Concrete Slab-on-Ground Crack and Joint Spalling Prevention of a General Spec Building

PNA™
CONSTRUCTION TECHNOLOGIES

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Contents

Evaluation Goals

Using information provided via e-mail, the following are evaluated in this report:

- **Concrete slab-on-ground cracking resistance** via ISLAB 2000 finite element analysis (FEA).
- **Joint deflection and resistance to cracking or spalling under lift truck loads**.

These serviceability-focused goals are evaluated herein with and without dowels.

While attempts have been made to ensure conservatism in inputs and load configurations, all analyses should be considered as generalized evaluations and not specific to the final design of this facility.

Finite Element Analysis (FEA) Design Assumptions

Concrete Surface Course Layer:

- Thickness: 7 in.
- Slab-on-ground sawcut panel size: 13.5 ft x 15 ft
- Elastic Modulus: 4,000,000 psi
- Poisson Ratio: 0.15
- Coefficient of Thermal Expansion: 4.40×10^{-6} /°F
- Unit Weight: 0.0870 lb/in.^{3}
- Equivalent Temperature Gradient (e.g., curling and warping): -15°F

Subgrade:

- Type: Winkler
- Modulus of Subgrade Support (k-value): 100 psi/in.

Joint Load Transfer Efficiency (LTE):

- Undoweled: 15%
- Doweled: 90%

Loading:

- Racks: Being a speculative building, the exact service loads are unknown. Thus, the building height of 35 ft was utilized to assume that rack legs will carry the load of 6 shelves of height 5 ft, with the 7th pallet in the column resting on a skid on the floor. Pallets were assumed to weigh 4,500 lb max each but, to not introduce too much conservatism into this analysis and because it is being used solely for comparative illustration, a working load adjustment of 75% is used – this effectively means that on average 25% of the shelves are empty in operations or, alternatively, that the average pallet weight is 75% of this 4,500 lb pallet max. With two-bay wide shelves, this results in end aisle column leg loads of 8,775 lb and all other rack leg loads in a continuous rack being 17,550 lb. There is much uncertainty as to both the orientation and location of the rack configurations with respect to the joints; rack configurations are assumed as illustrated in Appendix A based on the experience of PNA staff to consider both bottom-up slab stresses under back-to-back rack legs and to consider top-down slab stresses under the continuous back-to-back racks as well as any possible interaction with the lift truck. Rack foot size and leg spacing was assumed at a value in-line with typical industry averages.

- Lift Truck: Because the design max pallet weight is 4,500 lb, a standard lift truck with this capacity in its range was assumed (see appendix F for the lift truck details).

Concrete Slab Capacity

To develop a factor of safety on the concrete slab-on-ground cracking resistance requires first an understanding of the capacity of a concrete slab-on-ground. The maximum strength of a concrete slab in the field is greater than the flexural strength of an unsupported lab-cured concrete beam tested at 28-days. The slab capacity can be approximated as:

$$\sigma_{max}=(MOR_{avg}+t*MOR_{SD})\text{x } F_e \text{ x } C_1\text{x } C_2$$

where:

- σ_{max} = allowable concrete tensile strength, psi
- MOR_{avg} = specified concrete flexural strength, psi | specified strength minimum compressive strength of 4,500 psi is 503 psi flexural per the ACI 318 conversion equation
- t = standard normal deviate (z-score) | at 80% reliability on MOR tests, z-score = 0.84
- MOR_{SD} = standard deviation (SD) on concrete flexural strength, psi | coefficient of variation (COV) of ready-mixed concrete is approximately 15%, thus SD = 15% * MOR_{avg} = 75 psi
- F_e = 28-to-90 day strength correction factor | approximately (1.235*(1-COV)) = 1.05
- C_1 = beam-to-slab correction factor | 1.3 for bottom-up cracking and 1.0 for top-down cracking
- C_2 = fiber factor, assumed equal to 1 for concrete without macrosynthetic or steel fibers

The slab capacity for <u>bottom-up cracking</u> is:

$$\sigma_{max}^{\text{bottom-up - plain}} = (503 \text{ psi} + 0.84 \text{ x } 75 \text{ psi}) \text{ x } 1.05 \text{ x } 1.3 \text{ x } 1 = 773 \text{ psi}$$

The capacity for <u>top-down cracking</u> is:

$$\sigma_{max}^{\text{top-down}} = (503 \text{ psi} + 0.84 \text{ x } 75 \text{ psi}) \text{ x } 1.05 \text{ x } 1 \text{ x } 1 = 595 \text{ psi}$$

The Factor of Safety (FOS) in design against cracking is the ratio of slab capacity to maximum stress generated at the top or bottom concrete slab surface under the design loads.

