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Performance-Based Dowel Design

Lift-truck design changes require a new look at joint durability

By Wayne W. Walker and Jerry A. Holland

Serviceability is the name of the game with floor slabs that will have lift truck traffic. The most vulnerable places on such a floor slab are the joints. The joints break down when a lift truck moves toward the joint, deflecting down the edge of the slab panel it is on, then bumping against the joint face of the adjacent, slightly higher, panel.

Relying on aggregate interlock for long-term load transfer at the contraction joints of such slabs is impractical, as we have previously noted (see Ref. 1 and 2). The American Concrete Institute (ACI) publications have been recommending dowels at joints for a number of years.

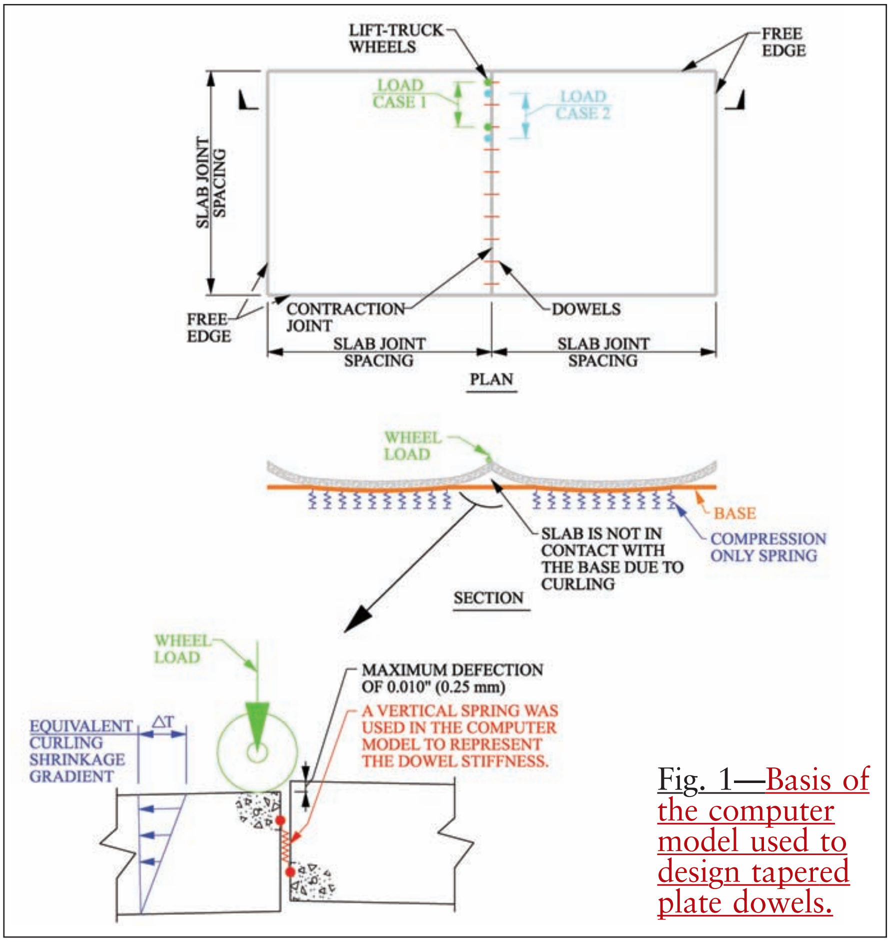


Fig. 1—Basis of the computer model used to design tapered plate dowels.

ACI 360R-06 "Design of Slabs on Ground" (see page 134 for a summary of this new document) states that "Doweled joints are recommended when positive load transfer is required," and ACI 302.1R-96 and ACI 302.1R-04 "Guide for Concrete Floor and Slab Construction" have similar recommendations.

Most slab thickness design procedures assume that load is transferred between adjacent slab panels. Our experience is that to protect the joints proper load transfer is especially important when significant lift truck traffic is anticipated. Thus, doweled contraction joints should be used to minimize joint spalling due to lift truck traffic, minimize lift truck maintenance cost, and share the load to prevent the higher stresses resulting from the loading of free edges. But when dowels are used, the slab designer should consider the properties of the dowel system specified, which include its geometry, installation tolerances, and bond-breaking material, along with the cost of the dowel system. If only one of these properties are compromised, then severe and costly problems could occur.

