Characterizing the Movement of Thin Concrete Overlay Panels Subject to Truck Loads

Thomas R. Burnham[1], P.E., Santiago B. Huerta[2], Manik Barman[3], Ph.D.

Abstract

The construction of thin concrete overlays as a pavement preservation option for both asphalt and concrete pavements is gaining popularity in the U.S. To reduce costs, as well as mitigate tendencies toward curling and warping, most thin bonded and unbonded concrete overlays are constructed with either smaller panels, or shorter length panels with undoweled transverse joints. Similar to undoweled concrete pavements on grade, thin undoweled concrete overlay projects have developed faulting of the transverse joints, sometimes at an early age. Toward the efforts to understand the mechanisms causing joint faulting in thin concrete overlays, this study sought to characterize the basic surface movements of thin overlay panels, including bending, translation, and joint load transfer, when subject to heavy vehicle loads. This study utilized digital image correlation (DIC) equipment to measure the dynamic displacement along the edge of thin bonded and unbonded concrete overlay panels loaded by heavy trucks. Testing showed that as the heavy front axle first lands on a thin overlay panel, localized bending is the predominant movement, regardless of panel length. For bonded concrete overlays on asphalt, most transverse joints did not show strong load transfer behavior, even when fiber-reinforced concrete was used. In addition to characterization of the panel surface movements, general correlation to observed joint faulting and panel distress was described. The findings from this study should serve useful to the continuing determination of the mechanisms causing joint faulting in thin concrete overlays.

Background

The construction of thin concrete overlays as a pavement preservation option for both asphalt and concrete pavements is gaining popularity in the U.S. In fact in some states, the number of concrete overlay construction projects often now exceeds that of new full-depth concrete pavement projects. The implementation of thin concrete overlay technology has developed over many years, and has resulted in a number of unique design characteristics compared to standard concrete pavements. Due to the inherent tendency for thinner concrete pavements to warp and curl due to environmental effects, thin concrete overlays are often designed with smaller panel sizes. In addition, due to physical limitations and the desire to reduce costs, thin concrete overlays are often constructed without dowel bars spanning the transverse joints. Interestingly, as

with undoweled concrete panels on grade subjected to heavy truck loads, many thin concrete overlays are developing early transverse joint faulting. Since joint faulting has a direct bearing

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on ride quality for users, there is much interest in determining the causes and potential solutions to deal with this issue.

Toward the efforts to determine the causes of transverse joint faulting in thin concrete overlays, it is important to characterize and understand the fundamental movements of the various components of thin concrete overlays. Thin concrete overlay systems can be composed of various pavement layers, including concrete over old asphalt (bonded concrete overlay of asphalt: BCOA or whitetopping), or concrete over old concrete with an interlayer (unbonded concrete overlay: UBOL). For BCOA overlays, layer bonding plays a critical role in reducing stresses within the thin concrete overlay, For UBOL overlays, the interlayer is made of a material, typically asphalt or geotextile fabric, designed to separate the movements of the individual concrete layers. Therefore, the various panel geometries and bonding conditions between layers in concrete overlay systems result in complex and changing movements that vary with traffic loading, environmental conditions and age.

The objective of this study was to characterize the surface movement of various thin concrete overlay sections when they were subject to heavy axle loads. In addition to loads applied by a heavy truck, loads were applied by a Falling Weight Deflectometer to measure load transfer behavior across transverse joints. The movement of the overlay panels subject to moving truck loads was primarily measured by innovative digital image correlation (DIC) equipment. Due to variable designs, environmental conditions and overlay ages at the time of testing, focus was placed more on general characterizing of basic panel surface movements, rather than detailed quantification of the measured displacements. For the thin concrete overlay test sections at the MnROAD test facility considered in this study, localized transverse joint displacements measured with the DIC equipment were compared to historical Falling Weight Deflectometer data.

Measuring Surface Movement in Concrete Overlays

Three primary movements of thin concrete overlays were the focus of this study; panel bending, panel translation (vertical or rotation), and load transfer across transverse joints. Figure 1 depicts the definitions of these movements as considered in this study. The idea for measuring these fundamental panel movements is to ascertain whether they could lead to mechanisms causing transverse joint faulting.

While it is possible to visually observe the surface of concrete overlays moving under heavy axle loads, the deflections are quite small. Therefore the methods and equipment needed to measure such small movements must be precise and repeatable. Falling Weight Deflectometer (FWD) devices remain a useful tool for quantifying such measurements in concrete pavement layers, including concrete overlays (Tutumluer and Sarker 2015, Gaspard and Zhang 2015, King and Roesler 2014, Li and Wen 2011). They are particularly suited to measuring joint load transfer efficiency, and as such, FWD data was utilized during this study. Another piece of equipment used in this study, developed by researchers at the MnROAD facility, consisted of a series of LVDT sensors suspended by long support tubes positioned over the edge of contiguous concrete panels. By simultaneously collecting data from the sensors as a vehicle passes, the deflection

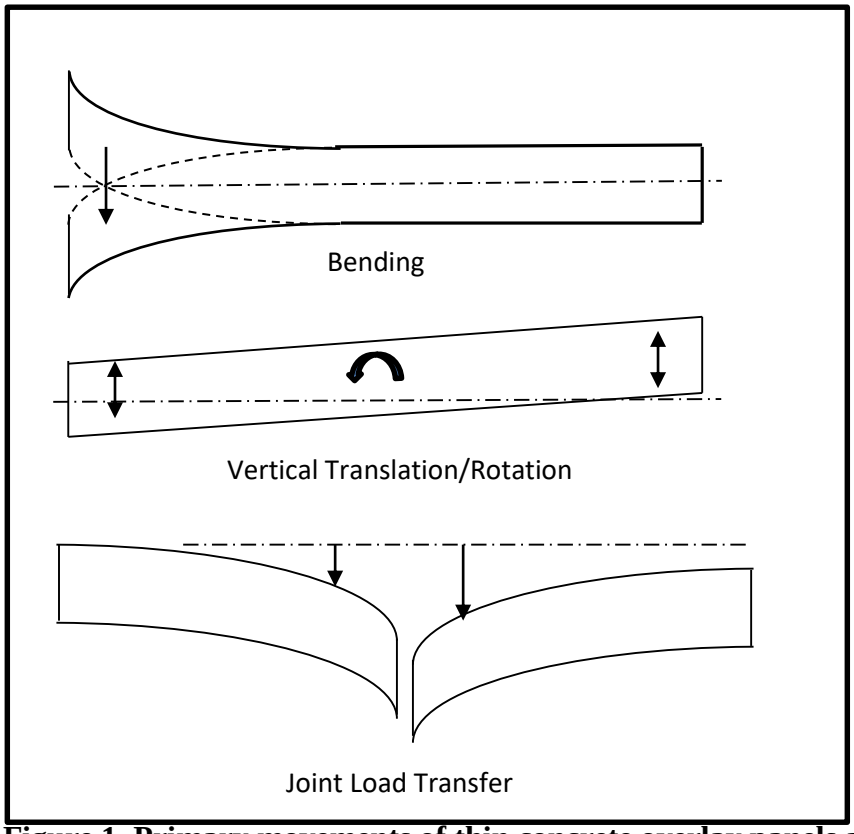


Figure 1. Primary movements of thin concrete overlay panels as considered in study.

along the edge of the panels could be measured. While this system was initially effective, users were concerned about the effect of wind gusts and "sticky" LVDT sensors, thus reliability became an issue.

