# Shrinkage Cracking in Concrete Tilt-Up Construction

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# Abstract

The purpose of this project is to investigate a particular, undesirable cracking pattern in concrete tilt-up panels that, until now, did not have a known definite cause. The cause of this cracking pattern is hypothesized to be due to shrinkage restraint of the concrete panels. The cracking under investigation occurs at the bottom corners of the Tilt-Up panels, suggesting that the base of the panel is restrained from shrinkage. This project models various components of Tilt-Up Construction that have potential for restraining the panels from shrinking. This project consists of the following main components.

The first aspect of this project was to investigate and become familiar with the means and methods of Tilt-Up Construction. To determine the potential shrinkage restraints on the panels, the connections and details associated with Tilt-Up must be thoroughly understood. This involved reviewing typical details of connections as well as contacting engineers and contractors in the field to determine the typical means and methods of Tilt-Up construction and construction sequencing.

Once typical construction practices were understood, the first shrinkage restraint investigated was the friction developed by the panel setting pads. Once the panel is ready to lift, it is set on grout pads or plastic shims, typically located at the ends of the panel. To determine the amount of restraint caused by friction, an experiment was conducted to determine the coefficient of static friction. Tests were run to find the coefficient of friction for concrete against grout, and concrete against plastic shims.

The third aspect of this project was to develop an effective computer model of stresses in Tilt-Up panels induced by shrinkage restraint. The goal of this model was to be able to run various scenarios, to determine the effects of panel concrete mix design, panel geometry, and construction sequencing.

The last aspect of this project was to collect enough data from the computer model to determine whether or not shrinkage restraint induces enough stress in the panel to initiate cracking, determine when the cracking would occur given construction sequencing, as well as determine if the cracking pattern

matches the pattern seen out in the field. Conclusions will have to be made on a case by case basis, but the panel specifications in this analysis were chosen from a Home Depot building in San Luis Obispo, CA, an as-built Tilt-Up project. After running about 70 different cases, it was discovered that the grout pads by themselves did not provide enough shrinkage restraint to initiate cracking in the panel. This led to further investigation of panel connections, specifically the panel to slab connection at the pour strip.

This paper concludes that when combining the shrinkage restraint from grout pad friction and pour strip reinforcement tension, there is potential for cracking in the panel. Even further, the cracking pattern determined from the computer model provides nearly an exact match to the actual cracks under investigation and measured in the field. Although this report provides evidence for potential cracking in Tilt-Up panels due to shrinkage restraint, recommendations for limiting the potential of cracking in panels will need to be made on a case by case basis.

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# 1.0 Introduction

This project is an investigation of shrinkage cracking in tilt-up construction. Means, methods, and sequencing of construction will be discussed in order to create a working model to determine shrinkage restraint stresses. An as-built tilt-up Home Depot in San Luis Obispo, CA contains the cracking pattern under investigation will be used as a case study throughout this project. Many contractors believe that these cracks are due to setting panels too hard, out-of-plane and in-plane flexure, lifting stresses, and other construction-related issues. However, due to the shape and location of the given cracking pattern, this paper seeks to find a correlation between the expected cracking and the shrinkage restraint at the base of the panel.

Concrete shrinkage is dependent on many factors and plays an important role in determining stresses due to shrinkage restraint. Although ACI 209R-92, "Prediction of Creep, Shrinkage and Temperature Effects in Concrete Structures", presents the most commonly used model for shrinkage and is used throughout this project, it is important to understand that determining concrete shrinkage behavior over time is a complex process that is currently not accurately quantifiable. To pinpoint the cracking pattern caused by shrinkage restraint, crack propagation must also be considered. Crack propagation ultimately explains the direction of the crack after the first crack is initiated in a tilt-up panel.

The first shrinkage restraint considered in this paper is friction from the setting pads located at the ends of a panel. Setting pads are traditionally one to two inch thick grout pads; however, plastic shims have been recommended to reduce friction restraint (Lawson and Steinbicker). To determine the amount of friction restraint on the panel, an accurate static coefficient of friction is needed. ACI 318-11 Section 11.6.4.3 provides a value of 0.6 for the static coefficient of friction of concrete on concrete. This value has been understood to be used for construction joints with wet concrete cast against dry concrete; whereas, a

tilt-up panel bearing on a grout pad or shim pack is a precast, dry connection. Part of this project involves an experiment determining an accurate coefficient of friction of precast concrete on a grout pad as well as precast concrete on a plastic shim pack. The coefficient of friction values obtained from this experiment will then be used in a computer model to determine the stresses induced by friction restraint on the panel.

The second shrinkage restraint considered in this paper is located at the panel to slab connection. This connection involves a construction joint called a "pour strip". The pour strip contains rebar reinforcement extending perpendicular from the panel that laps with rebar reinforcement extending from the slab on grade to transfer lateral load. There are also reinforcement bars that are placed longitudinally along the pour strip and parallel to the panel to accommodate for shrinkage and change in temperature in the pour strip. The longitudinal bars are hypothesized to be have potential shrinkage restraint, because they are reinforcing the concrete in the same direction as the pour strip. The pour strip restraint will be analyzed more thoroughly and be demonstrated in the computer model to determine the stresses induced on the panel.

To appropriately model the panel stresses due to shrinkage restraint in this project, a computer model was developed using SAP2000. The computer model uses temperature effects to simulate shrinkage effects. The computer model is useful in determining the stresses in the panel due to various restraints applied to the panel and shrinkage occurred over time. The time at which panel restraints are applied is an approximation based on typical construction sequencing. The computer model is also useful in predicting the location that a crack will initiate and where the crack will propagate, ultimately providing an approximate cracking pattern.

Solutions to reduce or prevent cracking in tilt-up panels will have to be made on a case by case basis. However, the computer model allows for various cases to be tested for recommendations to be made. Results from the computer model allow for pinpointing the approximate day that the panels will crack

given the construction sequencing and panel specifications. Validity for use of additional panel restraints will also be explored.

## 1.1 What is Tilt-Up?

Tilt-up construction is a form of concrete construction that is used mainly for large low-profile buildings given the means by which it is constructed. In tilt-up concrete construction, normally the wall panels are cast on the slab or on a casting slab next to the building which are then cured until the strength of the concrete is high enough for the wall panels to be tilted up by a crane into their final resting position. Contractors are constantly being pushed by owners and developers to shorten their schedules so that the same owners and developers can make more money given that their buildings are able to be rented/used earlier. Additionally, new construction techniques have emerged given new materials in the industry. There is now high early strength cement that allows for concrete to come up to strength much earlier than usual. This early strength cement combined with a 4000 psi mix, can lead to required strength to lift as quickly as 3 days given that 60% of 4000 psi is 2400 psi (Boral).This leads developers to pressure contractors to lift panels earlier so that projects are done quickly and money can be saved.

### Advantages:

A huge advantage to tilt-up construction is the fact that the members work more as precast members and an extremely tall but thin wall can be cast easily. Contractors run into huge issues when cast-in-place walls are tall and thin given that it can be hard to get a concrete hose all the way down the length of the wall. Most inspectors and specifiers do not allow wet concrete to drop more than 5 feet, although neither

ACI 301- 99, “Specifications for Structural Concrete,” nor ACI 318-02, “Building Code Requirements for Structural Concrete,” specify exactly how far the wet concrete can fall. These codes just highlight that concrete should be placed near or at its final location to avoid air voids that may be created throughout tight configurations of rebar (ACI 318-02). This creates issues for contractors to pour walls in a timely manner. Many warehouse buildings and distribution centers can be large, million square foot buildings with tall floor-to-roof heights so that large equipment or high rack storage can be accommodated. The tilt-up method reduces cost significantly given that the amount of formwork and safety equipment dramatically decreases because workers do not have to work high above the ground but rather are forming merely inches above the ground floor. These panels can also easily be cast to different shapes and sizes, which would be much more expensive if they were to be cast-in-place.

### Disadvantages:

The disadvantages for this type of construction include limitations for lifting concrete panels over 4 stories tall, not able to curve panels due to flat casting surfaces, and damaging slabs due to crane loads and formwork anchorage. In some cases, if the building slab space is limited, there may not be enough room to pour and lift the panels, requiring a temporary casting slab off-site.

Based on the type of building, tilt-up can offer many advantages to be the most effective choice for contractors. While the demand for rectangular warehouse buildings remains steady, tilt-up construction will remain the most effective method. This is why structural investigation of cracking in these panels is of high priority and value to the industry.

## 1.2 Cracking Pattern Under Investigation

There are two main types of cracking that occur in concrete: plastic shrinkage cracking and drying shrinkage cracking. The cracking being referred to in this investigation is drying shrinkage cracks. This cracking initiates at the bottom corners of the panel and travels diagonally towards the edge of the panel.

(See Figure 1.0 and 1.1). The types of cracking under investigation are illustrated at a local Home Depot in San Luis Obispo in Figure 1.0.

Figure 1.0 - Severe Cracking at Home Depot with subsequent patches

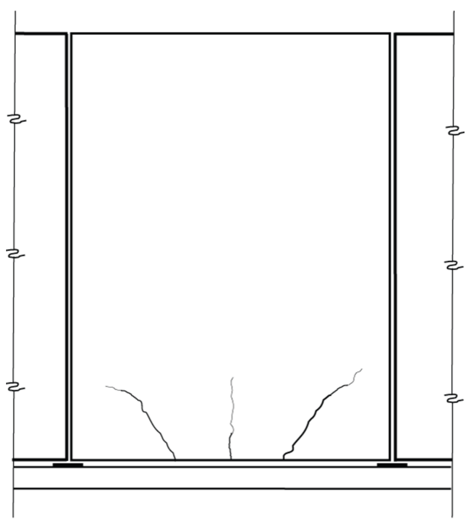


Figure 1.1 - Cracking Pattern hypothesized to be from shrinkage (Lawson)

There are also cracks that can occur in tilt-up construction, such as those that are formed when the panels are lifted. This cracking pattern is not being investigated in this research.

# 2.0 Hypothesis: Shrinkage Restraint

Although the cracking pattern under investigation in this paper does not have a know definite cause, there are a handful of indicators that provide enough evidence to hypothesize that they are due to shrinkage restraint. There are many contractors and engineers that believe these cracks are due to setting panels too hard, out-of-plane and in-plane flexure, lifting stresses, and other construction-related issues. The first thing to notice is the cracking pattern. The cracking pattern indicates the location, amplitude, and direction of the stresses that induced cracking. This cracking pattern indicates that the highest stresses in the panel are located at the base, and are tension stresses because concrete only cracks under tensile stress. Perhaps the biggest indicator at first glance is to notice that these cracks occur on both sides of the panel, as can be seen in Figure 2.0. Any out-of-plane flexure or lifting cracks would only occur on one side of the panel.


Figure 2.0 - Interior Panel Cracking at Home Depot, San Luis Obispo

At first glance, concrete cracking can look non-problematic and non-structural to some, but even small cracks can be weathered away with agents such as dirt and water and lead to problems with water exposure to rebar. At the very least these cracks can be serviceability issues where owners will complain about the appearance of the panel and have to pay to get them filled and painted over.

Before analysis and investigation can begin on shrinkage cracking, it is critical to understand the behavior in which concrete shrinks over time, the stresses necessary to initiate cracking, and the direction and degree to which a crack will travel once it is initiated.

## 2.1 Concrete Shrinkage

The American Concrete Institute explains that, “shrinkage, after hardening of concrete, is the decrease of concrete volume with respect to time. The volume decrease is due to changes in the moisture content of the concrete and physico-chemical changes, which occur without stress attributable to actions external to the concrete.” (ACI 209R-92; 3). How quickly this shrinkage occurs has some speculation around it but the article, “The Construction of Tilt-Up” would say that, “20% of the ultimate shrinkage takes place in the first three days. Rough estimates of the shrinkage process are as follows: 65% at the end of 30 days; 80% at the end of three months; and 90% after one year” (Ward 68). The total ultimate shrinkage of a concrete mix can change dramatically due to what goes into the mix and the environmental conditions that the mix experiences when it is curing. The following list explains these certain conditions and what happens to the ultimate shrinkage as these factors increase or decrease (ACI 209R-92):

1. As <u>Ambient Humidity Increases</u>, Shrinkage Decreases
2. As <u>Volume to Surface Area Ratio Increases</u>, Shrinkage Decreases
3. As <u>Slump</u> Decreases, Shrinkage Decreases,
4. As <u>Fine Aggregate Percent of Total Aggregates Decrease</u>, Shrinkage Decrease
5. As <u>Cement Content</u> Decreases, Shrinkage Decrease
6. As <u>Air Content</u> Decreases, Shrinkage Decreases
7. As <u>Time</u> Increases, Shrinkage Increases

## 2.2 Crack Initiation

Cracks are caused when the stresses in the concrete exceed the modulus of rupture of concrete. Although there is rebar in the panel, that rebar is not activated in tension until the concrete itself has cracked, therefore the rebar is not accounted for in the the modulus of rupture. The modulus of rupture for concrete in the ACI is taken as ($7.5 \times \sqrt{f'c}$) (ACI 318-14 Chapter 19.2.3.1) but is taken as ($7.5 \times 2/3 \times \sqrt{f'c}$) or ($5 \times \sqrt{f'c}$) to achieve the modulus of rupture witnessed during full scale panel tests done by SEAOSC (ACI 318-14R 11.8.4.1). The drop in the modulus of rupture is due to the internal restraining effect caused by the reinforcing steel. The shrinkage is restrained by the steel causing the steel to go into compression and the concrete to go into tension; thus the concrete has a predisposition to crack sooner (Lawson). Given that we will be using slender wall elements, ($5 \times \sqrt{f'c}$) will be used.

## 2.3 Crack Propagation

Once a crack initiates in a panel, it is important to understand how it travels so that an accurate cracking pattern prediction can be made. Crack propagation will ultimately explain the direction the crack travels after cracking is first initiated. This type of material behavior has it's own field of study called Fracture Mechanics and Crack Propagation. Crack propagation is when once a crack forms in a material, it takes far less stress in that material for that crack to continue to propagate through the material, due to the tip of the crack having a force in itself. This crack will eventually stop traveling if it enters into a zone where the stresses move from tension to compression in the direction causing the crack, or if the tension stress causing the crack lessens to a degree as to discontinue to crack in the material. This is important because as is discussed later, many cracks in the panel first occur along the bottom length of the panel and as they move throughout the panel, the cracks can continue to propagate even though the stresses do not appear to

be able to be high enough to initiate a crack. Furthermore, cracks can and will form in locations that do not necessarily appear to have the highest tension stress. This is because in the computer model there are no imperfections in the panel; yet in reality where there are small notches in the panel, stresses will flow more concentratedly around the location where the notch is, giving that location an even higher stress than experienced at other locations.

# 3.0 Potential Shrinkage Restraints

"If the shrinkage of concrete could take place without restraint, the concrete would not crack," (ACI 224.1R-07). More allowance for the concrete to shrink before providing rigid restraints, results in less drying cracking that will occur.

In most other aspects of tilt-up construction, limits have been placed on panel restraints particularly during early phases of construction when the panel is shrinking at a faster rate. These limits can be seen by "some engineers specify[ing] a delay in welding the panels together across the joint until roof erection is well underway to allow a larger percentage of the ultimate horizontal shrinkage to occur" (Lawson and Steinbicker). Slotted bolt connections have also been implemented to prevent shrinkage restraint at the panel to roof diaphragm connection.

There have also been limits set to stop cracking from occurring during other stages of construction such as lifting. "Ideally, the tilt-up panels can be erected without developing any cracks during the lifting process" (Lawson and Steinbicker). The panels are designed to handle stresses from lifting with consideration of adequate concrete strength, specified by the engineer.

The cracking pattern addressed in this paper is located at the base of the panel, suggesting that the base of the panel is being restrained from shrinkage. Shrinkage restraint due to friction at the setting pads,

reinforcement at the pour strip, and welded or bolted connections at the panel to foundation connection are the main areas of focus and will be further explored.

# 3.1 Restraint 1: Setting Pad Friction

If properly constructed then cracks should not be forming during these early phases of construction. No industry or code limits have been set yet on how the panels are set vertically, whether that be on shim packs or grout pads. It is hypothesized that bearing directly on the bearing pad restrains the panel and “the resulting tensile forces can combine with the vertical shear force to result in a cracking pattern of several radiating cracks in the lower quarter of the panels height” (Lawson and Steinbicker).

Although, there is a slurry that is placed beneath the panels which would seem to reduce the bearing of the wall panel directly on the setting pad, the high water content of the slurry mix between the panel and foundation will actually cause the slurry to shrink away from the panel. Once it shrinks away it may leave air pockets below the panel given that it wants to shrink downward due to gravitational self-weight and therefore no direct bearing on the continuous foundation is able to take place.

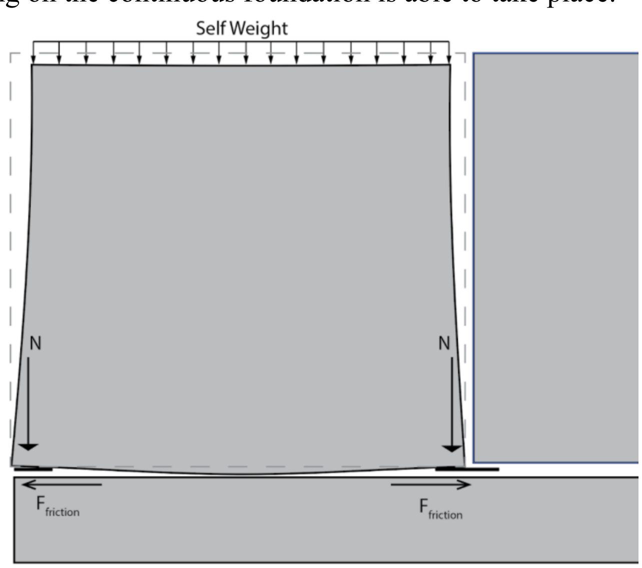



Figure 3.0 - FBD of Friction Panel Restraint

# 3.2 Friction Experiment

## MEASUREMENT OF THE STATIC COEFFICIENT OF FRICTION OF CONCRETE ON GROUT AND CONCRETE ON PLASTIC SHIMS

### 3.2.1 Introduction:

The purpose of this experiment was to empirically determine the static coefficient of friction of a concrete surface against a grout surface. Determining an accurate coefficient of friction is fundamental in an analysis of tilt-up cracking due to shrinkage restraint. In a tilt-up panel, this shrinkage restraint is believed to be the ends of the panel bearing on the grout setting pads. These setting pads are traditionally about 12" x 24" x 1.5" thick ready mix grout, or 4" x 6" x ¼" stacked high density plastic shims. The potential restraint is a friction force between these two surfaces, that is computed as the product of the normal (perpendicular) load on the setting pad (wall weight) and the coefficient of friction. Stresses induced by concrete panel shrinkage depend heavily on the degree to which the base of the wall is restrained. For example, if the coefficient of static friction is determined to be zero, then the base of the wall is not restrained and there will be no cracks or stresses induced from shrinkage. Alternatively, if the coefficient of friction is 1.0 or greater, there will be large stresses induced in the concrete panel before slippage can occur. The friction force equation is as follows:

$$F_{friction} = \mu_{static} \times N \qquad \text{(EQ-1)}$$

Currently, American Concrete Institute (ACI) estimates that the coefficient of static friction is 0.6 for wet concrete cast against dry concrete (ACI 318-11, Section 11.6.4.3), which may not be applicable due to setting pad restraint being dry concrete against dry grout. This value was used in setting up the experiment to appropriately anticipate the amount of weight and load that needs to be applied.