This article is a continuation of an article we wrote in 1998 (see Ref. 3), where we discussed the many benefits of plate dowels. Tapered plate dowels have been in use for over four years on a number of projects. In this article, we will discuss the benefits of using tapered plate dowels in contraction joints and provide design recommendations for the size and spacing of these dowels for industrial floors to accommodate lift truck loadings. These design recommendations are based on both strength and serviceability criteria for lift truck loadings and are more rational than the traditional method of selecting the dowel size and spacing based on slab thickness.

Historical dowel design

Most of the significant dowel research and corresponding recommendations (such as in References 4 and 5) were done in the 1940s and 1950s. These recommendations were for round dowels and for highway traffic loadings with wheels spaced 5 to 9 feet apart. The dowel recommendations in ACI 302.1R-04 are based on these highway types of loads and may not be conservative enough for some lift truck loadings, while being too conservative for some other types of loads. For industrial floor slabs where lift trucks will be used, the wheel loads can be higher than on a highway—the tires are a hard solid material (as opposed to the large, soft pneumatic tires used for highway traffic), the load contact area is over a smaller area (due to the hard solid tire material), and the wheels are at a much closer spacing (18 to 42 inches).

The recommendations for round dowels for highway traffic loadings were developed with the objective of limiting the bearing pressure of the dowel on the concrete. But there are other dowel design requirements that are important for industrial floors slabs with lift trucks, such as the relative deflection between the slab panels, the effect of curling on the deflection of slab panels with dowels, and how curling affects the distribution of the force in the dowels due to the wheel loads. None of these were considered.

Analytical approach

We have developed extensive computer programs, along with using a commercially available program, to analyze the forces in the dowels and to determine the relative differential deflection between the slab panels. The model used is shown in Fig. 1.

We used a nonlinear analysis using a finite plate element with a compression-only spring for the base support to simulate the curled-slab profile, which will lose base contact near the joints. This condition is common for slabs on ground (as noted in Reference 6) and will affect the magnitude and distribution of the forces in the dowels. Depending on the magnitude of the wheel load, the curled slab may or may not come back into contact with the base; this condition is accounted for in the computer model.

As part of this analysis, we have made the following assumptions:

1. Concrete strength. The compressive strength of the concrete is 3500 psi.

Benefits of tapered plate dowels

The dimensions of the tapered plate dowels we have used for the design recommendations were optimized so that the average plate width at the joint would be 2 inches for the ⅜-inch-thick dowel and 2½ inches for the ½-inch and ¾-inch thick dowels (see Fig. 2). These dowel dimensions are similar to the rectangular dowel plates in our previous article (Ref. 3), which are now included in ACI 302.1R-04.

Tapered plate dowels have the following benefits:

1. Because the relative differential deflection between slab panels controls dowel design for the typical industrial floor slab, we need to minimize the dowel bearing pressure on the concrete. That bearing pressure is the main component of the differential deflection, assuming a tight-fitting dowel in the formed concrete socket. A wide plate minimizes the bearing pressure and is a more efficient use of the steel than a round dowel.

2. The tapered shape, with a controlled thin bond breaker, allows the slab to move horizontally in both directions, which minimizes the number and size of slab restraint cracks (see Fig. 3), while providing immediate vertical load transfer.

3. The tapered shape also allows for a significant amount of horizontal misalignment of the dowel basket as it is positioned on the base.

Fig. 2—Tapered dowel dimensions.

