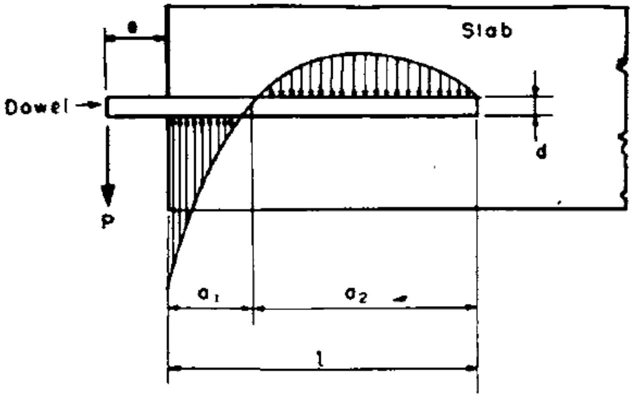
Dowel Optimization through Engineering

Nicole Dufalla, P.E.

PNA CONSTRUCTION TECHNOLOGIES

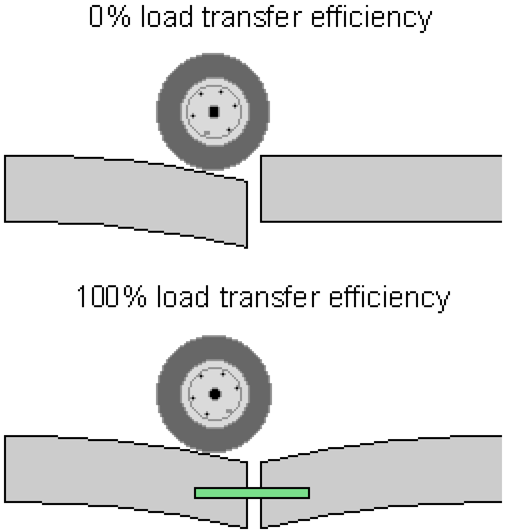
TODAY'S TALK

- 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**

… **<u>Load Transfer</u>** Devices?

GOALS OF LOAD TRANSFER DEVICES

- 1956 – ACI 325 – Structural Design **Considerations** for Pavement Joints

Title No. 53-1

Structural Design Considerations for Pavement Joints*

Reported by Subcommittee III, ACI Committee 325

E. A. FINNEY
Chairman

HENRY AARON
J. A. BISHOP
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J. D. LINDSAY
L. W. TELLER
W. VAN BREEMEN

SYNOPSIS

Considerations are presented for the structural design of joints in concrete pavements for highways and airports. A description, function, and classification of joints; assumptions and materials to be used; and joint design details are included. Special consideration is given to applicable design criteria for tie bars and dowels.

INTRODUCTION

It is recognized that unanimous agreement is not likely on all details of design practice with regard to common types of joints in concrete pavements for both highways and airports. This is due, in part, to variations in conditions, particularly climate and traffic volume, for which provisions must be varied in different areas, and in part to the lack of established theoretical guidance coupled with conflicting observations of the performance of similar designs in different localities. 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.

Because of its inherent weakness in tension, concrete is highly susceptible to cracking under tensile stresses induced by volume changes due to temperature fluctuation, autogenous shrinkage of the concrete at early age, and other causes. The nearest approach to obtaining an ideal concrete pavement comparatively free from cracks has been that of dividing the pavement into a series of slabs by introduction of joints of one kind or another, the slabs being as long as possible consistent with practical design requirements and within economic limitations. Depending on their design, the function of joints is to maintain within safe limits the stresses caused by expansion, contraction, and warping of the concrete.

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The report was submitted to the main committee (17 members) with 15 voting affirmatively and none negatively.

1

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"…

PNA CONSTRUCTION TECHNOLOGIES

ACI 360R-10
GUIDE TO DESIGN OF SLABS ON GROUND

Table 6.1—Dowel size and spacing for construction and contraction joints*

Slab depth, in. (mm)	Dowel dimensions, in. (mm)					Dowel spacing center-to-center,† in. (mm)		
	Construction joint		Contraction joint		Plate dowel			
	Round‡	Square§‖	Round‡	Square§‖		Round‡	Square§‖	Plate dowel
5 to 6 (130 to 150)	3/4 x 10 (19 to 250)	3/4 x 10 (19 x 250)	3/4 x 13 (19 x 330)	3/4 x 13 (19 x 330)	M/R#	12 (300)	14 (360)	18 (460)
7 to 8 (180 to 200)	1 x 13 (25 x 330)	1 x 13 (25 x 330)	1 x 16 (25 x 410)	1 x 16 (25 x 410)	M/R#	12 (300)	14 (360)	18 (460)
9 to 11 (230 to 280)	1-1/4 x 15 (32 x 380)	1-1/4 x 15 (32 x 380)	1-1/4 x 18 (32 x 460)	1-14 x 18 (32 x 460)	M/R#	12 (300)	12 (300)	18 (460)

*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 ¾ in. (19 mm) dowels across each 10 ft (3 m) wide lane joint
- Rapid (nonuniform) adoption through ‘20s and ‘30s
  - Two ½ in. (13 mm) x 4 ft (1.2 m), four 5/8 in. (16 mm) x 4 ft (1.2 m), eight ¾ 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 ¾ 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

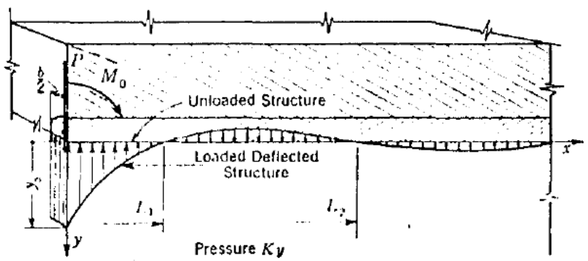


FIG. 1.—LOAD AND DEFLECTION DIAGRAM, SHOWING AN ELASTIC STRUCTURE EMBEDDED IN AN ELASTIC MASS

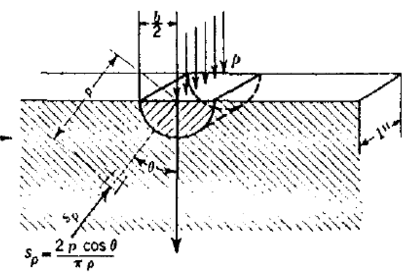


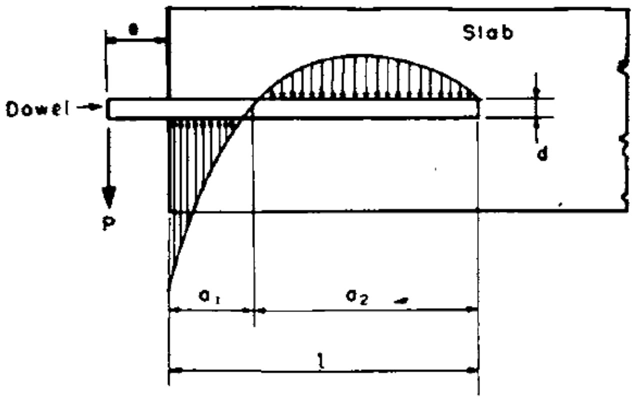
FIG. 2.—DISTRIBUTION OF STRESS IN AN ELASTIC MASS UNDER A DOWEL IF THE CONCRETE ABOVE THE DOWEL IS NEGLECTED

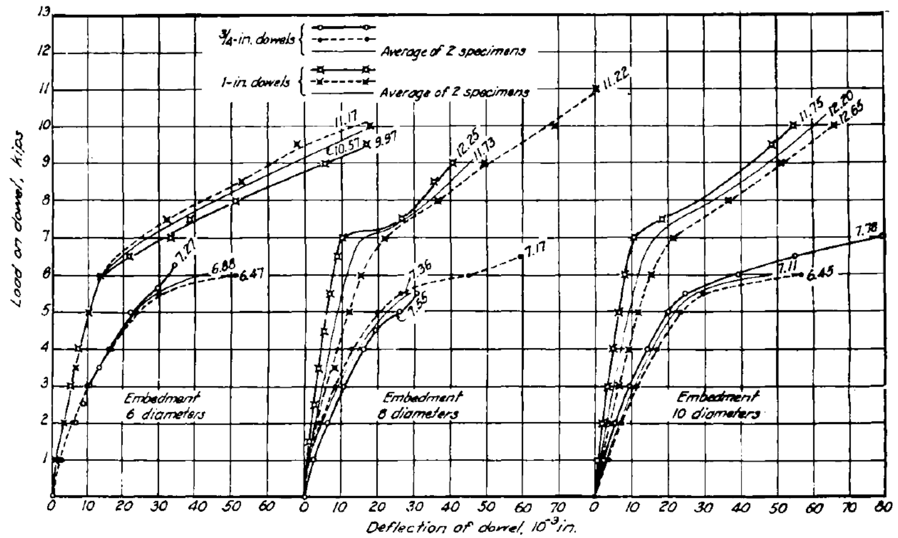
For x equal to 0, the deflection, y_0, at the face of the mass is:

$$y_0 = \frac{P - \beta M_0}{2 \beta^3 E_s I} \quad \text{(4)}$$

BEARING STRENGTH > COMPRESSIVE STRENGTH

- 1951 – Marcus – Navy – Load Carrying Capacity of Dowels at Transverse Pavement Joints





