A SunCam online continuing education course

Concrete Slabs-on-Grade: Warehouses II – Slab Design

by

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Course Outline:

Design of Slabs with Warehouse-Type Loading – Common Methods
Joint Layout
Joint Design Against Failure
Floor Flatness and Levelness
Specialty Slab Options
Finishes
Pre-Construction Meeting
References
Examination

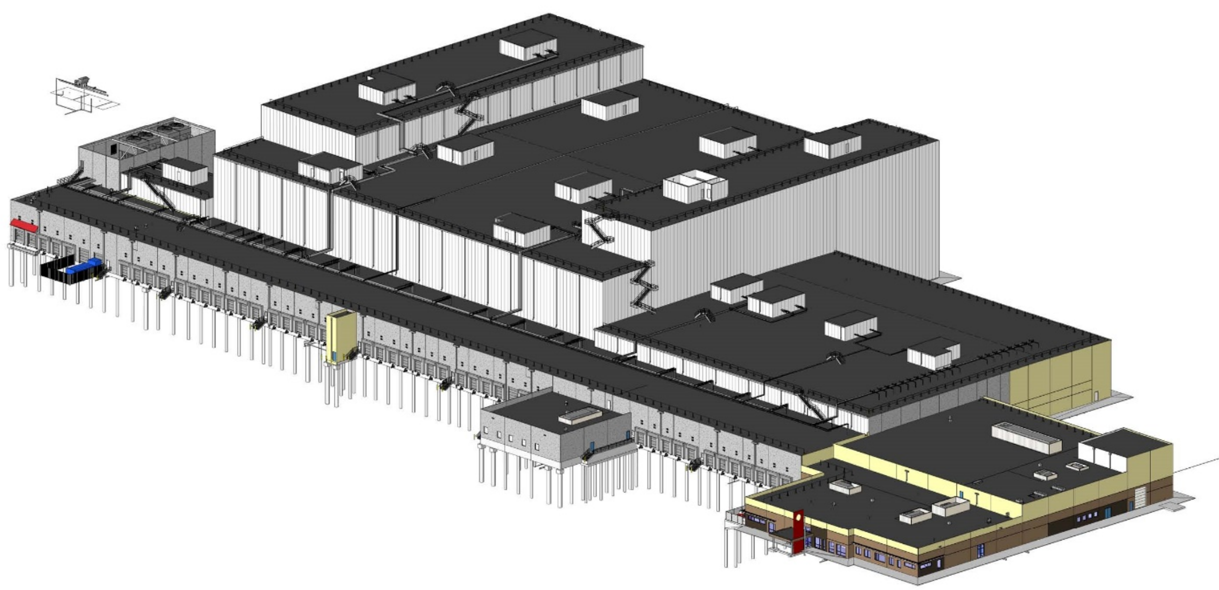


Fig. 1 - Computer rendering of a refrigerated food warehouse

Note prior to beginning the course:

This course is a continuation of the first warehouse course, which is *Concrete Slabs-on-Grade: Warehouses I – Background & Loading*

The following figures are added for convenient reference to the first warehouse course.

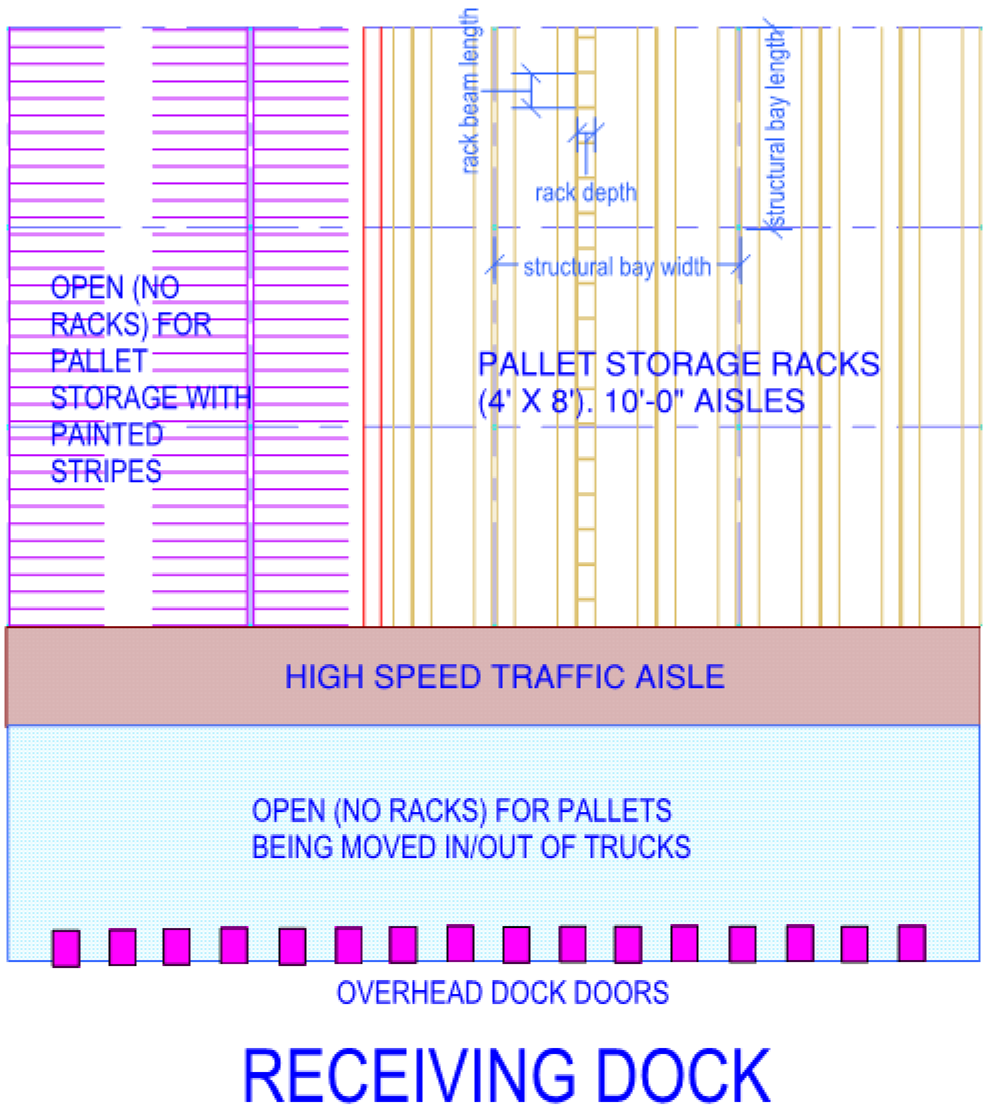


Fig. 2 - Portion of a typical warehouse floor in plan

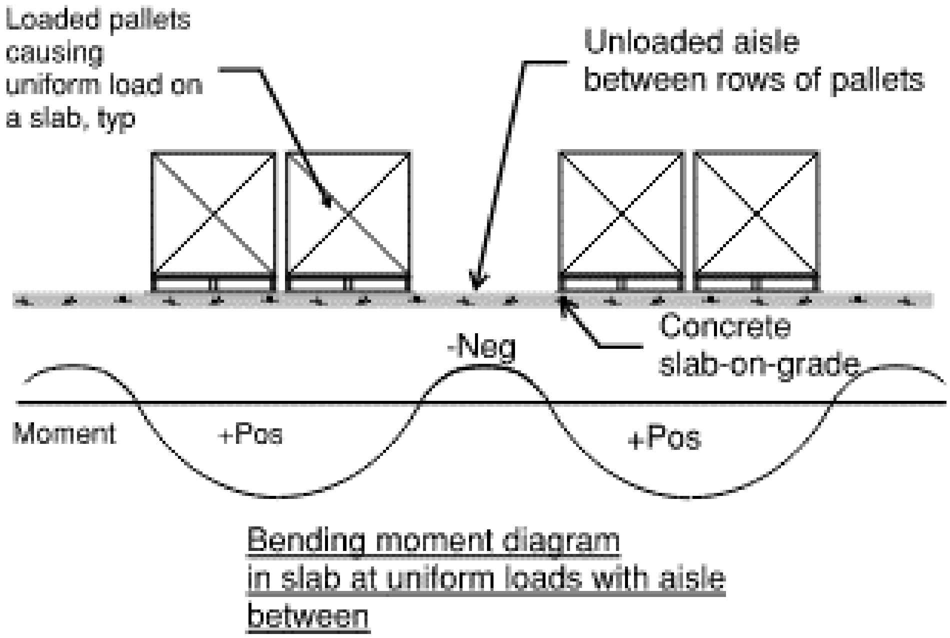


Fig. 24a – Pallets loading a slab with a free area between

https://commons.wikimedia.org/wiki/File:Modern_warehouse_with_pallet_rack_storage_system.jpg; Axisadman / CC BY-SA (https://creativecommons.org/licenses/by-sa/3.0)

Fig. 24b - Typical loads on slabs

https://commons.wikimedia.org/wiki/File:CEDIS_Soriana.jpg
Organizacion Soriana / CC BY-SA (https://creativecommons.org/licenses/by-sa/4.0)
Fig. 25 - Stacker lift making a placement/retrieval of a pallet

