Dowel Optimization through Engineering

Nicole Dufalla, P.E.
TODAY’S TALK

• Questioning standardized dowel design
  – How do we think dowels behave?
  – How did we used to think they behave?
  – How is this information used in standardized requirements?
  – How can we make designs more efficient?

• How can plate dowels solve some of these problems?
Why do we have dowels?

- Transfer part of load from one slab to next
- Reduce edge stress and deflection

“Theoretically, if the dowel is 100 percent efficient, the dowel will transfer one-half of the applied load from one slab to another. This is true if each slab at the joint deflects an equal amount and each assumes one-half of the applied load.”

- Principles of Pavement Design by Yoder and Witczak

... Load Transfer Devices?
GOALS OF LOAD TRANSFER DEVICES

• 1956 – ACI 325 – Structural Design Considerations for Pavement Joints

Mechanical load-transfer devices should possess the following attributes:

1. They should be simple in design so that they may be practical to install and permit positive encasement by the concrete.

2. They should be capable of distributing load stresses throughout the adjacent concrete in a manner such that these stresses will not exceed the allowable design value. In this respect, it is especially important that high localized stresses in the concrete at the joint face be prevented.

3. They should offer no material restraint at any time to the opening of the joints.

4. They should retain their mechanical stability under wheel-load weights and frequencies comparable to those for which the pavement itself has been designed.

5. They should be constructed in a manner such as to meet specified performance requirements relative to load-transfer capacity.

… doesn’t say “round dowel, 1/8 of t, @ 12” (300 mm) o/c”…
Table 6.1—Dowel size and spacing for construction and contraction joints*

<table>
<thead>
<tr>
<th>Slab depth, in. (mm)</th>
<th>Dowel dimensions, in. (mm)</th>
<th>Dowel spacing center-to-center, † in. (mm)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Construction joint</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Round‡</td>
<td>Square§‖</td>
</tr>
<tr>
<td></td>
<td>Contraction joint</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Round‡</td>
<td>Square§‖</td>
</tr>
<tr>
<td></td>
<td>Plate dowel</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Round‡</td>
</tr>
<tr>
<td>5 to 6 (130 to 150)</td>
<td>3/4 x 10 (19 x 250)</td>
<td>3/4 x 10 (19 x 250)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3/4 x 13 (19 x 330)</td>
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<tr>
<td></td>
<td></td>
<td></td>
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<tr>
<td>7 to 8 (180 to 200)</td>
<td>1 x 13 (25 x 330)</td>
<td>1 x 13 (25 x 330)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 x 16 (25 x 410)</td>
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<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 to 11 (230 to 280)</td>
<td>1-1/4 x 15 (32 x 380)</td>
<td>1-1/4 x 15 (32 x 380)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1-1/4 x 18 (32 x 460)</td>
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<td></td>
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*Table values based on a maximum joint opening of 0.20 in. (5 mm). Carefully align and support dowels during concrete operations. Misaligned dowels may lead to cracking. Spacings are based on dowels in direct contact with a thin bond breaker. Total dowel length includes allowance made for joint opening and minor errors in positioning dowels.

†Dowel spacing up to 24 in. (610 mm) for round, square, and plate dowels have been used successfully.

‡ACI Committee 325 (1956), Teller and Cashell (1958).
§Walker and Holland (1998).
§‖Square dowels should have compressible material securely attached on both vertical faces.

#M/R = manufacturers’ recommendations. Because of the various plate dowel geometries and installation devices available from different manufacturers, the manufacturers should be consulted for their recommended plate dowel size.
HISTORY OF DOWEL USE

• 1917-1918 Newport News, VA Army Camps
  – Two \( \frac{3}{4} \) in. (19 mm) dowels across each 10 ft (3 m) wide lane joint

• Rapid (nonuniform) adoption through ‘20s and ‘30s
  – Two \( \frac{1}{2} \) in. (13 mm) x 4 ft (1.2 m), four 5/8 in. (16 mm) x 4 ft (1.2 m),
    eight \( \frac{3}{4} \) in. (19 mm) x 2 ft (0.6 m)

• Numerous studies led to 1956 ACI 325 guide doc that became “standard dowel design” in much of the world:
  – Diameter – D/8, 12 in. (30 cm) spacing
  – Embedment to achieve max LTE: 8*dia for \( \frac{3}{4} \) in. (19 mm) or less &
    6*dia for larger dowels. 18 in. (45 cm) length chosen to account for
    joint/dowel placement variability.