A more innovative approach to the measurement of very small movements is through the use of digital image correlation (DIC) equipment. The application of this type of equipment is growing rapidly in the civil engineering field (Bell et al. 2014, Buttlar et al. 2014, Chehab et al. 2007, Dutton et al. 2013, Fayyad and Lees 2014, Gencturk et al. 2014, Kuntz et al. 2006)., and it seemed very suitable for the measurements sought in this study. In fact, the testing configuration was similar to, and could be directly compared to the LVDT device described previously. DIC equipment consists of one or more high resolution cameras, connected to a high speed processor. These systems have the capability to track the rapid movement of pixels to a resolution of less than 0.01 mm. The major advantages of these systems include the capability of 2 or 3 dimensional non-contact measurements, and the ability to post-process additional movement data within the captured views. The challenges of using such equipment for pavement testing include the need for non-obstructed sight to a target region, stable camera tripods, and the need to compensate for changing ambient light conditions.

Selected Projects

The projects selected for this study included six thin bonded concrete overlays on asphalt (BCOA) and five thin unbonded concrete overlays on concrete (UBOL). Table 1 lists the Location and basic description of the sections tested. Seven of the sections considered were test

Table 1. Concrete overlay sections included in study.

Test Location	Route Number	Age (yrs)	Overlay Description
MnROAD	Cell 160	2	127 mm BCOA, 1.8 x 1.8 m panels, fiber-reinforced concrete
Hutchinson, MN	CSAH 7	6	127 mm BCOA, 1.8 (var)L x 1.8W m panels
MnROAD	Cell 96	18	152 mm BCOA, 1.5L x 1.8W m panels, fiber-reinforced concrete
MnROAD	Cell 414	7	152 mm BCOA, 1.8 x 1.8 m panels
Nowthen, MN	CSAH 22	4	152 mm BCOA, 1.8 x 1.8 m panels
Rochester, MN	CSAH 22	4	165 mm, BCOA, 3.6 x 3.6 m panels
MnROAD	Cell 140	2	76 mm UBOL, 1.8 x 1.8 m panels, thin fabric interlayer, fiber-reinforced concrete
MnROAD	Cell 240	2	76 mm UBOL, 1.8 x 1.8 m panels, standard fabric interlayer, fiber-reinforced concrete
MnROAD	Cell 505	4	127 mm UBOL, 1.8 x 1.8 m panels, standard fabric interlayer
Twig, MN	TH 53	6	127 mm UBOL, 3.6 x 3.6 m panels, asphalt interlayer
MnROAD	Cell 405	7	127 mm UBOL, 4.6L x 4.3W m panels, permeable asphalt interlayer

Unit conversions: 25.4 mm = 1 inch, 1 m = 3.28 ft

cells located at the MnROAD facility in Albertville, MN (MnROAD 2015).

Testing scheme

The testing scheme for this study consisted of collecting dynamic surface displacement measurements along the lane/shoulder edge of concrete overlay panels using DIC equipment. This data was supplemented with historical transverse joint load transfer measurements conducted in the outside wheel path using a Falling Weight Deflectometer.

For the DIC measurements, an Imetrum Video Gauge™ system was used (Imetrum Limited, 2015). This system consisted of four high resolution cameras and a processing unit. Special paper targets were secured to small foam blocks temporarily bonded to the pavement surface along the edge of the tested panels. Figure 2 shows the DIC equipment and targets on several test panels. To capture the necessary resolution of displacements for high speed vehicles, data was collected at a sample rate of 1000 Hz.

Figure 3 shows the target positions and loading locations for the DIC and FWD testing. For projects with 1.8 m (6 ft) long panels, a group of the four contiguous panels were tested. In each panel, seven foam targets were placed along the lane/shoulder edge. In cases where the average panel lengths were less than 1.8 m (6ft), targets in positions 5 and 7 were not installed. Two additional targets were positioned on adjacent panels at each end of the four panel test section (i.e. target numbers 1, 2, 10, 11). Similarly, for projects with larger panels (3.6+ m, 12+ feet), each of the 2 contiguous panels tested had 7 targets, plus the additional targets on the adjacent panels.

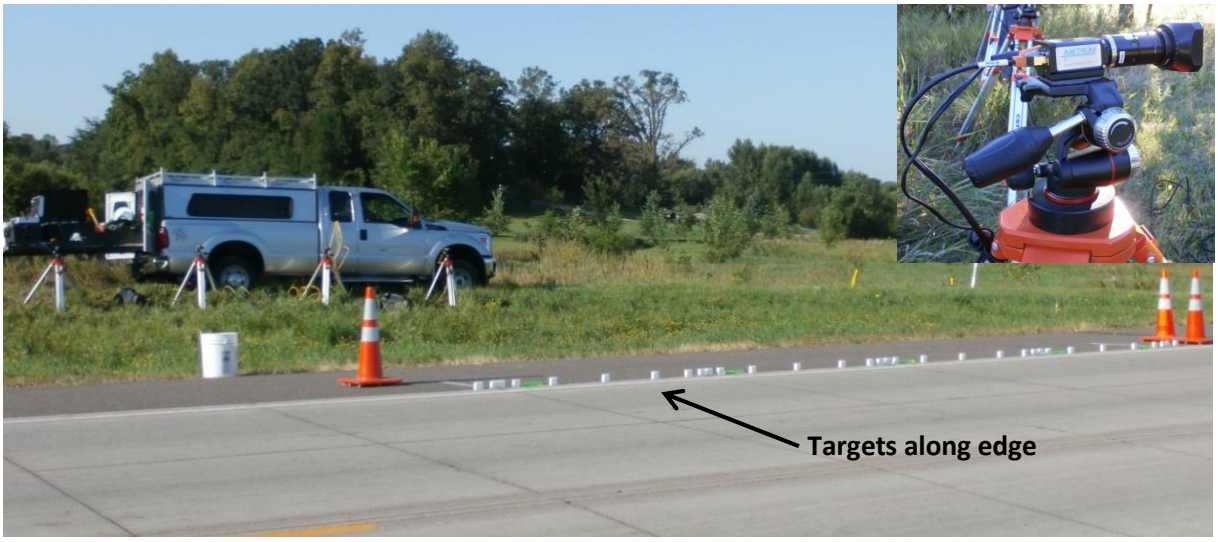


Figure 2. Typical setup during overlay movement testing. DIC camera (inset).

