ROOF DECKS A to Z

Part V: Precast, Prestressed Concrete Tees

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ABSTRACT

This is the fifth in a series of articles examining various deck types. Of the numerous considerations involved in selecting a roof system, the type of decking is among the most important. With the variety of decks to be encountered (both new and old), it is incumbent upon roofing experts to be the authority on these matters.

This article will explore features of precast, prestressed concrete decks—whether in a single- or double-tee profile. Use of these members in parking structures will also be considered. This is because 1) the domain of modern roof consulting now encompasses more than just roofs, 2) practitioners may well be asked to participate in the rehab of such members, and 3) there are similarities in their construction.

Figure 2 – Spans of 50 to 80 ft. are rather common, with some projects supplied in lengths in excess of this range. Transportation of precast tees may be the limiting factor in determining their maximum practical span.

INTRODUCTION

Precast, prestressed concrete tee panels offer many advantages that make them suitable for construction of elevated parking decks as well as the substrate for waterproofing and roofing systems. An unreinforced flat slab of suspended concrete would have little flexural strength and would surely fail under service loading.

Consequently, the shape is modified to have vertical legs, characterizing the "T" profile. These legs or stems contain heavier reinforcing steel (*Figure 1*). They can be manufactured in single- or double-tee configurations. Precast, prestressed concrete tees achieve their ability to support loads over large spans due to the depth of the stem (which results in a high-section modulus) as well as prestressing tendons placed along the lower part of the stem. With their efficient cross section, precast tees are often used where spans in excess of 60 ft. are desired. This makes them ideal for use in parking garages where the typical spans for a drive isle and parking stalls on either

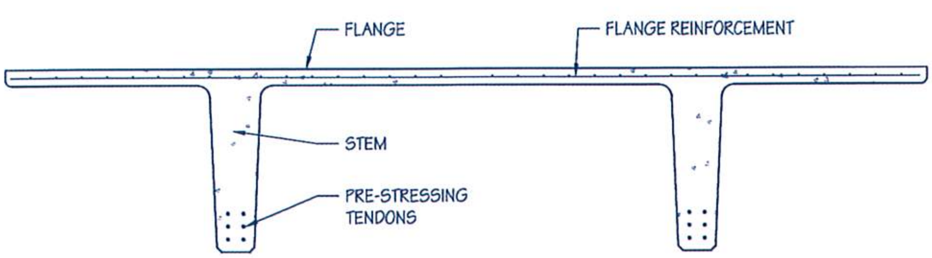

Figure 1 – Typical section through precast, prestressed double tees. Legs or stems contain the heavier reinforcing steel. The flange contains welded wire fabric.

Figure 3 – Camber of tees from compression induced by the embedded prestressing tendons. This is beneficial to counteract the dead-load, live-load, and creep deflection of panels.

side of the aisle are 60 ft. or more. Spans of 50 to 80 ft. are rather common, with some projects supplied in lengths well in excess of this range. Transportation of precast tees may be the limiting factor in determining their maximum span (*Figure 2*).

Tees are also suitable for many other applications, such as warehouses, large manufacturing facilities with house cranes within, paper machine rooms, turbine rooms, roofs of large ballrooms, decks for vegetative roofs over parking garages, etc. They have several advantages over some other deck types, including:

- Ability to support loads over large spans
- Rapid erection in the field
- Durable, if maintained and waterproofed properly
- Plant-manufactured, making them less dependent on a site's environmental conditions

Since they are heavy and large, tees require large cranes for erection. Therefore, their use is limited to low- and mid-rise structures where large cranes can lift them into place. Most tower cranes cannot effectively lift these large, heavy panels in high-rise construction.

MANUFACTURING AND INSTALLATION

The tees are manufactured in precast plants using prepared forms (also referred to as "beds"). They are in the same orientation as the panels are to be installed in the field (i.e., the stems and lower surfaces of the flange are smooth-formed, and the top surface is finished manually). Prestressing tendons are situated within the forms and are stretched (stressed) prior to placement of concrete.[1] Tendons are high-tensile-strength cables, typically of multiple strands. After placement of concrete and development of adequate compressive strength, tendon ends are cut, releasing the tension and imparting compression to the stems. This compression shortens the lower section of panels, resulting in upward curvature known as "camber" (*Figure 3*); this is beneficial to counteract the dead-load, live-load, and creep deflection of the panels.