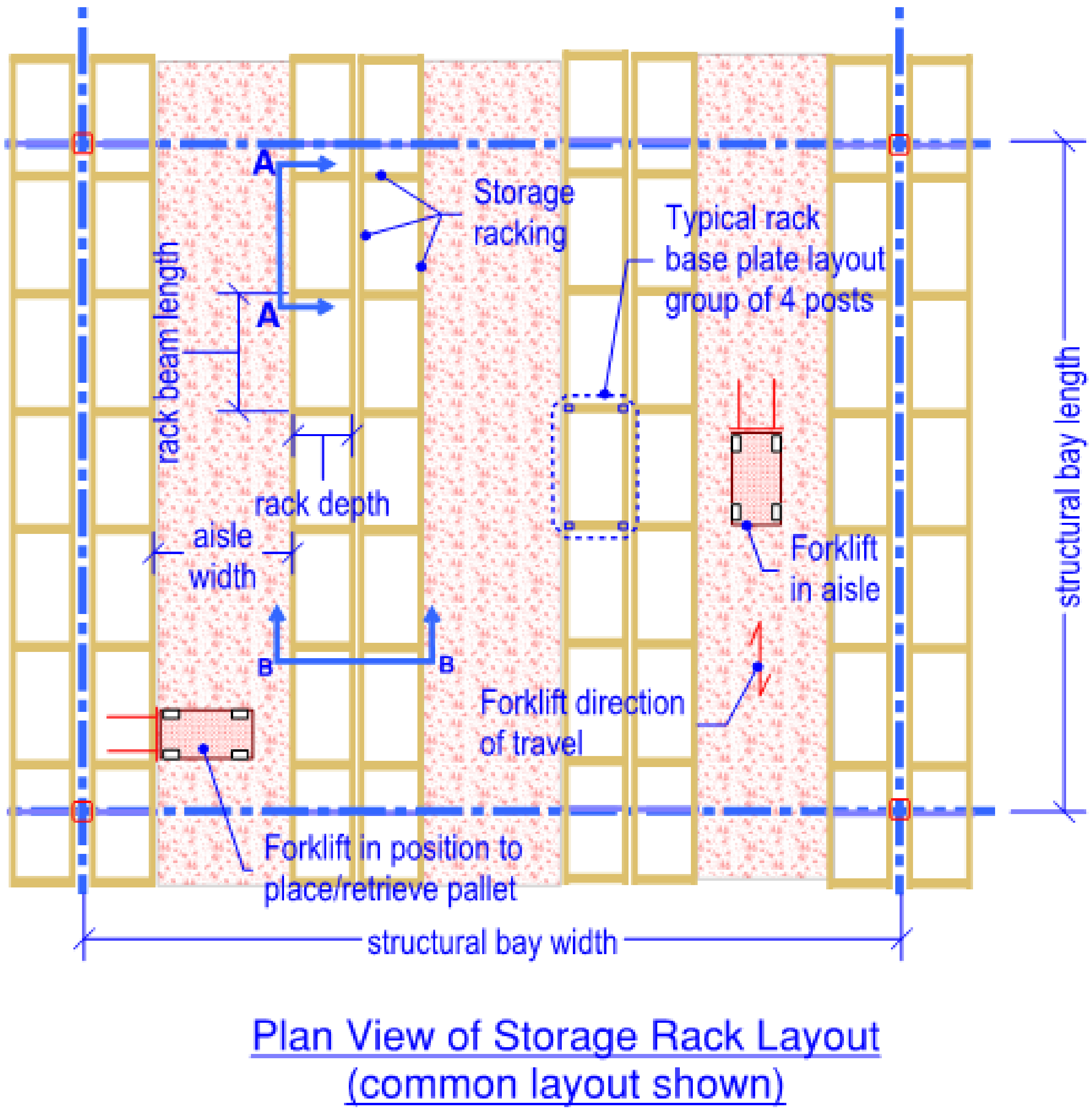


Fig. 26 - Typical rack and aisle layout

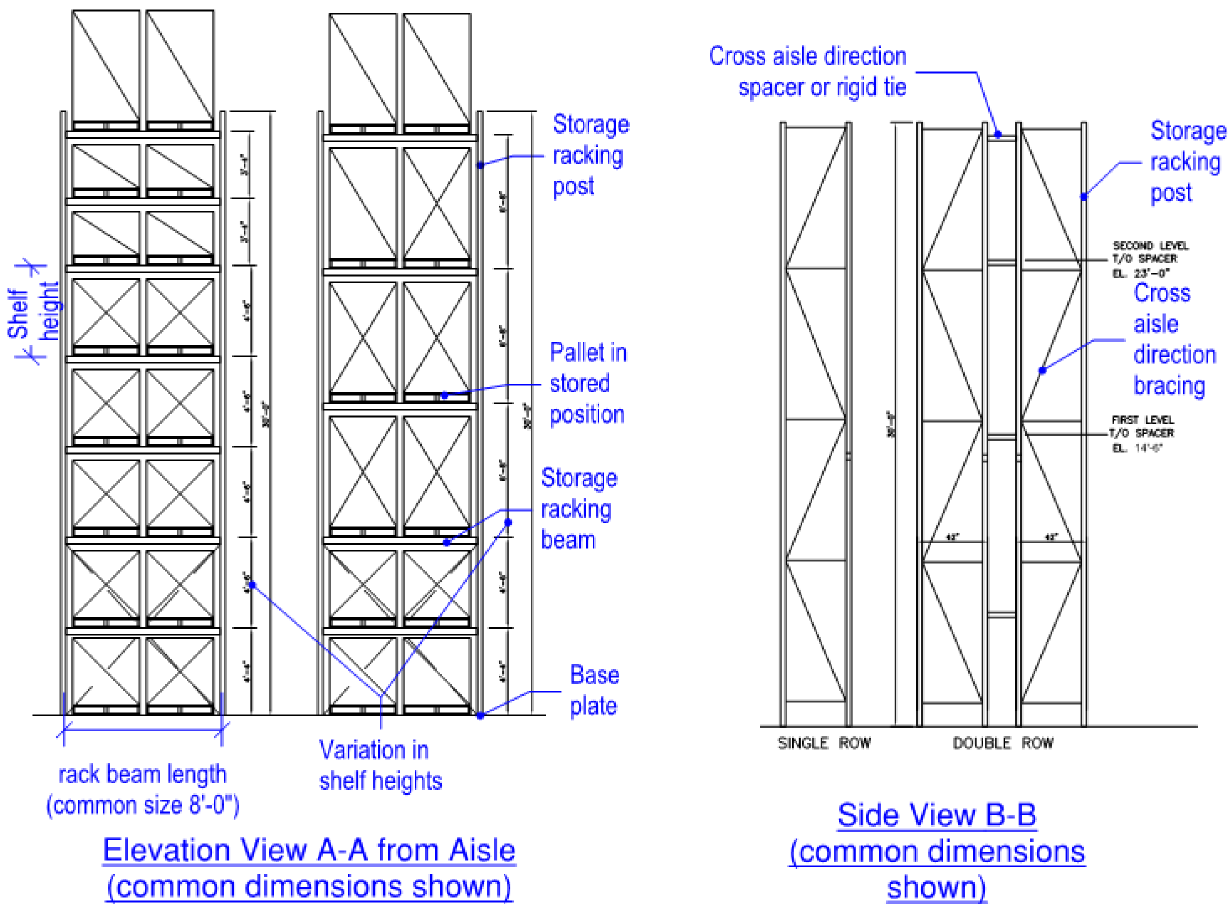


Fig. 27 - Typical storage rack construction

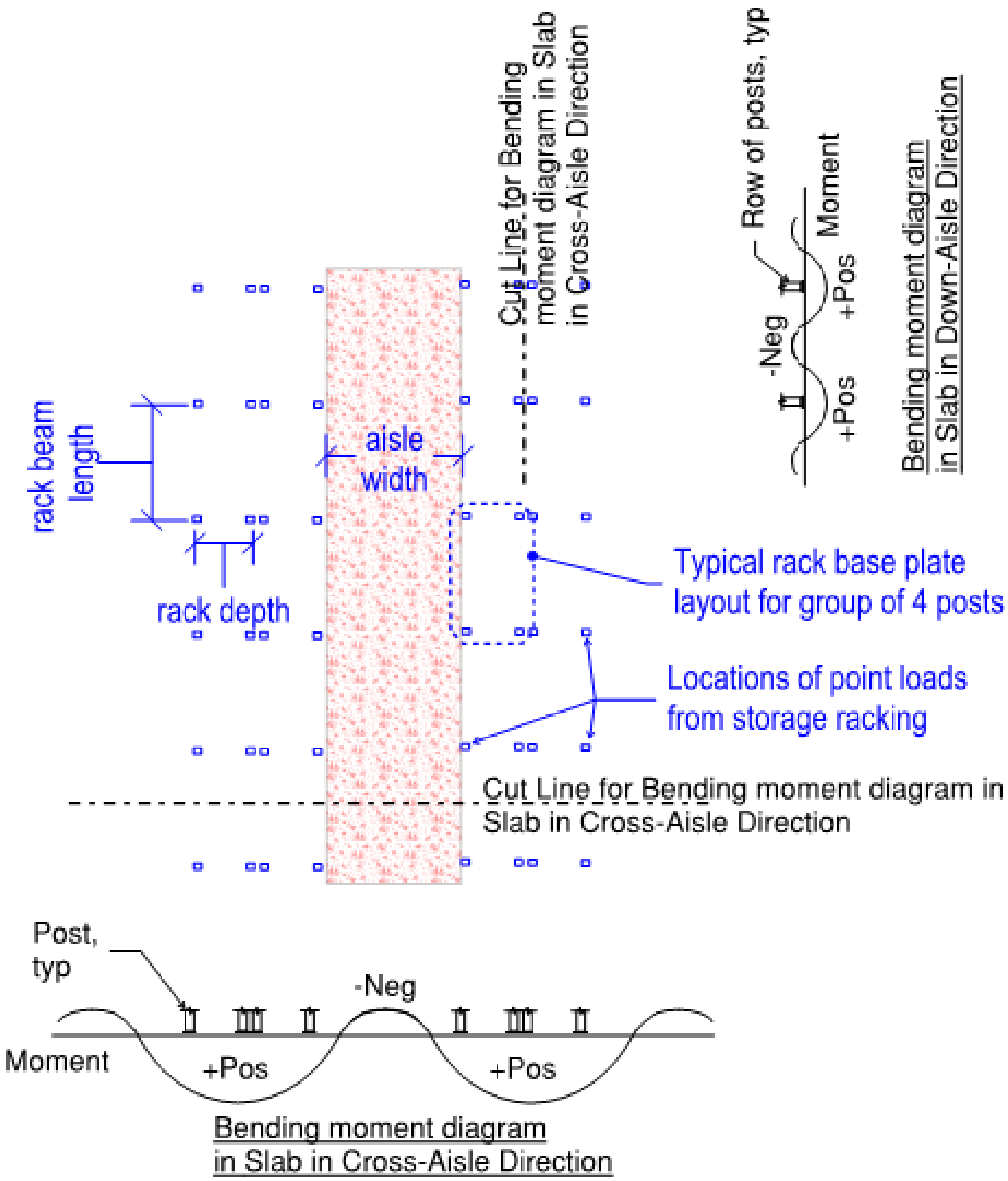


Fig. 28 - Moments in slab due to racking with clear aisles

Here begins the continuation from the first warehouse course, which is *Concrete Slabs-on-Grade: Warehouses I – Background & Loading.*

Design of Slabs With Warehouse-Type Loading – Common Methods

For a quick recap of some of the design options available are added here for convenient reference to the first course.

The list below is based on a list noted in Appendix D of the FEMA 460 document, *Seismic Considerations for Steel Storage Racks located in Areas Accessible to the Public*. It is as good a list as can be found on the subject of slab design. Availability of publications noted may vary.

In the words of the FEMA document, and highlighted in blue,

"The information presented below was issued by the City of Los Angeles Department of Building and Safety as Information Bulletin/Public-Building Code, Reference L.A.M.C. 91. 1806,
Document P/BC 2002 to be effective May 10, 2004…
"PURPOSE: This Information Bulletin establishes a list of acceptable analysis methods for slabs-on-grade
("SOG") as foundations.

"ACCEPTABLE DESIGN METHODS: The following methods of design and analysis for SOGs are acceptable:"

"• ACI Committee 360, "Design of Slabs-On-Grade - Reported by ACI Committee 360," ACI
360R-92, 1997.

• Packard, Robert G., "Slab Thickness Design for Industrial Concrete Floors on Grade," IS195.01D, Portland Cement Association, Skokie, Illinois, 1976.

• Departments of the Army and Air Force, Concrete Floor Slabs on Grade Subjected to Heavy
Loads," ARMY TM 5-809-12, Air Force AFM 88-3, Chapter 15, 1987.

• Department of Defense, "Engineering and Design: Rigid Pavements for Roads, Streets, Walks and Open Storage Areas," TM-5-822-6, U.S. Government Printing Office, Washington D.C., 1977.

• Wire Reinforcement Institute, "Formulas for Success: Innovative Ways to Reinforce Slabs-On-Ground," TF 705-R-03, 2003.

• Post-Tension Institute, "Design and Construction of Post-Tensioned Slabs on Ground," Phoenix, AZ, 1980.

The following are additional acceptable methods presented to the SEAOSC membership during a series of seminars held in March 2003 and available from SEAOSC:

• Equivalent Footing - Analysis of allowable loads is modeled by assuming a "saw-cut" square unreinforced section using the conventional working stress method.

• Integral Footing - Analysis of SOGs strength using empirical equations developed by the American Concrete Institute. (Design and Construction of Concrete Slabs on Grade, ACI SCM-11(86), American Concrete Institute, Detroit, 1980).

• Empirical Method - Method of analysis based on studies that compare the load test results to computer analysis. (Shentu, L., Jiang, D., Hsu, T. (1997). "Load Carrying Capacity for Concrete Slabs on Grade." Journal of Structural Engineering, ASCE, January 1997, pp 99-103.)"

The author would add to this list the following very comprehensive and helpful publication from overseas, which is based on a yield line-type method, but might be limited to reinforced slabs upon review due to the ultimate limit state thereby required for use:

• Technical Report 34 (TR 34), "Concrete Industrial Ground Floors - A Guide to Design and Construction", The Concrete Society, 2003.

Also, the following is a document based on the PCA method that is one of three methods noted in ACI-360. It is one that comes highly recommended from the author, and is a document that has been developed over many years. The fourth edition is recommended for today's slabs. Earlier versions may be dated. Combined with ACI 360, these are the definitive warehouse design publications.

• Tarr, Scott M., and Farny, James A.; *Concrete floors on ground*. Portland Cement Association. Skokie, Ill., 2008.

And lastly, a direct analytical approach could be used as well, especially for very unusual or unique loads. The author would round this list out with:

• Finite element analysis programs; Specific example: *SP Mats* module of Structure Point software (formerly PCA Mats)

Discussion on the list above follows.

ACI 360 – Background on the Westergaard Method – Basic slab-on-grade response to loading

In each design method, the **stiffness of the subgrade** must be considered. The geotechnical report should dictate a minimum subgrade coefficient for use in slab design, and this should be noted when preparing the soil subgrade compaction specifications. Fig. 29 from ACI 360 shows a typical soil and slab profile. A base and subbase are not always required, but a subbase is typically present. The thickness of the layers are dependent on the characteristics of the in situ soil, the slab design parameters, and recommendations from the geotechnical engineer. These layers can help serve as capillary breaks to limit the seepage of water to the concrete, and they can aid in the distribution of load below the slab by increasing the stiffness and strength of the soil profile, as well as making it more uniform in its support.

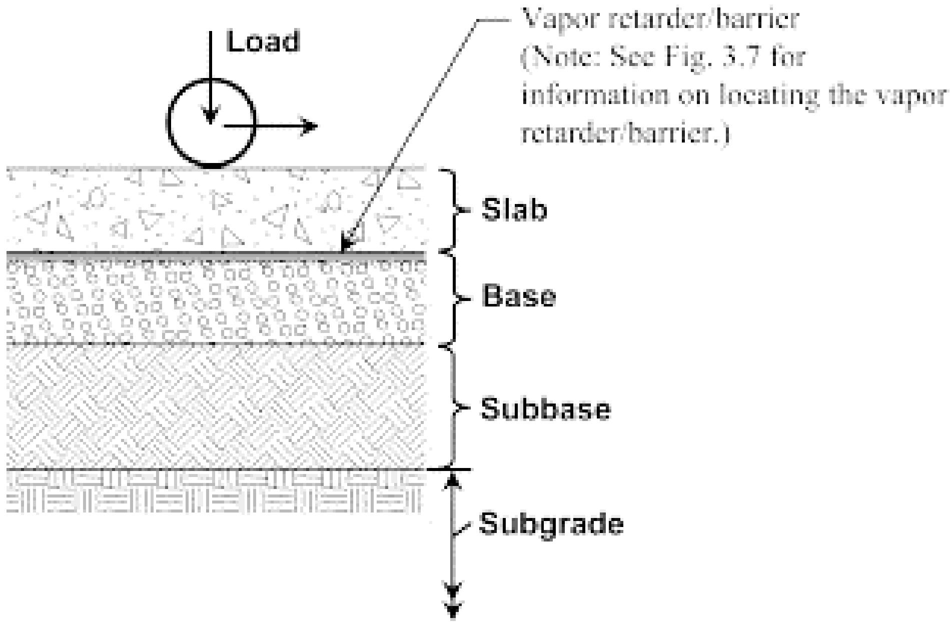


Fig. 29 – Slab-on-grade profile with soil– ACI 360

In Fig. 30 from ACI 360, the effects of subbase thickness on the modulus of subgrade reaction are shown. In design, an envelope of soil stiffness conditions with upper and lower bounds can be studied.

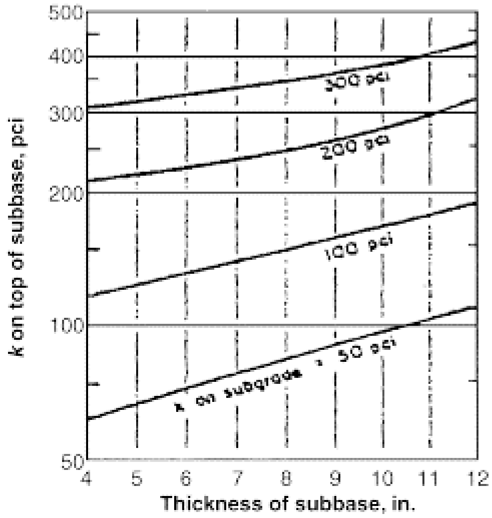


Fig. 3.6—Effect of subbase thickness on design modulus of subgrade reaction. (Note: 1 pci = 0.2714 MN/m^3; 1 in. = 25.4 mm.)

Fig. 30 (ACI 360)

In designing for slab thickness, the stiffness of the soil below the slab is an important factor in analytical or design tools. If the soil were as stiff as concrete, for example, and we assumed that the slab was free of voids (such as those caused by curling), loads would more or less be transferred in bearing to the soil below. Decreasing soil stiffness by degrees changes the behavior from bearing to that which depends on the relation between concrete section properties and the soil stiffness. In the 1920's, Westergaard developed methods for determining stresses in concrete road slabs. In many of the available analytical or approximate methods used to determine stresses in loaded building slabs, some form of Westergaard's work is generally used. The deformed shape of the slab, compatible shape of the soil, and the relative stiffnesses of the slab and soil are considered (Westergaard).