History summarized by Snyder 2011, “Guide to Dowel Load Transfer for
Jointed Concrete Roadway Pavements”
ORIGIN OF MECHANISTIC DOWEL MODELS

• 1940 – Friberg – Design of Dowels in Transverse Joints of Concrete Pavements … built on Timoshenko and Westergaard

For $x$ equal to 0, the deflection, $y_0$, at the face of the mass is:

$$y_0 = \frac{P - \beta M_0}{2 \beta^3 E_s I} \quad \text{(4)}$$
Actually concrete is able to withstand a concentrated bearing stress many times greater than $f_c'$ without being overstrained. The local bearing strength of concrete is dependent on many factors: dimensions of loaded area, depth of concrete below the dowel, and last but not least, shear and tensile strength of the concrete.
FOCUS FORCED ON BEARING

- 1956 – ACI 325 adaptation of 1951 – Marcus

### TABLE 6—CONCRETE BEARING STRESSES IN RELATION TO DOWEL DIAMETER

<table>
<thead>
<tr>
<th>Dowel diameter in.</th>
<th>Ultimate compressive strength of concrete fₐ' psi</th>
<th>Bearing stress at failure fₐ psi</th>
<th>Ratio fₐ'/fₐ</th>
<th>Allowable bearing stress fₐ', psi</th>
<th>Factor of safety, fₐ'/fₐ</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/8</td>
<td>3780</td>
<td>9873</td>
<td>2.61</td>
<td>3200</td>
<td>3.08</td>
</tr>
<tr>
<td>1/2</td>
<td>3850</td>
<td>9020</td>
<td>2.34</td>
<td>3100</td>
<td>3.01</td>
</tr>
<tr>
<td>1 1/4</td>
<td></td>
<td></td>
<td></td>
<td>3000</td>
<td></td>
</tr>
<tr>
<td>1 1/2</td>
<td></td>
<td></td>
<td></td>
<td>2900</td>
<td></td>
</tr>
<tr>
<td>1 3/4</td>
<td></td>
<td></td>
<td></td>
<td>2800</td>
<td></td>
</tr>
<tr>
<td>2 1/4</td>
<td></td>
<td></td>
<td></td>
<td>2650</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>3530</td>
<td>6450</td>
<td>1.83</td>
<td>2500</td>
<td>2.58</td>
</tr>
<tr>
<td>2 1/2</td>
<td>3610</td>
<td>6410</td>
<td>1.78</td>
<td>2000</td>
<td>3.20</td>
</tr>
</tbody>
</table>

Data from 1951 Marcus

ACI 1956 Factor of Safety
1956 ACI 325 WAS INTENDED TO NEVER BE A “STANDARD”

We regularly bother with nomographs and calculations for plastic shrinkage cracking, which creates a non-structural distress… but not for dowel design?

Fig. 13—Dowel diameter selection chart for dowels spaced 12 in. on center

\[
G = 1,500,000 \text{ lb per cu in.}
\]
Dowel Design Standardization

- 1956 – ACI 325 – Structural Design **Considerations** for Pavement Joints
  - Basis of current “standards”
  - Assumed round, steel dowel
  - Dowel placed @ mid depth
  - 1/8” per 1’ alignment tolerance
  - *Bearing stress presented as sole design criterion* based on poor assumptions
  - **No deflection criterion**
  - Dowel grouping assumptions were incorrect

Not optimized, but it’s worked

**TABLE 2—MINIMUM RECOMMENDED DOWEL REQUIREMENTS FOR EXPANSION OR CONTRACTION JOINTS IN HIGHWAY CONSTRUCTION***

<table>
<thead>
<tr>
<th>Pavement thickness, in.</th>
<th>Dowel diameter, in.</th>
<th>Dowel length, in.</th>
<th>Dowel spacing, in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>3/4</td>
<td>18</td>
<td>12</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>18</td>
<td>12</td>
</tr>
<tr>
<td>8</td>
<td>1 1/4</td>
<td>18</td>
<td>12</td>
</tr>
<tr>
<td>9</td>
<td>1 1/4</td>
<td>18</td>
<td>12</td>
</tr>
<tr>
<td>10</td>
<td>1 1/4</td>
<td>18</td>
<td>12</td>
</tr>
</tbody>
</table>

*For practical reasons adjustments have been made to the theoretical requirements as presented in Table 10.
The discussions which follow are applicable in certain cases only to highway pavements and in others only to airport pavements, although some have application to both conditions.