The flange of each panel is cantilevered from the stem. In order to resist tensile stresses that develop near the top of each flange, conventional reinforcing is placed in the flange. Since the flange is relatively thin and cantilevering lengths are small, the conventional flange reinforcing is usually welded wire fabric and is placed at approximately the mid-depth of the flange.[2] The welded wire helps resist flexural stresses from out-of-plane loads and provides a minimal amount of reinforcing to control drying shrinkage cracks. To protect from corrosion, prestressing tendons are typically coated with epoxy. Conventional reinforcement such as stirrups and welded wire fabric may also utilize protective coatings to resist corrosion.

Tees are cast using various types of concrete. Typically, 28-day compressive strengths ranging from 3,500 to 5,000 psi are used for casting the panels; however, they can also be readily manufactured with higher-strength concrete. If panels are intended to receive a concrete topping, the

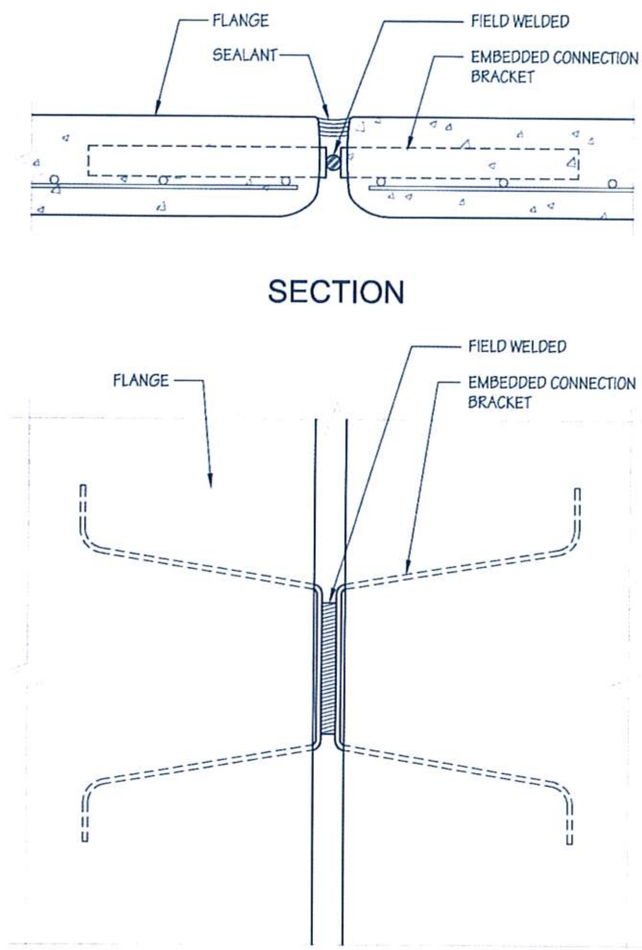

Figure 4 – Connection brackets transfer in-plane shear and allow panels to form a diaphragm. In most cases, the gap between adjoining brackets is filled with a steel bar or steel shim; they are then welded through the joint between panels.

top surface is floated and then roughed to help achieve good mechanical bond. If the panels are intended to be used without a topping, their top surface can be finished using a variety of methods. For parking deck applications, the top is typically a broom finish for improved traction.

DESIGN CONSIDERATIONS

As previously mentioned, precast, prestressed concrete tees derive their ability to support loads for large spans from their efficient cross-sectional shape and high tensile stresses in the prestressing tendons. When designing tees, several factors are considered. In most cases, each panel is designed to be simply supported at each end. As such, most tees bear on a supporting girder or beam. During manufacturing, a bearing plate is usually cast at ends of the stems to provide a uniform contact with the supporting surface. In many cases, the bearing surface is slightly recessed from the bottom of the stem. Bearing points of panels on the supporting beams or girders are typically laid with no mechanical connection on one end. Where mechanical connections are required (such as for seismic considerations), they are designed to allow longitudinal movement of the panels from temperature changes. A 60-ft.-long panel can experience more than ¾ in. of longitudinal movement due to temperature changes.