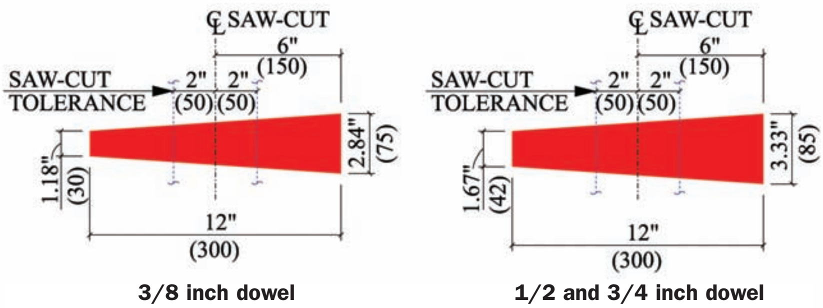
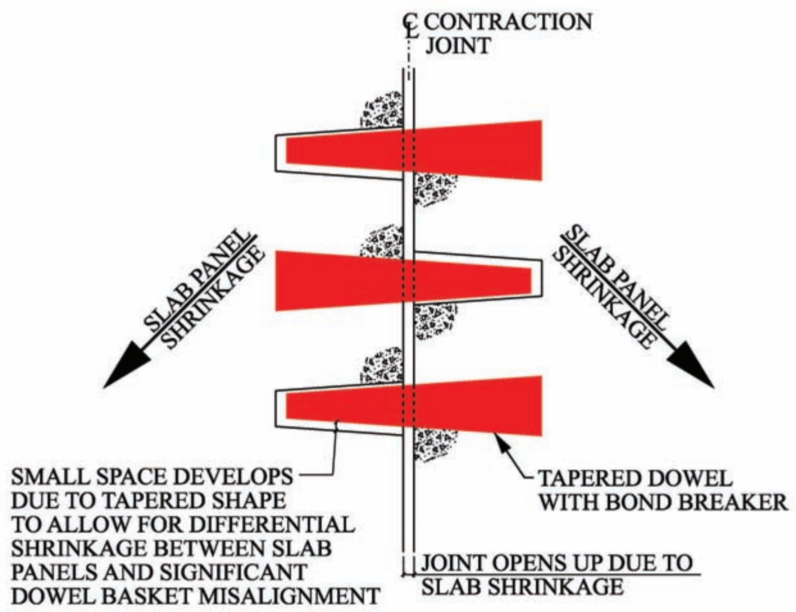


Fig. 3—Tapered dowel dimensions.



This is the strength recommended by ACI 302.1R-04 for steel-troweled floor slabs and hard-wheeled traffic.

2. Subgrade. The modulus of subgrade reaction for the base and soil support system is 150 pounds per cubic inch. This is a typical value for short-term loadings such as from lift trucks. Fortunately, the analysis for the dowel forces and relative deflection between the slabs is relatively insensitive to large changes in this value so it need only be approximate.

3. Dowel support properties. There has been much discussion (such as in Refs. 4 and 5) and some direct testing (see Ref. 7) to establish the concrete modulus of dowel support. The direct testing indicated that "a single value of the modulus of dowel support could not be used to back-predict the experimentally observed dowel deformations along the length of the dowel" but "overall joint load-displacement behavior appeared to be linear" (from Ref. 7). Testing (Ref. 5) also indicated that the joint load-displacement was linear after the initial looseness was taken up by the initial loading and a condition of full bearing was established.

The concrete modulus of dowel support also seems to vary with the width of the dowel (Ref. 4 and 5). Fortunately, the concrete modulus of dowel support value is relatively insensitive to the analysis and need only be approximate; we have chosen a value of 1,500,000 pounds per cubic inch. This value is what was used in Reference 4 for all dowel sizes, including the wider dowels, and is a little less than the value determined by testing for the wider dowel in Reference 5. The testing did indicate that the concrete modulus of dowel support varied some with the concrete compressive strength, but the value we have selected is representative of the 3500 psi concrete recommended for industrial floor slabs.

Because the dowel is tapered, we determined the dowel properties beyond the saw-cut location tolerance of 2 inches (see Fig. 2) on the smaller side. We found that the properties varied only slightly when compared with the properties using the average width of the dowel, and that this variation was in the same range as the other design variables. Alternating the directions of the dowels, as shown

One of the earliest uses of tapered plate dowels was this pavement section at the Atlanta Bonded Warehouse distribution center in Kennesaw, Ga. After four years of constant truck traffic there is no damage at the contraction joints even thought the slab is only 6 inches thick

in Fig. 3, also helps minimize this small difference. Therefore, we used the average dowel width in developing our recommendations.

We used the material properties mentioned above to determine the vertical spring in the computer model that represents the dowel stiffness that is used to transmit the wheel shear load to the adjacent panel and to determine the deflection and stresses in the dowel. These spring values (see Table 1), along with the deflection and stresses in the dowel, were determined using the equations in our previous article (Ref. 3).

