WATTS TOWERS: THE EFFECTS OF THERMAL CYCLES ON THE FORMATION AND BEHAVIOR OF CRACKS

An Undergraduate Research Scholars Thesis

By

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ABSTRACT

The Effects of Thermal Cycles on the Formation and Behavior of Cracks. (May 2013)

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The development of cracks in Portland Cement Concrete (PCC) and Grout has become a problem of rising concern in a country with an aging infrastructure. A detailed understanding of the causes as well as the behavior of these cracks is vital to preventing future formation and further propagation. This study examines a currently existing structure known as the Watt's Towers, or The Towers of Simon Rodia which exhibits extensive cracking.

The effects of thermal cycles, both daily and annual, on crack opening and closing for typical cracks were studied using the Towers as an example case. The study is used to determine whether or not thermal cyclical loading plays a significant role in the formation of cracks in mortar. Specifically, an array of cracks located at different sections on the Towers was outfitted with strain gauges, force transducers, and thermocouples to collect data on the crack width as a function of the ambient temperature. Using the Finite Element Analysis program LS-DYNA, a computer model was created to replicate these results. After many simulations a relationship between the thermal loading and the local stressing induced around the cracks was developed. It was determined that Crack gap movement is strongly correlated with temperature. It is an

inverse relationship: as the ambient temperature increases, the crack width increases. The cyclical nature of the crack width plays a significant role in the development of local stresses, and ensuing crack formation.

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NOMENCLATURE

FEA	Finite Element Analysis
LACMA	Los Angeles County Museum of Art
PCC	Portland Cement Concrete
TTI	Texas A&M University Transportation Institute
TxDOT	Texas Department of Transportation

CHAPTER I

INTRODUCTION

The Watts Towers are a national treasure. Also known as the Towers of Simon Rodia, they are a series of seventeen interconnected structures that were built over a period of thirty-three years in the Watts district of Los Angeles. They were built single handedly by an Italian immigrant named Sabato Rodia. He was a construction worker with little education, and no engineering expertise nor any training in the arts. Yet he managed to accomplish the amazing feat of building the towers which reaches up to almost[1] one-hundred feet in height. Although this is incredible, his construction methods have caused problems with the structures over their life.

After Rodia willed the structure away and retired, the structures have had to endure many attempts to have them destroyed. There was a fire inside of the property that destroyed Rodia's old quarters, and the city of Los Angeles had the towers condemned. The Structures were scheduled for demolition. In an attempt to save the structures a committee of artists, actors and architects banded together with the Los Angeles County Museum of Art formed the *Committee for Simon Rodia's Towers*. After some negotiations with the city a simple test was allowed to determine if the tallest of the towers was structurally sound. A large Lateral force was applied by attaching a cable to the top point of the tower and having a crane pull on it. When the crane was unable to bring the structure down, it was deemed structurally sound. Today the towers are operated and maintained by the LACMA, but are desperately in need of repairs.

[1] The Los Angeles building code limited structure to 100' at the Watts location so he built them to 99'

CHAPTER II

METHODOLOGY

This project will be analyzed on two different fronts. There will be a detailed simulation using a LS-DYNA Finite Element analysis to develop an analytical relationship between stresses induced by thermal cyclical loading, as well as physical testing in California to validate the simulation model. At the actual tower site extensive testing of the structure is being performed by the LACMA.

The LACMA has had the Towers outfitted with different types of transducers and strain gauges monitoring the structure at several locations. Aside from temperature, the LACMA is also checking the three other parameters that they feel may be adding to the deterioration of the towers. The phenomena of wind, temperature, strain, and crack gap motion are all being closely monitored. Lateral wind loading results in potentially high shear and moments at the tower supports which currently exhibit the greatest deterioration. The ambient temperature changes around the structure cause thermal expansions and contractions as the day goes on which can induce stressing in the members. The deformations in the towers main structural elements can could be causing high strains to develop in the members. Crack gap motion is being studied to be the independent variable by which the other parameters are measured against to determine their effect.