ACI 360 presents several equations based on Westergaard's methods.

Case 1: Load close to the corner of the slab:

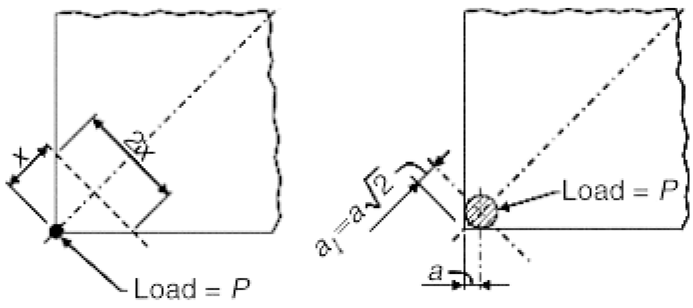


Fig. 6.1—Corner load on slab-on-ground.

(per ACI 360)

Maximum tensile stress in the top of the slab, as the slab acts like a **short cantilever** supported by soil, is given by:

$$f_t = \frac{3\,P}{h^2}\left[1 - \left(\frac{a\sqrt{2}}{L}\right)^{0.6}\right]$$

$$P = Load, pounds$$

$$a = radius\ of\ the\ loaded\ area\ \ (or\ one\ half\ the\ width\ of\ a\ square\ base\ plate)$$

$$E = modulus\ of\ elasticity\ of\ concrete, psi$$

$$h = slab\ thickness, in$$

$$f_t = tensile\ stress\ in\ concrete, psi$$

$$L = \sqrt[4]{\frac{Eh^3}{12\,(1 - \mu^2)k}}$$

$$L = radius\ of\ relative\ stiffness, in$$

$$k\ = modulus\ of\ subgrade\ reaction, pci$$

$$\mu =\ poisson's\ ratio\ for\ concrete, approx.\, 0.15$$

Case 2: Load located far away from the edges of the slab:
Maximum tensile stress in the bottom of the slab is given by:

$$f_b = 0.316\,\frac{P}{h^2}\left[log[h^3] - 4\log\left[\sqrt{1.6\,a^2 + h^2} - 0.675\,h\right] - \log(k) + 6.48\right]$$

Case 3: Load at the edge of the slab, but far away from the corners:
Maximum tensile stress in the bottom of the slab is given by:

$$f_b = 0.572\,\frac{P}{h^2}\left[log[h^3] - 4\log\left[\sqrt{1.6\,a^2 + h^2} - 0.675\,h\right] - \log(k) + 5.77\right]$$

The Westergaard methods are based on a comparison of maximum theoretical applied stress in a concrete section, for comparison to the allowable stress or rupture strength of the concrete. Allowable stress can be expressed as the strength of the material for the failure mode in question divided by a factor of safety. In this case, the rupture strength, f_r, is used to find the allowable bending stress, F_b, by applying a factor of safety, *FS*, as follows:

$$F_b = \frac{f_r}{FS} > f_b \; or \; f_t$$

ACI 318 uses a value of $7.5\sqrt{f_c'}$ for rupture strength, where f_c' is the compressive strength of the concrete in psi. To calibrate project-specific concrete, testing can be done on the concrete to estimate the bending strength, such as ASTM C78. The author has used a higher value of rupture modulus based on research, in the range of $9\sqrt{f_c'}$ at 28 days, and this value has been confirmed by ASTM C78 testing. It should be noted that a factor of safety will be applied to obtain an allowable stress. This is an engineering judgment call that needs to be reviewed by the Engineer of Record. Factors of safety will depend on a number of things, including, but those used are typically in the 1.5 to 2.1 range.

Elastic Methods Versus Plastic or Ultimate Limit State Methods

Westergaard-type equations rely on elastic analysis, where the slab stress is limited to the point of incipient local failure of a very small portion of the slab. This is an acceptable way to design a slab, and many would say it would be the most appropriate for unreinforced slabs. However, it should be noted that this will lead to thicker slabs when compared to slabs designed using plastic or ultimate limit states, which are based on the post-cracking strength of the slab.

The use of any of these methods should entail a closer review of other behavior, such as curling, cracking, slab deflections under load, and load transfer at joints. Also, adequate ductility of the concrete will be required for plastic or ultimate limit state methods. If plastic or ultimate limit state methods are used, it is recommended that a means of providing **ductility and post-crack residual strength** be used. This would include steel bar reinforcing, heavier steel mat reinforcing, steel fibers, or synthetic macrofibers. Application of elastic methods by PCA are described first, and then some of these plastic or ultimate limit state methods are described below.

To be fair, most methods assume no curling stresses, and, in fact, a slab that maintains contact with the ground. Some adjustment should be made for this, as a curled slab will behave differently where it has lifted off of the base soil. Conceivably, finite element analysis could include geometry and/or compression-only spring behavior, along with curled edges with gaps to model curling. Or, these additional behaviors could be factored in directly with some estimated stresses. In a design example for slabs with steel fibers, ACI 360 uses a value of 200 psi flexural tensile stress for combined shrinkage and curling stresses in the analysis.

PCA Method – Elastic Method

The PCA method is tailored for warehouse-type buildings, with various approaches to wheel and rack post loading, as well as finding a slab thickness for a given aisle width with uniform loading on either side. This design method is the basis of PCA's historical document, *Concrete Floors on Ground*. Obtaining the latest edition is recommended. Starting with the 4th edition, design charts began to include joint load transfer conditions explicitly. Earlier versions may be dated*. It is not useful to repeat the charts here without the accompanying extensive and nuanced background*, but the publication is readily available via pdf for a very reasonable price ($45 for the pdf version as of October, 2020).

In Chapter 5 of PCA's *Concrete Floors on Ground*, there are tables and charts that are based on common warehouse rack configurations, uniform floor load arrangements, and vehicle-types. The publication is extremely useful for typical warehouse slab design. Design methods are available for the following loading.

1. Vehicle Loading

a. Fatigue: Warehouse slabs will be subjected to numerous cycles of loading over time. Every time a forklift or pallet jack rolls over a joint is another cycle. Research has led industry experts to conclude that failure does not only occur due to single events, but also due to the accumulation of damage from repeated loads below the maximum allowable load. This is known as **fatigue loading.** The theory is that loads which induce stresses in the concrete above a given level will cause some degree of distress in concrete. The threshhold is 45% of the maximum stress. If you add up enough of these loads, the concrete will fail eventually. The following relationship between magnitude of loading and number of cycles to failure is posed by the PCA document:

N = the number of loads to produce a flexural fatigue cracking failure
σ = Maximum flexural tension stress induced by traffiic loading at the bottom of the slab at the joint, psi
MR = Flexural strength (Modulus of rupture value at 28 days), psi
SR = Stress ratio, given by SR = σ/MR

For SR ≥ 0.55, log(N) = 11.737−12.077 x SR
For convenience, can also be expressed as:
$N = 10^{11.737-12.077\,SR}$

For 0.45 < SR < 0.55 $N = \left(\frac{4.257}{SR-0.4325}\right)^{3.268}$

For SR ≤ 0.45 N = unlimited

The resulting table (PCA Table 5-1) in abbreviated fashion is as follows:

Stress Ratio, SR	Allowable load repetitions, N
0.45	Unlimited
0.50	762,043
0.55	124,523
0.60	30,927
0.65	7,700
0.70	1,917
0.75	477
0.80	119
0.85	30

0.90	7
0.95	2
1.00	0 (emprical value, not from equation above)

The factor of safety for a fatigue failure is the inverse of the stress ratio. PCA uses the term SF for factor of safety for fatigue.

So, SF = 1/SR

SF = 2.2 amounts to unlimited traffic. Per PCA, this value might be used for heavily trafficked areas. A lower SF of 1.4 to 2.0 might be used in lower traffic areas.

b. Joint load transfer

Joint load transfer is touched on in *Slabs-on-Grade: From the Ground Up*, and also discussed later in this course. Vertical load transfer is any means keeping opposing sides of the slab at a joint from moving separately as a wheel load crosses the joint (see Fig. 45). If the transfer is there, it drastically reduces stress at the joint. There are two main choices for providing a means of vertical load transfer:

- i) Aggregate interlock (friction between the slabs on either side of a sawcut-induced crack). The effectiveness of aggregate interlock depends on the joint size. (Fig. 34)
- ii) Dowels providing full load transfer at a joint. (Fig. 45)

If aggregate interlock is used, the following table is used to obtain a joint factor (JF) as long as the joint spacing is reasonable (based in judgement) to factor in effectiveness. This joint factor is used similar to a factor of safety when determining allowable stresses.

*Table 5-2. Joint Factors Based on Ultimate Concrete Shrinkage**

Ultimate concrete shrinkage, %	Joint factor
<0.052%	1.0
0.052 to 0.057	1.1
0.057 to 0.062	1.2
0.062 to 0.067	1.3
0.067 to 0.072	1.4
0.072 to 0.078	1.5
>0.078	1.6

*ACI 360R

c. PCA Charts for vehicles – steps explained further in the PCA publication. *Again, the charts aren't presented here*.
   i) From facility data, equipment info needed:
      1. Axle load
      2. Wheel spacing
      3. # of wheels on an axle
      4. Tire type, width, contact length
   ii) Data for slab/soil needed:
      1. Subgrade modulus
      2. Concrete flexural strength
      3. Ultimate shrinkage (at infinite time)
      4. Joint spacing
   iii) Figure out working stress using SF and JF
      1. $WS = \frac{MR}{SF\ x\ JF}$ (MR = Flexural strength, use MR = 9 $\sqrt{f_c'}$)
      2. Note that at this point, the slab designer could factor in curling stresses if desired by reducing MR to get a reserve strength value.
   iv) Then find working stress per 1000# of axle load
      1. Value = WS/(Axle load,kips)
   v) Enter charts using based on type of joint assumed and find a slab thickness

2. Post Loading

a. Design for post loading is based a single controlling design event (maximum post loads expected for a given rack post layout) rather than fatigue loading.

b. PCA Charts for vehicles – safety factors and steps explained further in the PCA publication. *A quick reminder that the charts aren't presented here, and that the publication itself is necessary to complete the slab design*.
   i) From facility data, equipment info needed:
      1. Maximum post loads
      2. Post spacings, x and y in plan
      3. Base plate area
      4. Tire type, width, contact length
   ii) Data for slab/soil needed:
      1. Subgrade modulus
      2. Concrete flexural strength
      3. Ultimate shrinkage (at infinite time)
   iii) Review notes in the publication on joint spacing and how slab edge stress may be reduced for good load transfer at the joint.
   iv) Note in particular the wider range of factors of safety involved depending on the application, as a racking collapse would be much more dangerous than fatigue failure of joints.
   v) Figure out working stress using SF and JF
      1. $WS = \frac{MR}{SF\ x\ JF}$ (MR = Flexural strength)
      2. Note that at this point, the slab designer could factor in curling stresses if desired by reducing MR to get a reserve strength value.
   vi) Then find working stress per 1000# of post load
      1. Value = WS/(Post load,kips)
   vii) Enter charts using based on type of joint assumed and find a slab thickness.

3. Distributed Loading
   a. This section of the PCA publication addresses distributed loads on slabs, including those occurring next to open travel aisles free of loads. *The charts and tables aren't presented here* due to the amount of nuanced background needed to use them.

The charts in the PCA publication address an assumed wheel load for a given number of repetitions to achieve a given factor of safety with a given wheel spacing and contact area. Thus, the use of the tables necessitates the use of a single forklift load that represents all traffic. A suggested alternate method is described below.

Fatigue study based on PCA method for variable wheel loads

If desired, the author proposes that an approximate study could be done directly if the wheel loading varies. Note that this is not part of the information presented by PCA. For a wide variety of loadings on a given slab, it may be necessary to divide the loads into categories by magnitude of loading and number of cycles, and the contributions of each category contribute to the total accumulation of damage. For example, if the amount of accumulated damage to failure is 1.0, and we divide loads into several categories, with various stress ratios for each category, we can examine the damage as follows:

- i = number of the category (1, 2, 3, … m)
- n_i = number of cycles in each category
- N_i = the number of loads to produce a flexural fatigue cracking failure for category i
- SR_i = Stress ratio for category i

Steps:
Step 1) Find out what the facility intends to use for equipment, what loads might be imposed by them, and how many cycles of load there might be for each loading. Here it might be a collection of good guesses, unless there is data to draw from.
Step 2) Divide the loads into a number of categories with a relevant SR_i for loading significacnt enough to load to failure (SR > 0.45). The loading under study might be the stress in the slab as the wheels cross joints, with the aid of Westergaard equations. It is recommended that the PCA method be studied for nuances in design choices.
Step 3) Use the equations or tables to get the values N_i. Apply a factor of safety SF and joint factor, JF in the manner described for a single type of vehicle by PCA.
Step 4) Figure out whether fatigue limits are met:

If $\sum_{i=1}^{m} \frac{n_i}{N_i} \, x \, FS \, x \, JF < 1$, fatigue limits are OK. If the value of the expression on the left is more than 1, a thicker slab may be required.

Plastic or Ultimate Limit State Methods:

The generally accepted model for the failure response of a concrete slab-on-grade to a point load applied via a round plate is shown in Fig. 31 (Several Sources: TR34, Walker and Holland (2001), Holland, *World of Concrete*). The deformation of the slab is circular dish shape with characteristic defining radii that will be described below. Progressive failure for gradually increasing load begins when the **slab first sags in the middle**, with concave shape up, developing positive moments (slab in tension on the bottom and compression on top) along radial lines. **Then the slab bends down, or hogs**, in negative moment (slab in compression on the bottom and tension on top), at a characteristic radius from the load center. The negative moment increases until failure occurs when the cracking moment is reached on top of the slab.

Side note: For serviceability crack concerns for loads less than ultimate loads but greater than that required to develop initial cracking, if bottom of slab cracking controls the design, the post-initial-crack behavior may be an acceptable result. (Holland and Walker, 2001).