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

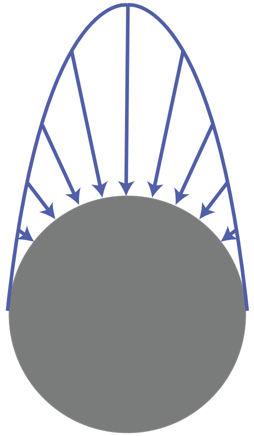
- 1956 – ACI 325 adaptation of 1951 – Marcus

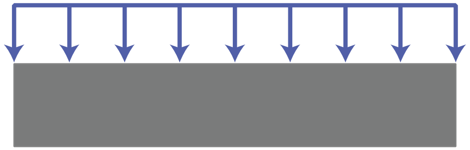
TABLE 6—CONCRETE BEARING STRESSES IN RELATION TO DOWEL DIAMETER

Dowel diameter in.	Ultimate compressive strength of concrete f_c', psi	Bearing stress at failure f_b' psi	Ratio $\frac{f_b'}{f_c'}$	Allowable bearing stress* f_b', psi	Factor of safety, $\frac{f_b'}{f_b}$
¾	3780	9873	2.61	3200	3.08
⅞	—	—	—	3100	—
1†	3850	9020	2.34	3000	3.01
1⅛	—	—	—	2900	—
1¼	—	—	—	2800	—
1⅜	—	—	—	2650	—
1½†	3530	6450	1.83	2500	2 58
2†	3610	6410	1.78	2000	3.20

Data from 1951 Marcus

ACI 1956 Factor of Safety





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

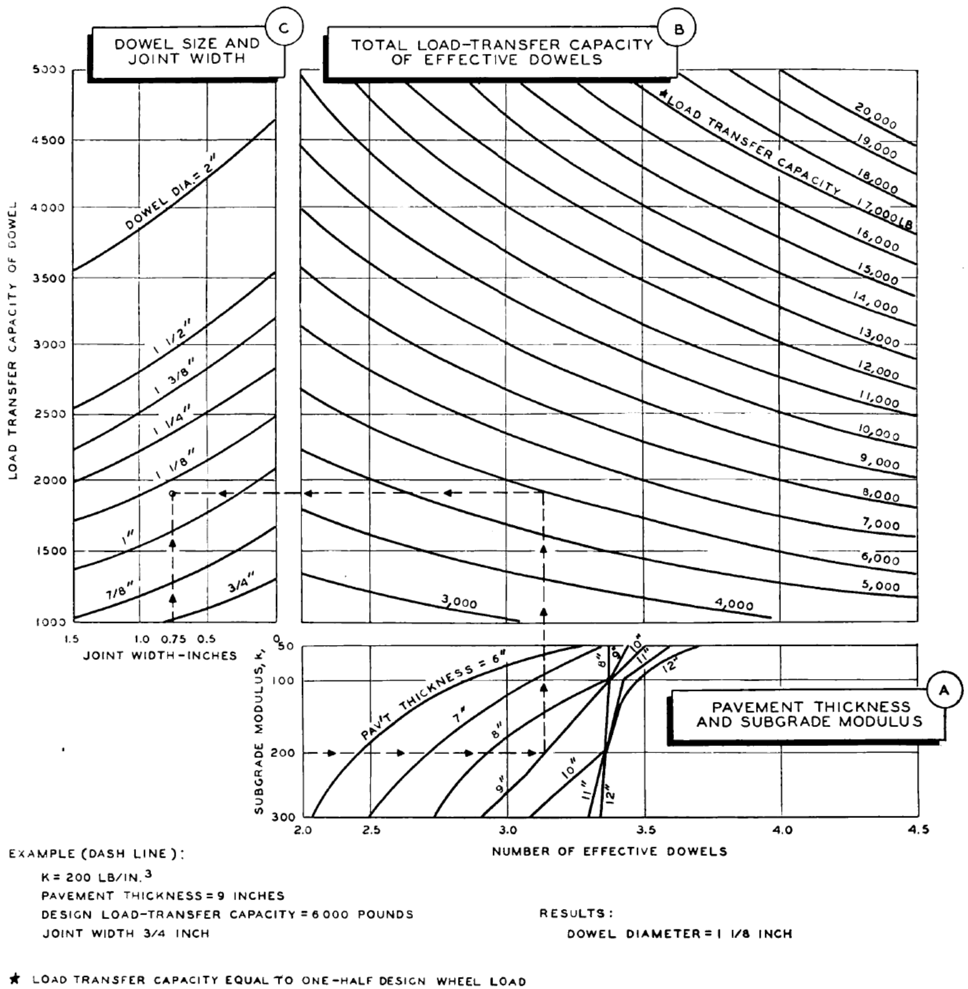


Fig. 13—Dowel diameter selection chart for dowels spaced 12 in. on center
G = 1,500,000 lb per cu in.

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

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*

Pavement thickness, in.	Dowel diameter, in.	Dowel length, in.	Dowel spacing, in.
6	¾	18	12
7	1	18	12
8	1	18	12
9	1 ¼	18	12
10	1 ¼	18	12

*For practical reasons adjustments have been made to the theoretical requirements as presented in Table 10.

OTHER NOTABLE QUOTES FROM 1956 – ACI 325

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

PNA CONSTRUCTION TECHNOLOGIES

MODELS DEVELOPED SINCE THE 1956 STANDARDIZATION ARE GENERALLY IGNORED

- 1958 – Teller & Cashel – BPR [FHWA] – Performance of Doweled Joints Under Repetitive Loading

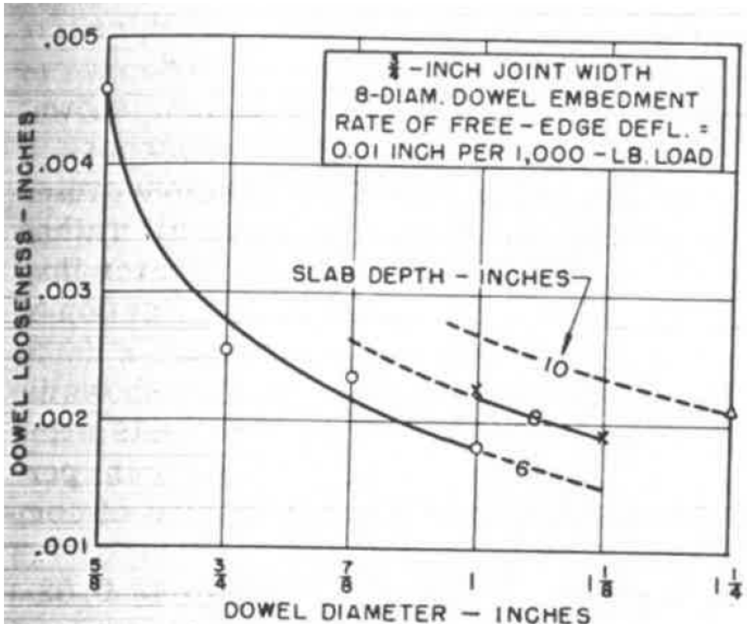
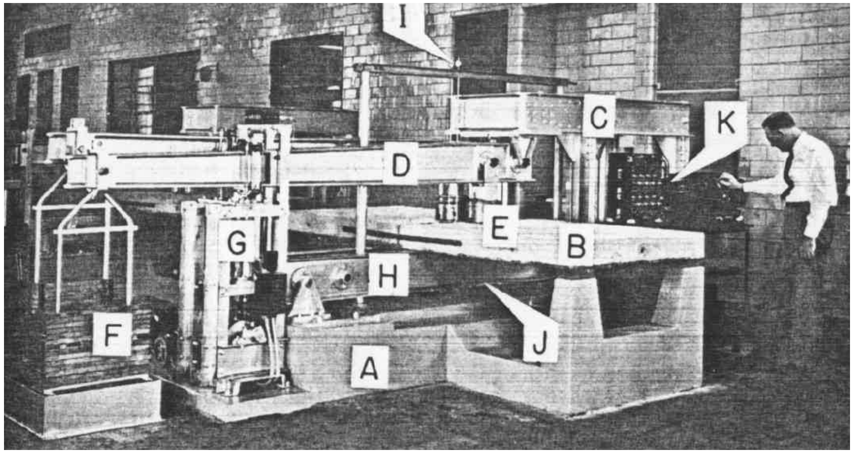


Figure 27. Relations between dowel diameter and dowel looseness resulting from 600,000 cycles of a 10,000-lb load (base measurements obtained at first cycle).