Since tees are placed on simple bearing points, they cannot resist lateral loads for the structure. In order to transfer in-plane shear movement and allow panels to form a diaphragm, tees need to be joined along edges of the flange. In the field, this is typically achieved by welding embedded steel brackets (which are exposed) along the edges of the flanges (*Figure 4*). In most cases, the panels are situated in place, and the gap between adjoining brackets is filled with a small-diameter steel bar or steel shim; they are then welded through the joint between panels. There are several such brackets along the length of each panel. They are primarily designed to transfer in-plane loads to resist lateral building frame movements. However, they also resist out-of-plane (vertical) movement that occurs when one panel is loaded differently than the adjacent panel. This happens frequently in parking garages as wheel traffic transfers from one panel to another.

In most cases, the side gap between panels ranges from ¾ to 1¼ in. If panels are to be topped, the concrete topping is placed after the adjoining panels are welded together. Topped panels are not typical below conventional roofing systems and do not necessarily rely on the welded side connections for load transfer. Instead, the concrete can be placed across joints and designed to accommodate such stresses. It is imperative that topping slab be designed to act compositely with the panels. Dowels need to be installed to ensure proper connection between the two. The composite action of the panels and their topping also helps provide a higher section modulus and stiffness for the panels.

After panels are welded together, the panel joints are treated and the topping slab is placed. For use with conventional roofing systems, joint treatment can merely consist of taping. Where used as an exposed deck or below adhered waterproofing systems, the joints are sealed with sealant and backer rod. The most widely used sealant type for joints is polyurethane. Although silicones have excellent performance, most

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Figure 5 – Parking deck joints are particularly prone to leakage. Backer rods cannot be properly installed at the embedded connection brackets, and the joint geometry makes them susceptible to failure.

silicone sealants have inferior toughness and abrasion resistance as compared to polyurethane. As such, they are typically not used for sealing joints of tees. However, many other sealant types can be used along panel joints if the joint design and in-service requirements are properly considered.

After treating the joints, the deck may be protected using a waterproofing membrane, a roofing assembly, or an elastomeric traffic-bearing membrane. All these systems must be designed to accommodate the anticipated movement at all panel joints. In some cases, exposed panels used for parking garage applications merely receive clear water-repellent to help improve durability. However, such systems need periodic reapplications and should be selected properly for each use.

TYPICAL DETERIORATION MECHANISMS AND REPAIR TECHNIQUES

Precast, prestressed concrete tees can be very durable. However, in many cases, deficiencies in their design, construction, or maintenance can result in premature distress. Deterioration is particularly prevalent on parking decks with no protective membrane applied over the deck surfaces. A detailed discussion of all deterioration mechanisms in concrete tees is beyond the scope of this article, but the following is a summary of prevalent deterioration mechanisms the authors have observed in decks constructed using concrete tees.

Leakage Through Joints

A parking deck constructed using tees can have thousands of linear feet of sealant joints. In the absence of a protective membrane such as a traffic-bearing membrane, these joints are a common avenue for water leakage (*Figure 5*). Joints are particularly prone to leakage due to the following factors:

- Each deck has a large quantity of sealant joints. Proper quality control/quality assurance of sealant application at these joints is difficult, given their quantity. Variations in workmanship and lack of surface preparation or primer application results in disbonding of sealant joints from the joint shoulders.
- As previously discussed, a backer rod cannot be properly installed at the embedded connection brackets. The joint geometry at those locations makes those joints more susceptible to failure.
- During installation, workers typically tool the joints to provide for an hourglass shape and ensure proper contact with the substrate. However, the concave shape of the joints results in water accumulation along each joint and deterioration of the sealant. In many cases, self-leveling sealant may be used to avoid the need for tooling of the joint; but even so, it is difficult to maintain a slightly recessed profile (to avoid damage by snowplow blades and traffic) that does not form a trough in which water will accumulate.
- Boot heel traffic can cause punctures and failures in the sealant joints. For this reason, a stiffer joint backing and lower-modulus sealants may be more suitable for horizontal applications.
- In some cases, sharp snowplow blades can cause damage to the sealant joints (and the protective coating). As such, establishing maintenance procedures for panel joints is critical. If snowplows are to be used, they should be equipped with rubber blades. Beyond this, power brushes to clear snow may prove more effective and less destructive to the joints.

