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.
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 properly 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 3300 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 3/8-inch-thick dowel and 2 1/2 inches for the 1/2-inch and 3/4-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...
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 1/8 inch to 1/4 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.

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-
tions with multiple plate dowel sizes and the different load cases, a conservative assumption was made to use the stiffer spring value of the 3⁄4-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 repeti-

### Table 2: Data on typical lift trucks

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

<table>
<thead>
<tr>
<th>Lift truck rated capacity, lbs</th>
<th>Total load on front wheels at rated capacity, lbs</th>
<th>Total load on front wheels at 75% of rated capacity, lbs</th>
<th>Load on a single wheel at 75% of rated capacity, lbs</th>
<th>Wheel spacing, inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>2500</td>
<td>2000</td>
<td>1000</td>
<td>18</td>
</tr>
<tr>
<td>4000</td>
<td>5000</td>
<td>4000</td>
<td>2000</td>
<td>18</td>
</tr>
<tr>
<td>8000</td>
<td>9000</td>
<td>7000</td>
<td>3500</td>
<td>18</td>
</tr>
</tbody>
</table>

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

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

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.
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, 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—1⁄2-inch dowel; 10-inch slab—3⁄4-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.

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 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 3/8-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.
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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References