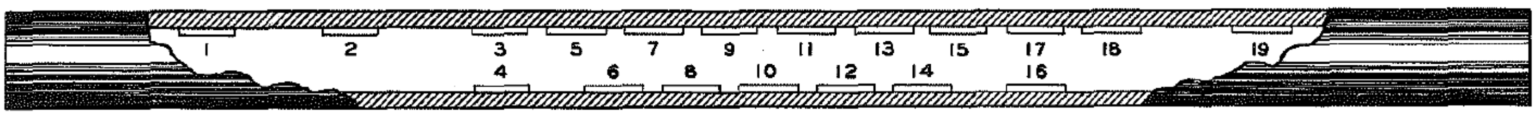


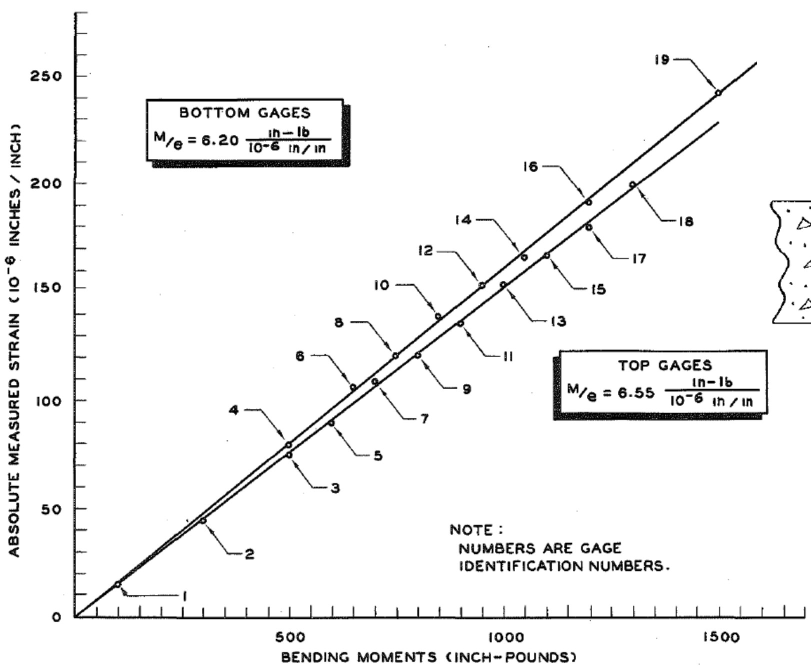
Looseness
Diameter
Joint Opening
Embedment

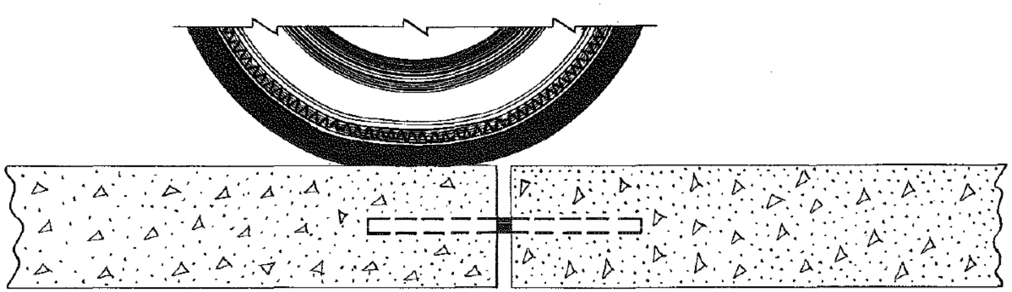
Grouping
Bearing
Other Stresses
Dowel Fatigue

EVEN TESTED STRAIN GAUGES INSIDE OF DOWELS

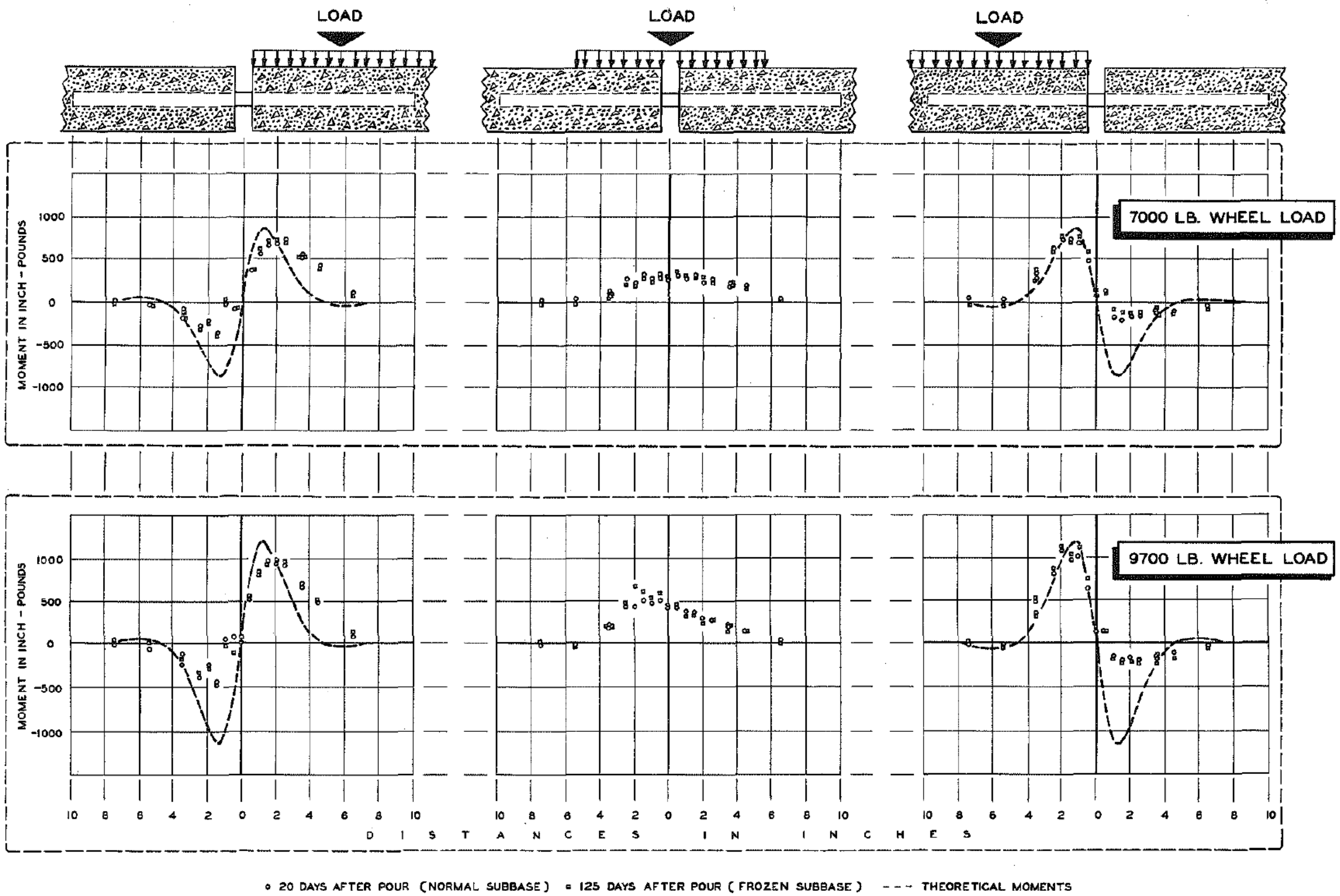
- 1956 – Milliman & Behr – MI DOT – The Experimental Determination of the Stress Distribution Along a Dowel at a Transverse Joint







WHICH VALIDATED OUR MECHANISTIC EQUATIONS



MOMENT DISTRIBUTION IN LOAD TRANSFER DOWEL

…why'd we stop using equations to engineer the solution on a case-by-case basis?