Although, there are many ways to determine the coefficient of friction experimentally, the test method used in this experiment is a load cell pull system. The load cell is attached to the material being pulled (concrete) as it rests on the grout pad. Once the pull begins, the load cell will determine the amount of tension force that is acting on the system. The load will continue to increase until it exceeds the friction force between the two surfaces and the material begins to slip. The force displayed on the load cell at the moment the system slips will be used to determine the coefficient of static friction. Please see Figure 3.1 below.

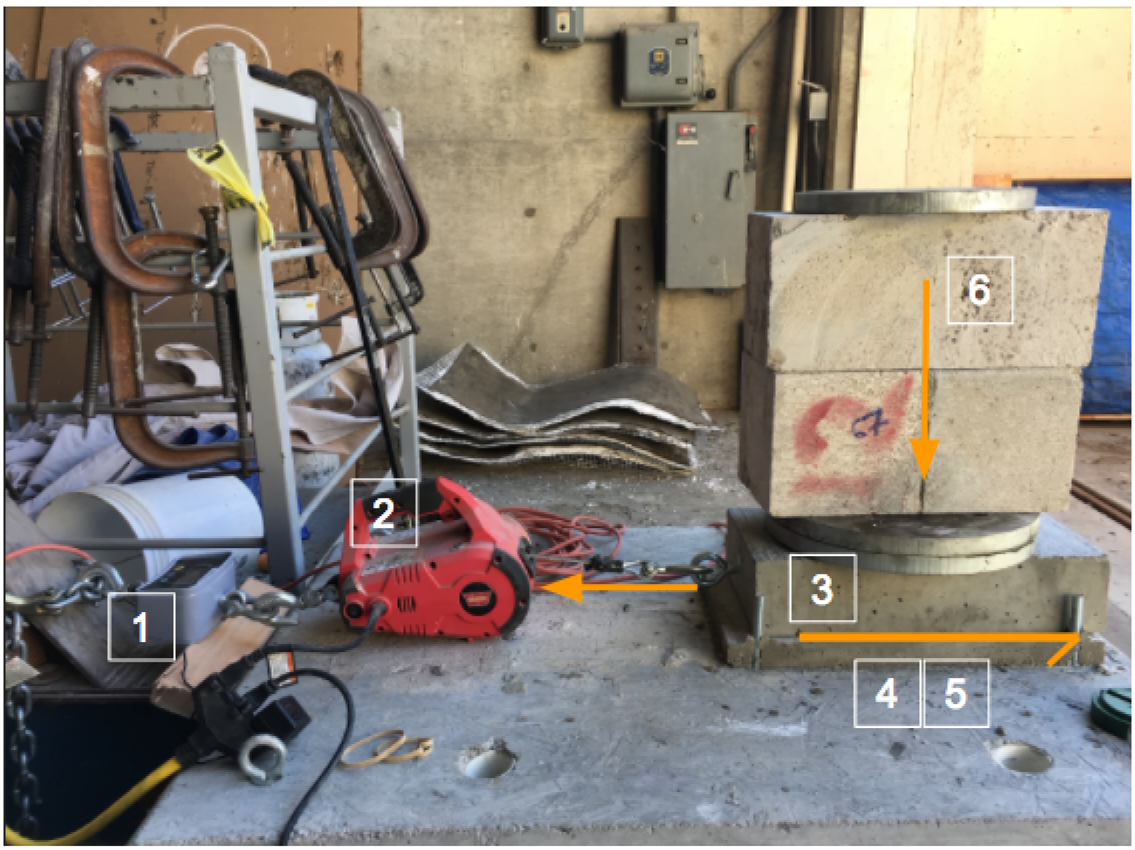



Figure 3.1: Friction Experiment Components 1. Load Cell 2. PullzAll 3. Precast concrete testing block 4. Grout Pad 5. Shim Pack 6. Additional Weight

In order to obtain accurate results, there many are other factors that need to be taken into consideration throughout the experiment. It is known that the coefficient of friction is largely determined on the type of

material and the surface roughness of the material. Unfortunately, concrete consists of many material types, various mix designs, and a variety of finishes based on the type of formwork used. Potentially, there could be many different friction coefficient values based on the application at hand. For this application, it was found that the typical field practice is multi-use MDO ply-form or sawn lumber formwork. Because these two types of formwork could give a different finished surface on a panel, both were tested in this experiment. For the grout specifications, non-shrink grout is often called out by the engineer for use under the panel and for the setting pads; however, it was determined that this specification is typically modified during construction because non-shrink grout typically takes longer to prepare, and the grout needs to be poured immediately so that the panel can fully bear on the continuous footing. The structural engineer of record does not design the continuous footing to take the panel weight as two point loads, therefore the contractor must make sure the panel is fully bearing on the continuous footing as quickly as possible (Lawson). Therefore, ready-mix grout is most commonly used and will be used for this experiment. The grout mix design used for this experiment was obtained for a typical tilt-up concrete project by Robertson's Ready Mix Concrete (Appendix B), a concrete supplier in Southern California. For the panel concrete mix design, a typical mix design was used and obtained by the Cal Poly ARCE Department (Appendix B). Although panel mix designs widely vary, they consist of the same materials, having negligible effect on the material surface. Admixtures are assumed to have no effect on the surface material properties of the concrete and thus not incorporated into the mix design used.

### 3.2.2 Procedure:

The main components of this experiment include an electronic load cell, *Warn PullzAll* pull machine, grout setting pad specimen, two concrete block specimens, and additional weights.

For the fabrication of the grout setting pad, the procedure was carefully taken into consideration to match field practices as close as possible. Given tilt-up contractors have various means and methods of

construction, this experiment was guided by the Construction of Tilt-Up and local practices (Ward; Baty). The grout pad was 20” long x 10” wide x 1.5” tall, and it’s main components were (4) 7” threaded dowels, 1” concrete nails, and 2” formwork (Figure 3.2). The threaded rods are used to guide the wall into place, and in this test were used to guide the block along the grout pad and give the formwork support. After the foundation was marked for the size and location of the grout pad, the holes for the threaded rods were drilled 3” deep with a 1” rotary hammer drill, cleaned out with an air compressor, and filled with Simpson Set-XP Epoxy and 7” threaded dowels. After the dowels were set, about (16) 1” concrete nails were hammered into the foundation acting as shear studs to prevent the grout pad from sliding during testing. The formwork used was ½” sanded birch plywood, 2” tall, and held together by nails and hot-melt adhesive.

Figure 3.2 - Grout Pad and Concrete Test Block Formwork

Once the grout pad formwork and preparation was finished, the grout was ready to be poured. The grout was batched and mixed manually in a wheel-barrow. Before the grout pad was poured, a slump test was performed in accordance with ASTM C143 procedures. The grout pad was then poured to a height of 1.5” and leveled with a trowel. The grout pad was given 9 days to cure before the system was tested. This cure time is more than adequate, because the strength of the grout pad will not have an effect on the results of the experiment, only the surface texture. Once the formwork was taken off, the edges of the pad were grinded down to ensure the grout pad was flat, level, and could be in complete bearing contact with the concrete. Before conducting any tests, all testing materials were cleaned off with an air compressor.

The second testing surface used was high-density plastic shims. These shims are common in much of the US, but are not traditional setting pad materials in much of California. Shims have been recommended

due to their convenience and low friction values. These shims will also be tested by placing them directly on top of the grout pad, under the concrete testing block. The high-density plastic shims used in this experiment varied in thickness and were stacked 4” x 6” *Super Shims*, manufactured by MeadowBurke, for the purpose of bearing setting pads below tilt-up panels. These shims typically come in various thicknesses so that the desired shim height can be desire by stacking shims. Figure 3.3 below shows the shim orientation and method of testing used in this experiment.

Figure 3.3 - Plastic Shim Pack Orientation and Setup

The specifications of the concrete blocks were influenced by matching field practices as close as possible as well as ensuring there was adequate surface area to bear on the grout pad for accurate testing results. Two concrete testing blocks were made at 18” long x 4” tall x 8” wide. Testing block 1 was formed with ½” sanded birch plywood and testing block 2 was formed with Douglas Fir-Larch #1 sawn lumber on the contact testing surface. The release agent used for the testing block formwork was Boiled Linseed Oil. A releasing agent was needed because typical tilt-up formwork is MDO or HDO plyform, which has a releasing agent coating on it to provide a smooth concrete finish. Boiled Linseed oil was chosen because it was the only releasing agent available in the area. Once the testing blocks were given 7 days to cure, the formwork was removed and holes were drilled to anchor the threaded eye bolt anchors with Simpson Set XP epoxy. These bolts were used to attach to the *Warn PullzAll* machine to pull the testing blocks along the grout pad. The anchors were given 24 hours to set before testing (Figure 3.4).

Figure 3.4 - Concrete Testing Blocks and Anchors

The weights used in the experiment consisted of fully grouted CMU blocks and steel plates. Each weight was weighed out individually with a digital scale, and stacked on top on the concrete testing block to achieve the desired force on the system.

Once all of the components of the system were prepared, the apparatus was set up and ready to test. The load cell was attached to an immovable steel frame with a steel chain. The pull machine was then attached to the load cell on one end, and the concrete testing block on the other. Ensuring the testing block was only pulled horizontally was taken into careful consideration (Figure 3.1). Testing was broken up into 4 parts, with each test pulling 300 lbs, 400 lbs, and 500 lbs respectively:

1. Concrete Testing Block 1 on Grout Pad
2. Concrete Testing Block 1 on Plastic Shim Packs
3. Concrete Testing Block 2 on Grout Pad
4. Concrete Testing Block 2 on Plastic Shim Packs

The load given by the digital load cell at first occurrence of slip was recorded for each test. The material surfaces were cleaned with an air compressor before each test to ensure no rolling friction was caused by debris and to reset the apparatus. Once results were collected, the static coefficient of friction can be

computed by simply dividing the recorded pull force at slip, by the amount of normal force (weight) applied on the system (EQ.1).

All other parameters, such as temperature, concrete/grout strength, and load duration were assumed to be negligible throughout this experiment. The method of recording pull force at initial slip, with the electronic load cell, has its limitations. The method of recording used was visually reading the gauge the moment the testing block slipped. The reason this method has limitations is due to the inability to properly record the "stick-slip" phenomena that occurs when pulling an object at rest. This friction response can be shown below.

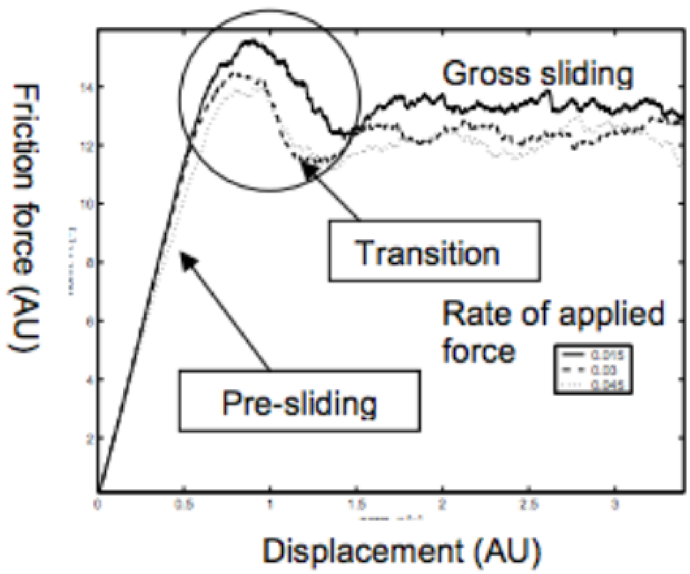



Figure 3.5 -Friction Force vs. Displacement with varying rates of applied force (Al-Bender).

The pull system used in the experiment could only pull at a fixed rate of speed, which was too fast for this application. Because the pull system rate of applied force was too fast, this caused difficulty in recording the maximum load at initial slip. An ideal load measuring system would be to use a computer program to measure the load applied over time at a much slower rate, to obtain the maximum load reached at peak (Figure 3.5). However, this method of measurement was not able to accurately obtain the maximum load. Therefore, it could be argued that the coefficient of static friction is greater than recorded. Another

limitation of this test method, was the amount of weight available to apply on the system. In an actual tilt-up panel to grout pad in the field, there would be approximately 30,000 lbs. applied to one grout pad; whereas, in the experiment only 500 lbs. were able to be applied to the system.

### 3.2.3 Results:

The table below displays the results from testing. The coefficient of static friction was calculated by dividing the tension force by the normal force:

$$F_{friction} = \mu_{static} \times N \quad , \qquad \mu_{static} = N / F_{friction}$$

Note that the Friction Force is the Tension Force recorded at initial slip.

| | Setting Pad | Normal Force (#) | Tension Force (#) | Coeff. of Friction | Average |
|---|---|---|---|---|---|
| TEST BLOCK #1 (1/2" sanded birch plywood formwork) | Grout Pad | 300 | 83 | 0.277 | 0.279 |
| | | 400 | 109.7 | 0.274 | |
| | | 500 | 143.2 | 0.286 | |
| | Plastic Shims | 300 | 21.3 | 0.071 | 0.074 |
| | | 400 | 30.9 | 0.077 | |
| | | 500 | 36.3 | 0.073 | |
| TEST BLOCK #2 (DF-L #1 sawn lumber formwork) | Grout Pad | 300 | 79.8 | 0.266 | 0.282 |
| | | 400 | 119.1 | 0.298 | |
| | | 500 | 141.2 | 0.282 | |
| | Plastic Shims | 300 | 29.1 | 0.097 | 0.093 |
| | | 400 | 35.9 | 0.090 | |
| | | 500 | 46.4 | 0.093 | |

The results from the experiment appear to not have any sort of pattern or means for interpolation. The coefficient of friction does not increase as the applied normal force increases. Therefore, it is not reasonable to assume a larger coefficient of friction at an actual normal force of 30,000 lbs.

Final coefficient of friction values for friction restraint at setting pad will be determined as the average taken by each setting pad condition:

| Setting Pad | Testing Specimen | Coeff. of Friction | Final Coeff. of Friction |
| --- | --- | --- | --- |
| Grout Pad | Block #1 | 0.279 | **0.281** |
| | Block #2 | 0.282 | |
| Plastic Shims | Block #1 | 0.074 | **0.083** |
| | Block #2 | 0.093 | |

### 3.2.4 Discussions/Conclusions:

Conclusions are generally straightforward with this experiment. Given information on field practices and testing capabilities, it can be concluded that the coefficient of static friction of dry grout against precast concrete is approximately 0.28. For a tilt-up application, this value seems to be accurate, based on the repetition of the experiment and hypothesis. However; due to the scale of the experiment, it could be argued that the coefficient of friction is higher than determined. Actual friction is somewhat nonlinear, and will vary based on the material type, surface roughness, and normal force applied. As explained in the procedure, the scale of the experiment is less than 2% of the actual application. With such a high load, friction is more likely to behave non-linearly and not be as predictable. In an attempt to be able to linearly interpolate the coefficient of friction at a higher load by varying the weight applied to the system, we found that we do not have significant evidence to interpolate. However, nonlinear friction analysis is out

of the scope of this experiment and will only be mentioned as something to take under consideration in future research.

An important thing to note in regards to the plastic shim testing is the orientation of the shims. The plastic shims have grooves that run longitudinally along the top and bottom of each shim. When the plastic shims are oriented in this manner and begin to slip, they slip between themselves and not between the concrete or grout. This is why the coefficient of friction in this experiment has been determined to be so low. However, in the field, these shim packs are not always oriented in this manner and are sometimes even wrapped in duct tape. This method of placing the shims can cause for a potential increase in the coefficient of static friction and if possible, should be avoided.

This determined coefficient of static friction (0.28) will be used in determining the base restraint in the shrinkage computer model. Please refer to the shrinkage model results and discussion for the effect of friction restraint on the concrete panels.

# 3.3 Restraint 2: Pour Strip

The second potential shrinkage restraint is located at the panel to slab connection. This connection involves a construction joint called a “pour strip”. The pour strip contains rebar reinforcement extending perpendicular from the panel that laps with rebar reinforcement extending from the slab on grade to transfer lateral load. There are also reinforcement bars that are placed longitudinally along the pour strip and parallel to the panel to accommodate for shrinkage and change in temperature in the pour strip. After the panel is placed on the setting pads, a grout slurry is placed in the space between the panel and foundation to infill the area between the setting pads. This slurry attempts to achieve fulling bearing of the panel on the continuous footing foundation. After that the pour strip is placed, which functions to connect rebar in the panel with rebar in the pour strip and rebar in the slab. It is important to note that the slab is

also shrinking as the walls are shrinking at approximately the same rate because in most cases designers will use the same mix for the tilt-up panels as they will use for the slab itself. This means that the rates of shrinkage for the walls as well as the panels are the same. The rebar tying from the slab to the panel is not resisting the panel but rather just along for the "shrinkage ride" and provides negligible shear friction. However, the rebar in the pour strip parallel to the panel will resist this shrinkage and because this rebar is tied to the panel, the rebar in the pour strip will impose a force upon the panel as it displaces. The amount of rebar in the pour strip that is engaged due to the proximity of the panel has not been investigated but can be determined that at least one bar would be engaged. See Figure 3.6 and 3.7 below:

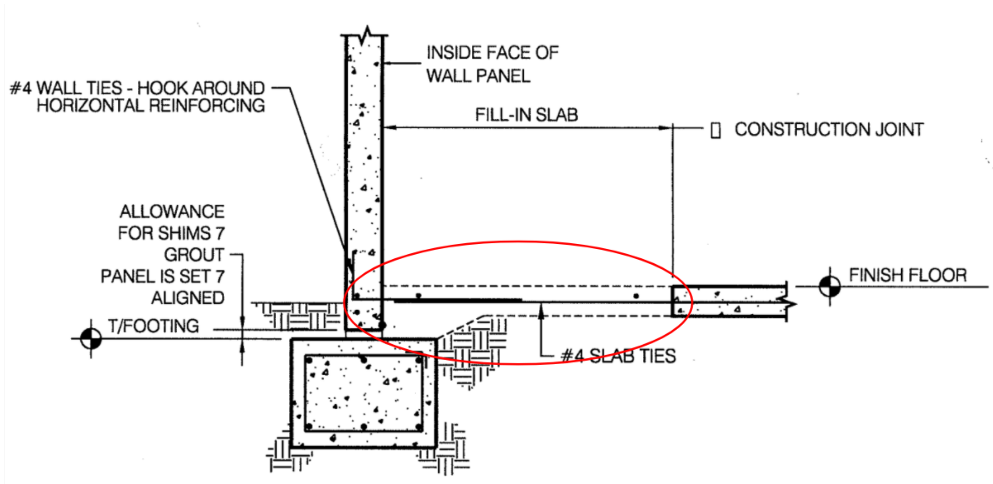



Figure 3.6 - Typical Panel to Slab Connection Detail (Ward)

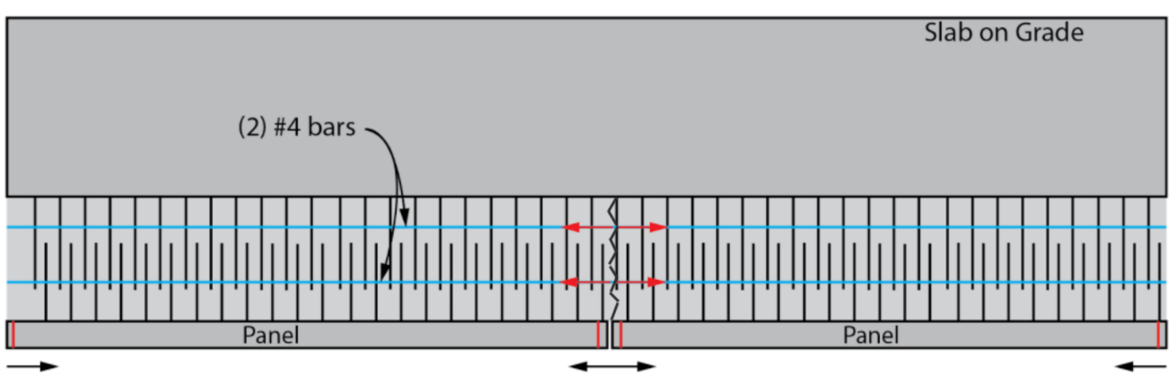



Figure 3.7 - FBD of Pour Strip Shrinkage Restraint

# 4.0 The Computer Model

## 4.1 Introduction:

The computer model in this project was designed to predict if a crack would form in a panel given various restraint conditions, panel mix designs, panel geometry, and construction sequencing. If a crack was predicted to initiate, the model would show where the first crack was likely to appear as well as where it was likely to travel through the panel. A computer model was used for analysis because stress outputs can be easily shown graphically and accurately, which cannot be efficiently or effectively computed by hand. After experimenting with various programs such as ETABS, RISA-2D, and SAP2000, it was decided that the problem being investigated would most effectively be computed by SAP2000. Programs like ETABS can perform this analysis, but ETABS is better at modeling whole systems. For example, ETABS makes lots of simplifications to individual members in order to give appropriate results for scenarios like a pushover analysis for large structures. On the other hand, SAP2000 does not make these sorts of simplifications and is therefore a much better program for a model of this scale.

