A SunCam online continuing education course

Concrete Slabs-on-Grade: Warehouses I – Background & Loading

by

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Course Outline:

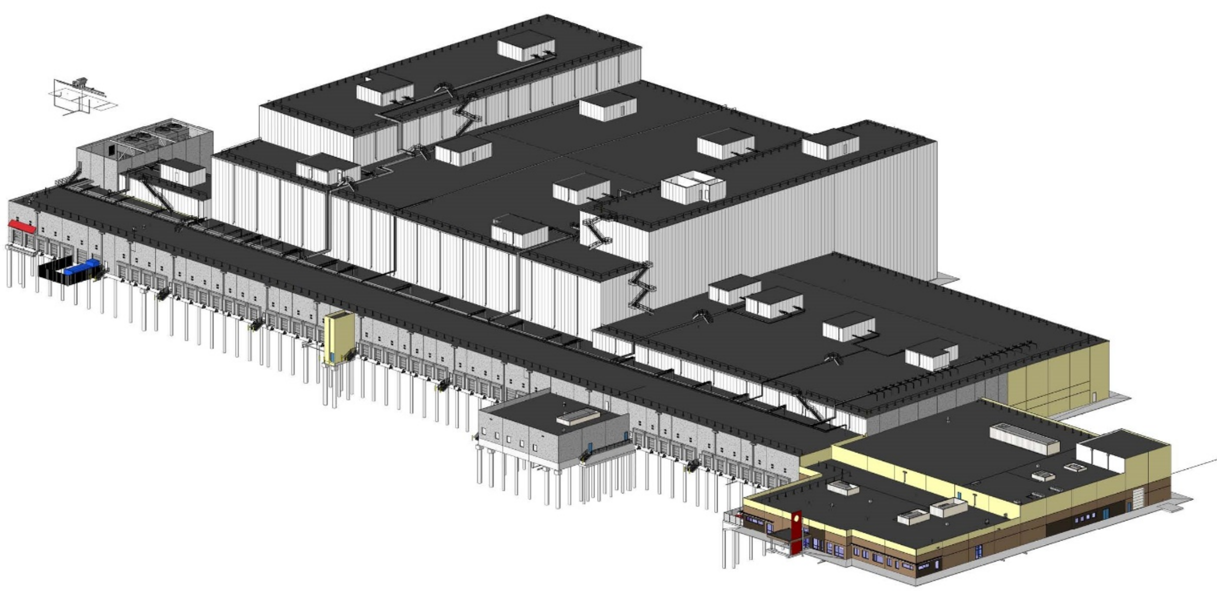


Fig. 1 - Computer rendering of a refrigerated food warehouse

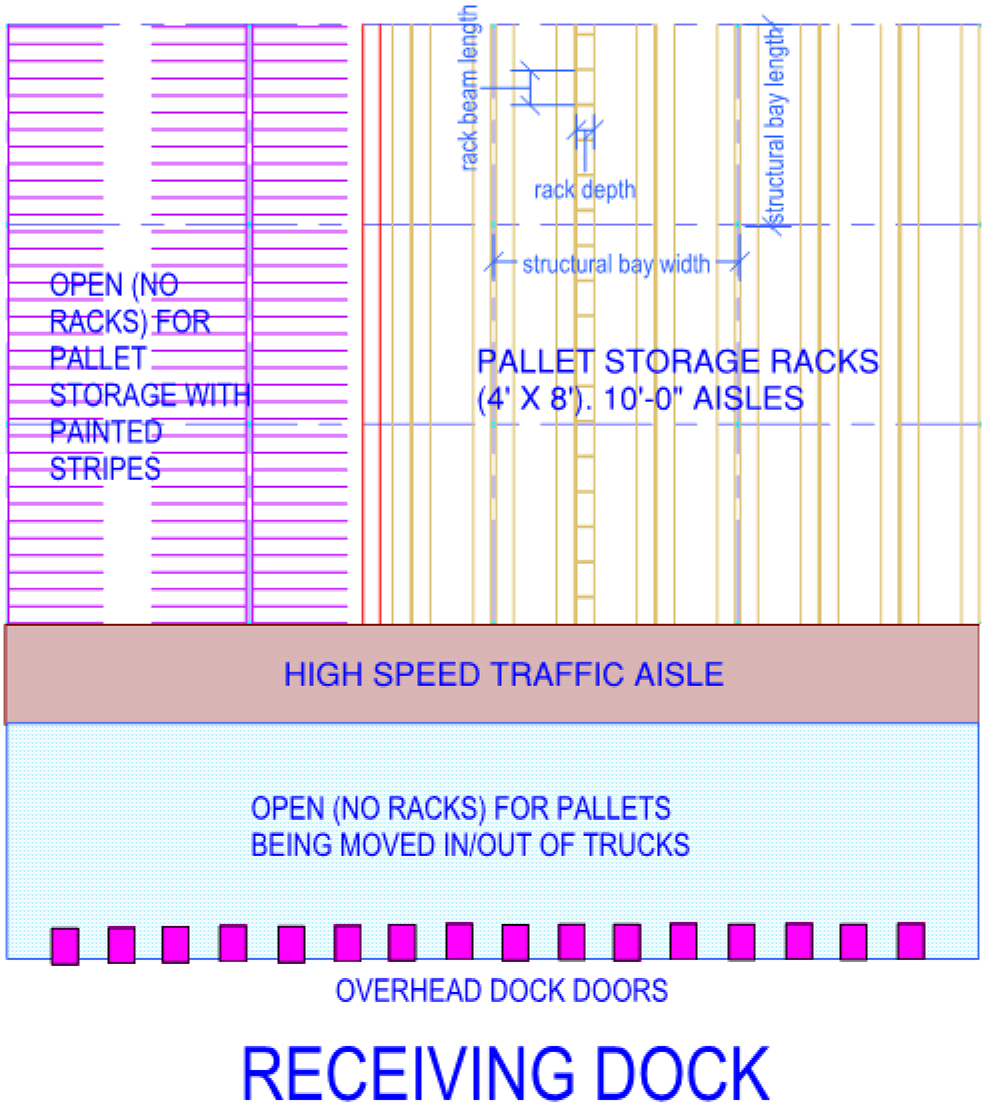


Fig. 2 - Portion of a typical warehouse floor in plan

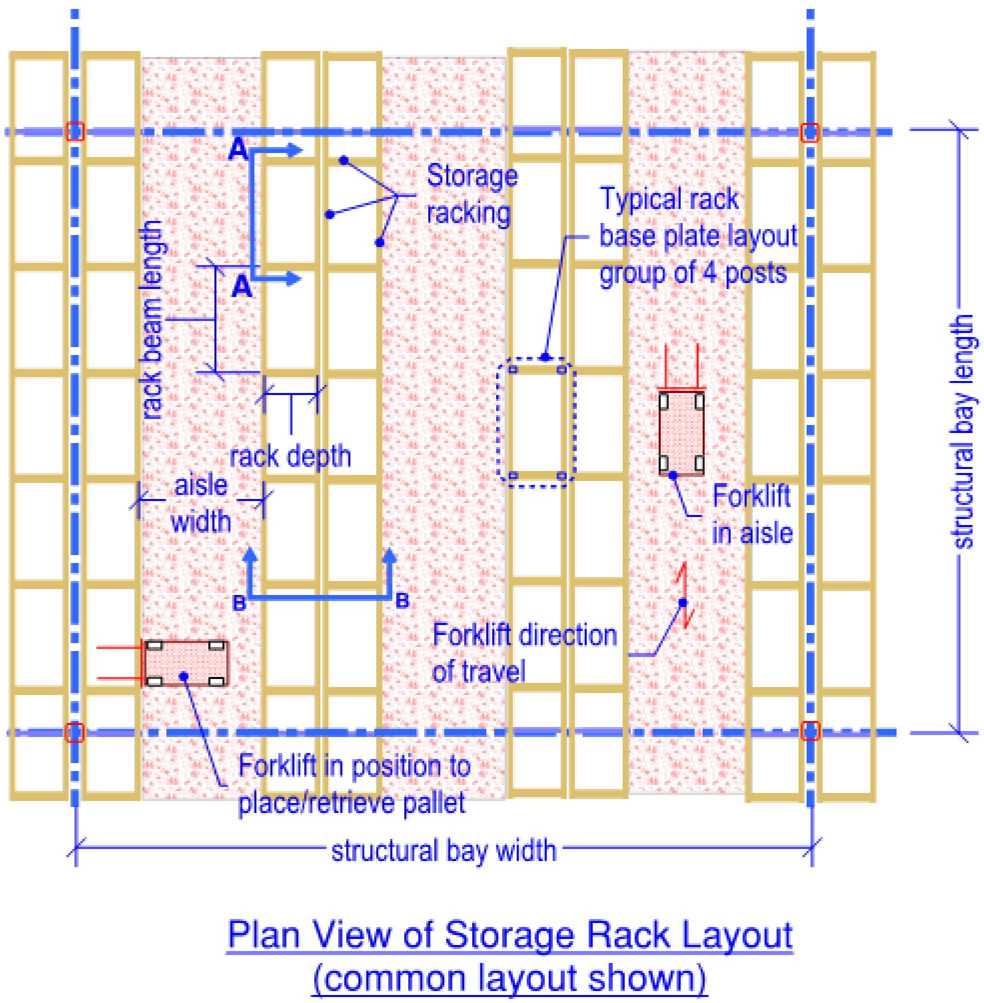
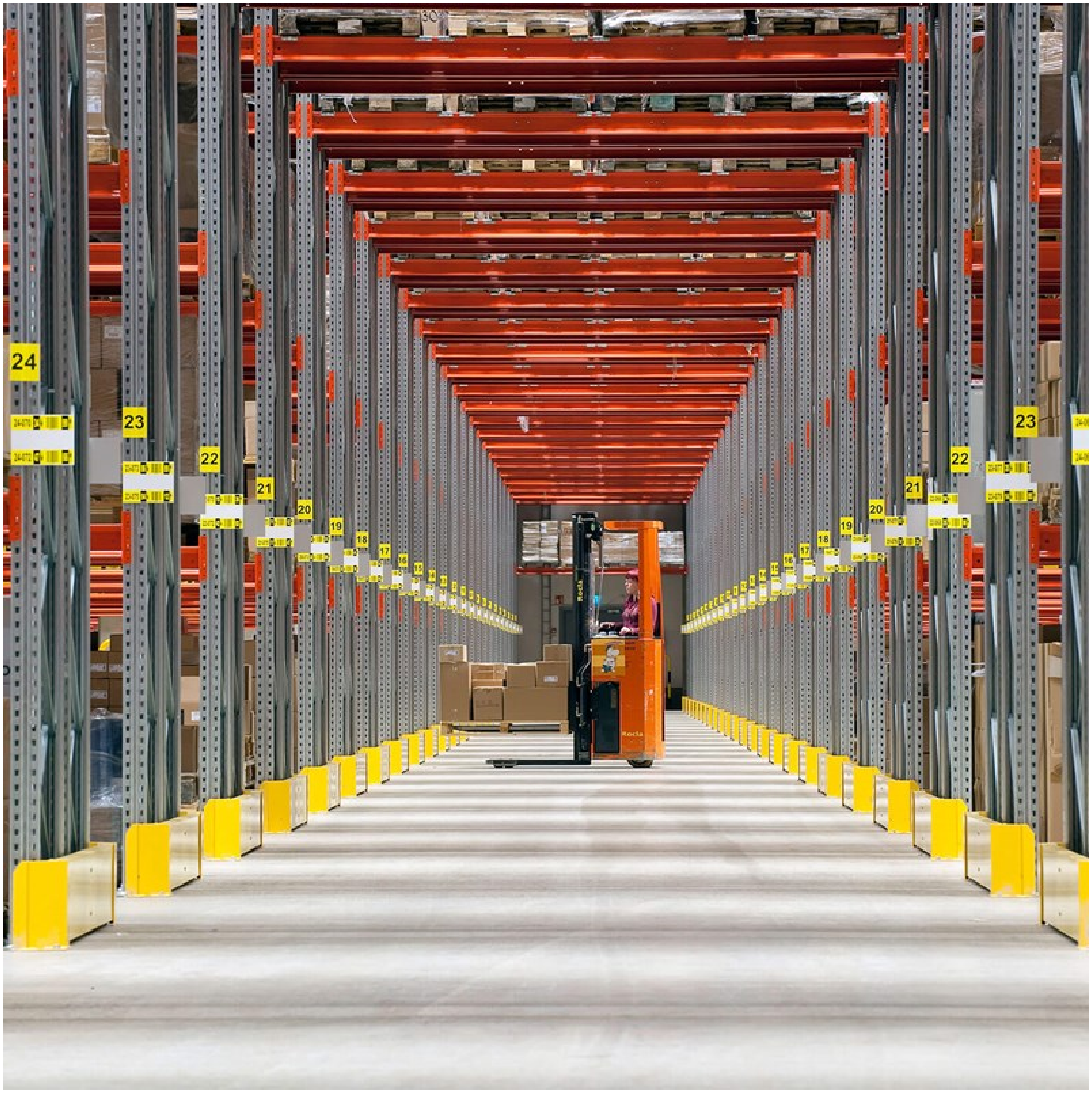


