ANALYSIS OF THE HEAT OF HYDRATION IN MASS CONCRETE STRUCTURES

by

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Thesis directed by Professor Chengyu Li

ABSTRACT

This thesis analyzes the temperature development and distribution in mass concrete structures, specifically a steam turbine generator pedestal, by comparing field data with a simulated finite element model in Ansys. A stress analysis was also performed to determine how the thermal loading impacts different areas of the structure.

The chemical reactions that occur as a result of combining cement and water cause significant heat generation in the concrete mixture. For mass concrete structures, the heat that is generated is dissipated quickly at the surface, but is retained at the center of the structure, achieving large maximum temperatures. The maximum temperature and temperature differential pose a risk to the structural integrity of the structure as excessive temperatures can induce tensile stresses in the structure, resulting in cracking. The temperatures, and therefore stresses, that are developed are time dependent and most commonly occur during the first few days after casting.

Temperature data was recorded for each of the concrete pours associated with the steam turbine generator pedestal, including the basemat, columns (8), and tabletop, with the use of thermocouples at select locations in the structure. The data was analyzed for the time history of the temperatures and the differentials.
A model was created in Ansys with a variety of input parameters to perform a thermal analysis by simulating the temperature results as seen in the field. The model reasonably represented the field results for each structure and proved to be a powerful tool to analyze scenarios for future pedestal structures. Using the same model, a parametric study was completed to understand the impacts of a variety of variables.

The thermal analysis was then applied to a structural analysis of the same model. The temperatures were applied as thermal loads at each nodal location of the structure. The model simulated how the stresses are developed over time and where they occur. Large stresses were seen at the surface and corners as a result of self-stress; other large stresses were seen towards the bottom of the structure as a result of restraint-stress.

The form and content of this abstract are approved. I recommend its publication.

Approved: Chengyu Li
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CHAPTER I

INTRODUCTION

Background

Portland cement is the key component that makes concrete a versatile material in many forms of construction. Cement allows concrete to be in a fluid initial state and harden over time to dramatically increase its strength. The hardening of concrete is a result of the hydration reaction which occurs between cement and water. This is an exothermic reaction generating heat within the structure. For small concrete operations, the heat generated doesn’t pose a risk to the structural integrity as the heat is dissipated quickly from the surface. However, for large concrete structures, the heat is released from the surface, but the heat generated in the middle is unable to dissipate due to the low thermal conductivity of concrete. The maximum temperatures and the temperature differential of the structure must be properly managed through the design and construction phases. If the temperatures exceed the allowable amounts, several issues can occur, however the most common issue is concrete cracking. The cracking is a result of thermal expansion and contraction between the middle and surface of the concrete and ultimately create tensile stresses which exceed the structure’s limit.

Understanding the behavior of concrete under extreme thermal conditions is essential in developing a thermal control plan which begins at the design phase. The thermal plan includes the concrete mix design, pre-cooling techniques, and post-cooling techniques. Several preventative measures can be set in place to manage these temperatures and the negative effects.
Research Approach

The purpose of this thesis is to assess how large concrete structures, classified as mass concrete, behave when a significant amount of heat is generated through hydration reactions. Field data from over 2,100 cubic yards of concrete from a power plant project have been analyzed to demonstrate the temperature patterns of the system and the resulting stresses that are developed. The data provides concrete pours under different initial conditions, concrete mix designs, and geometry. This allows observation of the thermal behavior and to determine how the above parameters impact the temperature results. In general, the concrete associated with mass concrete pours had a large increase in temperature during the first twelve hours. From there, the rate of temperature increase tapered, until the maximum was achieved. For the remaining hours that data was logged, the temperature of the structure gradually cooled at a steady rate. The temperature data was analyzed to determine the maximum temperature, as well as the temperature differential throughout the system.

The results provided in the field data are then simulated in the program, Ansys. Ansys can simulate the temperature and stresses within a system. Understanding the simulation capabilities, as it relates to field data, will provide valuable information to develop a thermal plan in future projects.

The thesis is presented in five different chapters – Introduction, Literature Review, Historic Field Data Analysis, Transient Thermal Analysis Simulation, and Thermal Stress Simulation.
Chapter II provides a brief history of concrete and how Portland cement evolved. This section also provides a summary of the material and thermal properties associated with concrete. These properties and the materials used play a large role in the chemical reactions that occur in concrete. These reactions are discussed further in Chapter II, as well.

Chapter III analyzes the temperature data from several mass concrete pours for a power plant project. The data assesses the concrete for the basemat, columns, and the tabletop. Several plots to illustrate the temperature curves and thermal differentials are provided.

Chapter IV simulates the temperature results from Chapter III through a finite element transient thermal analysis. These results are compared back to the actual field data for accuracy. Additionally, other simulations are run to consider different construction methods its impact on the thermal behavior of the structure.

Chapter V builds on the temperature analysis from Chapter IV and analyzes the thermal stresses that are developed as a result of the temperatures in the system. These stresses are simulated to determine where tensile stresses develop in the structure and how they change with respect to time.
CHAPTER II
LITERATURE REVIEW

History of Concrete and Cement

Every region of the world has its own history of how concrete and cement were developed and utilized. The invention of concrete dramatically changed the type of building and infrastructure that could be constructed. Concrete could provide strength and versatility to create immense structures that was once not possible. Concrete is prevalently used in today’s construction industry and is continuing to evolve and expand its potential.

The first uses of concrete date back to 3000 BC in Egypt. Their concrete was blocks composed of straw and straw in combination with gypsum and lime to create adherence of blocks. This combination of materials made the Egyptian Pyramids, at 455 feet high, a possibility. (Concrete and Cement History Timeline, 2017). New and innovative findings continued to develop throughout the years. The Greeks utilized a natural pozzolan that developed hydraulic properties when mixed with lime. Although the Greeks made this finding, the Romans mastered this form of construction by 200 BC. The Romans found great success in utilizing brick to serve as forms to the large limestone rocks secured with mortar. As the Roman construction became more immense, the need for a more durable material arose. Romans discovered a volcanic sand, pozzuolana that reacted with lime and water. The reaction caused hydration resulting in a durable, water resistant, and solid material. This material and methodology was used to create well-known structures, such as the Colosseum, Roman Baths, and the Pantheon (Gromicko & Vangeem).
While the early uses of concrete occurred very early on, it wasn’t until 1824 that Portland cement was invented by Joseph Aspdin. The creation of Portland cement is a major testament to the strength and durability of modern concrete (Concrete and Cement History Timeline, 2017).

**Material Properties of Concrete**

Despite the various forms of concrete in the early development phases, the concrete mix designs have become more standardized. Concrete is primarily made up of Portland cement, aggregate, and water. Depending on the application, pozzolans and admixtures can be used to alter the concrete properties. Concrete forms as a result of the cement paste, formed by cement and water, surrounding the aggregate creating a matrix. A hydration reaction occurs within the cement paste which allows the paste and aggregate to harden and gain strength to ultimately form concrete. Table 1 below provides the proportions of each material by weight for a typical concrete mix design.

<table>
<thead>
<tr>
<th>Material</th>
<th>Percent by Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>8.1</td>
</tr>
<tr>
<td>Portland Cement</td>
<td>14.7</td>
</tr>
<tr>
<td>Coarse Aggregate</td>
<td>46.5</td>
</tr>
<tr>
<td>Fine Aggregate</td>
<td>30.7</td>
</tr>
</tbody>
</table>

Concrete is considered economical due to the fact that the most expensive and energy-intensive material, Portland cement, only makes up 15% of concrete by weight. A single pound of cement can yield five to ten pounds of concrete (Thomas & Jennings).
Portland Cement

Portland cement is the combination of several compounds, as tabulated in Table 2.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium Oxide (lime)</td>
<td>CaO</td>
</tr>
<tr>
<td>Silicon dioxide (silica)</td>
<td>SiO₂</td>
</tr>
<tr>
<td>Aluminum oxide (alumina)</td>
<td>Al₂O₃</td>
</tr>
<tr>
<td>Iron Oxide</td>
<td>Fe₂O₃</td>
</tr>
<tr>
<td>Water</td>
<td>H₂O</td>
</tr>
<tr>
<td>Sulfate</td>
<td>SO₃</td>
</tr>
</tbody>
</table>

In order to form Portland cement, the calcium, silicon, aluminum, and iron are chemically combined and heated to a high-temperature (approximately 2,600°F). The combination of the compounds and the heat forms hard, rock-like pellets, known as clinker. In order to achieve the fine powder of cement, the clinker is ground extremely fine (How Cement is Made, 2017). The combination of the compounds tabulated above form the composition and proportions shown in Table 3.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Shorthand Formula</th>
<th>% by Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tricalcium aluminate</td>
<td>C₃A</td>
<td>10</td>
</tr>
<tr>
<td>Tetracalcium aluminoferite</td>
<td>C₄AF</td>
<td>8</td>
</tr>
<tr>
<td>Dicalcium silicate</td>
<td>C₂S</td>
<td>20</td>
</tr>
<tr>
<td>Tricalcium silicate</td>
<td>C₃S</td>
<td>55</td>
</tr>
<tr>
<td>Sodium oxide</td>
<td>N</td>
<td>Up to 2</td>
</tr>
<tr>
<td>Potassium oxide</td>
<td>K</td>
<td></td>
</tr>
<tr>
<td>Gypsum</td>
<td>CSH₂</td>
<td>5</td>
</tr>
</tbody>
</table>

The compounds above have a direct impact on the properties the concrete will exhibit and how the hydration reaction will occur. Optimizing the compounds will create different
results that can be more applicable for a variety of environments. The tricalcium aluminate (C₃A), does not provide a lot of strength, but will begin hydrating rapidly (if not impacted by gypsum) and generate significant heat in the structure. Tricalcium silicate (C₃S) and dicalcium silicate (C₂S) are both attributable to the concrete’s strength. However, the tricalcium silicate hydrates quickly in the process and provides the initial strength gain; the dicalcium silicate hydrates much slower and won’t provide the strength until the first week (Hydration of Portland Cement).

There are 5 categories of Portland cement as recognized in ASTM C 150, known as Ordinary Portland Cements (ACI Committee 207, 1996).

- **Type I**: This cement is used for typical construction which does not require special properties. Type I is not used for mass concrete as it does not manage the heat generated by hydration sufficiently. However, with certain admixtures, it could possibly be applied.

- **Type II**: Type II cement limits the amount of tricalcium aluminate C₃A used in the mixture. That compound’s hydration reaction is a large contributor to the early heat generated in the concrete. Because there is limited tricalcium aluminate used in Type II cement the concrete will only generate moderate heat thus making it ideal in mass concrete applications.

- **Type III**: Type III cement is also known as High-Early cement. This cement obtains a high strength very quickly. Generally, type III cement is not used for mass concrete structures. The typical application is for cold weather or to reduce the time of curing.
• **Type IV**: This cement, commonly known as, the low heat cement, which monitors the maximum $C_3A$, $C_3S$, and $C_2S$ used in the mixture. Because the compounds are limited, very little heat is generated. Under the consideration of low heat, it would make sense that Type IV is commonly used for mass concrete structures. However, this is not the case, Type IV is not commonly used as it is difficult to maintain and alternative methods have been developed to control the large temperature increases.

• **Type V**: Type V cement is applied when high sulfate resistance is necessary.

The following chart in Figure 1 provides the adiabatic temperature rise for each cement type.

![Figure 1 – Adiabatic Temperature Rise vs. Time for each Cement Type](image)

**Aggregate**

Aggregate can vary significantly depending upon the purpose and application of the concrete. The aggregate can be a soft sand to large, coarse rocks, or a gradation of each. Coarse aggregate, sized between No. 4 and 6 inches, must be hard and dense for the mass
concrete application. The size of the aggregate is largely dependent on the structure. For heavily-reinforced structures, the aggregate will likely be smaller to ensure it can flow through the reinforcement throughout the structure. When limitations, such as reinforcement, are not a factor, the coarse aggregate size is essentially unlimited thus reducing the cementitious material. However, economics, feasibility, and quality do play a large factor. Figure 2 optimizes the maximum aggregate size with the cement to achieve a given compressive strength level.

![Figure 2](image)

**Figure 2 – Relationship between Aggregate Size, Cement Content, and Concrete Compressive Strength**

Fine aggregate is also used in mass concrete structures. The fine aggregates are crucial to ensure a workable mixture (ACI Committee 207, 1996). While the gradations can be modified as needed, it must be within the parameters provided in Figure 3 below:
Water

Water is the third major ingredient in concrete. When applying water to the mix, it should not contain any particles that would facilitate hydration reactions. A common rule of thumb is that drinking water is acceptable (ACI Committee 207, 1996). Water, when combined with cement, acts as a binder of the aggregate. The water creates the hydration process which ultimately hardens the concrete (Scientific Principals).

**Thermal Properties of Concrete**

The thermal properties of concrete are determined by the four parameters, thermal conductivity, specific heat, density, and diffusivity. Each of these properties are affected by the heat associated with hydration of the cement and can provide a model for the effects of temperature and volume changes.

<table>
<thead>
<tr>
<th>Sieve designation</th>
<th>Percentage retained, individual by weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/8 in. (9.5 mm)</td>
<td>0</td>
</tr>
<tr>
<td>No. 4 (4.75 mm)</td>
<td>0.5</td>
</tr>
<tr>
<td>No. 8 (2.36 mm)</td>
<td>5-15</td>
</tr>
<tr>
<td>No. 16 (1.18 mm)</td>
<td>10-25</td>
</tr>
<tr>
<td>No. 30 (600 μm)</td>
<td>10-30</td>
</tr>
<tr>
<td>No. 50 (300 μm)</td>
<td>15-35</td>
</tr>
<tr>
<td>No. 100 (150 μm)</td>
<td>12-20</td>
</tr>
<tr>
<td>Pan fraction</td>
<td>3-7</td>
</tr>
</tbody>
</table>

*U.S. Bureau of Reclamation 1981*
The equation below, as defined by the ASTM, expresses the relationship between the thermal properties (ACI Committee 207, 2007).

\[ h^2 = \frac{K}{C_h \times \rho} \]

Where,

\( h = \) Thermal Diffusivity  \\
\( K = \) Thermal Conductivity  \\
\( C_h = \) Specific Heat  \\
\( \rho = \) Density

**Thermal Conductivity**

Conductivity is the ratio between the heat flux density of the structure to the temperature gradient. Rather, the measure of how well heat flows through a given material. Thermal conductivity of concrete is not a constant and changes with external temperature, degree of saturation, and the concrete mix composition (Chini & Parham, 2005). Typical values range from 1.0 to 2.05 Btu/ ft \( \times \) h \( \times \) °F, specifically determined by the aggregate type. (ACI Committee 207, 1996).

**Specific Heat**

The specific heat of concrete is defined as, “the amount of heat that a unit mass of material must gain or lose to change its temperature by a given amount”. Ultimately, it is a measure of how the concrete can undergo temperature changes due to the type of material, rather than the mass (Faruq, 2013). Typical values for concrete are approximately 0.179 to 0.25
Btu/ lb °F. The specific heat values for concrete are generally independent of the external conditions and materials (ACI Committee 207, 1996).

Density

Density is the ratio from mass to unit volume. This value is dependent on the various constituents of the concrete mix. Typical values for the density of concrete range from 140 to 150 lb/ft³.

Diffusivity

Diffusivity is the measure of the concrete's ability to experience temperature change. This value is an index ranging from 0.032 to 0.058 ft²/h, as determined by aggregate type. The higher the index, the easier heat will flow through the system. Typically, diffusivity and conductivity correspond, meaning a highly conductive structure will likely have a higher diffusivity index (ACI Committee 207, 1996).

Hydration

Hydration of cement is the reaction of cement with water, which forms the binding material. This occurs under a two-step process; 1) dissolution; 2) precipitation. When the water is mixed with the cement, the highly soluble materials in cement, gypsum (CSH₂), the silicates (C₃S and C₂S), and the aluminates (C₃A and C₄AF) dissolve in the water to create the pore solution. As the materials continue to dissolve, the water contributes hydroxyl ions which allows the ionic species to increase rapidly until the pore solution is supersaturated. This will allow the ions to combine to create new solid phases, known as hydration products (C-S-H and CA(OH)₂). The continuous dissolution of the cement materials is a result of the precipitation of
the supersaturated pore solution. There is a steady development of strength and hardening as this occurs. Although the true hydration process is a result of all cement minerals dissolving into the same pore solution, each reaction is analyzed separately to approximate the overall behaviors.

The overall process of cement hydration can be broken down into four phases as demonstrated in Figure 4.

![Figure 4 – Rate of Cement Hydration vs. Time](image)

The first phase of hydration begins rapidly and lasts about one minute. This is due to the rapid creation of the hydration products and the heat output from the dissolving cement. The products that are created surround the cement particles limiting further reaction from occurring, thus initiating phase 2. Phase 2, known as the induction period shows the rate of hydration plummeting and ultimately reaching a rate of zero reaction. This one to two-hour time frame is important as it allows the concrete to be mixed and poured in the field without reaching an unworkable level of hardness and/or strength. The reaction of the tricalcium
silicate initiates phase 3 with a rapid, but short increase in hydration. This typically begins less than 24 hours after the initial dissolution, but is highly dependent on the temperature and particle size of the cement. The rate of hydration will eventually reach its peak in this phase and begin to taper as the hydration products increase. The end of this phase generally marks the 30% completion of cement hydration. At stage 4, almost all of the hydration has occurred and the hydration products are remaining, primarily in the form of C-S-H gel and CH. This stage, known as the diffusion-limited reaction period, only hydrates further if water diffuses to areas where a reaction can occur. Due to the creation of hydration products, this occurs less and less (Thomas & Jennings).

