions);
- The strip widths generally should be between 600 and 900 mm (24 and 36 in.) to contain a reinforcement lap splice; and
- The strips should be closed (filled with concrete) 2 to 4 weeks following the slab placement.

Suprenant[2] presents guidelines that state:

- Concrete slabs with a length greater than 76 m should have a closure strip;
- The width of a strip containing lap splices should be between 900 and 1200 mm (36 and 48 in.); and
- The strips should be closed anytime from 2 to 12 weeks following the slab placement.

Suprenant's work provides further guidance on determining when to fill the strip by monitoring both the expansion of the closure strip and temperature.[2] The monitoring technique presented later in this article can potentially aid in this regard.

Kim and Cho present a numerical model for designing closure strips in multi-story RC buildings.[4] The model considers tensile stress relief in the slabs caused by the implementation of closure strips to determine where they are required and when they should be filled. To estimate the shrinkage stresses induced in each concrete floor slab, the model includes shrinkage strain with time, the level of creep relaxation over time, and the degree of restraint that the slab experiences from a building's structural elements.

Shrinkage and creep predictions can be determined using models published by ACI or the Euro-International Concrete Committee (CEB). For the former case, shrinkage strains with time are determined using models from ACI 209.2R-08,[9] in which shrinkage strains are represented as temperature changes (using a coefficient of thermal expansion) that are applied as a load case to the building's structural model. The axial stresses in the concrete slabs are then reduced due to creep relaxation in accordance with the ACI 209.2R-08 approach. If final tensile stresses in the model exceed the tensile strength of the concrete, a closure strip is required on that level. Kim and Cho also provide an equation to determine how long each strip should remain unfilled throughout the building.[4] Further details regarding this process can be found in Reference 4. In this article, the experience-based guidelines described by Suprenant[2] and the numerical model by Kim and Cho[4] will be compared to results from the closure strip monitoring case study.

The Monitoring Site

We monitored closure strips in the Rideau Centre Expansion, which is a large RC building in Ottawa, ON, Canada (Fig. 2). The building consists of seven 80 x 80 m (262 x 262 ft) concrete slabs—two below-ground floor slabs, one ground-level slab, and four elevated slabs (three above-ground floors plus the roof, each with a large oval opening). Each slab had a north-south closure strip and an east-west closure strip, as seen in Fig. 3(a). The locations of shear walls and columns are shown in Fig. 3(b).

The building's closure strips (Fig. 1) were 1 m (3.28 ft) wide and contained a reinforcement lap splice of 0.8 m (2.6 ft) at the monitored locations. The slabs and reinforcement on either side of the strip were physically independent of each other until the strip was closed 28 days later.

Figure 3(a) shows the order of placements for the slabs. The placements on either side of the closure strip were generally separated by 3 to 34 days. Only Zone 5b, in the southern portion of the building, was placed on both sides of the strip simultaneously, so the closure strips were monitored only in that zone (shown in Fig. 3(a)). Monitoring was limited to Levels 2 and 3. An aerial image of the building during construction (Fig. 4) shows Zone 5a placement on Level 3.

Instrumentation

Closure strip displacements were monitored using subminiature differential variable reluctance transducers (DVRTs) coupled with high-speed, wireless nodes (DVRT signal conditioners), all supplied by LORD Microstrain. The

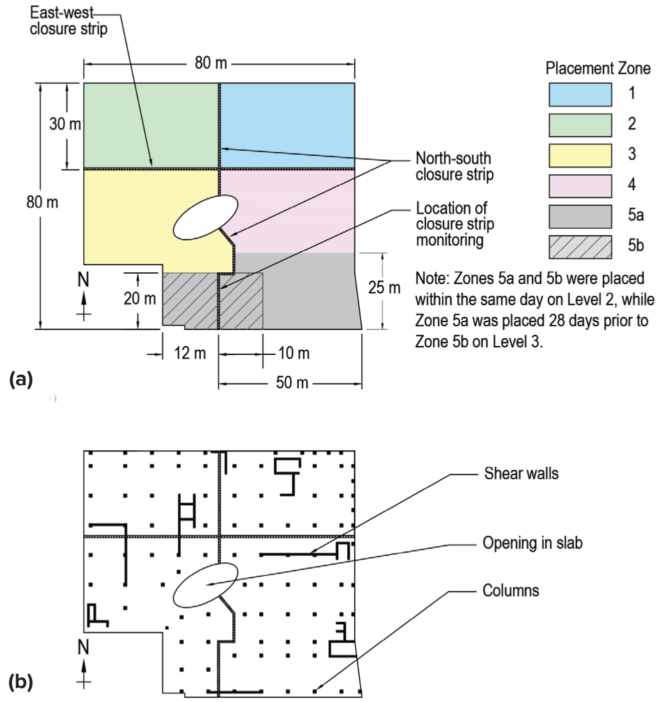

Fig. 3: Plans for the Rideau Centre Expansion project: (a) closure strips and concrete placement zones; and (b) shear walls and column locations