Corrosion and Distress in Connection Brackets

Given the long span of tees, deflections caused by loading can be significant. Current model building codes and standards limit deflection of structural slabs to L/240.[3] This means that deflection of 3 in. would be permissible for a fully loaded, 60-ft.-long panel. Often, the differential movement can be felt when standing on a panel while vehicles cross the side joints; however, the magnitude of this movement is considerably less than the maximum anticipated deflection.

Differential loading at connection brackets can be exacerbated when the top elevations of adjoining panels are not the same (*Figure 6*). This causes impact loads from vehicles to induce higher stresses at the connection brackets. These stresses can result in concrete cracking, in turn allowing water and deicing salts to penetrate the concrete and come in contact with the connection brackets. These cracks also allow water to bypass the sealant joints along panel connections and result in water leakage (as discussed above).

Whether concrete cracking or corrosion starts first, the combination makes connection brackets prone to corrosion damage. In

Figure 6 – Differential loading and stresses at connection brackets can result when adjacent panels are not the same height. Here, the difference in top-surface elevation is measured using a dial gauge micrometer.

Figure 7 – Whether the cracking or corrosion starts first, the combination makes connection brackets prone to damage. When investigating tees, exploratory openings are crucial to evaluate the condition of brackets.

most cases, corrosion of connection brackets is the first sign of deterioration (*Figure 7*). When investigating such decks, a thorough visual review of the concrete around the connection brackets and exploratory openings at connection brackets are crucial. Brackets can be found using an R-Meter, and removal of concrete around brackets is necessary for proper evaluation.

If connection brackets are found to be corroded or the cause of concrete cracking, retrofit brackets of various configurations can be designed and installed to transfer loads across the panel side joints. It should be noted that patching of the concrete around brackets should be avoided as a method of restoring the brackets. If the concrete around the brackets is patched, the patch should be carefully designed to accommodate the stresses that the brackets impose on the immediately surrounding concrete. Otherwise, the patched area will simply fail again.

Corrosion of Embedded Conventional Reinforcing

As previously indicated, welded wire fabric or reinforcing bars are placed at mid-depth in the flange concrete. Since flanges are relatively thin, it is difficult to place the reinforcing at an exact depth from the top surface to provide for proper concrete cover. In some cases, welded wire fabric can move during concrete placement, resulting in shallow concrete cover. If the panel is not protected with a coating, the topping layer will eventually carbonate, reducing the pH of the concrete. In combination with frequent exposure to moisture on the top surface, this results in corrosion of the embedded reinforcing. Another factor that can accelerate and promote corrosion of reinforcing steel is the presence of chloride ions. On parking deck applications where deicing salts are broadcast onto the deck, chlorides can permeate and reach the reinforcing steel. These chlorides quickly break down the passivating layer over steel and initiate the corrosion process.[4]

As indicated above, corroding steel can cause delamination and spalling of the concrete around it. If the welded wire fabric is placed at the proper depth, the likelihood of corrosion-induced delamination and spalling is reduced. Conventional repairs are typically used to address corroded, embedded reinforcing in the flange of the panels. However, if the corrosion has resulted in a significant loss of cross-sectional area, supplemental reinforcing will be needed to ensure proper capacity to support loads.

Similar to the reinforcing in the flanges, conventional reinforcing in the stems can also experience corrosion, resulting in cracking. These deficiencies should also be

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Figure 8 – Substandard adhesion of insulation over tees has been encountered in a number of instances. Concrete is a thermal sink and can become very cold, so direct mopping of hot asphalt should embody long-recognized cold-weather procedures. Note also the lack of taped decking joints.

