Dowel Bar Alternatives

58th Annual ICPA Workshop
February 2 – 4, 2022

Eric Ferrebee, P.E.
Director of Technical Services
ACPA
Load Transfer

- Ability of a slab to share load with neighboring slabs through shear mechanism(s)

- Primary Load Transfer Mechanisms:
  - Dowels/Tie Bars
  - Aggregate Interlock
  - Keyways

- Most commonly quantified as “(Deflection) Load Transfer Efficiency” or LTE
  - 0 – 100 percent range
Deflection Load Transfer

0% Load Transfer

Wheel Load

Direction of Traffic

Approach Slab

Leave Slab

100% Load Transfer

Wheel Load

Direction of Traffic

Approach Slab

Leave Slab

LT (%) = \frac{\text{Unloaded}}{\text{Loaded}} \times 100
Load Transfer

- Most commonly quantified as “(Deflection) Load Transfer Efficiency” or LTE

- HOWEVER -- Many other factors affect pavement deflections
  - Slab thickness
  - Edge support
    - Widened lanes, tied concrete shoulders or curb and gutter
    - Decrease edge & corner stresses & deflections
  - Foundation shear (stiffness)
  - And more ....

- Relative Deflection (RD) or Differential Deflection (DD) is probably a better indicator of the effectiveness of load transfer systems
Load Transfer Systems – Transverse Joints

➢ Original: aggregate interlock

➢ 1920s – present: mainly round steel dowels
Aggregate Interlock

Shear between aggregate particles below the initial saw cut

May be acceptable for:

- Few heavy loads
- Large, hard, abrasion-resistant coarse aggregate
- Joint movement <0.03”
**Dowels: Critical Structural Components of JCP**

- Provide Load Transfer
  - Reduce slab stresses
  - Reduce slab deflections, potential for erosion of support
- Restraint of Curl/Warp Deformation
- **Dowel System Structural Design:**
  - Affects dowel-concrete bearing stress, development of joint faulting
- **Dowel Material Durability (esp. corrosion-resistance):**
  - Needs to last for expected pavement service life
  - 20 – 35 years for conventional pavement and repairs
  - 40 - 100 years for long-life pavements
Q: How Long Have Dowels Been In Use?
A: 96 Years! (Almost As Long as PCCP)

- 1865 – First concrete pavement in the world built in Inverness, Scotland
- 1893 – First concrete pavement built in the U.S. (Court Street, Bellefontaine, OH)
- 1917-1918 – First use of dowel bars in concrete pavement transverse joints in the U.S.
Brief History of U.S. Dowel Design (through 1990)

- First U.S. use of dowels:
  - 1917-1918 Newport News, VA Army Camps
    - Two ¾-in dowels across each 10-ft lane joint

- Rapid (but nonuniform) adoption through ‘20s and ‘30s
  - 1926 practices: two ½-in x 4 ft, four 5/8-in x 4 ft, eight ¾-in x 2 ft

- Numerous studies in ‘20s, ’30s, ‘40s and ‘50s (Westergaard, Bradbury, Teller and Sutherland, Teller and Cashell, and others) led to 1956 ACI recommendations that became de facto standards until the ‘90s:
  - Diameter – D/8, 12-in spacing
  - Embedment to achieve max LTE:
    - 8*dia for 3/4-in or less, 6*dia for larger dowels.
    - 18-in length chosen to account for joint/dowel placement variability.
Illustrates recent trend toward larger dowels to reduce bearing stresses and minimize joint faulting and deflections.

*Data from 2009 survey of NCC member states

## Current SHA Practices* for dowel diameter by pavement thickness

<table>
<thead>
<tr>
<th>Slab Thickness (in)</th>
<th>6.0</th>
<th>6.5</th>
<th>7.0</th>
<th>7.5</th>
<th>8.0</th>
<th>8.5</th>
<th>9.0</th>
<th>9.5</th>
<th>10.0</th>
<th>10.5</th>
<th>11.0</th>
<th>11.5</th>
<th>12.0</th>
<th>12.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>California</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
</tr>
<tr>
<td>Iowa</td>
<td>0.750</td>
<td>0.750</td>
<td>0.750</td>
<td>0.750</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
</tr>
<tr>
<td>Illinois</td>
<td>1.000</td>
<td>1.000</td>
<td>1.250</td>
<td>1.250</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
</tr>
<tr>
<td>Indiana</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
</tr>
<tr>
<td>Michigan</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
</tr>
<tr>
<td>Minnesota</td>
<td>1.000</td>
<td>1.000</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
</tr>
<tr>
<td>Missouri</td>
<td>N/A</td>
<td>N/A</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
</tr>
<tr>
<td>North Dakota</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
</tr>
<tr>
<td>Ohio</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
</tr>
<tr>
<td>Texas</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1.000</td>
<td>1.125</td>
<td>1.250</td>
<td>1.375</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
</tr>
<tr>
<td>Wisconsin</td>
<td>N/A</td>
<td>N/A</td>
<td>1.000</td>
<td>1.000</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.250</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
<td>1.500</td>
</tr>
</tbody>
</table>
Current Dowel Bars (Typical)