**Hydration of Calcium Silicates**

As demonstrated in Table 3, the calcium silicates make up the majority of the portland cement composition. While the reactions for both silicates are similar, there are some significant differences. Tricalcium silicate is more soluble than dicalcium silicate and will therefore have a quicker rate of hydration and produce more hydration product. Additionally, tricalcium silicate is a key contributor to the early strength development in concrete while dicalcium silicate provides strength later in the phases. The reaction equations are as follows:

\[ C_3S + (1.3 + x)H \rightarrow C_{1.7}SH_x + 1.3CH \quad (\text{calcium silicate hyrdate & calcium hydroxide}) \]

\[ C_2S + (0.3 + x)H \rightarrow C_{1.7}SH_x + 0.3CH \quad (\text{calcium silicate hyrdate & calcium hydroxide}) \]

Where \( x \) is the amount of water associated with the C-S-H gel (Thomas & Jennings).
**Hydration of Tricalcium Aluminate**

Gypsum is a key mineral in the tricalcium aluminate reaction as it slows down the initial reaction. Without gypsum present, the cement paste would rapidly harden and would lose workability in an unreasonable timeframe. The reaction is as follows:

\[ C_3A + 3CSH_2 + 26H \rightarrow C_6AS_3H_{32} \quad \text{(mineral ettringite)} \]

On most occasions, the ettringite is converted into monosulfoaluminate within the first few days of the hydration reaction. This is a result of the ettringite becoming unstable due to the decrease in sulfate ions. This issue is seen when the gypsum is reacted entirely before the tricalcium aluminate (Thomas & Jennings). The reaction is as follows:

\[ 2C_3A + C_6AS_3H_{32} + 4H \rightarrow 3C_4ASH_{12} \quad \text{(monosulfoaluminate)} \]

The tetracalcium aluminoferrite creates a similar hydration product as it also has two reactions as a result of the gypsum. The first reaction the ettringite from the tricalcium aluminate reaction reacts with the gypsum and water followed by the newly created ettringite reacting with the ferrite to create garnets (Composition of Cement). The reactions are as follows:

\[ C_4AF + 3CSH_2 + 3H \rightarrow C_6(A,F)S_3H_{32} + (A,F)H_3 + CH \]

\[ C_4AF + C_6(A,F)S_3H_{32} + 2CH + 23H \rightarrow 3C_4(A,F)SH_{18} + (A,F)H_3 \]
Hydration Products

Calcium-Silicate-Hydrate (C-S-H) Gel

As stated in previous sections, the largest percentage of cement is the calcium silicates. Similarly, its reaction produces, Calcium-Silicate-Hydrate (C-S-H) gel attributes to approximately 50% of the total cement paste. The C-S-H gel helps the concrete gain its initial firmness due to gel binding to the cement particles. As the hydration process continues and more C-S-H is created, the gel grows outward with interconnected layers continuously built on itself. Concrete gains most of its strength from the increase in layers of the solid phases (Thomas & Jennings).

Calcium Hydroxide

While the C-S-H gel creates interconnected layers, the calcium hydroxide forms crystals. Calcium hydroxide is key to avoiding shrinkage of the concrete. The amount of shrinkage is reduced with the presence of calcium hydroxide because its crystalline structure remains intact as water is dried from the system, unlike C-S-H which collapses. Because the structure is unaffected, it acts as a restraint and reduces the shrinkage (Thomas & Jennings).

Delayed Ettringite Formation (DEF)

Ettringite was previously discusses as part of the hydration reactions. Ettringite is created early in the mixing process with the reaction between sulfate compounds, which are commonly added, and calcium aluminate from the cement. The ettringite is very important as it makes up the stiffness of the concrete. However, if the hydration process creates excessive temperatures, this ettringite can be destroyed (Ettringite Formation and the Performance of Concrete, 2001). This damage typically will occur after the concrete has exceeded 158°F at
which point the ettringite melts. The combination of the cooling concrete, which occurs later, and water can allow the ettringite to reform and cause internal volumetric expansion (Bartojay, 2012).

**Heat of Hydration**

All of the reactions previously discussed are exothermic reactions, meaning the hydration process creates and emits heat. This ultimately increases the internal temperature of the concrete. Depending upon the concrete application, this may or may not pose a risk to the concrete properties. Small concrete pours will not see the impact of the heat because it will dissipate into the environment. Mass concrete, however, can see a distinguished increase in internal temperatures because concrete has a low conductivity and the heat that is generated cannot be quickly dissipated from the center of the structure. This causes temperatures to exceed the allowable maximum and large temperature differentials throughout the structure. If the temperatures are not monitored, cracking is imminent (Portland Cement, Concrete, and Heat of Hydration, 1997).

**Mass Concrete**

Concrete is prevalently used in today’s construction industry in numerous applications. Additional challenges arise for projects including concrete dams, power plants, and large foundations as these are categorized as mass concrete which requires additional provisions. Mass concrete, as defined by The American Concrete Institute (ACI) is, “any volume of concrete with dimensions large enough to require that measures be taken to cope with generation of heat from hydration of the cement and attendant volume change to minimize cracking.” The heat from hydration that is generated by the reaction of cement and water will occur in all
concrete settings. However, in large scale concrete projects, this heat is unable to dissipate from the surface uniformly. The dramatic temperatures observed, specifically in mass concrete structures can create tensile stresses within the structure. If not properly managed, the maximum heat and/or the temperature differential can cause cracks in the structure. While some cracks are minor, severe cracks can develop from within the structure and have negative impacts to the integrity and durability of the structure.

Management of mass concrete occurs both at the design and construction phase. In design, the concrete mix design can dictate that amount of heat generated. The type and quantity of cement can be optimized in an effort to stay within the project’s temperature specifications. These mix designs will commonly require low-heat pozzolans in place of cement, which help maintain workability of the mixture. Examples of low-heat pozzolans are slag or fly ash which can significantly reduce the amount of heat generated without compromising the strength. Additionally, while the aggregate specified may not have an impact on the temperatures, there are certain types that are more conducive in mass concrete as they have limited expansion when exposed to heat.

At the time of construction, there are several methods that can be used in an effort to maintain the temperatures of the concrete. Prior to placing the concrete, the concrete mix temperature, as well as the ambient temperature should be considered. If the mix is too hot, ice is commonly added in place of mixing water to pre-cool the mixture. The concrete pour schedule must also be detailed to ensure that the pour sizes will not generate an unmanageable amount of heat. Some considerations must be the lift height, seasonal pour schedule, and placement schedule. Once the concrete is poured, the structure can be
insulated. This will prevent the surface temperatures from dissipating and reduce the temperature differential of the structure. Another method, which was implemented on the Hoover Dam, is to embed small piping through the structure to run cold water through. This helps regulate the temperatures throughout the structure in its entirety (Gajda & Vangeem, 2002).

**Thermal Stresses in Concrete**

The thermal stresses in concrete differ drastically in comparison to steel, as the thermal stresses are not proportional to the temperature change. The differences in behavior are a result of a varying modulus of elasticity, concrete creep, temperature differentials, coefficient of thermal expansion, and the degree of restraint (ACI Committee 207, 1996). As discussed previously, the temperature of the concrete increases rapidly early on in its lifecycle due to hydration. The concrete will eventually reach its peak temperature and will gradually cool over time. While the concrete is experiencing these temperature changes, the stresses and modulus of elasticity are also varying, but are minimal early on, as shown in Figure 5.

![Plot of Concrete Temperature, Modulus of Elasticity, and Stress with Respect to Time](image)

Figure 5 – Plot of Concrete Temperature, Modulus of Elasticity, and Stress with Respect to Time
The plot shows a peak in temperature while the hydration reaction occurs. During the initial temperature rise, the modulus of elasticity and relaxation coefficient, \( K(t, \tau_i) \), are at its lowest and stresses are near zero. Over time, the temperatures reach a maximum and decrease to a steady temperature, while increasing strength and stiffness. During the cooling process, the compressive stresses are reduced at the surface and instead, thermal tensile stresses develop. This is a result of the concrete internal and external temperature changes, increase in modulus of elasticity, and the restraint of the system. The tensile stresses that develop are significant. When these stresses are larger than the tensile strength of the structure, cracks will inevitably occur. These cracks can have a significant impact to the strength, integrity, and lifespan of the structure (Zhu, 2014).

**Thermal Stress – Self-Stress**

Self-stress is developed as a result of the structure itself. This will occur when the temperature is non-linearly distributed throughout the structure. The non-linear temperature is typically cooler at the surface and warmer in the center. As the heat is dissipated from the surface, shrinkage occurs, but is restrained by the warmer, inner surface of the structure which does not incur corresponding volumetric changes. The inner surface goes into compression, while the outer is in tension (Zhu, 2014). To maintain equilibrium, the overall self-stress requires that tension stress and compression stress are equal, as shown in Figure 6.
The thermal stresses related to self-stress are generally negligible when considering restraint stresses. This is because the temperature differentials between the surface, center, and ambient are managed reasonably with the insulation of the forms. However, self-stresses can become a greater issue when thermal shock is experienced. Thermal shock, as previously discussed, occurs as a result of extreme ambient temperatures, improper insulation of the forms, and removing the forms early (ACI Committee 207, 1996).

**Thermal Stress – Restraint Stress**

There are instances when the limits of a structure are partially or fully restrained, such as a solid rock foundation. As the temperature in the structure changes, it tends to deform slightly and incur volumetric changes. The dimensions, strength, and modulus of elasticity of the concrete and neighboring material will largely determine the degree of restraint, however, volumetric restraints are likely, even if minor. These restraints will also be greater in the concrete which is closer to the physical restraint. In the instance of a foundation, the bottom surface of the structure is retrained and will likely develop stress that exceeds the tensile strength of the structure. This will result in cracking at the base of the structure and propagate
upward and outward towards a lower stress section. Once a crack is initiated, the structure will have a lower threshold for tensile stress in the given area. These cracks can create a compounding issue and jeopardize the integrity of the structure (ACI Committee 207, 1996).

**Cracking in Concrete**

The thermal stresses discussed previously can create large tensile stresses in a concrete structure. The tensile stresses are developed due to temperature differentials in the structure and boundary constraints. If the tensile stresses developed exceed the tensile strength of the given structure, then cracking will occur.

In consideration of the boundary constraints, the following equation can be used to determine the thermal stress:

\[ \sigma = RK_pE\alpha\Delta T \]

Where,

- \( \sigma \) = thermal stress
- \( R \) = restraint coefficient
- \( K_p \) = stress relaxation coefficient caused by the creep of the concrete
- \( E \) = elastic modulus of concrete
- \( \alpha \) = coefficient of linear expansion of concrete
- \( \Delta T \) = temperature difference of concrete

The value of the thermal stress provided in the equation above must remain lower than the allowable tensile stress (with the safety factor), otherwise cracks are inevitable. Once a mass concrete structure has cracked, the structural integrity in its entirety is jeopardized. In an effort to keep the thermal stresses manageable, engineers can take certain precautions to
prevent cracking, including limiting the temperature differential in concrete, allowing movement of the structure by reducing the restraint coefficient, and increasing the tensile strength capacity of the structure (Zhu, 2014).

**Maximum Concrete Temperature**

In an effort to properly manage the quality of mass concrete, the temperature during the hydration process can be tracked. If the temperatures exceed values of 155 to 165 °F, then the ettringite formation may be delayed. If delayed, DEF occurs, and internal expansion and cracking may occur; sometimes years after concrete placement (Gajda & Vangeem, 2002). Additionally, if the concrete reaches temperatures that greatly exceed the steady state temperatures, drastic volume changes are to be expected. (ACI Committee 207, 1996)

**Maximum Concrete Temperature Differential**

A temperature differential will occur in a structure when a given point of the structure is different than that of the surface. The temperature changes induce volumetric changes, specifically contraction at the surface during cooling. This differential of temperature and volume can create tensile stresses that typically exceed the strength of the concrete, resulting in cracking (Gajda & Vangeem, 2002). During construction, the temperature differential is commonly managed by removing the forms at an opportune time. The forms are typically left on the structure, and sometimes insulated, to target surface temperatures that correspond to those at the center. When forms are removed prematurely, specifically on a cold day, the structure will experience “thermal shock” which will likely result in cracking. (ACI Committee 207, 2007). Not only is this differential experienced during the curing phase, known as mass gradient, it can also be an issue throughout the life of the structure due to ambient
temperature variations, known as surface gradient. Climates with temperatures that varies throughout seasons impact concrete surfaces. The concrete surface reacts to these temperature changes through contraction and expansion, however the center of the structures is much slower to react. The movement at the surface is being restrained by the center and causing tensile stresses (ie cracking) at the surface. These cracks, however, are relatively shallow as the temperature differential is dissipated rapidly (ACI Committee 207, 1996). The temperature differential in mass concrete structures will occur and is commonly limited to a maximum of 35°F difference between the hottest and coldest point at any given time.
CHAPTER III
HISTORIC FIELD DATA ANALYSIS

Project Background

A Combined Cycle Power Plant was constructed in 2015. In order to maintain compliance with the Clean Air – Clean Jobs Act the existing coal-fired units had to be retired and replaced with natural gas-fired units. The newly constructed power plant now provides a cleaner source of energy while still producing approximately 580 megawatts of energy.

Combined Cycle Power Plants are densely populated with structures in order for it to properly perform with efficiency. Specifically analyzed in this study was the Steam Turbine Generator Pedestal (STG). This turbine generator is structurally composed the basemat, columns, and the table top, each constructed primarily of structural concrete. Figure 7 provides the model of the STG. It is important to note that the STG is considered mass reinforced concrete, which differs from the mass concrete associated with dam construction. Mass reinforced concrete typically differs in the aggregate size, amount of water, and type of cement which ultimately attribute to less temperature control of the structure (ACI 207 Committee, 1996).
This study analyzes just under 2,200 cubic yards of concrete. Table 4 summarizes the dimensions and quantity of concrete, in cubic yards, required to construct each component; each which are classified as mass concrete.

Table 4 – Concrete Quantities and Dimensions for Steam Turbine Generator

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Quantity (CY)</th>
<th>General Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Basemat</td>
<td>928.3</td>
<td>112’L x 52.5’W x 4.5’D</td>
</tr>
<tr>
<td>2</td>
<td>Columns (8 EA)</td>
<td>644.7</td>
<td>8’L x 8’W x 34’H</td>
</tr>
<tr>
<td>3</td>
<td>Tabletop</td>
<td>606.1</td>
<td>100’L x 38’W x 6.5’D</td>
</tr>
</tbody>
</table>

There were two concrete mix designs used to construct all three components listed in Table 5. The first one, used for the basemat and table top is known as I-AA Base Mix and the
second one, used for the columns was used for all eight of the columns is known as I-AA Base Mix + Super Plasticizer (SP). Table 5 below tabulates the required parameters.

Table 5 – Concrete Mix Design Requirements

<table>
<thead>
<tr>
<th>Item</th>
<th>Design Parameter</th>
<th>I-AA Base Mix</th>
<th>I-AA Base Mix + SP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Strength</td>
<td>4,500 psi</td>
<td>4,500 psi</td>
</tr>
<tr>
<td>2</td>
<td>Air Content</td>
<td>6.0% +/- 2.0%</td>
<td>6.0% +/- 2.0%</td>
</tr>
<tr>
<td>3</td>
<td>Slump</td>
<td>2 to 4 in.</td>
<td>8 in. Max</td>
</tr>
<tr>
<td>4</td>
<td>Water/Cement Ratio</td>
<td>0.43</td>
<td>0.39</td>
</tr>
</tbody>
</table>

The required strength and air content is the same for both mix designs. I-AA Base Mix has a higher water/cement ratio than the I-AA Base Mix + SP, yet has a significantly smaller slump value. The primary difference in slump, despite the water content, is attributed to the superplasticizer which was added for the column mix. The superplasticizer acts as a lubricant to the cement grains which allows for a higher slump, or fluidity, without increasing the amount of water. The slump for I-AA Base Mix + SP is considered a plasticizer slump, as opposed to the standard water slump. When optimizing the design for mass concrete, it is important to consider the amount of water used in the mix as it is a key component to initiating and further facilitating the hydration reaction. A water slump of 2 to 4 inches, as required by the I-AA Base Mix, is typical in an effort to avoid reduced strength and durability (Concrete News, 2008).

The lower water/cement ratio from I-AA Base Mix to the I-AA Base Mix + SP can also be due to the addition of the superplasticizer. The standard water/cement ratio ranges from 0.4 and 0.6. The required 0.43 is on the low end of the spectrum likely to maintain workability and reduce generating heat as a result of hydration, while achieving a higher strength and reducing
shrinkage cracks. I-AA Base Mix + SP requires 0.39 because the superplasticizer is substituted in place of additional water.

The mix proportions are also important to understand. Table 6 provides the breakdown of each mix.