Fig. 3 - Portion of a typical warehouse floor at storage racking area in plan



https://commons.wikimedia.org/wiki/File:Pallet-racking-overview-page.jpg; rackingsystem.in / CC BY-SA (https://creativecommons.org/licenses/by-sa/4.0)

Fig. 4 - Stacker in a warehouse crossing a traffic aisle

https://commons.wikimedia.org/wiki/File:Carson_opens_new_center_to_improve_training_DVIDS512009.jpg ; Dustin Senger / Public domain

Fig. 5 – Typical Storage Racks

Warehouses: Purpose and Description

Warehouses are a fixture in the landscape of the worldwide distribution of goods. Shipping and receiving the *correct things* in the *right quantities*, in a *short amount of time*, *undamaged*, and with a *low risk* to workers, is a constant challenge. Whole segments within labor and education are dedicated to the study and application of methods designed to optimize the activities and links within supply chains. **Distribution logistics**, or the coordination of moving goods from place-to-place, has become critical to meeting industrial and consumer needs. **Materials handling logistics**, or the coordination of moving goods within an individual facility, involves many steps, and the success of the current on-demand culture of the global economy relies on the advancement of technology through innovation.

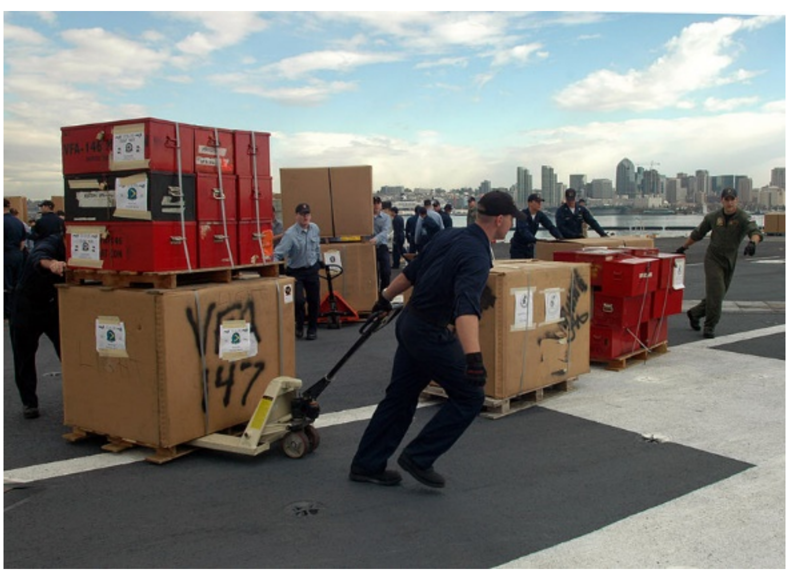
"Warehouse" is the common American term for individual facilities where goods are stored. Within the supply chain industry, warehouses that hold bulk quantities of goods until they are released to downstream users are called **"distribution centers".** This descriptive term highlights the primary purpose of the buildings. Bulk quantities of a wide variety of goods are shipped to distribution centers from their primary sources of production for mass assimilation and storage. Some of these bulk items are then delivered in reduced quantities to local end users upon request. Or, by breaking down a wide array of bulk goods into smaller quantities, specific combinations of these goods are collated and delivered to an individual end user, such as a retail store.

There are a variety of ways that goods are delivered to distribution centers, including trains, trailer trucks, and delivery trucks. Both upon arrival from their origin, and within facilities, one of the most common means of transporting goods is via **wood pallets** (see Fig. 6). These pallets are wooden platforms on which stacks of products are placed. The spaces within the shallow framework of wood pallets are tailored for the ready use of forks on a forklift (see Fig. 7) or pallet jack (see Figs.8, 9) to pick them up and carry them around from place-to-place, such as from the delivering trailer truck to storage racks. Other methods of materials handling include automatic sorting and rack placement, where machines, conveyors and cranes or lifts handle goods that are marked with special codes that are scanned and recognized by the materials handling software (see Figs.10, 11). An individual facility can employ a combination of these or other materials handling methods. Thus, understanding the end use of the facility is critical to designing its slab-on-grade components.


Fig. 6 – Wood Pallet

https://commons.wikimedia.org/wiki/File:Forklift-Truck.jpg; Source: Atlantic Training from http://www.atlantictraining.com/shop/c-forklift-training-115-1.html / CC BY-SA (https://creativecommons.org/licenses/by-sa/3.0)

Fig. 7 – Forklift



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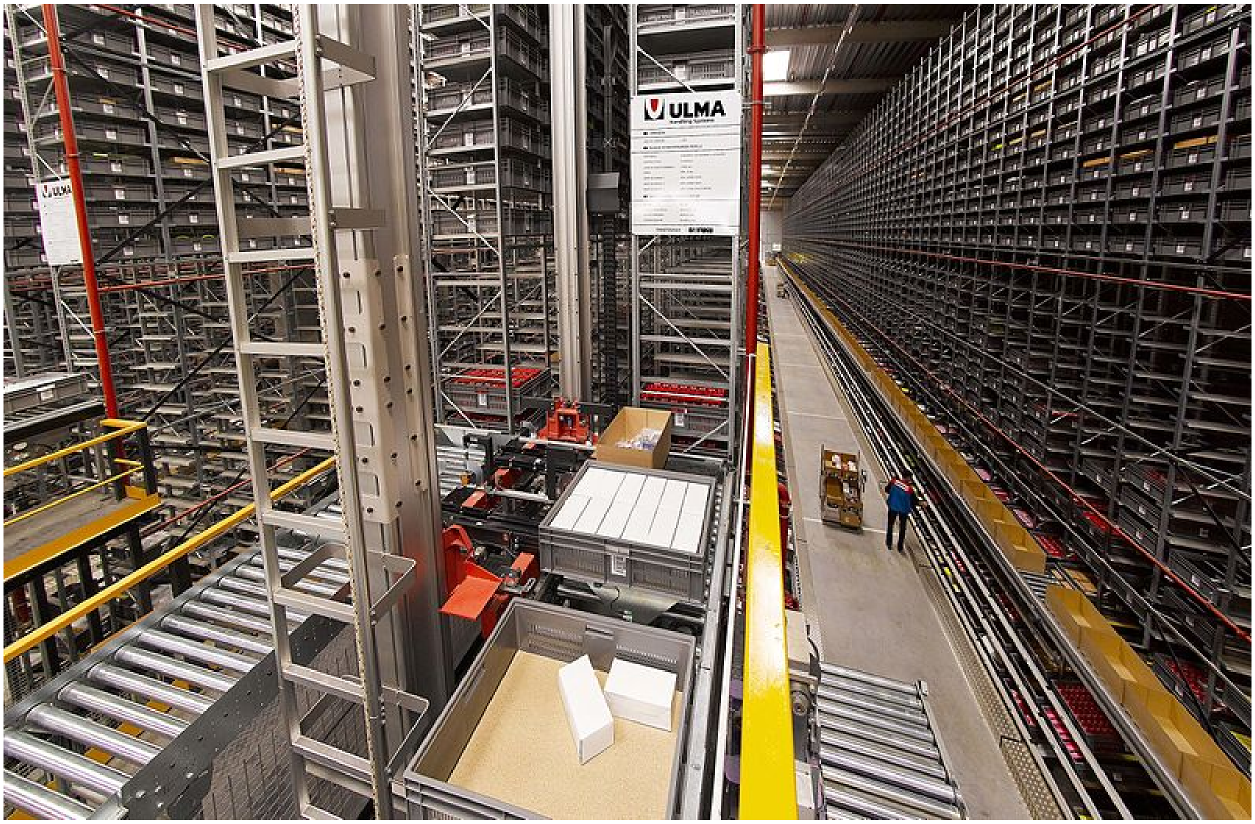
U.S. Navy photo by Mass Communication Specialist 3rd Class Philip Morrill / Public domain