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repaired. However, careful consideration should be given to the structural integrity of the stems, shoring, and required supplemental reinforcing.

Corrosion of Prestressing Tendons

Failure of sealant joints at panel ends where they abut the supporting beams can lead to water leakage at those areas. In roofing applications, failure of the roof covering can result in water leakage at the same locations. If such water penetration is not controlled, continued exposure to moisture can result in corrosion of prestressing tendons at panel ends. Prestressing tendons are particularly vulnerable at panel ends, since their cut ends are exposed at those locations. Corrosion of the prestressing tendons poses a serious risk of structural deficiencies.

Prestressing tendons cannot be readily replaced. Typically, their repair requires shoring of the tees to counteract dead and live loads. Damaged concrete around the tendon is then repaired, and deteriorated prestressing tendons are supplemented using externally applied fiber-reinforced polymer (FRP) applied as strips of composite materials bonded to the stem surfaces. The fiber reinforcing can consist of carbon fiber or glass fiber. These repair systems are proprietary in nature and are typically designed by the system manufacturer based on loading criteria established by an engineer.

Corrosion of Bearing Plates

Water leakage discussed above can lead to corrosion of bearing plates and distress at the stems and supporting beam/girders. Repair of such deterioration is difficult due to space constraints and shoring requirements. Specifying stainless steel bearing plates is a good practice. The bearing pads can then be constructed of elastomeric products that do not corrode. In situ repair of corroded bearing pads and embedded bearing plates is possible but requires careful consideration and proper shoring. Such repairs will likely involve removal of concrete around the bearing plates, replacing the bearing plates, and patching of the concrete. The importance of proper shoring design and installation when performing such repairs cannot be overstated.

Freeze/Thaw Deterioration

In general, most precast concrete is durable. The quality of concrete placed at precast plants can be better controlled, and it is typically cured more properly than site-placed concrete. However, in some cases, panels that are exposed to moisture and repeated freezing and thawing can suffer deterioration.[5] Freeze/thaw-damaged concrete typically exhibits a random cracking pattern and makes a dull sound when tapped with a sounding hammer. More importantly, the network of cracks results in significant diminution of its strength.

In most cases, advanced freeze-thaw deterioration can be visually identified; however, in its early stages, and to confirm the cause of observed cracking, petrographic examination of concrete cores should be performed.[6] Although a petrographic examination does not provide an accurate estimate of air content, it can help assess presence, extent, and pattern of micro-cracking within the concrete. An experienced petrographer can then correlate the cracking pattern with the general quality of the concrete and reach opinions regarding the cracking cause. More accurate estimation of air content can be performed through other standard test methods such as ASTM C457.[7]

Repair of advanced deterioration is not practical. If limited to the flange, it may be possible to remove the compromised portion and cast a new flange. Again, such repairs should be performed after careful consideration is given to the camber and upward "rebound" of panels once the weight of the flange is removed.

OTHER MECHANISMS OF DISTRESS

Several other deterioration mechanisms can be encountered in precast, prestressed concrete tees. These include, but are not necessarily limited to, delayed ettringite formation (DEF) and alkali-silica reactivity (ASR). DEF is typically encountered in precast components cured at high temperature to accelerate strength development. A detailed discussion of these is beyond the scope of this article.

STRUCTURAL STRENGTHENING

In order to repair cracking or to increase the structural capacity, it may be necessary to supplement reinforcing tendons in precast, prestressed tees. In the last few decades, fiber-reinforced polymer (FRP) sheets have gained widespread use for such applications. As previously mentioned, these repair systems are proprietary in nature. If considered as a repair technique, the root cause of cracking or other distress should be evaluated carefully. Both concrete and FRP have varying structural properties. As such, the design of such repairs will require careful analysis—usually performed by the repair system manufacturer with input from the engineer.