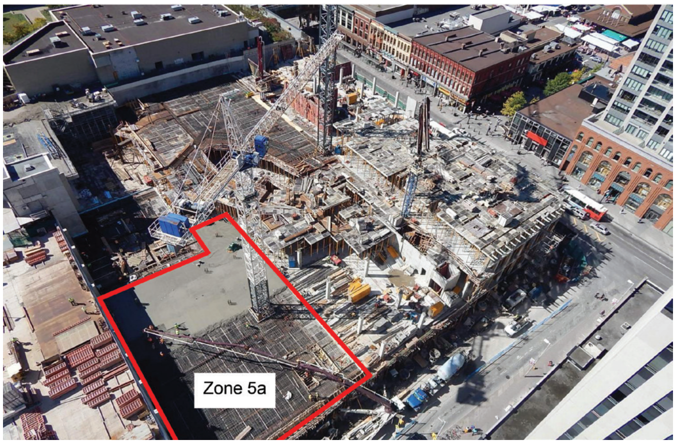

Fig. 4: Zone 5a placement on Level 3 at the Rideau Centre Expansion project *(photo courtesy of PCL Constructors Canada, Inc.)*

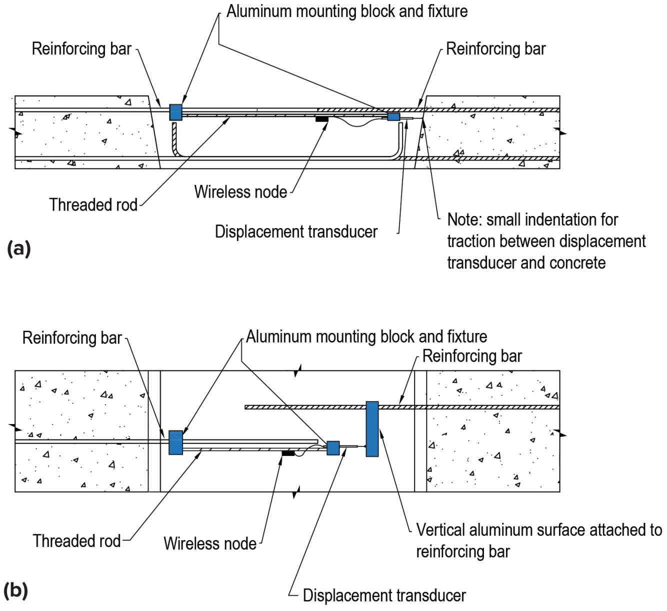

Fig. 5: Closure strip instrumentation using displacement transducer and wireless node: (a) side view of Level 2 setup; and (b) top view of Level 3 setup

wireless nodes measured ambient temperature within the strip while also recording and transmitting displacement and temperature measurements to a data logging computer. Two displacement transducers with wireless nodes were installed for redundancy on each monitored level.

The instrumentation setup for each displacement transducer and wireless node is shown in Fig. 5. A displacement transducer was attached to a reinforcing bar extending into the strip from one side, and the sensor head was positioned in contact with a bar or the concrete on the other side of the strip. This setup enabled the expansion/contraction of the strip itself to be measured.

The setups used on Level 2 were different from those used on Level 3. The sensor heads for the displacement transducers on Level 2 were placed in direct contact with the concrete slab, so the edge forms within the strip had to be removed before transducer installation. As a result, the transducers were not installed until 2 days after placement of the slab. The setup was improved on Level 3 (Fig. 5(b)): each transducer sensor head was installed in contact with a vertical aluminum bracket attached to the reinforcement extending from the opposite side. This enabled the displacement measurements to be taken immediately following the placement of the slab. In all installations, a plywood box was installed over the sensors and tied to the reinforcement in the strip to protect the instrumentation. Also in all installations, displacement and temperature readings were taken every 10 minutes until the closure strip was filled with concrete or the instrumentation was compromised.

Monitoring Results

Closure strip displacement and temperature measurements are shown in Fig. 6 and 7 for Level 2 and 3, respectively. The daily average temperature in Ottawa is also shown.[10] Negative displacement readings indicate expansion of the closure strip and therefore contraction of the slabs on either side of the strip. The thermal expansion of the instrumentation setup itself has been compensated for in the displacement measurements.