Fig. 8 – Pallet Jack Carrying Pallets

https://commons.wikimedia.org/wiki/File:Ride-on_pallet_jack.jpg; Kevin Rutherford / CC BY-SA (https://creativecommons.org/licenses/by-sa/4.0)

Fig. 9 – Electric Pallet Jack

Fig. 10 - Conveyor



https://commons.wikimedia.org/wiki/File:Almac%C3%A9n_Autom%C3%A1tico_Mini_Load.jpg
Ingenieria-logistica / CC BY-SA (https://creativecommons.org/licenses/by-sa/4.0)
Fig. 11 –Storage Racks Serviced by Automated Equipment

MATERIALS HANDLING VIA FORKLIFT AND PALLET JACKS

The most traditional ways of moving goods within a distribution center are via **forklifts and pallet jacks**. Forklifts have the ability to lift pallets and place them into or remove them from storage racks. Pallet jacks are solely for keeping pallets near the floor, and not into elevated rack positions. The forks of pallet jacks have wheels that roll over the flat bottom boards of the pallets, and then the forks are raised slightly by a lifting mechanism at the wheels to get the pallets off of the slab. Some pallet jacks have forks long enough to handle two or three pallets end-to-end.

Forklifts generally have larger tires that use solid rubber or air-filled rubber. The loading on the slab is dependent on several parameters. The self-weight of the forklift is substantial, typically in the 8,000#-9,000# range with various weight distributions on front and rear axles. Because a typical forklift has forks that reach out well beyond the front wheels, there is a significant overturning force on the forklift. The lift needs to be heavy enough to prevent being tipped over by a load on its forks, and the **front tires see an amplified portion of the load distribution** as a result. A typical forklift that can carry a 5,000# payload might weigh 9,000#, and have a 12,000# front axle loading on the slab. A depiction of the load on the front tires of a forklift is shown in Fig. 12. Some forklifts have legs that extend to the sides of the pallet to allow the front wheels to be at the sides of the pallet footprint, greatly decreasing the tendency to overturn (see Fig. 13).

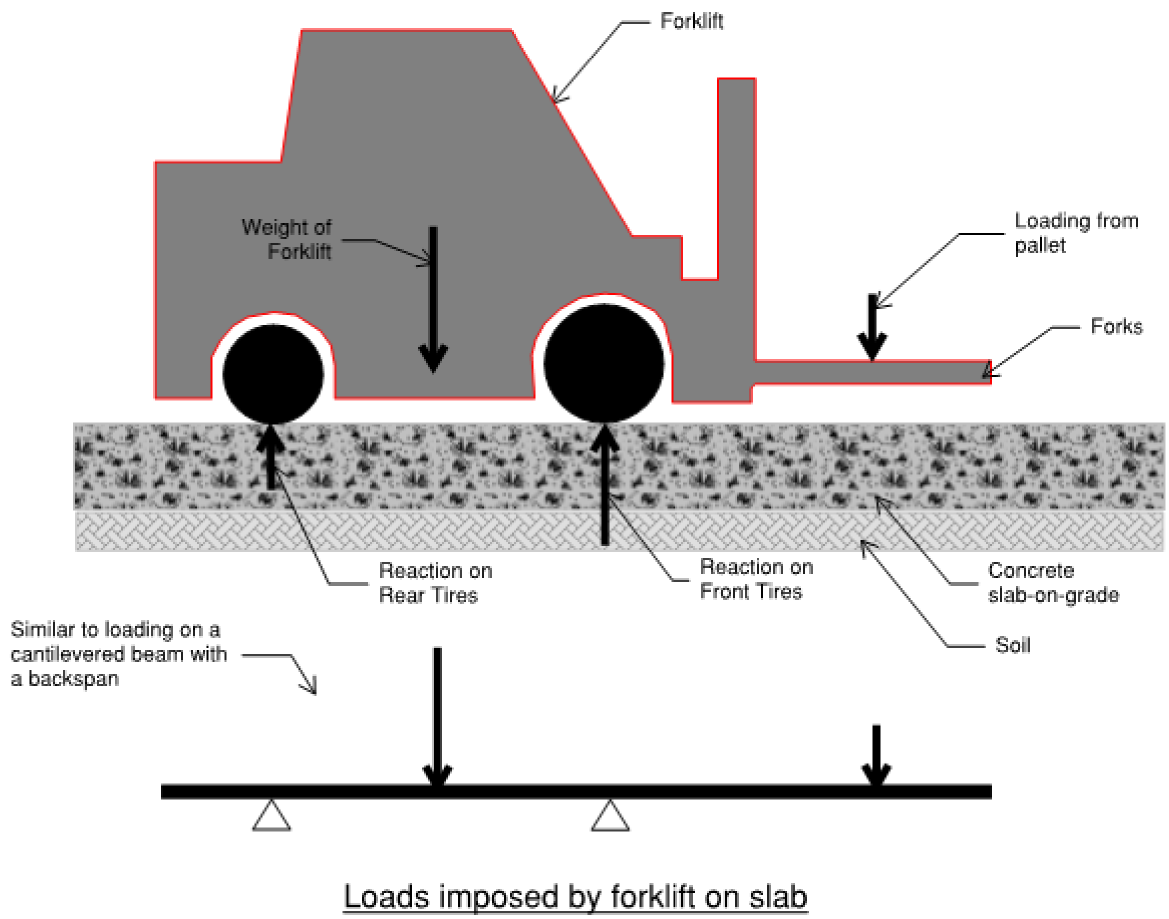


Fig. 12 - Forklift loading on slab

Fig. 13- Stacker with outrigger feet

Pallet jacks typically have smaller radius hard rubber tires (see Fig. 14). Pallet jacks can be hand-pulled or they may be automated through the use of a heavy battery (see Fig. 9). For the longer travel distances in a distribution center warehouse, pallet jacks are automated.

https://commons.wikimedia.org/wiki/File:Pallet_Jack.jpg; אני, Poo Poo - 2010 באוקטובר 11, 20:01 שיחה (IST) / CC BY-SA (https://creativecommons.org/licenses/by-sa/3.0)

Fig. 14 - Typical pallet jack wheels

Differences in Slabs: Typical Buildings versus Warehouses

The SunCam course *Slabs-on-Grade: From the Ground Up* focused on the general design of slabs-on-grade for typical buildings, mainly for nominal loading that a minimum thickness slab can handle, and built to minimize serviceability issues such as pronounced cracking that would affect floor finishes or appearance. Refer to *Slabs-on-Grade: From the Ground Up* course material for much of the background information on slabs.

The present SunCam course, *Slabs-on-Grade: Warehouse I – Background & Loading*, will focus on slabs-on-grade for industrial facilities, especially warehouses. Because of the greater importance of slab performance in relation to building function, and a pronounced increase in loading demands on these slabs, we need broader and more in-depth slab design considerations.

Differences between slabs in typical buildings and slabs in warehouses:

1) **Warehouse slabs generally do not need a vapor barrier** for normal ambient temps (heated as necesasary, but not cooled in hot weather) and dry conditions. Typical spaces such as office buildings may floor coverings such as vinyl tile that require vapor barriers.
2) **Floor finishes in warehouses are exposed concrete**, where typical spaces such as office buildings have floor coverings.
3) **Warehouses can experience a high volume of heavy wheeled traffic** that will degrade slab joints over time
4) **Warehouse slabs can be subjected to heavy concentrated loads from storage racking legs**
5) **Joint reinforcement and joint fill are often used in warehouses to protect joints from traffic**

Challenges of Slab Design and Maintenance in Warehouses

Many challenges exist for those who design and maintain slabs for warehouse buildings. **The performance of the slab is absolutely critical to efficient warehouse materials handling operations**. A survey of warehouses around the world would reveal a wide array of extreme loading conditions that concrete slabs are subjected to. Very heavy loads such as rolls of sheet metal are moved by forklifts with suitable load ratings. Hyster supplies forklifts that weigh 120,000#, and have the capacity to carry loads in the 80,000-100,000# range with front axle loads of 200,000#. Fig. 15 shows a heavy duty forklift.

https://commons.wikimedia.org/wiki/File:Canterbury%27s_Dedicated_Container_Lift.jpg; Ingolfson / Public domain

Fig. 15 - Forklift designed for very heavy loading

Most warehouse slabs are subject to equipment more mundane than that mentioned above, but the traffic they do see can be equally detrimental to the slab depending on the slab thickness, construction, and subgrade stability.

Joint and crack stability and degradation.

1) Reviewing the previous course, *Slabs-on-Grade: From the Ground Up*, prescriptive slab joints that are subject to warehouse traffic areas are either:

a) **Control joints** – straight line sawcuts roughly ¼ depth of the slab at a spacing that prevents random cracking that would otherwise result from concrete shrinkage. Typically, this spacing is in the 12 to 18 foot range in warehouses in each orthogonal direction (see Figs.16 & 17), or,
b) **Construction joints** – Straightline bulkheads where the concrete pour is terminated for a day's pour, and a subsequent concrete pour will be poured against it on another day.