Table 6 - Standard I-AA Base Concrete Mix Design

<table>
<thead>
<tr>
<th>Item</th>
<th>Material</th>
<th>Amount</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Type I-II Cement</td>
<td>483</td>
<td>Lb</td>
</tr>
<tr>
<td>2</td>
<td>Fly Ash</td>
<td>122</td>
<td>Lb</td>
</tr>
<tr>
<td>3</td>
<td>¾”-1” Aggregate</td>
<td>1,743</td>
<td>Lb</td>
</tr>
<tr>
<td>4</td>
<td>Sand</td>
<td>1,231</td>
<td>Lb</td>
</tr>
<tr>
<td>5</td>
<td>Water</td>
<td>262</td>
<td>Lb</td>
</tr>
<tr>
<td>6</td>
<td>Air</td>
<td>.55</td>
<td>Oz/cwt C+P</td>
</tr>
<tr>
<td>7</td>
<td>Viscocrete</td>
<td>4.0</td>
<td>Oz/cwt C+P</td>
</tr>
</tbody>
</table>

Table 7 - Standard I-AA + Superplasticizer Base Concrete Mix Design

<table>
<thead>
<tr>
<th>Item</th>
<th>Material</th>
<th>Amount</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Type I-II Cement</td>
<td>488</td>
<td>Lb</td>
</tr>
<tr>
<td>2</td>
<td>Fly Ash</td>
<td>122</td>
<td>Lb</td>
</tr>
<tr>
<td>3</td>
<td>¾”-1” Aggregate</td>
<td>1,739</td>
<td>Lb</td>
</tr>
<tr>
<td>4</td>
<td>Sand</td>
<td>1,287</td>
<td>Lb</td>
</tr>
<tr>
<td>5</td>
<td>Water</td>
<td>241</td>
<td>Lb</td>
</tr>
<tr>
<td>6</td>
<td>Air</td>
<td>.25</td>
<td>Oz/cwt C+P</td>
</tr>
<tr>
<td>7</td>
<td>Viscocrete</td>
<td>5.0</td>
<td>Oz/cwt C+P</td>
</tr>
</tbody>
</table>

Both concrete mix designs are similar, just minor differences in the quantity of each constituent. Each mix requires approximately 485 lbs of cement which is relatively high for mass concrete. The fly ash is used to provide additional strength without drastically increasing the amount of hydration reaction.
Due to the large quantities of concrete, the concrete temperature needed to be monitored prior to placement and during the cure process. The following temperature parameters were required by the project specifications:

- Concrete delivered with a temperature between 50°F and 90°F;
- Maximum concrete temperature after placement is not to exceed 180°F;
- Maximum temperature differential between center and surface is not to exceed 35°F.

It is important to note, that while the temperature differential was not to exceed 35°F, it was also performance based. If a larger differential was seen, but the temperature of the structure had achieved a specified temperature, the differential did not pose a risk.

In order to verify the temperature results, thermocouple sensors were installed at various locations in each structure with lead wires connecting to a data logger. Thermocouples are electronic temperature sensors that consist of welded wires of two different alloys. The sensors produce voltage that is dependent on the temperature changes. These voltages are different for each of the alloys, but can be measured and converted to output temperature readings.

The next sections will detail each specific operation and its results. The different geometry and quantities of the structures will impact the placement and temperature results.

Mass Concrete Temperature Results

Steam Turbine Generator Pedestal – Basemat

Extensive pre-work before pouring the concrete is done to ensure that the temperatures can be managed within specifications. If the temperatures exceed the
specifications, the structural integrity can be jeopardized and dramatic impacts to the project’s budget and schedule will be incurred. The basemat was performed in ten phases progressing horizontally and four lifts to complete in a single eight-hour shift. The structure was completed by working east to west in a little over 11-foot-wide sections and 1’-4” high lifts. Lift 1 was not completed entirely before proceeding to Lift 2. Instead, the concrete was poured in a diagonal progression, working on additional lifts of a given phase, while proceeding to another lift and phase. The diagram below provides a snapshot in time to demonstrate how structure was poured in phases. The white area with the “@” symbol indicate areas that have not been poured yet.

![Figure 8 – Snapshot of the Concrete Pour Procedure](image)

Four thermocouple sensors were installed into the basemat prior to the initial pour. Two sensors were installed near the top of the structure, one on the east side and one on the west. Additionally, two sensors were installed in the middle, one on the east side and one on the west. Ambient temperatures were also provided by Weather Underground’s historical weather database.
Temperature monitoring of the basemat began on June 23, 2013 just before 11:00 pm and concluded 107 hours later. Each sensor documented hourly readings of the temperature. The concrete temperature prior to placing ranged from 59°F to 63°F. A night shift operation was scheduled to avoid the high summer temperatures that could negatively affect the concrete. Table 8 summarizes the temperature readings after the given hours.

Table 8 – Basemat Temperature Sensor Summary

<table>
<thead>
<tr>
<th>Location</th>
<th>12 Hrs</th>
<th>24 Hrs</th>
<th>48 Hrs</th>
<th>72 Hrs</th>
<th>96 Hrs</th>
<th>107 Hrs</th>
<th>Max Temp</th>
<th>Max Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top, East Side</td>
<td>80.6</td>
<td>138.2</td>
<td>149.0</td>
<td>147.2</td>
<td>143.6</td>
<td>138.2</td>
<td>150.8</td>
<td>43 H</td>
</tr>
<tr>
<td>Top, West Side</td>
<td>91.4</td>
<td>143.6</td>
<td>152.6</td>
<td>149.0</td>
<td>143.6</td>
<td>138.2</td>
<td>152.6</td>
<td>43 H</td>
</tr>
<tr>
<td>Mid., East Side</td>
<td>80.6</td>
<td>138.2</td>
<td>152.6</td>
<td>149.0</td>
<td>145.4</td>
<td>143.6</td>
<td>152.6</td>
<td>43 H</td>
</tr>
<tr>
<td>Mid., West Side</td>
<td>114.8</td>
<td>143.6</td>
<td>152.6</td>
<td>149.0</td>
<td>145.4</td>
<td>143.6</td>
<td>152.6</td>
<td>37 H</td>
</tr>
</tbody>
</table>

The chart below in Figure 10 provides a summary of all of the temperature data extracted from the field.
The basemat foundation temperatures generally reflect the anticipated results. There is a large spike in temperature throughout the structure within the first 24 hours after concrete placement. It can be observed that the west side of the structure was poured first due to the earlier temperature rise due to the hydration reactions. After the first day, the rate of temperature increase tapered, but the temperature did continue to rise to a maximum of 152.6°F. Over the next hours, the documented temperatures continued to cool at a similar rate. The temperatures at both the east and west surface fluctuated more apparently in accordance with the ambient temperature. The middle temperatures were not impacted by the surrounding air temperatures as significantly.

When analyzing the differential temperature, a difference between the middle sensor and the top sensor, for a given side, is to be expected. This is because the heat on the top edge is able to disperse the heat generated at the surface. Based on the plot in Figure 11, the
differential for both the east and west sides was consistently minor when compared to the 35°F allowable differential. This can be attributed to the proper pour plan that allowed the middle section to emit the heat generated, rather than trap it below the surface.

![STG Basemat Foundation Temperature Differential Data](image)

**Figure 11 – Basemat Concrete Temperature Differential from Middle and Top Sensors**

**Steam Turbine Generator Pedestal – Columns**

The planning work associated with the columns was not nearly as extensive as the basemat, as each column was scheduled to be completed in one lift at one column per shift. The pour rate was planned at approximately 15 CY/hour. Managing the pour rate not only helps monitor the temperatures, but it also allows the concrete to gain enough strength without compromising the integrity of the form. As discussed in previous sections, this operation required a special concrete mix design, known as, I-AA Base Mix + Super Plasticizer.

The column concrete pours occurred over the course of eight days, at one column per day. The pours took place during day-shift on the last two weeks in July with a concrete
temperature prior to placing ranging from 61°F to 75°F. A temperature sensor was placed at the middle of the column and at the top surface to track hourly temperatures.

Table 9 summarizes the temperature readings at the given hours as well as the maximum temperatures documented.
The charts below in Figure 13 through Figure 20 provide a summary of all of the temperature data extracted from the field for each column.

### Table 9 - Column Temperature Sensor Summary

<table>
<thead>
<tr>
<th>Location</th>
<th>12 Hrs</th>
<th>24 Hrs</th>
<th>48 Hrs</th>
<th>72 Hrs</th>
<th>96 Hrs</th>
<th>108 Hrs</th>
<th>Max Temp</th>
<th>Max Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column 1, Top</td>
<td>136.4</td>
<td>134.6</td>
<td>132.8</td>
<td>122.0</td>
<td>116.6</td>
<td>111.2</td>
<td>138.2</td>
<td>13 H</td>
</tr>
<tr>
<td>Column 1, Mid</td>
<td>143.6</td>
<td>159.8</td>
<td>165.2</td>
<td>159.8</td>
<td>152.6</td>
<td>149.0</td>
<td>165.2</td>
<td>35 H</td>
</tr>
<tr>
<td>Column 2, Top</td>
<td>138.2</td>
<td>145.4</td>
<td>134.6</td>
<td>122.0</td>
<td>113.0</td>
<td>113.0</td>
<td>145.4</td>
<td>17 H</td>
</tr>
<tr>
<td>Column 2, Mid</td>
<td>140.0</td>
<td>158.0</td>
<td>165.2</td>
<td>159.8</td>
<td>149.0</td>
<td>145.4</td>
<td>165.2</td>
<td>36 H</td>
</tr>
<tr>
<td>Column 3, Top</td>
<td>140.0</td>
<td>141.8</td>
<td>131.0</td>
<td>122.0</td>
<td>111.2</td>
<td>109.4</td>
<td>143.6</td>
<td>17 H</td>
</tr>
<tr>
<td>Column 3, Mid</td>
<td>143.6</td>
<td>159.8</td>
<td>165.2</td>
<td>159.8</td>
<td>149.0</td>
<td>143.6</td>
<td>167.0</td>
<td>37 H</td>
</tr>
<tr>
<td>Column 4, Top</td>
<td>143.6</td>
<td>145.4</td>
<td>141.8</td>
<td>131.0</td>
<td>123.8</td>
<td>112.0</td>
<td>147.2</td>
<td>25 H</td>
</tr>
<tr>
<td>Column 4, Mid</td>
<td>141.8</td>
<td>156.2</td>
<td>161.6</td>
<td>158.0</td>
<td>150.8</td>
<td>145.4</td>
<td>161.6</td>
<td>34 H</td>
</tr>
<tr>
<td>Column 5, Top</td>
<td>140.0</td>
<td>141.8</td>
<td>132.8</td>
<td>125.6</td>
<td>120.2</td>
<td>122.0</td>
<td>143.6</td>
<td>14 H</td>
</tr>
<tr>
<td>Column 5, Mid</td>
<td>138.2</td>
<td>154.4</td>
<td>163.4</td>
<td>159.8</td>
<td>152.6</td>
<td>149.0</td>
<td>163.4</td>
<td>39 H</td>
</tr>
<tr>
<td>Column 6, Top</td>
<td>140.0</td>
<td>140.0</td>
<td>132.8</td>
<td>127.4</td>
<td>113.0</td>
<td>114.8</td>
<td>141.8</td>
<td>27 H</td>
</tr>
<tr>
<td>Column 6, Mid</td>
<td>143.6</td>
<td>159.8</td>
<td>165.2</td>
<td>159.8</td>
<td>152.6</td>
<td>149.0</td>
<td>165.2</td>
<td>34 H</td>
</tr>
<tr>
<td>Column 7, Top</td>
<td>143.6</td>
<td>149.0</td>
<td>136.4</td>
<td>122.0</td>
<td>114.8</td>
<td>109.4</td>
<td>149.0</td>
<td>20 H</td>
</tr>
<tr>
<td>Column 7, Mid</td>
<td>145.4</td>
<td>161.6</td>
<td>167.0</td>
<td>163.4</td>
<td>152.6</td>
<td>149.0</td>
<td>168.8</td>
<td>42 H</td>
</tr>
<tr>
<td>Column 8, Top</td>
<td>136.4</td>
<td>140.0</td>
<td>131.0</td>
<td>123.8</td>
<td>114.8</td>
<td>113.0</td>
<td>140.0</td>
<td>20 H</td>
</tr>
<tr>
<td>Column 8, Mid</td>
<td>145.4</td>
<td>159.8</td>
<td>167.0</td>
<td>159.8</td>
<td>152.6</td>
<td>147.2</td>
<td>167.0</td>
<td>34 H</td>
</tr>
</tbody>
</table>
Column 1 was poured on July 11, 2013 and began tracking temperature data around 10 am.

![Steam Turbine Generator Column 1](image1)

**Figure 13 – Column 1 Temperature Data vs. Time**

Column 2 was poured on July 10, 2013 and began tracking temperature data around 9 am.

![Steam Turbine Generator Column 2](image2)

**Figure 14 – Column 2 Temperature Data vs. Time**
Column 3 was poured on July 12, 2013 and began tracking temperature data around 10 am.

Figure 15 – Column 3 Temperature Data vs. Time

Column 4 was poured on July 13, 2013 and began tracking temperature data around 10 am.

Figure 16 – Column 4 Temperature Data vs. Time
Column 5 was poured on July 18, 2013 and began tracking temperature data around 9 am.

Figure 17 – Column 5 Temperature Data vs. Time

Column 6 was poured on July 19, 2013 and began tracking temperature data around 1:30 pm.

Figure 18 – Column 6 Temperature Data vs. Time
Column 7 was poured on July 19, 2013 and began tracking temperature data around 4:00 pm.

Finally, Column 8 was poured on July 24, 2013 and began tracking temperature data around 1:00 pm.
The temperature results for each column yielded results as expected. Within the first twelve hours, there was an immediate initial peak of temperature for each column. During this time, the readings between the center and surface temperature were generally consistent. However, when the surface of the column reached the maximum, the center temperature of the column continued to increase. As time progressed, the middle and top cooled at a consistent rate, however the middle temperature readings were significantly and consistently higher than the edge of the column. Column 7 yielded the highest maximum temperature at 168.8°F. Column 1 yielded the lowest maximum temperature at 138.2°F.

Having data to analyze for eight similar columns allows patterns to be recognized. In order to see the trends for both the middle temperatures and the top temperatures, they were each plotted in Figure 21 and Figure 22. For simplicity, the ambient temperature was averaged over time for all eight columns. The plots indicate that the middle of the columns had consistent temperatures and consistent rate of temperature gain/loss. The edge of the columns yielded variable results with rate of temperature decrease. Rather than a smooth reduction, the temperatures increased and decreased, but ultimately formed a downward trend in temperature. This is likely a function of the ambient temperatures effecting the surface temperature of the concrete.

The average maximum temperature at for the top sensor of each column is 143.6°F with a minimum of 138.2°F in column 1 and a maximum of 149.0°F in column 7. The average maximum temperature at for the middle sensor of each column is 165.4°F with a minimum of 161.6°F in column 4 and a maximum of 168.8°F in column 7. Column 7, as a whole, achieved the highest temperatures.
Figure 21 – Middle Temperature Comparison for Columns

The columns yielded significantly larger differentials between the middle and edge sensors as compared to the basemat previously discussed. Table 10 summarizes the largest temperature differential between the surface sensor and the center in each column.
The largest temperature differential was 43.2°F which was seen in three columns, column 3, column 6, and column 7. Column 3 and 6 both reached the maximum differential 90 hours after placement. At this time, the rapid heat generation has already occurred and the surface is able to dissipate heat at a quicker rate than the center. The 90-hour mark for column 3 was at approximately 4:30 am. The cooler ambient temperatures in the early morning may have had an impact on the larger differential. The peak differential for column 7 occurred 68 hours after initial placement. Column 7 also reached the highest maximum temperature among all of the columns. A significant center temperature can cause an increased temperature differential if heat is easily released at the surface. The smallest maximum temperature differential occurred in Column 4 at 28.8°F which was measured 93 hours after placement.

When considering all temperature differentials from the beginning of placement to the completion of data measurements, the average differential was 25.87°F.

The plot in Figure 23 provides all of the temperature differentials with respect to time. The temperature difference rapidly increases as the heat is generated through the cement hydration reaction. Over time, a temperature differential exists between the two sensors.

<table>
<thead>
<tr>
<th>Location</th>
<th>Time at Largest Differential</th>
<th>Edge Temperature</th>
<th>Middle Temperature</th>
<th>Differential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column 1</td>
<td>115 H</td>
<td>104.0</td>
<td>145.4</td>
<td>41.4</td>
</tr>
<tr>
<td>Column 2</td>
<td>70 H</td>
<td>122.0</td>
<td>159.8</td>
<td>37.8</td>
</tr>
<tr>
<td>Column 3</td>
<td>90 H</td>
<td>109.4</td>
<td>152.6</td>
<td>43.2</td>
</tr>
<tr>
<td>Column 4</td>
<td>93 H</td>
<td>123.8</td>
<td>152.6</td>
<td>28.8</td>
</tr>
<tr>
<td>Column 5</td>
<td>73 H</td>
<td>123.8</td>
<td>159.8</td>
<td>36.0</td>
</tr>
<tr>
<td>Column 6</td>
<td>90 H</td>
<td>113.0</td>
<td>156.2</td>
<td>43.2</td>
</tr>
<tr>
<td>Column 7</td>
<td>68 H</td>
<td>122.0</td>
<td>165.2</td>
<td>43.2</td>
</tr>
<tr>
<td>Column 8</td>
<td>73 H</td>
<td>122.0</td>
<td>159.8</td>
<td>37.8</td>
</tr>
</tbody>
</table>
however the difference remains generally the same. The columns yielded similar results, however column 4 stands out as an outlier. This column was significantly lower in comparison to the other columns. Column 7 also appears to have a steady increase in the temperature change for a longer period that the other columns. All columns tended to peak around 40 to 48 hours after placement, column 7 didn’t peak until around 72 hours.

The tabletop structure was the last structure analyzed for the Combined Cycle Power Plant. This structure wasn’t poured until September 2013 which is set on top of the eight columns. The tabletop, which is 6.5 feet thick, was poured in four lifts at the following heights: Lift 1: 24”, Lift 2: 24”, Lift 3: 18”, Lift 4: 12”. The table top was divided into two sections, the east and west side. Each side had its own concrete pump truck and was poured in a counterclockwise progression at approximately 80 CY/hour. Three thermocouples were installed
throughout the structure, one in the middle, one on the top, and one on the edge as shown in Figure 24.

![Figure 24 – Thermocouple Locations for Tabletop](image)

Data was logged beginning at 4:15 am on September 9, 2013, but not all of the concrete was poured until 1:15 pm. The concrete temperature prior to placing ranged from 63°F to 70°F. Table 11 summarizes the temperature data associated with the tabletop.