Cracking Resistance in the Concrete Slabs

Modeling the inputs described in this report per the model shown in Appendix A with and without doweled joints yields the following critical response results as extracted from the FEA results presented in Appendix B for the undoweled condition and Appendix C for the doweled condition:

Joint Type	Maximum Top Stress, psi	Maximum Bottom Stress, psi
Undoweled	418	456
Doweled	263	413

In both the doweled and undoweled scenarios, the maximum bottom stress is similar because this is caused by the concentrated load of back-to-back rack leg loads totaling over 35 kips in a relatively small area; even still, the doweled case has about 10% lower bottom stress. The top stress is much higher for the undoweled scenario than the doweled scenario; Appendix G provides a quick snapshot of why two-directional doweling can achieve such large reductions in stress, in this case > 37% reduction.

To illustrate the factor of safety (FOS) against either bottom-up or top-down cracking, the ratio of the maximum stress from the FEA model to the slab capacity is calculated:

SLAB CAPACITIES ANALYSIS		
Top-Down Capacity, psi	608	
Bottom-Up Capacity, psi	790	
	Undowel	Doweled
Top-Down Cracking FOS	1.5	2.3
Bottom-Up Cracking FOS	1.7	1.9
Design Stress Ratio	0.69	0.52
Allowable Load Repetitions at 85% Reliability on Fatigue	2,000	2,000,000

Joint Performance

Undoweled joints cannot provide long-term load transfer and joint performance assurance.
As noted in ACI 360R-10, "Guide to Design of Slabs-on-Ground":

> "Joint or crack stability measurements below 0.010 in. (0.25 mm) for joints or cracks subjected to lift truck wheel traffic with small hard wheels will have good service life (Tarr 2004; Walker and Holland 2007a). For lift truck traffic with large, cushioned rubber wheels, a joint or crack stability measurement of 0.020 in. (0.51 mm) should have good service life (Walker and Holland 1999, 2007a)."

The Walker and Holland 2007a reference of note in this quote is "Performance-Based Dowel Design," an article written by these industry experts at Structural Services, Inc. and which was written to facilitate design of PNA's PD3 dowels, which it has successfully done for the last decade. PNA has also since advanced the state of design with our doweling products, as shown in Appendices D and E.

Without more specific details on which to base a design, the 4,500 lb capacity lift truck again is used. Based on the Walker and Holland 2007a reference, 3/8 in. wide PD3 tapered plate dowels at 24 in. o/c are more than sufficient to carry a 4,000 lb lift truck in a 6 in. thick slab. We, therefore, are using this PD3 size and spacing to illustrate structural sufficiency for the 5,600 lb wheel loads at 45 in. spacing as found in the assumed lift truck. To simplify specifications and drawings, it can be of interest to maintain Diamond Dowel spacing on construction joints that is the same as the PD3 spacing in baskets in sawcut contraction joints.

Appendix D and E provide design reports of ¼ in. thick Diamond Dowels and 3/8 in. x 2 in. PD3 plate dowels, respectively, each at 24 in. o/c spacing in a 7 in. slab and with other inputs assumed as shown. While a more optimized design is always possible with a complete understanding of the service loads and their configuration, these designs are suitable for a spec building.