2) Also, **Random cracks** can appear due to tension forces due arising from shrinkage movements combined with frictional or obstructional restraint of the slab. (See Figs. 18 & 19).

Fig. 16 - Typical control joint patterns in a concrete slab

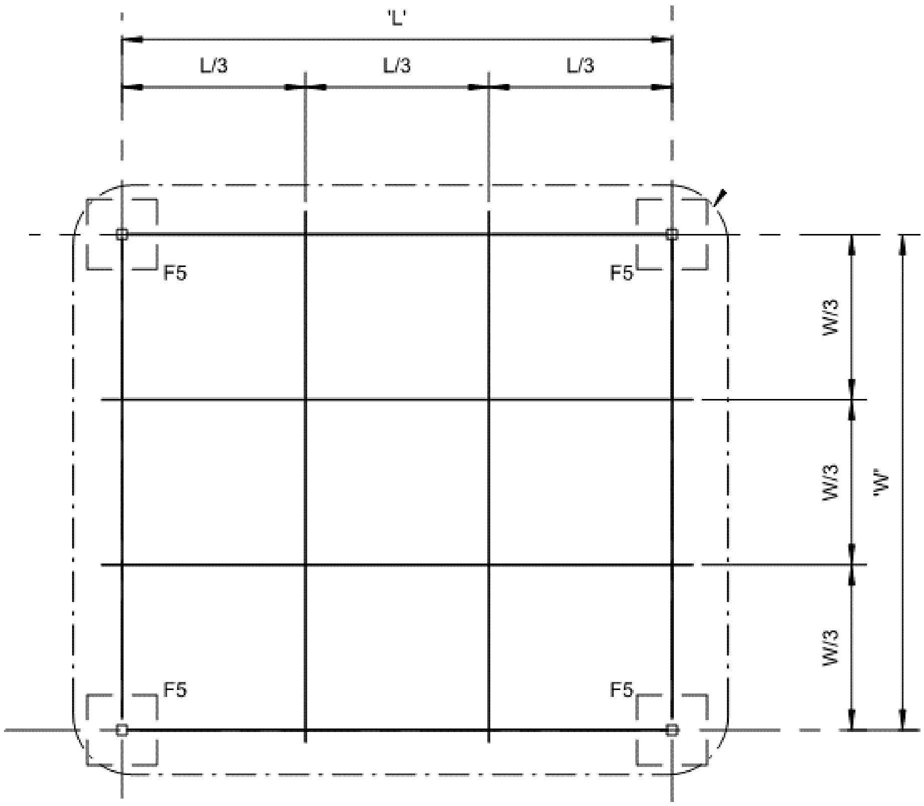


Fig. 17 - Control joint layout in a typical warehouse bay

Fig. 18 - Slab crack in a newer facility

Fig. 19 - Slab crack and joint degradation in an aging facility

3) **Cracks or joints have a finite opening width, and if large enough, are gradually worn down by the continual action of wheeled traffic, which hit the opening**.
4) Joints in slabs in high traffic areas generally need protection in the form of dowels or reinforcing at joints to keep slabs from deflecting to much at joints, and joint filler to

help preserve the integrity of joints. These are discussed in the second warehouse course.

5) Cracks may occur at locations where loading is potentially high, such as where a storage rack post bears on the slab. The crack is a discontinuity that weakens the slab.
6) Joints collect dirt & debris. Uncontrolled material in joints such as nails and pieces of wood or metal can damage wheels.
7) Wheels and tires will withstand a great deal of abuse, such as being rolled over the lower boards of the pallets, being worn by friction during turning, or being subject to wear, tear, and puncture from any debris that happens to be on the floor. Pallets will have broken pieces of wood or nails unseen that tires can roll over. Close observation of tires ready for disposal reveals bits of metal embedded in them, chunks of material removed from them, and a great deal of wear at the edges of the wheel.
8) **The construction and condition of the concrete slab has a great impact on the wear and tear of the materials handling equipment**. And vice versa, the action of the tires can affect the long-term durability of the concrete slab. This will be addressed in a following section.
9) To fix cracks or degraded joints, sawcuts and routing are used to open up cracks or remove spalls. Dust needs to be controlled. Joint repair products such as semi-rigid or structural epoxy are available. Ideally, the root cause for the crack is determined to see if the crack can be stabilized.
10) A good joint maintenance program means a reduction in back injuries, trips, and falls.
11) Aesthetics – Though cracks are inherent in concrete construction, no owner wants to see cracks. Slabs in warehouses are fully exposed to view.
12) The thicker a slab is, the less susecptible it will be to cracking and the more it will be able to withstand the bending and shear stresses at joints. Of course, thicker slabs cost more.
13) Small wheeled traffic is common. This means heavy loads on small hard contact areas rolling over joints. If joints are unstable, every bump is another cycle towards joint failure. Wheeled traffic will worsen joint conditions over time due to wear.
14) Slabs are difficult to repair with round-the-clock operations. Joint and crack maintenance is a major cost in facilities, as well as replacing damaged or worn wheels and equipment. Partial facility downtime may result if fixes can't be worked around.

Concrete shrinkage and movement

Shrinkage was discussed in depth in *Slabs-on-Grade: From the Ground Up*, but it's clear that controlling shrinkage is even more critical in warehouse slabs. Some additional notes on this:

1) It is highly recommended that the slab design engineer obtain shrinkage data for the local concrete mixes that will be used in a warehouse slab for a given project. Shrinkage in concrete varies across the country. Some areas will struggle to keep shrinkage under control with certain available aggregates. An engineer will need to know the shrinkage characteristics of the concrete to know how the concrete behavior (joint size) will affect performance under loading. Ideally, a 28-day test would give a benchmark for design prior to the first concrete slab pour. Even a 7-day test would help. Field measurements of shrinkage during construction would help validate the early tests.
2) Note that the **width of joints and cracks** will increase more over time as the concrete dries out, so they will grow over the course of the first year. ACI 209 recommends using the equation below for predicting shrinkage over time for standard concrete under standard 7-day moist curing conditions. ACI 209 has adjustment factors for variable conditions such as duration of moist cure. **The resulting shrinkage amounts are 44% at 28 days and 91% at 365 days.**

   $(\epsilon_{sh})_t = \frac{t}{35+t}(\epsilon_{sh})_u$
   t = time (days)
   $(\epsilon_{sh})_u$= ultimate shrinkage at infinite time
   $(\epsilon_{sh})_t$=shrinkage at time beyond 7 days
   (Per ACI 209)

3) ACI 360 bases its joint spacing recommendations on ultimate shrinkage of 0.052% to 0.110%. This is the expected range for warehouse slabs.
4) A goal of 0.04% at 28 days (approximately 0.08% ultimate shrinkage) is reasonable for most areas of the country for reputable concrete suppliers. The author has had success specifying this magnitude of shrinkage around the United States and Canada and had it proven via testing.

5) A goal of 0.02% at 28 days (approximately 0.04% ultimate shrinkage) would require a specialized design, with perhaps some uncommon measures such as shrinkage compensating concrete and shrinkage reducing admixtures to be used.
6) The shrinkage test should be ASTM C157 (dry storage method). (Tarr)
7) Relative humidity (RH) is routinely 10% greater or more at the base than top. The top is constantly trying to get to RH of the ambient air. The bottom is trying to get to RH of the base. (Tarr)
8) Shrinkage of a concrete slab will be reduced by some amount due to friction with the subrade. A typical reduction is 33% or 2/3 that expected without frictional restraint. However, this is a subjective and approximate figure.
9) It should be noted that direct measurement of joint width from the top of the slab may be misleading. The joint generally will be much less at the bottom of the slab due to the greater amount moisture at the soil elevation. Also, some randomness can be expected from bay to bay or joint to joint.
10) **Shrinkage is sensitive to many factors. See Fig. 20**. Some of these may be modified after the 28-day shrinkage test, and should be watched closely.

Table 13.1—Cumulative effect on adverse factors on concrete shrinkage (Tremper and Spellman 1963)

Effect of departing from use of best materials and workmanship	Equivalent increase in shrinkage, %	Cumulative effect
Temperatures of concrete at discharge allowed to reach 80 °F (27 °C), whereas with reasonable precautions, temperatures of 60 °F (16 °C) could have been maintained	8	1.00 × 1.08 = 1.08
Used 6 to 7 in. (150 to 180 mm) slump where 3 to 4 in. (76 to 100 mm) could have been used	10	1.08 × 1.10 = 1.19
Excessive haul in transit mixture, too long a waiting period at job site, or too many revolutions at mixing speed	10	1.19 × 1.10 = 1.31
Use of 3/4 in. (19 mm) maximum-size aggregate under conditions where 1-1/2 in. (38 mm) could have been used	25	1.31 × 1.25 = 1.64
Use of cement having relatively high shrinkage characteristics	25	1.64 × 1.25 = 2.05
Excessive "dirt" in aggregate due to insufficient washing or contamination during handling	25	2.05 × 1.25 = 2.56
Use of aggregates of poor inherent quality with respect to shrinkage	50	2.56 × 1.50 = 3.84
Use of an admixture that produces high shrinkage	30	3.84 × 1.30 = 5.00
Total increase	Summation 183%	Cumulative 400%

Fig. 20 - Cumulative impact of various factors on shrinkage (ACI 360)

11) **Curling:** Besides cracking, the tendency of slabs to dry out on top before they do on the bottom can cause a common phenomenon known as curling. Also, concrete that is allowed to cure in a more moist condition such as the bottom half of a slab will exhibit decreased final shrinkage. Differential drying shrinkage, or the shortening of the top relative to the base will result in a concave curvature that tends to lift the slab at its sawcut edges. If greatly exaggerated, the shape of the slab panel would resemble a rectangular dinner plate. This is shown in Figs. 21, 22, and 23, and is

described in more detail in *Slabs-on-Grade: From the Ground Up*. Curling is most pronounced at corners, where the slab is subject to curling in both directions. The lifting action is countered by the weight of the slab. Some additional notes on curling:

a) Per Holland, World of Concrete:
   i) Cracks in curled slabs may occur at the center of the slab panel where stresses are highest from combined slab self-weight and edge loading. Also, if wheel loads occur at corners, with higher curling and a smaller section to resist bending, cracks are more likely to result.
   ii) Increasing joint spacing means an increase in curling.
   iii) Doweled joints or lightly reinforced joints mean lower curling at joint.
   iv) Today's cement is more reactive (Blaine Value), thus final in-place strengths are often much higher than specified minimums.
   v) **Higher concrete strength means more shrinkage, a stiffer slab, and less creep over time. The result is more curling**.

b) Per Tarr:
   i) Curled slabs can be ground down at joints, but would also need to be grouted below the curled up slab to bring it back into contact with the ground
   ii) Trade-off: **Softer subgrade means length of cantilevered edge of curled slab is shorter due to more ready compatibility with soil deformation**
   iii) Clearance from a pallet to the slab can be in the range pf 1/8" on pallet jacks. This is low enough for the pallet between forward and rear sets of wheels to scrape the slab with wood or nails at the curled joint as the pallet passes over the joint

c) Any means of reducing the shrinkage in a slab will help reduce curling.