Given how similar shrinkage and temperature change effects are, there was no reason to look for software that can model concrete shrinkage on the computer. Shrinkage is uniform throughout the member and will naturally shrink towards the center of mass or where it is restrained. This behavior is practically identical to the behavior that uniform materials experience when temperature induces expansion or contraction of that material. Given that the concrete is all made from one mix design, the assumption is that the concrete in the field is a uniform material, thus the temperature model can be used. The effects of the reinforcing steel have been neglected for these simulations.

There are various models that can be used to model shrinkage. Given the scope and scale of this project, we were unable to delve deeper into more accurate models of shrinkage that can be used for this

application. For design and practical purposes, ACI 209R-92 is the industry standard for modeling shrinkage. A spreadsheet was made to assist in this research which when prompted with the inputs of a particular concrete mix would produce the same values as ACI 209R-92. This spreadsheet model was appropriate since this project involves a panel and not a “special structure” (ACI 209R-92, 2). Furthermore, shrinkage values over time are most accurate when they come from shrinkage experiments in the geographic region where the construction will take place, under the same conditions that the construction will be and not from generic models of shrinkage. “No prediction method can yield better results than testing actual materials under environmental and loading conditions similar to those expected in the field.” (ACI 209R-92, 4).

There are some advantages to this model given that it is “simple to use with minimal background knowledge” (ACI 209.2R-08, 8), but it is “Empirically based, thus does not model shrinkage or creep phenomena” (ACI 209.2R-08, 8). One of the biggest concerns is that,“This model overestimates measured shrinkage at low shrinkage values (equivalent to short drying times) and underestimates at high shrinkage values (typical of long drying times)” (ACI 209.2R-08, 9). The last portion of this commentary is not good for our model given that we are generally looking at long period drying time values and not at short drying time values since any cracks that occur can weather over time and be problems for owners. As noted later in this report, shrinkage seems to occur in this project’s panel model in a very linear progression all the way up to the ultimate value, whereas The Construction of Tilt-Up says that “20% of the ultimate shrinkage takes place in the first three days. Rough estimates of the shrinkage process are as follows: 65% at the end of 30 days; 80% at the end of three months; and 90% after one year” (Ward 68). For the computer model it is also important to note that either an average thickness or volume-surface ratio can be used as an adjustment factor. The volume-surface ratio was chosen given the irregularity in shape and large surface area of our model compared to most individual concrete members.

For those who wish to expand on this project, there are other models worth exploring. For example for "shrinkage strain prediction, Bazant-Bawaje B3 and GL2000 provide the best results." (ACI 209.2R-08, 11) One thing to note would be the fact that, "both Bazant-Bawaje B3 Shrinkage and creep models may require input data that are not generally available at time of design such as the specific concrete proportions and concrete mean compressive strength" (ACI 209.2R-08, 9). As one can see, there are some challenges given that the ACI 209 R section requires information about the mix that may not be readily available until after design.

A finite element mesh was introduced into the model in order to try to give a more realistic approach to how the wall would behave on its own, as well as give good coordinates on the model in order to investigate cracks at certain locations in height and width. If a too highly refined mesh is placed into the model then the duration for which it takes the model to run can be incredibly high. In fact, one could argue that it produces diminishing returns in terms of the time invested compared to more accurate stress results. The mesh used on all models for the following trials was 40 x 40. This number was selected because it gives a good mesh, being more than a single square per square foot, but also allows for the easy identification of locations along the wall and does not take an excessive amount of time to run through multiple model set ups. Typical run times were under 15 seconds.

No rebar was added to the model since the rebar in the panel will not activate in a concrete member until it cracks. Since the primary concern of the experiment was the first crack to initiate in the panel, it would not be necessary to add in rebar to the model.

The shrinkage experienced by the panel in the model was calculated by using a fix connection at the bottom left corner of the panel and a pin connection at the bottom right corner. Using a pin-pin connection made the model unstable and yielded poor results. Then a specific change in temperature would be applied and the displacement of the top right corner would be recorded. Self weight was turned off during

these trials because the resistance on the model due to gravity was not desired given that it would skew what the actual shrinkage of that panel would have been had it not been restrained. Then when the desired shrinkage values were seen, the model was then fixed at both bottom corners, self weight was turned on and then the internal stresses at key locations were recorded. The restraint forces given at the bottom corners were also checked to make sure that they did not exceed what the restraint condition being investigated was able to handle.

The modulus of rupture was taken as $(5 \times \sqrt{f'c})$ as explained in the cracking initiation Section 2.2.

## 4.2 Procedure:

There are many variables that could possibly explain why tilt-up panels, such as the panels located at the Home Depot in San Luis Obispo, CA, crack in the pattern being investigated. The computer model was used to control certain variables while changing others in order to try and make some conclusions with regards to the behavior that can be seen by the model. The main variables that we were trying to asses in terms of their impact on tilt-up structures were:

1. Case 1: Base Restraint of Grout Pads or Shim Packs
2. Case 2: Base Restraint of Grout Pads or Shim Packs with adjacent parallel Rebar in slab
3. Case 3: Base Restraint due to Panel-to-Foundation Connections
4. Panel Concrete Mix Design (Shrinkage Potential)
5. Panel Geometry
6. Construction Sequencing

Given these variables to consider, the primary setup for Case 1 was two different panel configurations, three different shrinkage potentials, four different durations before lift erection, and four different coefficients of friction. More specifically:

1. No Shrinkage, 32.5’ wide x 26 tall Panel 6.5” Thick (Appendix A Pg. 49)

2. No Shrinkage, 24’ wide x 26’ tall Panel 6.5” Thick (Appendix A Pg. 49)
3. Mix with High Shrinkage, 32.5’ wide x 26’ tall Panel 6.5” Thick (Appendix A Pg. 52)
4. Mix with High Shrinkage, 24’ wide x 26’ tall Panel 6.5” Thick (Appendix A Pg. 50)
5. Mix with Standard Shrinkage, 32.5’ wide x 26’ tall Panel 6.5” Thick (Appendix A Pg. 54)

All of these panels were tested with different lift dates (3, 7, 14, and 28 day lifts) and different coefficients of friction between the panel and grout pad (0.8 PCI Estimate given minimum and maximum values (Seeber Table 4.3.6.1), 0.6 ACI (ACI 318-11 Section 11.6.4.3), 0.28 experimentally) or shim pack (~0.11 experimentally).

## 4.3 Results:

After running the computer model, the first thing to note from the stress output that occurs directly due to the gravity load only on the panel is that it is very minimal relative to the stresses that will occur once shrinkage is present in the model. It should also be noted that at the bottom of the panels where the stress in the x-x direction (horizontal) is high, the stress in the z-z direction (vertical) is mostly insignificant given the fact that it is so tiny and contributes very little to the overall stress at that point. The stress in the x-x direction along the bottom of the panel is much larger than the stresses that occur anywhere else on the panel, even when combined with all of the other stress components. Given that this is the area that receives the most stress, the bottom of the panel was most closely monitored through many iterations of various models. In addition, the stress at the locations of 10, 30 and 50 percent of the total length of the bottom of the model were recorded. These values show where it is possible for the panel to crack given that the cracks will form at those locations. The stress values due to self weight make up only 10% of the total stress contribution (Appendix A Pg. 48).

Below you can see the direct stress pattern output for the x-x and z-z direction in Figure 4.0 and Figure 4.1 respectively. The output of the data has the convention that all positive numbers are in tension while all negative numbers are in compression and the scales for those values are to the right of the figures. The more blue colors represent zones of tension while the more purple colors represent zones of compression.

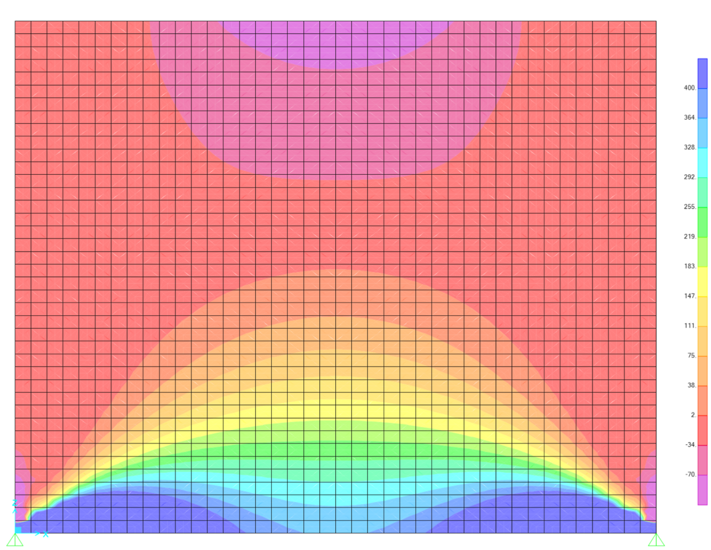



Figure 4.0 - Stress Output in X-X Direction

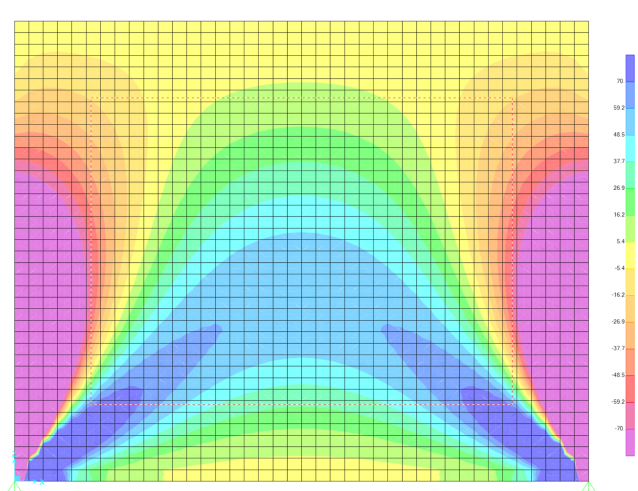



Figure 4.1 - Stress Output in the Z-Z Direction

The next figure is an attempt to combine Figures 4.0 and 4.1 for the reader so that one can understand what exactly is happening and in which directions the forces are occurring. As you can see from Figure 4.2 below there are various regions of the panel with different types of stresses. Large stress areas and small stress areas, various angles of combined stresses from 0 to 90 and zones of tension and compression. The bottom most region is where the x-x stresses dominate the z-z stresses encouraging the cracks to naturally travel vertically with small slants towards the edges of the panels depending on which side of center the crack initiates on. As the crack travels more vertically and towards the panel's edges the stresses in the z-z direction start to get closer to the stresses in the x-x meaning that the cracks will start to take on an angle closer to 45 degrees towards the panel's edges. The zones on the far left and right side of the panel are compression zones where once encountered the cracking should stop.

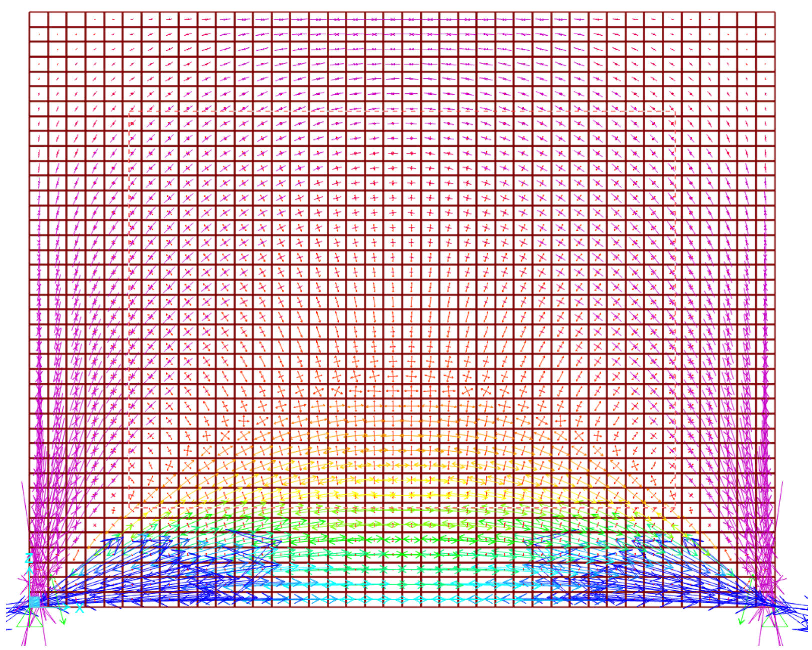


Figure 4.2 - Principal Stress Direction

Depending how influential crack propagation is, this compressive stress could be ineffective and the cracking could actually extend in the same direction as before. This would lead to an even more

horizontal crack as the crack approaches the outside of the panel. and not actually a reverse in direction which is what seems to appear from the output.

The authors went out to the Home Depot site in San Luis Obispo and mapped out the cracks that had occurred on selected panels. The black and white figure (Figure 4.3) illustrates one panel of interest for this paper. It is desirable to compare this observed cracking to the cracking pattern that the model had predicted.

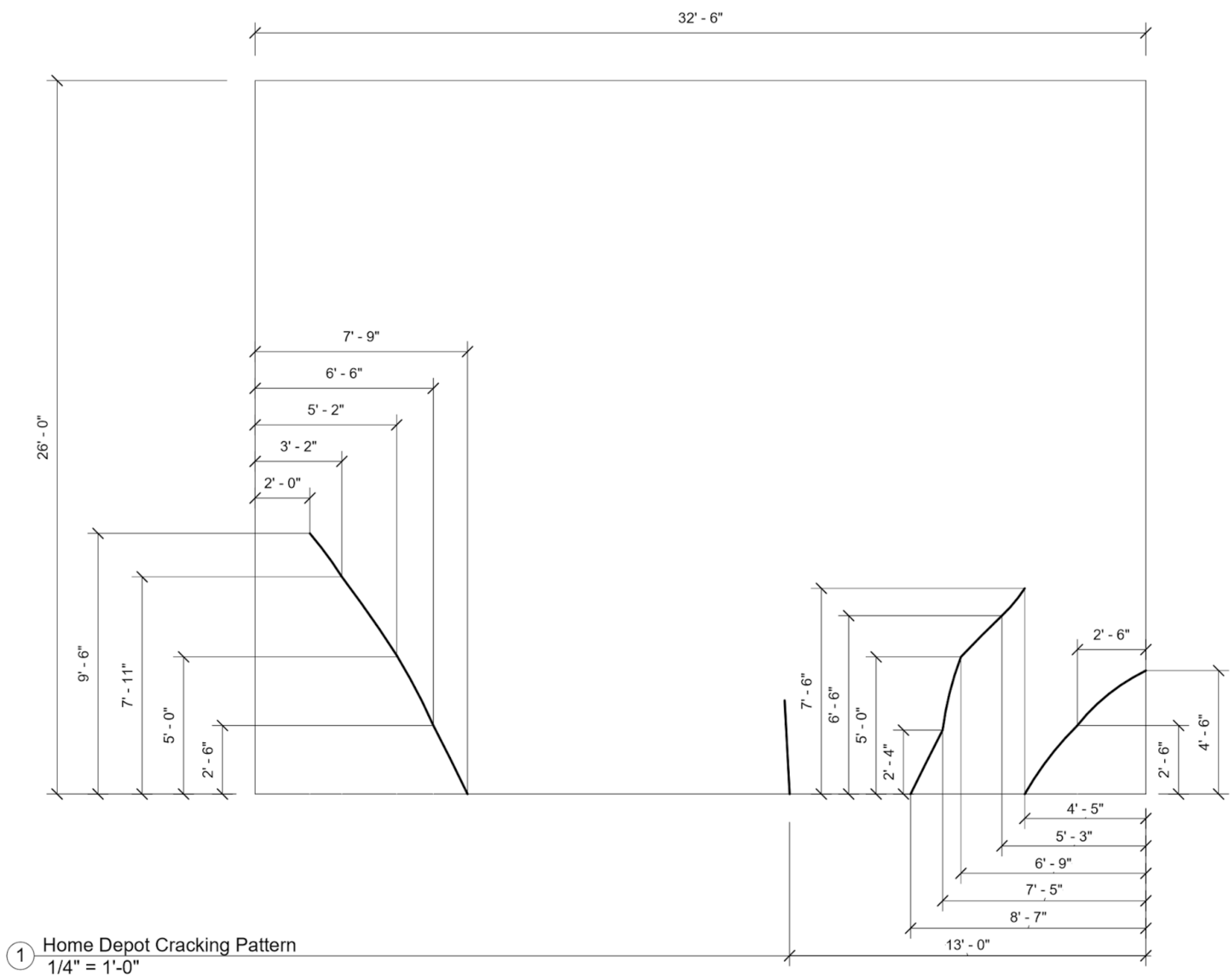



Figure 4.3 - Home Depot Cracks Mapped Out

The next several figures will look at how the cracks predicted by the computer model compare with the actual cracks seen in the field. These were compared by initiating the crack at the same location in the model as they start in the field and running the cracks perpendicular to the principal stress arrows. In the figures below, the portion of the crack in blue is what is predicted to occur given our knowledge of crack propagation. The portion in red represents what is believed to potentially occur with the crack entering a zone of compression.