**Table 11 - Tabletop Temperature Sensor Summary**

<table>
<thead>
<tr>
<th>Location</th>
<th>12 Hrs</th>
<th>24 Hrs</th>
<th>48 Hrs</th>
<th>72 Hrs</th>
<th>96 Hrs</th>
<th>108 Hrs</th>
<th>Max Temp</th>
<th>Max Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tabletop Top</td>
<td>134.6</td>
<td>140.0</td>
<td>140.0</td>
<td>132.8</td>
<td>118.4</td>
<td>116.6</td>
<td>141.8</td>
<td>36 H</td>
</tr>
<tr>
<td>Tabletop Middle</td>
<td>141.8</td>
<td>158.0</td>
<td>163.4</td>
<td>159.8</td>
<td>152.6</td>
<td>147.2</td>
<td>165.2</td>
<td>39 H</td>
</tr>
<tr>
<td>Tabletop Edge</td>
<td>131.0</td>
<td>132.8</td>
<td>127.4</td>
<td>114.8</td>
<td>105.8</td>
<td>102.2</td>
<td>132.8</td>
<td>13 H</td>
</tr>
</tbody>
</table>

The chart below plots all of the data extracted from each thermocouple and also compares it against the ambient temperature.
The concrete temperature data associated with the tabletop also yields expected results. The temperature increases at a steady rate for approximately the first 12 hours. At about 18 hours both the top and edge temperatures begin to level out. At that time, the middle temperature rate increase began slow down, but it continued to increase to a maximum temperature of 165.5°F. The temperature at the edge began to decrease around 48 hours, in comparison to the top at 72 hours. The rates of cooling were generally the same for all three locations in the tabletop. For the entire curing process, the edge remained the coolest while the middle was the warmest. The edge of the structure likely has more surface area exposed to the environment allowing it to dissipate heat quicker.

Additionally, the differential temperature data is plotted below.
The temperature differential seen within the first eight hours are slightly variable because the entire structure was not poured yet; some of these readings are based on the ambient temperatures rather than the concrete itself. The temperature difference between the middle and edge of the structure remained the largest throughout the data collection. The difference increased early on and leveled out to approximately 40°F difference. The difference between the middle and top sensor peaked at 34.2°F at 87 hours after placement. The difference between the top and edge sensor peaked at 19.8°F at 60 hours after placement.
CHAPTER IV
TRANSIENT THERMAL ANALYSIS SIMULATION

Introduction

To understand the thermal interactions of a system, a steady-state analysis or a transient analysis can be performed. A steady-state thermal analysis calculates the thermal loads on a system which do not vary with time. It determines how these loads impact the thermal properties and the temperature distribution of the system. A transient thermal analysis recognizes the temperature changes, and given thermal properties, with respect to time. Eventually a transient system will reach steady-state conditions. Because the curing process of concrete involves significant temperature changes over time, a transient thermal analysis will be used.

Using a program such as Ansys, allows the thermal analysis of the STG structure to be performed through a finite element thermal analysis. Finite element analyses, in general, simplify a given system by breaking it into minuscule sections, known as a discretized model composed of elements. Each of the elements have a given number of nodes that are interconnected to the neighboring nodes or surface. Ansys considers the internal heat generated through cement reactions and the temperature interaction between the surface concrete, air, and formwork to determine the temperature field response. The calculations begin with an initial temperature and is time-stepped incrementally measuring the temperature at each nodal element in the system.
**Theory**

The overall thermal analysis is based on the heat diffusion equation.

$$\rho C_p \frac{\partial T}{\partial t} = q + \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right)$$

Where,

- $\rho$ = density
- $C_p$ = Specific Heat
- $T$ = Temperature, $T(x,y,z)$
- $t$ = time
- $q$ = heat generation per unit volume
- $k$ = thermal conductivity

The heat diffusion equation defines that the rate of change of stored thermal energy within a given volume must be equal to the rate of energy transfer (conduction) plus the thermal energy generation of the volume. The solution provides the temperature distribution at any given time. Understanding the temperature distribution will also help facilitate the understanding of thermal stresses and thermal expansions.

In Bofang Zhu's book, he defines four different types of boundary conditions which can be applied to accurately determine the temperature distribution of a volume (Zhu, 2014).

1. The first boundary condition is temperature. A prescribed temperature can be assigned to a given surface. This value can change as a function of time.

2. The second boundary condition is heat flux on the surface. This value changes as a function of time and material conductivity. Heat flux is a measure of the heat flow rate intensity.
3. The third boundary condition is the heat transfer between the surface and the surrounding medium, typically air. This condition considers the temperature of the two materials transferring heat and conductivity, known as convection. Radiation can also be incorporated into this condition.

4. The final boundary condition is the heat transfer between two solids in contact. This is calculated through the measured temperatures of each surface and their conductivities.

In this analysis, the boundary condition associated with convection is applicable. The general principal behind natural convection is an increase in temperature of a give fluid reduces the density causing it to rise and forcing the colder molecules downward. The colder molecules will accept heat from the warmer source and rise carrying the heat and energy with it. This creates a constant motion of molecules continuing the heat transfer cycle.

The heat that is transferred between the structure and air is dependent on the heat transfer coefficient and temperature measurements of each material as defined in the following heat transfer rate equation.

\[ Q = hA(T_a - T_b) \]

Where,

- \( Q \) = heat transfer rate with respect to time
- \( h \) = heat transfer coefficient
- \( A \) = Area
- \( T_a \) = Structure’s Temperature
- \( T_b \) = Ambient Temperature
The concrete structure’s temperature is impacted by the ambient air surrounding it and is further impacted by the insulation provided by the winter blankets and formwork. As the heat is generated within the concrete and reaches the surface, the convection through the ambient air will accept heat from the surface until equilibrium of the system is achieved. The insulation of the structure impacts the heat transfer coefficient value and ultimately the heat flux between the structure and air.

**Ansys APDL Thermal Simulation**

Ansys is widely used for finite element analyses in a variety of applications. In Ansys, there are four steps to completing the analysis, Preprocessor, Solution, General Post Processing, and Time History Post Processing. The preprocessor step includes selecting material and element properties, drafting a model, developing the mesh, and applying the loads, specifically thermal loads. The solution step provides a selection of analyses and time step options for the analysis. Several time steps can be performed in one analysis, in addition to substeps for interim calculations between the time steps. The number of substeps should be optimized such that accurate results are provided, but not so many that the analysis time is drastically increased. Once the solution is obtained, the results can be reviewed in the general post processing step. This step depicts the solution on the model for a given time step and can also develop animations. Finally, the time history post processing step provides the results at a given location over time. These steps will be further detailed in the next sections.

**Material and Element Properties of Model**

Ansys has a vast selection of elements each with key features that make it suitable for a given analysis. For this specific analysis, SOLID70 was utilized. This three-dimensional element,
as shown below, is specifically used in thermal analyses due to the single degree of freedom, temperature, at each of the eight nodes (SOLID70 3-D Thermal Solid).

![Figure 27 – SOLID70 Ansys Element](image)

The mesh of the model was created to develop the discretized element model. A mapped mesh with hexahedron shapes was used for the columns. This creates a regular pattern of elements with the same shape for each. Due to the irregular shape of the basemat and tabletop, a free mesh was used for these components.

When building the model within Ansys, material thermal properties must be defined. The model was assigned material properties, as shown in Table 12. The concrete properties were assumed to be constant with time and temperature of the system. The density value was based off of the mix designs, while the thermal conductivity and specific heat were adopted from industry standards. The concrete, as placed in the field, may have differing parameters, but for the interest of the simulation these constants will be used.
Table 12 – Ansys Thermal Input Parameters

<table>
<thead>
<tr>
<th>Property</th>
<th>Value (U.S)</th>
<th>Value (SI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>143.6 lb/ft³</td>
<td>2,300 kg/m³</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>1.70 Btu/ft∗hr∗°F</td>
<td>10.6 kg/m∗h∗°C</td>
</tr>
<tr>
<td>Specific Heat</td>
<td>0.179 Btu/lb∗°F</td>
<td>0.75 kJ/kg∗°C</td>
</tr>
</tbody>
</table>

**Initial and Boundary Conditions**

An initial condition for temperature is also required. This value is the temperature of the in-place concrete, which serves as a baseline for the temperature changes to be calculated from. This value, as measured on-site, is the following.

Table 13 – Initial Conditions for each STG Component in Fahrenheit and Celsius

<table>
<thead>
<tr>
<th>STG Component</th>
<th>Initial Temperature (°F)</th>
<th>Initial Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basemat</td>
<td>61.7</td>
<td>16.5</td>
</tr>
<tr>
<td>Column (avg)</td>
<td>82.4</td>
<td>28.0</td>
</tr>
<tr>
<td>Tabletop</td>
<td>69.8</td>
<td>21.0</td>
</tr>
</tbody>
</table>

The next step in the Ansys analysis is to determine what boundary conditions to apply. Ansys has the capabilities to apply temperature, heat flow, convection, heat flux, heat generation, and radiation loads, which align with the four boundary conditions discussed above. The two conditions applied for this analysis are convection and heat generation.

The relationship between the concrete, insulation, and ambient air effect the temperature results. The insulation, including the formwork and a winter insulation blanket, wasn’t physically modeled, but was modeled through the value of the coefficient of convection. The formwork layer against the concrete structure was made of 5/8-inch steel. Due the small thickness and little impact on the convection, the coefficient of convection value for the
formwork was assumed to be zero. The insulating blankets that were wrapped on all surfaces, including formwork, exposed to the ambient air provide R-2.5 insulation. The R-value is the measure of the thermal resistance and its inverse is equivalent to the coefficient of convection. After calculating the inverse to be 0.4 Btu/hr*ft^2*°F and converting to the applicable input units, a coefficient of convection value of 8.17 kJ/hr*m^2*°C was input into the program for all three components. When the forms were removed, the blankets were put back into place and were assumed to remain for the entire duration of the analysis.

The basemat and columns each have one surface of the structure that is not blanketed, but is in contact with the subgrade and concrete respectively. In order to properly account for the heat transfer at these areas, the equation below was applied. For the column surface to the basemat, the coefficient of convection was input as 1.36 Btu/hr*ft^2*°F (7.73 kJ/hr*m^2*°C) and a value of 0.425 Btu/hr*ft^2*°F (2.415 kJ/hr*m^2*°C) was used for the basemat to subgrade.

\[
\text{Coefficient of Convection} = \frac{1}{\gamma}
\]

Where,

\[ \delta = \text{thickness of material} \]
\[ \gamma = \text{thermal conductivity of material} \]

As stated before, the convection is a function of the surrounding fluid, which in this analysis is ambient temperature. In order to model the heating and cooling associated with day and night, the ambient temperature is input as a sinusoidal function based on archived temperature data from neighboring weather stations. Figure 28 plots the ambient temperature formulas for
each STG component to align the temperature at Hour 1 with the initial temperatures as measured in the field.

![Ambient Temperature vs. Time](image)

**Figure 28 – Ambient Temperature vs. Time for Basemat, Column, and Tabletop**

Next, the heat generation rate must be input into the analysis. As discussed in previous sections, the hydration rate is time-dependent. As the cement hydrates an exothermic reaction occurs to generate heat within the system. In order to accurately model the heat generation, a formula with respect to time was calculated. Based on research recognized by the American Society of Civil Engineers, the adiabatic temperature rise, as a result of the hydration reaction, is defined by the following equation (Tanabe, 1985).

\[
T(t) = K(1 - e^{-\alpha t})
\]

Where,

\[
T(t) = \text{temperature, } ^\circ\text{C},
\]

\[
T = \text{the age, day},
\]

\[
K = \text{constant from Figure 29}
\]
The figure below determines the K and alpha constants based on the unit cement content of the concrete mix.

\[ Q(t) = KC_p \rho (1 - e^{-\alpha t}) \]

Where,

- \( T(t) = \) temperature, °C,
- \( T = \) the age, day,
- \( K = \) constant from Figure 29
- \( \alpha = \) constant from Figure 29
- \( C_p = \) specific heat capacity of concrete, kJ/kg°C
- \( \rho = \) density of concrete kg/m³
In Ansys, however, the allowable input parameter is the rate of heat generation, which can be determined through the derivative of the heat generation with respect to time. Because this analysis is performed hourly, the time unit is converted from days to hours. The heat generation rate can be calculated by the following equation.

\[
\text{Heat Generation Rate} = \frac{1}{24} KC_p \rho \alpha e^{-\frac{at}{24}}
\]

The K value was assumed to be 56°C and alpha was determined to be 1.75. While the values assumed are high on the spectrum, it is in alignment with the temperature rise seen in the field measurements. Figure 30 is the Heat Generation Rate for all structures of the STG.

![Heat Generation Rate](image)

**Figure 30 - Heat Generation Rate for Ansys Simulation**

The thermal analysis was performed for 1,000 hours with one substep per hour. The next sections provide the thermal results, as processed by the heat diffusion equation, for the basemat, columns, and tabletop.
Ansys APDL STG Thermal Simulation Results

**Basemat**

The basemat temperatures generated from the Ansys simulation are compared to the field measured data below. Figure 31 provides the west side and Figure 32 provides the east side of the basemat.

![Basemat West Ansys Simulation](image)

**Figure 31 - Temperature vs Time for West Basemat Simulation**
Both simulations follow similar trends to the actual field measurements. The simulation consistently shows a temperature differential between the center and edge of each side. The field results have similar temperatures until approximately 120 hours elapsed. This reduced differential is likely a result of proper thermal management through the pour schedule in the field. The pour schedule was not implemented in the simulation which is likely why the larger differential is seen. The simulated heat generation rate does not appear to be as significant as seen in the field, but ultimately yielded a similar maximum temperature after a specific amount of time. Another observation is that the ambient temperature effected the surface temperature in the field more significantly than the simulation results. This could be a result of improper insulation of the blankets. The following figures show the temperature distribution of the basemat after 1, 12, 24, 48, 60, 120, and 500 hours have elapsed.
Figure 33 – Basemat Temperature Field at Hour 1 in YZ Cross-Section

Figure 34 – Basemat Temperature Field at Hour 1 in XZ Cross-Section
Figure 35 – Basemat Temperature Field at Hour 12 in YZ Cross-Section

Figure 36 – Basemat Temperature Field at Hour 12 in XZ Cross-Section
Figure 37 – Basemat Temperature Field at Hour 24 in YZ Cross-Section

Figure 38 – Basemat Temperature Field at Hour 24 in XZ Cross-Section
Figure 39 – Basemat Temperature Field at Hour 48 in YZ Cross-Section

Figure 40 – Basemat Temperature Field at Hour 48 in XZ Cross-Section
Figure 41 – Basemat Temperature Field at Hour 60 in YZ Cross-Section

Figure 42 – Basemat Temperature Field at Hour 60 in XZ Cross-Section
Figure 43 – Basemat Temperature Field at Hour 120 in YZ Cross-Section

Figure 44 – Basemat Temperature Field at Hour 120 in XZ Cross-Section
Figure 45 – Basemat Temperature Field at Hour 500 in YZ Cross-Section

Figure 46 – Basemat Temperature Field at Hour 500 in XZ Cross-Section
Columns

The column temperatures as measured in the field are compared to the simulated temperatures in Figure 47. The simulated results closely match temperatures seen in the field. The concrete cooling trends are very similar for both the middle and the surface; even the ambient temperature impacts are accurately modeled. Based on the graph, the heat was generated quicker at the surface than the finite element analysis demonstrated, but similar maximum temperatures were yielded. The heat generated in the center of the column is accurately modeled.

![Column Ansys Simulation](image)

Figure 47 - Temperature vs Time for Column Simulation

The following figures show the temperature distribution of the column after 1, 12, 24, 48, 60, 120, and 500 hours have elapsed.
Figure 48 – Column Temperature Field at Hour 1 in XZ Cross-Section

Figure 49 – Column Temperature Field at Hour 1 in XY Cross-Section
Figure 50 – Column Temperature Field at Hour 12 in XZ Cross-Section

Figure 51 – Column Temperature Field at Hour 12 in XY Cross-Section
Figure 52 – Column Temperature Field at Hour 24 in XZ Cross-Section

Figure 53 – Column Temperature Field at Hour 24 in XY Cross-Section
Figure 54 – Column Temperature Field at Hour 48 in XZ Cross-Section

Figure 55 – Column Temperature Field at Hour 48 in XY Cross-Section
Figure 56 – Column Temperature Field at Hour 60 in XZ Cross-Section

Figure 57 – Column Temperature Field at Hour 60 in XY Cross-Section
Figure 58 – Column Temperature Field at Hour 120 in XZ Cross-Section

Figure 59 – Column Temperature Field at Hour 120 in XY Cross-Section
Figure 60 – Column Temperature Field at Hour 500 in XZ Cross-Section

Figure 61 – Column Temperature Field at Hour 500 in XY Cross-Section
The three locations in the tabletop that were measured in the field are compared to the simulated results in Figure 62.

