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Journal

Joint Failures:

The Undoing of Double-Tee Parking Garages

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The rhythmic thumping of car tires across a garage deck is the hallmark of a precast double-tee parking garage and a familiar part of modern life. Precast garages have become the most common form of free-standing parking structure across the United States. That most people can immediately recognize this cadenced sound is testament to the adaptability and widespread use of these structures.

In most of the country, pre-topped double-tee construction is the dominant structure type for freestanding garages. The term, *double-tee,* refers to the section profile of the precast concrete members, which resembles a pair of uppercase letters: "TT." The *flanges,* or horizontal arms of the tees, act as both the structural deck and wearing surface. The structure is simply lifted into place and connected, with little more than sealant and paint striping left to complete the project.

Leaks and spalls might seem like minor nuisances, but they can signal serious structural distress.

However, precast has its weaknesses, the most prevalent of which are related to the very construction method that makes it so desirable. Consisting of many pieces lifted into place and joined, precast structures require numerous connections. Most of these connections are embedded below sealant joints, which can and will eventually leak. It is no small concern, then, that the total length of such joints is measured not in feet, but rather in *miles,* and no wonder that most issues plaguing such structures are associated with these connections and sealant joints.

Deck joints support traffic and are subjected directly to water and deicing chemicals. They are prone to leaks, spalls, and fractured connections - three defects that go hand-in-hand. Fractured connections cause leaks, which cause spalls; conversely, leaks cause fractured connections, which can lead to spalls. In fact, it is uncommon to see one defect without another. To understand how and why these defects occur, and why they matter, it

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Corrosion of dissimilar metals.

Edge spall due to the heat of welding.

Abrupt failure between tee and shear wall.

is necessary to understand the components, how they function, and how they have evolved over time.

Pre-Topped vs. Topped: Let's Be Clear

Precast concrete garages fall into two classifications, depending on whether the surface of the precast deck beams is "topped" with a layer of concrete after being lifted into place, or if it is cast integral with the beam flange during manufacture. Unfortunately, "topped" doesn't indicate "when," and there can be confusion about this important distinction. *Pre-topped* is now the accepted industry term for a concrete surface cast integral with the tee. This is the most common form of construction found outside of high-seismic areas and the garage type further discussed herein.

Connection Loading

Double-tees are connected together to form a deck that acts as a *diaphragm,* which is an unintuitive way of saying a big flat beam on its side. When subject to a horizontal force, such as from wind and seismic events, the deck acts like a beam to transmit these forces to shear walls and bracing.

As with any beam under load, the diaphragm bends, creating tension on one side and compression on the other; these are termed *chord forces.* This loading also causes the deck sections to slide against one another; these are termed *shear forces.* To resist these forces, connections are located along the joints between members, with connections at the ends of the joints called *chord connections* and connections located between them called *shear connections.*

Chord connections transmit large tensile and compressive loads and are often a single strong connection at either end of the joint. The shear connections are typically located at around five feet on center along the joint and also transmit vertical vehicle wheel loads across the connection.

Connection Evolution

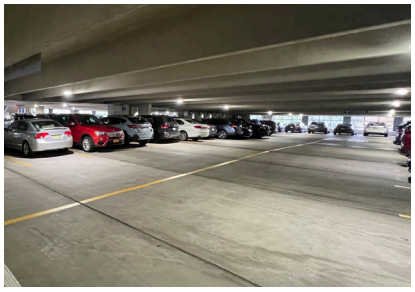
It is an unfortunate reality of precast garage construction that these connections have been problematic through the years and, while they have evolved over time, have not yet been perfected. While there was originally no specific standard, early chord and shear connections were similar in design, varying only in size, if at all. They generally consisted of a vertical plate that was anchored with rebar welded to the back side and cast into the edge of the tee. As the precast tees were lifted into place, the plates were connected to each other by welding a *slug,* consisting of a smooth steel dowel, between plates of adjacent beams.

Configuration

In early designs, this slug was located in line with the rebar that was attached to the backside of the plates to allow a smooth transition of tensile force across the joint. However, it also created very rigid connections between the tees and a very rigid deck. As the deck contracted during winter months, this rigidity caused excessive tensile stress to develop between shear walls. This stress caused many connections to abruptly fracture, often with a "bang."

