Design and Construction of Highway Pavement Joint Systems

Dowel and Tie Bar Design Considerations

Part 2

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Dowel Alignment and Location Requirements
The Goal

- Dowels that are:
  - **Aligned** such that they impose no intolerable restraint on joint opening/closing
  - **Located** such that they provide adequate long-term load transfer
    - Are not so close to the surface or subbase as to cause shear failures
    - Have the required embedment depth
    - Are not too far from (or close to) each other or the pavement edge
Misalignment

- Any deviation in either the horizontal or vertical plane from a true alignment condition (e.g., horizontal skew or vertical tilt).
Mislocation

- Any deviation of a dowel bar from its planned location. DOES NOT LOCK THE JOINT!
Sources of Misalignment and Mislocation
Dowel Bar Installation

➢ Transverse joints
   ▪ Pre-positioned using baskets
   ▪ Placed using DBIs

Source: Shiraz Tayabji, Fugro Consultants, Inc.
Basket Handling is Key
Pre-Placement (e.g., Dowel Baskets)

- Staked to supporting layer
  - Basket height and dowel-to-dowel spacing set; concern for mislocation?
  - If staking sufficient and dowel basket properly aligned and located, concern for misalignment?
  - Misalignment typically due to insufficient staking and/or paving operations
Dowel Basket Placement

- Securing the baskets

Which way is the paver moving?
Basket Shifted During Construction
Poor Dowel Alignment
Recommended Practices

• Cut the shipping wire?
Factors Impacting DBI Placement

Accuracy of insertion forks

- DBI setup is key to get dowels parallel to pavement edge/surface and also spaced properly

Automated saw cut location indicator
Placement Factors Impacting Alignment/Location

- **Baskets**
  - Basket rigidity and design
    - wire sizes, leg shapes ("J" vs "A"/"V"/"U")
  - Basket stability – pins, support layer, shipping wires, etc.
    - See FHWA Tech Brief: Dowel Basket Anchoring Methods – May 2016
  - Concrete placement and paving processes
  - Placed relative to top of base

- **Dowel Bar Insertion (DBI)**
  - Consolidation around dowel bars
  - Concrete mixture too stiff or too soft
  - Equipment problems (e.g., damaged insertion forks)
  - Placed relative to top of concrete
  - “Floating” dowel bars (e.g., FRP dowels)?

SAWCUT LOCATION!!
Sawcut Not Over Dowel Bar
Recommended Practices

• Durable marking on subbase for location of sawcuts
• Both sides of the pavement!
Avoiding Saw Cut Location Issues

- Locate (verify) edge dowels BEFORE sawing...
Issues are Visible in Results

Typical Joint  Basket Opened  Anchoring Issue  Missing Dowels
Potential Impacts of Misalignment/Mislocation on Pavement Performance
## What’s the Concern?

<table>
<thead>
<tr>
<th></th>
<th>Spalling</th>
<th>Cracking</th>
<th>Load Transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal Skew</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Vertical Tilt</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Horizontal Translation</td>
<td>–</td>
<td>–</td>
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<tr>
<td>Longitudinal Translation</td>
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<td>Yes</td>
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<tr>
<td>Vertical Translation</td>
<td>Yes</td>
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</table>
Potential Dowel Misalignment Problems
Potential Dowel Misalignment Problems
Misalignment and Mislocation Thresholds
NCHRP 10-69 Research Approach

Field Evaluation
- MIT Scan – Measurement of dowel alignment
- Visual distress survey
- Faulting measurements
- FWD measurements of load transfer efficiency

Laboratory Testing
- Dowel pullout testing
- Dowel shear testing

3-D Finite Element Modeling using ABAQUS
- Modeling of the laboratory test
- Modeling of a pavement joint

Pavement Performance Modeling
- Use of MEPDG pavement performance models
- Equivalent dowel diameter concept

Design and Construction Guidelines Development as Appendix
Field Evaluation

- 35,000 dowels | 2,300 joints | 60 projects | 17 states
- Typical range of misalignment/mislocation with no significant effect on pavement performance:
  - Horizontal skew or vertical tilt: < 0.5 in. over 18 in. dowel
  - Longitudinal translation: ± 2 in. over 18 in. dowel
  - Vertical translation: ± 0.5 in. for 12 in. or less in thickness
Laboratory Testing

- 64 single-dowel misalignment/mislocation tests

Two-part test:
- Pull-out to simulate joint opening
- Shear test to simulate loading on damaged system

Results:
- Dowel lubrication significantly affects pullout force
- Dowel rotation as extreme as 2 in. per 18 in. dowel does not affect shear capacity
- Reduction in concrete cover from 3.25 in. to 1.25 in. causes severe reduction in ultimate shear capacity
- Reduction in dowel embedment length to 3 in. and less significantly reduces shear capacity
- Combinations of misalignment and mislocation have a compounding effect on shear performance
Effect of Embedment Length

Initial slope = shear stiffness
Max shear force = shear capacity
Effect of Embedment Length

1 in. dowel
9 in. embedment
Peak bearing stress = 2,465 psi

1 in. dowel
5 in. embedment
Peak bearing stress = 2,751 psi, (11% incr.)