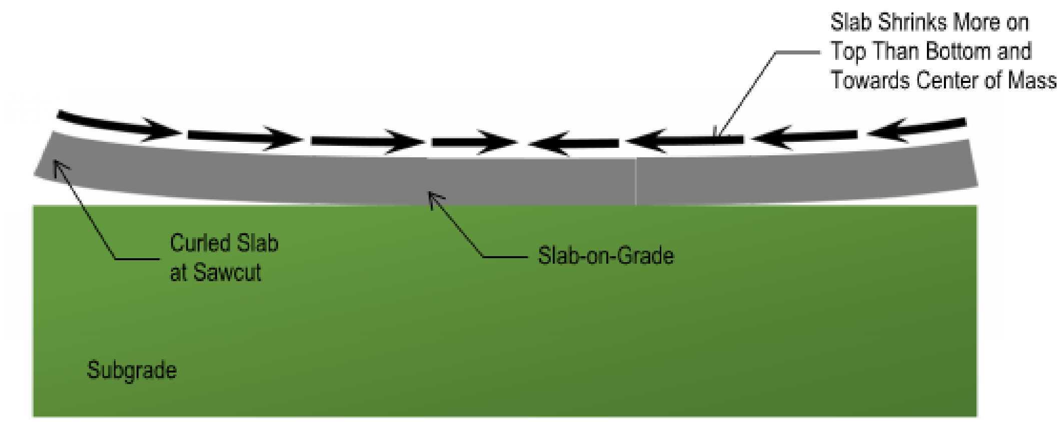


Fig. 21 - Upward curling of slab

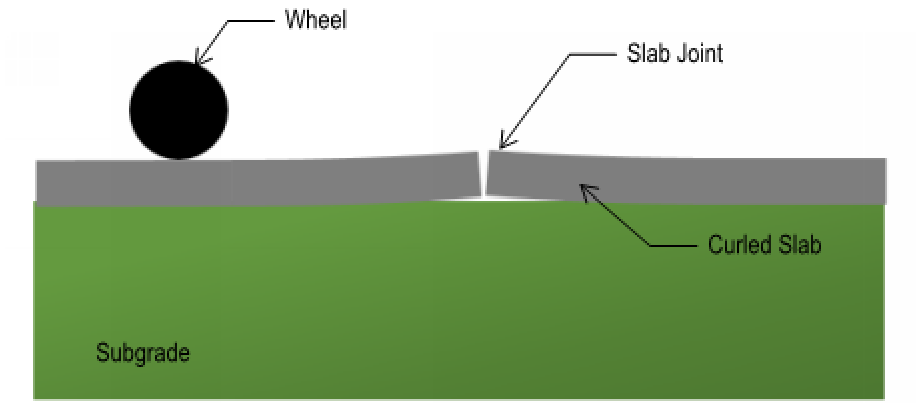


Fig. 22 - Wheel approaching a joint in a curled slab

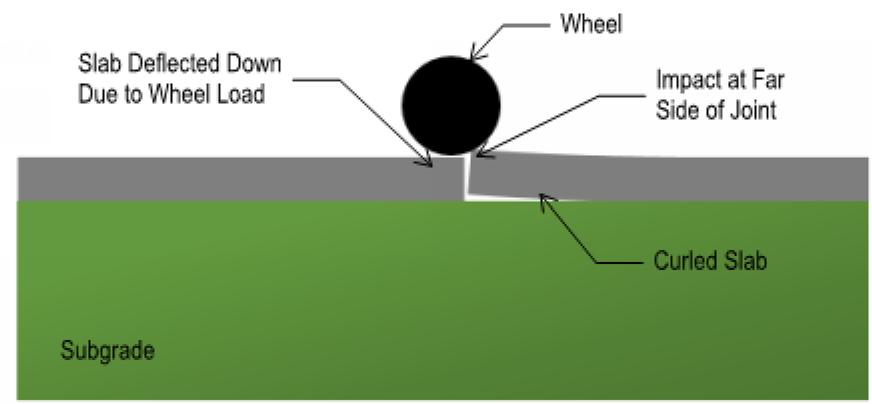


Fig. 23 - Wheel deflecting the near curled slab and impacting the far curled slab

Aerial View of Warehouse Site with Building Shell Nearing Completion

Site Selection and Subgrade & Soil Preparation

Finding site locations that are suitable for warehouse-type buildings can be difficult. Buiding footprints of distribution centers are routinely 20 acres or more in size. Ideal soil and site conditions might include:

1. **Stable, solid, and stiff natural soils**
2. Relatively flat terrain to avoid massive cut/fill areas
3. Ground water that would not historically impact subgrade stability or slab settlement either by its high level or by its absence (see forthcoming anecdote on dessicant soils)
4. Uniform soils across a site, or if non-uniformity exists, with differences gradual enough that abrupt differential settlement can be avoided
5. Limited depth of organic material to remove
6. Predictable in situ soil and if previously filled, done with adequate compaction and with controlled materials
7. Good slope stability if adjacent grade changes are present

8. Soils that are non-reactive with moisture, air, or other things that will be in the ground (metals, cement, etc.)
9. Minimal harmful underground off-gases. Normally, no vapor barrier is present for ambient temperature facilities (e.g., radon, methane)
10. No deep-seated voids and no potential for them to form (e.g., Karst formations or underground mines)
11. **Close to highways and with good and well-maintained access roads.**
12. **Close to a population center for a reliable workforce pool**
13. Reasonable cost for the land
14. Good location for the transportation model to work
15. Close enough to a concrete plant to limit the time for concrete to be in the truck before setting

So, the chances of having this type of site be available is becoming more and more remote. Thus, a business owner needs good partnership with people who can assess what the feasible options might be in a geographic area, and also partners that can help develop sites with soils and other conditons that are less than ideal. Some examples of site issues that the author has been called to observe and address follow.

Note: Refer to the SunCam course *Slabs-on-Grade: From the Ground Up* for a discussion on specific information required from the geotechnical engineering report for the design of slabs on grade. Two of the examples are repeated below out of convenience.

1. Sloped site

There is a retail distribution center in the Inland Empire region of California that is built on a fairly uniformly sloped site. This building is nearly half a mile long, and it would have been extremely costly to re-slope the site or adjust the site elevations with cut and fill, and a major operations hurdle to use 1:20 ramps. So, the whole building slab-on–grade is sloped at 1/16" per foot. This is slight enough that during a visit, it is difficult to tell which way it is sloped.

2. Iron Pyrite

At a distribution center in upstate New York, the top soil is underlain by shale, which is a sedimentary rock that can be fractured and removed by blasting. However, the shale contains a percentage of iron pyrite, as seen by faint veins of miniscule gold flakes (a.k.a. fool's gold) against the black rock. Iron pyrite, when exposed to air and water, can form crystals through an oxidation process, which produces acid, and the reaction progresses further. Rock crystals can be seen in outlying rocks, and those that are exposed after blasting. The formation of crystals causes the soil matrix to expand by several inches, in unpredictable amounts and locations. If a slab were built on this soil, it leaves the possibility for the soil matrix to raise up in local areas, causing cracking and heaving, which would greatly disrupt warehouse activities. The solution to staibize the site was to blast the shale out to several feet down, lay down a barrier to encapsulate the shale from being exposed to air and water, and covering this with non-reactive compacted fill.

3. **Expansive soils**

The soil profile in many areas of the United States is characterized by expansive soils. **These soils are generally a fat clay that expands with increases in moisture content**, and shrinks when moisture is decreased. These expansive clays are common to the Dallas area for example. The soil is fairly dry for much of the year, but seasonal ground water fluctuations make these soils troublesome for road and building construction. When this soil is identified as a significant issue, there are several options that can be considered. Removing and replacing is an option, as well as moisture conditioning and lime-treating the soil. Water injection is also an option, but it is not as effective as moisture conditioning.

At a warehouse with expansive soil, the soils also had corrosive properties. Underground fire loop piping lay around and below a distribution center over 1 million square feet in size. The pipe was corroded through in several locations. Massive amounts of water poured into the soil with each breach. This increase in moisture content lead to the activation of expansive clays in the soil matrix, and heaved the slab throughout the building. Being an industrial facility, the movement of the slab at joints is an on-going disruption for the operation of forklifts and pallet jacks.

4. Cut and Fill sites

Cut and fill exercises are fairly common, and balancing site soils to minimize importing and exporting of soils is a normal procedure. Generally, fill portions are closely monitored for settlement. If a soils report is not available during a site selection process, a very rough rule of thumb for sites with fines included in the soil is 1% settlement for the thickness of fill in the first year, 1% in the next 10 years, and 1% in the next 100 years. For fill sites with fill areas 10 feet or more fill in thickness, this may be a real issue for long term settlement. A surcharge over a period of time (piling soil up to preload and consolidate it) could be used to speed up the settlement. Gravel or larger aggregate fill types could be used to lessen the long term settlement of the fill layer. Settlement of the soil below the fill also needs to be understood.