In comparison to the other models, the simulated results of the tabletop differ the most from the field results. However, the trends of the heating and cooling temperatures are similar at all three locations. While the trends are similar, the magnitude of the temperature measured in the field was larger than the analysis due to the heat generation. The maximum temperature in the field was 165.2°F as compared to 157.6°F in the Ansys results. The top and edge results were consistent with the field measurements considering the edge location was always cooler than the surface. The following figures show the temperature distribution of the tabletop after 1, 12, 24, 48, 60, 120, and 500 hours have elapsed.
Figure 63 – Tabletop Temperature Field at Hour 1 in YZ Cross-Section

Figure 64 – Tabletop Temperature Field at Hour 1 in XZ Cross-Section
Figure 65– Tabletop Temperature Field at Hour 12 in YZ Cross-Section

Figure 66– Tabletop Temperature Field at Hour 12 in XZ Cross-Section
Figure 67— Tabletop Temperature Field at Hour 24 in YZ Cross-Section

Figure 68— Tabletop Temperature Field at Hour 24 in XZ Cross-Section
Figure 69– Tabletop Temperature Field at Hour 48 in YZ Cross-Section

Figure 70– Tabletop Temperature Field at Hour 48 in XZ Cross-Section
Figure 71 – Tabletop Temperature Field at Hour 60 in YZ Cross-Section

Figure 72 – Tabletop Temperature Field at Hour 60 in XZ Cross-Section
Figure 73– Tabletop Temperature Field at Hour 120 in YZ Cross-Section

Figure 74– Tabletop Temperature Field at Hour 120 in XZ Cross-Section
Figure 75 – Tabletop Temperature Field at Hour 500 in YZ Cross-Section

Figure 76 – Tabletop Temperature Field at Hour 500 in XZ Cross-Section
Ansys APDL Dependent Variable Study

It is known that mass concrete temperatures are impacted by environmental factors, constituents of the concrete mix design, construction methods, etc. While the temperatures seen are a cumulation of the factors previously mentioned, the Ansys program makes it feasible to isolate a variable and observe the impact it has on the structure. Because of the reasonably accurate simulation between the actual STG temperatures and those provided by Ansys, the STG column model will be used to perform an analysis of how different parameters effect the concrete and to what extent.

In the following analyses, several trials were run with will all consistent input data, excluding the one variable in question. Each variable will be analyzed to recognize the impact it has on the concrete temperature and temperature differential. The concrete data that was input into the analysis is as follows:

Table 14 – Input Parameters for Dependent Variable Study

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Value (English)</th>
<th>Value (SI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Density</td>
<td>143.6 lb/ft.³</td>
<td>2,300 kg/m.³</td>
</tr>
<tr>
<td>2</td>
<td>Specific Heat</td>
<td>0.179 Btu/lb°F</td>
<td>0.75 kJ/kg Btu/hr°F</td>
</tr>
<tr>
<td>3</td>
<td>Thermal Conductivity</td>
<td>1.7 Btu/ft/hr°F</td>
<td>10.6 kg/m/hr°C</td>
</tr>
<tr>
<td>4</td>
<td>Initial Temperature</td>
<td>82.4°F</td>
<td>28°C</td>
</tr>
<tr>
<td>5</td>
<td>Ambient Temperature</td>
<td>=72+14*sin((PI/12)*t+0.75) °F</td>
<td>=22+8*sin((PI/12)*t+0.75) °C</td>
</tr>
<tr>
<td>6</td>
<td>Thermal Convection Coefficient</td>
<td>0.4 Btu/hr*ft²°F</td>
<td>8.17 kJ/hr*m²°C</td>
</tr>
<tr>
<td>7</td>
<td>Heat Generation Rate</td>
<td>= 189.17 * e^{-1.75t/24} Btu/ft³</td>
<td>= 7,043.75 * e^{-1.75t/24} kJ/m³</td>
</tr>
<tr>
<td>8</td>
<td>Model Size</td>
<td>8 x 8 x 34 ft</td>
<td>2.44 x 2.44 x 10.36 m</td>
</tr>
</tbody>
</table>
Initial Temperature of Concrete

The column temperature distribution was modeled four times, each with the different initial temperatures of 0°F, 32°F, 64°F, and 97°F. As expected, the higher the initial temperature, the higher the temperatures in the concrete at both the surface and the center. The maximum temperature was 180°F with the largest differential at 43°F. The cooler initial temperatures had a significantly larger increase in temperature. The 0 °F initial temperature rose 82 °F to achieve a maximum temperature of 91 °F. After about 15 days, the surface temperature for all four trials were within a few degrees of each other. The cooler initial temperatures are consistent with chilling the concrete prior to placement. The maximum temperatures are manageable and the temperature differentials are minor.

The plot for the surface temperatures, center temperatures, and the differential can be referenced in Figure 77, Figure 78, Figure 79, respectively.
Figure 78 – Temperature vs. Time at Column Center for Various Initial Temperatures

Figure 79 – Temperature Difference vs. Time for Column at Various Initial Temperatures
**Ambient Temperature**

The column was also analyzed for a variety of ambient temperatures. The four ambient temperatures are intended to model the four different seasons seen in Colorado. Each season is modeled by sinusoidal functions with varying amplitudes and vertical shifts. The temperatures in at the surface are almost identical for spring and fall seasons, however the springs season did yield a larger gradient. Because of the low temperatures associated with winter, larger temperature differences were seen. If performing a winter concrete pour, proper insulation will be necessary to keep the heat maintained at the surface. Overall, the maximum temperature was 167.5 °F for the summer months with a maximum differential of 53°F in winter.

The plot for the surface temperatures, center temperatures, and the differential can be referenced in Figure 80, Figure 81, Figure 82, respectively.

![Temperature vs. Time at Column Surface for Various Ambient Temperatures](image)

*Figure 80 – Temperature vs. Time at Column Surface for Various Ambient Temperatures*
Figure 81 - Temperature vs. Time at Column Center for Various Ambient Temperatures

Figure 82 – Temperature Difference vs. Time Between Column Center and Surface for Various Ambient Temperatures
Structure Insulation

Structure insulation is an important consideration in mass concrete pours as it can minimize the temperature differential and avoid thermal shock. In this analysis, the convection coefficient was modified to model no insulation, 1” plywood, one R-2.5 rated winter protection blanket, and one R-5 rated winter protection blanket. The minimal amplitudes indicate that the ambient air has a significantly less impact on the temperatures at the surface of the structure when it is more insulated. The insulation did not impact the rate of temperature increase, but it did affect the overall maximum temperatures achieved both at the surface and center of the column. The rate of cooling was also dependent on the level of insulation. The structure exposed to ambient air had a dramatic drop in temperature over a short amount of time. The maximum temperature measured was 171 °F for the R-5 rated winter protection blanket and a maximum differential of 75 °F for the column without insulation. After 1,000 hours, the heavily insulated column is still cooling at a steady rate while all of the others have reached equilibrium with the ambient air. It is clear that the existing environment must be considered when determining the type of insulation. Excessive insulation may provide temperature that exceeds the allowable amount, yet minimal insulation will undoubtedly cause extreme temperature differentials resulting in cracking.

The plot for the surface temperatures, center temperatures, and the differential can be referenced in Figure 83, Figure 84, Figure 85, respectively.
Figure 83 - Temperature vs. Time at Column Surface for Various Insulation Methods

Figure 84 - Temperature vs. Time at Column Center for Various Insulation Methods
Cement Concentrations

Because it is the cement’s reaction with water that generates the heat it is expected that the more cement in the concrete mix, the hotter the structure will get. The Ansys results were consistent with this expectation. The mix designs with the larger cement dosage generated significantly larger temperatures. The maximum temperature and maximum differential were seen in the column with 400 kg/m³ of cement with temperatures of 156 °F and 34 °F respectively. This maximum temperature was 55% higher than the column with 100 kg/m³ of cement. It can also be observed that the higher rate of temperature increase also resulted in a faster rate of cooling at the surface and the center of the column. Under the conditions tested, all four cement dosages yielded results within standard acceptable ranges.

The plot for the surface temperatures, center temperatures, and the differential can be referenced in Figure 86, Figure 87, Figure 88, respectively.
Temperature vs. Time at Column Surface for Various Cement Dosages

Figure 86 - Temperature vs. Time at Column Surface for Various Cement Dosages

Temperature vs. Time at Column Center for Various Cement Dosages

Figure 87 - Temperature vs. Time at Column Center for Various Cement Dosages
Size of Structure

The size of the structure significantly affected the temperature results. The cube models with dimensions 13.1 feet and 19.7 feet yielded maximum temperatures within a few degrees. However, the rate of cooling was much slower for the larger specimen. After 1,000 hours, the largest column had not reached ambient temperatures, compared to the smaller cubes whose center reached equilibrium around 500 hours. Another important observation is the extensive time the largest cube endured a temperature differential over 40 °F. This differential existed from hour 82 through 672. Over the course of these 584 hours, or 24 days, significant stresses can occur as a result of the differential and increase in rigidity during this time.

The plot for the surface temperatures, center temperatures, and the differential can be referenced in Figure 89, Figure 90, Figure 91, respectively.
**Figure 89** - Temperature vs. Time at Column Surface for Various Structure Sizes

**Figure 90** - Temperature vs. Time at Column Center for Various Structure Sizes
Figure 91 - Temperature Difference vs. Time for Column for Various Structure Sizes
CHAPTER V
THERMAL STRESS ANALYSIS SIMULATION

Introduction

Thermal stresses that develop in mass concrete pose a large risk to the integrity of the structure as it can cause cracking. The stresses in mass concrete occur as a result of the combination between significant heat generation and concrete’s inability to dissipate heat quickly. Large temperatures are seen in the middle of the concrete structure creating a large differential with the surface temperature. The large temperatures at the core of the structure cause material expansion while the surface is shrinking due to the cooling with the ambient temperature. The exterior tends to resist the movement at the center causing stresses to develop at the surface. The larger temperature differential between the center and the surface, the more extreme and opposing contraction/expansion behavior will be seen within the structure. Other stresses can develop due to restraining forces. If the structure is restrained and unable to expand and contract with the changing temperatures, high stresses may occur and they may result in cracking.

While the stresses within the structure are typically self-equilibrating, they have the potential to exceed the allowable amount of the structure. The tensile stresses specifically cause concern due to concrete’s poor performance under tension. The development of stresses which lead to cracking is why the thermal control of mass concrete is crucial.
Theory

The calculations performed in the structural analysis are based on the stiffness method and the stress-strain relationship. The stiffness method is defined by the following equation.

\[
\{F\} = [K] \times \{U\}
\]

Where,

\( F \) = Applied forces
\( K \) = Stiffness Matrix
\( U \) = Displacement

Conversely, the displacement can be determined by the inverse of the stiffness matrix. The stiffness matrix contains the geometric properties and represents the materials resistance of element under loading. The applied forces for this analysis are the thermal loads from the thermal analysis. The following equation represents the inverse stiffness matrix.

\[
\{U\} = [K]^{-1} \times \{F\}
\]

Once the displacement it known at all locations throughout the model, the stresses can be determined by the following equation.

\[
\{\sigma\} = [D] \times (\{\varepsilon\} - \{\varepsilon^{th}\})
\]

Where,

\( \sigma \) = Stress Vector
\( D \) = Elasticity Matrix
\( \varepsilon \) = Strain Vector (\( \Delta u/L \))
\( \varepsilon^{th} \) = Thermal Strain Vector (\( \Delta t\alpha \))
The elasticity matrix, as well as the strains associated with temperature differentials and displacement, impact the stress concentration of the structure. The elasticity matrix is primarily dependent on the material properties. The Ansys analysis calculates the stresses at every nodal location of the structure for each applied time step.

**Coefficient of Thermal Expansion**

The coefficient of thermal expansion is material property related to how much it expands when exposed to heat, and more specifically, the change in length per unit temperature rise.

\[
\alpha = \frac{(l_f - l_0)}{l_0(T_f - T_0)} = \frac{1}{l \left( \frac{dl}{dT} \right)}
\]

Where,

- \(l_0\) = original length
- \(l_f\) = final length
- \(T_0\) = initial temperature
- \(T_f\) = Final temperature

The coefficient value is primarily dependent on the coarse aggregate of the concrete. The type of aggregate and quantity will both effect its thermal expansion. However, the most accurate values are based on the concrete mix and the weighted average of each constituent. Typical values range from 5 to 7 x 10^{-6} in/in/°F.

**Modulus of Elasticity**

The modulus of elasticity is related to the stiffness or rigidity of the concrete. During the early stages of concrete, the modulus of elasticity is minimal which provides the workability and
fluidity of the concrete at this time. The modulus quickly increases and eventually reaches a value ranging from $4.1-5.7 \times 10^6$ psi.

**Poisson’s Ratio**

Poisson’s Ratio describes the relative change in lateral dimensions when force is applied longitudinally and vice versa. Ultimately, it is the ratio of the lateral and longitudinal strains within the elastic range. Common values for the Poisson’s Ratio range between 0.16 and 0.20 and will slightly increase as the concrete cures. This increase is generally insignificant and will not be considered in this analysis.

**Ansys APDL Structural Simulation**

The previous chapter discusses the overview of the Ansys simulation process. The procedure to perform a structural analysis is similar and builds on the thermal results from the simulation in Chapter IV. The temperatures at each node for a given time was input into the stress analysis as a temperature load. This was done by loading the temperature-time file and assigning the time to the given time-step in the structural analysis.

**Material and Element Properties of Model**

The element used for the thermal model is known as SOLID45 (SOLID45 3-D Structural Solid). The element type was assigned because is optimal for solid 3-D analyses with eight nodes for $x$, $y$, and $z$ translations.
The model was meshed identically to the thermal analysis with the same nodes and elements. This allowed identical locations to be referenced in both the thermal and structural models. Prior to running the simulation, the material properties, including the density, the coefficient of thermal expansion, poisson’s ratio and the modulus of elasticity, must be put into the program.

The density was input as 143.6 lb/ft³ (2,300 kg/m³) which is based off of the concrete mix designs and is in line with industry standards. The value of $5.889 \times 10^{-5}$ /°F ($1.06 \times 10^{-6}$/°C) was adopted for the coefficient of thermal expansion. While the other values were assumed to be constant, the modulus of elasticity varied with time throughout this analysis. Premature concrete has a very low modulus of elasticity, but as cement hydrates and hardens, the modulus of elasticity drastically increases. The stresses that are developed are directly related to the modulus of elasticity through Hooke’s Law.

The values for modulus of elasticity were obtained through the maturity method as performed and measured in the field. The maturity method, as recognized by ASTM C1074,
provides a method of estimating in field concrete strength, by means other than strength of 7-day and 28-day cylinder breaks. The maturity of the concrete is a measure of the strength based on the age and temperature of the concrete. The concept assumes that similar concrete maturities will yield similar strengths, despite a different time/temperature combination to achieve a given maturity. The Nurse-Saul formula can be used to determine the maturity index.

\[ M(t) = \sum [(T_a - T_0) \times \Delta t] \]

Where,

- \( M(t) \) = the maturity index, °C-hr
- \( T_a \) = Average Temperature for a time interval, °C
- \( T_0 \) = datum temperature, 0 °C
- \( \Delta t \) = specified time interval, hour

In order to correlate a maturity index to the corresponding strength, cylinders must be tested to generate a strength-maturity curve which will serve as the basis for all field testing. The cylinders test the temperature and strength at various ages to establish consistent and accurate results of the strength and maturity relationship. The plot below represents the strength-maturity curve for the mix designs used for the STG concrete pours.
The measured temperature in the field allowed the strengths to be estimated at any given time. The following relationship between concrete strength and modulus of elasticity was used to determine how the modulus of elasticity developed over time (ACI Committee 207, 2007).

\[ E = 57,000 \sqrt{f_c'} \]

Where,

- \( E \) = Modulus of Elasticity, psi
- \( f_c' \) = Compressive Strength, psi

The calculated modulus of elasticity was input into the analysis at the respective time-step.
Boundary Conditions and Loads

In order to isolate the stresses induced by the thermal gradients, only temperature loads were applied in this analysis. As previously discussed, the nodal results of the thermal analysis are input into the structural analysis. Because the meshing is identical in both trials, the temperature will be recognized at all nodes for any given time.

The analysis only applied a boundary condition restraining the bottom of the structure in the x, y, and z directions. This allowed the concrete to deform with minimal constraint to see how the thermal distribution impacted the deformation and stresses. The analysis was performed at approximately 12-hour intervals to reach the 7-day results, then continued at 24-hour intervals until the 28-day mark. Each interval represents a time-step with several sub-steps to ensure accuracy.

Ansys APDL STG Structural Simulation Results

After the structural simulation was completed, the results were analyzed. In the following sections, the following is provided for each component:

- Stress Diagram through vertical section of structure
- Stress diagram through horizontal section of structure (excluding the basemat)
- Ansys FEM model of stress nodal solution at 48 hours. The cross section corresponds with the vertical section of the stress diagram
- Ansys FEM model of stress nodal solution at 48 hours. The cross section corresponds with the horizontal section of the stress diagram (excluding the basemat)
• Discrete Model identifying locations of stress analysis
• Stress vs Time plot at a variety of locations of the structure

In general, the results of the FEM analysis were consistent with what was expected. The stress at the center of the structure was in compression while the top and bottom surfaces were in tension. These stresses continued to develop and increase overtime. However, by hour 672 (28 days) the internal thermal stresses at most locations neared zero.

The stresses seen over time are representative of the self-stress of the structures. The center is in compression and attempting to expand. The surface is much cooler and resists this movement and induces tensile stresses. As shown in the diagrams, these stresses only need to be closely monitored (via temperatures) during the early ages of concrete and eventually level out.

The tensile stresses at the bottom of the structure, specifically in the column and tabletop, remain significant even after 28 days. These stresses represent the restraint stresses. The bottom of each structure has been models with a restraint to prevent any movement or displacement. Since the rest of the structure is expanding and contracting with various temperatures, stresses are induced and maintained at the bottom of the surface. As previously discussed, these stresses pose a greater risk to the structure as they begin towards the bottom and can propagate upwards.