For some time, it became fashionable to move the slug up to the top of the plates, such that it was not in line with the rebar anchorage. This allowed the assembly to form something of a hinge, permitting the connection to open and close slightly. However, this placed prying forces on the welds, weakening the connections and

Continuous leaks indicate failed sealant and, possibly, an unzipped joint.



Miles of joints mean miles of maintenance.

eventually causing failures due to low-cycle fatigue.

Remarkably, this attempt at stress relief was often extended to the chord connection, the sole purpose of which is to transmit large tensile loads. Intentionally forming such a hinge was a fatal defect that destroyed the connection. Their frailty was so pronounced that many of these connections fractured simply due to cold weather. Many garages still exist today with this inherent defect.

This configuration of the slug also had another unintended consequence: it tended to elevate the slug into the sealant joint where it quickly caused the sealant to wear through and leak.

Heat of Welding

The most common problems in early double-tee garages were leaks at connections, the most serious of which originated at concrete cracks caused by welding of the connection. The plates to which the slug was welded were typically embedded within the concrete, such that they were encased without room for expansion. As the connections were welded, the plates expanded, causing microcracks in the concrete. These cracks would eventually leak, allowing moisture and chlorides to penetrate behind the connection plate. For early connections made of dissimilar metals, this was far more insidious a defect than a simple leak or water stain on a car.

Fatigue Stress

Shear connections are primarily designed to withstand loads from seismic events and from passing vehicles. As seismic shear forces are far greater than those created by vehicles, the latter were rarely considered, if at all. Regrettably, this oversight has proven consequential, as the repeated cycling of stress in the welds from garage traffic leads to eventual fatigue failure of the connections. This inherent design flaw is common to all previous and modern connections.

Fractured flange connection caused by cyclical fatigue stress.

The first connections to fail are located at the center of the deck, where traffic is concentrated. These failures quickly spread along the joint through stress redistribution, until the entire joint is severed and the deck diaphragm destroyed. Such failures are readily identified by movement of the joint as vehicles pass over it. This movement quickly causes the overlying sealant joint to fail, creating a large leak along the length of the joint. Because such deterioration is commonly observed in precast garages, it is often shrugged off as little more than a nuisance. However, it is important to remember that these are seismic connections necessary for the stability of the garage. Loss of connections along a joint is a serious structural defect and a life safety issue.

For more on this topic, see ***https://on.hoffarch.com/double-tee-connections*** *and* ***https://on.hoffarch.com/fatigue-failure****.* ■

Dissimilar Metals

Early connections often consisted of stainless-steel plates welded to regular carbon steel rebar. These two materials are incompatible in a corrosive environment, which causes the carbon steel rebar to corrode at an accelerated rate due to galvanic action. This corrosion can weaken and eventually sever the rebar, or it can travel along the bar and cause an *edge spall* (concrete fracture that breaks away from the surface) exposing the connection to further degradation.

Fractures and spalls at these connections are among the most common defects requiring repair at garages of this type of construction. Unfortunately, such repairs can be both costly and short-lived. The repair requires concrete patches that are constantly stressed by flexing and movement of the embedded connection, causing them to prematurely fail.

Slug vs. Bar

Early connections almost universally employed dowel-type slugs to join the embedded plates, which required a *flare bevel groove weld* between the flat surface of the plate and the round surface of the dowel. At the time, there was widespread misunderstanding as to how these welds should be designed, and it is rare to find older construction drawings where they are depicted correctly. Typically, the desired weld size was called out on the drawings, and the dowel diameter was

Deteriorating connection repair.

Connection fracture from high slug position.

Fractured rebar at flange connection.

Edge spall.

Failed connection due to fatigue stress.

increased or decreased at the time of construction to fit the joint width.

Unfortunately, such specifications evince a fundamental misunderstanding of appropriate weld design; by code, the weld must fill the curved crevice completely, so weld size was dictated by the diameter of the curved surface. In small joints, where the slug size was small, the resulting thin welds led to weak connections. Conversely, as joint width increased, the welds would become exponentially larger, such that a one-inch joint would require a massive weld and a one-and-a-quarter-inch joint would require a weld large enough to literally cook the adjacent concrete.