... have been blindly applied to all applications despite difference in performance requirements, load magnitudes, load contact area, etc.

In this recommendation, the spacing of dowels has been standardized at the spacing which is most often used, that is, 12 in. For balanced load-transfer design between the edge of the pavement and the center, a variable spacing, smaller at the edges and greater at the center, would be the optimum. However, this is not practical and, therefore, a uniform spacing is recommended.

... more evidence of the foresight of the original engineers

Recommendations for load transfer at joints have been based on the most commonly used type of load-transfer device, the common round steel dowel. If proprietary load-transfer devices are used in lieu of dowels they must have, for the given conditions, a load-transfer capacity equal to or better than that of the recommended dowel.

... engineering completed but not fully considered in ACI
MODELS DEVELOPED SINCE THE 1956 STANDARDIZATION ARE GENERALLY IGNORED


Figure 27. Relations between dowel diameter and dowel looseness resulting from 600,000 cycles of a 10,000-lb load (base measurements obtained at first cycle).

Looseness Diameter Joint Opening Embedment

Grouping Bearing Other Stresses Dowel Fatigue
EVEN TESTED STRAIN GAUGES INSIDE OF DOWELS

- 1956 – Milliman & Behr – MI DOT – The Experimental Determination of the Stress Distribution Along a Dowel at a Transverse Joint
WHICH VALIDATED OUR MECHANISTIC EQUATIONS

...why'd we stop using equations to engineer the solution on a case-by-case basis?
Dowel group action has long been understood too.

See “Principles of Pavement Design” by Yoder and Witczak (1975) for one of the simplest explanations.
Dowel Grouping Action Per 1956 – ACI 325 Assumption

<table>
<thead>
<tr>
<th>Dowel Spacing</th>
<th># of Dowels</th>
</tr>
</thead>
<tbody>
<tr>
<td>12” o/c</td>
<td>2.7</td>
</tr>
<tr>
<td>18” o/c</td>
<td>2.0</td>
</tr>
<tr>
<td>24” o/c</td>
<td>1.6</td>
</tr>
<tr>
<td>30” o/c</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Dowels Engage over a Distance of 1.8 \( \times \) Radius of Relative Stiffness

Inputs: \( h = 6” \) | \( E = 4,000,000 \) psi | \( k = 100 \) psi/in. | \( \mu = 0.15 \)
Calculated: \( l = 29.3 \) in. | \( 1.8 \times l = 52.7 \) in.
Dowel Grouping Action Per FEA Model Via 1979 – Tabatabaie et al.

<table>
<thead>
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<th>Dowel Spacing</th>
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<tr>
<td>12” o/c</td>
<td>1.8</td>
</tr>
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<td>1.4</td>
</tr>
<tr>
<td>24” o/c</td>
<td>1.2</td>
</tr>
<tr>
<td>30” o/c</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Dowels Engage over a Distance of 1.0 * Radius of Relative Stiffness

Inputs: $h = 6”$ | $E = 4,000,000$ psi | $k = 100$ psi/in. | $\mu = 0.15$
Calculated: $l = 29.3$ in.
IMPACT OF THIS INCORRECT ASSUMPTION MADE IN 1956 – ACI 325 DOCUMENT

The image shows a graph with two lines representing different assumptions about the relative stiffness of dowels. The x-axis represents dowel spacing in inches, ranging from 12 to 30. The y-axis represents the number of effective dowels.

- The blue line represents an assumption of 1.8 times the radius of relative stiffness.
- The red line represents an assumption of 1 times the radius of relative stiffness.

The graph indicates the following:
- Overprediction in the number of effective dowels is shown by the blue line.
- Underprediction in load on critical dowel is shown by the orange line.
- The percentage of overprediction and underprediction is indicated on the secondary y-axis, ranging from 0% to 100%.

The graph highlights the impact of different assumptions on the efficiency and load-bearing capacity of dowels in construction.
SUMMARY OF CONCERNS WITH THE “STANDARD”

- Factor of safety on bearing stress set at over 3x
  - All other responses ignored
- Dowel grouping action underpredicts critical dowel load by approximately 50%
- Recommendations were for edge of pavement loading
- Recommendations were recommendations… they’ve served us well but we can now do better
STANDARDIZED = USUALLY UNDEROPTIMIZED

**Standardization**
Covers >99% of design scenarios but requires a high factor of safety to cover the risk of the most extreme design scenarios.