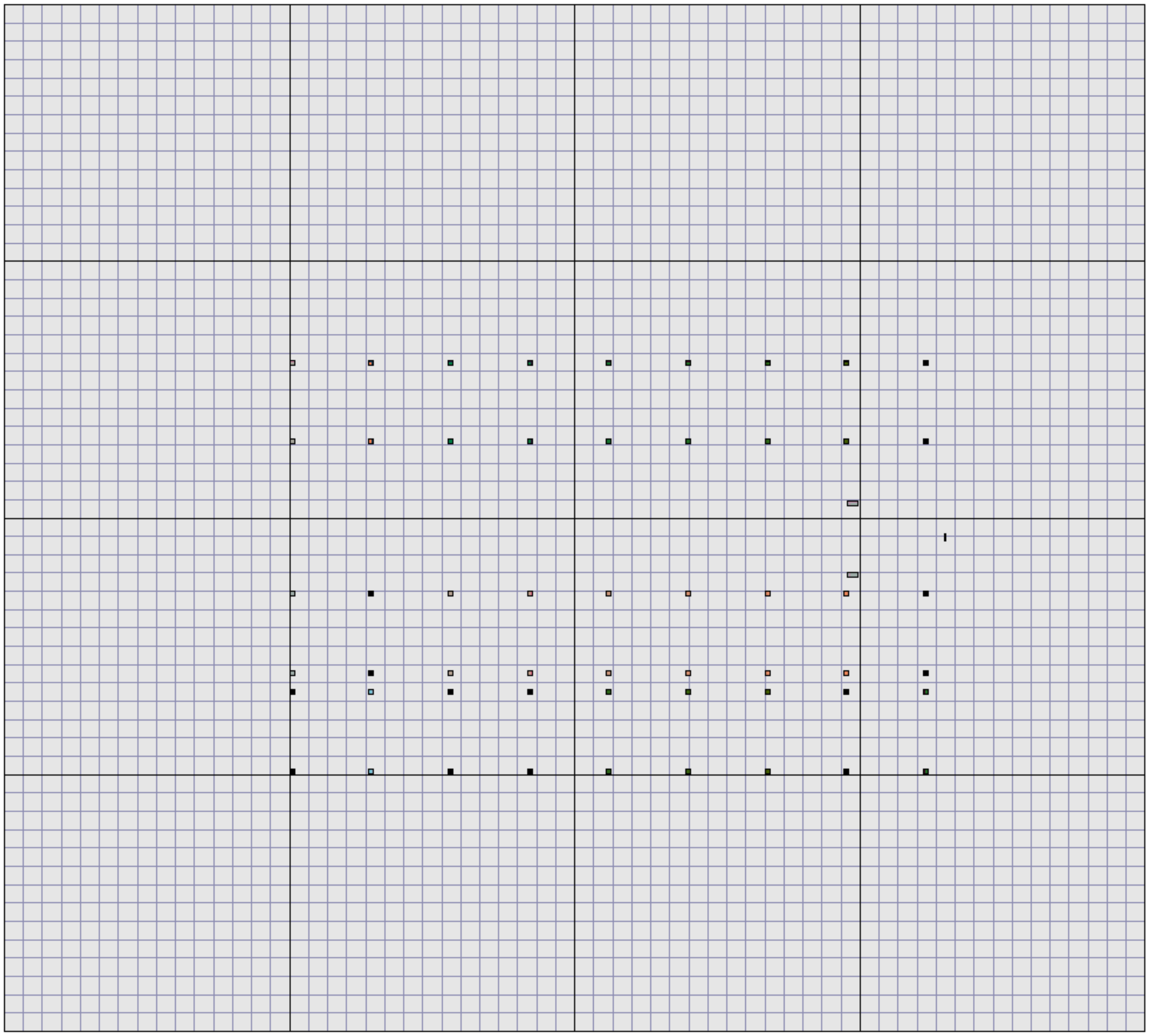
Discussion and Recommendations

Doweled jointed plain concrete slabs have a higher factor of safety than undoweled concrete slabs for the assumed and typical rack and lift truck loads detailed in this report. Doweled construction joints should include ¼ in. Diamond Dowels at 24 in. o/c and doweled sawcut contraction joints should include 3/8 in. PD3 dowels at 24 in. o/c.

Additional Analyses

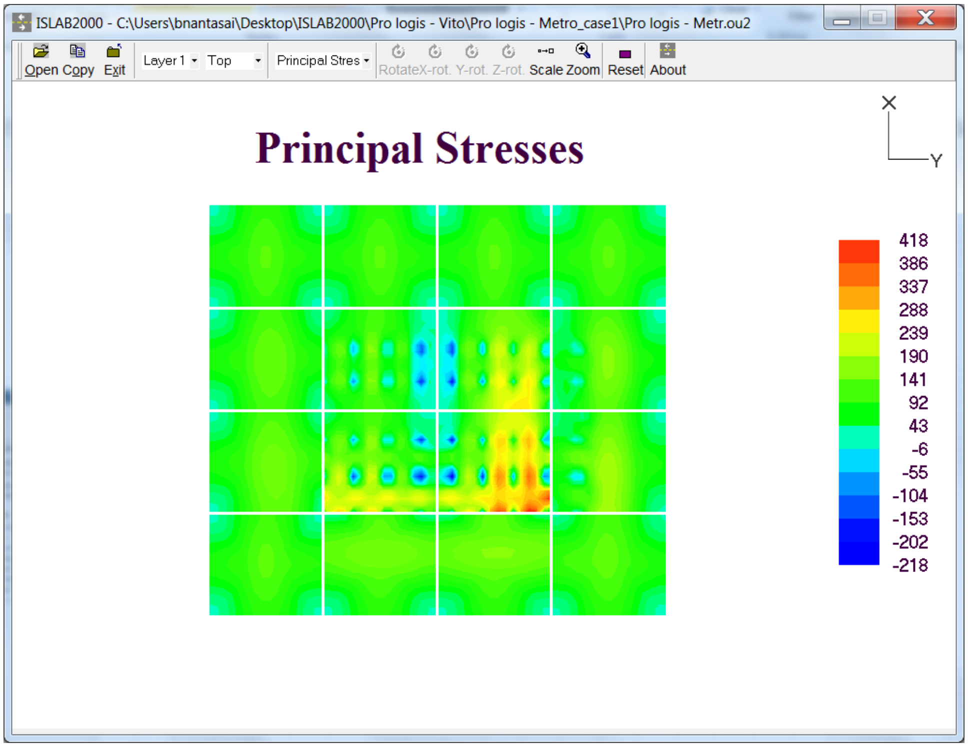
While this document aims to serve as a preliminary analysis based on anticipated and typical rack loading and other factors, PNA extends the offer of more project-specific FEA for the rack, tank, lift-truck, mezzanine, and other loaded areas of this facility if such analyses are of value to the owner.