DOWEL GROUP ACTION HAS LONG BEEN UNDERSTOOD TOO

STRESSES IN DOWEL BARS **101**

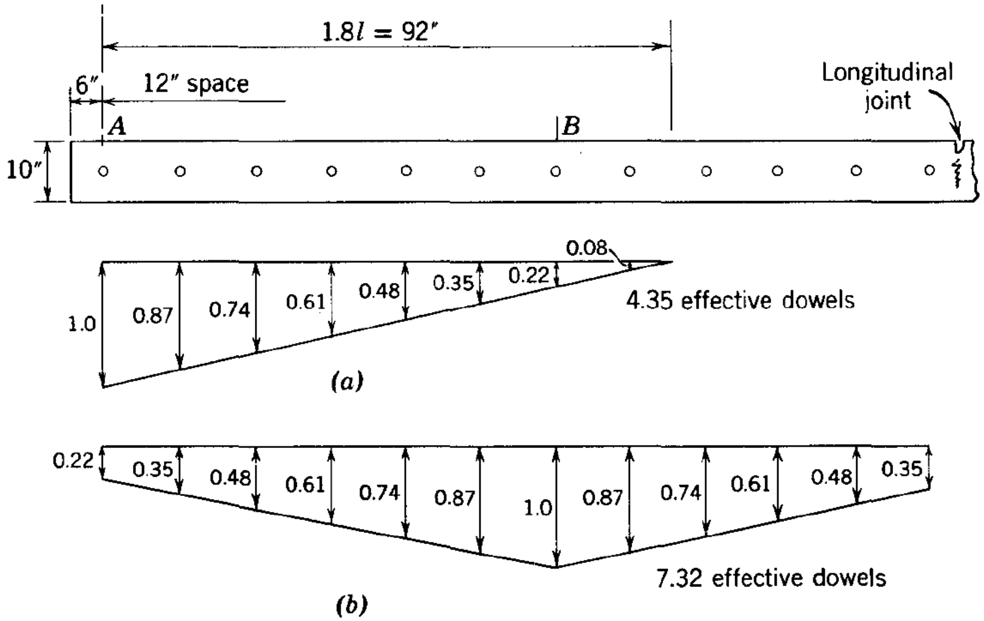


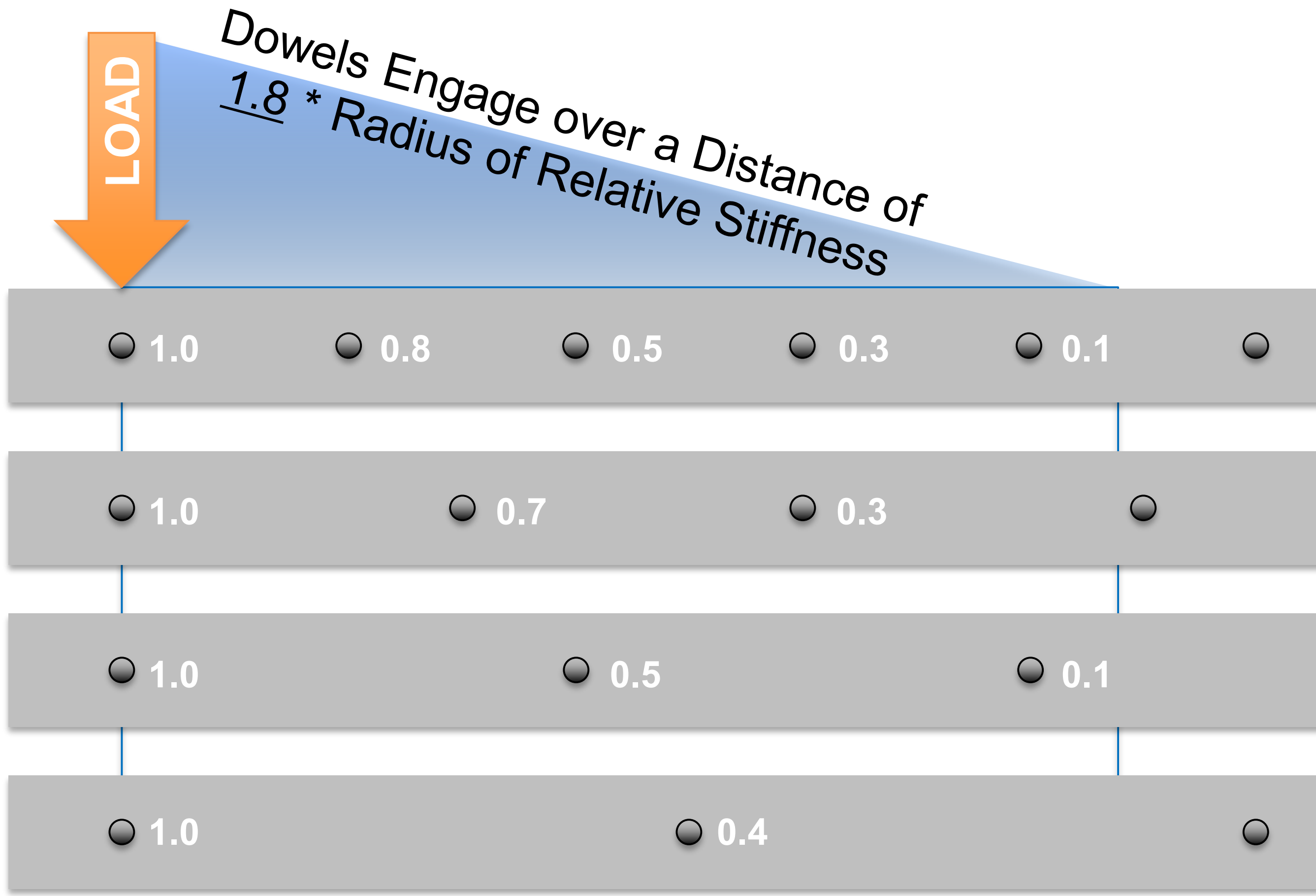
Figure 3.12. Loads on dowel group; pave = 10 inches, k = 50 psi, ¾-inch round dowels spaced 12 inches c–c. (*a*) Effective dowels due to load at *A*; (*b*) effective dowels due to load at *B*.

See “Principles of Pavement Design” by Yoder and Witcazk (1975) for one of the simplest explanations.