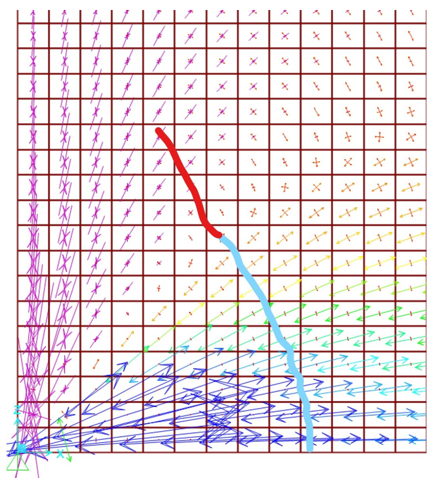


Figure 4.4 - Model Predicted Left Crack

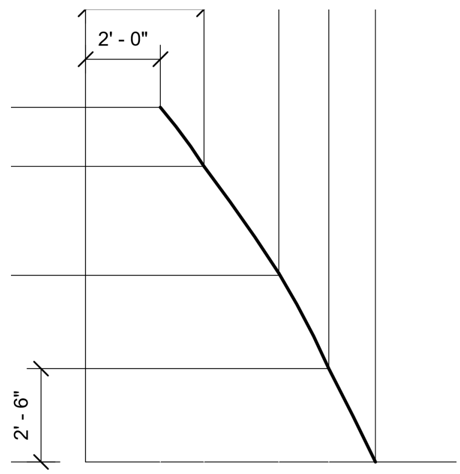



Figure 4.5 - Actual Left Crack

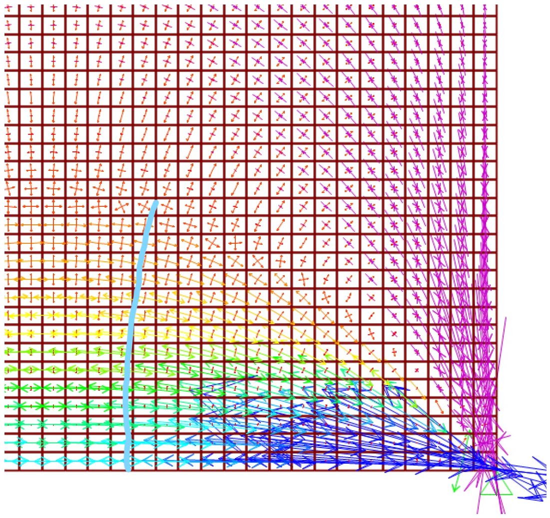


Figure 4.6 - Model Predicted Middle Crack

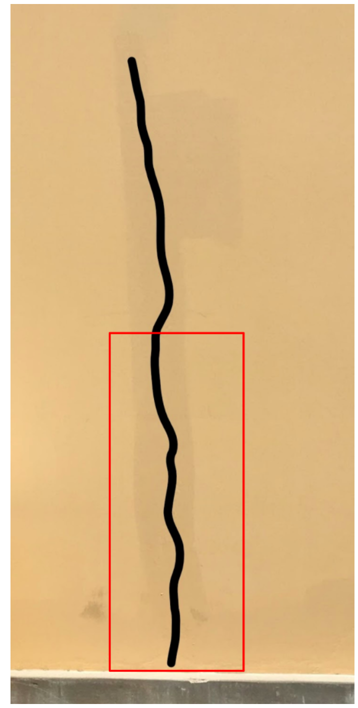


Figure 4.7 - Actual Middle Crack

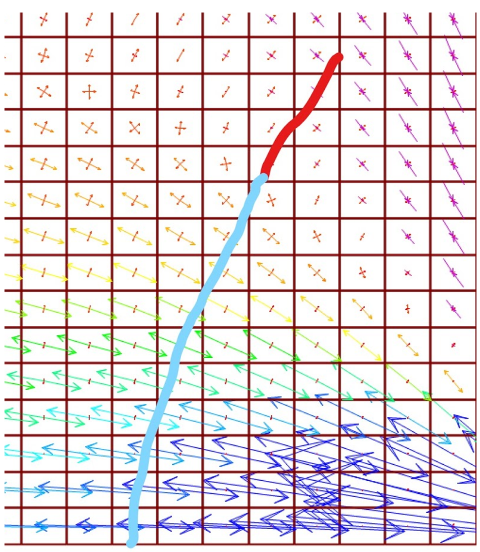


Figure 4.8 - Model Predicted Right Crack 1

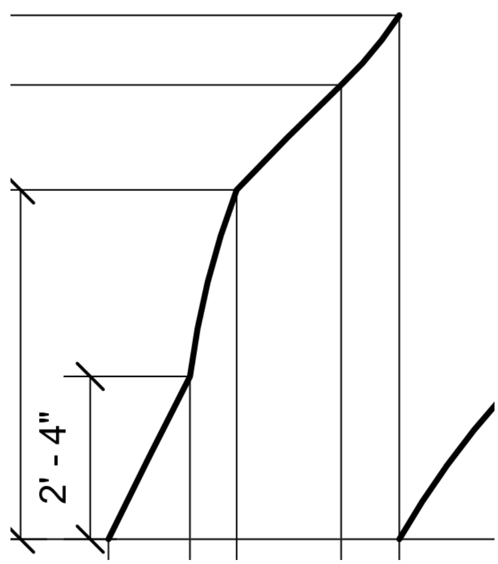



Figure 4.9 - Actual Right Crack 1

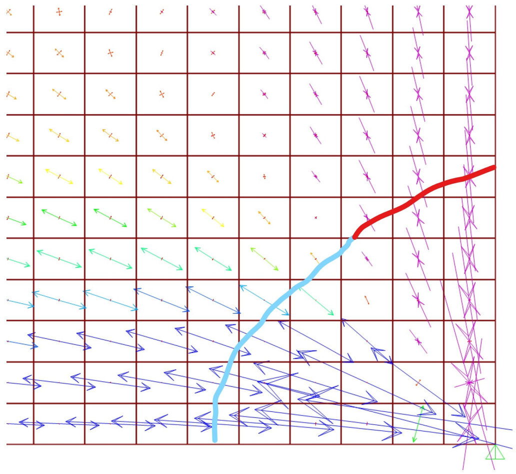


Figure 4.10 - Model Predicted Right Crack 2

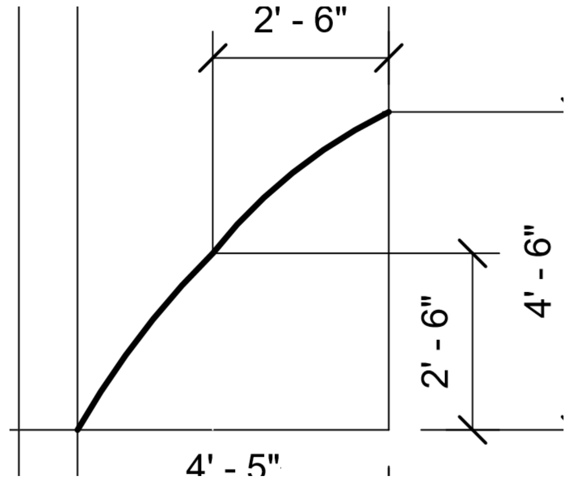



Figure 4.11 - Actual Right Crack 2

The figures above illustrate that the crack patterns produced by the computer model are very similar to the crack patterns that were actually produced in the Home Depot panel. The middle crack slightly leans the other way than what was expected. Given that this crack should form last because the middle of the panel receives less stress than other portions of the panel in the X-X direction, there could be residual stresses that affect its direction. Furthermore, stresses above the blue zone in Figure 4.6 were so complex so the crack propagation potential cracking was not predicted.

However, none of the computer models using a coefficient of friction of 0.28 or lower predicted cracking in the panel. This was due to the fact that at 10% of the length of the panel (or 3.25' from the panel edge), the stress induced in the X-X direction was predicted at 268 psi, but the modulus of rupture of 4000 psi concrete is estimated at 316 psi using $5\sqrt{f'c}$. The research focused on this distance from the edge of the panel given that this distance is significant enough to not just be a minor crack at the very corner of the panel but would generate a crack of substantial size and would turn into the cracks that this research is concerned with. Using these computer models, one can see what are the important and unimportant factors when considering tilt-up panel restraint cracking.

In studying the potential for crack initiation, the restraint force potential was the most important factor followed by the mix design (and ultimate shrinkage values) and the construction sequencing. A factor that seemed to be insignificant was the rate of early age shrinkage versus the concrete's rise in the modulus of rupture with respect to time as seen in Figure 4.12 below:

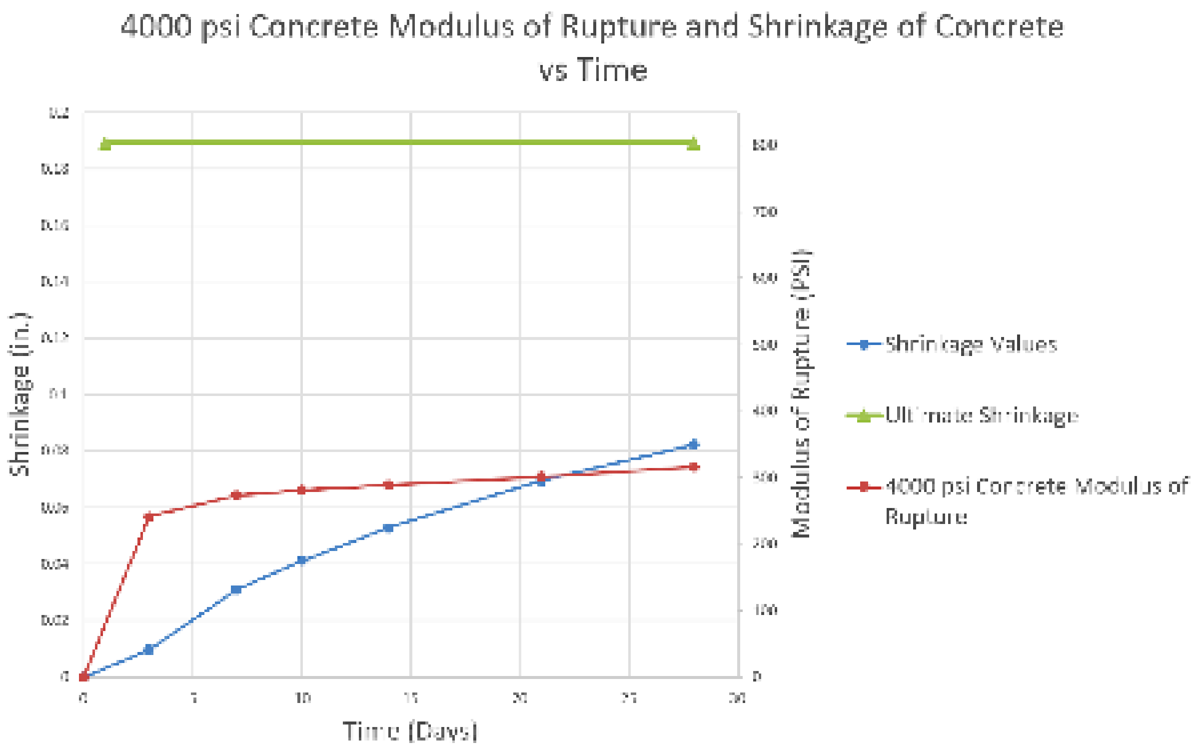



Figure 4.12 - Modulus of Rupture and Shrinkage vs Time

The Modulus of Rupture is $5\sqrt{f'c}$ and the compressive values of concrete were interpolated using graphs in the PCA (PCA Pg. 54). The graph above shows that the modulus of rupture values at an early age are much higher values with respect to their ultimate value than the early values that the shrinkage obtains relative to its ultimate shrinkage value. This would seem to indicate that the worst potential for cracking would occur at their ultimate values rather than values at an earlier time period especially within the first year. The panel geometry and length did not seem to be crucial because the values from the model with panel size 32.5' x 26' were sufficiently similar to the panel size of 24'x26' in proportion. In fact, the

coefficients of friction that are required to create the friction forces in each panel to cause the stress to induce a crack initiating at 10% of the panels length was only 0.02 different. Being that a value of 0.45 was necessary for the 32.5' x 26' panel (Appendix Pg. 53) and a value of 0.47 was necessary for the 24' x 26' panel (Appendix Pg. 51). This means that the restrained force required to cause cracking was proportionally very similar in both cases in relation to the total weight of the walls. This seems to suggest that a longer or shorter wall does not have much effect on the stresses that are induced as long as the wall continues to behave as a deep beam under gravity. Without many more cases done in terms of wall size, it is still a little bit of a leap to say that any geometry does not have a significant impact but the trend for walls acting as a deep beam suggests little impact.

At this point we started to investigate Case 2: Friction Restraint and Pour Strip Restraint for a Home Depot panel being 32.5' x 26' tall and 6.5" thick. A detail was obtained for a Home Depot in Portland, Oregon, that was designed in the same era by the same engineering firm as the Home Depot in San Luis Obispo; and without being able to obtain the plans for the project in San Luis Obispo it was assumed that both project details would be similar. The detail in question had three number 4 rebars in the pour strip running in parallel to panels at various distances from the panel. It was assumed that one of the rebar would be fully activated in this case due to its proximity to the wall and the fact that without testing, a conservative number for this restraint force should be assumed. Now instead of the restraint force being $(N)(\mu) = (34.33\ kips)(0.28) = 9.61\ kips$ due to the grout pad, the restraint was increased by $(As)(Fy) = (0.2)(60{,}000\ ksi) = 12\ kips$ fully yielding for a total potential restraint force of 21.61 kips. Figure 4.13 below shows the conditions that will lead up to the cracking of the panel.

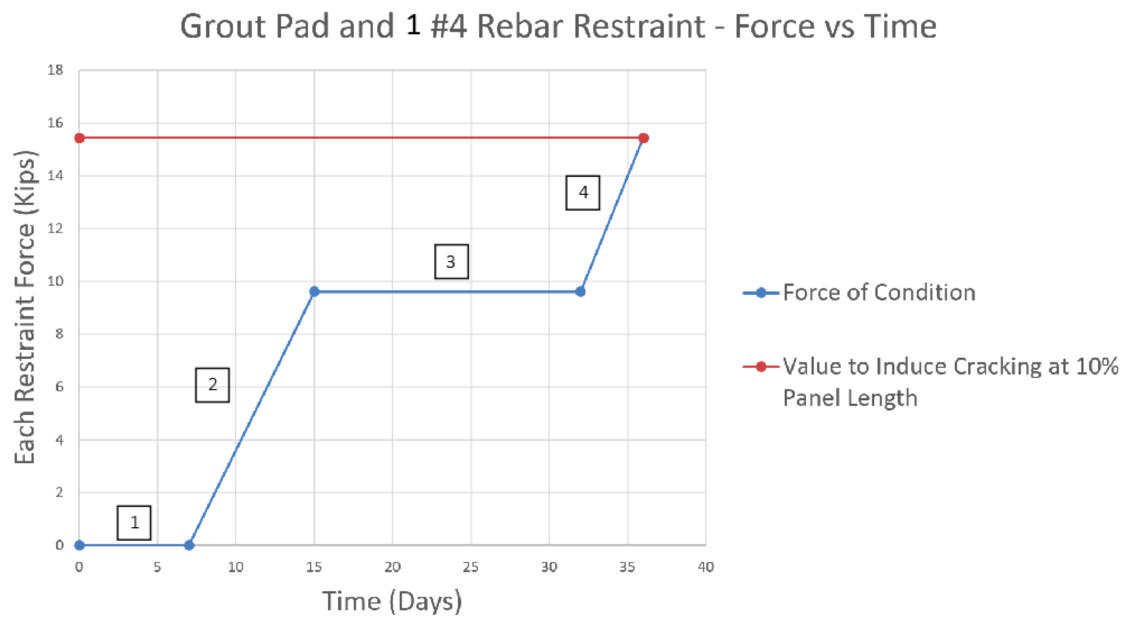



Figure 4.13 - Grout Pad and #4 Rebar Restraint - Force vs Time

1. The panel is tilted at 7 days after casting. No shrinkage has caused a restraint force on the panel until placed on grout pads.

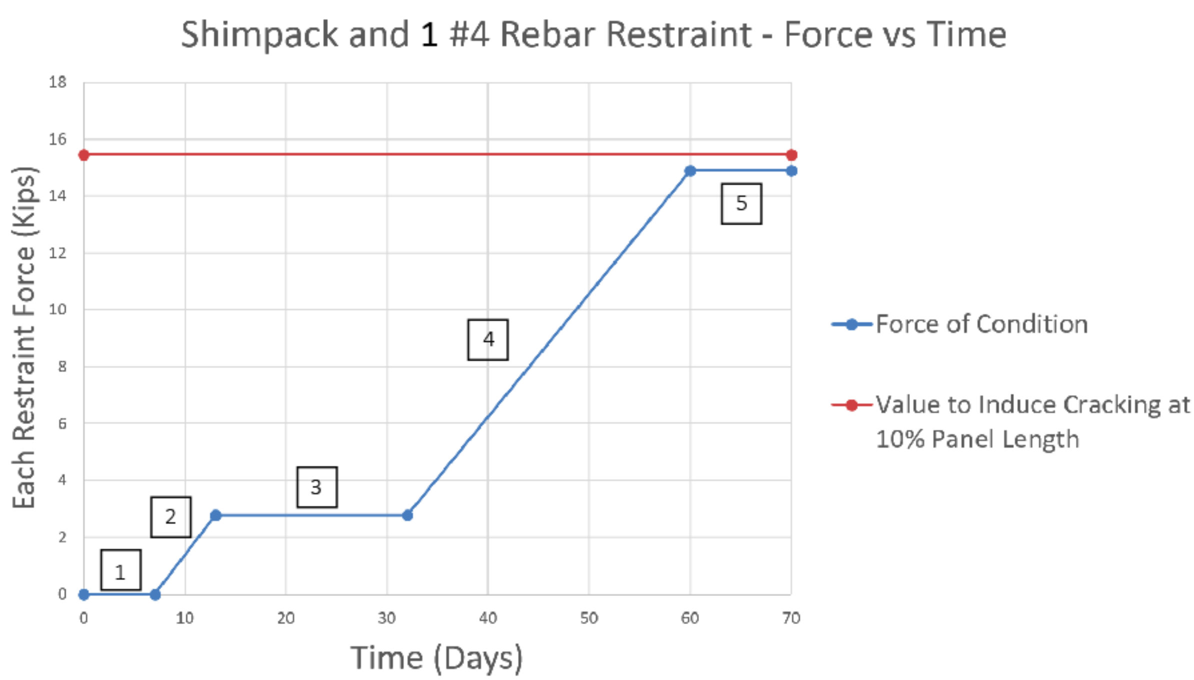
2. The grout pads start to generate a restraint friction force on the panel due to the panel's shrinkage.

3. The grout pad no longer can handle the restraint force imposed by the panel's shrinkage and now the panel is sliding on top of the grout pad as the frictional restraint is overcome.

4. The pour strip, which is subsequently poured adjacent to the panel, starts to come up to strength on day 32 when the strip is placed and the panel's shrinkage starts to generate more restraint force, this time due to the pour strip rebar. This force becomes large enough to generate a crack in the panel.

The panel cracks at a restraint force of 15.45 kips at each panel side because this is the force in the panel that will induce cracking at 10% of the panel length or 3.25' with a value of 318 psi, which is larger than the estimated modulus of rupture of 4000 psi concrete, being 316 psi.

The case of a shim pack along with the pour strip restraint from (1) #4 rebar is shown below in Figure 4.14.