The Stress vs. Time plot for each of the structures indicate where the higher tensile stresses and compression stresses develop overtime. Because corners and edges are typically susceptible to tensile stresses they are analyzed in this model. The red dotted line represents
the allowable tensile strength. This is calculated from the tensile relationship with compression by the following equation:

\[ f_t = 6\sqrt{f'_c} \]

Where,

\( f_t \) = tensile strength of concrete, psi

\( f'_c \) = compressive strength of concrete, psi

The compressive strength is determined by the maturity index discussed in previous sections. The actual structures constructed in the field contained reinforcement which would dramatically increase the tensile stress capacity of the structure, however the rebar reinforcement was not considered in this analysis.
Figure 94 – Stress Diagram in Y-Direction for Basemat at Different Time Steps

Figure 95 – Location of Basemat Vertical Stress Diagram
Figure 96 – Locations of Stress Analysis in Basemat

Figure 97 – Stress vs. Time at Various Basemat Locations
In the plot in Figure 97, the four locations of the thermocouples are analyzed in addition to the east side top corners (Corner 1 and Corner 2). The tensile stresses seen approach the maximum allowable of the structure; cracking would be likely, specifically at the corners. The jagged results are likely a result of inconsistencies of the free mesh. Refinement of the mesh may provide more accurate results; however, the trends of the stress are in line with the anticipated results. The lower tensile stresses seen may be attributable to the minimal temperature differential.
Column

Figure 98 - Stress Diagram in X-Direction for Column at Various Time Steps

Figure 99 – Location of Column Horizontal Stress Diagram
Figure 100 – Stress Diagram in Y-Direction for Column at Various Time Steps

Figure 101 - Location of Column Vertical Stress Diagram
Figure 102 – Locations of Stress Analysis for the Column

Figure 103 – Stress vs. Time at Various Column Locations
The two locations of the thermocouples were analyzed for stresses. As expected, the center of the structure was in compression while the surface was in tension. The center edge of the surface and the surface corner at the top of the column was also considered. The corner yielded the highest tensile stress and is the most likely to crack. The surface edge and surface center had similar development of stresses after casting.
Figure 104 - Stress Diagram in Z-Direction for Tabletop at Various Time Steps

Figure 105 - Location of Tabletop Z-Direction Stress Diagram
Figure 106 - Stress Diagram in Y-Direction for Tabletop at Various Time Steps

Figure 107 - Location of Tabletop Y-Direction Stress Diagram
Figure 108 – Locations of Stress Analysis for the Tabletop

Figure 109 – Stress vs. Time at Various Tabletop Locations
All three thermocouple locations, as well as two corners were analyzed for stresses. Corner 1 is the furthest x-coordinate at z=0 and corner 2 is the furthest z-coordinate at x=0. When compared to the maximum tensile stress, both corners and the edge are likely to crack. The corners yielded the highest tensile stress, but the edge endured the tensile stresses for a longer duration. The tabletop had a significant temperature differential which is facilitating these large stresses.
CHAPTER VI

CONCLUSION

The objective of this thesis study was to understand the behavior of mass concrete structures under thermal loading due to the heat generated from hydration. The conclusions based on the findings are as follows:

- The finite element analysis program, Ansys, and the input parameters of this STG analysis can accurately simulate the temperature field of structures in similar volume and geometry as the basemat, column, and tabletop. The measured temperature data from the STG project are in alignment with those calculated through the Ansys finite element analysis.

- Initial temperature, ambient temperature, cement dosages, insulation, and structure size all play a significant role in the thermal behavior of a given mass concrete structure. While these can be modeled individually, all parameters must be considered simultaneously to understand the net effect of the temperature distribution.

- Large temperature differentials within a given structure combined with the stiffening of the structure develop tensile stresses at the surface. These stresses cannot be ignored as the magnitude can exceed the structures tensile limit and result in cracking.

Ansys is a powerful program with numerous features to analyze structures. In order to expand on the efforts from this thesis and use Ansys to its full potential, a few different scenarios can be implemented in future studies. By doing the following, the results may yield a higher level of accuracy when compared to the field measurements.
• The actual pour plan and progression can be incorporated into the analysis using the Kill/Alive elements in Ansys. Although these pours are relatively small, in comparison to a dam, the thermal results may be improved and different stresses may be developed at the interfaces of the lifts and phases. Additionally, this may optimize pour plans in the field based on the results.

• A study of the formwork can be performed. The formwork will provide different restraints which will go to zero once the formwork is removed. This may cause a spike in stresses upon removal, or provide larger stresses due to more external restraints and limited movement with thermal expansion.

• Elaborate on the stress study to understand and model how the cracks impact the long-term behavior of the structure.
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Hydration of Portland Cement.


“Scientific Principles.” Concrete: Scientific Principles, University of Illinois, matse1.matse.illinois.edu/concrete/prin.html.


Thomas, Jeff, and Hamlin Jennings. The Science of Concrete. Northwestern University, iti.northwestern.edu/cement/aboutTheAuthor.html.


APPENDIX A

Thermal Analysis Ansys Command Data

Basemat Thermal Analysis – Command Data

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/*
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,KXX,1,,10.6
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,C,1,,.75
MPTEMP,,,,,,,,
MPTEMP,1,0
MPDATA,DENS,1,,2300
SMRT,6
SMRT,7
MSHAPE,1,3D
MSHKEY,0
/*
CM,_Y,VOLU
VSEL,,,,,1
CM,_Y1,VOLU
CHKMSH,'VOLU'
CMSEL,S,_Y
/*
VMESH, _Y1
!*  
CMDELE, _Y  
CMDELE, _Y1  
CMDELE, _Y2  
!*  
FLST, 5, 829, 2, ORDE, 2  
FITEM, 5, 1  
FITEM, 5, -829  
CM, _Y, ELEM  
ESEL, , , , P51X  
CM, _Y1, ELEM  
CMSEL, S, _Y  
CMDELE, _Y  
!*  
!*  
EREF, _Y1, , , 1, 0, 1, 1  
CMDELE, _Y1  
!*  
!*  
ANTYPE, 4  
/UI, MESH, OFF  
FLST, 2, 9, 5, ORDE, 4  
FITEM, 2, 11  
FITEM, 2, -15  
FITEM, 2, 17  
FITEM, 2, -20  
/GO  
!*  
!*  
SFA, P51X, 1, CONV, 8.17, %ATEMP%  
FLST, 2, 1, 5, ORDE, 1  
FITEM, 2, 16  
/GO  
!*  
!*  
SFA, P51X, 1, CONV, 2.414, %ATEMP%  
FLST, 2, 1, 6, ORDE, 1  
FITEM, 2, 1  
/GO  
!*  
!*  
BFV, P51X, HGEN, %HGEN%  
FLST, 2, 1796, 1, ORDE, 2  
FITEM, 2, 1  
FITEM, 2, -1796  
IC, P51X, TEMP, 16.5,  
FINISH  
/SOL  
!*  
!*  
ANTYPE, 4  
!*  
TRNOPT, FULL  
LUMP, 0  
!*  
DELTIM, 1, 1, 1  
OUTRES, ERASE  
OUTRES, ALL, 1  
LNSRCH, 1  
NEQIT, 1000  
TIME, 1000  
/STATUS, SOLU  
SOLVE
Column Thermal Analysis - Command Data

/COM, ANSYS RELEASE Release 19.0      BUILD 19.0      UP20171214      14:42:11
/input, menu, tmp,"
/GRA, POWER
/GST, ON
/FLO, INFO, 3
/GRO, CURL, ON
/CPLANE, 1
/REPL, RESIZE
/WPS, 0
/REPL, RESIZE
/FILNAME, Large Col, 0
/CWD, 'C:\Users\Kelsey.Petersen\Desktop\ANSYS REV'
*DEL, _FNCNAME
*DEL, _FNCMTID
*DEL, _FNCCSYS
*SET, _FNCNAME, 'ATEMP'
*SET, _FNCCSYS, 0
! /INPUT, D:\My Folder\Thesis\Ansys Tables\Column 3 AmbTemp.func,,1
*DIM, %_FNCNAME%, TABLE, 6, 12, 1,,,, %_FNCCSYS%
!
! Begin of equation: 22 + 8 * sin((Pi * {TIME}/12) + .75)
*SET,%_FNCNAME%(0,0,1), 0.0, -999
*SET,%_FNCNAME%(2,0,1), 0.0
*SET,%_FNCNAME%(3,0,1), 0.0
*SET,%_FNCNAME%(4,0,1), 0.0
*SET,%_FNCNAME%(5,0,1), 0.0
*SET,%_FNCNAME%(6,0,1), 0.0
*SET,%_FNCNAME%(0,1,1), 1.0, -1, 0, 3.14159265358979310, 0, 0, 1
*SET,%_FNCNAME%(0,2,1), 0.0, -2, 0, 1, -1, 3, 1
*SET,%_FNCNAME%(0,3,1), 0, -1, 0, 12, 0, 0, -2
*SET,%_FNCNAME%(0,4,1), 0.0, -3, 0, 1, -2, 4, -1
*SET,%_FNCNAME%(0,5,1), 0.0, -1, 0, .75, 0, 0, -3
*SET,%_FNCNAME%(0,6,1), 0.0, -2, 0, 1, -3, 1, -1
*SET,%_FNCNAME%(0,7,1), 0.0, -1, 9, 1, -2, 0, 0
*SET,%_FNCNAME%(0,8,1), 0.0, -2, 0, 8, 0, 0, -1
*SET,%_FNCNAME%(0,9,1), 0.0, -3, 0, 1, -2, 3, -1
*SET,%_FNCNAME%(0,10,1), 0.0, -1, 0, 22, 0, 0, -3
*SET,%_FNCNAME%(0,11,1), 0.0, -2, 0, 1, -1, 1, -3
*SET,%_FNCNAME%(0,12,1), 0.0, 99, 0, 1, -2, 0, 0
! End of equation: 22 + 8 * sin((Pi * {TIME}/12) + .75)
!--> *DEL, _FNCNAME
*DEL, _FNCMTID
*DEL, _FNCCSYS
*SET, _FNCNAME, 'HGEN'
*SET, _FNCCSYS, 0
! /INPUT, D:\My Folder\Thesis\Ansys Tables\HGEN9.func,,1
*DIM,%_FNCNAME%, TABLE, 6, 12, 1,,,, %_FNCCSYS%
!
! Begin of equation: 7043.75 * exp(-1.75 * {TIME}/24)
*SET,%_FNCNAME%(0,0,1), 0.0, -999
*SET,%_FNCNAME%(2,0,1), 0.0
*SET,%_FNCNAME%(3,0,1), 0.0
*SET,%_FNCNAME%(4,0,1), 0.0
*SET,%_FNCNAME%(5,0,1), 0.0
*SET,%_FNCNAME%(6,0,1), 0.0
*SET,%_FNCNAME%(0,1,1), 1.0, -1, 0, 0, 0, 0, 0
*SET,%_FNCNAME%(0,2,1), 0.0, -2, 0, 1, 0, 0, -1

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*SET, %_FNCNAME%(0,3,1), 0, -3, 0, 1, -1, 2, -2
*SET, %_FNCNAME%(0,4,1), 0.0, -1, 0, 1.75, 0, 0, -3
*SET, %_FNCNAME%(0,5,1), 0.0, -2, 0, 1, -3, 3, -1
*SET, %_FNCNAME%(0,6,1), 0.0, -1, 0, 1, -2, 3, 1
*SET, %_FNCNAME%(0,7,1), 0.0, -2, 0, 24, 0, 0, -1
*SET, %_FNCNAME%(0,8,1), 0.0, -3, 0, 1, -1, 4, -2
*SET, %_FNCNAME%(0,9,1), 0.0, -1, 7, 1, -3, 0, 0
*SET, %_FNCNAME%(0,10,1), 0.0, -2, 0, 7043.75, 0, 0, -1
*SET, %_FNCNAME%(0,11,1), 0.0, -3, 0, 1, -2, 3, -1
*SET, %_FNCNAME%(0,12,1), 0.0, 99, 0, 1, -3, 0, 0

! End of equation: 7043.75*exp(-1.75*{TIME}/24)

! -->
/AUX15
!*
IOPTN, IGES, SMOOTH
IOPTN, MERGE, YES
IOPTN, SOLID, YES
IOPTN, SMALL, YES
IOPTN, GTOLER, DEFA
IGESIN, 'STG Model - Exploded - 1 column - reoriented', 'iges', 'D:\My Folder\Thesis\KP MODEL'

VPLOT
!*
!*
/NOPR

KEYW, PR_SET, 1
KEYW, PR_STRUC, 0
KEYW, PR_THERM, 1
KEYW, PR_FLUID, 0
KEYW, PR_ELMAG, 0
KEYW, MAGNOD, 0
KEYW, MAGEDG, 0
KEYW, MAGHFE, 0
KEYW, MAGELC, 0
KEYW, PR_MULTI, 0
/GO
!*

/COM,
/COM, Preferences for GUI filtering have been set to display:
/COM, Thermal
!* FINISH
/PREP7
!* ET, 1, SOLID70
!* TOFFST, 273
!* MPTEMP, , , , , , , ,
MPTEMP, 1, 0
MPDATA, KXX, 1, 10.6
MPTEMP, , , , , , , ,
MPTEMP, 1, 0
MPDATA, C, 1, .75
MPTEMP, , , , , , , ,
MPTEMP, 1, 0
MPDATA, DENS, 1, 2300
FLST, 2, 6, 5, ORDE, 2
FITEM, 2, 7
FITEM, 2, -12
AESIZE, P51X, .4064,
MSHAPE, 0, 3D
MSHKEY, 1
!* CM, _Y, VOLU
VSEL, _ , , , 1
CM, _Y1, VOLU
CHKMESH, 'VOLU'
CMSEL, S, _Y
!* VMESH, _Y1
!* CMDELE, _Y
CMDELE, _Y1
CMDELE, _Y2
!* /UI, MESH, OFF
!* ANTYPE, 4
!* TRNOPT, FULL
LUMPM, 0
!* FLST, 2, 5, 5, ORDE, 3
FITEM, 2, 7
FITEM, 2, 9
FITEM, 2, -12
/GO
!*
!* SFA, P51X, 1, CONV, 8.17, %ATEMP%
FLST, 2, 1, 5, ORDE, 1
FITEM, 2, 8
/GO
!*
!* SFA, P51X, 1, CONV, 7.73, %ATEMP%
FLST, 2, 1, 6, ORDE, 1
FITEM, 2, 1
/GO
!*
!* BFV, P51X, HGEN, %HGEN%
FLST, 2, 1225, 1, ORDE, 2
FITEM, 2, 1
FITEM, 2, -1225
IC, P51X, TEMP, 28,
FINISH
/SOL
!* ANTYPE, 4
!* TRNOPT, FULL
LUMPM, 0
!* DELTIM, 1, 1, 1
OUTRES, ERASE
OUTRES, ALL, 1
LNSRCH, 1
NEQIT, 100
TIME, 1000
!* /STATUS, SOLU
SOLVE
FINISH
Tabletop Thermal Analysis – Command Data

/COM, ANSYS RELEASE Release 19.0 BUILD 19.0 UP20171214 15:26:50
/input, start, ans, 'C:\Program Files\ANSYS Inc\ANSYS Student\v190\ANSYS\apdl\'

*/

*SET, _FNCNAME(0), 0
*DEL, _FNCTMTID
*DEL, _FNCCSYS
*SET, _FNCNAME, 'ATEMP'
*SET, _FNCCSYS, 0

! /INPUT, D:\My Folder\Thesis\Ansys Tables\Tabletop Ambient Temp.func,,,,,1

*DIM, %_FNCNAME%, TABLE, 6, 10, 1,,,, %_FNCCSYS%

! Begin of equation: 17+3.5*sin(.261799*(TIME)+4.3)

*SET, %_FNCNAME%(0,0,1), 0.0, -999
*SET, %_FNCNAME%(2,0,1), 0.0
*SET, %_FNCNAME%(3,0,1), 0.0
*SET, %_FNCNAME%(4,0,1), 0.0
*SET, %_FNCNAME%(5,0,1), 0.0
*SET, %_FNCNAME%(6,0,1), 0.0
*SET, %_FNCNAME%(0,1,1), 1.0, -1, 0, 0.261799, 0, 0, 1
*SET, %_FNCNAME%(0,2,1), 0.0, -2, 0, 1, -1, 3, 1
*SET, %_FNCNAME%(0,3,1), 0, -1, 0, 4.3, 0, 0, -2
*SET, %_FNCNAME%(0,4,1), 0.0, -3, 0, 1, -2, 1, -1
*SET, %_FNCNAME%(0,5,1), 0.0, -1, 9, 1, -3, 0, 0
*SET, %_FNCNAME%(0,6,1), 0.0, -2, 0, 3.5, 0, 0, -1
*SET, %_FNCNAME%(0,7,1), 0.0, -3, 0, 1, -2, 3, -1
*SET, %_FNCNAME%(0,8,1), 0.0, -1, 0, 17, 0, 0, -3
*SET, %_FNCNAME%(0,9,1), 0.0, -2, 0, 1, -1, 1, -3
*SET, %_FNCNAME%(0,10,1), 0.0, 99, 0, 1, -2, 0, 0

! End of equation: 17+3.5*sin(.261799*(TIME)+4.3)

!-->

*SET, %_FNCNAME%(0,0,1), 0.0, -999
*SET, %_FNCNAME%(2,0,1), 0.0
*SET, %_FNCNAME%(3,0,1), 0.0
*SET, %_FNCNAME%(4,0,1), 0.0
*SET, %_FNCNAME%(5,0,1), 0.0
*SET, %_FNCNAME%(6,0,1), 0.0
*SET, %_FNCNAME%(0,1,1), 1.0, -1, 0, 0, 0, 0, 0
*SET, %_FNCNAME%(0,2,1), 0.0, -2, 0, 1, 0, 0, -1
*SET, %_FNCNAME%(0,3,1), 0, -3, 0, 1, -1, 2, -2
*SET, %_FNCNAME%(0,4,1), 0.0, -1, 0, 1.75, 0, 0, -3
*SET, %_FNCNAME%(0,5,1), 0.0, -2, 0, 1, -3, 0, 0
*SET, %_FNCNAME%(0,6,1), 0.0, -1, 0, 1, -2, 3, 1
*SET, %_FNCNAME%(0,7,1), 0.0, -2, 0, 24, 0, 0, -1
*SET, %_FNCNAME%(0,8,1), 0.0, -3, 0, 1, -1, 4, -2
*SET, %_FNCNAME%(0,9,1), 0.0, -1, 7, 1, -3, 0, 0
*SET, %_FNCNAME%(0,10,1), 0.0, -2, 0, 7043.75, 0, 0, -1
*SET, %_FNCNAME%(0,11,1), 0.0, -3, 0, 1, -2, 3, -1
*SET, %_FNCNAME%(0,12,1), 0.0, 99, 0, 1, -3, 0, 0