PNA CONSTRUCTION TECHNOLOGIES

DOWEL GROUPING ACTION PER 1956 – ACI 325 ASSUMPTION

DOWEL SPACING	# OF DOWELS
12” o/c	2.7
18” o/c	2.0
24” o/c	1.6
30” o/c	1.4



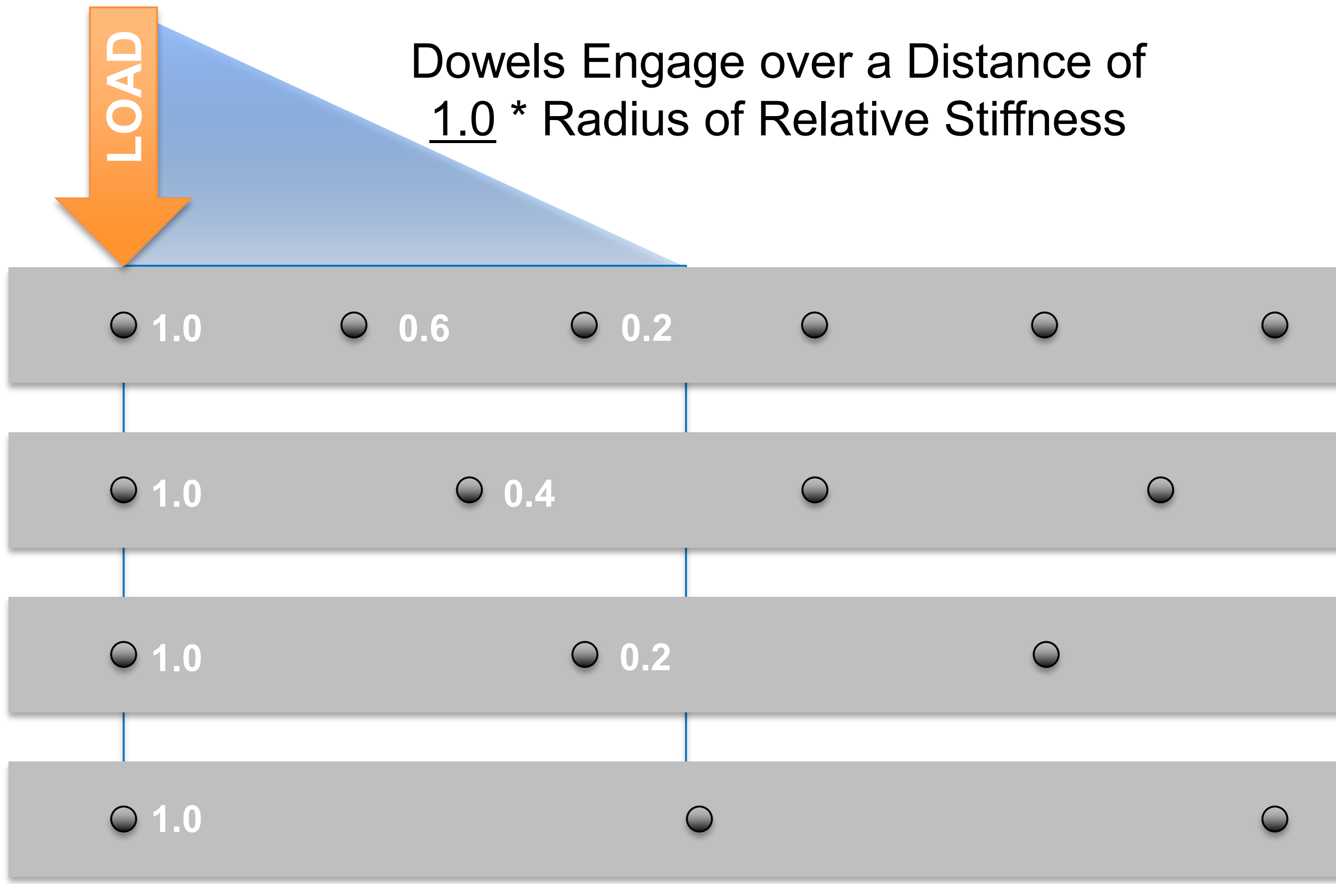
Inputs: h = 6” | E = 4,000,000 psi | k = 100 psi/in. | μ = 0.15
Calculated: l = 29.3 in. | 1.8*l = 52.7 in.

PNA CONSTRUCTION TECHNOLOGIES

DOWEL GROUPING ACTION PER FEA MODEL VIA 1979 – TABATABAIE ET AL

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

DOWEL SPACING	# OF DOWELS
12” o/c	1.8
18” o/c	1.4
24” o/c	1.2
30” o/c	1.0



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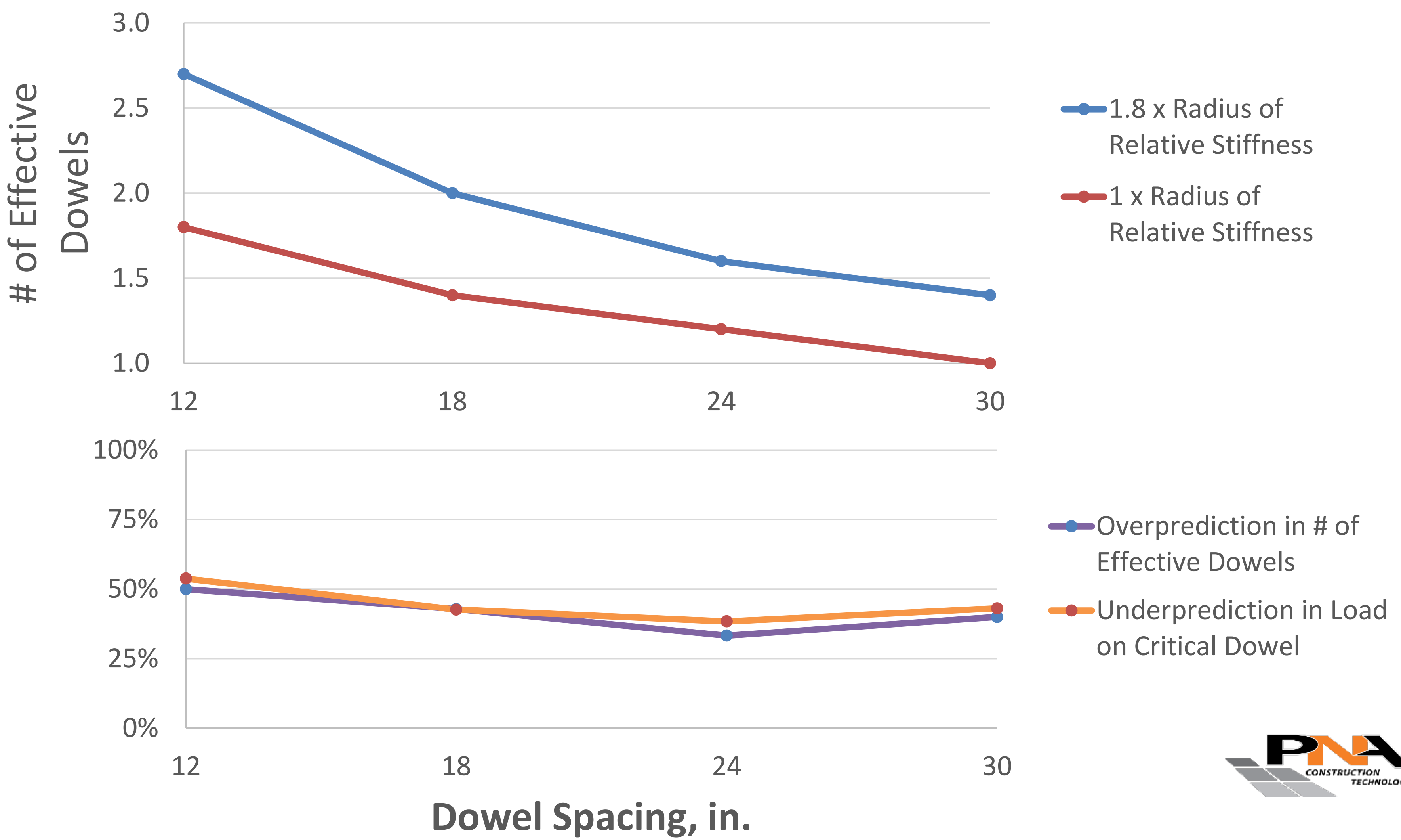
IMPACT OF THIS INCORRECT ASSUMPTION MADE IN 1956 – ACI 325 DOCUMENT