4. Slab curling. We have used an equivalent shrinkage gradient of 45° F between the top and bottom of the slab to establish the curling profile of the slab. This value was chosen based on the many slab profiles that we have taken for 6-inch-thick slabs with 15-foot joint spacing where the corner of the slab panel would be approximately ⅛ inch to ¼ inch higher than the center of the panel. This value is somewhat higher than the 30° F gradient that we used in some of our previous analyses, which were based on much earlier data, and is probably an indication that concrete shrinkage has increased somewhat over the years (described in detail in Refs. 6 and 8).

5. Loads from lift trucks. We have used two load cases for each of the different lift trucks. For the first load case, the lift truck was positioned on top of the dowel, and for the second load case, it was positioned between the dowels. The force in the dowel for the load case that produced the maximum differential deflection between the slab panels was used as the maximum allowable load for the dowel. Typically, for dowels at close spacing, the lift truck position on top of the dowel produced the maximum force in the dowel and the maximum deflection. For dowels spaced farther apart, the lift truck positioned between the dowels produce the maximum deflection. Even though the force in the dowel was less with the lift truck positioned between the dowels, the deflection of the slab spanning between the dowels became significant. Therefore, the allowable loads for the dowels spaced farther apart were reduced to account for this transverse slab deflection and to meet our maximum differential deflection criteria.

Table 1:
Vertical dowel spring values

Tapered plate dowel thickness, inches	Vertical dowel spring value, kips/inch
⅜	498
½	791
¾	1100

We used typical lift truck load data for two of the most common types of lift trucks with solid tires: the traditional (counterbalanced) lift truck and the pallet lift truck. Our experience is that only about 75% of the rated load capacity of the lift truck is moved with a regular frequency and rarely does the lift truck move the full rated capacity. Because the design criterion is based on fatigue, it would be more rational to base the selection of the dowels on the most common repetitive loading. Therefore, we have used 75% of the lift truck's rated capacity for our design recommendations. For the few facilities where the full rated capacity of the lift truck is moved on a frequent basis, the data in Table 2 can be used to show the ratio of the values in the design graphs.

6. Joint width. We assumed a maximum joint opening size of 0.20 inches, which should be sufficient for normal joint spacings used with typical concrete mixes.

7. Slab thickness. Three common slab thicknesses were used for the analysis: 6, 8, and 10 inches, with joint spacings of 15, 18, and 21 feet, respectively.

8. Dowel spacing. Five different dowel spacings were used for the analysis: 12, 18, 24, 30, and 36 inches.

9. Load-dowel combinations. To simplify the number of possible combina-

Table 2: Data on typical lift trucks

Traditional lift truck				
Lift truck rated capacity, lbs	Total drive axle load at rated capacity, lbs	Total load on drive axle at 75% of rated capacity, lbs	Load on a single wheel at 75% of rated capacity, lbs	Wheel spacing, inches
2000	6400	5900	2950	30
4000	10,700	9700	4850	36
8000	18,600	16,600	8300	36
12,000	26,400	23,400	11,700	42

Pallet lift truck				
Lift truck rated capacity, lbs	Total load on front wheels at rated capacity, lbs	Total load on front wheels at 75% of rated capacity, lbs	Load on a single wheel at 75% of rated capacity, lbs	Wheel spacing, inches
2000	2500	2000	1000	18
4000	5000	4000	2000	18
8000	9000	7000	3500	18

Table 3. Maximum total differential deflection between slab panels when the lift truck is positioned on top of the dowel.

Dowel size, inch	Maximum force, lbs	Initial dowel looseness, inch	Elastic deflection due to loading, inch	Increase in dowel looseness due to repetitive loading, inch	Total deflection, inch
3/8	2710	0.002	0.00543	0.00257	0.010
1/2	4300				
3/4	5980				

These values were modified (as shown on the graphs) when the deflection of the slab between more widely spaced dowels became significant.

Photos: Crown Equipment Corp.

tions with multiple plate dowel sizes and the different load cases, a conservative assumption was made to use the stiffer spring value of the ¾-inch plate for all of the load cases. This conservative assumption increased the force in the dowels by 15% for the worst case, but in most cases, only by 3% to 8%.