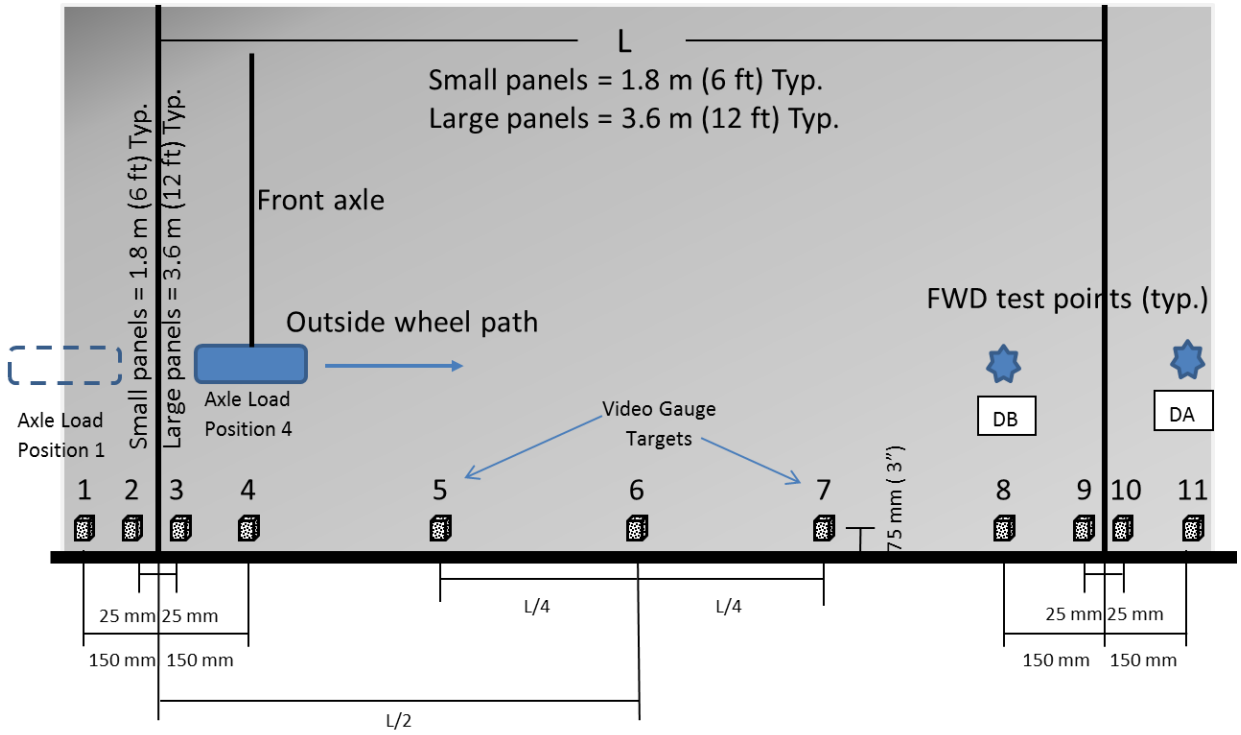


Figure 3. Plan view of target and loading configurations for DIC and FWD testing in this study.

For projects with 3.6 m (12 feet) wide lanes, the targets were placed 76 mm (3 inches) in from each panel's longitudinal edge (near shoulder). On projects with widened edge panels, primary targets were positioned just outside the painted fogline, with additional targets mounted near the lane/shoulder edge. Data from these additional targets was not included in this paper.

Except for the Rochester CSAH 22 project, which used live truck traffic, vehicle loading of all other overlay panels consisted of a fully loaded (355 kN, 80,000 lb) 5-axle tractor trailer truck

from the MnROAD facility. For this paper, only the displacements caused by the 53.4 kN (12 kip) front axle traveling at a speed of 40mph were analyzed. Additional data, collected for other trucks and passenger vehicles passing through the test sites during testing, will be analyzed in the future. For the MnROAD concrete overlay test sections, the joint load transfer data collected from the DIC system was compared to historical transverse joint load transfer measurements collected from a Dynatest Model 8000 Falling Weight Deflectometer (FWD) applying a 26.7 kN (6000 lb) load.

DIC Testing Results

The primary objective of this study was to characterize the basic surface movements of thin concrete overlay panels when subject to heavy truck loads. Due to the logistics of measuring surface movements as vehicles passed by, only the displacements along the lane/shoulder edge of the test panels could be determined. As mentioned previously, to provide some insight into the potential shortfalls of this approach, transverse joint displacements gathered along the edge of the panels (with DIC) were compared to historical FWD joint load transfer data gathered in outside wheel path locations.

The analysis for this study involved comparisons of displacement between various target locations to determine whether the overlay panels were bending or rigidly translating under dynamic axle loads. Again, due to the limitations of target location, only movement along the panel edge could be characterized. It is recognized that the surface movement in other interior locations of the panels could be quite different, due to the inherent two-dimensional bending of concrete panels under load. Once procedures are developed for measuring the displacements of the interior portion of panels using DIC equipment, valuable information will become available to validate the approach taken in this study.

The basic data processing procedure to determine panel bending, vertical translation and/or rotation, involved the following steps. First, the baseline displacement data (prior to axle loading) for the Target 4 location (150 mm into panel, see Figure 3) was de-noised using a 100 point running average procedure. Then the displacement value at the time the front axle passed Target 4 (Load Position 4) was determined by subtracting its peak value from the previously determined (unloaded) baseline value. Load Position 4 was chosen for analysis, as this was thought to be the loading situation that leads most to mechanisms causing transverse joint faulting. For the same elapsed time used for Target 4, the momentary change in displacement values of Targets 5, 6, and 8 were also determined. Figure 4 shows one example of the peak selection process. Note that direct comparison of displacement magnitudes at individual targets for different vehicle passes could not be made, since wheel load wander was not measured or accounted for during the analysis. It is equally important to remember that the displacements are relative to a baseline displacement reading, and do not portray the actual shape of the panel at any point. To establish the actual profile shape of the panels during a vehicle pass, the built-in shape of the panels (at rest) would need to be determined. Future research efforts will be directed toward such determination.

Figure 5 shows one example of the displacements of one panel with the MnROAD truck front axle at Position 4. Again, no physical relation to actual panel shape is reflected in the plot. From the plot, it appears that the significant difference in displacement between Targets 4 and 5 (and

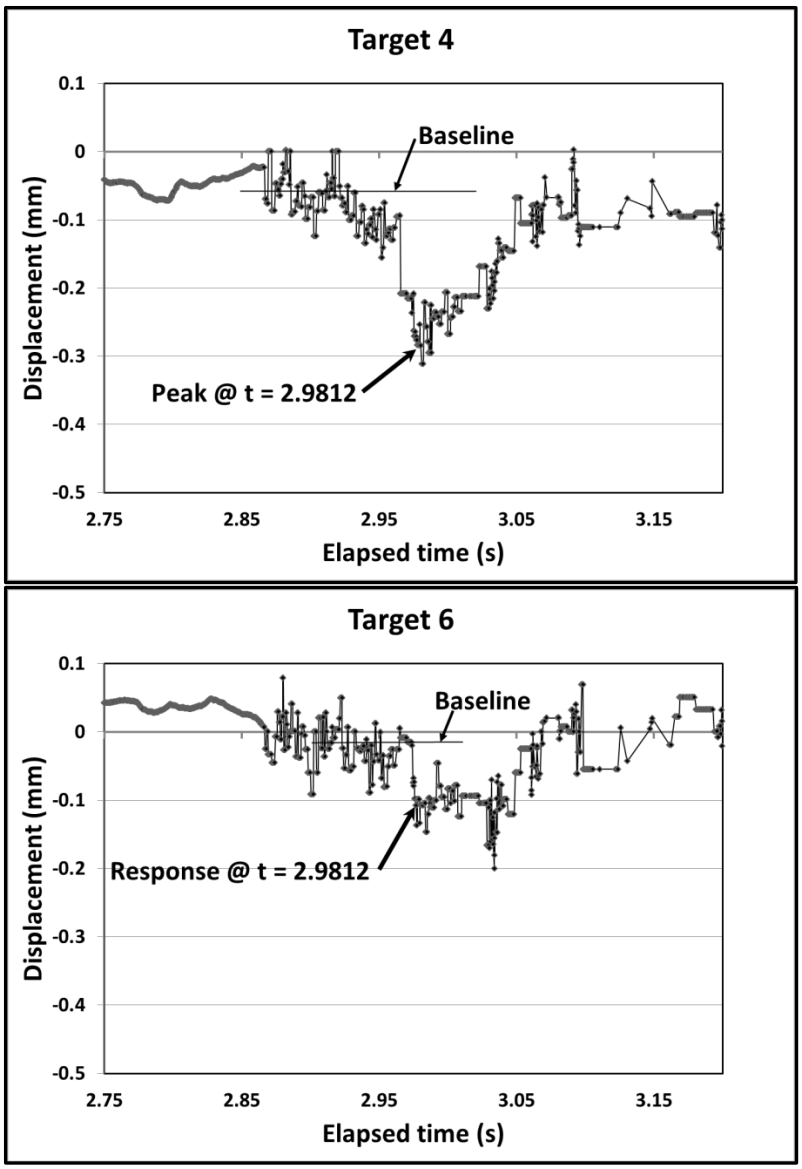


Figure 4. Measured displacements at Targets 4 and 6 with the front axle at Position 4.