Appendix A – Assumed Rack and Lift Truck Load Configuration

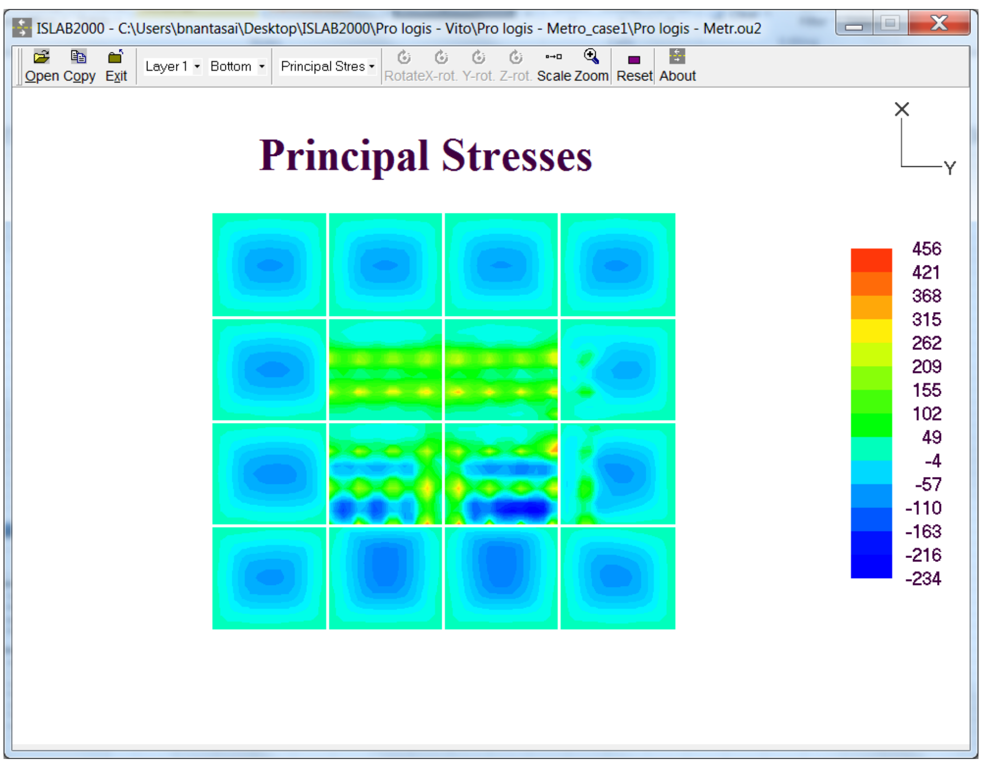


Appendix B – FEA Results– Undoweled Joints

Top Stresses on the Concrete Slab

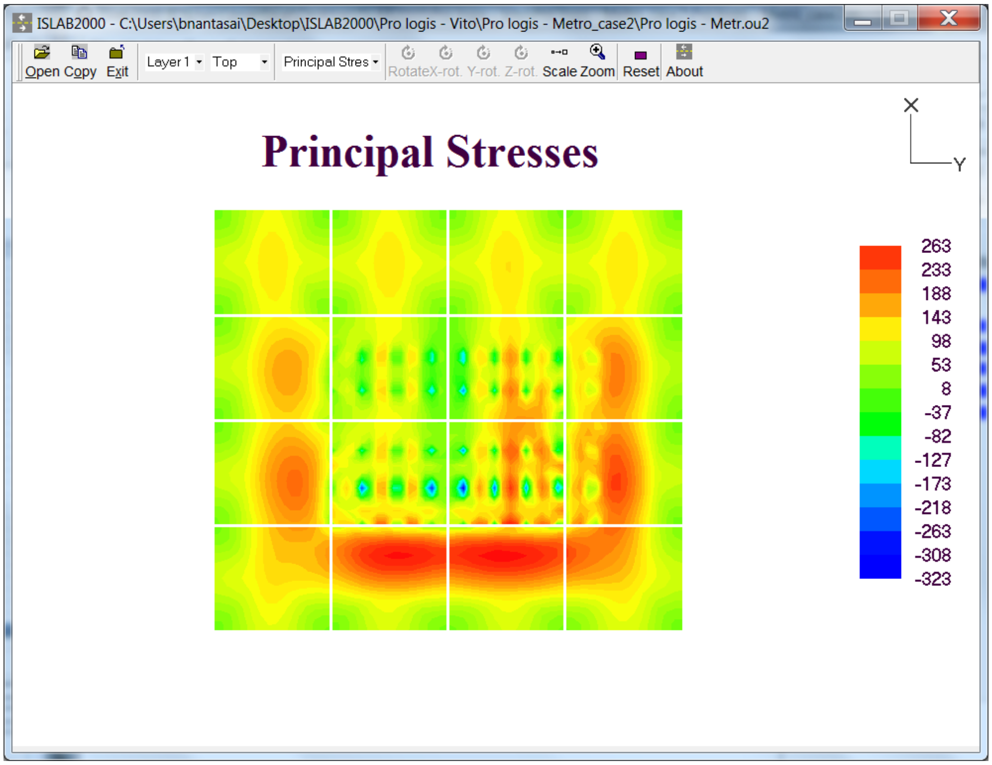


Bottom Stresses on the Concrete Slab

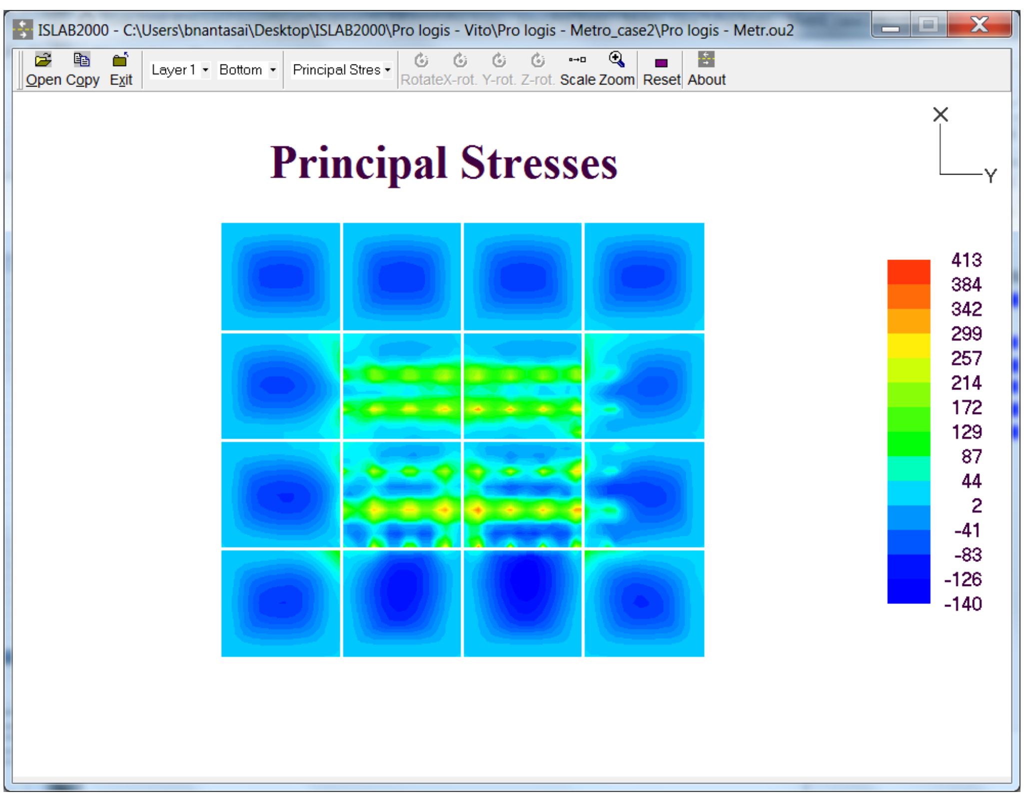


Appendix C – FEA Results – Doweled Joints

Top Stresses on the Concrete Slab



Bottom Stresses on the Concrete Slab



Appendix D – Typical 7" Spec Building Diamond Dowel Design

Minimum Allowed Factor of Safety (FS)	1.2

Loading	
Load #1 (closest to slab corner), lb	5,600
Load #1 on a free edge?	No
Load #2, lb	5,600
Spacing between Load #1 and #2, in.	45.0
Wheel Type	Hard

Dowel Geometry and Materials	
Width at Center, in.	6.36
Thickness, in.	0.250
Length, in.	6.36
Taper per Side, °	45.0
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	4,066,840
Compressive Strength, psi	4,500
Poisson's Ratio	0.15

Concrete Slab/Pavement System	
Slab/Pavement Thickness, in.	7.0
Concrete Cover Over/Under Dowel, in.	3.38
Edge of Slab to First Dowel, in.	9.0
Joint Crack Opening, in.	0.090
Joint Load Transfer Efficiency (LTE), %	90%
Modulus of Dowel Support, psi/in.	1,500,000
Ground-Supported Slab	
Modulus of Subgrade Support, psi/in.	100