Tapered plate dowel design values

Most of the testing and corresponding design recommendations have been for round dowels used in pavements with highway pneumatic wheel loads. Dowels for industrial floor slabs that have lift trucks, with smaller hard wheels and higher more concentrated loads than a highway pavement would experience, should have a different design criteria. We have used the testing done for round dowels, along with our experience, to develop design recommendations for these tapered plate dowels to be used in industrial floor slabs subjected to lift trucks. Our recommendations are based on the following design values:

1. Slab and dowel deflections. Serviceability is typically what controls the design and spacing of dowels in industrial floor slabs with lift-truck traffic. The main serviceability design requirement is to limit the differential deflection between the slab panels in order to minimize joint spalling due to the lift truck's hard wheels hitting the joint edges (see Fig. 1). This differential deflection is the summation of the following slab and dowel deflections:

- *Initial dowel looseness.* This is the state of adjustment in which the initial looseness is being taken up and a condition of full bearing is being established. This initial dowel looseness can be from coatings applied to prevent bond, water or air voids under the dowel, or shrinkage of the concrete during hardening.
- *Elastic deflection due to loading.* This is the elastic deflection (both shear and flexural) of the steel dowel and the deflection of the concrete due to the bearing stress. The equations for these deflections were developed in our previous article (Ref. 3).
- *Increase in dowel looseness due to repetitive loading.* This increase in dowel deflection is due to the wear of the dowel concrete socket during repet-

Fig. 4—Tapered plate dowel spacings for 6-inch-thick slabs.

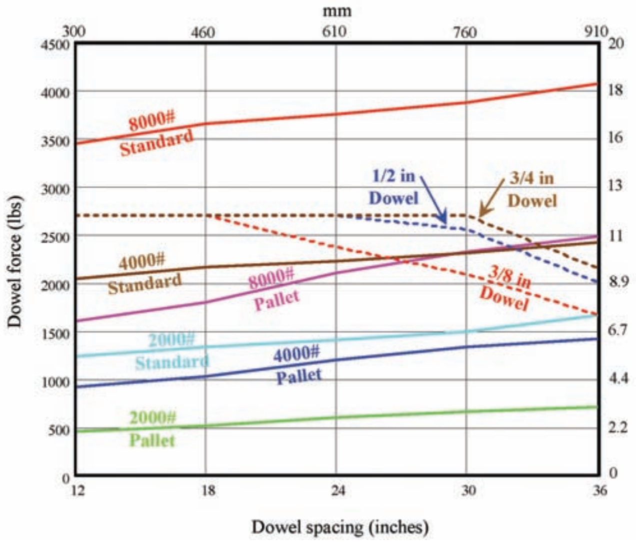


Fig. 5—Tapered plate dowel spacings for 8-inch-thick slabs.

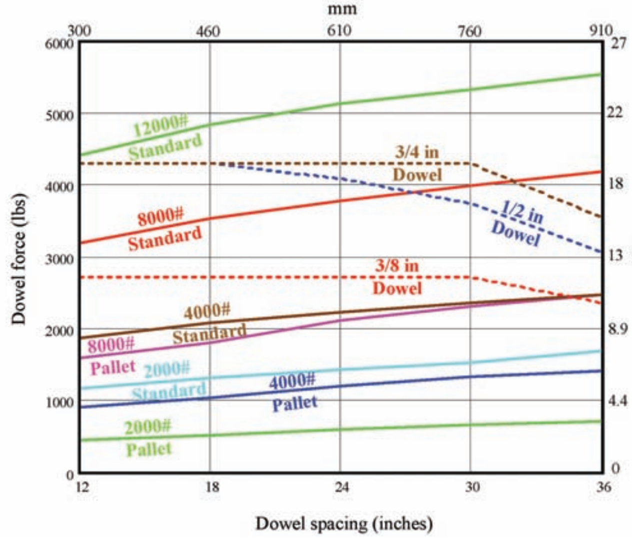
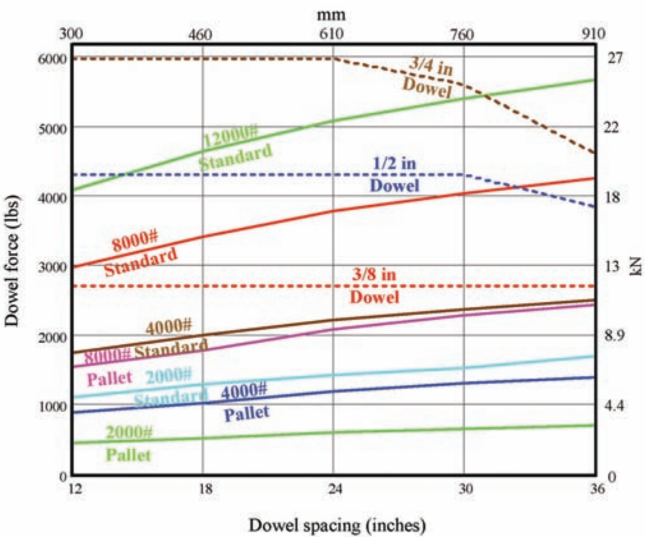