OTHER ROOFING CONSIDERATIONS

Roof decks constructed of precast, prestressed concrete tees pose a particular challenge with surface drainage. Each panel is originally constructed with a camber. Yet in-service deflections due to creep and to dead and live loads can change the camber considerably over the service life of the roof covering. As such, the drainage design should anticipate these changes in surface elevation of the panels. Moreover, once installed, the panel ends may form a dead flat zone that must be corrected; consequently, a topping course of lightweight insulating concrete (LWIC) may be applied to produce drainage contours that cannot be configured into the panels themselves.

When board insulation is installed over panels in hot bitumen, a bituminous primer should be first applied, and decking joints should be taped. Tees are a thermal sink and can become very cold, so direct mopping of hot asphalt should embody long-recognized cold-weather procedures. The authors have encountered substandard adhesion of insulation in a number of instances (*Figure 8*). Alternatively, if a topping course of LWIC is applied, a base ply will need to be used, along with fasteners appropriate for that material.

With compressive strengths exceeding 3,500 psi, a roofing system can certainly be mechanically attached to panels using appropriate concrete anchors; however, all such devices would require predrilled holes, with the likelihood of some encountering

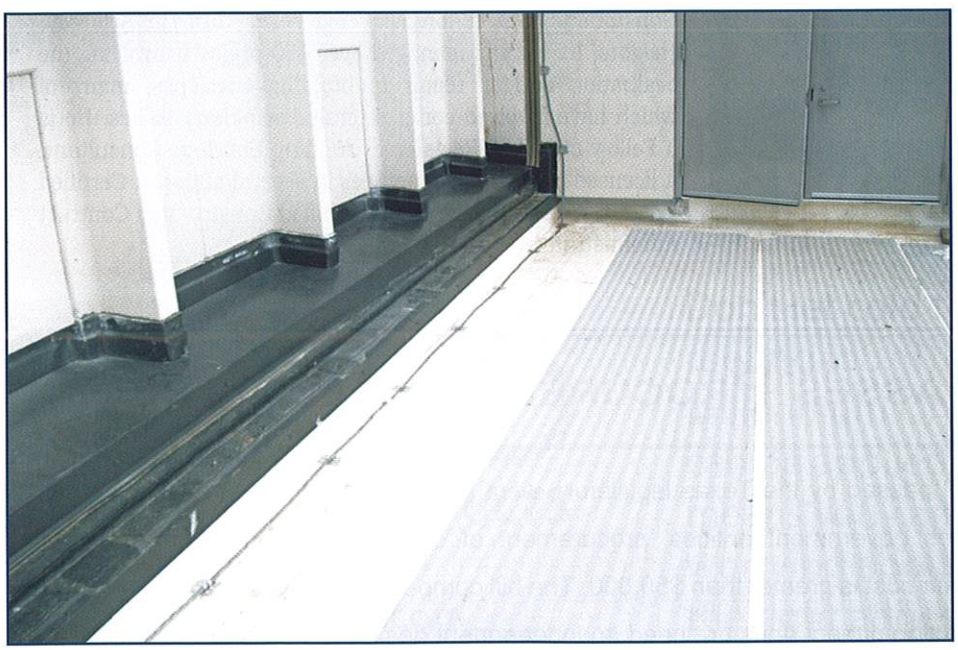
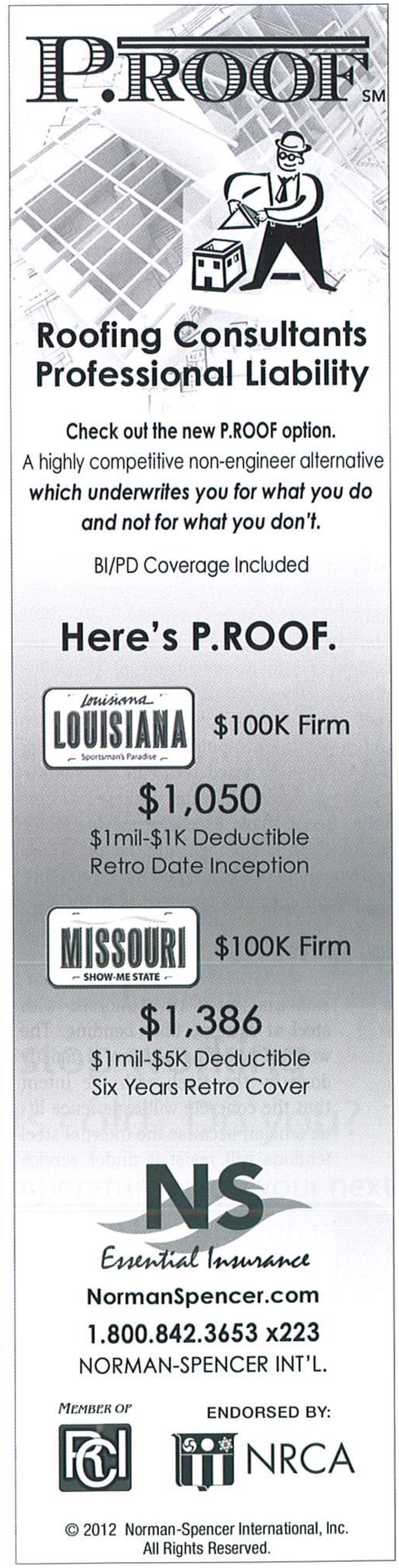