Graph 4.14 - Shim pack and #4 Rebar Restraint - Force vs Time

1. The Panel is tilted up at 7 Days and no shrinkage has caused a restraint force on the panel prior to tilting.

2. The shim pack starts to generate a restraint friction force on the panel due to the panel's shrinkage.

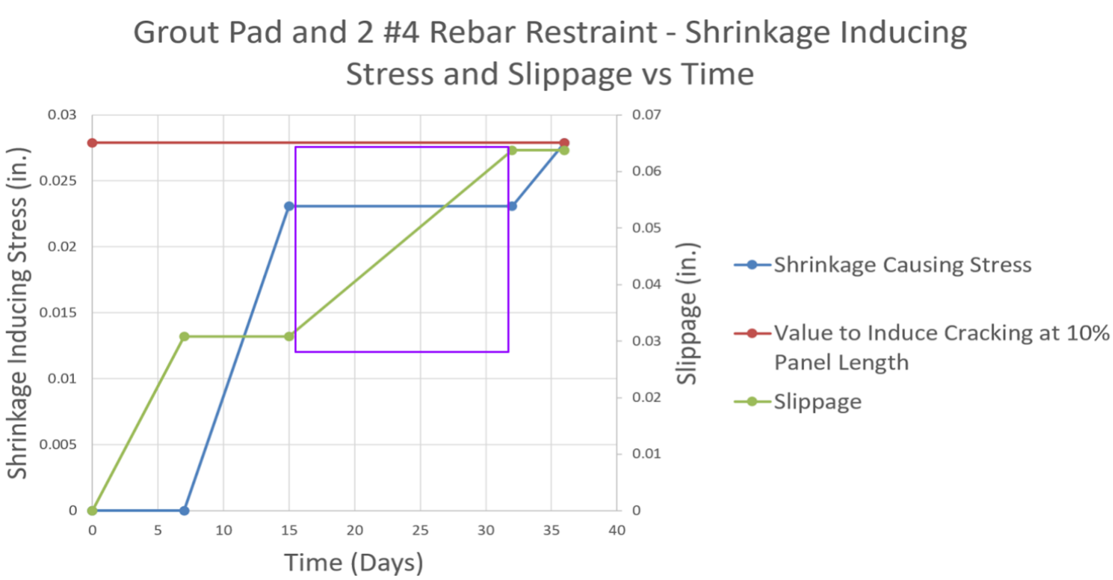
3. The shim pack no longer can handle the restraint force imposed by the panel's shrinkage and now the panel is sliding on top of the grout pad as the frictional restraint is overcome.

4. The pour strip starts to come up to strength on day 32 when the strip is placed and the panel's shrinkage starts to generate more restraint force, this time due to the pour strip rebar.

5. The pour strip restraint in addition to the shim pack friction restraint force never are large enough to produce a stress large enough in the panel to induce cracking. This means that the rebar in the pour strip yields and the panel slides on top of the shim pack onward until ultimate shrinkage.

The main difference between Figure 4.13 and Figure 4.14 is the restraint force generated by the setting pads, indicated as number 2 on the graph. The grout pad's restraint force is much larger than the shim pack restraint force and thus in combination with the rebar is likely to lead to cracking in the panel. On the other hand, the shim pack, given its low coefficient of friction under the same condition, did not generate enough force to cause a crack in our computer model.

The next graph and explanation below will demonstrate why construction sequencing can be so important for the construction of tilt up.



Graph 4.15 - Shrinkage and Slippage vs Time

Please note that the graph above has two vertical axis values and scales. Being able to look at shrinkage inducing stress and slippage can be valuable because by adding up the value on the Shrinkage Inducing Stress axis at 36 days (0.279 inches) and the Slippage value at 36 days (0.0637 inches) we see that the total shrinkage value to induce cracking at 10% of the panel length occurs after a total shrinkage of 0.092

inches. Meaning that the panel's ultimate shrinkage has to be at least 0.092 inches in order to crack the panel. If for instance the potential shrinkage of the panel considering all of the other variables was 0.094 inches, you could place the pour strip just a couple of days later (area in the purple box), that would allow the shrinkage that would end up causing restraint force to turn into slippage. By delaying the pour strip, the potential would not reach the 0.0933 inches necessary to crack the panel. With this type of system, a construction or engineering company can help predict whether the mix they specify along with date of lift will lead to a crack. In cases where an excessive restraining force is put in place, it would become very crucial to try and let the panel slip as much as possible before the restraint is put in place. This is due to the fact that any slippage that occurs during that time will take away from the panel's potential to crack in the future, by having less total shrinkage left.

## 4.4 Computer Model Conclusions:

Some of the limitations of the model include, but are not limited to, the following concerns. The computer model uses idealized conditions which can never be fully present in the field. Given what we were exploring the conditions seem to be very closely identical but even with the shrinkage model nothing will be completely perfect. Another limitation of the computer model were how many different cases we were able to run using the model. Looking through the appendix it is shown that we were able to test about 70 different combinations of variables but much more work is needed for anything to be completely thorough.

# 5.0 Conclusion

As we have seen from the experimental values in combination with the computer model results, cracks can initiate given that there is a pour strip restraint from a minimum of one #4 rebar in addition to friction restraint from a grout pad. Whereas, if a plastic shim pack is used, shrinkage cracking could be avoided or minimized. Another possible solution to reduce shrinkage that has been practiced is using multiple setting pads moved away from the panel joints towards the middle of the panel. Moving the setting pads in from the panel edge allows the setting pads to resist less shrinkage as well as force the stresses to rip through more concrete.

Although this research did not investigate the situation where a panel is connected directly to the foundation through a welded connection, it follows that this condition at the ends of the panel would lead to just as much, if not more, severe cracking. Anchorage from the panel to the foundation is an important discussion topic because there is currently some back and forth in regards to whether or not this anchorage should be required. The Tilt-Up Concrete Association has made two position statements on panel to foundation connections in reference to ACI specifications as well as high seismic zone considerations and requirements (Baty). In high seismic zones, occasionally uplift can occur due to overturning of the panels. If any uplift occurs at the ends of the panels, they must be tied down to the foundation.  If there is no uplift or overturning in a panel, and a panel-to-foundation connection is still required, a possible solution to reduce shrinkage restraint is to place the connection in the middle of the panel. If the welded or bolted connection is located in the middle of the panel, it will not restrain the wall from shrinking because the panel is shrinking towards the bottom middle. Welding for these types of connections take place in the field and take place very early on in the construction sequence because grout between the panel and foundation can not be placed until the welds are finished in some cases. Due to panel shrinkage over time, the earlier these restraints are installed, the more likely cracking is to take

place. Although recommendations need to be made on a case by case basis, it can generally be recommended to avoid providing rigid restraints to the ends of panels, due to they will almost certainly crack. Below Figure 5.0 and 5.1 are typical details suggested by Tilt-Up Concrete Association for panel to foundation anchorage, and potentially can increase the likelihood of shrinkage cracking within the panel.

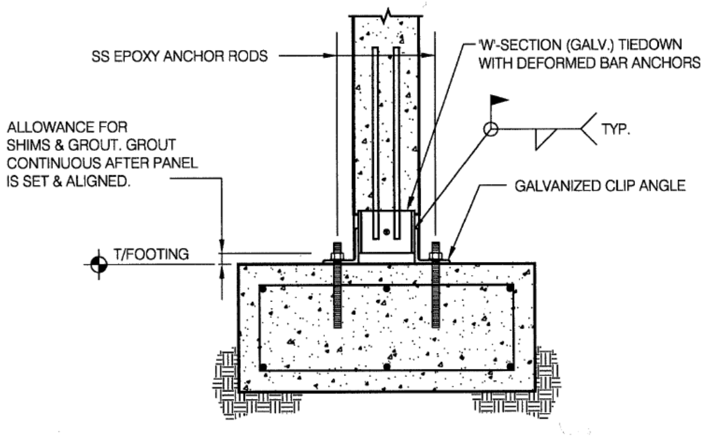



Figure 5.0 - Welded Foundation to Connection (Ward)

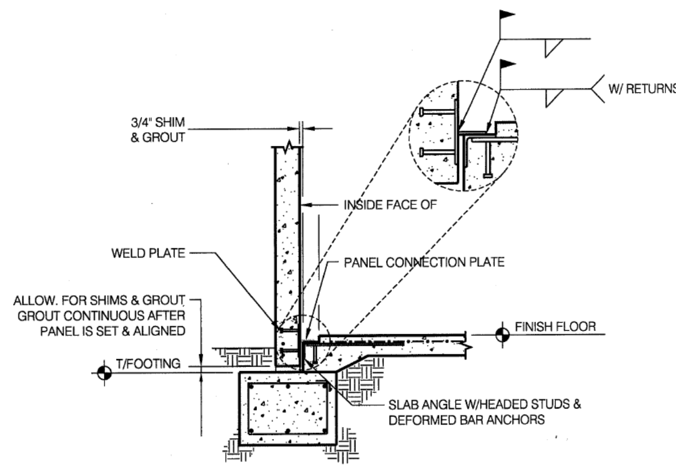



Figure 5.1 - Welded Foundation Connection (Ward)

Having a welded condition between the panel and foundation looks and functions very similarly to what the condition from a panel-to-panel connection used to be. In the past, panel-to-panel connections used to be welded as can be seen in Figures 5.2. However, this type of welded condition led to undesirable cracking surrounding these connections as can be seen in Figure 5.3 below.

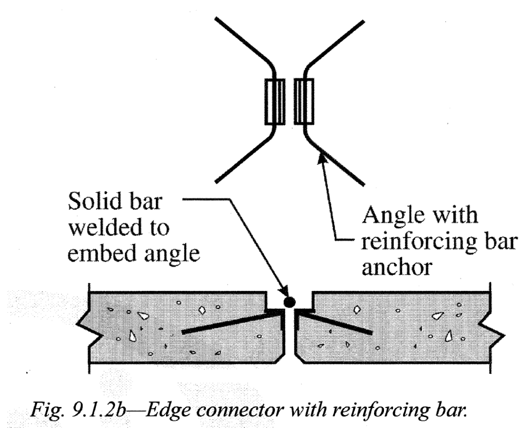



Figure 5.2 - Welded Panel to Panel (Ward)

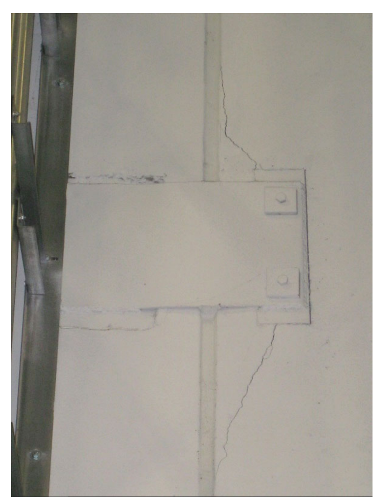


Figure 5.3 - Panel to Panel Restraint Cracking (Lawson and Steinbicker)

Once building owners started to take notice of these cracks, contractors and engineers were under pressure to develop new ideas and considerations for how panels should be connected with each other. Slotted-bolt connections between panels have been introduced and brought into practice in order to reduce this type of restraint as can be seen in Figure 5.4.

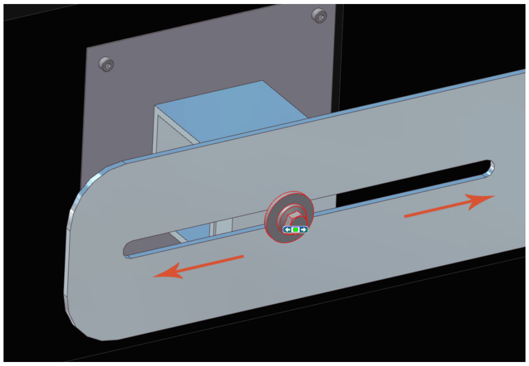


Figure 5.4 - Slotted-Bolt Concept

It should be noted that similar considerations have been taken into account for the panel-to-roof connection. Although restraints between panels and other elements have been fixed above grade, we can conclude that tilt-up panels also have the potential to be heavily restrained at the base. It would follow that any negative side effects of restraining panels at the top would have the same consequences as at the base of the panels, based on the results found in this paper. Going forward, rigid foundation to panel connections need to start resembling the slotted connections currently in practice for panel-to-panel connections higher in the panel, or be placed away from the extreme edges of the panel width.

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# APPENDIX A

**ACI 209 Prediction of Shrinkage**

Description: This program will, when given inputs, calculate the shrinkage that your concrete member will experience over a set span of time. Just input all the values in blue

Esht after 7 days = (T/(35+T))*Eshu

Technically for steam cured
Esht after 1-3 days = (T/(55+T))*Eshu

"In the absence of specific creep and shrinkage data for local aggregates and conditions, the average values suggested for Eshu =
0.00078 xYsh
Where Ysh equals adjustment factors found by questions (2-12)-(2-30) which covers creep as well

| INPUT | | |
|---|---|---|
| Ambient Relative Humidity | 40 | In Relative Humidity in Percent |
| Volume | 790920 | in^3 |
| Surface Area | 252486 | in^2 |
| Slump | 4 | In Inches |
| Fine Aggregates Percentage | 27.2 | Percentage is Weight vs Weight of Total Aggregate |
| Cement Content | 573 | Pounds Per Cubic Yard |
| Air Content | 0.0125 | Air Content as a Decimal |
| Length of Wall | 32.5 | in Feet |
| Time | 37 | in Days (Manually calc < 3 Days see above) |

| OUTPUT | | |
|---|---|---|
| Ambient Relative Humidity | 40 | In Relative Humidity in Percent |
| Volume | 790920 | in^3 |
| Area | 252486 | in^2 |
| Slump | 4 | In Inches |
| Fine Aggregates Percentage | 27.2 | Percentage is Weight vs Weight of Total Aggregate |
| Cement Content | 573 | Pounds Per Cubic Yard |
| Air Content | 0.0125 | Air Content in Percentage |
| Length of Wall | 32.5 | in Feet |
| Time | 37 | in Days |
| | 0 | |
| Ysh Calculated by Equations = | 0.609 | |
| Total Shrinkage Present = | 0.09517 | inches |
| Inches/Inch | 0.00024 | in/in |
| vs | | |
| 1/8" in 20 FT Shrinkage Assump = | 0.203125 | inches |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1 | Ambient Relative Humidity Factor (2-15 and 2-16) | 1 | | Ysh = | 1.4-0.010Lambda<br>3.0 - 0.030Lambda<br>Where lambda is = to Relative Humidity in Percent | for 40 =< Lambda =< 80<br>for 80 =< Lambda =< 100 |
| 2a | Average Thickness of Member Greater Than 6" (2-19)-(2-20) | | | Shrinkage First Year<br>Ysh = 1.23 - 0.038h<br>Shrinkage Ultimate<br>Ysh = 1.17-0.029h | h is height in inches<br><br>h is height in inches | |
| OR | | | | | | |
| 2b | Volume-Surface Ratio Method (2-22) | Can't Be Less than 0.2<br>0.93 | Prelim Value<br>0.93 | Shrinkage<br>Yvs = 1.2 exp(-0.12 v/s) | | v and s have to be same units |
| 3 | Slump (2-24) | 1.05 | | Ys = 0.89 + 0.041s | | s is slump in inches |
| 4 | Fine Aggregates Percentage (2-26)-(2-27) | 0.68 | | Fines =< 50%<br>Yfines = 0.30 + 0.014F<br>Fines > 50%<br>Yfines = 0.90 + 0.002F<br>F is the ratio of fine aggregate to total aggregate by weight expressed as a percentage | | |
| 5 | Cement Content (2-28)<br>If cement content is increased and water-cement ratio is kept constant, slump and creep will increase | 0.96 | | Yc = 0.75 +0.00036c<br>where c is cement content in pounds per cubic yard | | |
| 6 | Air Content (2-30) | 0.95 | | Yair = 0.95 + 0.008air<br>air = air content in percentage | | |

Impacts of Self Weight on Panel Stresses

Note: All stresses given are the x-x stresses at the bottom of the panel where stress values are the largest
Mesh = 40x40

| Panel Size 32.5' x 26' | | | | | |
|---|---|---|---|---|---|
| | 150 | pcf (self-weight) | | | |
| | 26 | feet | | | |
| | 32.5 | feet | | | |
| | 6.5 | inches | | | |
| | 68.66 | kips | PSI at 10% | 27.5 | psi |
| | | | PSI at 30% | 12.5 | psi |
| Max Reactions at Corners | 34.33 | kips | PSI at 50% | 11.74 | psi |

| Panel Size 24' x 26' | | | | | |
|---|---|---|---|---|---|
| | 150 | pcf (self-weight) | | | |
| | 24 | feet | | | |
| | 26 | feet | | | |
| | 6.5 | inches | | | |
| | 50.70 | kips | PSI at 10% | 25 | psi |
| | | | PSI at 30% | 11 | psi |
| Max Reactions at Corners | 25.35 | kips | PSI at 50% | 10 | psi |

High Shrinkage Mix - Dimensions 24 x 26

| | |
|---|---|
| Thermal Coeffiecient of Expansion | 0.0000055 |
| Mesh = | 40x40 |

| | | |
|---|---|---|
| Weight of Panel | 150 | pcf |
| | 26 | Feet |
| | 24 | Feet |
| | 6.5 | inches |
| | 50.70 | kips |
| Max Reactions at Corners | 25.35 | kips |

| | | |
|---|---|---|
| Volume | 584064 | in^3 |
| SA | 187512 | in^2 |

| Material | Friction Coefficient | Force | |
|---|---|---|---|
| Welded | 1 | N/A | kips |
| PCI Value | 0.8 | 20.28 | kips |
| ACI 318 | 0.6 | 15.21 | kips |
| Exp Grout | 0.28 | 7.10 | kips |
| Exp Shim | 0.11 | 2.79 | kips |

| Max Shrinkage Values | | |
|---|---|---|
| 3 days | 0.00888 | inches |
| 7 days | 0.02865 | inches |
| 14 days | 0.04911 | inches |
| 30 Days | 0.0764 | inches |
| 730 Days | 0.16403 | inches |
| | | |
| 3->730 Max Shrink = | 0.15515 | inches |
| 7 ->730 Max Shrink = | 0.13538 | inches |
| 14->730 Max Shrink = | 0.11492 | inches |
| 30->730 Max Shrink = | 0.08763 | inches |

| High Shrinkage Mix | | |
|---|---|---|
| Ambient Relative Humidity | 40 | In Relative Humidity in Percent |
| Volume | 584064 | in^3 |
| Area | 187512 | in^2 |
| Slump | 4 | In Inches |
| Fine Aggregates Percentage | 37.7 | Percentage is Weight vs Weight of Total Aggregate |
| Cement Content | 661 | Pounds Per Cubic Yard |
| Air Content | 0.04 | Air Content in Percentage |
| Length of Wall | 26 | in Feet |
| Time | 5000 | in Days |
| | | |
| Ysh Calculated by Equations = | 0.765 | |
| Total Shrinkage Present = | 0.17070 | inches |
| Inches/Inch | 0.00059 | in/in |
| vs | | |
| 1/8" in 20 FT Shrinkage Assump = | 0.15 | inches |

Notes:
Red = Restraint Governs, Meaning that Slips before full Shrink
Green = Shrinkage Governs, Meaning That Restraint Can Hold
Yellow = Stresses are enough to develop cracking

## Restraint

Columns: Welded, PCI, ACI 318, Exp Grout, Exp Shim

## Tilt At

### 3 Days

| 3 Days + Welded | | |
|---|---|---|
| Max Force on Restraint = | N/A | kips |
| Max Horiz Shrinkage = | 0.15515 | inches |
| Which Governs? | | |
| Temp | | F |
| One Restraint Force | | inches |
| PSI at 10% | | psi |
| PSI at 30% | | psi |
| PSI at 50% | | psi |

| 3 Days + PCI | | |
|---|---|---|
| Max Force on Restraint = | 20.28 | kips |
| Max Horiz Shrinkage = | 0.15515 | inches |
| Which Governs? | Restraint | |
| Temp | -16.6 | F |
| Horizontal Shrinkage | 0.0263 | inches |
| PSI at 10% | 423 | psi |
| PSI at 30% | 149 | psi |
| PSI at 50% | 117 | psi |

| 3 Days + ACI 318 | | |
|---|---|---|
| Max Force on Restraint = | 15.21 | kips |
| Max Horiz Shrinkage = | 0.15515 | inches |
| Which Governs? | Restraint | |
| Temp | -14.11 | F |
| Horizontal Shrinkage | 0.0224 | inches |
| PSI at 10% | 363 | psi |
| PSI at 30% | 128 | psi |
| PSI at 50% | 101 | psi |

| 3 Days + Exp Grout | | |
|---|---|---|
| Max Force on Restraint = | 7.10 | kips |
| Max Horiz Shrinkage = | 0.15515 | inches |
| Which Governs? | Restraint | |
| Temp | -10.28 | F |
| Horizontal Shrinkage | 0.0163 | inches |
| PSI at 10% | 270 | psi |
| PSI at 30% | 96 | psi |
| PSI at 50% | 76 | psi |

| 3 Days + Exp Shim | | |
|---|---|---|
| Max Force on Restraint = | 2.79 | kips |
| Max Horiz Shrinkage = | 0.15515 | inches |
| Which Governs? | Restraint | |
| Temp | -8.15 | F |
| Horizontal Shrinkage | 0.0021 | inches |
| PSI at 10% | 220 | psi |
| PSI at 30% | 79 | psi |
| PSI at 50% | 63 | psi |