Fig. 6—Tapered plate dowel spacings for 10-inch-thick slabs.



itive loading. We have used the information in Reference 5 to develop a relationship between the dowel concrete bearing pressure and the increase in dowel looseness due to the repetitive loading. In developing this relationship, we determined the concrete modulus of dowel support for each of the dowel diameters used (since concrete modulus of dowel support varies with the dowel diameter), used the percentage of load transfer noted in the testing, and then used the equations in Reference 3 to determine the concrete bearing pressures. The test data is plotted in Fig. 7 (page 7) along with the best-fit third-order polynomial regression curve. The test data was for 600,000 cycles of loading, and it was interesting to note that approximately one-half of the looseness occurred in only the first 40,000 cycles.

■ *Deflection of the slab between dowels.* When the dowels are spaced farther apart, the deflection of the slab spanning between the dowels becomes significant. For the load cases where this controls, this deflection is included as part of the total deflection.

2. Allowable total differential deflection. In our previous article (Ref. 6) several years ago, we recommended that the vertical differential deflection between the slab panels be limited to 0.020 inch. This recommendation was based on the lift trucks that were more common at that time and which had large cushion rubber wheels. In the last few years, there has been a trend by the lift truck manufacturers to use harder smaller wheels. These smaller diameter wheels and the larger wheels with harder plastic material impact the slab's joint edge with a higher force, causing joint spalling to occur sooner. Based on our experiences with these lift trucks using the smaller wheels and the larger wheels with harder plastic material, the summation of the deflections noted above should not exceed 0.010 inch (see Table 3). This recommendation assumes that the joint is properly filled full depth with a semi-rigid joint filler, and that the joint filler is properly maintained.

3. Maximum dowel force. No testing has been done to establish the maximum force that can be repetitively applied to a dowel for different slab thickness before a concrete rupture failure occurs. Therefore, we have limited the maximum force for each slab thickness to the following dowel sizes: 6-inch slab—3⁄8-inch dowel; 8-inch slab—½-inch dowel; 10-inch slab—¾-inch dowel. These values are consistent with the dowel size recommendations for the different slab thickness in ACI 302.1R-04.

4. Steel dowel flexural fatigue. In none of the tests in the regular program in Reference 5 "was there a failure of any of the steel dowels, in spite of the relatively high flexural stresses and the relatively large number of stress reversals in some of the tests." In the Reference 5 regular testing program, the flexural stress at the joint face (which would be less than the maximum flexural stress) varied from 13,700 psi to 27,200 psi (depending on the dowel diameter) for

Greased Dowels

In the field, grease is often applied to round dowels in an uncontrolled manner resulting in a too-thick coating. We have observed many slabs where the grease was thick enough to create a void such that the round dowel was able to move without transferring wheel loads between adjacent panels. A loose-fitting or soft dowel sleeve can have the same effect. Even with a controlled thin coating, as was used in Reference 5, the initial dowel looseness ranged from approximately 0.004 to 0.002 inch, depending on the diameter of the dowel. This initial dowel looseness can be a significant portion of the total allowable movement—we have estimated the initial looseness for the plate dowel to be 0.002 inch for a dowel with a very thin bond breaker coating. If an uncontrolled thickness of grease is used, the initial dowel looseness can easily exceed the total allowable movement. Also, we have observed that when grease is used, the dowel creates a high bearing stress at the face of the concrete joint, thereby causing this area to erode further and to increase the slab-joint differential movement. Using the thinnest concrete bond breaker possible is therefore very important in order to minimize the initial dowel looseness.