Targets 4 and 6) signifies bending near the approach end of the panel, while Target 8 shows a small downward translation near the leave end of the panel.

Figure 6 shows plots of the typical responses of the small panel BCOA (whitetopping) projects considered in this study. Cell 96, shown in Figure 6 a), shows the typical variation in response between four different (contiguous) panels. Except for Target 8 in Panel 1, all displacements in Cell 96 demonstrate a similar pattern in the downward direction. While the accuracy of DIC signal response and the corresponding peak displacement calculations was not specifically determined in this study, the typical signal noise had a range of ±0.05 mm. Therefore, slightly upward displacement in the plots reflect virtually no movement when the tire load is at Position 4. The focus of this study was on general characterization of movement, and not the specific quantification of displacements. Nevertheless, it is interesting that the general range in the

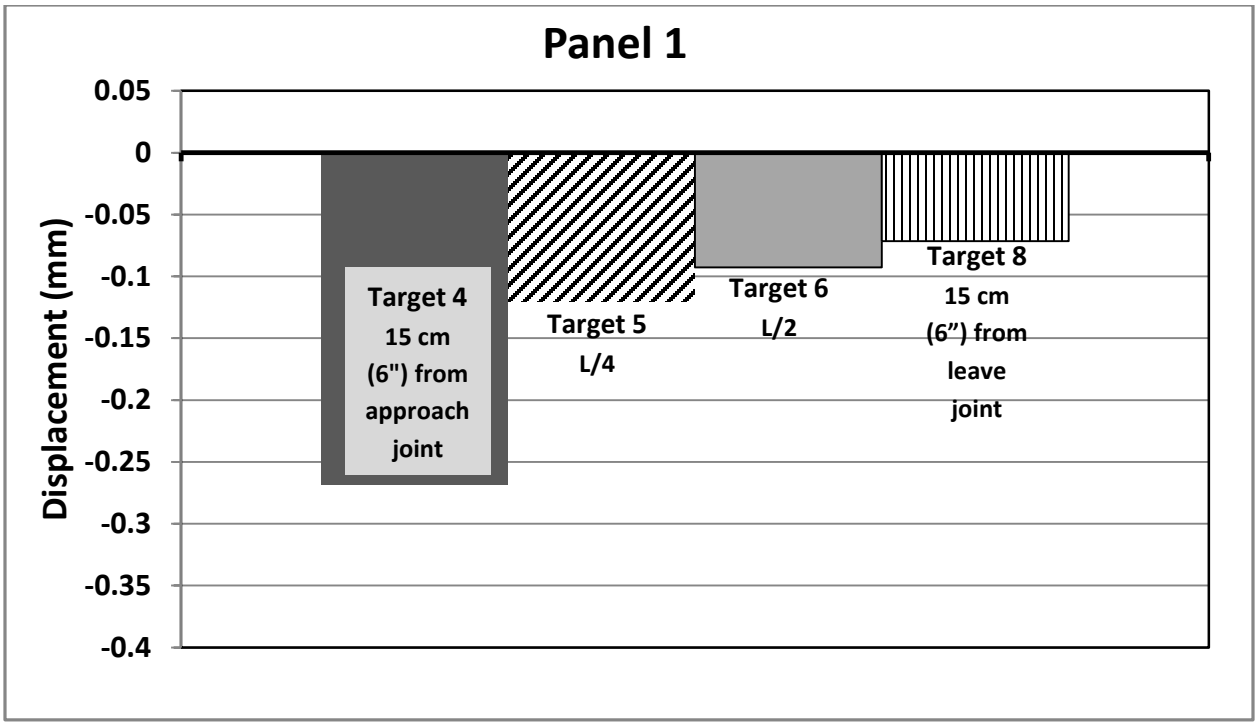
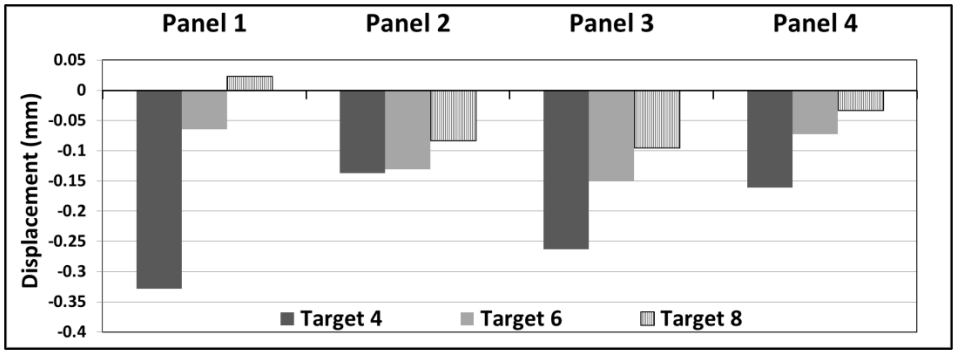


Figure 5. Displacements at various DIC targets from MnROAD truck front axle load at Position 4.

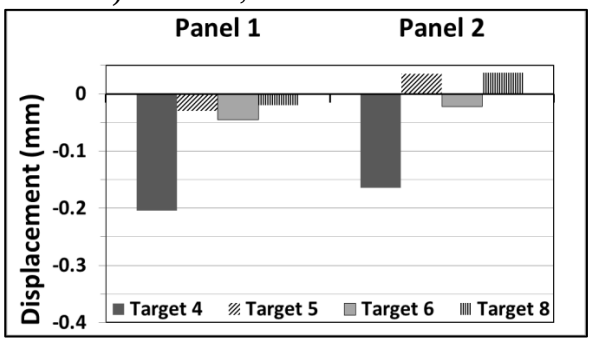
magnitude of measured displacements is similar to that found in a study of thicker concrete panels on grade (Minkarah et al. 1984).

For Cell 414, shown in Figure 6 b), it appears that the only substantial movement in the panel for Load Position 4 occurs directly under the load. This indicates that there is bending near the approach end of the panels. This is similarly reflected in the response of panels on CSAH 7 and CR 22. The difference in responses in Cell 96, which experiences more downward translation of Targets 6 and 8, is likely a result of the fact that this section is over 18 years old, and has been subject to over 16 million ESALs of interstate traffic in its lifetime. Due to the widespread deterioration of the joints in Cell 96, the joint sealing is no longer effective, allowing water to reach and degrade the underlying asphalt layer. Surprisingly, there are no cracked panels to date in this section, perhaps due to its 150 mm (6 inch) thickness, small panel size, and the use of a fiber reinforced concrete mix. Panel 1 of Cell 160, also a fiber–reinforced concrete overlay, exhibits similar behavior to Cell 96, but the other panels reflect behavior suggesting that much of the middle and leave portions of the panels are still bonded to the underlying asphalt, thus restraining motion. This again reflects the variability in the behavior of individual panels, which can be strongly influenced by whether particular transverse joints fully deploy during their service.