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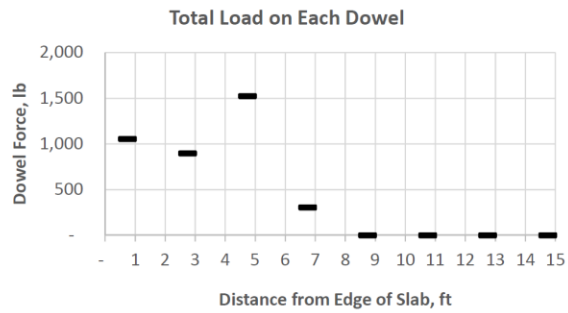
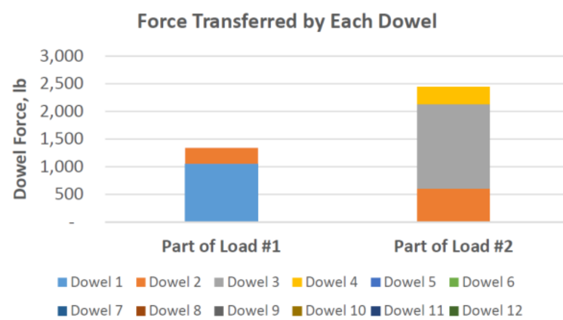
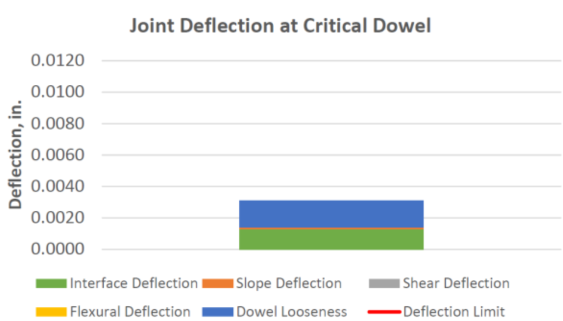
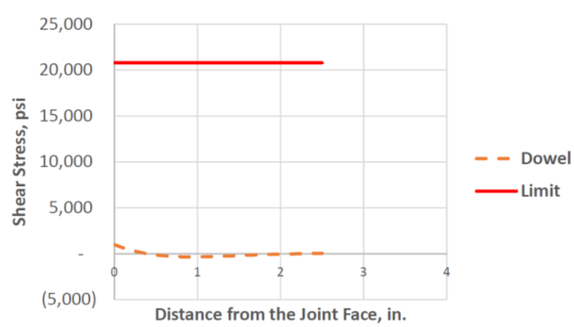
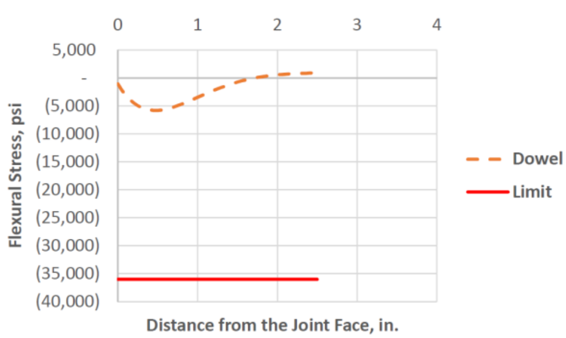
Response Criteria	Limit	Design	FS
Joint Differential Deflection, in.	0.0100	0.0044	2.27
Dowel Flexural Stress, psi	36,000	5,820	6.19
Dowel Shear Stress, psi	20,785	986	21.09
Concrete Bearing Stress, psi	34,589	945	36.61
Concrete Shear Cone Capacity, lb	4,504	1,524	2.96

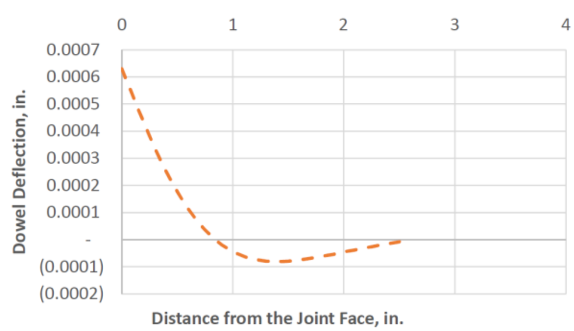












- Design is according to *Tapered Plate Dowel Design for Concrete Slabs and Pavements | Theory Manual* -