...but what is limit on bearing stress?
ACPA and PCA Documents

- **ACPA 2006** – SR999P, “Evaluating and Optimizing Dowel Bar Alignment”
- **PCA 2005** – R&D 2894, “Dowel Bar Alignments of Typical In-Service Pavements”
NCPTC 2011 – “Guide to Dowel Load Transfer Systems for Jointed Concrete Roadway Pavements”
FHWA Guidance


FHWA (2017?) – “Dowel Alignment Testing and Tolerances” – new tech brief, currently in review
Longitudinal Translation (18 in. bar)

- **FHWA 2007:**
  - **Accept:** < 2 in.
  - **Reject:** any joints with < three bars with a minimum embedment length of 6 in. in each wheel path

- **MTO (Canada) 2007:**
  - **Accept:** < 50 mm [2 in.]
  - **Reject:** >75mm [3 in.]

- **NCHRP 2009:** **Accept:** < 2.1 in.

- **CPTech 2011:** Notes that NCHRP 2009 showed no significant loss of shear capacity until embedment length < 4 in.; embedment length as low as 2 in. provided shear capacity of 5,000 lb, more than sufficient for critical dowels in highways
Vertical Translation

**FHWA 2007:**
- **Accept:** $\pm 1$ in.
- **Reject:** concrete cover $< 3$ in. or sawcut depth

**MTO (Canada) 2007:**
- 200mm slab: mid-depth $\pm 6$mm ($R/R \pm 10$mm)
- 225mm slab: mid-depth $+15/-12$mm ($R/R +23/-17$mm)
- 250mm slab: mid-depth $+25/-15$mm ($R/R +35/-25$mm)

**NCHRP 2009:**
- **Accept:** $\pm 0.5$ in. for $T \leq 12$ in. or $\pm 1$ in. for $T > 12$ in.
- **Reject:** concrete cover $\leq 2$ in. or sawcut depth

**CPTech 2011:** Notes that **NCHRP 2009** showed no difference between dowels at mid-depth and those located more than 1 in. closer to surface
Do Dowels Really Need to be at Mid-Depth?

- Dowel requires only adequate cover (concrete shear capacity) and to avoid conflict with saw cut

- NCC 2011 – provides recommendations for standardization, for example:
  - For Slab Thickness 10-12 in.
    - Dowel diameter: 1.5 in.
    - Height to dowel center: 5 in.
NCHRP 2009: 
- **Accept:** ± 1 in.
- This is fixed with baskets
- Many documents (e.g., FHWA 2007) identify horizontal translation as a concern but do not provide guidance on allowable magnitude
- Many state agency specs omit a tolerance
- Cover depth with edge of pavement is key
- Dowels @ 12 in. o.c. is VERY conservative
Alignment of *Individual* Dowel (18 in.)

- **FHWA 2007:**
  - **Accept:** component misalignment < 0.6 in.
  - **Reject:** SDM > 1.5 in.

- **MTO 2007:**
  - **Accept:** component misalignment < 15mm [0.6 in.]
  - **Reject:** component misalignment > 38mm [1.5 in.]

Single Dowel Misalignment (SDM) = \[ \sqrt{(Horizontal Skew)^2 + (Vertical Tilt)^2} \]
Alignment of Individual Dowel (18 in.)

NCHRP 2009: Dowel rotations up to 2 in. have a negligible effect on pullout and shear performance

- **Accept:** component misalign < 0.5 in.
- **Reject:** SDM > 3 in.