5. Water migration or intrusion

Water migration within the soil matrix under a warehouse slab can be extremely detimental. At a large dry goods warehouse, a breach in the roof due to a rain water leader obstruction led led to approximately 2 inches of widespread standing and running water. The voids created by the removal of fines under the slab made for an unstable slab base in many areas, particularly where curling had made a ready channel for flow. The slab was scanned to discover where the voids existed, and the underslab voids were subseuently filled with pressurized grout.

6. **Desiccant or collapsible soils**

At a large distribution center in an otherwise dry Colorado climate, rain water from heavy periodic thunderstorms seeped under the building over several decades. Soils in general have a compaction or settlement level that depends on moisture. The site soils on this site were very dry, and classified as desiccant or collapsible soils, **meaning that the natural state of the deeper soils was fairly loose, and would compact and therefore settle with enough water being introduced**. At original construction, these soils were only compacted at a shallow depth. So, with the historical lack of moisture in the deeper soils, the potential was always there for them to settle more with added moisture. With the introduction of rain water down to a considerable depth of the soil profile, the soils settled. As a result of non-uniform, differential settlement, the slab experienced significant distress. Slab joints opened up and adjacent edges of concrete joints lifted or sank relative to one another up to 2 inches, which was too much for materials handling equipment to handle. The problem worsened as storm drains underground were breached, and the corners of the building settled, allowing rain to pond and pour over the shallow parapets instead of reaching the roof drains.

7. Soil settlement and tall racking

The impact of soil settlement may have an impact on rack out-of-plane and movement tolerance. Tall racks 30 or more in height will lean if the floor slopes due to settlement. If automated racking is used, the tolerance for movement after initial installation will depend on the accuracy required for the automation to behave normally without being affected. Some rack systems have very little tolerance for leaning or sagging racks, and there will be limited ways to adjust the position of the racking in service.

Loading on Slabs-on-Grade

A variety of loading can be present in a building. This course will focus mainly on non-building loads, because those are the type that will be present in most warehouse slab designs. As noted previously**, if building loads (specifically those that support building components or their lateral systems, not including storage rack loading) are required to be supported by the slab, those slabs would fall under the American Concrete Institute (ACI) design code, ACI 318, for building foundations**. The author has designed buildings with roofs, floors, lateral systems, and wall braces that are supported by storage racking. In other words, the framing that holds the building up and the storage racking are one in the same, and ACI 318 would need to be used in this case as well.

Non-building loads can be classified as static or dynamic. Static loads are those that are single events that are imposed for durations of minutes or hours to days. Dynamic loads are those whose durations are fleeting, but can be repeated over and over.

Static loads

If loads are static, then they could be short-term or long-term. If long-term, long-term settlement may need to be studied, depending on the magnitude versus the flexibility of the slab and the subgrade. Long term loading would include things such as posts from storage racks with heavier combinations of pallets that are stored for months or years without being moved. Short term loading would include frequently moved pallets in storage racks or on the slab.

Dynamic Loads

If loads are dynamic, the magnitude a life cycle study of the slab is necessary to determine if the number of cycles and range of stresses will lead to fatigue failure. Examples of dynamic loads are wheel loads from moving forklifts and pallet jacks.
A special case of dynamic loading is seismic loading. With lumped masses stored in storage rack positions, severe ground shaking in an earthquake can accelerate the masses by transmitting motion through the storage racking. Storage racks are designed

as ductile elements to absorb energy through steel yielding. The resulting motions will subject the slab to horizontal shear and vertical forces due to overturning. This is not presented in great depth in this course.

Typical Loading (see Figs. 24a through 28)

Some of the typical loading types include:

1. **Uniform loads**
    a. **Loads spread over a given larger area**
    b. **Examples: Groups of pallets stacked in open slab areas; Machinery or equipment on a housekeeping pad**
    c. Joint and edge locations should be considered, both near joint corners and not near joint corners. Vertical load transfer across joints is a factor.
    d. The soil may settle in the short and long term depending on soil characteristics, magnitude and duration of loading, and amount of area affected.
    e. These loads will generally be transferred to the soil in bearing. However, if areas adjacent to the loaded area are free of loads, then the slab will have negative moments at the load-free area (see Fig. 24a).

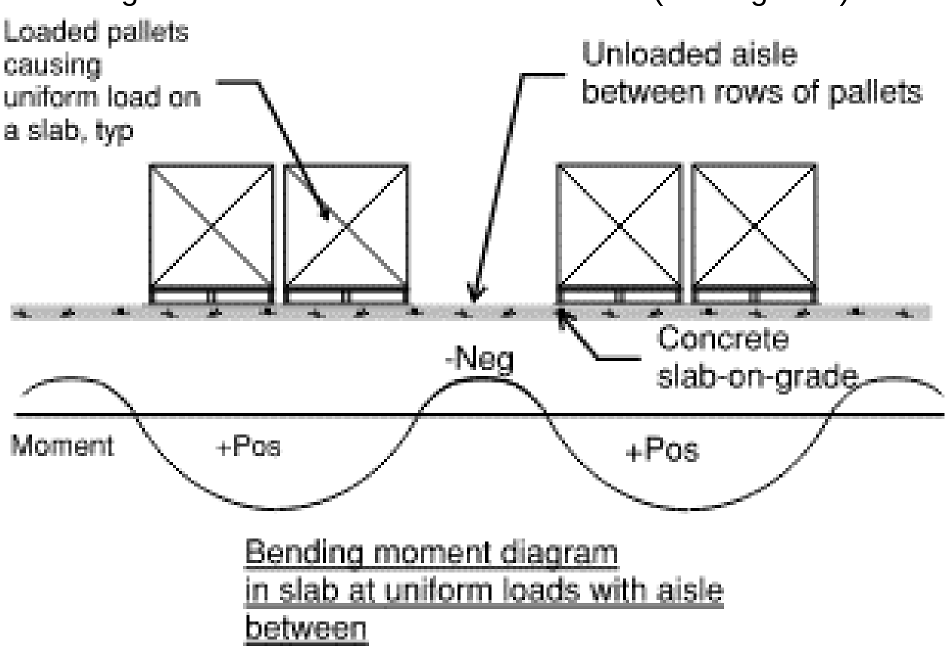


Fig. 24a – Pallets loading a slab with a free area between

2. **Point loads**
    a. **Loads concentrated over small areas**
    b. **Examples: Storage rack legs at base plates; Wheel loads from forklifts on wheels or tires**
    c. Closely spaced groups of point loads should be reviewed to determine the critical and controlling cases. Wheel loads from forklifts centered, say, 3'-0" apart would be one load case. Another load case might be the forklift as it passes by a heavily loaded rack leg, or when the forklift is placing or retrieving pallets from a storage rack near one or two rack legs close by.
    d. Tire types are very important to know, such as the material of a tire, its deformability characteristics, and whether a tire is solid or a pressurized rubber with a given air pressure. The net result of this will be an assumed tire pressure on the slab a given area. Note that solid wheels will wear on the outside first, leaving less contact area.
    e. In the United States, the design code that applies for steel storage racks is published by the Rack Manufacturers Institute (RMI). This code includes the loads imposed by the storage racks that are to be resisted by the supporting slab-on-grade. Racks are generally composed of modular beam components that support pallets, and rack posts or legs support the beams. Load is transferred to the slab at base plates. One design criteria that needs to be met is downward concentrated load at the base plates. Typically, the owner supplies the maximum expected loading in the racks in all contributing positions, with some probability distribution of occurrence. When considering seismic loading, the overturning force and base shear is also considered. In seismic load cases, the weight of the stored material is reduced based on the decreased likelihood of the maximum weight being present in all contributing rack storage positions during a major seismic event.
    f. Soil may settle in the short and long term, depending on the soil characteristics, magnitude and duration of loading, and the size of area affected.
    g. Joint and edge locations should be considered, both near joint corners and not near joint corners. Orientation of the joints (parallel and perpendicular) will matter. Vertical load transfer across joints is a factor, and is discussed later.
    h. Generally speaking, the slab will have both positive (sagging) and negative (hogging) moments due to hogging of the slab as the loaded area tends to sag under the loading. Additional loads may complicate things. For example,

storage racks may have forklift travel aisles nearby, and the loads from forklifts may increase stresses in the slab.