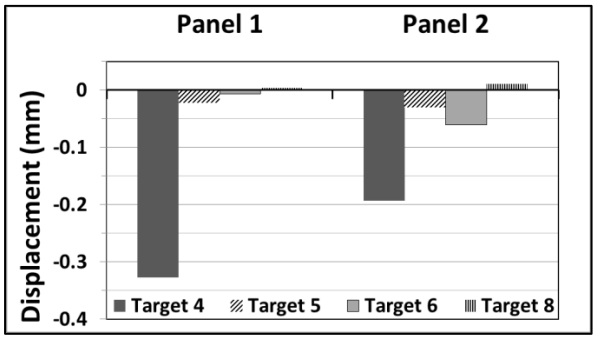
Figure 7 shows the response of a large panel BCOA (whitetopping) project included in this study. Note that for this project location, the loading came from large trucks in the live traffic stream, rather than the MnROAD truck. Therefore, axle loads were unknown, but the trucks appeared to be fully loaded. The behavior of the larger panels closely resembles that of many of the smaller panel BCOA projects previously discussed, in that the landing of the wheel load onto



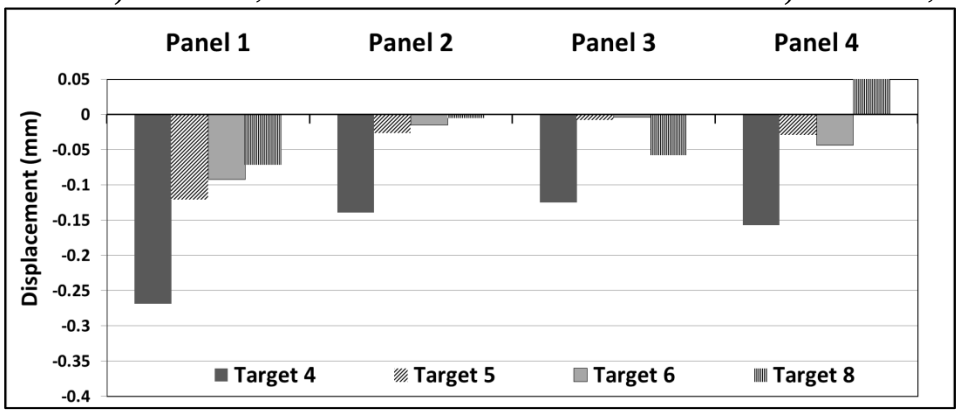
a) Cell 96, Run 1



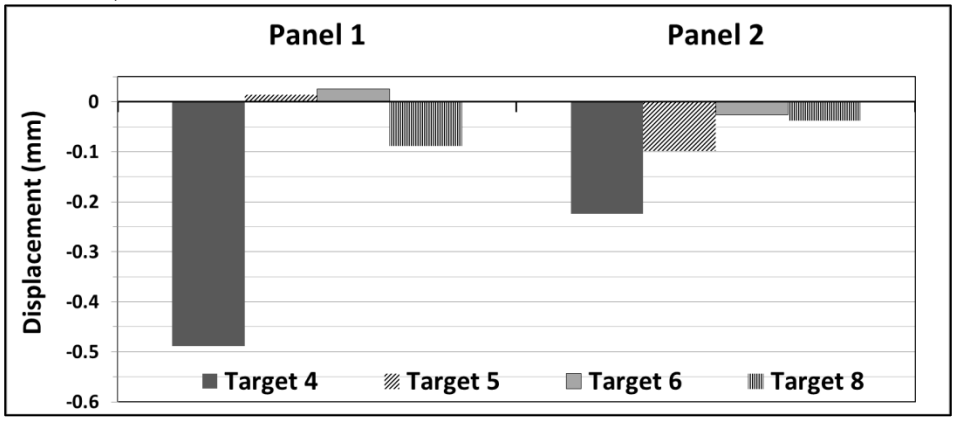
b) Cell 414, Run 7



c) CSAH 7, Run 1



d) Cell 160, Run 2



e) CR 22 Nowthen, Run 6 (Note: vertical scale increased to 0.6 mm)

Figure 6. Response of small panel BCOA (whitetopping) edge locations with front axle at Position 4 within each panel.

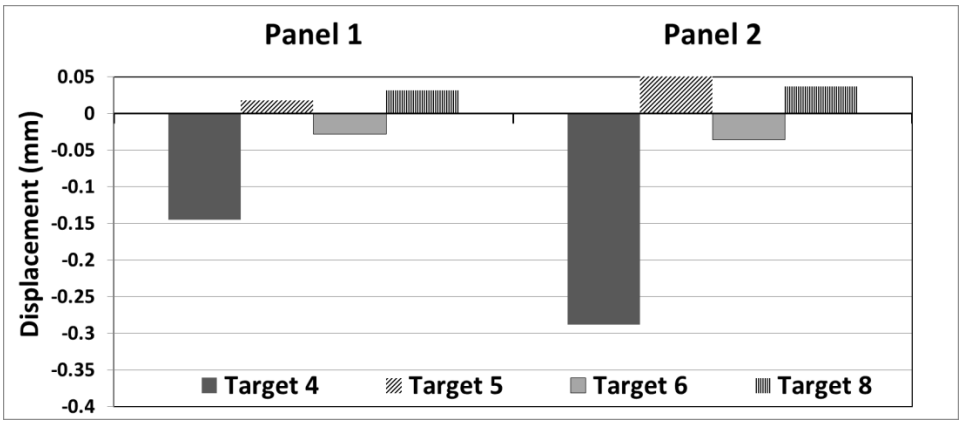


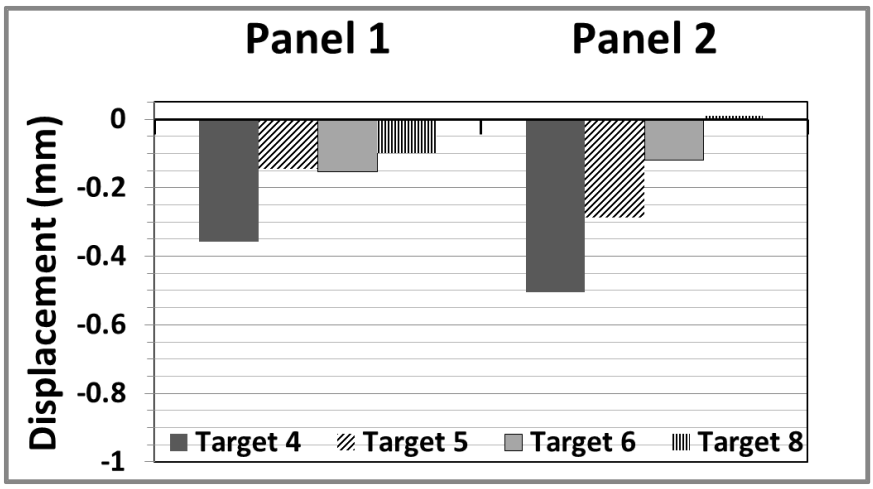
Figure 7. Response of large panel BCOA (whitetopping) edge locations with front axle at Position 4 within each panel. Project: CSAH 22 Rochester, 3.6 x 3.6 m (12 x 12 ft) panels, live traffic (load unknown).

the panel results in significant panel bending near the transverse joint. The remaining portions of the panels in the CSAH 22 Rochester project appear to minimally influenced by the initial loading of the panel. Of course as an axle load travels along the panel, other locations within the panel could experience other critical displacements and stresses. It should be noted that this project has developed significant transverse joint faulting after only 4 years of service.