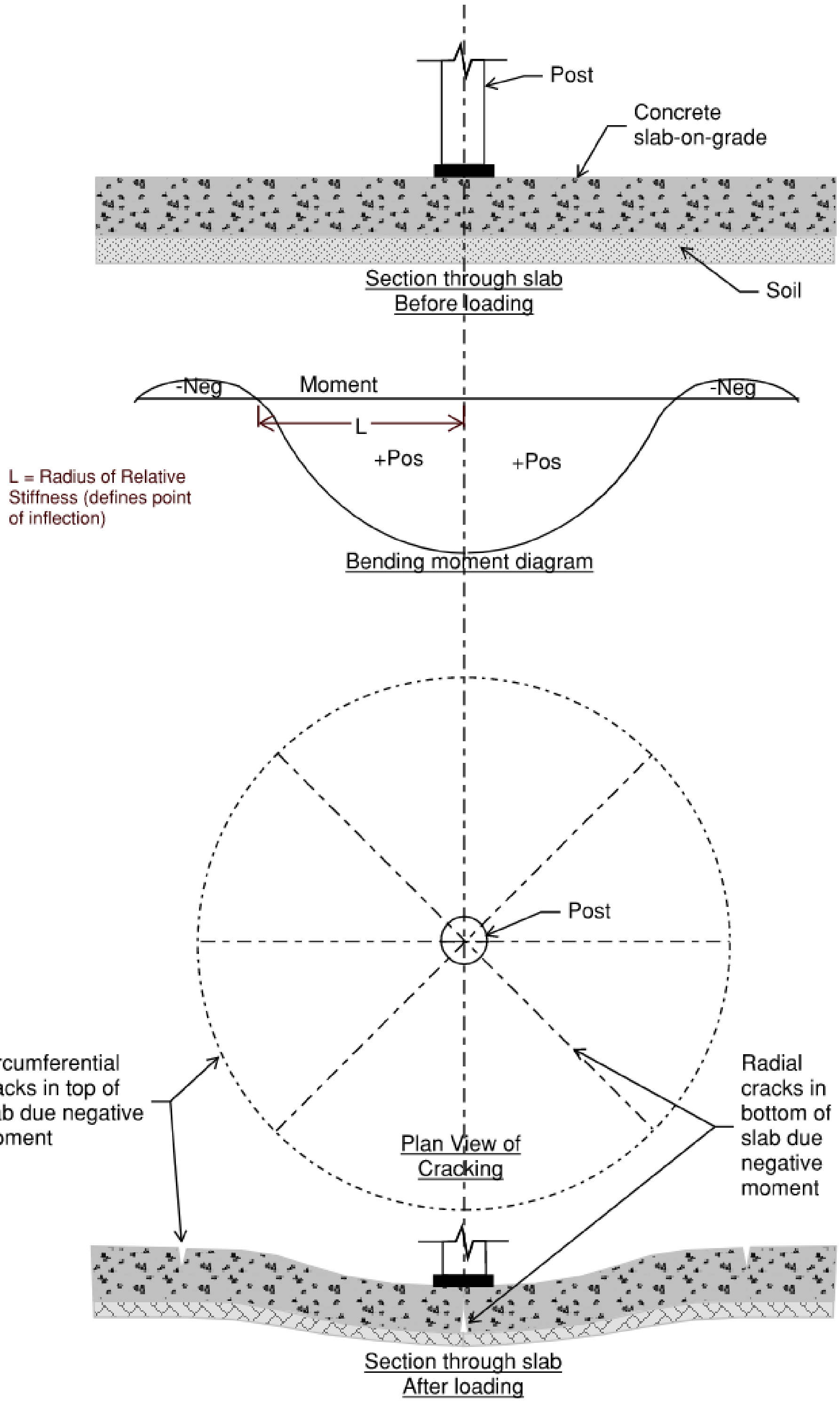


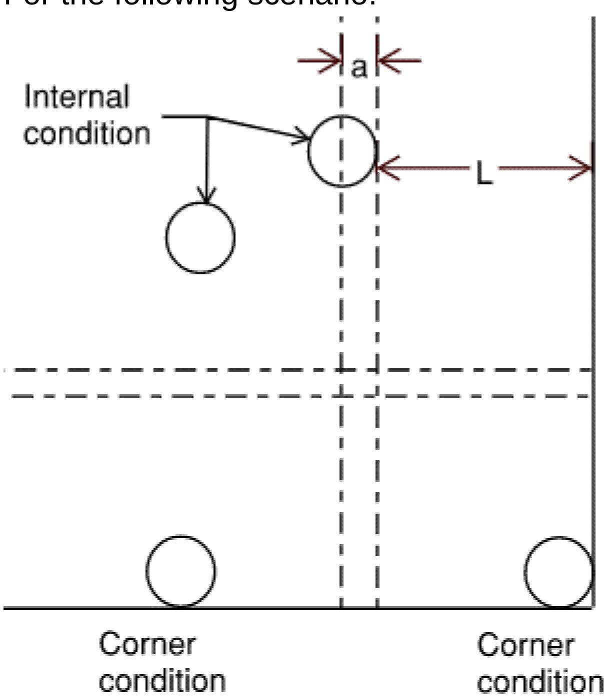
Fig. 31 – Slab cracking behavior due to a post load

Yield-Line Theory – Plastic/Ultimate Method:

TR34 presents a **yield line theory method** of slab design based on studies by such authors as Meyerhof (1962), where the failure mechanism is similar to that described in Fig. 31. The concept of yield lines is a widely acceptable analysis method with provisions in building code design publications such as ACI 318. It involves an assumed failure shape **where the material in question bends to the yield limit along failure lines** and then the moment that caused that yielding remains constant through failure. The rotation of the first crack or yield line is assumed to continue plastically due to ductile behavior. So, the expectation is that the material has some post-crack strength to allow for this.

In TR34, the yield line failures that take place along positive moment regions are assumed to occur in a ductile manner due to concrete containing steel or synthetic fibers or steel reinforcing. Minimum amounts of reinforcing are recommended. The literauture mainly focuses on concrete slabs with steel fibers, but the use of the equations could be extrapolated to slabs with steel reinforcing.
The equations for rack post loading are as follows:

For the following scenario:



a = equivalent contact radius of the load

$$L = \sqrt[4]{\frac{E_c h^3}{12\,(1-\ \mu^2)k_s}}$$

Where,

$$L = radius\ of\ relative\ stiffness, in$$
$$h = slab\ thickness, in$$
$$\mu = \ poisson's\ ratio\ for\ concrete$$

<u>Case I: Internal load – center of load is more than (L+a) from a free edge or joint</u>

a/L = 0, $P_u = 2\pi\left(M_p + M_n\right)$

a/L > 0.2, $P_u = 4\pi\left(M_p + M_n\right)/\left[1 - \frac{a}{3L}\right]$

Use linear interpolation for a/L between 0 and 0.2.

<u>Case II: Edge load - center of load is located on an edge more than (L+a) from a free corner or the intersection of two joints</u>

a/L = 0, $P_u = \{\pi(M_p + M_n\ )/2\} + 2\ M_n$

a/L > 0.2, $P_u = \left\{\{\pi(M_p + M_n\ )/2\} + 4\ M_n\right\}/\left[1 - \frac{2a}{3L}\right]$

Use linear interpolation for a/L between 0 and 0.2.

<u>Case III: Corner load - center of load is located at distance a from the two edges forming a corner</u>

a/L = 0, $P_u = 2\pi M_n$

a/L > 0.2, $P_u = 4\ M_n/\left[1 - \frac{a}{L}\right]$

Use linear interpolation for a/L between 0 and 0.2.

P_u = Storage rack load

Positive moment capacity: $M_p = As\ Fy\ d$ / *FS*

Negative moment capacity: $M_n = f_r x\ S$/*FS*

FS = factor of safety

As = area of steel reinforcing for unit width

Fy = yield strength of reinforcing,

fr = Concrete rupture modulus = $9\sqrt{f_c'}$ in psi (value suggested by author)

S = Section modulus of concrete per unit width

As should be an amount of reinforcing adequate to ensure **ductility,** or the ability of a material to yield, but undergo more deformation while maintaining some post-yield strength. Even though this is outside of buidling code design, concrete building codes can guide this. ACI recommends minimum reinforcing ratio of 0.0018 for footings and mat foundations. The British Standard 8110 recommends a minimum percentage of 0.13% for rectangular sections subject to flexure. The building code does not require the slab design to follow these strictly. The author would lean towards the 0.13% range.

For determining limits on **proximity of adjacent loads**, per TR3, "The influence of an additional load… at a distance x from…[the load center] is as follows:

If x < L, "the positive bending moment at …[the load center] will increase"

If L < x < 3L, "the positive bending moment at …[the load center] will decrease, but by a relatively small amount."

If x > 3L, "the additional load will have negligible influence on the bending moment at …[the load center]."

Cases for multiple wheel loads, line loads, and uniform loads are also presented in the TR34 document, in the form of direct equations, making it very suitable for use in a spreadsheet.

Simplified Analytical Method by Shentu, Jiang, and Hsu - Plastic/Ultimate Method

Shentu, et al, developed a relationship between load and slab thickness based on the ultimate limit state of failure observed in load tests and from robust finite element modeling (FEM). A multiaxial state of stress is included in the constitutive model, and the concrete behavior is captured from first crack to collapse of the slab under load. Loading in the finite element model is increased incrementally. The FEM program checks the elements of the mesh at each step, and adjusts the stiffness contributions of elements as they crack. The key characteristic behavior that allows this method to reflect a closer approximation to test results is the **horizontal thrust** that develops as the slab is squeezed between the load above and soil below, while being restrained laterally in all directions by the main body of the slab. The state of compression thereby created does not prevent cracks, but enough of the slab remains intact well beyond the initial cracking for significant post-crack strength to develop. Even with generous factors of safety, the failure loading predicted by the model is substantially greater than that obtained by other methods of analysis.

As a caution in using this approach, the designing engineer will need to consider the things which do not appear to be addressed in this research, including curling and shrinkage stresses, and joint proximity and construction. Also, if applying this method to the analysis of the slab due to seismic forces from a rack post, the uplift values on a cracked slab during repeated cycles of alternating upward and downward forces due to overturning need to be considered.

The use of the method developed by Shentu, et al, is listed as an acceptable method of slab design in FEMA 460. An excellent summary of the use of this method is also found in "Load Carrying Capacity, Concrete Slabs-On-Grade Subject to Concentrated Loads", by Azzi and Laird. They further recommend a reduction factor to account for slightly different theoretical results for thicker slabs. The resulting equations are:

$$P_u = 1.72\ x\ \left[\frac{k_s R_1}{E_c} x\ 10^4 + 3.60\right] f_1'\ d^2$$

$$P_a = \frac{P_u}{FS}$$

$$P_u = Load\ carrying\ capacity\ of\ slab, pounds$$

$$P_a = allowable\ load\ carrying\ capacity\ of\ slab, pounds$$

$$FS = factor\ of\ safety$$

$$R_1 = radius\ of\ the\ loaded\ area\ \ or\ one\ half\ the\ width\ of\ a\ square\ base\ plate$$

$$E_c = modulus\ of\ elasticity\ of\ concrete, psi$$

$$k_s = modulus\ of\ subgrade\ reaction, pci$$

$$f_1' = tensile\ carrying\ capacity, psi$$

$$d = slab\ thickness, in$$

Or, slab thickness can be derived directly from,

$$d = \sqrt{\frac{FS\ x\ P_u}{1.72\ x\ \left[\frac{k_s R_1}{E_c} x\ 10^4 + 3.60\right]\ f_1'\beta}}$$

Where the load reduction factor, β, introduced by Azzi and Laird is given by β = 1.0 for slabs < 7" thickness, and β = 0.85 for slabs ≥ 7" thickness.

For determining limits on proximity of adjacent loads, the following parameter is established:

$$l = \sqrt[4]{\frac{E_c h^3}{12\,(1 - \mu^2)k_s}}$$

Where,

$$l = radius\ of\ relative\ stiffness, in$$
$$h = slab\ thickness, in$$
$$\mu = poisson's\ ratio\ for\ concrete$$

The radius of relative stiffness is the generally accepted distance from the centerline of load to the inflection point in the slab (moment transitions from positive to negative), see Fig. 31. It is clearly partially dependent on subgrade stiffness, and is used in determining how close adjacent loads can be without affecting slab stress calculations. Per Azzi and Laird, "A load that is within a distance of 1.5 times the radius of relative stiffness from another load may have an influence on slab stresses."

Punching shear and one-way shear

There are no hard and fast rules for punching and one-way shear strength of slabs-on-grade. In Tarr and Farny, it is suggested that, "The size of the base plate be large enough so that concrete bearing stress under maximum service load does not exceed 4.2 times the 28-day modulus of rupture, or one-half this value for loads applied at slab edges or corners." This assumes an **allowable shear of 0.27 times the modulus of rupture** and the failure surface defined by the area of the base plate extended an additional half the slab depth on all sides, but excluding the contribution of any sides with a joint.

Joint Layout

Control joints, sawcutting, construction joints and isolation joints for unreinforced slabs in typical buildings was described in detail in *Slabs-on-Grade: From the Ground Up*.