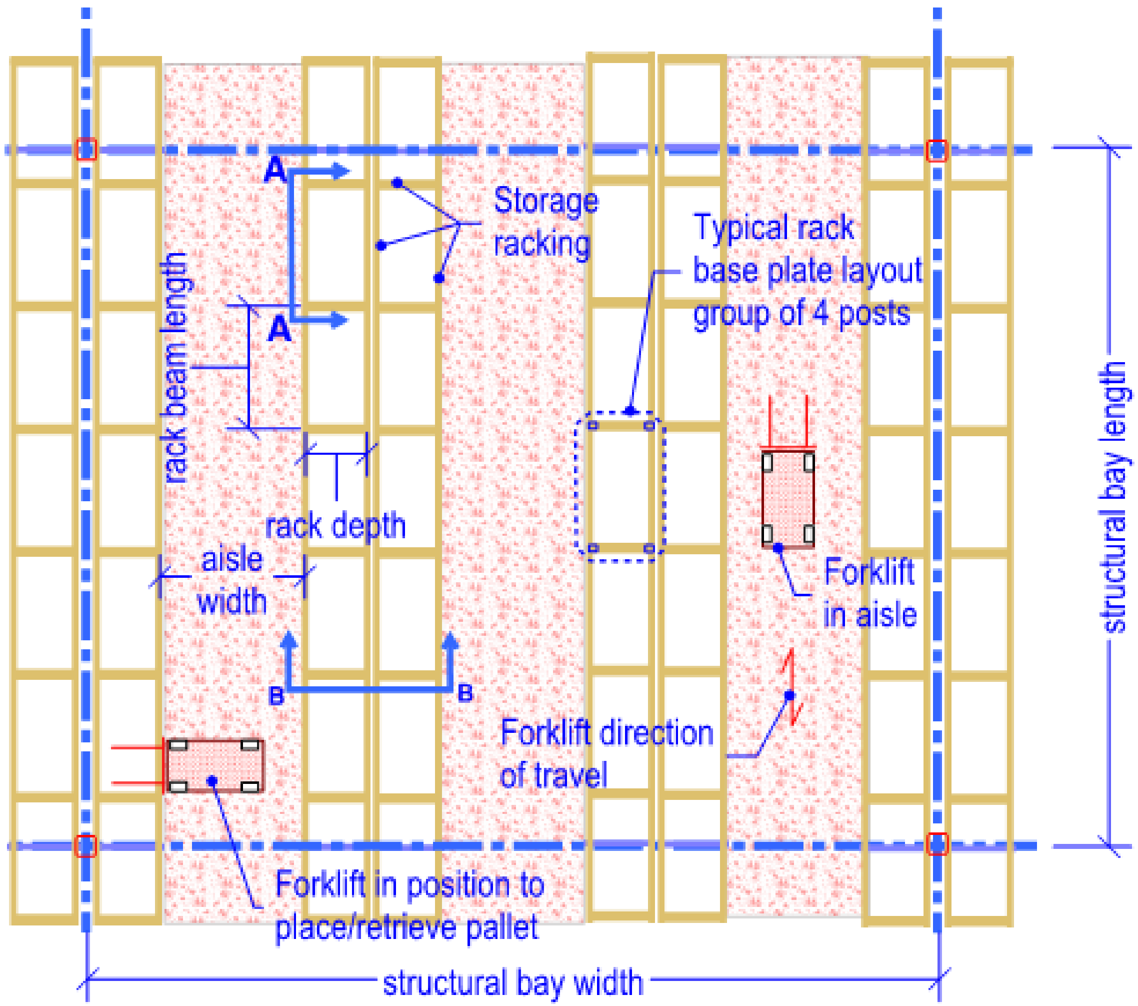
i. In designing the slab, the bending and shear strength of the slab is considered local to the base plate. A design can be completed using various methods of slab design. These are discussed later.
j. Joint design for wheel loads is not limited to one-time events. The wheels will impose cyclic loading of joints based on the sheer number of times the joint is crossed by materials handling equipment.

3. Line loads

a. **Loads imposed over a narrow width and long length**
b. **Examples: Concrete block partition walls; Rail-mounted equipment**
c. Wider line loads, or closely spaced groups of parallel line loads may be better approximated by uniform loads over an area
d. To a lesser degree than uniform loads, line loads will generally be effectively transferred to the soil in bearing.
e. The soil may settle in the short and long term depending on soil characteristics, magnitude and duration of loading, and amount of area affected.
f. Joint and edge locations should be considered, both near joint corners and not near joint corners. Orientation of the joints (parallel and perpendicular) will matter. Vertical load transfer across joints is a factor.

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



Plan View of Storage Rack Layout
(common layout shown)