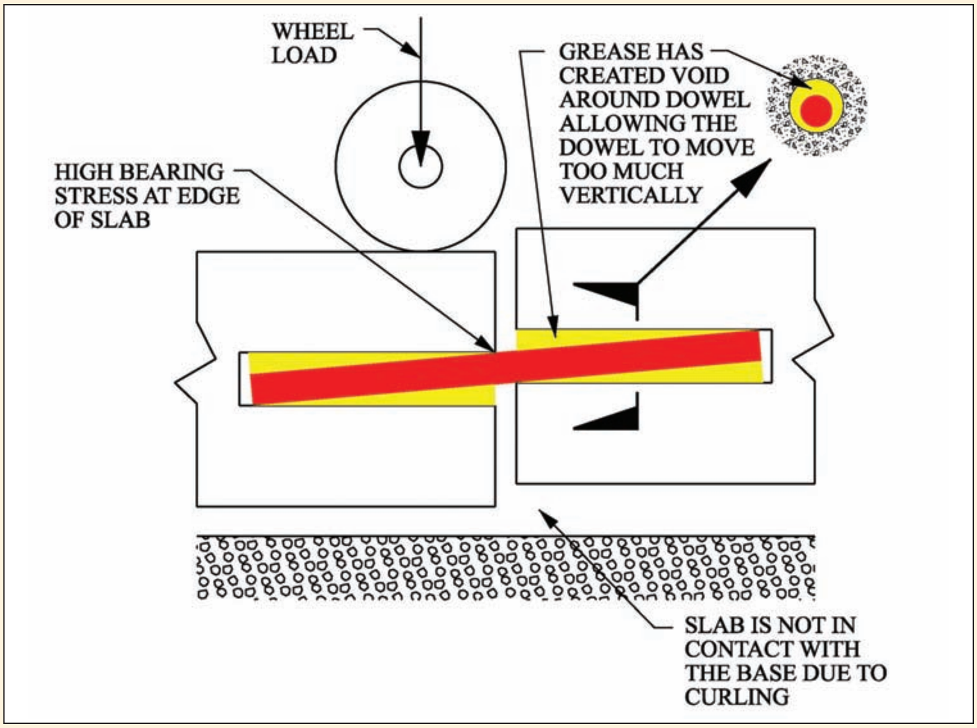
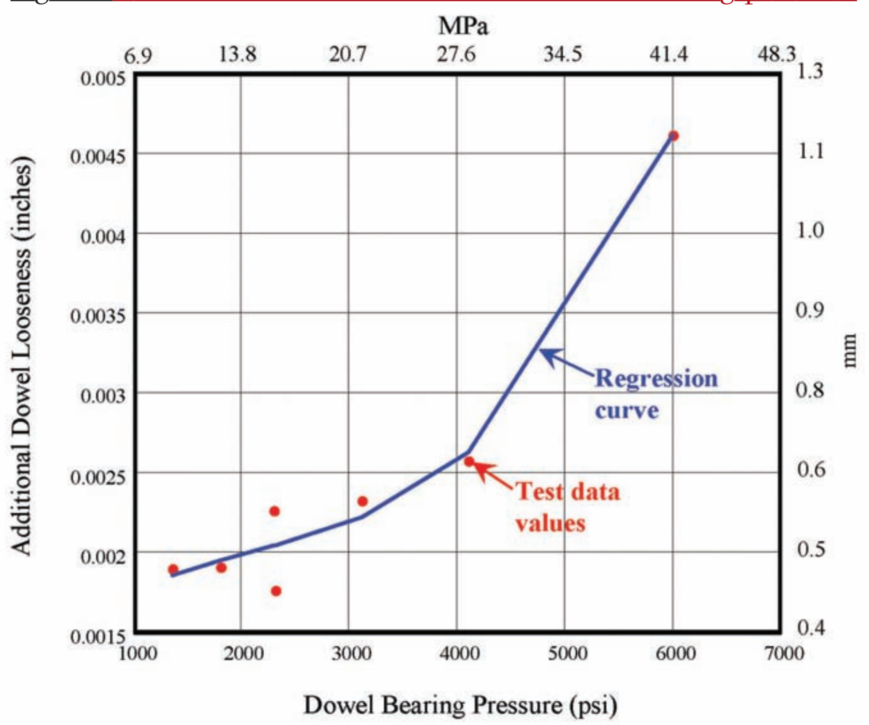


Fig. 7—Additional dowel looseness versus dowel bearing pressure.