Further, there was misunderstanding regarding the strength of such welds, as they were perceived to be superior due to their size. In fact, the opposite was true: these bloated flare bevel groove welds (joining a round bar to a flat plate) were far weaker than a *fillet weld* (joining two flat metal surfaces) of comparable size. They were also particularly sensitive to fatigue failure.

The industry eventually acknowledged these shortcomings and, in the late 1990s, transitioned to use of a flat steel *erection bar,* also commonly referred to as a *jumper plate,* attached with simple fillet welds.

The Modern Connection

Since the early 2000s, the precast industry has embraced and endorsed the *flexible shear connection,* which is now used in virtually all pre-topped double-tee garages. In place of the earlier assembly that joined flat connection plates to embedded rebar, this newer design consists of a bent ribbon of steel formed such that the ends are twisted and bent back into the concrete to provide anchorage. Their flexibility derives from the position of the anchorage, which, located not directly behind the face plate, but rather at its ends, allows the plate to bend slightly and so relieve stress.

In addition to affording flexibility, this connection solves two other issues: corrosion and edge spalls. Formed from stainless steel, the connection has no carbon steel component to undergo galvanic corrosion and cause an edge spall. Furthermore, manufacturers typically supply a removable form with the connection that creates a space around the faceplate, allowing it to expand during welding without cracking the concrete. This accommodation for movement, coupled with recognition within the industry that excessive welding is detrimental, has greatly diminished leaks associated with concrete cracking and spalls.

However, the modern flexible connection has not been a complete solution, as it still retains the same basic architecture that allows fatigue failure of welds. Despite some improvements, repair of weld fatigue fractures remains among the most common structural repairs performed in precast double-tee garages.

Connection Maintenance

The health of a garage is usually apparent, if you know where to look, and catching defects early can save a lot of time, money, and effort down the road. The following are common symptoms and what they may reveal, along with proactive measures that are important for the safety and integrity of the garage.

Sealant Joint Failure

The sealant joint is the simplest and most neglected of the routine maintenance items. Joints can leak for many reasons; however, all can lead to serious conditions if not promptly addressed. Routine inspection and maintenance extends the service life of

Replacing sealant at a garage's top deck.

sealant and is a worthwhile and cost-effective measure.

Noticing the pattern of observed leaks can offer clues as to their cause.

Random Leaks: Leaks can be caused by many factors, some of which are benign and some more serious. Is there a pattern? Random leaks may simply be caused by sealant failure. Check the sealant joint above for adhesive failures or cuts. High heel punctures are also a common problem and concentrate near points of egress and elevators.

Intermittent Leaks: Are the leaks located at connections? This can be caused by a poorly performed sealant joint or by slugs intruding on the sealant, either of which should be noticeable from above. If there are no obvious defects in the sealant, the adjacent concrete may have cracked due to welding of the connection. If the connection is the older style, attached to embedded rebar, then this is a serious issue that will cause the connection to degrade and eventually fail. In any case, such defects should be assiduously repaired and maintained.

Continuous Leaks: A leak that extends along most or all of a joint may indicate poor adhesion of the sealant, which has simply failed. However, this condition may also signal an "unzipped" joint, where all the connections have fractured. Without connections to limit the movement of the joint, the allowable stress on the sealant is quickly overcome, causing it to fail. It is helpful to watch the joint as a car drives over it; if it moves noticeably, it is fractured, a serious structural issue that should be addressed with urgency.

Once the location of leaks has helped identify their cause, the next step is to remedy the underlying issues.

Sealant Replacement: A sealant joint replacement project is an expensive endeavor. Installed correctly, this investment can be expected to last 10 to 15 years. However, this range can be greatly extended through periodic inspection and routine maintenance.

> "The sealant joint is the simplest and most neglected of the routine maintenance items."

More importantly, as leak repairs are performed, more serious defects, such as cracked and spalling concrete along the sealant joint edge, are promptly discovered and mitigated before more expensive repairs are necessary.