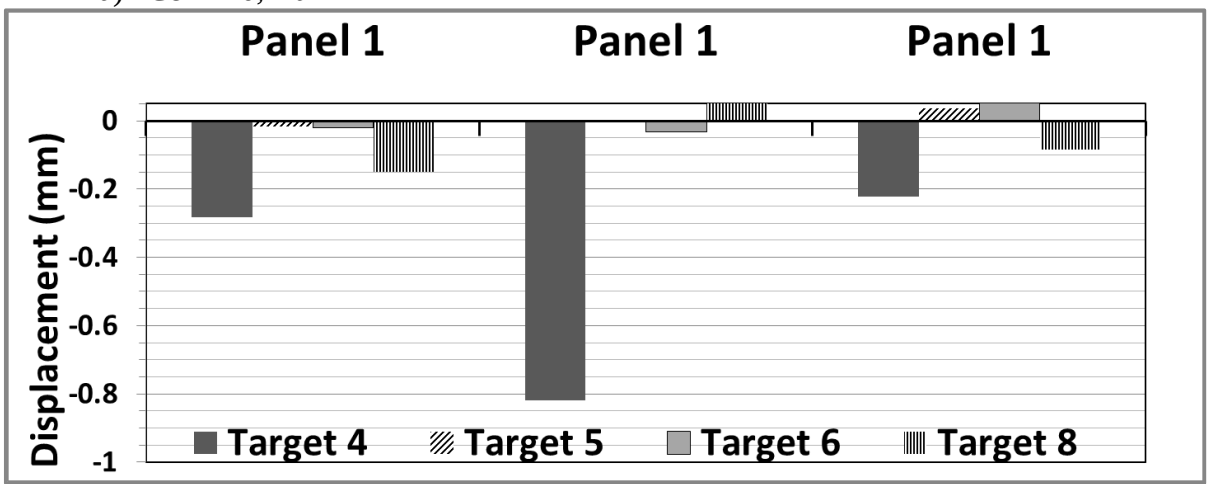
Figure 8 shows the response of the small panel unbonded concrete overlay (UBOL) projects considered in this study. MnROAD Cell 140 is an ultrathin 75 mm (3 inch) thick fiber-reinforced concrete overlay constructed on a one-half U.S. standard weight (270 g/m^2, 8 oz/yd^2) non-woven geotextile fabric interlayer. Cell 240 has the same concrete overlay thickness, but was placed on a more standard weight interlayer fabric (500 g/m^2, 15 oz/yd^2). From Figure 8, it appears there is a distinct difference in the behavior of the two overlay designs as the load enters a panel. Cell 140, with the thinner fabric, experiences more displacement in Target locations 5, 6 and 8, portraying a tipping motion of the entire panel. Cell 240, with the standard weight fabric, surprisingly deflects less than Cell 140 panels near Target 4, except in cases like Panel 1 Run 3, in Figure 8 b. In that case, the panel appears to bend near the loaded end, with a displacement far exceeding that of all panels measured in this study. As will be shown later, there is a fundamental difference in joint load transfer behavior between these two designs. This behavior is could be due to the differing amounts of compression of the fabric interlayers, combined with the contribution of the fibers spanning across transverse joints. The thicker Cell 505, having no fibers in the concrete mix and lying on a standard weight fabric interlayer, demonstrated the least overall panel movements of the UBOL projects tested, with only minor bending near Target 4.

Figure 9 shows the response of the large panel unbonded concrete overlay (UBOL) projects considered in this study. Cell 405 was constructed with a permeable asphalt interlayer and experiences both bending and panel tip-in. Many of the neighboring test panels have multiple cracking distresses, particularly in the region near the approach end of the panels. This might explain why there is such different behavior among panels.

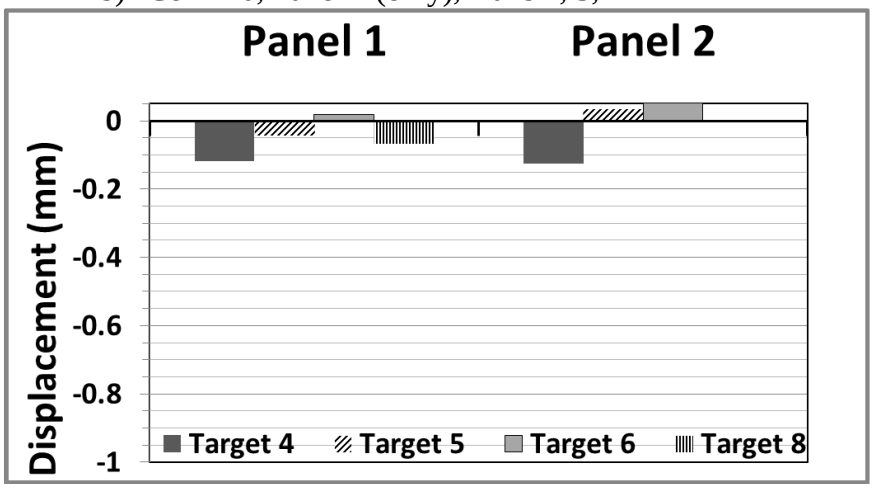
TH53 was constructed on a standard asphalt interlayer and demonstrated the highest variability in responses of the UBOL sections measured. Figure 9 b) shows there is definite bending near



a) Cell 140, Run 1

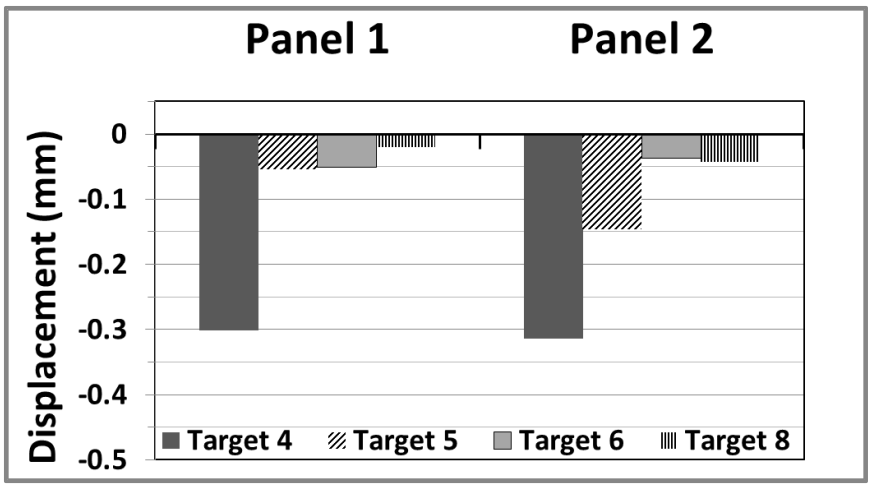


b) Cell 240, Panel 1 (only), Runs 2, 3, 4

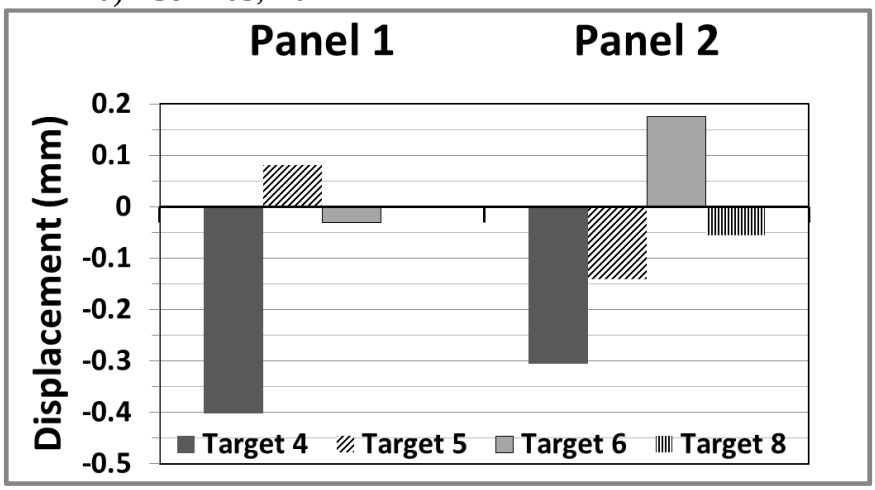


c) Cell 505, Run 2

Figure 8. Response of small unbonded concrete overlay panel edge locations with front axle at Position 4 within each panel.



a) Cell 405, Run 2



b) TH 53, Run 5

Figure 9. Response of large unbonded concrete overlay panel edge locations with front axle at Position 4 within each panel.