- Typical length = 18 in
- Typical Spacing = 12 in
- Typical diameter
  - Roads: 1.0 - 1.5 in
  - Airports: 1.5 - 2.0 in
- Epoxy or other coating typically used for corrosion protection
**DOWELS (LENGTH 18")**

<table>
<thead>
<tr>
<th>Pavement Thickness (D)</th>
<th>Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>6”-6 1/2”</td>
<td>3/8&quot;</td>
</tr>
<tr>
<td>7”-8 1/2”</td>
<td>1&quot;</td>
</tr>
<tr>
<td>9”-10 1/2”</td>
<td>1 1/4&quot;</td>
</tr>
<tr>
<td>≥11”</td>
<td>1 1/2&quot;</td>
</tr>
</tbody>
</table>

**Dowel Bar Layout**

- Plain Steel Dowel Bars
- Sheet Metal Bottom Strip For Expansion Joints Only (See Note #9)
- Bend Up Against End Of Pavement After Forms Are Removed
“Optimized” Dowel Spacing

- Trend toward reducing standard dowel installations from 12 dowels per 12-ft lane to 11
  - Increase distance from lane edge to outside dowels to reduce incidence of paver-induced misalignment
- Concentrated dowels in wheel paths
  - Common in dowel bar retrofit applications
  - Some trends for new construction
- Evaluate bearing stresses for alternate spacings using DowelCAD software
Dowel Diameter

- Not a standard, not tied to pavement thickness
- A part of concrete pavement system design
  - Impacts faulting, IRI and other performance measures through resulting bearing stress, differential deflection, deflection energy, etc.
Impact of Dowel Diameter on Joint Faulting

![Graph showing the impact of dowel diameter on joint faulting. The x-axis represents age in months, ranging from 0 to 350. The y-axis represents faulting for a 10-inch slab, in inches. The graph includes lines for different dowel diameters: 1" dia dowel, 1.25" PCC, 1.375" PCC, and 1.5" dia dowel.]

**Example** for 10-in slab with specific traffic and climate ... not a design chart!
Dowel Length

- Standard typically 18 in (since 1950s)
- Based on embedment requirements to match behavior of Timoshenko 1925 analysis (semi-infinite embedded bar)
Timoshenko & Lessel’s Wire Deflection Equation

\[ y = \frac{e^{-\beta x}}{2 \beta^2 E_s I} \left[ P_{\text{Crit}} \cos \beta x - \beta M_o (\cos \beta x - \sin \beta x) \right] \]

- \( y \) = Deflection in steel
- \( \beta \) = Relative stiffness of steel-concrete system
- \( x \) = Distance from face of concrete
- \( M_o \) = Bending moment at face of concrete
  = \(-P_t z/2\)
- \( z \) = Crack width
- \( P_{\text{Crit}} \) = Load transferred by critical wire
Dowel Length

- Standard typically 18 in (since 1950s)
- Based on embedment requirements to match behavior of Timoshenko 1925 analysis (semi-infinite embedded bar)
- A few states successfully use shorter dowels in new construction (e.g., 15 inches in MN)
- Shorter embedment lengths are supported by research dating to 1950s
1-in dowel, 9-inch embedment

Peak Bearing Stress = 2465 psi
Peak Bearing Stress = 2751 psi
Recommendations: Dowel Length

- For round, metallic dowels, *provide a minimum of 4 inches of embedment on each side of joint*

- Select dowel length to include embedment requirements and tolerances for placement and joint sawing variability
  - *Shorter dowels are possible for retrofit and full-depth repairs where dowel placement and joint location are known more precisely*
The Corrosion Problem

- Corrosion - the destruction or deterioration of a metal or alloy substrate by direct chemical or electrochemical attack.
- Corrosion of reinforcing steel and dowels in bridges and pavements causes cracking and spalling.
- Corrosion costs an estimated $276B per year in the U.S. alone!
Effects of Corrosion on JCP Dowels

- Loss of Cross-Section at Joint
  - Poor Load Transfer
  - Reduced Curl-Warp Restraint

- Joint Lockup (Corrosion Products)
  - Spalling
  - Crack Deterioration
  - Premature Failure
Dowel Corrosion Solutions:
Barrier Techniques

- Form Oil, Grease, Paint, Epoxy, Plastic
  - Coating breach → corrosion failure
- Stainless Steel Cladding and Sleeves
  - Relatively expensive
  - Corrosion at coating breaches (including ends), accelerated due to galvanic reaction.
Epoxy Coatings