### 7 Days

| 7 Days + Welded | | |
|---|---|---|
| Max Force on Restraint = | N/A | kips |
| Max Horiz Shrinkage = | 0.13538 | inches |
| Which Governs? | | |
| Temp | | F |
| One Restraint Force | | inches |
| PSI at 10% | | psi |
| PSI at 30% | | psi |
| PSI at 50% | | psi |

| 7 Days + PCI | | |
|---|---|---|
| Max Force on Restraint = | 20.28 | kips |
| Max Horiz Shrinkage = | 0.13538 | inches |
| Which Governs? | Restraint | |
| Temp | -16.6 | F |
| Horizontal Shrinkage | 0.0263 | inches |
| PSI at 10% | 423 | psi |
| PSI at 30% | 149 | psi |
| PSI at 50% | 117 | psi |

| 7 Days + ACI 318 | | |
|---|---|---|
| Max Force on Restraint = | 15.21 | kips |
| Max Horiz Shrinkage = | 0.13538 | inches |
| Which Governs? | Restraint | |
| Temp | -14.11 | F |
| Horizontal Shrinkage | 0.0224 | inches |
| PSI at 10% | 363 | psi |
| PSI at 30% | 128 | psi |
| PSI at 50% | 101 | psi |

| 7 Days + Exp Grout | | |
|---|---|---|
| Max Force on Restraint = | 7.10 | kips |
| Max Horiz Shrinkage = | 0.13538 | inches |
| Which Governs? | Restraint | |
| Temp | -10.28 | F |
| Horizontal Shrinkage | 0.0163 | inches |
| PSI at 10% | 270 | psi |
| PSI at 30% | 96 | psi |
| PSI at 50% | 76 | psi |

| 7 Days + Exp Shim | | |
|---|---|---|
| Max Force on Restraint = | 2.79 | kips |
| Max Horiz Shrinkage = | 0.13538 | inches |
| Which Governs? | Restraint | |
| Temp | -8.15 | F |
| Horizontal Shrinkage | 0.0021 | inches |
| PSI at 10% | 220 | psi |
| PSI at 30% | 79 | psi |
| PSI at 50% | 63 | psi |

### 14 Days

| 14 Days + Welded | | |
|---|---|---|
| Max Force on Restraint = | N/A | kips |
| Max Horiz Shrinkage = | 0.11492 | inches |
| Which Governs? | | |
| Temp | | F |
| One Restraint Force | | inches |
| PSI at 10% | | psi |
| PSI at 30% | | psi |
| PSI at 50% | | psi |

| 14 Days + PCI | | |
|---|---|---|
| Max Force on Restraint = | 20.28 | kips |
| Max Horiz Shrinkage = | 0.11492 | inches |
| Which Governs? | Restraint | |
| Temp | -16.6 | F |
| Horizontal Shrinkage | 0.0263 | inches |
| PSI at 10% | 423 | psi |
| PSI at 30% | 149 | psi |
| PSI at 50% | 117 | psi |

| 14 Days + ACI 318 | | |
|---|---|---|
| Max Force on Restraint = | 15.21 | kips |
| Max Horiz Shrinkage = | 0.11492 | inches |
| Which Governs? | Restraint | |
| Temp | -14.11 | F |
| Horizontal Shrinkage | 0.0224 | inches |
| PSI at 10% | 363 | psi |
| PSI at 30% | 128 | psi |
| PSI at 50% | 101 | psi |

| 14 Days + Exp Grout | | |
|---|---|---|
| Max Force on Restraint = | 7.10 | kips |
| Max Horiz Shrinkage = | 0.11492 | inches |
| Which Governs? | Restraint | |
| Temp | -10.28 | F |
| Horizontal Shrinkage | 0.0163 | inches |
| PSI at 10% | 270 | psi |
| PSI at 30% | 96 | psi |
| PSI at 50% | 76 | psi |

| 14 Days + Exp Shim | | |
|---|---|---|
| Max Force on Restraint = | 2.79 | kips |
| Max Horiz Shrinkage = | 0.11492 | inches |
| Which Governs? | Restraint | |
| Temp | -8.15 | F |
| Horizontal Shrinkage | 0.0021 | inches |
| PSI at 10% | 220 | psi |
| PSI at 30% | 79 | psi |
| PSI at 50% | 63 | psi |

### 28 Days

| 28 Days + Welded | | |
|---|---|---|
| Max Force on Restraint = | N/A | kips |
| Max Horiz Shrinkage = | 0.08763 | inches |
| Which Governs? | Shrinkage | |
| Temp | -55 | F |
| One Restraint Force | 99.8 | kips |
| PSI at 10% | 1339 | psi |
| PSI at 30% | 470 | psi |
| PSI at 50% | 366 | psi |

| 28 Days + PCI | | |
|---|---|---|
| Max Force on Restraint = | 20.28 | kips |
| Max Horiz Shrinkage = | 0.08763 | inches |
| Which Governs? | Restraint | |
| Temp | -16.6 | F |
| Horizontal Shrinkage | 0.0263 | inches |
| PSI at 10% | 423 | psi |
| PSI at 30% | 149 | psi |
| PSI at 50% | 117 | psi |

| 28 Days + ACI 318 | | |
|---|---|---|
| Max Force on Restraint = | 15.21 | kips |
| Max Horiz Shrinkage = | 0.08763 | inches |
| Which Governs? | Restraint | |
| Temp | -14.11 | F |
| Horizontal Shrinkage | 0.0224 | inches |
| PSI at 10% | 363 | psi |
| PSI at 30% | 128 | psi |
| PSI at 50% | 101 | psi |

| 28 Days + Exp Grout | | |
|---|---|---|
| Max Force on Restraint = | 7.10 | kips |
| Max Horiz Shrinkage = | 0.08763 | inches |
| Which Governs? | Restraint | |
| Temp | -10.28 | F |
| Horizontal Shrinkage | 0.0163 | inches |
| PSI at 10% | 270 | psi |
| PSI at 30% | 96 | psi |
| PSI at 50% | 76 | psi |

| 28 Days + Exp Shim | | |
|---|---|---|
| Max Force on Restraint = | 2.79 | kips |
| Max Horiz Shrinkage = | 0.08763 | inches |
| Which Governs? | Restraint | |
| Temp | -8.15 | F |
| Horizontal Shrinkage | 0.0129 | inches |
| PSI at 10% | 220 | psi |
| PSI at 30% | 79 | psi |
| PSI at 50% | 63 | psi |

313 psi will be achieved at 10% Length when coefficient of friction is 0.47 This occurs with a temp applied of -12 F

High Shrinkage Mix - Dimensions 32.5 x 26

| | |
|---|---|
| Thermal Coeffiecient of Expansion | 0.0000055 |
| Mesh = | 40x40 |

| | | |
|---|---|---|
| Weight of Panel | 150 | pcf |
| | 26 | Feet |
| | 32.5 | Feet |
| | 6.5 | inches |
| | 68.66 | k |
| Max Reactions at Corners | 34.33 | |

| Material | Friction Coefficient | Force | |
|---|---|---|---|
| Welded | 1 | N/A | kips |
| PCI Value | 0.8 | 27.46 | kips |
| ACI 318 | 0.6 | 20.60 | kips |
| Exp Grout | 0.28 | 9.61 | kips |
| Exp Shim | 0.11 | 3.78 | kips |

| Max Shrinkage Values | | |
|---|---|---|
| 3 days | 0.01200 | inches |
| 7 days | 0.03878 | inches |
| 14 days | 0.06648 | inches |
| 28 Days | 0.10342 | inches |
| 730 Days | 0.22204 | inches |
| | | |
| 3 -> 730 Max Shrink = | 0.21004 | inches |
| 7 -> 730 Max Shrink = | 0.18326 | inches |
| 14 -> 730 Max Shrink = | 0.15556 | inches |
| 30 -> 730 Max Shrink = | 0.11862 | inches |

| High Shrinakge Mix ACI Output | | |
|---|---|---|
| Ambient Relative Humidity | 40 | In Relative Humidity in Percent |
| Volume | 790920 | in^3 |
| Area | 252486 | in^2 |
| Slump | 4 | In Inches |
| Fine Aggregates Percentage | 37.7 | Percentage is Weight vs Weight of Total Aggregate |
| Cement Content | 661 | Pounds Per Cubic Yard |
| Air Content | 0.04 | Air Content in Percentage |
| Length of Wall | 32.5 | in Feet |
| Time | 5000 | in Days |
| | | |
| Ysh Calculated by Equations = | 0.765 | |
| Total Shrinkage Present = | 0.23107 | inches |
| Inches/Inch | 0.00059 | in/in |
| vs | | |
| 1/8" in 20 FT Shrinkage Assump = | 0.203125 | inches |

Notes:
Red = Restraint Governs, Meaning that Slips before full Shrink
Green = Shrinkage Governs, Meaning That Restraint Can Hold
Yellow = Stresses are enough to develop cracking

## Tilt At

**Restraint** — Welded | PCI | ACI 318 | Exp Grout | Exp Shim

### 3 Days

| 3 Days + Welded | | |
|---|---|---|
| Max Force on Restraint = | N/A | kips |
| Max Horiz Shrinkage = | 0.21004 | inches |
| Which Governs? | Shrinkage | |
| Temp | | F |
| Horizontal Shrinkage | | inches |
| PSI at 10% | | psi |
| PSI at 30% | | psi |
| PSI at 50% | | psi |

| 3 Days + PCI | | |
|---|---|---|
| Max Force on Restraint = | 27.46 | kips |
| Max Horiz Shrinkage = | 0.21004 | inches |
| Which Governs? | Restraint | |
| Temp | -17.55 | F |
| Horizontal Shrinkage | 0.0376 | inches |
| PSI at 10% | 419 | psi |
| PSI at 30% | 151 | psi |
| PSI at 50% | 122 | psi |

| 3 Days + ACI 318 | | |
|---|---|---|
| Max Force on Restraint = | 20.60 | kips |
| Max Horiz Shrinkage = | 0.21004 | inches |
| Which Governs? | Restraint | |
| Temp | -14.95 | F |
| Horizontal Shrinkage | 0.0321 | inches |
| PSI at 10% | 361 | psi |
| PSI at 30% | 132 | psi |
| PSI at 50% | 106 | psi |

| 3 Days + Exp Grout | | |
|---|---|---|
| Max Force on Restraint = | 9.61 | kips |
| Max Horiz Shrinkage = | 0.21004 | inches |
| Which Governs? | Restraint | |
| Temp | -10.79 | F |
| Horizontal Shrinkage | 0.0231 | inches |
| PSI at 10% | 268 | psi |
| PSI at 30% | 96 | psi |
| PSI at 50% | 79.9 | psi |

| 3 Days + Exp Shim | | |
|---|---|---|
| Max Force on Restraint = | 3.78 | kips |
| Max Horiz Shrinkage = | 0.21004 | inches |
| Which Governs? | Restraint | |
| Temp | -8.55 | F |
| Horizontal Shrinkage | 0.0183 | inches |
| PSI at 10% | 207 | psi |
| PSI at 30% | 79.5 | psi |
| PSI at 50% | 65.7 | psi |

### 7 Days

| 7 Days + Welded | | |
|---|---|---|
| Max Force = | N/A | kips |
| Max Horiz Shrinkage = | 0.18326 | inches |
| Which Governs? | Shrinkage | |
| Temp | | F |
| Each Restraint Force | | kips |
| PSI at 10% | | psi |
| PSI at 30% | | psi |
| PSI at 50% | | psi |

| 7 Days + PCI | | |
|---|---|---|
| Max Force on Restraint = | 27.46 | kips |
| Max Horiz Shrinkage = | 0.18326 | inches |
| Which Governs? | Restraint | |
| Temp | -17.55 | F |
| Horizontal Shrinkage | 0.0376 | inches |
| PSI at 10% | 419 | psi |
| PSI at 30% | 151 | psi |
| PSI at 50% | 122 | psi |

| 7 Days + ACI 318 | | |
|---|---|---|
| Max Force on Restraint = | 20.60 | kips |
| Max Horiz Shrinkage = | 0.18326 | inches |
| Which Governs? | Restraint | |
| Temp | -14.95 | F |
| Horizontal Shrinkage | 0.0321 | inches |
| PSI at 10% | 361 | psi |
| PSI at 30% | 132 | psi |
| PSI at 50% | 106 | psi |

| 7 Days + Exp Grout | | |
|---|---|---|
| Max Force on Restraint = | 9.61 | kips |
| Max Horiz Shrinkage = | 0.18326 | inches |
| Which Governs? | Restraint | |
| Temp | -10.79 | F |
| Horizontal Shrinkage | 0.0231 | inches |
| PSI at 10% | 268 | psi |
| PSI at 30% | 96 | psi |
| PSI at 50% | 79.9 | psi |

| 7 Days + Exp Shim | | |
|---|---|---|
| Max Force on Restraint = | 3.78 | kips |
| Max Horiz Shrinkage = | 0.18326 | inches |
| Which Governs? | Restraint | |
| Temp | -8.55 | F |
| Horizontal Shrinkage | 0.0183 | inches |
| PSI at 10% | 207 | psi |
| PSI at 30% | 79.5 | psi |
| PSI at 50% | 65.7 | psi |

### 14 Days

| 14 Days + Welded | | |
|---|---|---|
| Max Force on Restraint = | N/A | kips |
| Max Horiz Shrinkage = | 0.15556 | inches |
| Which Governs? | Shrinkage | |
| Temp | | F |
| One Restraint Force | | kips |
| PSI at 10% | | psi |
| PSI at 30% | | psi |
| PSI at 50% | | psi |

| 14 Days + PCI | | |
|---|---|---|
| Max Force on Restraint = | 27.46 | kips |
| Max Horiz Shrinkage = | 0.15556 | inches |
| Which Governs? | Restraint | |
| Temp | -17.55 | F |
| Horizontal Shrinkage | 0.0376 | inches |
| PSI at 10% | 419 | psi |
| PSI at 30% | 151 | psi |
| PSI at 50% | 122 | psi |

| 14 Days + ACI 318 | | |
|---|---|---|
| Max Force on Restraint = | 20.60 | kips |
| Max Horiz Shrinkage = | 0.15556 | inches |
| Which Governs? | Restraint | |
| Temp | -14.95 | F |
| Horizontal Shrinkage | 0.0321 | inches |
| PSI at 10% | 361 | psi |
| PSI at 30% | 132 | psi |
| PSI at 50% | 106 | psi |

| 14 Days + Exp Grout | | |
|---|---|---|
| Max Force on Restraint = | 9.61 | kips |
| Max Horiz Shrinkage = | 0.15556 | inches |
| Which Governs? | Restraint | |
| Temp | -10.79 | F |
| Horizontal Shrinkage | 0.0231 | inches |
| PSI at 10% | 268 | psi |
| PSI at 30% | 96 | psi |
| PSI at 50% | 79.9 | psi |

| 14 Days + Exp Shim | | |
|---|---|---|
| Max Force on Restraint = | 3.78 | kips |
| Max Horiz Shrinkage = | 0.15556 | inches |
| Which Governs? | Restraint | |
| Temp | -8.55 | F |
| Horizontal Shrinkage | 0.0183 | inches |
| PSI at 10% | 207 | psi |
| PSI at 30% | 79.5 | psi |
| PSI at 50% | 65.7 | psi |

### 28 Days

| 28 Days + Welded | | |
|---|---|---|
| Max Force on Restraint = | N/A | kips |
| Max Horiz Shrinkage = | 0.11862 | inches |
| Which Governs? | Shrinkage | |
| Temp | -55 | F |
| One Restraint Force | 126.3 | kips |
| PSI at 10% | 1257 | psi |
| PSI at 30% | 451 | psi |
| PSI at 50% | 360 | psi |

| 28 Days + PCI | | |
|---|---|---|
| Max Force on Restraint = | 27.46 | kips |
| Max Horiz Shrinkage = | 0.11862 | inches |
| Which Governs? | Restraint | |
| Temp | -17.55 | F |
| Horizontal Shrinkage | 0.0376 | inches |
| PSI at 10% | 419 | psi |
| PSI at 30% | 151 | psi |
| PSI at 50% | 122 | psi |

| 28 Days + ACI 318 | | |
|---|---|---|
| Max Force on Restraint = | 20.60 | kips |
| Max Horiz Shrinkage = | 0.11862 | inches |
| Which Governs? | Restraint | |
| Temp | -14.95 | F |
| Horizontal Shrinkage | 0.0321 | inches |
| PSI at 10% | 361 | psi |
| PSI at 30% | 132 | psi |
| PSI at 50% | 106 | psi |

| 28 Days + Exp Grout | | |
|---|---|---|
| Max Force on Restraint = | 9.61 | kips |
| Max Horiz Shrinkage = | 0.11862 | inches |
| Which Governs? | Restraint | |
| Temp | -10.79 | F |
| Horizontal Shrinkage | 0.0231 | inches |
| PSI at 10% | 268 | psi |
| PSI at 30% | 96 | psi |
| PSI at 50% | 79.9 | psi |

| 28 Days + Exp Shim | | |
|---|---|---|
| Max Force on Restraint = | 3.78 | kips |
| Max Horiz Shrinkage = | 0.11862 | inches |
| Which Governs? | Restraint | |
| Temp | -8.55 | F |
| Horizontal Shrinkage | 0.0183 | inches |
| PSI at 10% | 207 | psi |
| PSI at 30% | 79.5 | psi |
| PSI at 50% | 65.7 | psi |

318 psi will be achieved at 10% when coefficient of friction is 0.45 This occurs with a temp applied of -13 F