Target 4 for each panel. Although the two test panels on the TH53 project had noticeable transverse joint faulting, they did not exhibit visible cracks. Numerous neighboring panels on this project however have both faulted joints and a large corner crack on the approach end of the panels.

Joint Load Transfer Behavior

Besides analyzing the DIC measurements to characterize the bending and translation of the overlay panels in this study, the data was used to characterize the load transfer behavior (differential displacements) across the transverse joints. Since only edge displacements could be gathered using the DIC targets, it was deemed important to compare displacements caused by the MnROAD truck front axle to those collected in the outer wheelpath via FWD testing. This section describes that comparison.

The first column of plots in Figure 10 show the joint load transfer response from DIC testing of small panel BCOA (whitetopping) edge locations with the MnROAD truck front axle load at

Position 1 (see Figure 3). Data consisted of measured displacements at Targets 1 and 4. The second column of plots in Figure 10 shows the joint load transfer response from FWD testing conducted in the outer wheelpath in April 2015. Additional joints are included in the FWD plots, as these are routinely tested on a seasonally basis. For a reasonable comparison to DIC responses, only the FWD tests conducted in the DB position (see Figure 3) with a 26.7 kN (6,000 lb) load were analyzed.

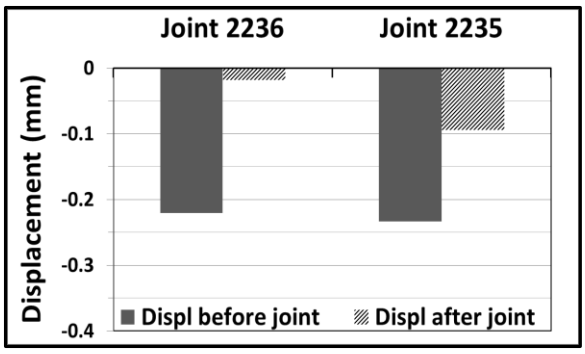
From Figure 10, it appears that regardless of panel thickness, age, or the use of fiber-reinforced concrete (Cell 160), it appears that there is a substantial difference in displacement across the transverse joints near the edge of the BCOA panels tested. The FWD test results for loading in the wheelpath show similar behavior, but the difference in displacement across the transverse joints is much less than the edge of the panels. In the case of Cell 160, the DIC results show virtually no load transfer across the joint, whereas the FWD results indicate more sharing of the load across the joints. This behavior is likely due to less cross-sectional area of concrete near the panel edge, as well as fewer available fibers to share the load. The spike in displacement shown in Figure 10 f) coincides with a substantially faulted transverse joint.

Figure 11 shows similar plots as Figure 10 for testing of small panel unbonded concrete overlay (UBOL) test cells at MnROAD. Cells 140 and 240, the ultrathin FRC UBOL sections on two different weight fabrics, showed quite different behavior. DIC results for Cell 140 showed much lower displacements than Cell 240, but also showed more sharing of the load across the joint. FWD testing in the wheelpath showed the opposite behavior. For Cell 505, both DIC and FWD testing showed similar behavior, as well as displacement magnitudes. Although the fabric interlayer weights were the same under both cells, the thicker non fiber-reinforced concrete panels in Cell 505 (127 mm [5 inch] thick) deflected about half as much as the thinner (75 mm [3 inch] thick)panels in Cell 240.

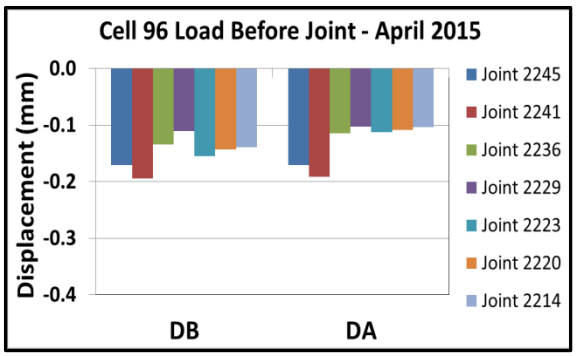
Conclusions and Recommendations

While the occurrence of faulted joints in thin concrete overlays has been commonly observed since their adoption, determination of the mechanisms causing joint faulting have not been readily explored. Through characterization of the basic movements of thin concrete overlay panels subject to heavy truck loads, the aim of this study was to begin determining such mechanisms.

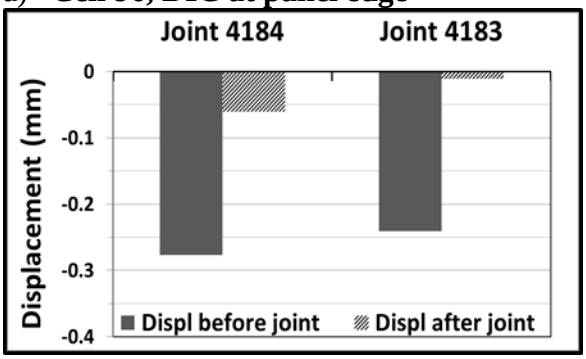
In this study, characterization of the movement of thin concrete overlay panels was determined primarily using innovative Digital Image Correlation (DIC) equipment. The measurement of the displacement of select locations along the lane/shoulder edge of overlay panels revealed some interesting behaviors. Nearly all overlay types, regardless of panel size or thickness experience appreciable bending as an axle loads the leading end of a panel. Without the knowledge of the actual shape of the panel however, it was not possible to determine whether the panels were bending down into the underlying layers, or simply flattening from a curled-up position. This downward bending can create high hydraulic pressures, which can strip asphalt-based interlayer materials, thus creating a void. The bending could also cause consolidation of the interlayer, again creating a void. Movement of the edge for the remaining length of the panels was varied, but was either progressive, indicating some tipping of the panel, or minimal, indicating