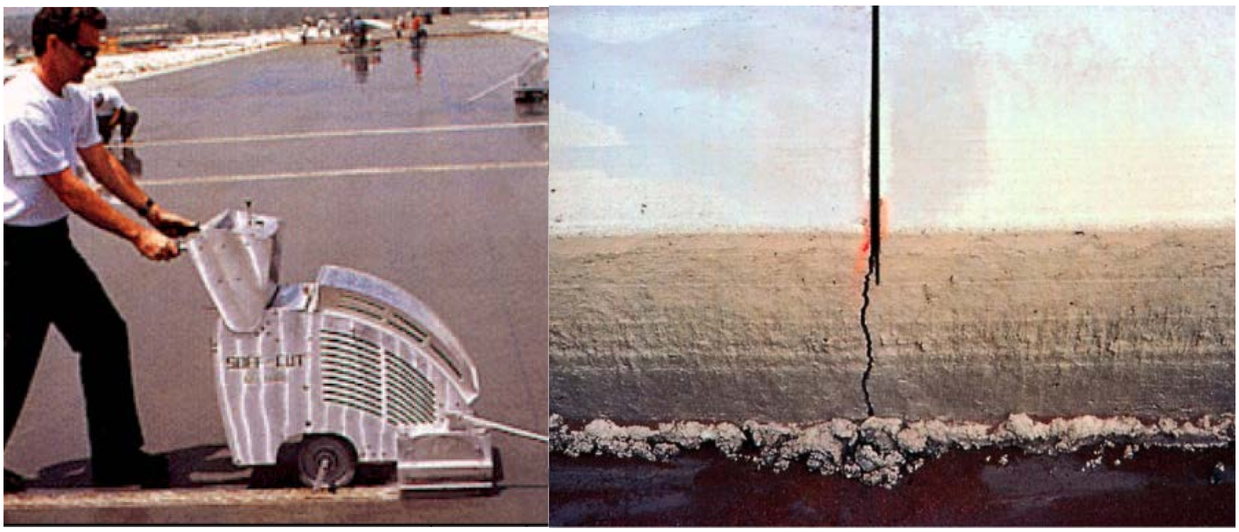
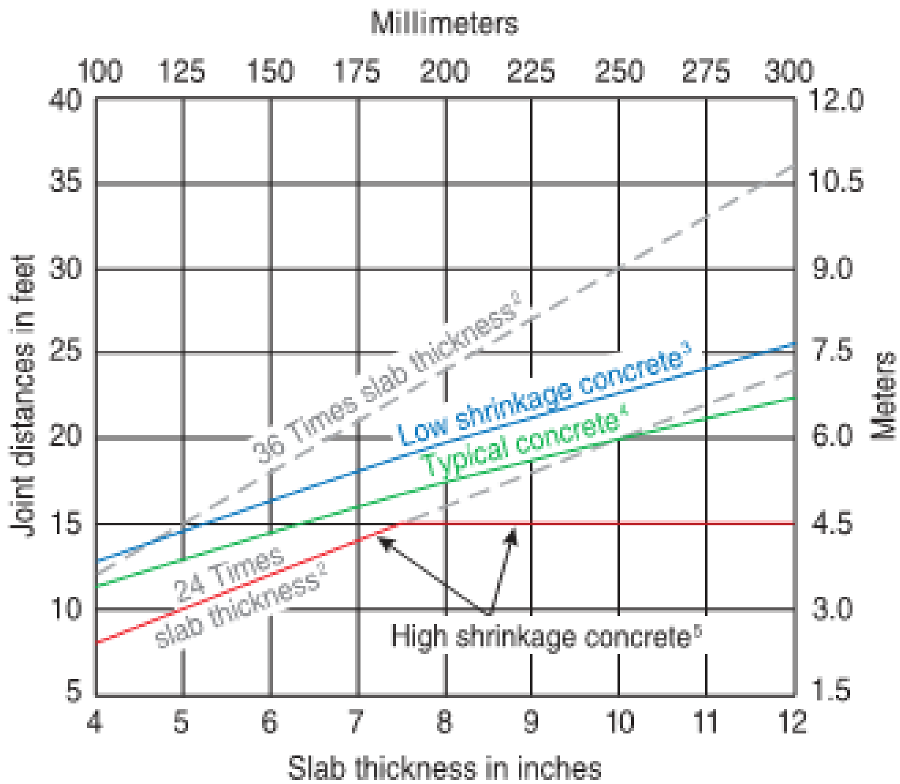


Fig. 32 - Sawcutting new concrete, and joint with crack induced by sawcut (MnDOT)

The same concepts apply to warehouse slabs. Control joint layout for warehouses depend on a number of parameters. Shrinkage characteristics of the slab will need to be understood. Preventing random cracks due to shrinkage restraint will be a goal, and how much joints will open up due to shrinkage will also factor in. Obviously, the larger the joint spacing, the larger the joint width can be expected with shrinkage. Expectations of joint aggregate interlock performance will also need consideration, as was discussed in *Slabs-on-Grade: From the Ground Up*, and further discussed below. Joints should be kept perpendicular to traffic, with parallel joints free of main travel aisles. Luckily, there is guidance from the industry. ACI recommends the following **joint spacing** for unreinforced slabs (see Fig. 33), from PCA's Concrete Floors on Ground. Note that the **upper and lower bounds are 24 and 36 times the slab thickness, respectively**:



NOTES:

1. Joint spacing recommendations based on reducing the curling stresses to minimize mid-panel cracking (Walker-Holland 2001). See discussion in Section 5.2 for joint spacing for aggregate interlock.
2. Joint spacing criteria of 36 and 24 times the slab thickness which has been utilized in the past is shown for reference.
3. Concrete with an ultimate dry shrinkage strain of less than 520 millionths placed on a dry base material.
4. Concrete with an ultimate dry shrinkage strain of 520 to 780 millionths placed on a dry base material.
5. Concrete with an ultimate dry shrinkage strain of 780 to 1100 millionths placed on a dry base material.

Figure 6-12. Joint spacing recommendations based on ultimate concrete shrinkage potential (ACI 360R).

Fig. 33 – Recommended control joint spacing

Walker and Holland (1999) performed finite analysis on modeled slabs and found that slab thickness and joint spacing can affect curling stresses dramatically. They state that

15 ft joint spacing is significantly better for curling stresses than 30 ft joint spacing. Additionally, an increase the modulus of subgrade can increase the curling stress, especially for shorter joint spacings. So, efforts to stiffen the subgrade may not be advantageous beyond a certain point. If we pick two slab thicknesses, 6" and 8", results were as follows:

a. 6" slab – 18 ft joint spacing, curling stress = 303 psi
b. 6" slab – 15 ft joint spacing, curling stress = 217 psi
c. 8" slab – 24 ft joint spacing, curling stress = 350 psi
d. 8" slab – 15 ft joint spacing, curling stress = 143 psi

The lower range of modulus of rupture for bending in concrete used in practice is 410 psi. **If the curling stress is high, it reduces the reserve strength** near the joint to resist wheel loads. Walker and Holland also found that higher strength concrete results in higher curling stresses due to the increase in concrete shrinkage and stiffness, both resulting in greater curling. The lesson here is keep joints to a maximum of 15 feet if possible, and use concrete in the range of 3,000 to 3,500 psi.

Additional notes on joints per Tarr (2013):

1. Cap joint spacing at 30x slab thickness for joint aggregate interlock, which is limited to widths of 0.035" or less for effective use.
2. Note that closer spaced joints may not activate and cause dominant joints to be more prevalent.
3. Avoid T-shaped joints. Sympathetic cracking may follow the tee stem, continuing in the direction of the sawcut extended.
4. Keyways will spall at the concave side due to the weak section of concrete near top with wheeled traffic, and are not recommended.
5. Note that observing the top of slab may not be the best indicator of joint width. A crack or joint is likely smaller a base due to a V-shaped crack. If confirmation is needed, a concrete core drilled cylinder may be taken. A practical effective crack width to use for determining aggregate interlock may be that found at 1/2 or 2/3 the height of slab (as shown in the core sample).

And per Basham, a conventional wet saw should use a sawcut depth of 1/4 to 1/3 of slab thickness 4 to 12 hours after finishing. Early entry saws should use a saw cut of 1"to 1.5" in depth (1 to 4h after finishing)

Joint Design Against Failure

The potential for fatigue and impact damage in warehouse slabs is unavoidable. At the joints, the conditions are most severe. Here the slab may be moving differentially, depending on where the wheel is at in comparison to the joint, and curling and joint width as well as the type of wheel and its loading will all need to be considered. There are ways to make joints more stable against wear and tear.

Again, the two types of joints that are used in traffic areas of slabs on grade are control joints and construction joints. We will look at both of these separately, but first we can explore the options, beginning with a discussion on aggregate interlock.

Load Transfer

Load Transfer - Aggregate Interlock

One method of load transfer at a joint is **aggregate interlock**, which is the reliance on the crack at a control joint to transfer load across it (see *Slabs-on-Grade: From the Ground Up*, and Fig. 34). When the slab cracks after the sawcut is performed, there is a roughness to the interface from one side of the crack to the other. For typical warehouses with high traffic volume and forklift loading, caution should be used when counting on this for main traffic aisles.

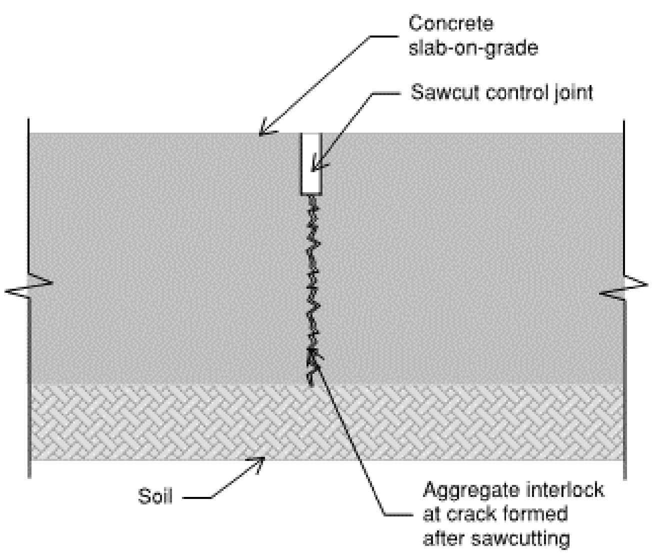


Fig. 34 – Aggregate interlock

One might consider aggregate interlock a reliable method for areas with lower loading or minimal traffic volumes. However, rack layouts and facility usage may be revised in the future. That being said, it is worthwhile to explore the limits of aggregate interlock for any slab being considered. Colley and Humphrey performed research for PCA on slabs to determine the effectiveness of aggregate interlock (Colley, B.E. and Humphrey, H.A., 1967, "Aggregate Interlock at Joints in Concrete Pavements," *Development Department Bulletin* D124, Portland Cement Association, Skokie, IL.). They loaded plates near the edges of a slab joints to see how well the load would be passed to the far side of the joint. They defined "effectiveness", E, as

$$E\ (\%) = \frac{2\ d_j'}{d_j +\ d_j'}\ x\ 100$$

where d_j is the deflection of the slab at the near side of the joint d_j' is the deflection of the slab at the far side of the joint. An example curve of the results is shown in Fig. 35.

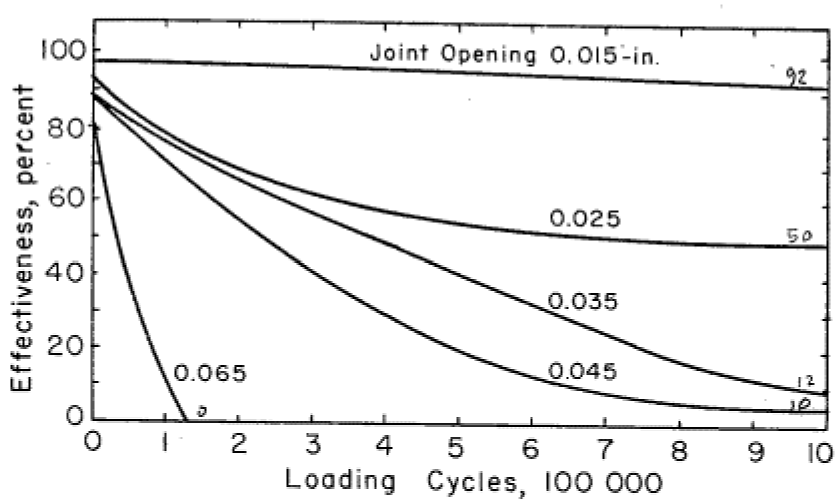


Figure 11. Influence of joint opening on effectiveness, 7-in. concrete slab, 6-in. gravel subbase.

Fig. 35 - Effectiveness of opened joint (Colley and Humphrey)

Colley and Humphrey found that the value of E depends on a number of things. They summarized this in an empirical expression as noted below, where EI is the endurance index, which is "obtained by dividing the area under the curve of effectiveness vs cycles by the area that would be developed if the joint retained an effectiveness of 100 percent throughout one million load applications."

$$EI\ (\%) = 230\ \frac{h}{P\ w}\sqrt{k}$$

Where:
h = depth of roughened surface, in
P = wheel load, #
w = joint opening, in
k = foundation modulus, pci
(per Colley and Humphrey)

And shown graphically in Fig. 36.

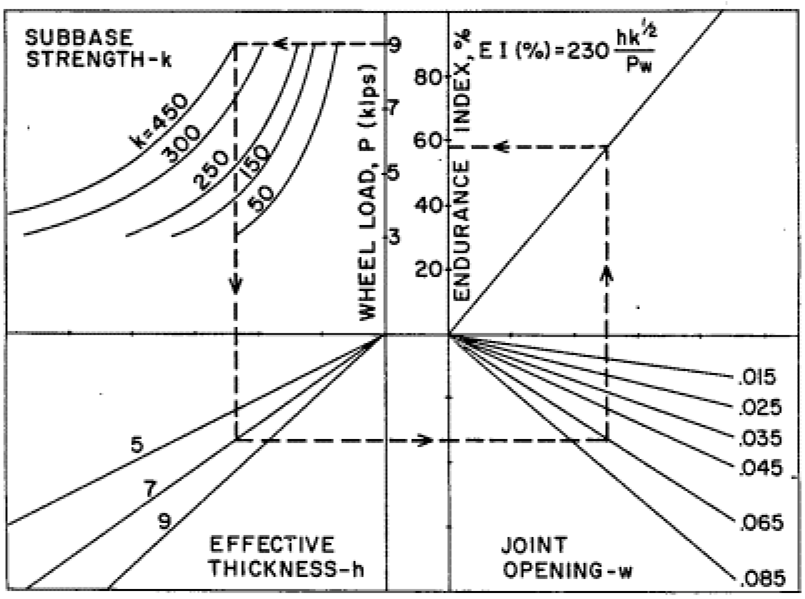


Figure 22. Endurance of joints.