Robertsons Shrinkage Mix - Dimensions 32.5 x 26

| | |
|---|---|
| Thermal Coeffiecient of Expansion | 0.0000055 |
| Mesh = | 40x40 |

| | | |
|---|---|---|
| Weight of Panel | 150 | pcf |
| | 26 | Feet |
| | 32.5 | Feet |
| | 6.5 | inches |
| | 68.66 | kips |
| Max Reactions at Corners | 34.33 | kips |

| Material | Friction Coefficient | Force | |
|---|---|---|---|
| Welded | 1 | N/A | kips |
| PCI Value | 0.8 | 27.46 | kips |
| ACI 318 | 0.6 | 20.60 | kips |
| Exp Grout | 0.28 | 9.61 | kips |
| Exp Shim | 0.11 | 3.78 | kips |

| Max Shrinkage Values | | |
|---|---|---|
| 3 days | 0.00957 | inches |
| 7 days | 0.03086 | inches |
| 14 days | 0.05291 | inches |
| 28 Days | 0.08231 | inches |
| 730 Days | 0.17671 | inches |
| 3->730 Max Shrink = | 0.16714 | inches |
| 7 ->730 Max Shrink = | 0.14585 | inches |
| 14->730 Max Shrink = | 0.1238 | inches |
| 30->730 Max Shrink = | 0.0944 | inches |

| Normal Shrinkage Mix | | |
|---|---|---|
| Ambient Relative Humidity | 40 | In Relative Humidity in Percent |
| Volume | 790920 | in^3 |
| Area | 252486 | in^2 |
| Slump | 4 | In Inches |
| Fine Aggregates Percentage | 27.2 | Percentage is Weight vs Weight of Total Aggregate |
| Cement Content | 573 | Pounds Per Cubic Yard |
| Air Content | 0.0125 | Air Content in Percentage |
| Length of Wall | 32.5 | in Feet |
| Time | 5000 | in Days |
| Ysh Calculated by Equations = | 0.609 | |
| Total Shrinkage Present = | 0.18390 | inches |
| Inches/Inch | 0.00047 | in/in |
| vs | | |
| 1/8" in 20 FT Shrinkage Assump = | 0.203125 | inches |

Notes:
Red = Restraint Governs, Meaning that Slips before full Shrink
Green = Shrinkage Governs, Meaning That Restraint Can Hold
Yellow = Stresses are enough to develop cracking

**Restraint** Welded | PCI | ACI 318 | Exp Grout | Exp Shim

**Tilt At**

3 Days

| 3 Days + Welded | | |
|---|---|---|
| Max Force on Restraint = | N/A | kips |
| Max Horiz Shrinkage = | 0.16714 | inches |
| Which Governs? | Shrinkage | |
| Temp | | F |
| One Restraint Force | | inches |
| PSI at 10% | | psi |
| PSI at 30% | | psi |
| PSI at 50% | | psi |

| 3 Days + PCI | | |
|---|---|---|
| Max Force on Restraint = | 27.46 | kips |
| Max Horiz Shrinkage = | 0.16714 | inches |
| Which Governs? | Restraint | |
| Temp | -17.55 | F |
| Horizontal Shrinkage | 0.0376 | inches |
| PSI at 10% | 419 | psi |
| PSI at 30% | 151 | psi |
| PSI at 50% | 122 | psi |

| 3 Days + ACI 318 | | |
|---|---|---|
| Max Force on Restraint = | 20.60 | kips |
| Max Horiz Shrinkage = | 0.16714 | inches |
| Which Governs? | Restraint | |
| Temp | -14.95 | F |
| Horizontal Shrinkage | 0.0321 | inches |
| PSI at 10% | 361 | psi |
| PSI at 30% | 132 | psi |
| PSI at 50% | 106 | psi |

| 3 Days + Exp Grout | | |
|---|---|---|
| Max Force on Restraint = | 9.61 | kips |
| Max Horiz Shrinkage = | 0.16714 | inches |
| Which Governs? | Restraint | |
| Temp | -10.79 | F |
| Horizontal Shrinkage | 0.0231 | inches |
| PSI at 10% | 268 | psi |
| PSI at 30% | 96 | psi |
| PSI at 50% | 79.9 | psi |

| 3 Days + Exp Shim | | |
|---|---|---|
| Max Force on Restraint = | 3.78 | kips |
| Max Horiz Shrinkage = | 0.16714 | inches |
| Which Governs? | Restraint | |
| Temp | -8.55 | F |
| Horizontal Shrinkage | 0.0183 | inches |
| PSI at 10% | 207 | psi |
| PSI at 30% | 79.5 | psi |
| PSI at 50% | 65.7 | psi |

7 Days

| 7 Days + Welded | | |
|---|---|---|
| Max Force on Restraint = | N/A | kips |
| Max Horiz Shrinkage = | 0.14585 | inches |
| Which Governs? | Shrinkage | |
| Temp | | F |
| One Restraint Force | | inches |
| PSI at 10% | | psi |
| PSI at 30% | | psi |
| PSI at 50% | | psi |

| 7 Days + PCI | | |
|---|---|---|
| Max Force on Restraint = | 27.46 | kips |
| Max Horiz Shrinkage = | 0.14585 | inches |
| Which Governs? | Restraint | |
| Temp | -17.55 | F |
| Horizontal Shrinkage | 0.0376 | inches |
| PSI at 10% | 419 | psi |
| PSI at 30% | 151 | psi |
| PSI at 50% | 122 | psi |

| 7 Days + ACI 318 | | |
|---|---|---|
| Max Force on Restraint = | 20.60 | kips |
| Max Horiz Shrinkage = | 0.14585 | inches |
| Which Governs? | Restraint | |
| Temp | -14.95 | F |
| Horizontal Shrinkage | 0.0321 | inches |
| PSI at 10% | 361 | psi |
| PSI at 30% | 132 | psi |
| PSI at 50% | 106 | psi |

| 7 Days + Exp Grout | | |
|---|---|---|
| Max Force on Restraint = | 9.61 | kips |
| Max Horiz Shrinkage = | 0.14585 | inches |
| Which Governs? | Restraint | |
| Temp | -10.79 | F |
| Horizontal Shrinkage | 0.0231 | inches |
| PSI at 10% | 268 | psi |
| PSI at 30% | 96 | psi |
| PSI at 50% | 79.9 | psi |

| 7 Days + Exp Shim | | |
|---|---|---|
| Max Force on Restraint = | 3.78 | kips |
| Max Horiz Shrinkage = | 0.14585 | inches |
| Which Governs? | Restraint | |
| Temp | -8.55 | F |
| Horizontal Shrinkage | 0.0183 | inches |
| PSI at 10% | 207 | psi |
| PSI at 30% | 79.5 | psi |
| PSI at 50% | 65.7 | psi |

14 Days

| 14 Days + Welded | | |
|---|---|---|
| Max Force on Restraint = | N/A | kips |
| Max Horiz Shrinkage = | 0.1238 | inches |
| Which Governs? | Shrinkage | |
| Temp | | F |
| One Restraint Force | | inches |
| PSI at 10% | | psi |
| PSI at 30% | | psi |
| PSI at 50% | | psi |

| 14 Days + PCI | | |
|---|---|---|
| Max Force on Restraint = | 27.46 | kips |
| Max Horiz Shrinkage = | 0.1238 | inches |
| Which Governs? | Restraint | |
| Temp | -17.55 | F |
| Horizontal Shrinkage | 0.0376 | inches |
| PSI at 10% | 419 | psi |
| PSI at 30% | 151 | psi |
| PSI at 50% | 122 | psi |

| 14 Days + ACI 318 | | |
|---|---|---|
| Max Force on Restraint = | 20.60 | kips |
| Max Horiz Shrinkage = | 0.1238 | inches |
| Which Governs? | Restraint | |
| Temp | -14.95 | F |
| Horizontal Shrinkage | 0.0321 | inches |
| PSI at 10% | 361 | psi |
| PSI at 30% | 132 | psi |
| PSI at 50% | 106 | psi |

| 14 Days + Exp Grout | | |
|---|---|---|
| Max Force on Restraint = | 9.61 | kips |
| Max Horiz Shrinkage = | 0.1238 | inches |
| Which Governs? | Restraint | |
| Temp | -10.79 | F |
| Horizontal Shrinkage | 0.0231 | inches |
| PSI at 10% | 268 | psi |
| PSI at 30% | 96 | psi |
| PSI at 50% | 79.9 | psi |

| 14 Days + Exp Shim | | |
|---|---|---|
| Max Force on Restraint = | 3.78 | kips |
| Max Horiz Shrinkage = | 0.1238 | inches |
| Which Governs? | Restraint | |
| Temp | -8.55 | F |
| Horizontal Shrinkage | 0.0183 | inches |
| PSI at 10% | 207 | psi |
| PSI at 30% | 79.5 | psi |
| PSI at 50% | 65.7 | psi |

28 Days

| 28 Days + Welded | | |
|---|---|---|
| Max Force on Restraint = | N/A | kips |
| Max Horiz Shrinkage = | 0.0944 | inches |
| Which Governs? | Shrinkage | |
| Temp | -44 | F |
| One Restraint Force | 97.3 | kips |
| PSI at 10% | 1011 | psi |
| PSI at 30% | 363 | psi |
| PSI at 50% | 289 | psi |

| 28 Days + PCI | | |
|---|---|---|
| Max Force on Restraint = | 27.46 | kips |
| Max Horiz Shrinkage = | 0.0944 | inches |
| Which Governs? | Restraint | |
| Temp | -17.55 | F |
| Horizontal Shrinkage | 0.0376 | inches |
| PSI at 10% | 419 | psi |
| PSI at 30% | 151 | psi |
| PSI at 50% | 122 | psi |

| 28 Days + ACI 318 | | |
|---|---|---|
| Max Force on Restraint = | 20.60 | kips |
| Max Horiz Shrinkage = | 0.0944 | inches |
| Which Governs? | Restraint | |
| Temp | -14.95 | F |
| Horizontal Shrinkage | 0.0321 | inches |
| PSI at 10% | 361 | psi |
| PSI at 30% | 132 | psi |
| PSI at 50% | 106 | psi |

| 28 Days + Exp Grout | | |
|---|---|---|
| Max Force on Restraint = | 9.61 | kips |
| Max Horiz Shrinkage = | 0.0944 | inches |
| Which Governs? | Restraint | |
| Temp | -10.79 | F |
| Horizontal Shrinkage | 0.0231 | inches |
| PSI at 10% | 268 | psi |
| PSI at 30% | 96 | psi |
| PSI at 50% | 79.9 | psi |

| 28 Days + Exp Shim | | |
|---|---|---|
| Max Force on Restraint = | 3.78 | kips |
| Max Horiz Shrinkage = | 0.0944 | inches |
| Which Governs? | Restraint | |
| Temp | -8.55 | F |
| Horizontal Shrinkage | 0.0183 | inches |
| PSI at 10% | 207 | psi |
| PSI at 30% | 79.5 | psi |
| PSI at 50% | 65.7 | psi |

318 psi will be achieved at 10% when coefficient of friction is 0.45 This occurs with a temp applied of -13 F

Robertsons Mix - Dimensions 32.5 x 26 - Investigating Early Cracking

Thermal Coeffiecient of Expansion 0.0000055
Mesh = 40x40

| | | |
|---|---|---|
| Weight of Panel | 150 | pcf |
| | 26 | Feet |
| | 32.5 | Feet |
| | 6.5 | inches |
| | 68.66 | kips |
| Max Reactions at Corners | 34.33 | kips |

| Material | Friction Coefficient | Force | |
|---|---|---|---|
| Welded | 1 | N/A | kips |
| PCI Value | 0.8 | 27.46 | kips |
| ACI 318 | 0.6 | 20.60 | kips |
| Exp Grout | 0.28 | 9.61 | kips |
| Exp Shim | 0.11 | 3.78 | kips |

| Max Shrinkage Values | | | | PSI | % of Total | PSI | 5root(F'c) | |
|---|---|---|---|---|---|---|---|---|
| 0 | days | 0 | | | | 0 | 0 | |
| 3 | days | 0.00957 | inches | 4000 | 0.583 | 2332 | 241.45 | psi |
| 7 | days | 0.03086 | inches | 4000 | 0.746 | 2984 | 273.13 | psi |
| 10 | days | 0.04115 | inches | 4000 | 0.791 | 3164 | 281.25 | psi |
| 14 | days | 0.05291 | inches | 4000 | 0.834 | 3336 | 288.79 | psi |
| 21 | days | 0.06944 | inches | 4000 | 0.909 | 3636 | 301.50 | psi |
| 30 | days | 0.1893 | inches | 4000 | 1 | 4000 | 316.23 | psi |
| | | | | | | | | |
| 3-> 21 Max Shrink = | | 0.05987 | inches | | | | | |
| 7 -> 21 Max Shrink = | | 0.03858 | inches | | | | | |
| 10->21 Max Shrink = | | 0.02829 | inches | | | | | |
| 14-> 21 Max Shrink = | | 0.01653 | incches | | | | | |

| Max Shrinkage Values | | | PSI | % of Total | 5root(F'c) | |
|---|---|---|---|---|---|---|
| 3 days | 0.00957 | inches | 4000 | 0.583 | 241.45 | psi |
| 7 days | 0.03086 | inches | 4000 | 0.746 | 273.13 | psi |
| 10 days | 0.04115 | inches | 4000 | 0.791 | 281.25 | psi |
| 14 days | 0.05291 | inches | 4000 | 0.834 | 288.79 | psi |
| | | | | | | |
| 3-> 14 Max Shrink = | 0.04334 | inches | | | | |
| 7 -> 14 Max Shrink = | 0.02205 | inches | | | | |
| 10->14 Max Shrink = | 0.01176 | inches | | | | |

| Max Shrinkage Values | | | PSI | % of Total | 5root(F'c) | |
|---|---|---|---|---|---|---|
| 3 days | 0.00957 | inches | 4000 | 0.583 | 241.45 | psi |
| 7 days | 0.03086 | inches | 4000 | 0.746 | 273.13 | psi |
| | | | | | | |
| 3 -> 7 Max Shrink = | 0.02129 | inches | | | | |

| Mix 2 | | |
|---|---|---|
| Ambient Relative Humidity | 40 | In Relative Humidity in Percent |
| Volume | 790920 | in^3 |
| Area | 252486 | in^2 |
| Slump | 4 | In Inches |
| Fine Aggregates Percentage | 27.2 | Percentage is Weight vs Weight of Total Aggregate |
| Cement Content | 573 | Pounds Per Cubic Yard |
| Air Content | 0.0125 | Air Content in Percentage |
| Length of Wall | 32.5 | in Feet |
| Time | 5000 | in Days |
| | | |
| Ysh Calculated by Equations = | 0.609 | |
| Total Shrinkage Present = | 0.18390 | inches |
| Inches/Inch | 0.00047 | in/in |
| vs | | |
| 1/8" in 20 FT Shrinkage Assump = | 0.203125 | inches |

Stresses that occur from Tilt Date until 21 Days

Notes:
Red = Restraint Governs, Meaning that Slips before full Shrink
Green = Shrinkage Governs, Meaning That Restraint Can Hold
Yellow = Stresses are enough to develop cracking

**Restraint** Welded | PCI | ACI 318 | Exp Grout | Exp Shim

**Tilt At**

3 Days

| 3 Days + Welded | | |
|---|---|---|
| Max Force on Restraint = | N/A | kips |
| Max Horiz Shrinkage = | 0.05987 | inches |
| Which Governs? | Shrinkage | |
| Temp | | F |
| One Restraint Force | | kips |
| PSI at 10% | | psi |
| PSI at 30% | | psi |
| PSI at 50% | | psi |

| 3 Days + PCI | | |
|---|---|---|
| Max Force on Restraint = | 27.46 | kips |
| Max Horiz Shrinkage = | 0.05987 | inches |
| Which Governs? | Restraint | |
| Temp | -17.55 | F |
| Horizontal Shrinkage | 0.0376 | inches |
| PSI at 10% | 419 | psi |
| PSI at 30% | 151 | psi |
| PSI at 50% | 122 | psi |

| 3 Days + ACI 318 | | |
|---|---|---|
| Max Force on Restraint = | 20.60 | kips |
| Max Horiz Shrinkage = | 0.05987 | inches |
| Which Governs? | Restraint | |
| Temp | -14.95 | F |
| Horizontal Shrinkage | 0.0321 | inches |
| PSI at 10% | 361 | psi |
| PSI at 30% | 132 | psi |
| PSI at 50% | 106 | psi |

| 3 Days + Exp Grout | | |
|---|---|---|
| Max Force on Restraint = | 9.61 | kips |
| Max Horiz Shrinkage = | 0.05987 | inches |
| Which Governs? | Restraint | |
| Temp | -10.79 | F |
| Horizontal Shrinkage | 0.0231 | inches |
| PSI at 10% | 268 | psi |
| PSI at 30% | 96 | psi |
| PSI at 50% | 79.9 | psi |

| 3 Days + Exp Shim | | |
|---|---|---|
| Max Force on Restraint = | 3.78 | kips |
| Max Horiz Shrinkage = | 0.05987 | inches |
| Which Governs? | Restraint | |
| Temp | -8.55 | F |
| Horizontal Shrinkage | 0.0183 | inches |
| PSI at 10% | 207 | psi |
| PSI at 30% | 79.5 | psi |
| PSI at 50% | 65.7 | psi |

7 Days

| 7 Days + Welded | | |
|---|---|---|
| Max Force on Restraint = | N/A | kips |
| Max Horiz Shrinkage = | 0.03858 | inches |
| Which Governs? | Shrinkage | |
| Temp | | F |
| One Restraint Force | | kips |
| PSI at 10% | | psi |
| PSI at 30% | | psi |
| PSI at 50% | | psi |

| 7 Days + PCI | | |
|---|---|---|
| Max Force = | 27.46 | kips |
| Max Shrinkage = | 0.03858 | inches |
| Which Governs? | Restraint | |
| Temp | -17.55 | F |
| Shrinkage | 0.0376 | inches |
| PSI at 10% | 419 | psi |
| PSI at 30% | 151 | psi |
| PSI at 50% | 122 | psi |

| 7 Days + ACI 318 | | |
|---|---|---|
| Max Force on Restraint = | 20.60 | kips |
| Max Horiz Shrinkage = | 0.03858 | inches |
| Which Governs? | Restraint | |
| Temp | -14.95 | F |
| Horizontal Shrinkage | 0.0321 | inches |
| PSI at 10% | 361 | psi |
| PSI at 30% | 132 | psi |
| PSI at 50% | 106 | psi |

| 7 Days + Exp Grout | | |
|---|---|---|
| Max Force on Restraint = | 9.61 | kips |
| Max Horiz Shrinkage = | 0.03858 | inches |
| Which Governs? | Restraint | |
| Temp | -10.79 | F |
| Horizontal Shrinkage | 0.0231 | inches |
| PSI at 10% | 268 | psi |
| PSI at 30% | 96 | psi |
| PSI at 50% | 79.9 | psi |

| 7 Days + Exp Shim | | |
|---|---|---|
| Max Force on Restraint = | 3.78 | kips |
| Max Horiz Shrinkage = | 0.03858 | inches |
| Which Governs? | Restraint | |
| Temp | -8.55 | F |
| Horizontal Shrinkage | 0.0183 | inches |
| PSI at 10% | 207 | psi |
| PSI at 30% | 79.5 | psi |
| PSI at 50% | 65.7 | psi |

10 Days

| 10 Days + Welded | | |
|---|---|---|
| Max Force on Restraint = | N/A | kips |
| Max Horiz Shrinkage = | 0.02829 | inches |
| Which Governs? | Shrinkage | |
| Temp | -13.2 | F |
| One Restraint Force | 15.8 | kips |
| PSI at 10% | 322 | psi |
| PSI at 30% | 118 | psi |
| PSI at 50% | 95 | psi |

| 10 Days + PCI | | |
|---|---|---|
| Max Force on Restraint = | 27.46 | kips |
| Max Horiz Shrinkage = | 0.02829 | inches |
| Which Governs? | Shrinkage | |
| Temp | -13.2 | F |
| One Restraint Force | 15.8 | kips |
| PSI at 10% | 322 | psi |
| PSI at 30% | 118 | psi |
| PSI at 50% | 95 | psi |

| 10 Days + ACI 318 | | |
|---|---|---|
| Max Force on Restraint = | 20.60 | kips |
| Max Horiz Shrinkage = | 0.02829 | inches |
| Which Governs? | Shrinkage | |
| Temp | -13.2 | F |
| One Restraint Force | 15.8 | kips |
| PSI at 10% | 322 | psi |
| PSI at 30% | 118 | psi |
| PSI at 50% | 95 | psi |

| 10 Days + Exp Grout | | |
|---|---|---|
| Max Force on Restraint = | 9.61 | kips |
| Max Horiz Shrinkage = | 0.02829 | inches |
| Which Governs? | Restraint | |
| Temp | -10.79 | F |
| Horizontal Shrinkage | 0.0231 | inches |
| PSI at 10% | 268 | psi |
| PSI at 30% | 96 | psi |
| PSI at 50% | 79.9 | psi |

| 10 Days + Exp Shim | | |
|---|---|---|
| Max Force on Restraint = | 3.78 | kips |
| Max Horiz Shrinkage = | 0.02829 | inches |
| Which Governs? | Restraint | |
| Temp | -8.55 | F |
| Horizontal Shrinkage | 0.0183 | inches |
| PSI at 10% | 207 | psi |
| PSI at 30% | 79.5 | psi |
| PSI at 50% | 65.7 | psi |