Fig. 26 - Typical rack and aisle layout

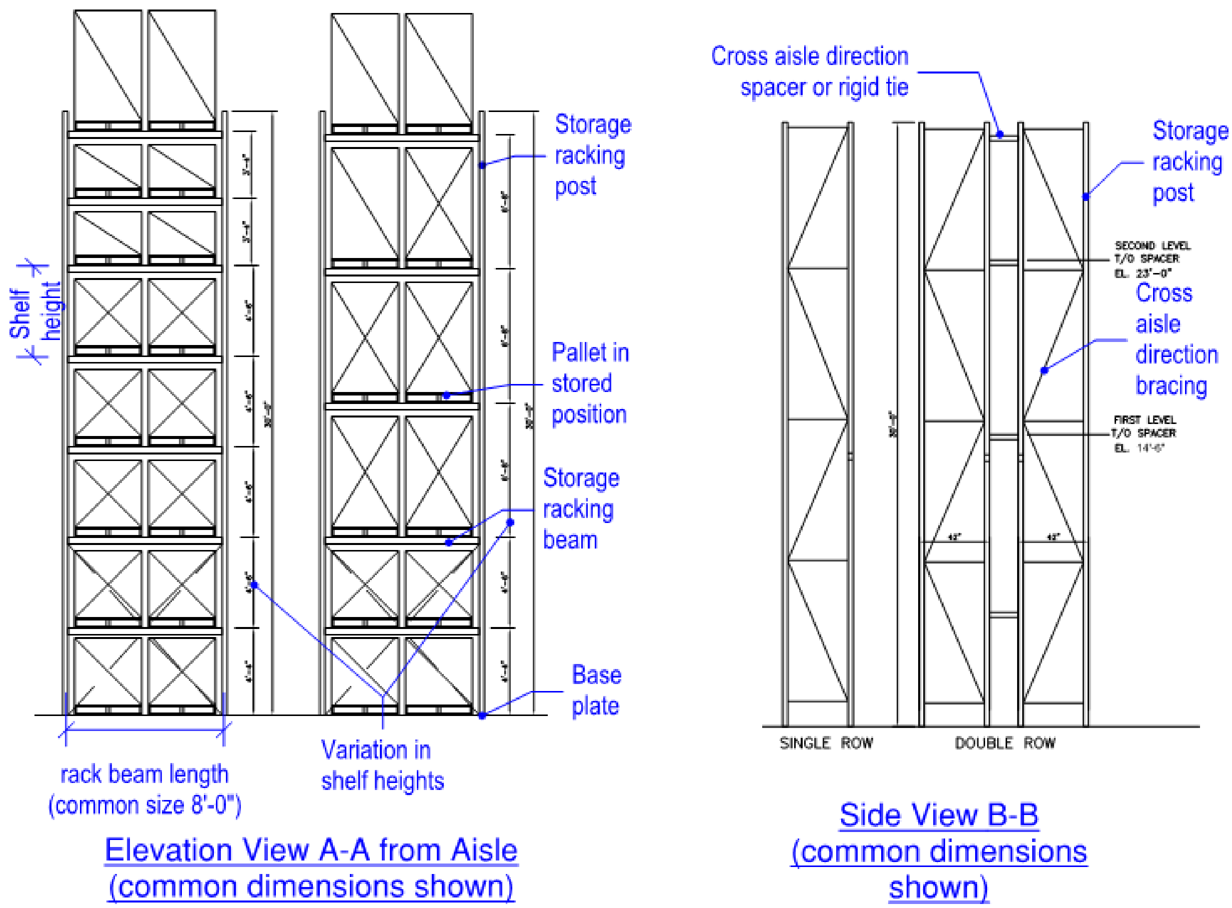


Fig. 27 - Typical storage rack construction

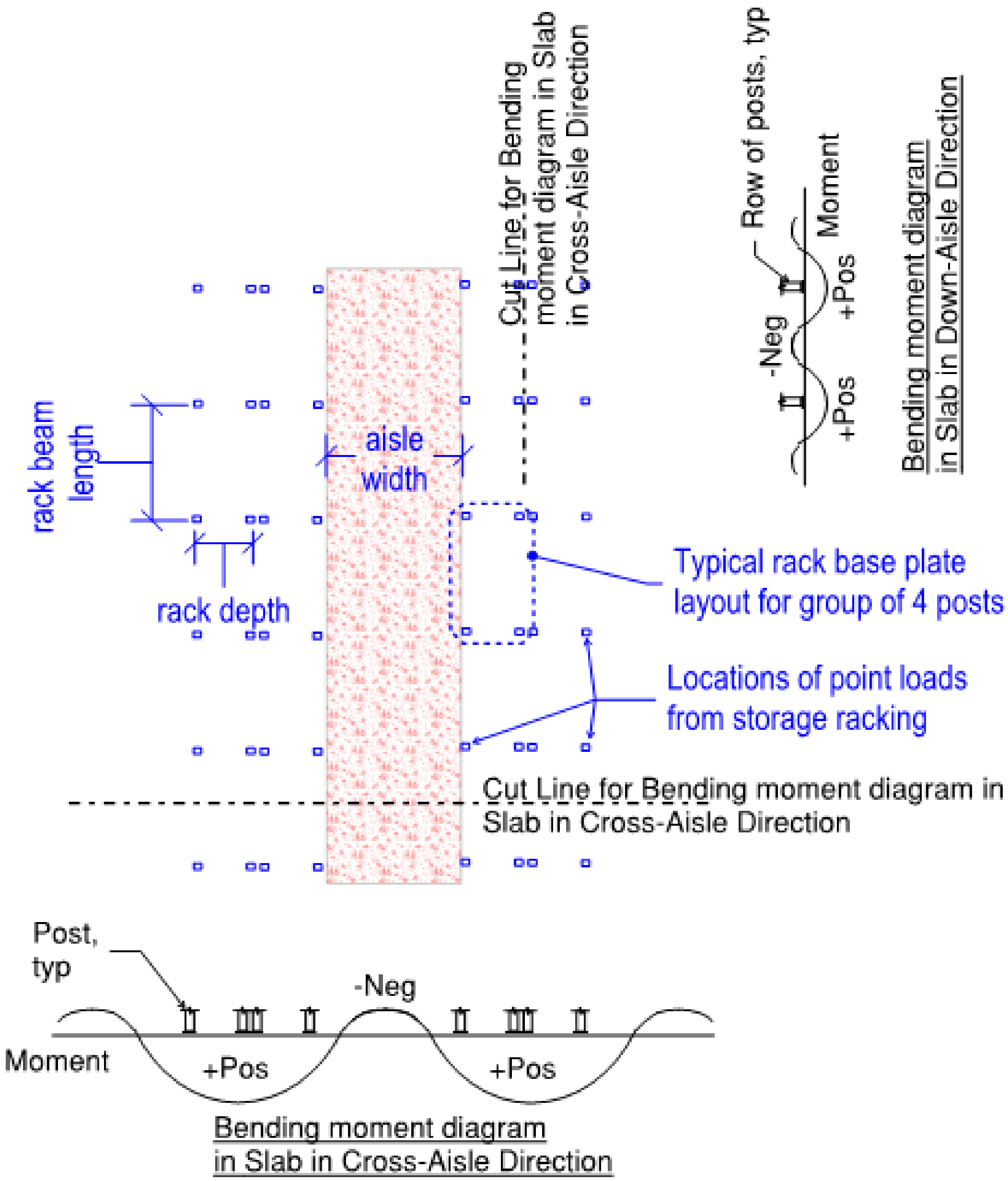


Fig. 28 - Moments in slab due to racking with clear aisles

4. Special loads:
   1) Automation equipment:
      a. Cranes that store and retrieve storage containers or trays
         i. Travel rail and anchor forces (acceleration, braking)
         ii. End run crash loading
         iii. Falling crash loading (sim to passenger elevators)
      b. Equipment within automated areas such as elevator-type lifts
   2) Lateral loads (mainly seismic) from designated bracing bays within rack systems
   3) Building loads from storage racks that support walkways, elevated storage retrieval vehicle pathways, storage mezzanines, roofs, exterior walls, and so on.
   4) Conveyor leg loading, or conveyor mezzanines.
   5) Conveyor systems with telescoping framing that reach into trucks at loading docks (large overturning forces including uplift)
   6) Special ground-supported equipment (e.g., vibrating machines)
   7) **Base Plates of bollards designed to stop wayward materials handling vehicles**
      a. Bumper height or low-to-ground height
      b. Overhead door height – lifts are sometimes left up by mistake, and can crash into crash bars protecting the headers of fire separation doors
   8) Crash loads from materials handling vehicles striking the posts of storage racks or mezzanines, where the base plates attach to the slab.
   9) Construction loads from construction equipment such as lifts and cranes.
   10) Because warehouse slabs offer significant strength and weight compared to typical buildings, they may also be called upon to anchor temporary bracing for exterior walls such as free-standing precast concrete or tilt-up concrete walls. The resource for determining loading on building components due to temporary loading is ASCE 37.

Design of Slabs With Warehouse-Type Loading – Intro and Options

There are numerous tools and methods available for the design of slabs. Mainly, the slab thickness, concrete strength, and joint treatment are certainly the focus, but there are many factors that need to be weighed. The slab design in industrial facilities is not a one-size-fits-all approach. A few things to consider:

1. **Slab loading data** from warehouse operations:
    a. **Materials handling equipment and wheel/tire types**
    b. **Load info for forklifts and pallet jacks**; magnitude of different types of loading, and number of cycles for life cycle study
    c. **Storage rack types** and expected loading including anchorage forces from rack overturning in seismic zones
        i. Expectations in higher seismic zones; For example, a rack supplier may demand that the anchorages develop the strength of the steel base plate anchors to develop ductility of anchor; One solution the author has successfully used: slab designer pushes back and requests that the ductile element be located in the steel assembly, such as a thinner base plate.
    d. Uniform loads and other miscellaneous loading
2. Site soil characteristics and expectations for soil performance under loading per the geotechnical report
3. Engineering judgement from the slab designer
4. Experience and opinion of facility – things they have learned, things they absolutely want to have and want to avoid. For example, flexibility in rack layout and/or equipment travel paths may be desired by the owner, in which case a design specific to a precise rack and travel layout may not apply, and a more random layout may need to be assumed. It may be a good idea to state assumptions about slab design on the drawings so it is obvious in the future
5. Local concrete practices and trends; Local expertise in certain types of concrete
6. **Appetite of operations for repairs, both to slab and equipment**. The owner may be risk averse, in which case they may opt for higher factors of safety in slab strength design, and more protection against deterioration at slab joints. Or, the owner may be willing to consider a specialty slab system that have a higher front and cost, but more guarantees on performance, such as a shrinkage compensating concrete slab.

7. Ability to repair slab; Some automated racking will be largely inaccessible for major repairs. The rack framing may be so closely spaced and so near the floor that remedial action would be extremely difficult to achieve without dismantling rack framing and anchorage.
8. Know implications of slab failure; E.g., If the slab supports storage racks in a retail area exposed to the public (Costco, Home Depot, etc.), the factors of safety for failure modes need to be increased.
9. Depending on the storage rack system and/or supplier, the tolerance of the racking for initial flatness and levelness, as well as overall tolerance for the initial differential slab elevation, may need to be considered to meet operational needs. Criteria such as FEM 9.831 and 9.832 criteria for European racking can be very challenging to meet.

Further Notes on Slab on Grade Design:

a) Hardy Cross once said about concrete, “Strength is essential, but otherwise unimportant.” The stength of the concrete is important, but only to a point. A standard slab mix design calls for f’c = 3,500 to 4,000 psi. This is generally adequate for most slabs. Higher cement contents will yield higher concrete strengths. However, because **an increase in the cement content correlates to an increase in shrinkage**, concrete design strength over 4,000 psi may not be called for. Also, since the bending and shear strength of concrete vary as the square root of the concrete strength, this diminishes the value of increased cement. Furthermore, an increase in cement content will drive up the cost of the concrete, and because the joints control the design, the use of higher strength concrete will be largely wasted on the vast quantities used between joints.
b) Note that increasing the section thickness at the joints would necessarily introduce two undesireable complications. First, the time and labor to dig the subgrade (soil under the slab) to form the thicker sections would be disadvantageous, especially given the need to coordinate pre-determined joint locations. Also, as the concrete shrinks, the “knuckle” created by the thicker section would tend to restrain the slab under its own weight. Because concrete shrinks toward its center of mass between control joints, it could easily develop enough tension in the slab to cause an uncontrolled crack at the thinner (weakest) section of slab away from the joint.
c) Some slabs will need to be designed using ACI 318. Opinions vary, but this might also include mezzanines that see more building-type loading. The Engineer of

Record will need to apply some engineering judgment for these types of decisions.

Once enough information has been collected to execute a slab design, a decision on method of design can be chosen. It may depend on the nature of the loading and conditions. If the loading is more conventional, more standard methods of design may apply. Cost studies can be done for various options (joint types, joint spacing, reinforcing, fibers, expected shrinkage, etc.).

Resources for Designing Slabs for Warehouse-Type Loading

The choices of methods for designing concrete slabs-on-grade are numerous, and the opinions on the merits, applicability, and risks or conservatism of those methods vary widely.

Some very **basic questions to ask** as a project appears at an engineer's desk:

1. What is the extent of my own, my company's or my peer group's knowledge on the subject?
2. What are the problems that I, my company's experts or my peers have observed with slabs? Are the root causes of those problems known, and do they apply to this project?
3. What is the architect's, contractor's and owner's experience level with warehouse slabs and what can I learn from them? Are there advocates on these teams with strong opinions and good communication skills whose talent, experience and knowledge I can leverage to help steer the project towards wise strategic investments in good slab design?
4. Who are the industry experts that I, my company's experts, my peers, the architect, the owner, or the contractor know or that I can learn from? Can I partner with them and leverage their interest to market their skills, knowledge, and products or services?
5. Does it make sense to hire experts to enhance the slab design, whether it be guidance, peer review, or wholesale delegated design? Does it make sense for the contractor to partner with a design-build concrete subcontractor whose main business is designing and building industrial slabs?
6. What will I at my desk be in control of, and do I have the right architect, contractor, and owner to buy into the design, and help carry it out with good quality assurance and control, and a willingness and ability to help champion the design all the way through construction?
7. What do I need to do to communicate the importance of key aspects of slab design and construction so the expectations that I have going into construction are known and met (shrinkage limits, curing and weather protection, testing, etc.)?

8. Does the project team need to hire a third party with expertise in concrete slab designs to help with quality assurance and control, will this third party have a strong presence and opinion in the field, will they hold the concrete subcontractor accountable, and will they be good at documenting where specific things varied from the contract documents?
9. If something goes wrong with the concrete later, and the QA/QC personnel wasn't effectively looking for key things, catching them, documenting them, and following up to make sure they were corrected, how difficult will it be to get to the root causes when things go wrong at a later date?

An engineer can always lean on the conservative side, and provide a slab thickness with reinforcing or fiber content that reflect that conservative approach. But, when an owner sees how the slab down the street was designed for the same loads, but for less cost, and with no real additional risk, that owner will factor that knowledge in on the next project. The author is not trying to dissuade a conservative approach to design. However, the investment of a slab-on-grade is a significant part of the project budget for an owner, and this requires significant due diligence on the engineering side, especially if warehouse slabs are a new area for a design firm. A $10,000-$15,000 investment to have an outside engineering partner that regularly designs slabs that optimize the construction budget could be a good investment to enhance a firm's reputation and build its knowledge base.

The question about what can be controlled on a project is an extremely important one. If it becomes clear that shrinkage, curling, subgrade, level of execution, or other key parts of slab design and construction cannot be reliably controlled, then that should be accounted for in the slab design. For example, the amount of shrinkage (and curling) expected or that can be reliably counted on will impact decisions on joints, slab thickness, and factors of safety. Before the concrete is placed, the engineer should have a clear picture of how these things will play out on a project. Leaning on the contract documents will always be helpful, but hoping for the best and not getting it won't help the owner get the building slab they need on the schedule they've promised to investors or stakeholders.

A few **fundamental questions should be tracked when examining possible methods** of slab design:
1. Does the slab design method reflect true concrete behavior by being compared to field or laboratory testing?

2. Does the method rely on elastic limits of the slab (incipient cracking or initial failure), or does it rely on ultimate limits that are staged or stepped from initial cracks to thorough concrete failure ("plastic" or post-crack failure)?
3. Does the method apply to slabs that are unreinforced? Or does the method require that the slab be reinforced to provide ductility sufficient to enable predictable post-crack behavior?
4. What are the assumptions about joint locations and construction, cracks, curling and shrinkage and how do they affect how the design method is carried out?

The author is aware of several approaches to slab design, but the list is not exhaustive, and there a many not mentioned that may deserve attention based on their merits. So, the reader is encouraged to do their own research on this if called upon to design a warehouse slab. For example, there is a whole realm of pavement design that uses time-tested software and experiences of DOT's that could be reviewed for use with warehouses. (And the author welcomes feedback on this list.)

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)

Implementing these design methods, as well as joint design and finishing will be presented in the second warehouse course:
Slab-on-Grade: Warehouses II – Slab Design.

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