Fig. 36 - (Colley and Humphrey)

Some specific data of note in the report was as follows. For a 7” slab with a 6” gravel base to stay at 50% effectiveness at one million cycles, the joint opening needed to be about .025”. For a 9” slab with a 6” gravel base to stay at 50% effectiveness at one million cycles, the joint opening needed to be about .035”. **The effectiveness of aggregate interlock drops steeply with increasing joint size.**

So, again, unless joint size or number of load cycles can both be practically controlled or are naturally limited, caution should be exercised in applying this method of joint load transfer. Per ACI 360: “If the designer cannot be sure of positive long-term shear transfer at the joints through aggregate interlock, then positive load-transfer devices should be used at all joints subjected to wheeled traffic."

Load Transfer – Reinforcing

Type I – Steel reinforcing to control joint size
Some slabs are designed with reinforcing sufficient to control the crack sizes, thereby allowing for control joints to be omitted. The amount of steel varies, but the author has has good results with reinforcing in the 0.5% to 0.6% range. Construction joints at reinforced slabs with 0.5% or more reinforcing by area should use this same amount of steel across the joint, but the steel needs to have a lapped and embedded near and across the joint so the bar is fully developed in tension. An alternative to this might be to use an armored joint, which will be described in a later course.

Type II – Steel reinforcing to enhance aggregate interlock
ACI 360 mentions the strategy of using of a small amount of reinforcing (0.1% by area) to enhance the aggregate interlock mechanism. Guidelines are provided in that publication that promote the success of this strategy, including following the recommended joint spacing, the use of construction joints at 125' maximum spacing, and other advisory measures.

Load Transfer Devices

The reliance on aggregate interlock for joint load transfer has its limitations. But, there are many alternatives for slab designs. There is a long history of the use of round dowels at joints in the design of highway pavements. It is common to find round dowels in the standard details of the nation's finest transportation departments, and they are surely performing admirably in outdoor pavements. Other alternatives include rectangular, tapered or diamond dowels.

The function of dowels is to allow for joints to continue to move due to drying shrinkage while also providing vertical load transfer. This means the dowels need to be able to slip away from at least one side of the joint (bond breaker applied), and ideally also have space to move parallel to the joint on one side of the joint. Walker and Holland have published two excellent articles that sums up the use of plate dowels in slabs (Walker and Holland, 1998, and Walker and Holland, 2007).

Joint transfer devices may be strategically located only at areas with the most severe traffic conditions to optimize costs. A well-defined traffic pattern is generally required.

Load Transfer Devices at Construction joints – Dowels

At construction joints, it would be very risky to omit dowels or some other means of joint stabilization at these abrupt discontinuities, as the slab alone does not have any means of load transfer from one slab to the other across the joint. Round rigid steel dowels across a joint are an option (see Fig. 42). Typical sizes are ½" in diameter and 2'-0" in length. Dowels are centered on the joint, and one end should be greased. However, as described in *Slabs-on-Grade: From the Ground Up*, the most common type of dowel is the diamond dowel, Figs. 37, 38, 39. Diamond dowels are simple to use, and the formwork does not need to be drilled through. Also, the load transfer is excellent, with the widest section of the dowel being placed at the location of highest bending and shear stresses. See Fig. 40 for a depiction of the fixed-fixed condition.

The diamond dowels are steel plates that are laid flat and oriented at 45 degrees to the joint. A sample installation for standard buildings is 1/4" thick x 4-1/2" x 4-1/2", with a given on-center spacing, and centered in the slab. There is a unique method of placing these. A rigid plastic housing of adequate strength is first nailed onto initial concrete edge form and gets included in the first concrete pour. The dowel is then slipped into the housing for the second pour. This means that the contractor does not need to provide holes in the formwork to accommodate a plate dowel placed in the first pour. Another advantage of these dowels is the allowance for shrinkage movement in two directions. The plastic housing is designed with an allowance for movement parallel to the joint, and naturally the dowel slips out of the housing is there is movement perpendicular to the joint. As mentioned, concrete panels shrink toward their center of mass, so near the corners, the slab is moving diagonally. This leads to a component of movement both parallel and perpendicular to the slab joint.

Fig. 37– Insert at edge of construction joint set into first concrete pour, with second concrete pour to follow. Square dowels shown to be placed at a construction joint placed in insert that was set into first concrete pour, with second concrete pour to follow (https://www.pna-inc.com/products-designs/diamond-dowel-system)

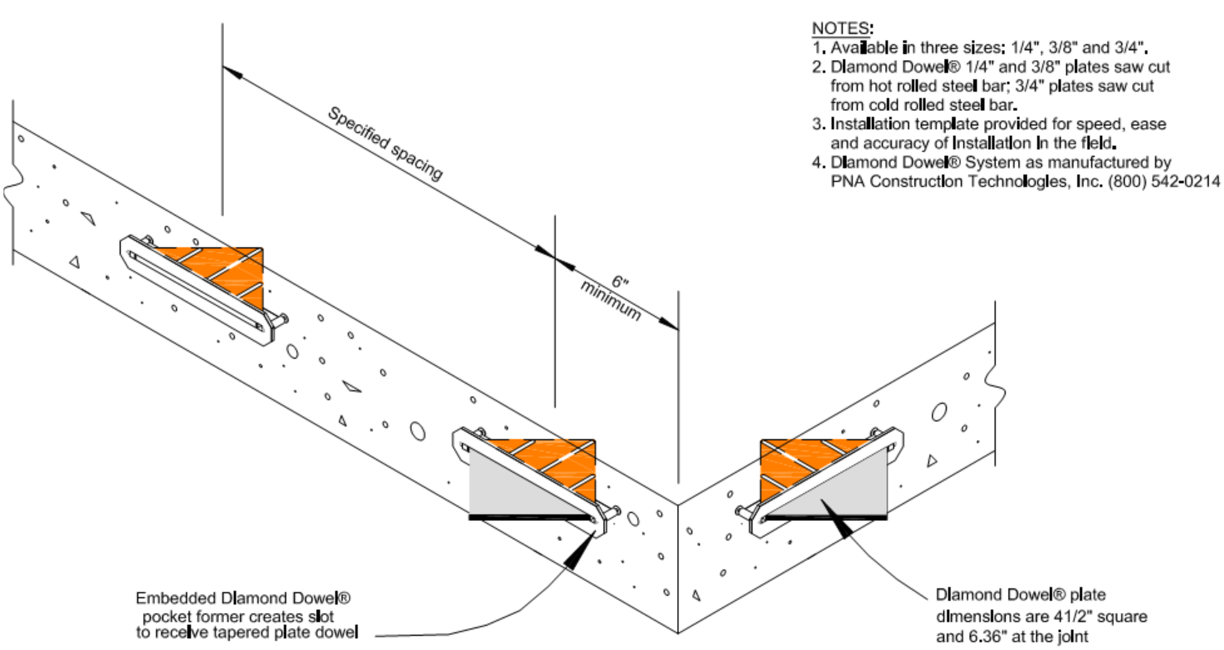


Fig 38 - Diamond dowels by PNA

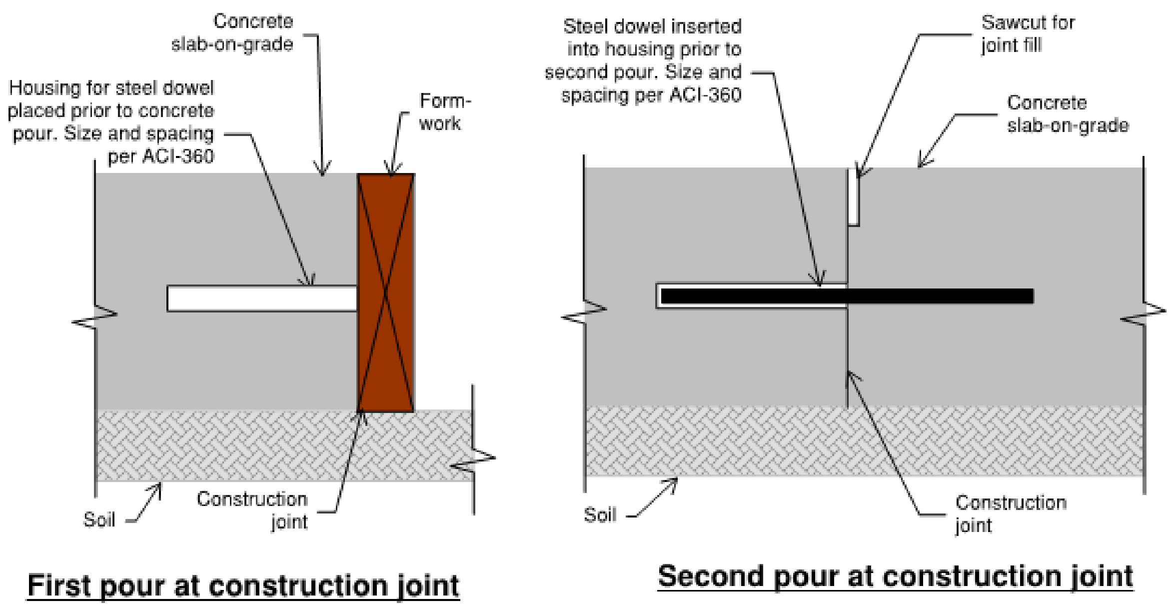


Fig. 39 – Diamond dowel placement

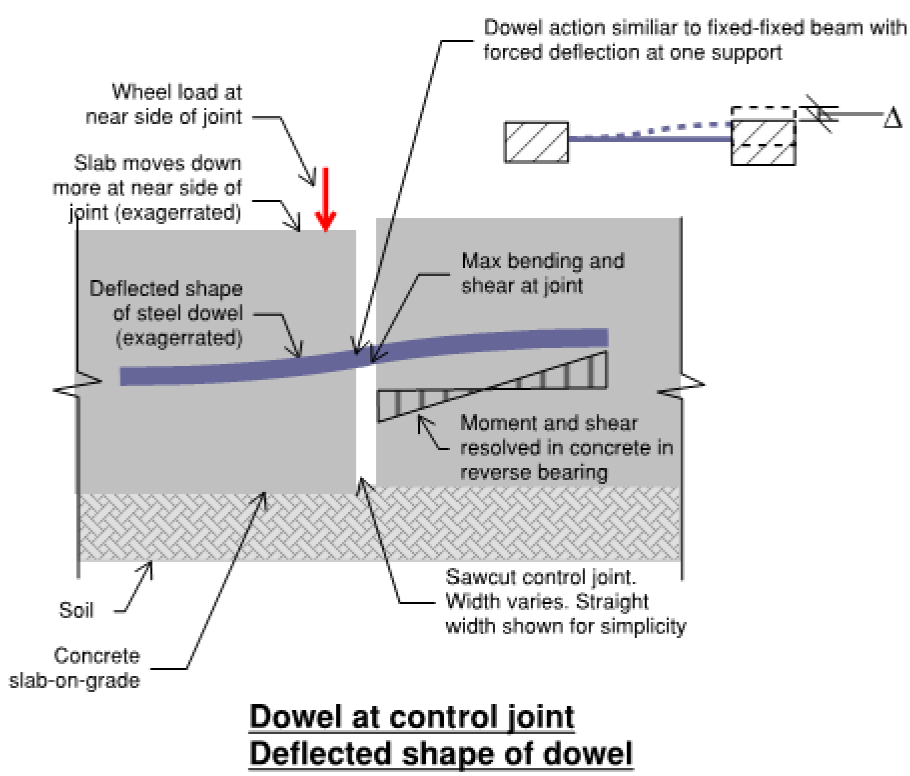


Fig. 40 - Diamond dowel action

ACI 360 recommends the following for dowel size and spacing.

Table 5.2—Dowel size and spacing for diamond-shaped load plates (Walker and Holland 1998)

Slab depth, in. (mm)	Diamond load plate dimensions, in. (mm)	Diamond load plate spacing center-to-center, in. (mm)
5 to 6 (130 to 150)	1/4 x 4-1/2 x 4-1/2 (6 x 110 x 110)	18 (460)
7 to 8 (180 to 200)	3/8 x 4-1/2 x 4-1/2 (9 x 110 x 110)	18 (460)
9 to 11 (230 to 280)	3/4 x 4-1/2 x 4-1/2 (19 x 110 x 110)	20 (510)

Note: Table values based on maximum joint opening of 0.20 in. (5 mm). Construction tolerances required make it impractical to use diamond-shaped load plates in sawcut contraction joints.

Fig. 41 - Recommended diamond dowel size and spacing (ACI 360).

Load Transfer Devices at Control joints – Dowels and Dowel Baskets

Two types of dowels, round and tapered dowel baskets, are shown in Figs. 42 & 43. The function of the dowel basket is to allow the control joint to open up under shrinkage movements, but to maintain vertical load transfer across the joint. The tapered variety of dowel has an additional benefit. First, note that the dowel is wider on one side, but that the wider end is placed so it resides alternately on side of the joint, then the other. As the concrete shrinks, the dowel holds to the side with the wider end, and when the joint opens up, there is a gap that develops, allowing space to move for any movement parallel to the joint. See Figs. 44 through 48 for dowel basket use and spacing, and some construction details.