! End of equation: 7043.75*exp(-1.75*(TIME)/24)

!-->

/AUX15
!*  
IOPTN, IGES, SMOOTH
IOPTN, MERGE, YES
IOPTN, SOLID, YES
IOPTN, SMALL, YES
IOPTN, CORDER, DEFA
IGESIN, 'STG Model Tabletop - Exploded m - reoriented', 'iges', 'D:\My Folder\Thesis\KP Model\'
V PLOT
!*  
!*  
/NOPR
KEYW, PR_SET, 1
KEYW, PR_STRUC, 0
KEYW, PR_THERM, 1
KEYW, PR_FLUID, 0
KEYW, PR_ELMAG, 0
KEYW, MAGNOD, 0
KEYW, MAGEDG, 0
KEYW, MAGHFE, 0
KEYW, MAGELC, 0
KEYW, PR_MULTI, 0
/GO
!*  
/COM, Preferences for GUI filtering have been set to display:
/COM,  Thermal
!*  
FINISH
/PREP7
!*  
ET, 1, SOLID70
!*  
TOFFST, 273
!*  
MPTEMP, , , , , , , ,
MPTEMP, 1, 0
MPDATA, KXX, 1, , , 10.6
MPTEMP, , , , , , ,
MPTEMP, 1, 0
MPDATA, C, 1, , , .75
MPTEMP, , , , , , ,
MPTEMP, 1, 0
MPDATA, DENS, 1, , , 2300
SMRT, 6
SMRT, 7
MSHAPE, 1, 3D
MSHKEY, 0
!*  
CM, _Y, VOLU
VSEL, , , , , , , , , , , , , , 1
CM, _Y1, VOLU
CHKMSSH, 'VOLU'
CMSEL, S, _Y
!*  
VMESH, _Y1
!*  
CMDELE, _Y
CMDELE, _Y1
CMDELE, _Y2
!*  
FLST, 5, 357, 2, ORDE, 2
FITEM, 5, 1
FITEM,5, -357
CM, _Y, ELEM
ESEL, , , , P51X
CM, _Y1, ELEM
CMSEL, S, _Y
CMDELETE, _Y
!*
!*
EREFS, _Y1, , , 1, 0, 1, 1
CMDELETE, _Y1
!*
!*
ANTYPE, 4
!*
TRNOPT, FULL
LUMPMD, 0
!*
FLST, 2, 18, 5, ORDE, 2
FITEM, 2, 19
FITEM, 2, -36
/GO
!*
!*
SFA, P51X, 1, CONV, 8.17, %ATEMP%
FLST, 2, 1, 6, ORDE, 1
FITEM, 2, 1
/GO
!*
!*
BFV, P51X, HGEN, %HGEN%
FLST, 2, 886, 1, ORDE, 2
FITEM, 2, 1
FITEM, 2, -886
IC, P51X, TEMP, 21,
/US, MESH, OFF
FINISH
/SOL
!*
ANTYPE, 4
!*
TRNOPT, FULL
LUMPMD, 0
!*
DELTIM, 1, .1, 1
OUTRES, ERASE
OUTRES, ALL, 1
LNSRCH, 1
NEQIT, 100
TIME, 1000
/STATUS, SOLU
SOLVE
FINISH
APPENDIX B

Structural Analysis Ansys Command Data

Basemat Structural Analysis – Command Data

/COM, ANSYS RELEASE Release 19.0      BUILD 19.0      UP20171214      18:54:43
/input, menust, tmp, "'
/GRA, POWER
/GST, ON
/PLO, INFO, 3
/GRO, CURL, ON
/CPLANE, 1
/REPLOT, RESIZE
WPSTYLE,,,,,,,0
/REPLOT, RESIZE
/CWD, 'C:\Users\Kelsey.Petersen\Desktop\Ansys Stress'
/FILNAME, BASemat1, 0
*DEL, _FNCNAME
*DEL, _FNCMID
*DEL, _FNCCSYS
*SET, _FNCNAME, 'HGEN'
*SET, _FNCCSYS, 0
! /INPUT, D:\My Folder\Thesis\Ansys Tables\HGEN9.func,,,,1
*DIM, %_FNCNAME%, TABLE, 6, 12, 1,,,, %_FNCCSYS%
! Begin of equation: 7043.75*exp(-1.75*{TIME}/24)
*SET, %_FNCNAME%(0,0,1), 0.0, -999
*SET, %_FNCNAME%(2,0,1), 0.0
*SET, %_FNCNAME%(3,0,1), 0.0
*SET, %_FNCNAME%(4,0,1), 0.0
*SET, %_FNCNAME%(5,0,1), 0.0
*SET, %_FNCNAME%(0,1,1), 1.0, -1, 0, 0, 0, 0, 0
*SET, %_FNCNAME%(0,2,1), 0.0, -2, 0, 1, 0, 0, -1
*SET, %_FNCNAME%(0,3,1), 0, -3, 0, 1, -1, 2, -2
*SET, %_FNCNAME%(0,4,1), 0.0, -1, 0, 1.75, 0, 0, -3
*SET, %_FNCNAME%(0,5,1), 0.0, -2, 0, 1, -3, 3, -1
*SET, %_FNCNAME%(0,6,1), 0.0, -1, 0, 1, -2, 3, 1
*SET, %_FNCNAME%(0,7,1), 0.0, -2, 0, 24, 0, 0, -1
*SET, %_FNCNAME%(0,8,1), 0.0, -3, 0, 1, -1, 4, -2
*SET, %_FNCNAME%(0,9,1), 0.0, -1, 7, 1, -3, 0, 0
*SET, %_FNCNAME%(0,10,1), 0.0, -2, 0, 7043.75, 0, 0, -1
*SET, %_FNCNAME%(0,11,1), 0.0, -3, 0, 1, -2, 3, -1
*SET, %_FNCNAME%(0,12,1), 0.0, 99, 0, 1, -3, 0, 0
! End of equation: 7043.75*exp(-1.75*{TIME}/24)
!-->
*DEL, _FNCNAME
*DEL, _FNCMID
*DEL, _FNCCSYS
*SET, _FNCNAME, 'ATEMP'
*SET, _FNCCSYS, 0
! /INPUT, D:\My Folder\Thesis\Ansys Tables\Basemat Ambient Temp.func,,,,1
*DIM, %_FNCNAME%, TABLE, 6, 10, 1,,,, %_FNCCSYS%
! Begin of equation: 31+11*sin(.261799*{TIME}+3.5)
*SET, %_FNCNAME%(0,0,1), 0.0, -999
*SET, %_FNCNAME%(2,0,1), 0.0
*SET, %_FNCNAME%(3,0,1), 0.0
*SET, %_FNCNAME%(4,0,1), 0.0

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*SET, % FNCNAME%(5,0,1), 0.0
*SET, % FNCNAME%(6,0,1), 0.0
*SET, % FNCNAME%(0,1,1), 1.0, -1, 0, .261799, 0, 0, 1
*SET, % FNCNAME%(0,2,1), 0.0, -2, 0, 1, -1, 3, 1
*SET, % FNCNAME%(0,3,1), 0, -1, 0, 3.5, 0, 0, -2
*SET, % FNCNAME%(0,4,1), 0.0, -3, 0, 1, -2, 1, -1
*SET, % FNCNAME%(0,5,1), 0.0, -1, 9, 1, -3, 0, 0
*SET, % FNCNAME%(0,6,1), 0.0, -2, 0, 11, 0, 0, -1
*SET, % FNCNAME%(0,7,1), 0.0, -3, 0, 1, -2, 3, -1
*SET, % FNCNAME%(0,8,1), 0.0, -1, 0, 31, 0, 0, -3
*SET, % FNCNAME%(0,9,1), 0.0, -2, 0, 1, -1, 1, -3
*SET, % FNCNAME%(0,10,1), 0.0, 99, 0, 1, -2, 0, 0
! End of equation: 31+11*sin(.261799*(TIME)+3.5)

!-->
/AUX15
!*
!*
ILOPTN, IGES, SMOOTH
ILOPTN, MERGE, YES
ILOPTN, SOLID, YES
ILOPTN, SMALL, YES
ILOPTN, GTOLE, DEFA
IGESIN, 'STG Model Basemat - Exploded m - reoriented', 'iges', 'D:\My Folder\Thesis\KP MODEL'\nVPLOT
!* 
!* 
/NOPR
KEYW, PR_SET, 1
KEYW, PR_STRUCT, 1
KEYW, PR_THERM, 0
KEYW, PR_FLUID, 0
KEYW, MAGNOD, 0
KEYW, MAGEDG, 0
KEYW, MAGHFE, 0
KEYW, MAGELC, 0
KEYW, PR_MULTI, 0
/GO
!* 
/COM,
/COM, Preferences for GUI filtering have been set to display:
/COM, Structural
!* 
FINISH
/PREF7
!* 
et, 1, 45
TOFFST, 273
!* 
MPTEMP, , , , ,
MPTEMP, 1, 0
MPDATA, EX, 1, 8727
MPDATA, PRXY, 1, 2
MPTEMP, , , , ,
MPTEMP, 1, 0
MPDATA, DENS, 1, 2300
MPTEMP, , , , ,
MPTEMP, 1, 0
UMF, 1, REF, ,
MPDATA, ALFX, 1, 0.0000106
SMRT, 6
SMRT, 7
MSHAPE, 1, 3D
MSHKEY, 0
!* CM, Y, VOLU
VSEL, , , 1
CM, Y1, VOLU
CHKMSH, 'VOLU'
CMSEL, S, Y
!* VMESH, Y1
!* CMDELE, Y
CMDELE, Y1
CMDELE, Y2
!* FLST, 5, 829, 2, ORDE, 2
FITEM, 5, 1
FITEM, 5, -829
CM, Y, ELEM
ESEL, , , P51X
CM, Y1, ELEM
CMSEL, S, Y
CMDELE, Y
!* EREF, Y1, , , 1, 1, 1
CMDELE, Y1
!* *
ANTYPE, 0
FLST, 2, 1, 5, ORDE, 1
FITEM, 2, 16
!* /GO
DA, P51X, ALL,
/UI, MESH, OFF
LDREAD, TEMP,,, 1, , 'BM', 'rth', '..\ANSYS REV\' FINISH /SOL
NSUBST, 12, 0, 0
OUTRES, ERASE
OUTRES, ALL, 1
LNSRCH, 1
NEQIT, 100
TIME, 1
LSWRITE, 1,
FINISH
/PREF7
LDREAD, TEMP,,, 6, , 'BM', 'rth', '..\ANSYS REV\' FINISH /SOL
TIME, 6
LSWRITE, 2,
FINISH
/PREF7
!* MPTEMP,,,,,,,
MPTEMP, 1, 0
MPDE, EX, 1
MPDE, PRXY, 1
MPDATA, EX, 1, , 11431
MPDATA, PRXY, 1, , 0.2
LDREAD, TEMP,,, 12, , 'BM', 'rth', '..\ANSYS REV\'
FINISH
/SOL
TIME, 12
LSWRITE, 3,
FINISH
/PREP7
!*
MPTEMP, , , , , , ,
MPTEMP, 1, 0
MPDE, EX, 1
MPDE, PRXY, 1
MPDATA, EX, 1,, 18446
MPDATA, PRXY, 1,, 0.2
LDREAD, TEMP,,, 24, , 'BM', 'rth', .. \ANSYS REV\'
FINISH
/SOL
TIME, 24
LSWRITE, 4,
FINISH
/PREP7
!*
MPTEMP, , , , , , ,
MPTEMP, 1, 0
MPDE, EX, 1
MPDE, PRXY, 1
MPDATA, EX, 1,, 22493
MPDATA, PRXY, 1,, 0.2
LDREAD, TEMP,,, 36, , 'BM', 'rth', .. \ANSYS REV\'
FINISH
/SOL
TIME, 36
LSWRITE, 5,
FINISH
/PREP7
!*
MPTEMP, , , , , , ,
MPTEMP, 1, 0
MPDE, EX, 1
MPDE, PRXY, 1
MPDATA, EX, 1,, 24624
MPDATA, PRXY, 1,, 0.2
LDREAD, TEMP,,, 48, , 'BM', 'rth', .. \ANSYS REV\'
FINISH
/SOL
TIME, 48
LSWRITE, 6,
FINISH
/PREP7
!*
MPTEMP, , , , , , ,
MPTEMP, 1, 0
MPDE, EX, 1
MPDE, PRXY, 1
MPDATA, EX, 1,, 25579
MPDATA, PRXY, 1,, 0.2
LDREAD, TEMP,,, 60, , 'BM', 'rth', .. \ANSYS REV\'
FINISH
/SOL
TIME, 60
LSWRITE, 7,
FINISH
/PREP7
!*
LDREAD, TEMP,,,72, , 'BM', 'rth',',..\ANSYS REV\'
FINISH
/SOL
TIME, 72
LSWRITE, 8,
FINISH
/PREP7
!* MPTEMP,,,,
MPTEMP, 1, 0
MPDE, EX, 1
MPDE, PRXY, 1
MPDATA, EX, 1,, 26092
MPDATA, PRXY, 1,, 0.2
LDREAD, TEMP,,,84, , 'BM', 'rth',',..\ANSYS REV\'
FINISH
/SOL
TIME, 84
LSWRITE, 9,
FINISH
/PREP7
!* MPTEMP,,,,
MPTEMP, 1, 0
MPDE, EX, 1
MPDE, PRXY, 1
MPDATA, EX, 1,, 26423
MPDATA, PRXY, 1,, 0.2
LDREAD, TEMP,,,96, , 'BM', 'rth',',..\ANSYS REV\'
FINISH
/SOL
TIME, 96
LSWRITE, 10,
FINISH
/PREP7
!* MPTEMP,,,,
MPTEMP, 1, 0
MPDE, EX, 1
MPDE, PRXY, 1
MPDATA, EX, 1,, 26423
MPDATA, PRXY, 1,, 0.2
LDREAD, TEMP,,,108, , 'BM', 'rth',',..\ANSYS REV\'
FINISH
/SOL
TIME, 108
LSWRITE, 11,
FINISH
/PREP7
LDREAD, TEMP,,,120, , 'BM', 'rth',',..\ANSYS REV\'
FINISH
/SOL
TIME, 120
LSWRITE, 12,
FINISH
/PREP7
!* LDREAD, TEMP,,,168, , 'BM', 'rth',',..\ANSYS REV\'
FINISH
/SOL
TIME, 168
LSWRITE, 13,
FINISH
/PREP7
LDREAD, TEMP,,,192, , 'BM', 'rth',',..\ANSYS REV\'
FINISH
/SOL
TIME, 192
LSWRITE, 14,
FINISH
/PREP7
LDREAD,TEMP,,,240,,'BM','rth','..\ANSYS REV\'
FINISH
/SOL
TIME,240
LSWRITE,15,
FINISH
/PREP7
LDREAD,TEMP,,,288,,'BM','rth','..\ANSYS REV\'
FINISH
/SOL
TIME,288
LSWRITE,16,
FINISH
/PREP7
LDREAD,TEMP,,,336,,'BM','rth','..\ANSYS REV\'
FINISH
/SOL
TIME,336
LSWRITE,17,
FINISH
/PREP7
LDREAD,TEMP,,,384,,'BM','rth','..\ANSYS REV\'
FINISH
/SOL
TIME,384
LSWRITE,18,
FINISH
/PREP7
LDREAD,TEMP,,,432,,'BM','rth','..\ANSYS REV\'
FINISH
/SOL
TIME,432
LSWRITE,19,
FINISH
/PREP7
LDREAD,TEMP,,,480,,'BM','rth','..\ANSYS REV\'
FINISH
/SOL
TIME,480
LSWRITE,20,
FINISH
/PREP7
LDREAD,TEMP,,,528,,'BM','rth','..\ANSYS REV\'
FINISH
/SOL
TIME,528
LSWRITE,21,
FINISH
/PREP7
LDREAD,TEMP,,,576,,'BM','rth','..\ANSYS REV\'
FINISH
/SOL
TIME,576
LSWRITE,22,
FINISH
/PREP7
LDREAD,TEMP,,,624,,'BM','rth','..\ANSYS REV\'
/REPLT,RESIZE
FINISH
/SOL
TIME,624
Column Structural Analysis – Command Data