- Most common approach to corrosion prevention since 1970s (usually ASTM A775 “green” epoxy)
- Long-term performance has varied with environment, coating properties, construction practice and other factors
  - Sometimes unreliable for long performance periods.
Dowel Epoxy Coatings

- Typical product: ASTM 775 (green, “flexible”)
- ASTM 934 (purple/grey, “nonflexible”) has been suggested
  - Perception of improved abrasion resistance (but green meets same spec requirement)
  - Mancio et al. (2008) found no difference in corrosion protection
- What is needed:
  - Durability, resistance to damage in transport, handling, service
  - Standardized coating thickness
Epoxy Coatings for Dowels: Better Stuff is Available!

American Highways “Armour Coat” 2-component fusion-bonded system
Dowel Corrosion Solutions: Corrosion-Resistant/Noncorroding Materials

- **Stainless Steel (Solid, Tubes)**
  - Expensive (solid bars and, to a less extent, grout-filled tubes)
  - Deformation and slab cracking concerns (hollow tubes only)

- **“Microcomposite” Steel**
  - Sufficient corrosion resistance?

- **GFRP/FRP Products**
  - Utilized in a handful of states
  - Limited long-term performance sections, but promising
Dowel Corrosion Solutions: Barrier/Cathodic Protection

- Galvanic (Sacrificial)
  - Inexpensive and self-regulating
  - Appears well-suited for pavement dowel applications (zinc cladding or sleeve)
## Composite Protection:
**Epoxy plus Galvanizing (Tubular Dowel)**

- High-strength, Grade 60 structural steel tubing
- Heavy wall-to-outside diameter ratio
- G40, G90 galvanized coating with epoxy
  - A775, A934 or ARO/A934
- Epoxy-coated to state requirements
- End plugs limit intrusion

O-Dowel 2-layer Epoxy-Galvanized tubular dowel system
O-Dowel 3-layer ARO/A934/Galvanized tubular dowel system
Other Advantages of Emerging Dowel Technologies

- **Corrosion and Storage Benefits**
  - Shipping and long-term storage concerns can be relieved

- **Installation Benefits**
  - Some materials and geometries result in lightweight dowel baskets that can be easily placed

- **Two-Directional Load Transfer**
Alternate Dowel Bar Materials

- Many materials are suitable
  - Selection should consider environmental conditions, design requirements (performance life), cost considerations
- Structural, behavioral considerations favor continued use of metallic products
  - No design adjustments needed (dowel diameter, spacing)
  - Stainless steel (316L) and zinc-sleeved products currently offer the best combination of predictable structural behavior and corrosion resistance
  - Microcomposite steel is less corrosion-resistant
- What about FRP dowels (E of FRP is 20% of steel E)?
  - Modify dowel diameter and/or spacing for similar bearing stress, joint deflections
“Optimized” Dowel Designs

- Reduce bearing stress while holding cross-sectional area constant (or reducing it)

- Examples:
  - Elliptical Dowels
  - Plate Dowels
  - Hollow Dowels (MnDOT)
## DowelCAD 2.0

### Dowel Comparison Analysis and Design

#### Input Parameters
- **Dowel Spacing:** 12 inches
- **Concrete Elastic Modulus:** 4000000 psi
- **Slab Thickness:** 12 inches
- **Slab Support Reaction Modulus:** 300 psi/inch
- **Joint Opening:** 0.25 inches
- **Wheel Load:** 9000 lbs
- **Tire Pressure:** 90 psi

#### Output Parameters
- **Dowel Diameter(s) (inches):**
  - 1
  - 1.25
  - 1.5
  - 1.75
  - 2
  - 1.41
  - 1.66
  - 1.98

#### Load Transfer (%)
- **Deflection LTE:**
  - 71.6
  - 77.2
  - 80.8
  - 83.2
  - 84.8
  - 75.3
  - 75.9
  - 79.1
- **Stress LTE:**
  - 26.1
  - 30.1
  - 33.1
  - 35.4
  - 37.1
  - 28.6
  - 29.0
  - 31.6
- **Effectiveness:**
  - 46.2
  - 47.0
  - 47.5
  - 47.8
  - 48.0
  - 46.7
  - 46.8
  - 47.2

#### Bearing Stress (psi)
- **Edge Loading:**
  - 1479
  - 1060
  - 788
  - 602
  - 469
  - 1246
  - 758
  - 565
- **Corner Loading:**
  - 2469
  - 1744
  - 1284
  - 975
  - 755
  - 2060
  - 1252
  - 926

---

[Legend: Green = Acceptable Option, Yellow = Acceptable for Wide Lanes, Tied Shoulders, Good Support, and/or Low Traffic, Red = Unacceptable Option]
Various Plate Dowel Assemblies