Figure 9 – Tees used to form building walls. The re-entrant corners and turns make this handcrafted flashing slow and arduous.



the embedded reinforcement. This makes mechanical attachment of roofing systems to these decks an unattractive option. Instead, modern foam adhesives are the preferred method for board insulation attachment.

Just as with parking decks, side-joint elevation differences can be challenging. Since adjacent panels can have slightly varying cambers, differential surface elevations as high as 1 in. can result. The use of LWIC topping can address this issue. Otherwise, filler insulation will be needed to form a smooth substrate for roof coverings.

Tees may even be used to form a building's exterior walls. This can create a flashing dilemma in which there are lower roof levels or additions onto buildings with such walls. As shown in *Figure 9*, the reentrant corners and turns make this handcrafted flashing slow and arduous.

SUMMARY REMARKS

Precast, prestressed concrete tees offer many advantages and can be very durable. Accordingly, they may serve as the building's substrate for multiple reroofing phases. Deterioration of tees from failed roof coverings is relatively uncommon unless water entrapment has persisted for a long time. Exposed tees can be compromised by extensive water leakage, deicing salts, freeze/thaw, excessive service loads, improper deck openings, and the like. These aspects should be evaluated by the consulting practitioner in the course of study.

ENDNOTES

1. Concrete is relatively weak in tension and must be reinforced with steel at extreme fiber bending. The work of resisting tension is mostly done by the steel, with the intent that the concrete will experience little tension because the internal steel tendons will resist it under service loading.
2. For durability and corrosion resistance, building codes require that reinforcing members smaller than No. 6 bars should have a minimum concrete cover of 1½ inch.
3. ACI 318. This deflection limit applies to finishes attached to the slab that could be damaged by such deflections. For roof structures, the deflection limit is greater (more lenient) at L/180.
4. In high-alkaline environments, a passivating layer is formed over steel. This layer protects the steel against corrosion. Alkalinity of recently placed concrete ranges from a pH of 10 to 12.
5. To resist freeze/thaw deterioration, air-entraining admixtures are blended into concrete. The required air content (percent of volume of air compared to the total volume of the concrete) can vary, depending on coarse aggregate size and severity of exposure to freeze/thaw cycles. Model building codes include requirements for air entrainment.
6. Petrographic examination of concrete includes microscopic evaluation of concrete samples and thin sections (sections so thin that light passes through them). ASTM C856 provides a recognized standard for performing petrographic examinations.
7. The air void system is not the only factor that influences concrete's resistance to freeze-thaw cycles. Other factors such the ratio of water to cementitious material can also influence freeze/thaw resistance.

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TEXAS PASSES PROCUREMENT LAW

A new materials procurement bill passed by the Texas legislature went into effect September 1, 2013. Texas House Bill 1050 regulates government entities' procurement of construction goods through purchasing cooperatives when their cost is greater than $50,000. The bill compels public entities to certify in writing that their co-op construction project does not need an independent design professional. It also requires design professionals on publicly funded projects to disclose any possible conflicts of interest.