- **100%**  <1% Not Covered
- **50%**  1-2% Optimized by standardization
- **0%**  97-98% Underoptimized

Standardized design costs you more $$ than it needs to for your project.
OPTIMIZATION EFFORTS OF THE LAST 25 YEARS

- Alternate shapes | square, rectangle, elliptical, etc.
- Alternate materials | stainless, zinc-sleeved, FRP, etc.
- Alternate spacing | wheel-path only, non-uniform, etc.
- Advanced models | shear cone, looseness/fatigue, etc.
INNOVATION IS HERE!
There is a growing trend towards abandoning these “standards”…

$ saving, reliable engineering
Dowel Design Considerations That We Can Calculate Right Now for Any Project!

- Critical dowel from group action
- Responses for *shapes & materials*
  - Joint deflection
  - Dowel flexural stress
  - Dowel shear stress
  - Concrete bearing stress
  - Concrete shear cone capacity
- Deflection between dowels
DESIGN TOOLS ALLOW FOR QUICK PROJECT-SPECIFIC DOWEL OPTIMIZATION

Manufacturer’s recommendations are appropriate when supported by thorough engineering.

CONCRETE MATERIAL MATTERS!
DOWELS – OPTIMIZED GEOMETRY

• National Concrete Pavement Technology Center:
  – "For any given dowel pattern, it is possible to strive for further performance improvements and efficiencies through the use of non-round dowels (e.g., elliptical or flat plate shapes)..."
  – "A second benefit of some plate dowels (i.e., those with tapered/diamond shapes or other design features that allow lateral displacement) is their ability to accommodate slab movements in two directions, such as are experienced in airport aprons, parking lots and other area paving applications."

• ACI 330.2R-17 Details:
EXAMPLE OF SHAPE IMPACT ON RESPONSES

- Shape impacts shear transfer, bearing stress, etc. through differences in width, thickness, area, and moment of inertia.

Keeping area of 1 in² (6.5 cm²)

SAFETY FACTOR IN DESIGN:

<table>
<thead>
<tr>
<th>Response Criteria</th>
<th>1.13” (2.9 cm) Diameter</th>
<th>1” x 1” (2.5 x 2.5 cm)</th>
<th>2” x 0.5” (5 x 1.3 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint Deflection</td>
<td>1.83</td>
<td>1.73</td>
<td>1.89</td>
</tr>
<tr>
<td>Dowel Flexural Stress</td>
<td>3.78</td>
<td>4.30</td>
<td>3.44</td>
</tr>
<tr>
<td>Dowel Shear Stress</td>
<td>10.37</td>
<td>10.37</td>
<td>10.37</td>
</tr>
<tr>
<td>Concrete Bearing Stress</td>
<td>2.74</td>
<td>2.54</td>
<td>2.94</td>
</tr>
<tr>
<td>Concrete Shear Cone Capacity</td>
<td>1.52</td>
<td>1.55</td>
<td>1.82</td>
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DEFLECTION IS JUST ONE FAILURE
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</tr>
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<td></td>
<td>Round ²</td>
<td>Square ²Ⅲ</td>
</tr>
<tr>
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TAPERED PLATE DOWEL SPACING IN SAWCUT CONTRACTION JOINTS – 12” O/C NONEXISTENT!

**Cumulative Sales (14Q1 - 16Q3)**

- Dowel Spacing in Contraction Joint Basket, in.
TAPERED PLATES IN ROADWAYS?

• Tested at MnROAD – less deflection than round dowels!
• DDI and roundabout standards – should alternate dowel technologies and construction methods be considered?

• Current standards and geometries already “lock” joint:
  – ¼” (6 mm) horizontal skew along a 18” (45 cm) dowel = 0.80° angle
  – With 15’ (4.6 m) joint spacing, > 0.80° angle between joints on < 1,080’ (330 m) horizontal curve radius
PD3 for Sawcut Contraction Joints

DiamondDowel for Construction Joints
Thank you for your time.

Nicole Dufalla, P.E. | ndufalla@pna-inc.com

QUESTIONS?