Source: ACI 360 R-10
Restraint of Movements in Area Pavements
Restraint of Odd-shaped Panels and Roundabouts
Plate dowels for slip-formed or ‘new-to-existing’ joints
Epoxy-grouted CoVex™ Plates
Plastic debonding sleeves installed
Plate Dowels at MnROAD: Preliminary Test Results

- >2.5 million ESALs to date

Performance Summary
- Joint performance is good
- Joint deflection less than round dowels
- Consolidation is good
- LTE in acceptable range
- Less cracking

Core sample showing consolidation above and below plate

3/8” x 12” PD³ basket assembly
Future Research Topic

What criterion (or criteria) should be used to determine dowel load transfer system equivalency?
Easiest Path to Approval/Acceptance?

Prove comparable behavior and performance of alternate dowel system to current standard (cylindrical steel dowels)
Basis for Determining System Equivalency

- Bearing Stress?
  - Determined analytically
  - High significance in many faulting models
  - Includes influence of slab stiffness, foundation stiffness (through $l$)

- Deflection-based Criteria?
  - LTE?
  - Joint Stability?
  - Others?
LTE as a measure of equivalence?

- LTE is a measure of *system* behavior, not dowel equivalence.

- LTE is worthless without overall deflection reference
  - Example #1: $d_L = 0.05\text{mm}$, $d_{UL} = 0.025\text{mm}$, LTE = 50% … but is this bad?
  - Example #2: $d_L = 5\text{mm}$, $d_{UL} = 4\text{mm}$, LTE = 80% … but is this good?
ACI 360 definition: “... a joint’s ability to limit differential deflection of adjacent slab panel edges when a service load crosses the joint ... the smaller the measured differential deflection number the better the joint stability.”
Joint Stability

- ACI 360.R-10):
  - < 0.010 in. (0.25 mm) (small, hard-wheeled lift truck traffic)
  - < 0.020 in. (0.51 mm) (larger, cushioned rubber wheels)

- What is appropriate for road pavements?
- Should the criterion vary with functional applications (e.g., streets vs highways)?
- Should the criterion vary with foundation design and environmental conditions (e.g., stabilized vs unbound base, and wet vs dry climate)?
What criterion (or criteria) should be used to determine dowel load transfer system equivalency?

- What distresses or other performance parameters are associated with inadequate dowel systems?
- What dowel parameters affect these distresses?
- Do these criteria change with other system parameters, such as foundation type/stiffness? In other words, should equivalency criteria be dynamic?

**Underlying question: what do we really need from load transfer systems?**
Current AASHTO Dowel Spec Details

- Originally approved in 1975
  - Predominant corrosion-resistant dowel was epoxy-coated solid steel
  - Directly applicable to 1.25-inch cylindrical epoxy-coated dowels

- Structural Testing
  - Load-Deflection (Static Load, Single Dowel)
  - Pullout

- Durability Testing
  - Abrasion
  - Corrosion
  - Chemical Resistance
  - Cathodic Disbonding
  - Coating Hardness
  - Coating Impact Resistance
Limitations of Current AASHTO Dowel Specs

- Not directly applicable to many dowel products being used and developed today
  - Can’t evaluate different dowel materials
    - Different tests needed for different materials, different coatings
  - Can’t evaluate behavior of groups of dowels (including effects of nonuniform spacing)

Difficult for manufacturers to innovate.
Difficult for agencies to adopt new products.
New ACPA “Universal” Dowel Specifications

➢ M 254 – Standard Specification for Dowel Bars for Concrete Pavement
   ➢ Specification developed to address the requirements for manufacture and installation of all types of dowel bars (coated or not, corrosion-resistant or not, cylindrical or not, metallic or not) intended for use in concrete pavements.
   ➢ Dowels qualified as engineered load transfer systems, not as individual products.

➢ T 253 – Standard Method of Test for Dowel Bars for Concrete Pavement
   ➢ Methods to test:
     ➢ Structural behavior of dowel load transfer systems using modified protocol
     ➢ Ability of dowels to withstand the effects of weathering, de-icing chemicals, abrasion and other measures of dowel durability.
     ➢ Suite of applicable durability tests varies with dowel materials and coatings.
Revised NCC/ACPA T253 Load-Deflection Test Schematic
[Validation Testing 2022 Qtr1]

Steel Load Plate – 2.5 cm [1.0 inch] thick x 30 cm [12 inches] dia. over 6mm [1/4-inch] rubber sheet (Shore A Hardness 50)

40kN [9000 lbs] load

Rigid Support (Typical for 2)

Deflection Measurement Locations

1.2 m [48 inches]

9.5mm [3/8 in] width (Typical for 2)
Guide and Tech Brief
Available from National Concrete Pavement Technology Center at Iowa State University