600,000 load cycles, and no failures occurred. In one special test to produce a steel flexural fatigue failure, two dowels were loaded to produce a flexural stress of 18,800 psi and 22,800 psi for 600,000 load cycles, and then loaded to produce a flexural stress of 24,300 psi and 28,200 psi, for an additional 892,000 load cycles before failure occurred. The maximum flexural stress for the tapered load plates occurs for the ⅜-inch plate and is approximately 18,000 psi. As shown by the testing done above, this stress is well below the value that would cause a steel flexural fatigue failure.

Results

Using the analytical approach, and the tapered load plate dowel design values noted above, we have developed design graphs so the slab designer can easily select and evaluate different dowel plate sizes and spacings for the expected slab thickness and maximum lift truck

more efficient use of material, will minimize the restraint due to horizontal shrinkage in all directions, and will accommodate a significant amount of misalignment of the dowel basket during construction. ■

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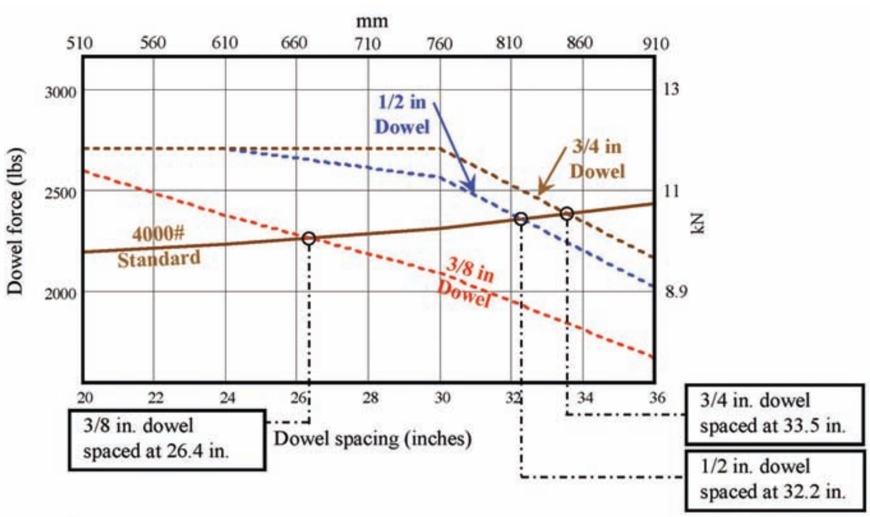
(see Figs. 4, 5, and 6 on page 6). An example is worked out in Fig. 8 (the graph in Fig. 8 is an enlarged portion of Fig. 4) for a 4000-pound capacity traditional lift truck on a 6-inch-thick slab. The example shows that a slab designer can easily select the proper dowel spacing for the different dowel sizes and evaluate which solution is the most economical.

We have provided design graphs based on a rational design approach appropriate for lift trucks on industrial floors so that the slab designer can easily select the dowel size and spacing. The slab designer can also use these graphs to evaluate different dowel sizes and spacings to determine the most economical solution. There are many benefits to using tapered plate dowels with a controlled thin bond-breaker. The tapered plate dowel will provide immediate vertical load transfer, is a

Above: Tapered dowel baskets can easily be installed by one person. Note the contraction joint lines painted on the base to assist in fast, accurate dowel location just ahead of concrete placement. Below: Tapered dowels at the intersection of a contraction joint and a construction joint. We used diamond plate dowels to support the construction joint. The pocket former on the diamond plate dowel and the thin bond breaker on the tapered dowel (no grease required on either dowel) allows vertical load transfer but horizontal freedom of movement in all directions.

Fig. 8—Tapered plate dowel spacing example for a 4000-pound standard lift truck on a 6-inch-thick slab.



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