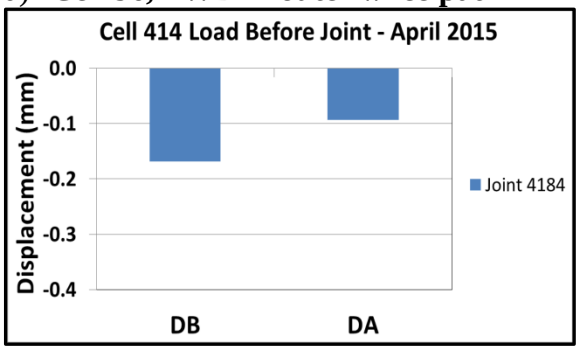
a) **Cell 96, DIC at panel edge**



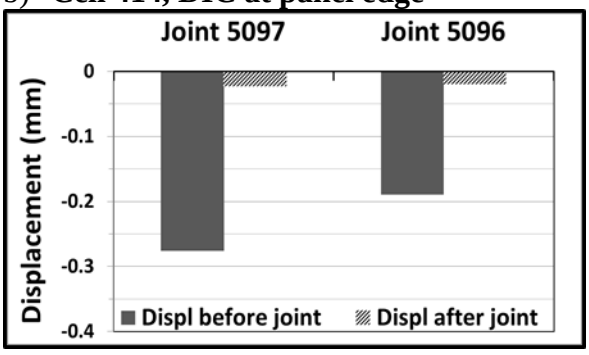
d) **Cell 96, FWD in outer wheelpath**



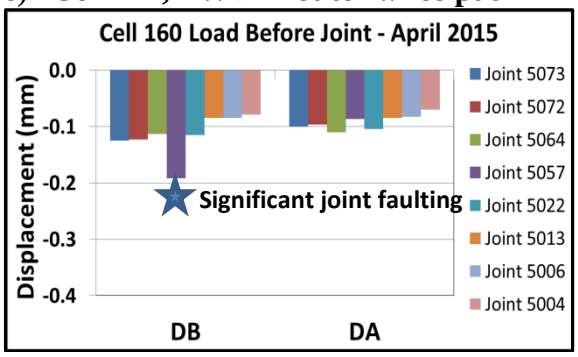
b) **Cell 414, DIC at panel edge**



e) **Cell 414, FWD in outer wheelpath**



c) **Cell 160 (FRC), DIC at panel edge**

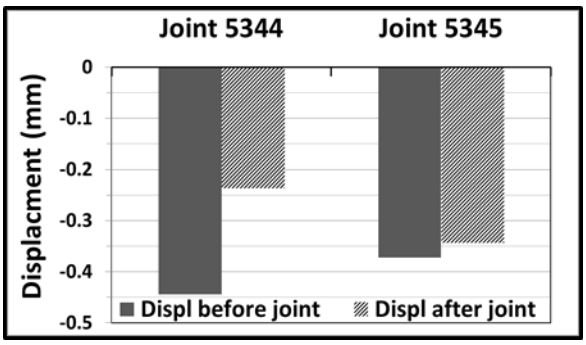


f) **Cell 160, FWD in outer wheelpath**

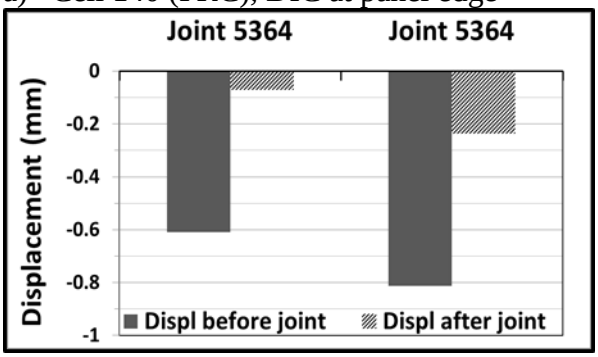
Figure 10 Differential deflection responses across MnROAD small panel BCOA transverse joints as measured by DIC with axle load was at Position 1, and FWD with load in Position DB.

high stiffness within the panel or the contribution of composite action with the underlying layers. The "tipping" type of behavior was prevalent in the oldest BCOA Cell 96. Although this test cell has endured over 18 years of intestate traffic without cracked panels, it did experience significant joint faulting that had to be diamond ground to keep the section in service.

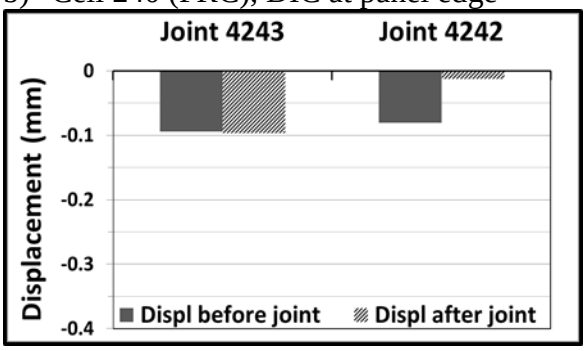
A comparison of the load transfer movement across transverse joints was also analyzed. In general, load transfer behavior measured with DIC at the edge of BCOA panels was poor. FWD testing in the wheelpath revealed a more moderate load transfer behavior. This is perhaps not surprising, as there is more cross-sectional area, and in some sections fibers to help transfer the load in the interior portions of the joints. Measurement of the load transfer behavior of thin



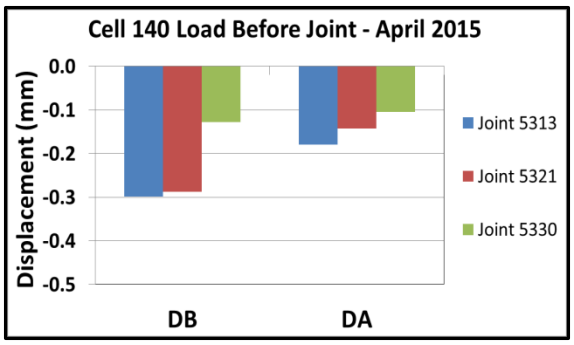
a) Cell 140 (FRC), DIC at panel edge



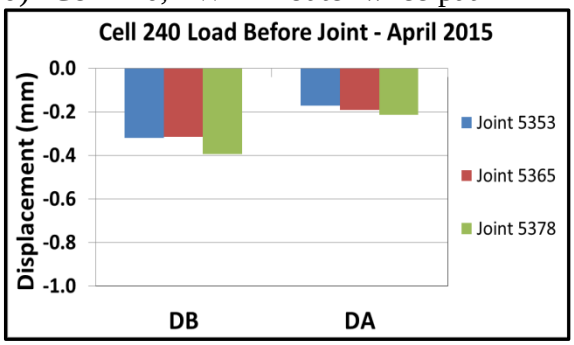
b) Cell 240 (FRC), DIC at panel edge



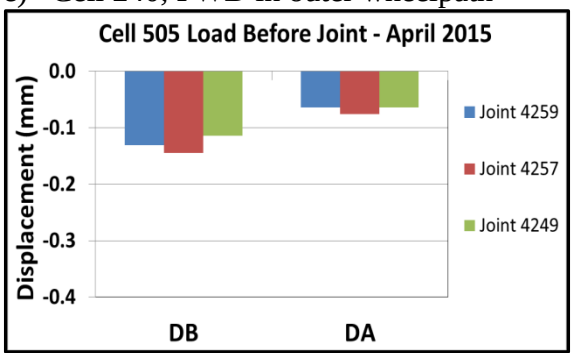
c) Cell 505, DIC at panel edge



d) Cell 140, FWD in outer wheelpath



e) Cell 240, FWD in outer wheelpath



f) Cell 505, FWD in outer wheelpath

Figure 11 Differential deflection responses across MnROAD small panel UBOL transverse joints as measured by DIC with axle load was at Position 1, and FWD with load in Position DB.

UBOL sections show differences in displacements and load sharing due to the different weights of fabric interlayers supporting them.

This study was only able to address a small part of the potential information that can be gathered using DIC equipment. Nevertheless, the findings from this study should serve useful to the continuing determination of the mechanisms causing joint faulting in thin concrete overlays. Future studies should use the capabilities of the technology to examine the three-dimensional movement of entire panels. Efforts should also be directed at measuring the actual surface shape of the panels, which then can be used with measured displacements to determine how overlay panels interact with their supporting layers.

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