  Acceptance is slightly less than FHWA recommendation and reject is 2x FHWA

A combination of low concrete cover and low embedment length has a more adverse effect on dowel performance than either of the two misalignments
**Considering All Dowels in a Joint**

- **Joint Score (JS)** – Means of assessing locking potential; evaluated for a single transverse joint between adjacent longitudinal joint(s) and/or pavement edge(s):

  \[
  \text{Joint Score (JS)} = 1 + \sum_{i=1}^{n} W_i
  \]

  where:
  - \( n = \) number of dowels in the single joint
  - \( W_i = \) weighting factor for dowel \( i \)
**Excessive Misalignment = “Lock”**

The potential for restraining a single joint:

- **JS ≤ 5**  | very low risk of joint restraint
- **5 < JS ≤ 10**  | low risk of joint restraint
- **10 < JS ≤ 15**  | moderate risk of joint restraint; potentially locked
- **JS > 15**  | high risk of joint restraint; joint locked

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**Restraint**

<table>
<thead>
<tr>
<th>Single Dowel Misalignment (SDM)</th>
<th>W, Weighting Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDM ≤ 0.6 in. (15 mm)</td>
<td>0</td>
</tr>
<tr>
<td>0.6 in. (15 mm) &lt; SDM ≤ 0.8 in. (20 mm)</td>
<td>2</td>
</tr>
<tr>
<td>0.8 in. (20 mm) &lt; SDM ≤ 1 in. (25 mm)</td>
<td>4</td>
</tr>
<tr>
<td>1 in. (25 mm) &lt; SDM ≤ 1.5 in. (38 mm)</td>
<td>5</td>
</tr>
<tr>
<td>1.5 in. (38 mm) &lt; SDM</td>
<td>10</td>
</tr>
</tbody>
</table>

NOTE: Values identical in **FHWA 2007, PCA 2005, ACPA 2006**
Alignment of Single Joint

Joint Score (JS) = 1 + \sum_{i=1}^{n} W_i

JS < JST | Accept
Impact of Joint Score on Pavement Performance (ACPA Study)
Findings from the ACPA Study

- Dowel alignments are generally very good, but
  - Almost all projects contained at least a few significantly misaligned bars
  - None of the sections surveyed exhibited any distress
- Occasional, isolated “locked joints” may have no significant effect on pavement performance
- Poor dowel alignment may cause looseness around dowels, impacting LTE but not cracking
- Dowel alignment achieved using baskets and DBI are comparable
Joint Scores for a DBI Placement in KS
KS, NB I-35 – 6 years old
Joint Scores for a 30-year old Section in GA
... but no faulting!

So maybe Joint Score is not the holy grail of dowel bar alignment characterization.
Measuring Dowel (Mis)alignment and (Mis)Location
Measuring (Mis)alignment – the hard way!
2000s – MIT Introduced

- 2000 – Magnetic imaging tomography (MIT) device developed in Germany specifically for dowel bar imaging in concrete pavements
- 2001 – MIT Scan exhibited at conf in Orlando
- 2002 – Caltrans purchases a unit
- 2005 – FHWA adopts MIT Scan as ready-to-implement technology under CPTP; 3 units available for loan and 1 unit on MCL
- 2008 – FHWA loan program continued under the ACPT program
- ... use of GPR evaluation also continued
2010s – Other Devices Introduced

- Hilti – Pulse Radar Imaging
  - Utilizes sound waves
  - Like GPR, can also detect other issues, such as delamination
- MIRA – Ultrasonic tomography
- Hilti & MIRA are time consuming
- ... continued use of GPR and MIT-SCAN
Recent GPR Dowel Imaging

- KY and NM field testing; MO experimenting

Hyperbola shapes

Toughbook

SIR-20 Two-channel control unit

Antenna 2

Antenna 1

(a) Transverse joint testing
Example GPR Imaging

GPR image of doweled pavement joint showing 4 dowels and 2 nearby tie bars, produced by Hilti PS1000 device. Source: Hilti, Inc.
2017

MIT-Dowel-Scan
Rail-Free Device

- Laser-guided single-person operation
- Can be used on “green” concrete
- Accurate measurements of depth, side-shift and alignment of dowels and tie bars within 1 minute of completing scan
- Still electro-magnetic pulse induction technology – 10 sensors

Source: Garry Aicken, KSE Testing Equipment
Where We Are Now ...

- Imaging technologies are being adopted and improved rapidly
- Guidance on their use is also evolving

**Personal** opinions:

- Can always dig out or core, but not ideal
- MIRA and Hilti devices are currently good for forensic work but too labor intensive (for now) for production work
- GPR can test joints quickly for production, can see nonmetallic and nonmagnetic dowels, but accuracy may be lower than MIT-Scan devices (for now)
- MIT Scan2-BT is currently the most widely used device
- Spec tolerances vary between devices!!
Concepts for Dowel Alignment Specifications
The Goals

- Provide indicators of adequate construction process control (i.e., define unqualified acceptance levels).
  - Consider use of incentives/disincentives (PWL) to encourage good process control.

- Avoid conditions that are likely to result in reduced levels of pavement performance or service life (i.e., define unqualified rejection levels).

- Provide better guidance on when expensive corrective actions (i.e., remove and replace, etc.) are really necessary.