Level 2

The instrumentation on Level 2 was installed 2 days following the placement of the main slab; thus, the first 2 days of closure strip behavior were not captured for this level. It is

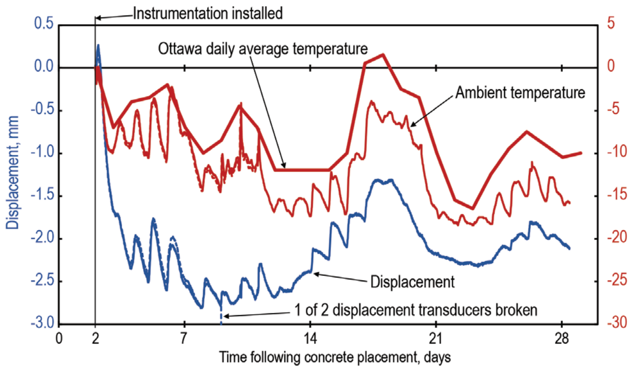

Fig. 6: Closure strip displacement and temperature measurements for Level 2 (Note: 1 mm = 0.04 in.; °F = 1.8 × °C + 32)

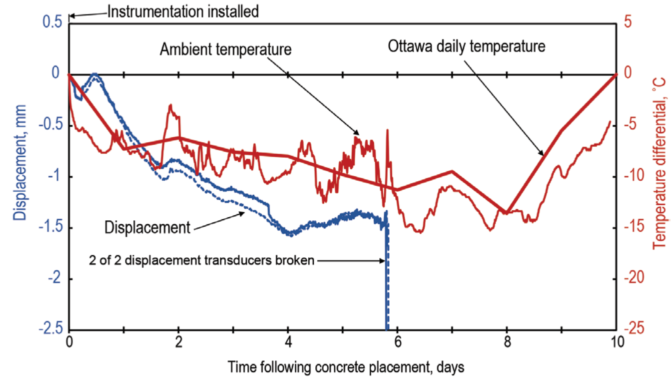

Fig. 7: Closure strip displacement and temperature measurements for Level 3 (Note: 1 mm = 0.04 in.; °F = 1.8 × °C + 32)

also evident in Fig. 6 that one of the two displacement transducers was compromised at 9 days. However, both transducers were in good agreement prior. The other transducer remained in place until the closure strip was filled with concrete at 29 days. Most of the slab shrinkage measured appears to occur before day 9, with a maximum displacement of −2.8 mm (−0.11 in.) on day 8. It can be seen that the displacement readings correspond to temperature changes throughout the monitored period. As the temperature increases, the slabs on either side of the strip expand, and vice versa. After the first week of readings, it appears that the displacement behavior is primarily governed by temperature changes. At 19 days, the ambient temperature approaches its initial value, so the displacement reading of −1.3 mm (−0.05 in.) can be assumed to be primarily caused by slab shrinkage.

The rate of change of displacement is largest at the start of monitoring. This is the expected shrinkage behavior, and it indicates that shrinkage occurred prior to installation of the transducers. However, the observation that the maximum displacement occurred only 8 days after placement is inconsistent with the common assumption that about 40% of the ultimate shrinkage strain occurs within 4 weeks following a placement[2,5,9] It should be noted that Eskildsen et al.[3] also found that floor slab behavior within a large building differed from predictions based on ACI 209.2R.

Level 3

The improved instrumentation setup used on Level 3 (Fig. 5(b)) captured closure strip behavior immediately following the concrete placement; however, both displacement transducers were compromised on day 6 (Fig. 7). As indicated in Fig. 7, displacements appear to increase before they start to decrease, indicating that the slab initially expanded. This was probably the result of thermal expansion of the concrete and reinforcement associated with heat of hydration, and the observation is in agreement with a previous field study that showed that concrete reached its peak temperature within the first day following placement.[11]

After shrinkage commences on Level 3 (at approximately 0.5 days), the rate of shrinkage slowly decreases during the monitored period. The displacement magnitudes are lower than were experienced on Level 2 at similar times. This is unexpected because vertical elements typically provide less restraint and thus allow more movement on upper levels.[2,4] The lower displacement magnitudes on Level 3 may be explained by the fact that Zone 5b was placed 28 days following Zone 5a placement on Level 3 (Fig. 3(a)), reducing the amount of concrete undergoing early shrinkage during the monitoring period on Level 3 compared to Level 2.