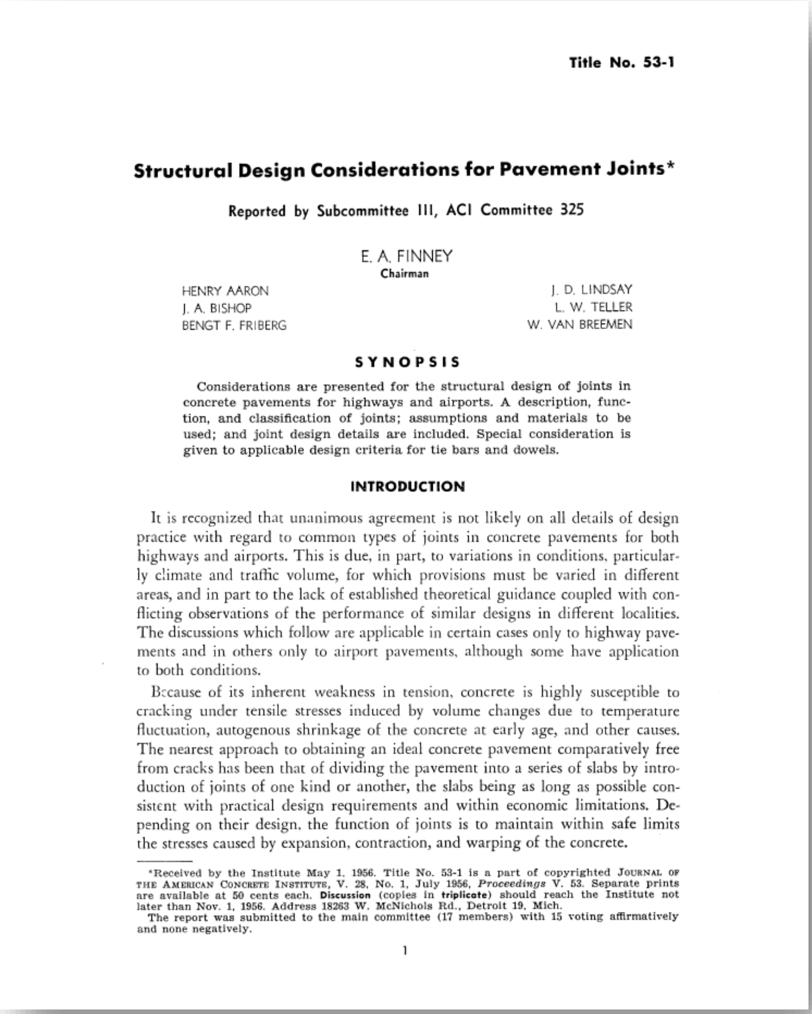


SUMMARY OF CONCERNS WITH THE "STANDARD"

- 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



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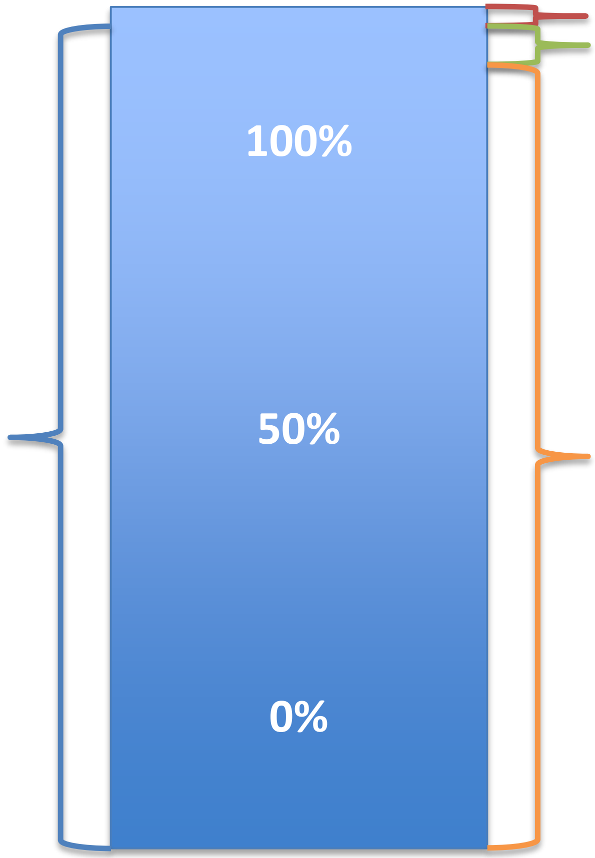
STANDARDIZED = USUALLY UNDEROPTIMIZED

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



% of Design Scenarios

<1% Not Covered

1-2% Optimized by standardization

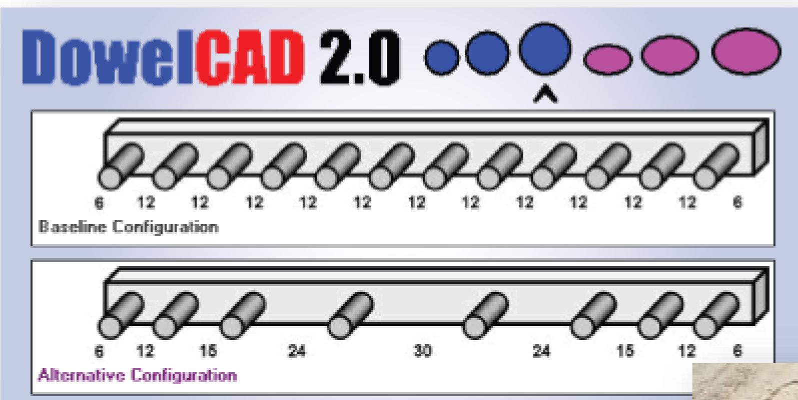
97-98% Underoptimized

Standardized design costs you more $$ than it needs to for your project

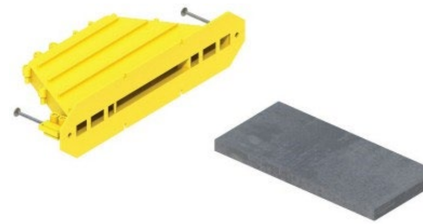
PNA CONSTRUCTION TECHNOLOGIES

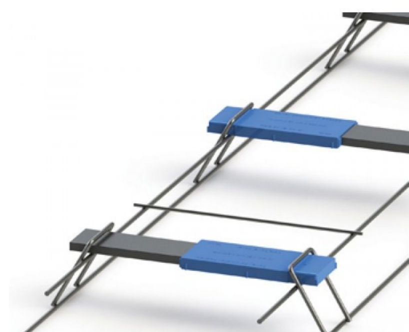
OPTIMIZATION EFFORTS OF THE LAST 25 YEARS

- **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!