14 Days

| 14 Days + Welded | | |
|---|---|---|
| Max Force on Restraint = | N/A | kips |
| Max Horiz Shrinkage = | 0.01653 | inches |
| Which Governs? | Shrinkage | |
| Temp | -7.7 | F |
| One Restraint Force | 1.464 | kips |
| PSI at 10% | 202 | psi |
| PSI at 30% | 74 | psi |
| PSI at 50% | 60 | psi |

| 14 Days + PCI | | |
|---|---|---|
| Max Force on Restraint = | 27.46 | kips |
| Max Horiz Shrinkage = | 0.01653 | inches |
| Which Governs? | Shrinkage | |
| Temp | -7.7 | F |
| One Restraint Force | 1.464 | kips |
| PSI at 10% | 202 | psi |
| PSI at 30% | 74 | psi |
| PSI at 50% | 60 | psi |

| 14 Days + ACI 318 | | |
|---|---|---|
| Max Force on Restraint = | 20.60 | kips |
| Max Horiz Shrinkage = | 0.01653 | inches |
| Which Governs? | Shrinkage | |
| Temp | -7.7 | F |
| One Restraint Force | 1.464 | kips |
| PSI at 10% | 202 | psi |
| PSI at 30% | 74 | psi |
| PSI at 50% | 60 | psi |

| 14 Days + Exp Grout | | |
|---|---|---|
| Max Force on Restraint = | 9.61 | kips |
| Max Horiz Shrinkage = | 0.01653 | inches |
| Which Governs? | Shrinkage | |
| Temp | -7.7 | F |
| One Restraint Force | 1.464 | kips |
| PSI at 10% | 202 | psi |
| PSI at 30% | 74 | psi |
| PSI at 50% | 60 | psi |

| 14 Days + Exp Shim | | |
|---|---|---|
| Max Force on Restraint = | 3.78 | kips |
| Max Horiz Shrinkage = | 0.01653 | inches |
| Which Governs? | Shrinkage | |
| Temp | -7.7 | F |
| One Restraint Force | 1.464 | kips |
| PSI at 10% | 202 | psi |
| PSI at 30% | 74 | psi |
| PSI at 50% | 60 | psi |

| Stresses that occur from Tilt Date until 14 Days |
|---|
| Notes:<br>Red = Restraint Governs, Meaning that Slips before full Shrink<br>Green = Shrinkage Governs, Meaning That Restraint Can Hold<br>Yellow = Stresses are enough to develop cracking |

**Restraint**

**Tilt At**

3 Days

Welded

| 3 Days + Welded | | |
|---|---|---|
| Max Force on Restraint = | N/A | kips |
| Max Horiz Shrinkage = | 0.04334 | inches |
| Which Governs? | Shrinkage | |
| Temp | | kips |
| One Restraint Force | | inches |
| PSI at 10% | | psi |
| PSI at 30% | | psi |
| PSI at 50% | | psi |

PCI

| 3 Days + PCI | | |
|---|---|---|
| Max Force on Restraint = | 27.46 | kips |
| Max Horiz Shrinkage = | 0.04334 | inches |
| Which Governs? | Restraint | |
| Temp | -17.55 | F |
| Horizontal Shrinkage | 0.0376 | inches |
| PSI at 10% | 419 | psi |
| PSI at 30% | 151 | psi |
| PSI at 50% | 122 | psi |

ACI 318

| 3 Days + ACI 318 | | |
|---|---|---|
| Max Force on Restraint = | 20.60 | kips |
| Max Horiz Shrinkage = | 0.04334 | inches |
| Which Governs? | Restraint | |
| Temp | -14.95 | F |
| Horizontal Shrinkage | 0.0321 | inches |
| PSI at 10% | 361 | psi |
| PSI at 30% | 132 | psi |
| PSI at 50% | 106 | psi |

Exp Grout

| 3 Days + Exp Grout | | |
|---|---|---|
| Max Force on Restraint = | 9.61 | kips |
| Max Horiz Shrinkage = | 0.04334 | inches |
| Which Governs? | Restraint | |
| Temp | -10.79 | F |
| Horizontal Shrinkage | 0.0231 | inches |
| PSI at 10% | 268 | psi |
| PSI at 30% | 96 | psi |
| PSI at 50% | 79.9 | psi |

Exp Shim

| 3 Days + Exp Shim | | |
|---|---|---|
| Max Force on Restraint = | 3.78 | kips |
| Max Horiz Shrinkage = | 0.04334 | inches |
| Which Governs? | Restraint | |
| Temp | -8.55 | F |
| Horizontal Shrinkage | 0.0183 | inches |
| PSI at 10% | 207 | psi |
| PSI at 30% | 79.5 | psi |
| PSI at 50% | 65.7 | psi |

7 Days

| 7 Days + Welded | | |
|---|---|---|
| Max Force on Restraint = | N/A | kips |
| Max Horiz Shrinkage = | 0.02205 | inches |
| Which Governs? | Shrinkage | |
| Temp | -10.3 | F |
| One Restraint Force | 8.326 | kips |
| PSI at 10% | 257 | psi |
| PSI at 30% | 95 | psi |
| PSI at 50% | 77 | psi |

| 7 Days + PCI | | |
|---|---|---|
| Max Force on Restraint = | 27.46 | kips |
| Max Horiz Shrinkage = | 0.02205 | inches |
| Which Governs? | Shrinkage | |
| Temp | -10.3 | F |
| One Restraint Force | 8.326 | kips |
| PSI at 10% | 257 | psi |
| PSI at 30% | 95 | psi |
| PSI at 50% | 77 | psi |

| 7 Days + ACI 318 | | |
|---|---|---|
| Max Force on Restraint = | 20.60 | kips |
| Max Horiz Shrinkage = | 0.02205 | inches |
| Which Governs? | Shrinkage | |
| Temp | -10.3 | F |
| One Restraint Force | 8.326 | kips |
| PSI at 10% | 257 | psi |
| PSI at 30% | 95 | psi |
| PSI at 50% | 77 | psi |

| 7 Days + Exp Grout | | |
|---|---|---|
| Max Force on Restraint = | 9.61 | kips |
| Max Horiz Shrinkage = | 0.02205 | inches |
| Which Governs? | Restraint | |
| Temp | -10.3 | F |
| One Restraint Force | 8.326 | kips |
| PSI at 10% | 257 | psi |
| PSI at 30% | 95 | psi |
| PSI at 50% | 77 | psi |

| 7 Days + Exp Shim | | |
|---|---|---|
| Max Force on Restraint = | 3.78 | kips |
| Max Horiz Shrinkage = | 0.02205 | inches |
| Which Governs? | Restraint | |
| Temp | -8.55 | F |
| Horizontal Shrinkage | 0.0183 | inches |
| PSI at 10% | 207 | psi |
| PSI at 30% | 79.5 | psi |
| PSI at 50% | 65.7 | psi |

10 Days

| 10 Days + Welded | | |
|---|---|---|
| Max Force on Restraint = | N/A | kips |
| Max Horiz Shrinkage = | 0.01176 | inches |
| Which Governs? | Shrinkage | |
| Temp | -5.5 | F |
| One Restraint Force | -4.3 | kips |
| PSI at 10% | 150 | psi |
| PSI at 30% | 56 | psi |
| PSI at 50% | 46 | psi |

| 10 Days + PCI | | |
|---|---|---|
| Max Force on Restraint = | 27.46 | kips |
| Max Horiz Shrinkage = | 0.01176 | inches |
| Which Governs? | Shrinkage | |
| Temp | -5.5 | F |
| One Restraint Force | -4.3 | kips |
| PSI at 10% | 150 | psi |
| PSI at 30% | 56 | psi |
| PSI at 50% | 46 | psi |

| 10 Days + ACI 318 | | |
|---|---|---|
| Max Force on Restraint = | 20.60 | kips |
| Max Horiz Shrinkage = | 0.01176 | inches |
| Which Governs? | Shrinkage | |
| Temp | -5.5 | F |
| One Restraint Force | -4.3 | kips |
| PSI at 10% | 150 | psi |
| PSI at 30% | 56 | psi |
| PSI at 50% | 46 | psi |

| 10 Days + Exp Grout | | |
|---|---|---|
| Max Force on Restraint = | 9.61 | kips |
| Max Horiz Shrinkage = | 0.01176 | inches |
| Which Governs? | Shrinkage | |
| Temp | -5.5 | F |
| One Restraint Force | -4.3 | kips |
| PSI at 10% | 150 | psi |
| PSI at 30% | 56 | psi |
| PSI at 50% | 46 | psi |

| 10 Days + Exp Shim | | |
|---|---|---|
| Max Force on Restraint = | 3.78 | kips |
| Max Horiz Shrinkage = | 0.01176 | inches |
| Which Governs? | Restraint | |
| Temp | -5.7 | F |
| Horizontal Shrinkage | 0.0122 | inches |
| PSI at 10% | 152 | psi |
| PSI at 30% | 58 | psi |
| PSI at 50% | 48 | psi |

| Stresses that occur from Tilt Date until 7 Days |
|---|
| Notes:<br>Red = Restraint Governs, Meaning that Slips before full Shrink<br>Green = Shrinkage Governs, Meaning That Restraint Can Hold<br>Yellow = Stresses are enough to develop cracking |

**Restraint**

**Tilt At**

3 Days

Welded

| 3 Days + Welded | | |
|---|---|---|
| Max Force on Restraint = | N/A | kips |
| Max Horiz Shrinkage = | 0.02129 | inches |
| Which Governs? | Shrinkage | |
| Temp | -9.9 | F |
| One Restraint Force | 7.27 | kips |
| PSI at 10% | 246 | psi |
| PSI at 30% | 91 | psi |
| PSI at 50% | 74 | psi |

PCI

| 3 Days + PCI | | |
|---|---|---|
| Max Force on Restraint = | 27.46 | kips |
| Max Horiz Shrinkage = | 0.02129 | inches |
| Which Governs? | Shrinkage | |
| Temp | -9.9 | F |
| One Restraint Force | 7.27 | kips |
| PSI at 10% | 246 | psi |
| PSI at 30% | 91 | psi |
| PSI at 50% | 74 | psi |

ACI 318

| 3 Days + ACI 318 | | |
|---|---|---|
| Max Force on Restraint = | 20.60 | kips |
| Max Horiz Shrinkage = | 0.02129 | inches |
| Which Governs? | Shrinkage | |
| Temp | -9.9 | F |
| One Restraint Force | 7.27 | kips |
| PSI at 10% | 246 | psi |
| PSI at 30% | 91 | psi |
| PSI at 50% | 74 | psi |

Exp Grout

| 3 Days + Exp Grout | | |
|---|---|---|
| Max Force on Restraint = | 9.61 | kips |
| Max Horiz Shrinkage = | 0.02129 | inches |
| Which Governs? | Shrinkage | |
| Temp | -9.9 | F |
| One Restraint Force | 7.27 | kips |
| PSI at 10% | 246 | psi |
| PSI at 30% | 91 | psi |
| PSI at 50% | 74 | psi |

Exp Shim

| 3 Days + Exp Shim | | |
|---|---|---|
| Max Force on Restraint = | 3.78 | kips |
| Max Horiz Shrinkage = | 0.02129 | inches |
| Which Governs? | Restraint | |
| Temp | -8.55 | F |
| Horizontal Shrinkage | 0.0183 | inches |
| PSI at 10% | 207 | psi |
| PSI at 30% | 79.5 | psi |
| PSI at 50% | 65.7 | psi |

| |
|---|
| Notes: |
| Red = Restraint Governs, Meaning that Slips before full Shrink |
| Green = Shrinkage Governs, Meaning That Restraint Can Hold |
| Yellow = Stresses are enough to develop cracking |

32.5' wide x 26' tall Panel 6.5" Thick

## Experimental Grout Pads and 1 #4 Rebar

| Grout Pad Force Derivation | | | | Rebar Force Derivation | |
|---|---|---|---|---|---|
| 34.33 kips (dead load) x 0.28 = | 9.61 | kips | | AsFy = 0.2in^2*(60,000 ksi) | |
| | | | | = 12 kips | |

| Experimental Grout | | | | Restraints from (1) #4 Rebar | | | Combined Restraint Force | | |
|---|---|---|---|---|---|---|---|---|---|
| Max Force = | 9.61 | kips | | 12 | kips | | Max Force = | 21.61 | kips |
| Max Shrinkage = | | inches | | | | | Max Shrinkage = | | |
| Which Governs? | Restraint | | | | | | Which Governs? | Restraint | |
| Temp | -10.79 | F | + | | | = | Temp | -15.35 | F |
| Shrinkage | 0.0231 | inches | | | | | Shrinkage | 0.0329 | inches |
| PSI at 10% | 268 | psi | | | | | PSI at 10% | 370 | psi |
| PSI at 30% | 96 | psi | | | | | PSI at 30% | 135 | psi |
| PSI at 50% | 79.9 | psi | | | | | PSI at 50% | 108 | psi |

| Restraint Need to Crack Panel | | |
|---|---|---|
| Max Force = | 15.45 | kips |
| Max Shrinkage = | | |
| Which Governs? | Restraint | |
| Temp | -13 | F |
| Shrinkage | 0.0279 | inches |
| PSI at 10% | 318 | psi |
| PSI at 30% | 116 | psi |
| PSI at 50% | 93 | psi |

## Shim Packs and 1 #4 Rebar

| Shim Pack Force Derivation | | | | Rebar Force Derivation | |
|---|---|---|---|---|---|
| 34.33 kips (dead load) x .083 = | 2.85 | kips | | AsFy = 0.2in^2*(60,000 ksi) | |
| | | | | = 12 kips | |

| Shim Pack | | | | Restraints from (1) #4 Rebar | | | Combined Restraint Force | | |
|---|---|---|---|---|---|---|---|---|---|
| Max Force = | 2.85 | kips | | 12 | kips | | Max Force = | 14.85 | kips |
| Max Shrinkage = | | inches | | | | | Max Shrinkage = | | |
| Which Governs? | Restraint | | | | | | Which Governs? | Restraint | |
| Temp | -8.22 | F | + | | | = | Temp | -12.77 | F |
| Shrinkage | 0.0176 | inches | | | | | Shrinkage | 0.0274 | inches |
| PSI at 10% | 211 | psi | | | | | PSI at 10% | 313 | psi |
| PSI at 30% | 78 | psi | | | | | PSI at 30% | 114 | psi |
| PSI at 50% | 63 | psi | | | | | PSI at 50% | 91 | psi |

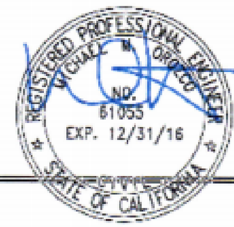
| Restraint Need to Crack Panel | | |
|---|---|---|
| Max Force = | 15.45 | kips |
| Max Shrinkage = | 0.14585 | |
| Which Governs? | Restraint | |
| Temp | -13 | F |
| Shrinkage | 0.0279 | inches |
| PSI at 10% | 318 | psi |
| PSI at 30% | 116 | psi |
| PSI at 50% | 93 | psi |

# APPENDIX B

Grout Mix Design used for Grout Pad in Friction Experiment:

# ROBERTSON'S

ROCK * SAND * BASE MATERIALS
READY MIX CONCRETE




Date: 9/19/2016

**Concrete Mix Design #: RS300P41**

| | | | |
|---|---|---|---|
| Project: | Monster Energy Distribution Center - Rialto | | |
| Contractor: | Hallin & Herrera, Inc. | | |
| Description: | 3000 psi 3/8" Pump Mix | **Grout Under Panels** | |
| Strength (f'c): | 3000 psi | W/C ratio: | 0.60 |
| Slump: | 4 " | Sack Content: | 7.00 sk. |
| Max. Size of Agg.: | 3/8 " | Gal/sk.: | 6.71 |
| Pump Type: | 2" line pump | Un. Wt.: | 139.5 |

**ALL CONCRETE IS MIXED AND DELIVERED IN ACCORDANCE WITH ASTM C-94**

*Aggregate Weights are SSD; Moisture in Aggregates Must be Considered When Determining Total Mix Water*

| **Contents:** | | **MIX DESIGN PROPORTION** Batch Wt. | %used | Sp. Gr. | Volume |
|---|---|---|---|---|---|
| Cement (ASTM C-150) | | 658 | 100 | 3.15 | 3.35 |
| Fly Ash-Class F (ASTM C-618) | | 0 | 0 | 2.33 | 0.00 |
| Sand | | 1895 | 70 | 2.62 | 11.60 |
| 1-1/2" x 3/4" | | 0 | 0 | 2.67 | 0.00 |
| 1" x #4 | | 0 | 0 | 2.65 | 0.00 |
| 3/8" x #8 | | 822 | 30 | 2.65 | 4.97 |
| Water | 47.0 gal. | 391.5 | | | 6.27 |
| Entrapped Air | 3 % | | | | 0.81 |
| | Wt. = | 3767 | | Vol. = | 27.00 |

**ADMIXTURES :**
None

Remark: The project engineer should review this mix to ensure compliance to the project specifications

**PLEASE FORWARD STRENGTH DATA TO ROBERTSON'S TECHNICAL SERVICES FOR STATISTICAL ANALYSIS**

| Size | % | AGGREGATE GRADATIONS 2" | 1 1/2" | 1" | 3/4" | 1/2" | 3/8" | No 4 | No 8 | No 16 | No 30 | No 50 | No 100 | No 200 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 1/2" | 0 | 100 | 95 | 33 | 7 | 3 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1" | 0 | 100 | 100 | 95 | 70 | 38 | 12 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3/8" | 30 | 100 | 100 | 100 | 100 | 100 | 96 | 18 | 2 | 1 | 1 | 0 | 0 | 0 |
| WCS | 70 | 100 | 100 | 100 | 100 | 100 | 100 | 98 | 80 | 60 | 39 | 18 | 6 | 2 |
| Combined | 100 | 100 | 100 | 100 | 100 | 100 | 99 | 74 | 57 | 42 | 28 | 13 | 4 | 1 |

Sand Source : Robertson's Rialto
Rock Source : Robertson's Rialto
Cement : Portland Cement Type II/V
Fly Ash : Class F

Aggregates meet ASTM C-33

(951) 685-2200 ext 6381    P.O. Box 3600 Corona, CA 92878    Fax (951) 280-1429

Concrete Test Block Mix Design, ARCE Department, Cal Poly, San Luis Obispo, CA:

| Material | Quantity (lbs) |
| --- | --- |
| Water | 12.25 |
| Cement | 21.25 |
| Coarse Aggregate | 56.25 |
| Fine Aggregate | 34.5 |