Appendix E – Typical 7" Spec Building PD3 Dowel Basket Design

Minimum Allowed Factor of Safety (FS)	1.2

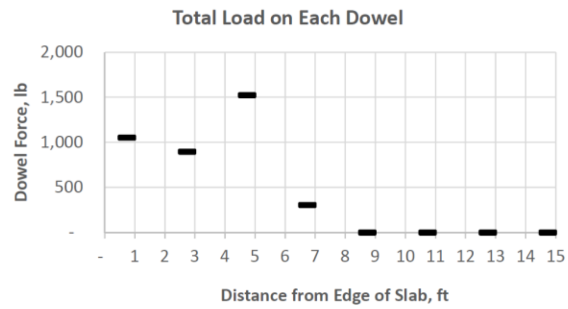
Loading	
Load #1 (closest to slab corner), lb	5,600
Load #1 on a free edge?	No
Load #2, lb	5,600
Spacing between Load #1 and #2, in.	45.0
Wheel Type	Hard

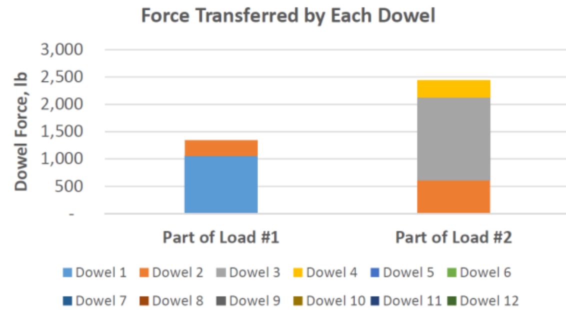
Dowel Geometry and Materials	
Width at Center, in.	2.00
Thickness, in.	0.375
Length, in.	12.0
Taper per Side, °	4.0
Center-to-Center Spacing, in.	24.0
Elastic Modulus, psi	29,000,000
Shear Modulus, psi	11,154,000
Yield Strength, psi	36,000

Concrete Material	
Elastic Modulus, psi	4,066,840
Compressive Strength, psi	4,500
Poisson's Ratio	0.15

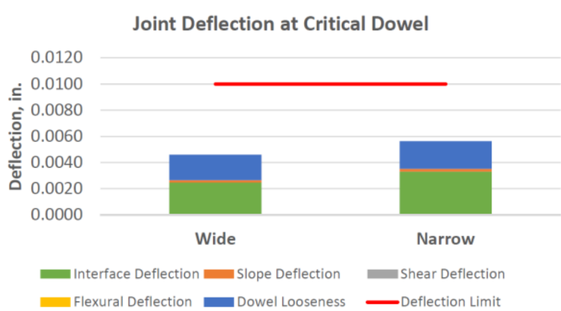
Concrete Slab/Pavement System	
Slab/Pavement Thickness, in.	7.0
Concrete Cover Over/Under Dowel, in.	3.31
Edge of Slab to First Dowel, in.	9.0
Joint Crack Opening, in.	0.090
Joint Load Transfer Efficiency (LTE), %	90%
Joint Construction Tolerance, +/- in.	2.0
Modulus of Dowel Support, psi/in.	1,500,000
Ground-Supported Slab	
Modulus of Support, psi/in.	100

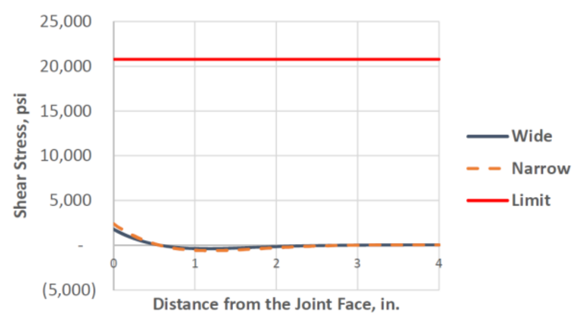
Response Criteria	Limit	Design	FS
Joint Differential Deflection, in.	0.0100	0.0070	1.43
Dowel Flexural Stress, psi	36,000	10,926	3.29
Dowel Shear Stress, psi	20,785	2,380	8.73
Concrete Bearing Stress, psi	8,084	2,475	3.27
Concrete Shear Cone Capacity, lb	4,116	1,524	2.70

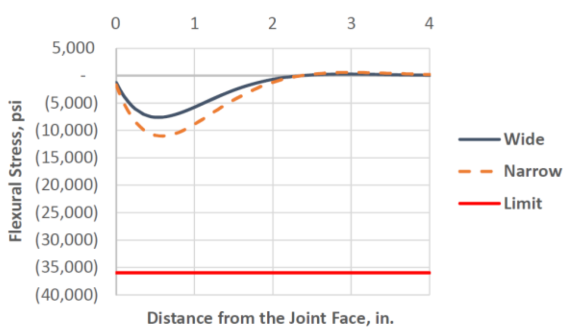


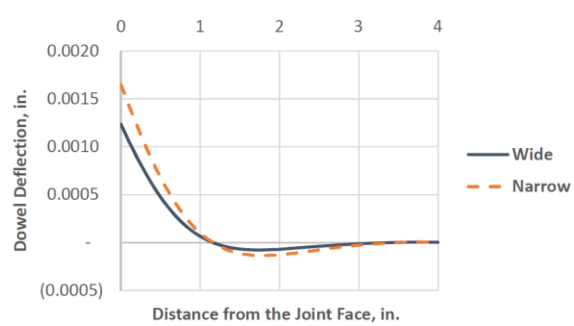


Responses shown below are for the WIDE and NARROW sides of the critical dowel with the joint face starting at a joint construction tolerance's away from the dowel center