It is also important to note that a full-scale sealant replacement project is an opportunity to inspect the condition of the flange connections. Fatigue failures become more prevalent as the garage ages, so this type of in-depth inspection is a valuable measure to protect the public from an unstable garage structure. The inspection is best performed by a professional engineer and/or weld inspector, who can identify undersized, defective, cracked, or broken welds and direct appropriate repairs before deficiencies cause more serious issues.

Soffit Cleaning: An important part of any sealant joint repair and replacement project is cleaning the water stains on the ceiling below the leaking joint. This is not just an aesthetic concern; it is difficult to locate leaking joints on a deck soffit that has never been cleaned. Conversely, leaking joints are easily detectible on a clean soffit just by the tell-tale water stains.

Concrete Spalls

Spalls along the edge of the double-tee flange are typically created by corroding rebar at the older style flange connections. Microcracking around the connection due to the heat of welding allows chloride-laden moisture to penetrate down to the steel reinforcing.

While they may look innocuous, edge spalls point to a serious condition. This latent defect potentially affects all such connections in the garage. By the time one connection has degraded to spall the concrete, many more have already been irreversibly affected. These connections are numbered in the thousands, so early detection is key to mitigating deterioration and extending the service life of the garage.

Leaks at connections due to welding.

A welder repairs a broken connection.

As with spalls at the drive surface of the deck, overhead spalls are typically caused by corroding rebar at older style connections. The difference is that overhead spalls tend to remain undetected until they fall, creating a hidden overhead hazard. Unfortunately, overhead spalls also do not typically occur in isolation; once one is detected, more will soon follow. Vigilance is then warranted to maintain a safe garage.

Moving Joints and Broken Connections

A moving joint indicates that the connections have been severed and there is a complete failure of the diaphragm. Severed connections diminish the general stability of the garage and resistance to seismic forces.

Fracture of individual connections can be obvious, such as when concrete is spalled and rebar is visibly broken. However, other connections can be compromised without any visible signs. Fatigue fractures typically occur at center connections first and spread along the joint to the outer connections. Until enough connections have failed, there is no visible movement when cars pass over the joint, and the sealant is not stretched far enough to fail and leak. The only way to detect such failures is to conduct a *joint movement survey.*

A joint movement survey is easy to perform and should be conducted on all pre-topped double-tee garages annually. This requires two people, one driving a vehicle and the other walking. The person walking alongside the vehicle places their foot on the joint and, as the tire rolls across, feels for movement, which indicates a compromised connection beneath. In this manner, most broken connections can be located long before they spread along the joint. Once a moving joint is detected, the sealant should be opened to verify the broken connections. Any suspected issues need to be brought to the attention of a qualified engineer for assessment.

Repair, Retrofit, and Replacement

Connection repairs are critical to restore the required structural capacity of the assembly. Where the field weld (the weld accessible within the sealant) is cracked or broken, a design professional should determine the cause of the fracture before repairs are undertaken. If it was an abrupt failure from an obvious flaw or incident, it may simply need to be rewelded. However, if the failure was due to fatigue, the entire field slug or erection bar should be removed and a new bar installed.

Failure of embedded connections (located within the concrete) is more problematic. The concrete must first be excavated to fully expose the connection. Next, an appropriate weld repair must be developed for the specific configuration involved. Finally, the concrete must be repaired. This repair area will necessarily be stressed by the embedded connection every time a vehicle passes over it or when the weather changes. While such repairs are necessary and common, they can be short-lived.

In many cases, the repair may require complete reconstruction of the connection. This can be performed by excavating the concrete and installing new rebar and connection plates; however, these modifications are very expensive and also temporary, for the same reasons stated above.

▲ *Clockwise from bottom left:* Soffit discoloration due to leaks, corrosion at an overhead edge spall, spalled concrete ready to fall, failed patch repair at an edge spall, and repair in progress for dissimilar metal corrosion of reinforcing bars.

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representative projects

Precast Double-Tee Garages

Each type of garage construction has its own characteristic challenges, and precast concrete double-tee garages are no exception. For these parking structures, the thousands of linear feet of joints between precast members are the Achilles heel of the assembly, where no end of problems at sealant joints and welded connections cause headaches for garage owners and property managers.