- Simplify measurement/control process.
Basis for Alignment Criteria

- Identify distresses and conditions that may result from each type of misalignment/mislocation.
- Develop acceptance/action/rejection criteria based on measures of misalignment/mislocation for individual dowels or groups of dowels, as appropriate.

Criteria must recognize:

- Target (acceptance) levels (easily achievable with good practices)
- Process correction levels (fails to meet target levels, but no anticipated performance problems)
- Corrective action levels (possible performance problems)
Example: Rotational Misalignment Limits

Distress Mechanisms

- Dowel Groups: Restraint of Joint Function
  - Development of dominant joints
    - Sealant failure, infiltration of water and incompressibles
  - Load transfer system failure
    - Deep joint spalling, loss of load transfer, higher deflections/stresses, reduced pavement life
  - Possible mid-panel cracking

Alignment Criteria

- Dowel Groups: Control Restraint of Joint Function
  - PWL on Joint Score
  - Limit consecutive restrained joints (e.g., MARL < 60 ft)
Example: Rotational Misalignment Limits

Distress Mechanisms – Individual Dowels
- Local failure of concrete surrounding dowel, loss of individual dowel LT
- Surface spalling (dowel end near surface due to severe vertical rotation)
- Deep corner spalling (significant rotation of dowel near pavement edge)

Alignment Criteria – Individual Dowels
- PWL spec based on SDM values
- Corrective actions only for critical dowels (wheel paths, edge dowels)
  - Allowable SDM based on distance from edge
Considering Measurement Accuracy of Equipment

Very important to understand measurement accuracy of devices – different measurement accuracy may mean different testing spec limits!

Example:

- Longitudinal Offset (Side Shift) Acceptance = 2 inches
- Longitudinal Offset (Side Shift) Rejection = 5 inches
- Device A accuracy = +/− ¼ inch
  - Accept values less than 2.25 inches, Reject values exceeding 4.75 inches
- Device B accuracy = +/− ½ inch
  - Accept values less than 2.50 inches, Reject values exceeding 4.50 inches
ACPA’s Dowel Alignment Guide Specification

- Version 4.1 June 2017
- Incorporates most of the concepts presented today, including PWL.
<table>
<thead>
<tr>
<th>Criterion</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
<th>Limit Adjustments for Alternative Equip Tolerances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite Misalignment</td>
<td>0 in.</td>
<td>0.75 in.</td>
<td>Decrease upper limit by (rot. accuracy – 0.25 in [6mm])</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[19mm]/18 in.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>[450mm]</td>
<td></td>
</tr>
<tr>
<td>Side Shift (Longitudinal Translation)</td>
<td>-2 in. [-50mm]</td>
<td>2 in. [50mm]</td>
<td>Increase lower limit and decrease upper limit by (long. trans. accuracy – 0.5 in [12mm])</td>
</tr>
<tr>
<td>Horizontal Translation</td>
<td>N/A*</td>
<td>N/A*</td>
<td>N/A*</td>
</tr>
<tr>
<td>Depth (Distance from Pavement Surface to Dowel Centroid)</td>
<td>Nominal Slab Thickness/2 - ½ in [13mm]</td>
<td>Nominal Slab Thickness/2 + ½ in [13mm]</td>
<td>Increase lower limit and decrease upper limit by (depth accuracy – 0.25 in [6mm])</td>
</tr>
<tr>
<td>Joint Score</td>
<td>0</td>
<td>15</td>
<td>Adjust weighting factors, not JS limit.</td>
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<tbody>
<tr>
<td>Criterion</td>
<td>Rejection Levels</td>
<td>Limit Adjustments for Alternative Equip Tolerances</td>
<td></td>
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<tr>
<td>Composite Misalignment</td>
<td>&gt; 2 in. [50mm]</td>
<td>Decrease by (rot. accuracy – 0.25 in [6mm])</td>
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<tr>
<td>Side Shift (Longitudinal Translation)</td>
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<td>Decrease by (long. trans. accuracy – 0.5 in [12mm])</td>
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</tr>
<tr>
<td>Horizontal Translation</td>
<td>N/A*</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>Depth (Distance from Pavement Surface to Dowel Centroid)</td>
<td>&lt; Saw Cut Depth + ¼ in [6mm] + dowel diameter/2 or &gt; Slab Thickness – (2 inches [50mm] + dowel diameter/2) **</td>
<td>Decrease upper limit by (depth accuracy – 0.25 in [6mm])</td>
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<tr>
<td>Joint Score</td>
<td>MEPL &gt; 60 ft</td>
<td>Adjust weighting factors, not JS limit.</td>
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</table>
Acknowledgments

- Garry Aicken – KSE Testing Equipment
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Next up: Placement and Joint Spacing Considerations