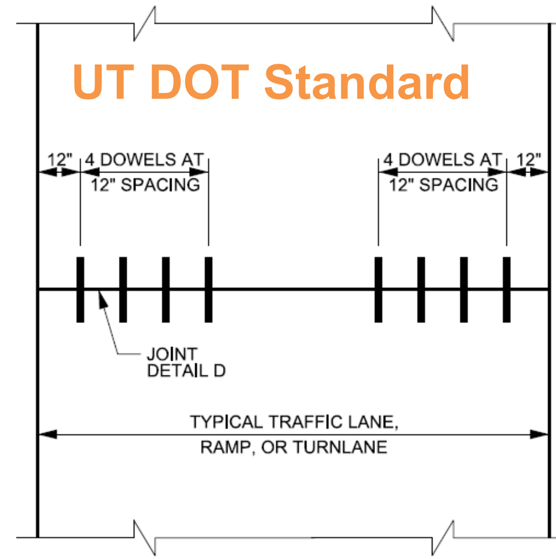


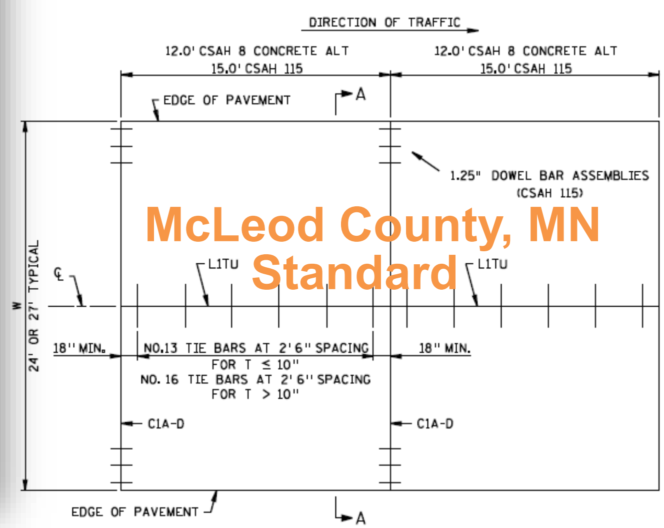


DOTS ARE NOW COMFORTABLE WITH CHANGE

There is a growing trend towards abandoning these "standards"…

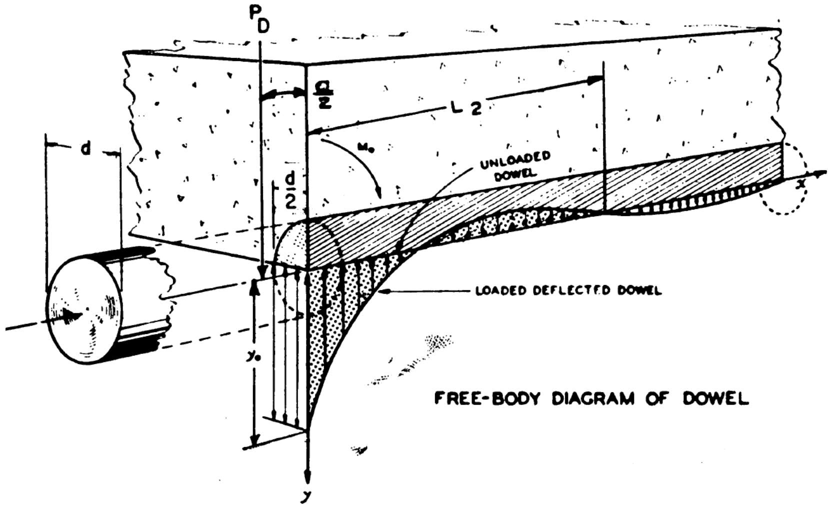
$ saving, reliable engineering

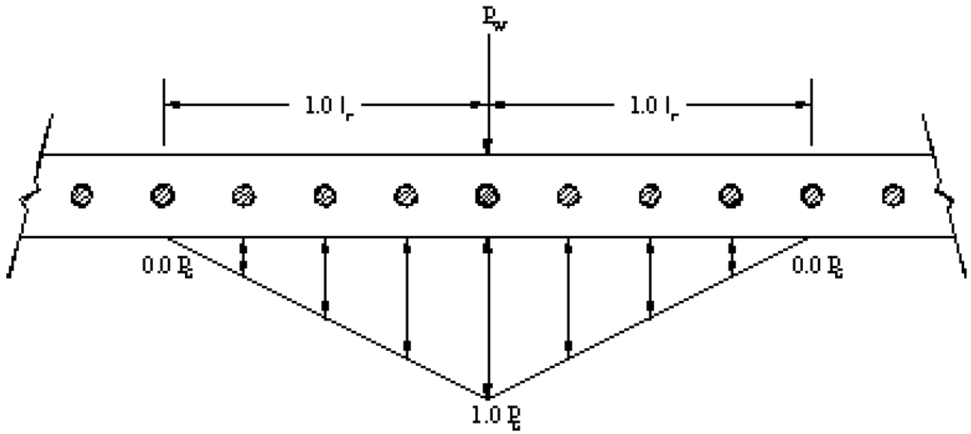


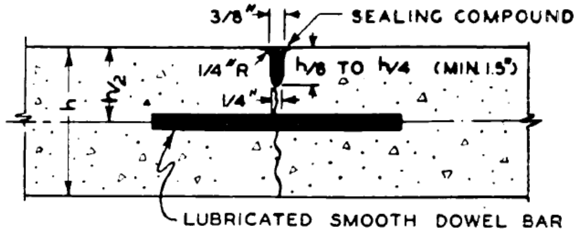


DOWEL DESIGN CONSIDERATIONS **<u>THAT WE CAN CALCULATE RIGHT NOW FOR ANY PROJECT!</u>**

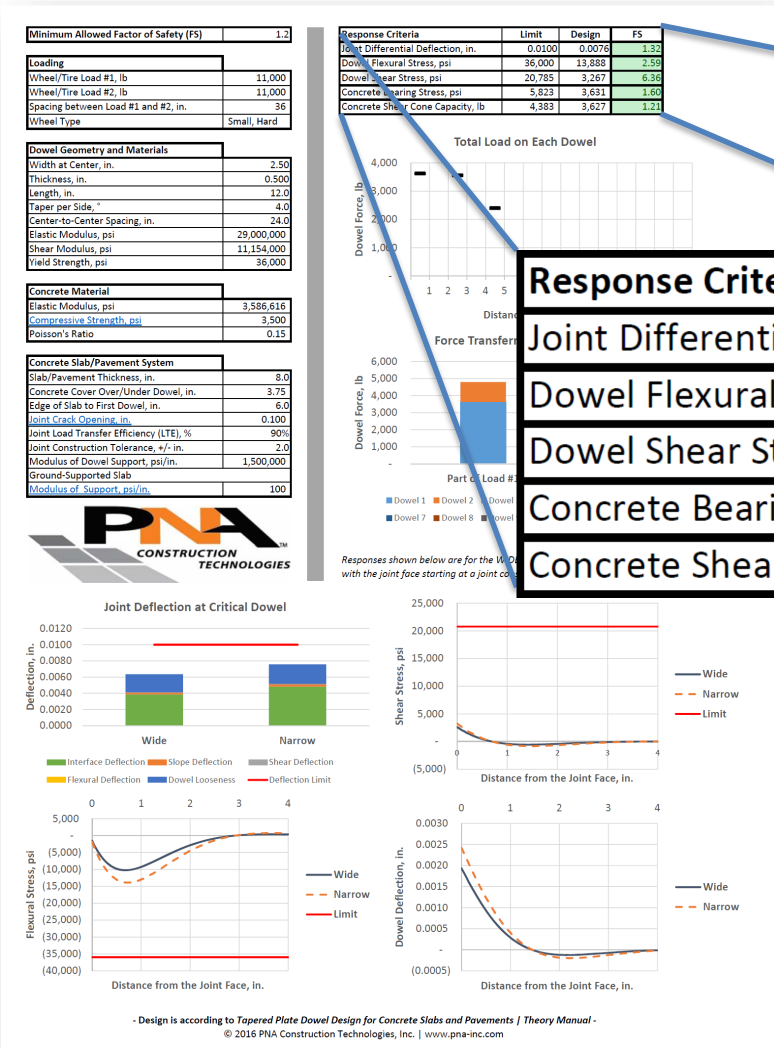
- Critical dowel from group action
- Responses for *<u>shapes & materials</u>*
  - Joint deflection
  - Dowel flexural stress
  - Dowel shear stress
  - Concrete bearing stress
  - Concrete shear cone capacity
- Deflection between dowels







DESIGN TOOLS ALLOW FOR QUICK PROJECT-SPECIFIC DOWEL OPTIMIZATION



Minimum Allowed Factor of Safety (FS)	1.2

Loading	
Wheel/Tire Load #1, lb	11,000
Wheel/Tire Load #2, lb	11,000
Spacing between Load #1 and #2, in.	36
Wheel Type	Small, Hard

Dowel Geometry and Materials	
Width at Center, in.	2.50
Thickness, in.	0.500
Length, in.	12.0
Taper per Side, °	4.0
Center-to-Center Spacing, in.	24.0
Elastic Modulus, psi	29,000,000
Shear Modulus, psi	11,154,000
Yield Strength, psi	36,000

Concrete Material	
Elastic Modulus, psi	3,586,616
Compressive Strength, psi	3,500
Poisson's Ratio	0.15

Concrete Slab/Pavement System	
Slab/Pavement Thickness, in.	8.0
Concrete Cover Over/Under Dowel, in.	3.75
Edge of Slab to First Dowel, in.	6.0
Joint Crack Opening, in.	0.100
Joint Load Transfer Efficiency (LTE), %	90%
Joint Construction Tolerance, +/- in.	2.0
Modulus of Dowel Support, psi/in.	1,500,000
Ground-Supported Slab	
Modulus of Support, psi/in.	100

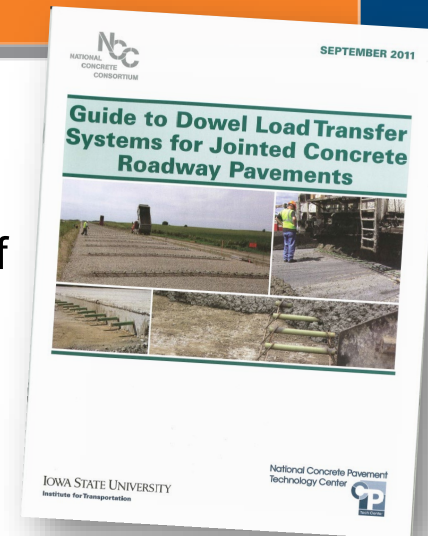
- Design is according to *Tapered Plate Dowel Design for Concrete Slabs and Pavements | Theory Manual* -

Response Criteria	Limit	Design	FS
Joint Differential Deflection, in.	0.0100	0.0076	1.32
Dowel Flexural Stress, psi	36,000	13,888	2.59
Dowel Shear Stress, psi	20,785	3,267	6.36
Concrete Bearing Stress, psi	5,823	3,631	1.60
Concrete Shear Cone Capacity, lb	4,383	3,627	1.21

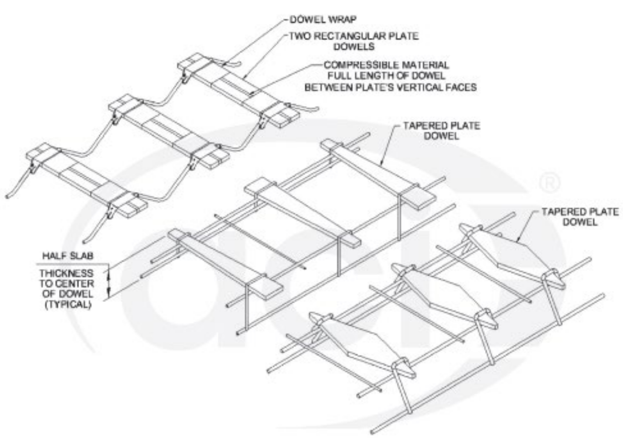
Manufacturer's recommendations are appropriate when supported by thorough engineering.