/COM, ANSYS RELEASE Release 19.0 BUILD 19.0 UP20171214 14:03:37
<input,start,ans,'C:\Program Files\ANSYS Inc\ANSYS Student\v190\ANSYS\apdl'
/FILNAME,ColNoFORMS,0 !*
/NOPR
KEYW,PR_SET,1
KEYW,PR_STRUCT,1
KEYW,PR_THERM,0
KEYW,PR_FLUID,0
KEYW,PR_ELMAG,0
KEYW,MAGNOD,0
KEYW,MAGEGD,0
KEYW,MAGHE,0
KEYW,MAGELC,0
KEYW,PR_MULTI,0
/GO !*
/COM, Preferences for GUI filtering have been set to display:
/COM,  Structural !*
/CWD,'C:\Users\Kelsey.Petersen\Desktop\Ansys Stress'
/PREF7 !*
!* 
FINISH
/AUX15 !*
/IOPTN, IGES, SMOOTH
/IOPTN, MERGE, YES
/IOPTN, SOLID, YES
/IOPTN, SMALL, YES
/IOPTN, GTOLE, DEFA
IGESIN, 'STG Model - Exploded - 1 column - reoriented', 'iges', 'D:\My Folder\Thesis\KP MODEL\'
VPLOT !*
FINISH
/PREF7 
et,1,45 
TOFFST,273
!* 
MPTEMP,,,,,,, 
MPTEMP,1,0 
MPDATA,EX,1,,8727 
MPDATA,PRXY,1,,0.2 
MPTEMP,,,,,,, 
MPTEMP,1,0 
MPDATA,DENS,1,,2300 
MPTEMP,,,,,,, 
MPTEMP,1,0 
UMP,1,REF,1, 
MPDATA,ALPX,1,,0.0000106 
FLST,2,6,5,ORDE,2 
FITEM,2,7 
FITEM,2,-12 
AESIZE,P51X,.4064, 
MSHAPE,0,3D 
MSHKEY,1 
!* 
CM,_Y,VOLU 
VSEL, , , , , 1 
CM,_Y1,VOLU 
CHKMSSH,'VOLU' 
CMSEL,S,_Y 
!* 
VMESH,_Y1 
!* 
CMDELE,_Y 
CMDELE,_Y1 
CMDELE,_Y2 
!* 
FLST,2,1,5,ORDE,1 
FITEM,2,8 
!* 
/GO 
DA,P51X,ALL, 
LDREAD,TEMP,,,6,'LargeCol','rth', '..\ANSYS REV\' 
FINISH 
/SOL 
NSUBST,12,0,0 
OUTRES,ERASE 
OUTRES,ALL,1 
LNSRCH,1 
NEQIT,100 
TIME,1 
LSWRITE,1, 
FINISH 
/PREP7 
!* 
MPTEMP,,,,,,, 
MPTEMP,1,0 
MPDE,EX,1 
MPDE,PRXY,1 
MPDATA,EX,1,,10843 
MPDATA,PRXY,1,,0.2 
LDREAD,TEMP,,,6,'LargeCol','rth', '..\ANSYS REV\' 
FINISH 
/SOL 
TIME,6 
LSWRITE,2, 
FINISH 
/PREP7
/*
MPTEMP,,
MPTEMP,1,0
MPDE,EX,1
MPDE,PRXY,1
MPDATA,EX,1,,16363
MPDATA,PRXY,1,,0.2
LDREAD,TEMP,,,12, 'LargeCol','rth','..
ANSYS REV"
FINISH
/SOL
TIME,12
LSWRITE,3,
FINISH
/PREP7
*/

/*
MPTEMP,,
MPTEMP,1,0
MPDE,EX,1
MPDE,PRXY,1
MPDATA,EX,1,,21089
MPDATA,PRXY,1,,0.2
LDREAD,TEMP,,,24, 'LargeCol','rth','..
ANSYS REV"
FINISH
/SOL
TIME,24
LSWRITE,4,
FINISH
/PREP7
*/

/*
MPTEMP,,
MPTEMP,1,0
MPDE,EX,1
MPDE,PRXY,1
MPDATA,EX,1,,24019
MPDATA,PRXY,1,,0.2
LDREAD,TEMP,,,36, 'LargeCol','rth','..
ANSYS REV"
FINISH
/SOL
TIME,36
LSWRITE,5,
FINISH
/PREP7
*/

/*
MPTEMP,,
MPTEMP,1,0
MPDE,EX,1
MPDE,PRXY,1
MPDATA,EX,1,,25068
MPDATA,PRXY,1,,0.2
LDREAD,TEMP,,,48, 'LargeCol','rth','..
ANSYS REV"
FINISH
/SOL
TIME,48
LSWRITE,6,
FINISH
/PREP7
*/
LDREAD, TEMP,,, 60, 'LargeCol', 'rth', '..\ANSYS REV\' FINISH /SOL TIME, 60 LSWRITE, 7, FINISH /PREP7 *
MPTEMP,,,,,,,
MPTEMP,1,0
MPDE, EX, 1
MPDE, PRXY, 1
MPDATA, EX, 1,, 26092
MPDATA, PRXY, 1,, 0.2
LDREAD, TEMP,,, 72, 'LargeCol', 'rth', '..\ANSYS REV\' FINISH /SOL TIME, 72 LSWRITE, 8, FINISH /PREP7 LDREAD, TEMP,,, 84, 'LargeCol', 'rth', '..\ANSYS REV\' FINISH /SOL TIME, 84 LSWRITE, 9, FINISH /PREP7 LDREAD, TEMP,,, 96, 'LargeCol', 'rth', '..\ANSYS REV\' FINISH /SOL TIME, 96 LSWRITE, 10, FINISH /PREP7 LDREAD, TEMP,,, 108, 'LargeCol', 'rth', '..\ANSYS REV\' FINISH /SOL TIME, 108 LSWRITE, 11, FINISH /PREP7 *
MPTEMP,,,,,,,
MPTEMP,1,0
MPDE, EX, 1
MPDE, PRXY, 1
MPDATA, EX, 1,, 25423
MPDATA, PRXY, 1,, 0.2
LDREAD, TEMP,,, 120, 'LargeCol', 'rth', '..\ANSYS REV\' FINISH /SOL TIME, 120 LSWRITE, 12, FINISH /PREP7 LDREAD, TEMP,,, 168, 'LargeCol', 'rth', '..\ANSYS REV\' FINISH /SOL TIME, 168 LSWRITE, 13, FINISH /PREP7
LDREAD, TEMP,,, 192, 'LargeCol', 'rth', '.. \ANSYS REV'
FINISH
/SOL
TIME, 192
LSWRITE, 14,
FINISH
/PREP7
LDREAD, TEMP,,, 240, 'LargeCol', 'rth', '.. \ANSYS REV'
FINISH
/SOL
TIME, 240
LSWRITE, 15,
FINISH
/PREP7
!*
LDREAD, TEMP,,, 288, 'LargeCol', 'rth', '.. \ANSYS REV'
FINISH
/SOL
TIME, 288
LSWRITE, 16,
FINISH
/PREP7
LDREAD, TEMP,,, 336, 'LargeCol', 'rth', '.. \ANSYS REV'
FINISH
/SOL
TIME, 336
LSWRITE, 17,
FINISH
/PREP7
LDREAD, TEMP,,, 384, 'LargeCol', 'rth', '.. \ANSYS REV'
FINISH
/SOL
TIME, 384
LSWRITE, 18,
FINISH
/PREP7
LDREAD, TEMP,,, 432, 'LargeCol', 'rth', '.. \ANSYS REV'
FINISH
/SOL
TIME, 432
LSWRITE, 19,
FINISH
/PREP7
LDREAD, TEMP,,, 480, 'LargeCol', 'rth', '.. \ANSYS REV'
FINISH
/SOL
TIME, 480
LSWRITE, 20,
FINISH
/PREP7
LDREAD, TEMP,,, 528, 'LargeCol', 'rth', '.. \ANSYS REV'
FINISH
/SOL
TIME, 528
LSWRITE, 21,
FINISH
/PREP7
LDREAD, TEMP,,, 576, 'LargeCol', 'rth', '.. \ANSYS REV'
FINISH
/SOL
TIME, 576
LSWRITE, 22,
FINISH
/PREF7
LDREAD, TEMP,,,624, 'LargeCol','rth','.\ANSYS REV\'
FINISH
/SOL
TIME,624
LSWRITE,23,
FINISH
/PREF7
LDREAD, TEMP,,,672, 'LargeCol','rth','.\ANSYS REV\'
FINISH
/SOL
TIME,672
LSWRITE,24,
LSSOLVE,1,24,1,
FINISH
/POST1
!* 
/EFACET,1
PLNSOL, S,1, 0,1.0
FINISH

Tabletop Structural Analysis – Command Data

/COM, ANSYS RELEASE Release 19.0      BUILD 19.0      UP20171214       13:15:28
/input, start, ans,'C:\Program Files\ANSYS Inc\ANSYS Student\v190\ANSYS\apdl\'
!* 
/FILNAME, TTTEST, 0 
/CWD,'C:\Users\Kelsey.Petersen\Desktop\Ansys Stress'
/AUX15 
!* 
!* 
/NOPR
KEYW, PR_SET,1
KEYW, PR_STRUC,1
KEYW, PR_THERM,0
KEYW, PR_FLUID,0
KEYW, MAGNOD,0
KEYW, MAGEDG,0
KEYW, MAGHFE,0
KEYW, MAGELC,0
KEYW, PR_MULTI,0
/GO
!* 
/COM,
/COM, Preferences for GUI filtering have been set to display:
/COM, Structural 
!* 
FINISH
/PREF7
et,1,45
!* TOFFST,273 
!* MPTEMP,,,,,,,
MPTEMP,1,0
MPDATA,EX,1,,8727
MPDATA,PRXY,1,,.2
MPTEMP,,,,,,,
MPTEMP,1,0
MPDATA, DENS,1,,2300
MPTEMP,,,,,,,,
MPTEMP,1,0
UIMP,1,REFT,,
MPDATA,ALPX,1,,.0000106
/DIST, 1 ,1.082226,1
/REP,FAST
/DIST, 1 ,1.082226,1
/REP,FAST
/DIST, 1 ,1.082226,1
/REP,FAST
/DIST, 1 ,1.082226,1
/REP,FAST
/DIST, 1 ,1.082226,1
/REP,FAST
/DIST, 1 ,1.082226,1
/REP,FAST
SMRT,6
SMRT,7
MSHAPE,1,3D
MSHKEY,0
!*
!*
!*
FINISH
/AUX15
!* 
IOPTN,IGES,Smo00HTH
IOPTN,MERGE,YES
IOPTN,SOLID,YES
IOPTN,SMALL,YES
IOPTN,GTOLER,DEFA
IGESIN,'STG Model Tabletop - Exploded m - reoriented','iges','D:\My Folder\Thesis\KP MODEL\'
VPLOT
!* 
FINISH
/PREF7
CM, _Y, VOLU
VSEL, , , , 1
CM, _Y1,VOLU
CHKMSH,'VOLU'
CMSEL,S, _Y
!* 
VMESH, _Y1 
!* 
CMDELE, _Y
CMDELE, _Y1
CMDELE, _Y2 
!* 
FLST,5,357,2,ORDE,2
FITEM,5,1
FITEM,5,-357
CM, _Y,ELEM
ESEL, , , ,P51X
CM, _Y1,ELEM
CMSEL,S, _Y
CMDELE, _Y 
!* 
!* 
EREF, _Y1, , ,1,0,1,1
CMDELE, _Y1 
!*
!*
/Ui,Mesh,Off
Antype,0
Flst,2,1,5,Orde,1
Fitem,2,31
!*
/Go
Da,P51x,All,
Ldread,Temp,,,1,,'Tabletop','rth',..\ANSYS REV\'
Finish
/Sol
Nsust,12,0,0
Outres,Erase
Outres,All,1
Lnsrch,1
Nequit,100
Time,1
Lswrite,1,
Finish
/Pref7
!*  
Mptemp,,,,,,,
Mptemp,1,0
Mpde,ex,1
Mpde,prxy,1
Mpdata,ex,1,,9495
Mpdata,prxy,1,,0.2
Ldread,Temp,,,6,,'Tabletop','rth',..\ANSYS REV\'
Finish
/Sol
Time,6
Lswrite,2,
Finish
/Pref7
!*  
Mptemp,,,,,,,
Mptemp,1,0
Mpde,ex,1
Mpde,prxy,1
Mpdata,ex,1,,14281
Mpdata,prxy,1,,0.2
Ldread,Temp,,,12,,'Tabletop','rth',..\ANSYS REV\'
Finish
/Sol
Time,12
Lswrite,3,
Finish
/Pref7
!*  
Mptemp,,,,,,,
Mptemp,1,0
Mpde,ex,1
Mpde,prxy,1
Mpdata,ex,1,,21089
Mpdata,prxy,1,,0.2
Ldread,Temp,,,24,,'Tabletop','rth',..\ANSYS REV\'
Finish
/Sol
Finish
/Aux12
Finish
/Sol
Time,24
LSWRITE, 4, 
FINISH 
/PREP7 
!* 
MPTEMP, , , , , , , 
MPTEMP, 1, 0 
MPDE, EX, 1 
MPDE, PRXY, 1 
MPDATA, EX, 1,, 23203 
MPDATA, PRXY, 1,, 0.2 
LDREAD, TEMP,,, 36, , 'Tabletop', 'rth', ...\ANSYS REV' 
FINISH 
/SOL 
TIME, 36 
LSWRITE, 5, 
FINISH 
/PREP7 
!* 
MPTEMP, , , , , , , 
MPTEMP, 1, 0 
MPDE, EX, 1 
MPDE, PRXY, 1 
MPDATA, EX, 1,, 25068 
MPDATA, PRXY, 1,, 0.2 
LDREAD, TEMP,,, 48, , 'Tabletop', 'rth', ...\ANSYS REV' 
FINISH 
/SOL 
TIME, 48 
LSWRITE, 6, 
FINISH 
/PREP7 
!* 
MPTEMP, , , , , , , 
MPTEMP, 1, 0 
MPDE, EX, 1 
MPDE, PRXY, 1 
MPDATA, EX, 1,, 25579 
MPDATA, PRXY, 1,, 0.2 
LDREAD, TEMP,,, 60, , 'Tabletop', 'rth', ...\ANSYS REV' 
FINISH 
/SOL 
TIME, 60 
LSWRITE, 7, 
FINISH 
/PREP7 
!* 
MPTEMP, , , , , , , 
MPTEMP, 1, 0 
MPDE, EX, 1 
MPDE, PRXY, 1 
MPDATA, EX, 1,, 25579 
MPDATA, PRXY, 1,, 0.2 
LDREAD, TEMP,,, 72, , 'Tabletop', 'rth', ...\ANSYS REV' 
FINISH 
/SOL 
TIME, 72 
LSWRITE, 8, 
FINISH 
/PREP7 
!* 
MPTEMP, , , , , , , 
MPTEMP, 1, 0 
MPDE, EX, 1
MPDE, PRXY, 1
MPDATA, EX, 1,, 26092
MPDATA, PRXY, 1,, 0.2
LDREAD, TEMP,,, 84, , 'Tabletop', 'rth', ...
ANSYS REV
FINISH
/SOL
TIME, 84
LSWRITE, 9,
FINISH
/PREP7
*
MPTEMP,,,,,,,
MPTEMP, 1, 0
MPDE, EX, 1
MPDE, PRXY, 1
MPDATA, EX, 1,, 26092
MPDATA, PRXY, 1,, 0.2
LDREAD, TEMP,,, 96, , 'Tabletop', 'rth', ...
ANSYS REV
FINISH
/SOL
TIME, 96
LSWRITE, 10,
FINISH
/PREP7
*
LDREAD, TEMP,,, 108, , 'Tabletop', 'rth', ...
ANSYS REV
FINISH
/SOL
TIME, 108
LSWRITE, 11,
FINISH
/PREP7
*
MPTEMP,,,,,,,
MPTEMP, 1, 0
MPDE, EX, 1
MPDE, PRXY, 1
MPDATA, EX, 1,, 26423
MPDATA, PRXY, 1,, 0.2
LDREAD, TEMP,,, 120, , 'Tabletop', 'rth', ...
ANSYS REV
FINISH
/SOL
TIME, 120
LSWRITE, 12,
FINISH
/PREP7
LDREAD, TEMP,,, 168, , 'Tabletop', 'rth', ...
ANSYS REV
FINISH
/SOL
TIME, 168
LSWRITE, 13,
FINISH
/PREP7
LDREAD, TEMP,,, 192, , 'Tabletop', 'rth', ...
ANSYS REV
FINISH
/SOL
TIME, 192
LSWRITE, 14,
FINISH
/PREP7
LDREAD, TEMP,,, 240, , 'Tabletop', 'rth', ...
ANSYS REV
FINISH
/SOL
FINISH
/PREP7
LDREAD,TEMP,,,240,,'Tabletop','rth','..\ANSYS REV\'
FINISH
/SOL
TIME,240
LSWRITE,15,
FINISH
/PREP7
LDREAD,TEMP,,,288,,'Tabletop','rth','..\ANSYS REV\'
FINISH
/SOL
TIME,288
LSWRITE,16,
FINISH
/PREP7
LDREAD,TEMP,,,336,,'Tabletop','rth','..\ANSYS REV\'
FINISH
/SOL
TIME,336
LSWRITE,17,
FINISH
/PREP7
LDREAD,TEMP,,,384,,'Tabletop','rth','..\ANSYS REV\'
FINISH
/SOL
TIME,384
LSWRITE,18,
FINISH
/PREP7
LDREAD,TEMP,,,432,,'Tabletop','rth','..\ANSYS REV\'
FINISH
/SOL
TIME,432
LSWRITE,19,
FINISH
/PREP7
LDREAD,TEMP,,,480,,'Tabletop','rth','..\ANSYS REV\'
FINISH
/SOL
TIME,480
LSWRITE,20,
FINISH
/PREP7
LDREAD,TEMP,,,528,,'Tabletop','rth','..\ANSYS REV\'
FINISH
/SOL
TIME,528
LSWRITE,21,
FINISH
/PREP7
LDREAD,TEMP,,,576,,'Tabletop','rth','..\ANSYS REV\'
FINISH
/SOL
TIME,576
LSWRITE,22,
FINISH
/PREP7
LDREAD,TEMP,,,624,,'Tabletop','rth','..\ANSYS REV\'
FINISH
/SOL
TIME,624
LSWRITE,23,
FINISH
/PREP7
LDREAD,TEMP,,672,,'Tabletop','rth',.'\ANSYS REV\'
FINISH
/SOL
TIME,672
LSWRITE,24,
LSSOLVE,1,24,1,
FINISH
/POST1
!* /EFACET,1
PLNSOL, S,1, 0,1.0
FINISH