Fig 42- Round dowels (MnDOT)

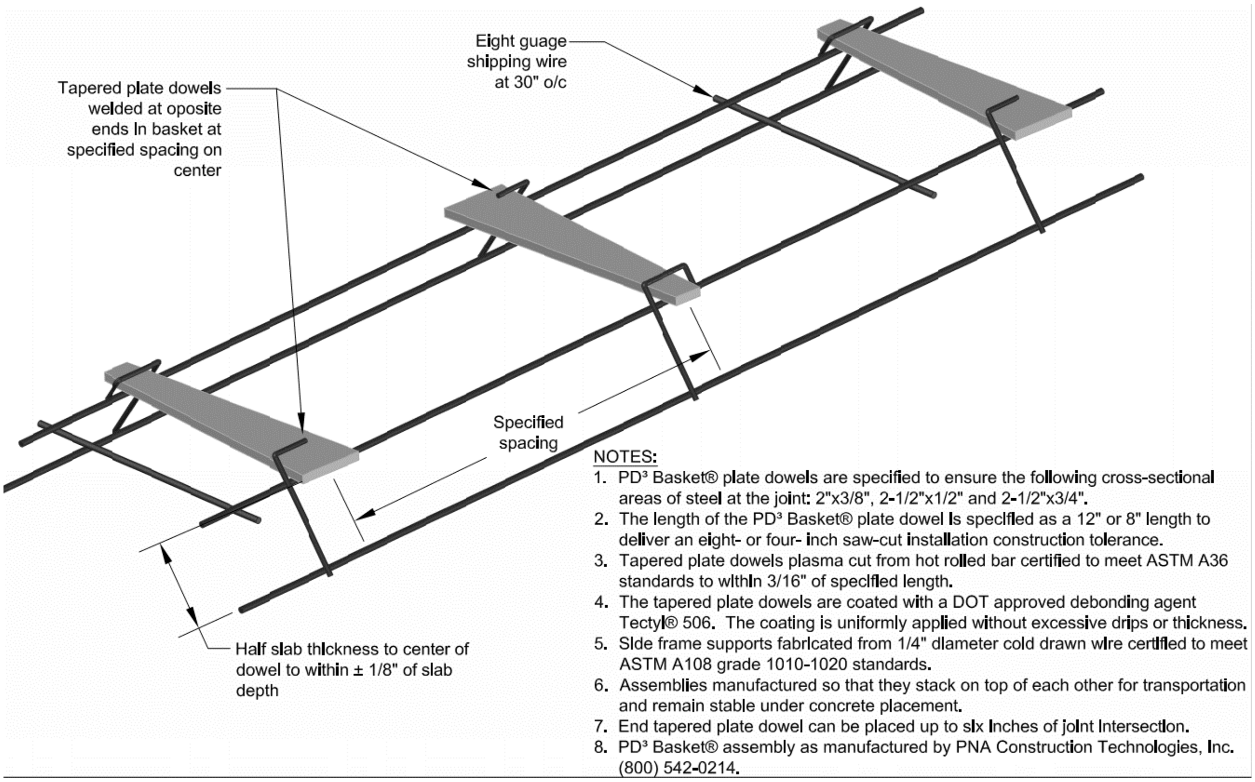


Fig. 43 - Tapered dowels by PNA (PD^3 Basket dowels)

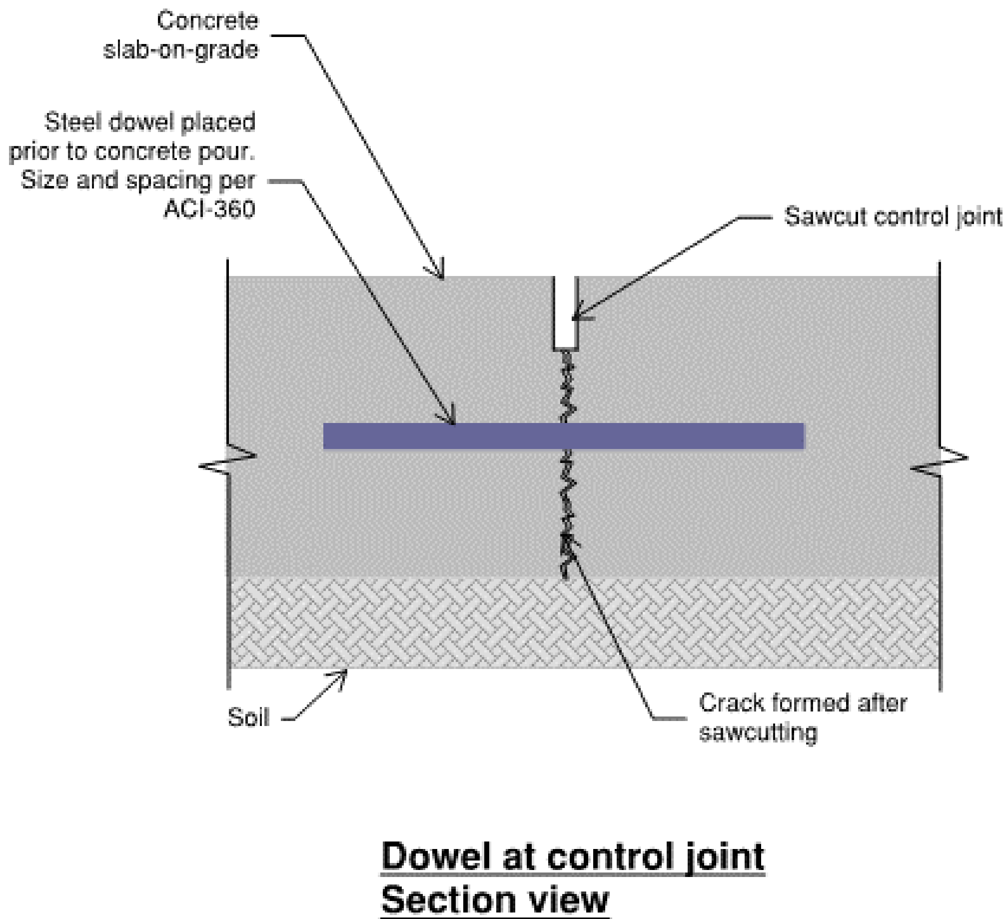
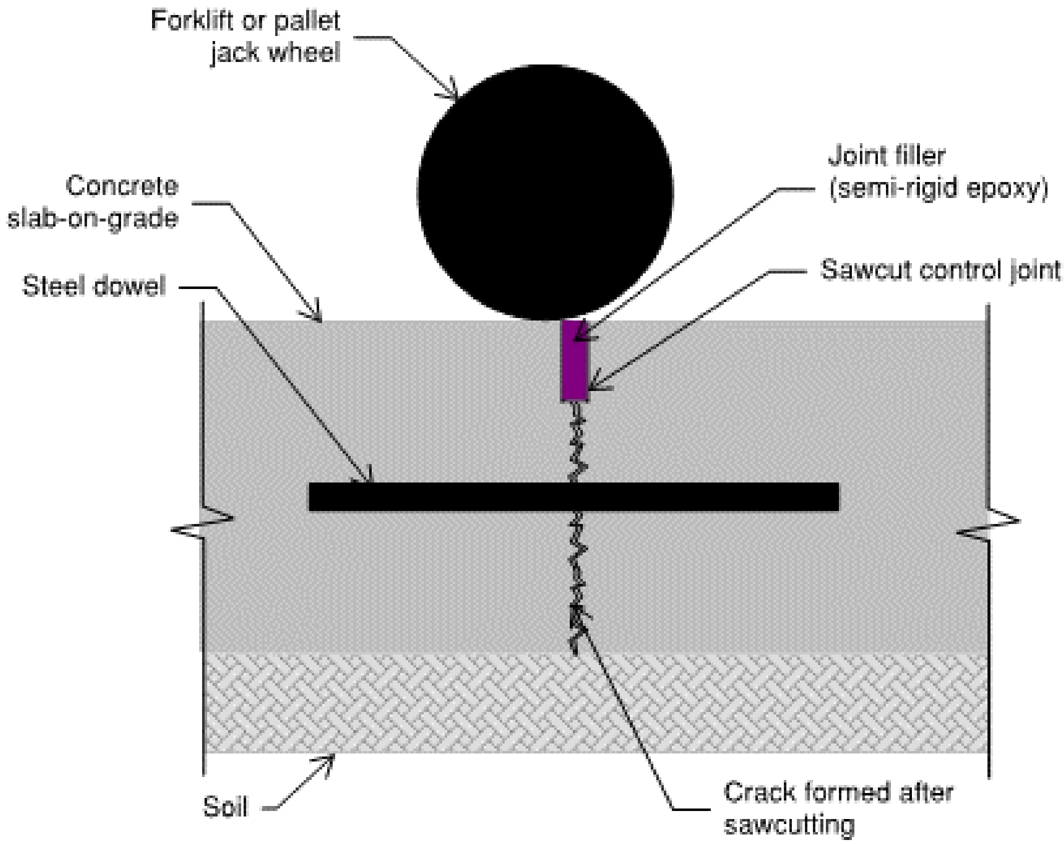
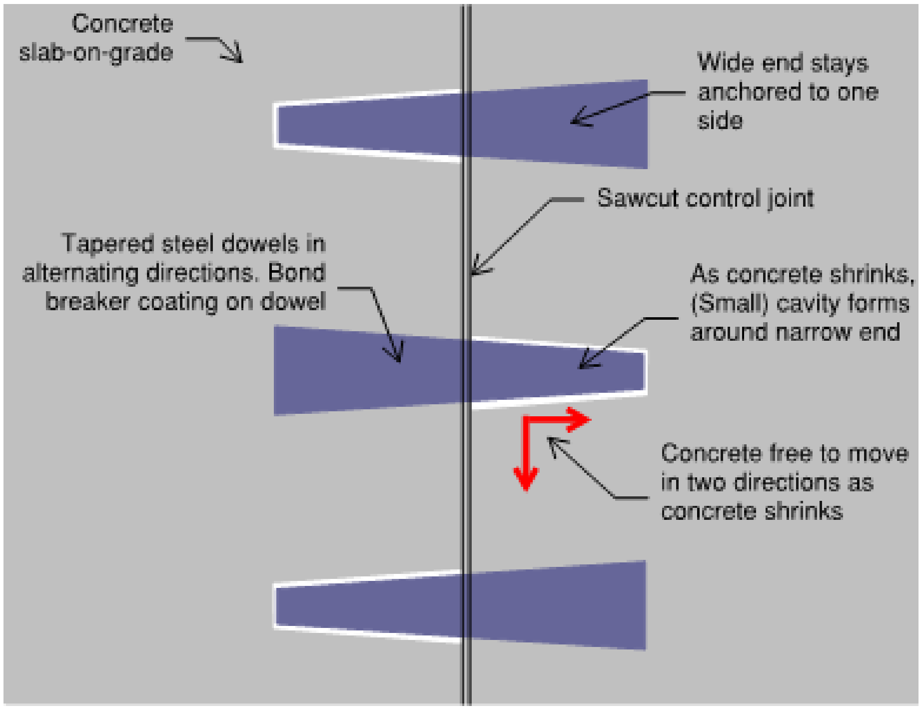


Fig. 44 - Dowel at a control joint



Dowel at control joint

Fig. 45 - Wheel and joint filler at a control joint



Dowel at control joint
Plan view

Fig. 46 - Plan view of tapered dowels

Table 5.1—Dowel size and spacing for round, square, and rectangular dowels*

Slab depth, in. (mm)	Dowel dimensions,† in. (mm)			Dowel spacing center-to center, in. (mm)		
	Round	Square	Rectangular‡	Round	Square	Rectangular
5 to 6 (130 to 150)	3/4 x 14 (19 x 360)	3/4 x 14 (19 x 360)	3/8 x 2 x 12 (9 x 51 x 300)	12 (300)	14 (360)	19 (480)
7 to 8 (180 to 200)	1 x 16 (25 x 410)	1 x16 (25 x 410)	1/2 x 2-1/2 x 12 (13 x 64 x 300)	12 (300)	14 (360)	18 (460)
9 to 11 (230 to 280)	1-1/4 x 18 (32 x 460)	1-1/4 x 18 (30 x 450)	3/4 x 2-1/2 x 12 (19 x 64 x 300)	12 (300)	12 (300)	18 (460)

*ACI Committee 325 (1956); Walker and Holland (1998).
†Total dowel length includes allowance made for joint opening and minor errors in positioning dowels.
‡Rectangular plates are typically used in sawcut contraction joints.
Notes: Table values based on a maximum joint opening of 0.20 in. (5 mm). Dowels must be carefully aligned and supported during concrete operations. Misaligned dowels may lead to cracking.

Fig. 47 - Recommended joint dowel size and spacing (ACI 360).