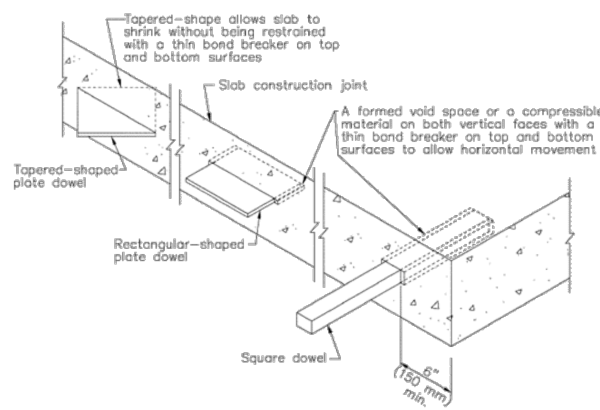
<u>CONCRETE MATERIAL MATTERS!</u>

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:**





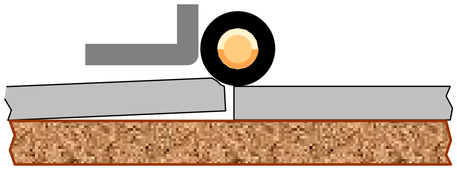
EXAMPLE OF SHAPE IMPACT ON RESPONSES

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

Keeping area of 1 in^2 (6.5 cm^2)
SAFETY FACTOR IN DESIGN:

Response Criteria	1.13” (2.9 cm) Diameter	1” x 1” (2.5 x 2.5 cm)	2” x 0.5” (5 x 1.3 cm)
Joint Deflection	1.83	1.73	1.89
Dowel Flexural Stress	3.78	4.30	3.44
Dowel Shear Stress	10.37	10.37	10.37
Concrete Bearing Stress	2.74	2.54	2.94
Concrete Shear Cone Capacity	1.52	1.55	1.82

DEFLECTION IS JUST ONE FAILURE



PNA CONSTRUCTION TECHNOLOGIES

ACI 360R-10
GUIDE TO DESIGN OF SLABS ON GROUND

Table 6.1—Dowel size and spacing for construction and contraction joints*

Slab depth, in. (mm)	Dowel dimensions, in. (mm)					Dowel spacing center-to-center,† in. (mm)		
	Construction joint		Contraction joint		Plate dowel			
	Round‡	Square§‖	Round‡	Square§‖		Round‡	Square§‖	Plate dowel
5 to 6 (130 to 150)	3/4 x 10 (19 to 250)	3/4 x 10 (19 x 250)	3/4 x 13 (19 x 330)	3/4 x 13 (19 x 330)	M/R#	12 (300)	14 (360)	18 (460)
7 to 8 (180 to 200)	1 x 13 (25 x 330)	1 x 13 (25 x 330)	1 x 16 (25 x 410)	1 x 16 (25 x 410)	M/R#	12 (300)	14 (360)	18 (460)
9 to 11 (230 to 280)	1-1/4 x 15 (32 x 380)	1-1/4 x 15 (32 x 380)	1-1/4 x 18 (32 x 460)	1-14 x 18 (32 x 460)	M/R#	12 (300)	12 (300)	18 (460)

*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.

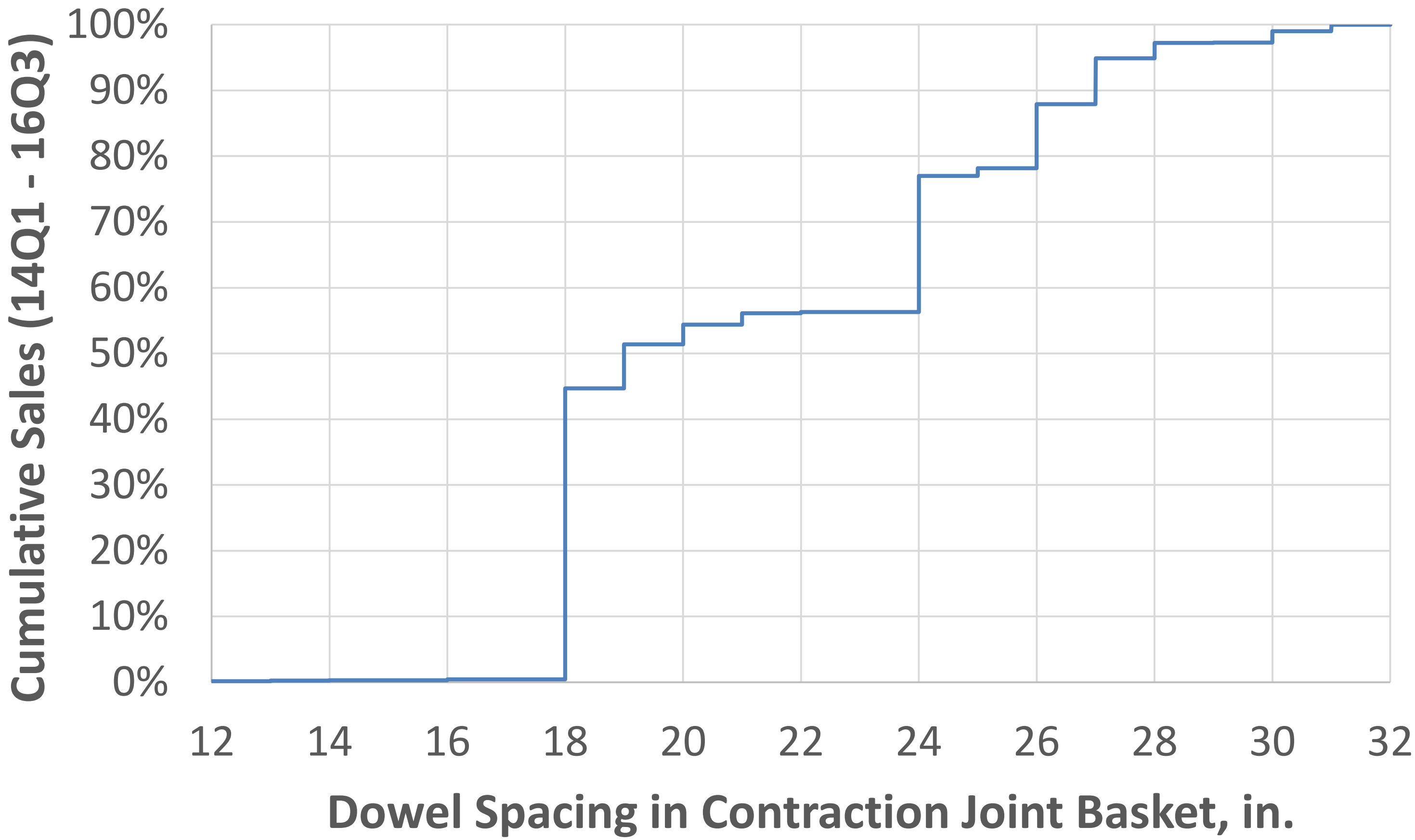
‡ACI Committee 325 (1956), Teller and Cashell (1958).

§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.

TAPERED PLATE DOWEL SPACING IN SAWCUT CONTRACTION JOINTS – 12” O/C NONEXISTENT!



TAPERED PLATES IN ROADWAYS?

MnROAD
Safer, Smarter, Sustainable Pavements Through Innovative Research

- 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

PNA CONSTRUCTION TECHNOLOGIES

PD3 for Sawcut Contraction Joints

DiamondDowel for Construction Joints

PNA CONSTRUCTION TECHNOLOGIES

Thank you for your time.

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QUESTIONS?