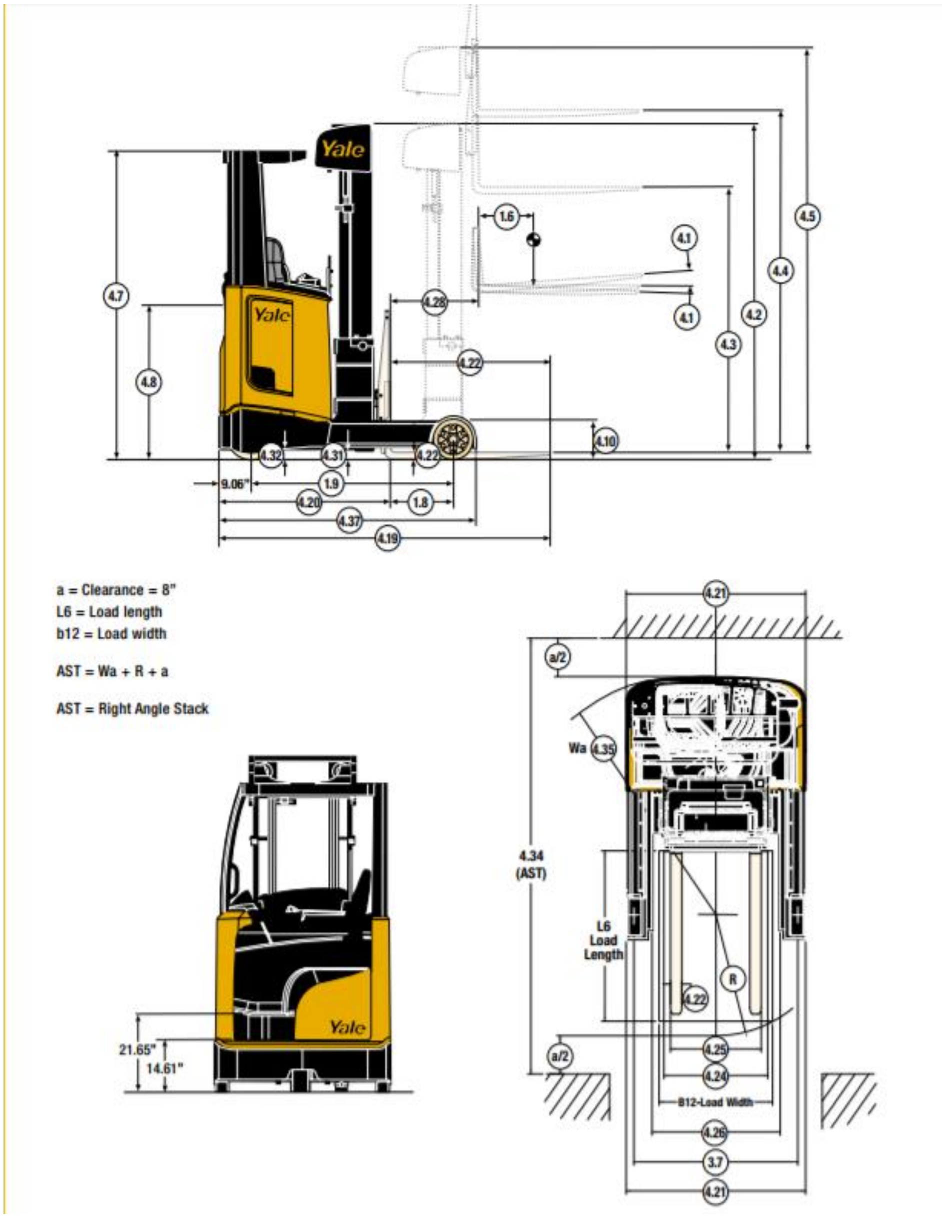






- Design is according to *Tapered Plate Dowel Design for Concrete Slabs and Pavements | Theory Manual* -

Appendix F – Assumed Lift Truck – Yale MR with 5,500lb Load Capacity



More details available at:

- http://www.yale.com/uploadedFiles/Yale/Content/North-America/Product_Range/MR14-25-SpecSheet.pdf
- http://www.yale.com/uploadedFiles/Yale/Content/North-America/Product_Range/MR14-25-brochure.pdf

Appendix G – Summary of the Value of Two Directional Doweling