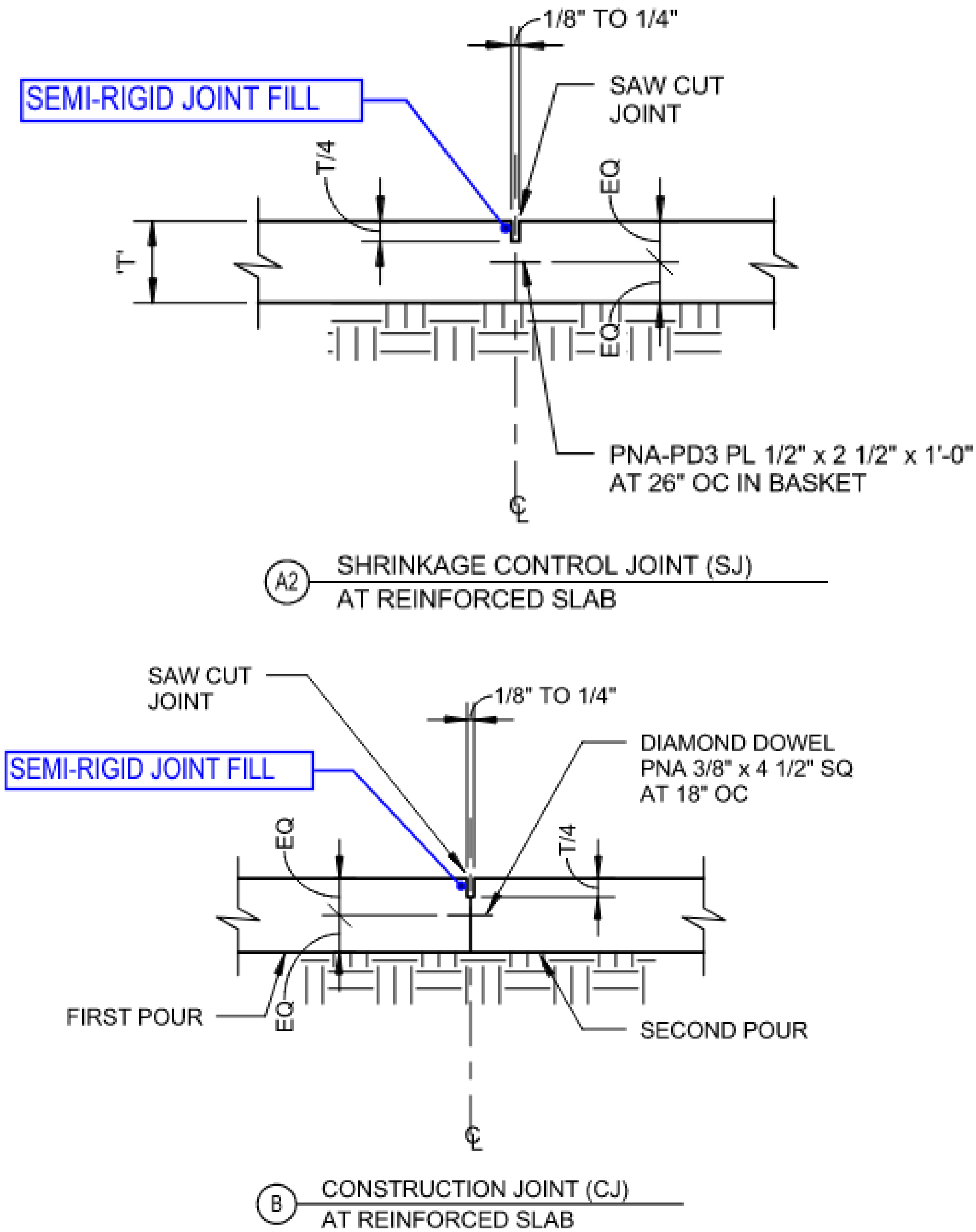


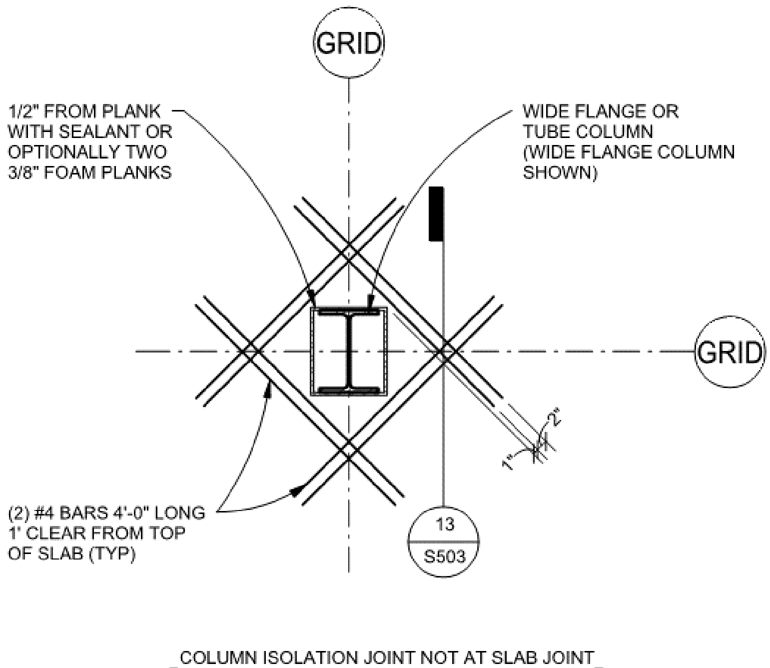
Fig. 48 - Slab-on-grade joint details

One more note on joints:

1) **The use of a vibrator at joint devices is imperative for the devices to work properly**. If there are honeycomb voids, the devices may become loose, or there may be weak sections in the concrete that are subject to higher stresses.

Isolation Joints

There will be many building components that will make the use of control joints difficult to employ with complete regularity. Objects such as columns, bollards and doorways will project through the plane of the slab, and with enough lateral movement of the slab due to drying shrinkage or temperature effects, the restraint can induce cracking at the margin of the object. The joints that provide relief at these objects are called **isolation joints**, with an intentional gap and a compressible filler material, an example of which is shown in Fig. 49. Re-entrant corners will exist where floor areas follow building geometry and at transitions between adjacent areas that require discontinuities in the slab. Special details may be required.



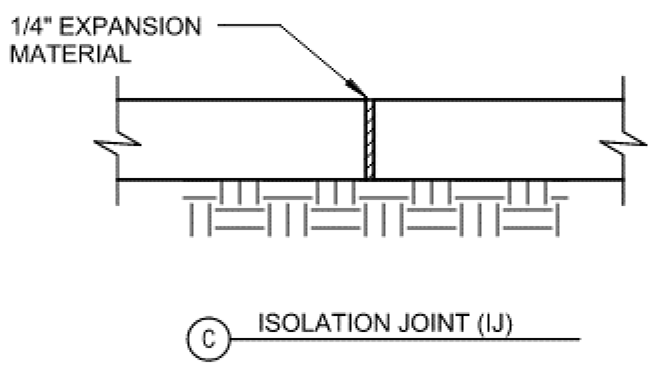


Fig. 49 - Details for typical isolation joints

Joint Protection

Hard-wheeled traffic can be detrimental to slab joints. Over time, the action of repeated cycles of forklift and pallet jack loading across a joint will tend to break the joint down. ACI 360 notes two ways to protect a joint: armored angles or plates or joint filler. Armored plates will be shown in a later course. Joint filler is discussed below.

Joint Filler

To mitigate degradation of otherwise unprotected slab joints, it is highly recommended in warehouses with small wheeled traffic to have a protective filler material placed in joints. There would be a high risk or premature joint failure without it. Appropriately enough, this material is called **joint filler**. It has evolved over time with the increased demand on joint performance due to smaller and harder wheels, and round-the-clock operations of distribution centers. **Joint filler allows for normal control joint construction while still provding excellent protection against cracking and spalling**. Some notes:

Fig. 50 - Joint filler in slab joints

1) The most common type of material used is semi-rigid joint filler. Per ACI 360, “Certain types of semi-rigid epoxy or polyurea are the only materials known to the committee that can fill joints and provide sufficient shoulder to the edges of the concrete and prevent joint breakdown.” Metzger/McGuire has an excellent publication on the subject called *Concrete Joint Filler*. Per Metzger/McGuire, the concept is to fill joints with an epoxy product that has “sufficient rigidity to avoid deflection, protecting edges from impact damage”, “sufficient resiliency to absorb impact”, and a low tensile and adhesive strength to allow the joint to move without restraining it. Separation from one or both sides of the joint is expected. They also provide guidelines for conditions for replacement such as joint spalling and when the joint filler starts pulling out of the joint. **Joint filler is used in both construction and contraction joints**. The joint filler is ony intended to be a partial depth installation. Generally, the depth of joint filler is the depth of the sawcut or a maximum of 2 inches. Where contraction joints are large, silica sand can be used to choke off the joint. At construction joints, a backer rod is used to define the joint filler depth.
2) Good joint filler materials have sufficient tensile elongation to perform in a ductile manner.
3) The timing of joint filler ideally occurs as late as practically possible in the construction phases of a building. It would even be best to wait until the ambient operating temperature and humidity were achieved (e.g., during HVAC commissioning). However, it is often the case that construction sequence dictates jointfilling in the first 90 days. If this is the case, it is recommended that the joint filler be inspected at one year or so later to assess its condition and be replaced as necessary.
4) In cold storage faciltites, the joint filler should occur some time during the temperature draw down sequence to allow so the temperature shrinkage has minimal affect on the joint filler material.

Floor Flatness and Levelness

Warehouses with storage racking may require stricter floor flatness/floor levelness (FF/FL) criteria compared to typical buildings. The basics of this topic are covered in *Slabs-on-Grade: From the Ground Up*. There are many factors to consider. Taller racks (>30 feet in height) will be more susceptible to leaning. If the floor slopes slightly at the base, this is magnified several times at the top of the racking. For racking with automated materials handling equipment, tolerances for flatness can be very strict, as the pathways and clearances need to be predictable, with limited ability to adjust things later. Racks that have narrow aisles and use automated high reach lifts may need superflat floors, which are a specialty type of warehouse slab to be discussed in a later course.

There are **two basic ways to call out FF/FL tolerances** for warehouse slabs.

1) **Random-traffic patterns – Materials handling equipment will move in multiple directions, either randomly, or orthogonally**
2) **Defined-traffic patterns**

For random traffic patterns, the entire slab needs to be poured to the FF/FL tolerance in both directions. For defined traffic patterns, the FF/FL for traffic areas may be different than the rest of the slab. Generally, this is used for rack systems with very narrow aisles, where forklifts are wire-guided by radio signals in aisles that are just wide enough for them to pass through (Fig. 51), usually with very tall racking. So, the travel aisles need to be very flat, but assuming the racking can be adjusted at install, really the very flat portions only need to occur at travel aisles (defined traffic patterns).

Chapter 7 of PCA's *Concrete Floors on Ground* provides guidance. Based on this, and on the author's experience, the concrete specifications for typical warehouses would have FF/FL requirements in the range of:
FF/FL = 25/17 for normal lift traffic alone (no racks),
FF/FL = 35/25 for shorter racking of, say, 20'-0" final product height, and
FF/FL = 50/35 for taller or automated racking with, say, final product heights of 35'-0" or greater.

Note **that FF/FL testing is to be performed 24 to 72 hours after concrete placement**. Because shrinkage and curling will continue well after, it is once again a good reason to limit curling. For racking or equipment very susceptible to issues with curling, the floor may need to be re-surveyed and perhaps subject to grinding in severe cases.

Specialty Slab Options

There are slab constructino solutions that have been developed to eliminate the number of slab joints and reduce the common durability issues with slabs. The author plans to address these specialty slabs in a future course. Some of the more common ones include:

1) Slabs with **shrinkage compensating concrete**

- A special Type K cement is used whose tendency to expand puts the concrete in a state of compression before the onset of drying shrinkage, thereby eliminating shrinkage concerns.

2) Slabs with **steel fibers**

- Fibers were discussed in Course 1. Steel fibers would allow for enhanced ductility, and therefore yield line analysis could be used. Impact and fatigue resistance, as well as shrinkage and curling reduction are common enhancements that depend on the type and dosage of steel fibers.

3) Slabs with **macrofiber**

- Similar improvements to slab performance as steel fibers

4) Slabs designed with **continuous reinforcing**

- Slabs with enough reinforcement to provide ductile strength, reduce crack sizes to sizes that can be largely ignored, and eliminating control joints.

5) **Post-tensioned slabs**

- Slabs-on-grade that are poured with post-tensioning cables and mild reinforcing in them, with the cables pulled later to induce a state of compression in the slab. This leads to wide areas of pours without control joints.

The future course will also include information on special rack types such as automated racking, as well as the design of cold storage facilities, and special detailing for unique warehouse situations.

https://commons.wikimedia.org/wiki/File:VAN_(Very_narrow_aisle)_AGV,_courtesy_of_Egemin_Automation_Inc..jpg; AGVExpertJS / CC BY-SA (https://creativecommons.org/licenses/by-sa/3.0)

Fig. 51 - Very narrow aisle racking

Finishes

The exposed surfaces of warehouse slabs take a lot of abuse from various activities. Wood pallets with sharp wood edges and nails will abrade the concrete surface over time. Hard troweling of the concrete paste at the surface will help with this. However, it is good to have additional protection against surface wear. **There are several options available.**

1) Sealer/Hardener: Silicate sealers
    a. These are surface treatments that penetrate and harden the top layer of concrete.
2) Integral Hardeners
    a. Similarly, these harden the surface of concrete, but are an additive to the concrete mix, so would provide protection for a slab that might experience more depth of wear.
3) Shake-on or Shoveled-on Mineral Hardener (e.g., trap rock)
    a. There are flat flakes of rock that are spread by spraying them on with a shovel or by the use of a shake-on machine that drops them on the slab in an even manner.

ACI 302 defines floor types by class in Table 2.1, and recommends finishes for classes. Here is the excerpt for the two main warehouse (non-specialty) classes:

Table 2.1—Classes of floors on the basis of intended use and the suggested final finish technique

Class	Anticipated type of traffic	Use	Special considerations	Final finish
5. Single course	Exposed surface—industrial vehicular traffic, that is, pneumatic wheels <u>and moderately soft solid wheels</u>	Industrial floors for manufacturing, processing, and warehousing	Good uniform subgrade, joint layout, abrasion resistance, curing	Hard steel-troweled finish
6. Single course	Exposed surface— heavy-duty industrial vehicular traffic, that is, hard wheels <u>and heavy wheel loads</u>	Industrial floors subject to heavy traffic; may be subject to impact loads	Good uniform subgrade, joint layout, load transfer, abrasion resistance, curing	Special metallic or mineral aggregate surface hardener; repeated hard steel-troweling

Most typical warehouses will fall in the Class 5 category, and will receive a hard steel-troweled finish to densify and strengthen the surface, and then have a coating of silicate sealer applied. ACI 302 and Chapter 8 of PCA's *Concrete Floors on Ground* provide in-depth guidance on this subject. This includes advising that normal practices of lower water/cement ratios, good curing methods, and use of hard aggregates will aid the abrasion resistance of concrete slabs.

Pre-Construction Meeting

One of the most important stages of a warehouse project is the pre-construction meeting. It's where all parties come together to discuss how the concrete slab construction will be planned for and executed. Some topics to review:

1) Safety and equipment:
   a. Screed types:
      i. Laser
      ii. Truss
   b. Truck/pump access and pour methods
   c. Pour environment
      i. Air quality
      ii. Seasonal issues
      iii. Time of day/night
      iv. Indoor/outdoor
      v. Options to mitigate adverse conditions / thresholds for canceling pours
2) Construction operation and logistics:
   a. Other trades/materials
      i. Soils/subgrade procedures and issues
      ii. Underground plumbing or electrical ducts
      iii. Insulation and heating coil contractors
      iv. Reinforcing
   b. Schedule – test pours, main pours, sequence
   c. Working hours for pours
   d. Control and construction joint locations
   e. Roof in place or not
   f. Vapor barrier locations
   g. Joints at protruding elements (columns, bollards, etc.)
   h. Joints to miss rack legs or base plate anchors & options at conflicts
   i. Reinforcing to miss rack base plate anchors & options at conflicts
   j. Mix designs
      i. Pre-pour testing and timing
3) Quality control and assurance
   a. Plan and parties for special inspections and testing
   b. Any third party oversight
   c. FF//FL and other special tolerances
   d. Air, slump, temp, cylinders

   i. Agree on quantity, frequency, reporting
   ii. Will it be different for pour days with >500 yards of concrete; can the frequency be dialed back
e. Special tests
   i. Flexural beam tests and shrinkage tests on field samples– to calibrate design assumptions about concrete properties

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