Also, the displacement readings do not appear to correspond to temperature changes as clearly on Level 3 as seen on Level 2. While the temperature readings on Level 2 indicate significant and clear diurnal temperature fluctuations (typical changes of 7°C [13°F]), the temperature readings on Level 3 do not exhibit clear diurnal behavior. However, when there are large daily temperature changes on Level 3 (for instance, at 2 days and just before 4 days) the displacement readings do respond, though to a lesser extent than seen on Level 2.

Difficulties of closure strip monitoring

Despite having protective covers, three of the four installed transducers were damaged during the monitoring period (refer to Fig. 6 and 7). Damage may have occurred because of a high level of construction traffic near the open closure strips, including installation of shoring (Fig. 8). Also, the protective covers may have been temporarily removed, as indicated by noisy ambient temperature readings between 9 and 11 days after placement of Level 2 (Fig. 6)—such readings would be expected to occur if the wireless node was exposed to rapid temperature fluctuations caused by intermittent sunlight and shade. Finally, the instrumentation on Level 3 was exposed to the elements before placement as well as construction activity during concrete placement. These observations indicate that future studies should include more robust instrumentation, better protection systems, and better communication between researchers and field personnel.

Fig. 8: Shoring for the next floor built directly above an open closure strip *(photo courtesy of A. Brault)*

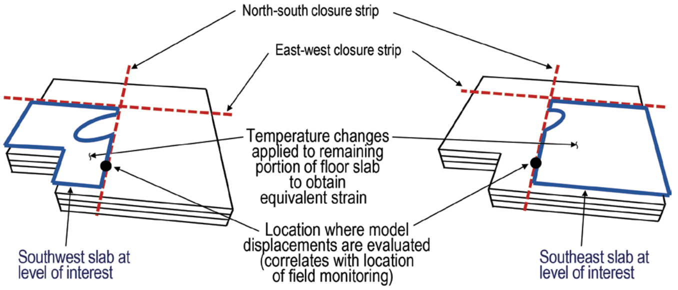

Fig. 9: Locations at which model displacements were evaluated (and field monitored) for southwest and southeast slab

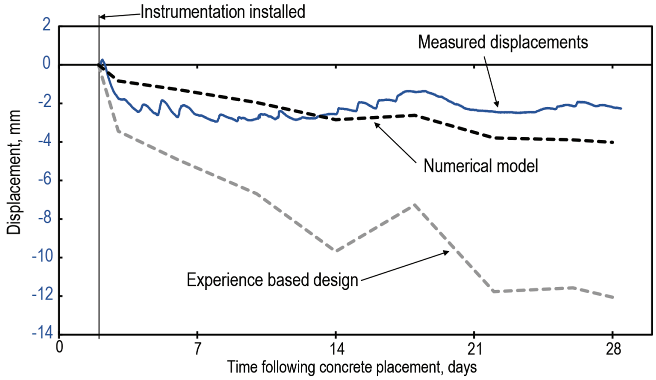

Fig. 10: Comparison of closure strip measured displacements for Level 2 with experience-based design and numerical model predictions

Monitoring Results Compared to Design Approaches

In this section, the monitoring results are compared to predictions from an experience-based design approach[2] and from a numerical model.[4] Predictions from each approach were converted into expected closure strip displacements.

The approach described by Suprenant[2] is the only experience-based method that is used for comparison, as it is the only one that provides predictions of closure strip displacements. Using this approach, closure strip displacements were predicted at the monitored location on Level 2. Inputs were slab lengths of 12 m (39.4 ft) and 50 m (164 ft) on the left and right of the closure strip, respectively (Fig. 3), and an assumed thermal coefficient of expansion for RC of 10×10^{-6}/°C (5.5×10^{-6}/°F).[12]

The numerical model presented by Kim and Cho[4] accounts for restraint effects from building specific components. General displacements were predicted using a commercial finite element analysis (FEA) program, ETABS,[13] which was used in the design of the monitored building. To convert predictions from the numerical model into displacements that would occur within the strip at any given time, portions of the building were removed from the FEA model to represent earlier construction stages. All floors above the level of interest were removed, and all portions of floor slab north of the east-west closure strip were removed. Furthermore, because the movement of the north-south closure strip was measured, the remaining portion of slab on the level of interest was divided along the north-south closure strip into two portions (Fig. 9).

As per the method presented by Kim and Cho, temperature changes (in conjunction with the measured ambient temperatures) were input to provide equivalent strains associated with shrinkage at specific times following the placement of the slab.[4] Displacement values from the FEA model at the monitored location were then recorded. Because the shrinkage for each placement commenced at a different time, different equivalent temperatures were applied to specific areas in the model to represent the overall movement at the closure strip.