Fortunately, there are solutions. At Hoffmann, we've been diagnosing and treating parking structure distress since the heyday of the freestanding garage in the late 20th century. Our projects specific to double-tee, precast concrete parking structures include:

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Town Center Garage
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Yearly Assessments Since 2009

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Bronx, New York
Assessment and Repairs

Seneca Niagara, Seneca Allegany, and
Seneca Buffalo Creek Resort Casinos
Niagara Falls, Salamanca, & Buffalo, NY
Investigation/Repair of 3 Parking Garages

Eversource Energy
Berlin, Connecticut
Parking Garage Survey and Repairs

St. Francis Hospital & Heart Center
North and Woodland Street Garages
Port Washington, New York
Condition Assessments

Greenwich Hospital
Greenwich, Connecticut
Parking Garage Assessment and Repairs

MacDougall-Walker Correctional Inst.
Suffield, Connecticut
Garage Engineering Analysis & Rehabilitation

Mohegan Sun Casino
Riverview & Indian Summer Garages
Uncasville, Connecticut
Parking Garage Repairs

Westchester Medical Center
Valhalla, New York
Initial Condition Assessment per State of New York Parking Garage Inspection Rule

Aetna Headquarters, Flower St. Garage
Hartford, Connecticut
Condition Assessment and Repairs

UConn Health Center
Farmington, Connecticut
Garage Assessment and Rehabilitation

Amgen, PS1 Parking Garage
West Greenwich, Rhode Island
Assessment and Maintenance Plan

Norwalk Hospital
Norwalk, Connecticut
Parking Garage Investigation and Repairs

One Washingtonian Center
Gaithersburg, Maryland
Parking Garage Assessment and Repairs

St. Francis Hospital, Collins St. Garage
Hartford, Connecticut
Condition Assessment and Repairs

New Haven Correctional Center
New Haven, Connecticut
Parking Garage Condition Assessment

The Hospital of Central Connecticut
New Britain, Connecticut
Garage Assessment and Rehabilitation

State University of New York System Administration, Plaza Parking Garage, Albany, NY, *Comprehensive Parking Deck Rehabilitation and Structural Consultation.*

Foxwoods Resort Casino, Grand Pequot and Great Cedar Garages, Mashantucket, CT, *Condition Assessments and Repairs.*

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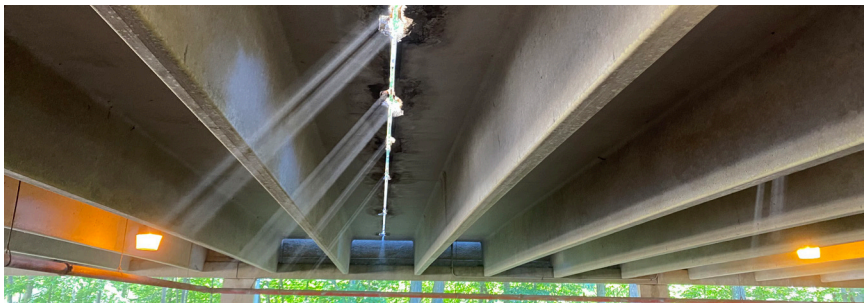

Daylight shines through an open flange-to-flange joint during a connection repair project.

Lastly, the connection can be replaced with a surface-mounted connection from below. However, such a connection must be rigid to transmit required vertical and diaphragm forces, while also flexible to permit expansion and contraction of the deck.

Finding Connection with Precast Garages

Owners and managers feeling out of joint by the many ways precast garages can go awry can take comfort in the decades of experience now guiding rehabilitation strategies. While the best approach is to identify and remediate emerging problems early, even systemic issues can be resolved.

The first step is comprehensive evaluation by a design professional experienced in precast construction, which may include probes at strategic locations to reveal hidden signs of trouble. Edge spalls, leaks, and moving joints are probably pointing to deeper problems that bear uncovering. Knowing the cause and extent of underlying problems allows repair dollars to target critical issues with solutions that address immediate hazards while protecting the long-term integrity of the facility. For owners of busy garages, that's sure to bring even the most disjointed of parking structure relationships back in line. ■

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