Level 2 comparison

In Fig. 10, the Level 2 closure strip displacements are compared to predictions from both the experience-based design guidelines[2] and the numerical model[4] at 2, 3, 6, 10, 14, 18, 22, 26, and 28 days following the concrete placement. The predicted displacements from the experience-based approach are up to 600% larger than the measured displacement values. This overestimation makes sense, as the experience-based design guidelines do not account for restraint provided by building specific vertical elements. The numerical model predictions correlate more accurately with the measured closure strip displacements. However, there are still significant differences between the two, especially toward the end of the monitoring period when the measured displacement magnitudes are consistently about 50% lower than the model's predictions.

When one considers the large errors that are expected with creep and shrinkage models,[9] and the effects that varying temperature gradients throughout the structure would have on strip behavior (it was not feasible to monitor this effect in this study), the predictions are remarkably close. If shrinkage were unrestrained, the movement within the closure strip at this location is estimated to be −14.4 mm (−0.57 in.) at day 29 (determined using the method described in ACI 209.2R-08 and considering the effects of temperature). The measured displacement was only −2.3 mm (−0.09 in.) at day 29, however, suggesting that much of the shrinkage movement was restrained. The numerical model indicates the displacement is about −4 mm (−0.16 in.) at day 29, indicating that it captures the slab restraint caused by the building's vertical elements (Fig. 3(b)) quite well.

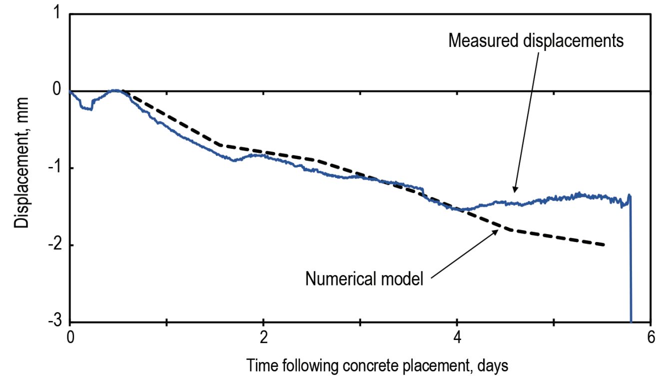

Fig. 11: Comparison of closure strip measured displacements for Level 3 with numerical model predictions

Level 3 comparison

In Fig. 11, Level 3 closure strip displacements are compared to predictions from the numerical model at 0.5, 1.5, 2.5, 3.5, 4.5, and 5.5 days following the concrete placement. The predictions begin 0.5 days following the placement, as this is when the measured displacements suggest that shrinkage commenced. The experience-based design approach was not included because this approach does not provide specific guidance on predicting displacements when slab placements on each side of the closure strip are separated by several days (Zone 5a and 5b in Fig. 3 on Level 3).

The numerical model predictions correlate well with the measured displacements (the difference is less than 20% for most of the monitored period)—the correlation is better than typically expected when considering the high variability of concrete shrinkage and creep.[9] However, the monitoring period was much shorter for Level 3, making it tough to conclude whether the discrepancies would have increased at later times.

Conclusions

Current design approaches for closure strips are limited and are mostly based upon industry experience, with little consideration of building specific parameters. A numerical design model described in Reference 4 does, however, provide detailed guidelines for consideration of building specific features.

Results from a monitoring program during construction of a large RC building in Ottawa (the Rideau Centre Expansion) indicate that an available experience-based method[2] overestimates closure strip movement significantly. However, the results also show that the indicated numerical model shows promise for predicting closure strip behavior. This suggests that building specific elements should be considered (and not just the length of the slab) when estimating RC slab shortening, and ultimately when designing closure strips in RC buildings.

The closure strips in the monitored building were designed using an experience-based method. The strips on Level 2 and 3 were left open for approximately 28 days, and no visible or significant shrinkage cracks were found on either level. While this indicates that the closure strip designs on these levels were successful, it's possible that the same outcome would have occurred if the strips had been filled sooner. Considering that closure strips can have significant cost and scheduling implications on a project, future work should aim to refine the available design approaches for determining the need, spacing, and open time for closure strips.

Real time measurements of closure strip movement could greatly help design engineers with making an informed decision on when to fill the strip. The monitoring technique used in this study can be used to collect real-time data regarding the behavior of closure strips during the construction of a building (as seen in Fig. 6 and 7). While this case study showed that the developed monitoring method is viable, we recommend improvements to the robustness of the setup for future use.

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