For this study the effects of the thermal cyclical loading will be of primary concern. The LACMA selected a typical crack opening on one of the members leading into a base support for one of the tallest towers. Since the primary crack openings run parallel to the steel reinforcement it was conventional to mount the displacement transducer on the perimeter on the member spanning the crack. The displacement transducer is setup to send a data point every twenty minutes that it is running to a centralized portable data logger system.

On the other front of the study, a detailed computer model of the system was created. In order to do this a few different things had to be established. Primarily:

- What parameters are of concern?
- What portion of the towers should be modeled?
- What type of analysis will need to be performed?
- What results need to be outputted?

It was decided that the best tool to perform this analysis was LS-DYNA. This program utilizes complex computational algorithms to analyze anything from simple FEA models to something with millions of elements.

In the case of this study a small section of the member that was used by the LACMA was modeled. In order to avoid unnecessarily high computation times only a five foot segment of the member was used. It is modeled with five layers of concentric rings of solid brick elements. The inner most layer represents a steel pipe. The other four layers are all PCC mortar. The segment is modeled to stand vertically on one end with the bottom face constrained from all rotation and translation. A single crack with a maximum width of approximately two millimeters runs parallel to the steel reinforcement just as it is in the real member. The segment is displayed as modeled below in *figures 1 and 2*:

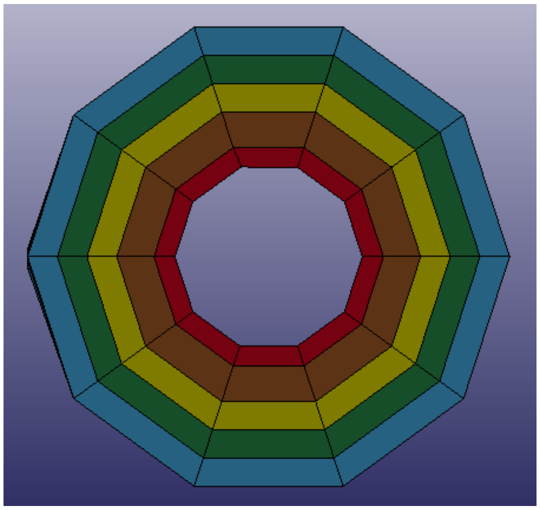

Figure 1: Top View

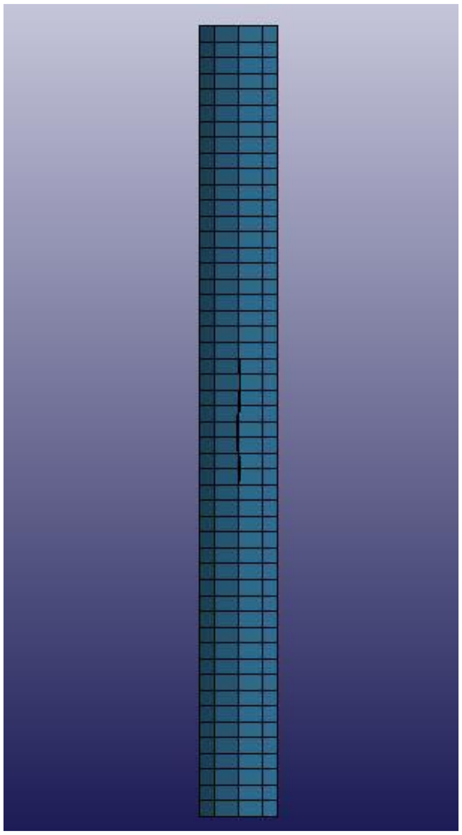

Figure 2: Front View Showing the Crack

For the sake of simplicity and to avoid unnecessary material testing, the materials are assumed to be isotropic and elastic. This assumption is valid within the range of stresses exhibited in this study. The two materials are also treated as isotropic with regard to their thermal properties. The parameters used in the simulation are summarized below in *Table 1*. The units are shown in the unit system that LS-DYNA utilizes.

Table 1: Summary Table of Parameters

	Physical Properties			**Thermal Properties**		
Material	Density (tonne/mm^3)	Young's Modulus (MPa)	Poisson's Ratio	Coefficient of Thermal Expansion (℃$^{-1}$)	Thermal Conductivity (tonne mm/s^3 K	Heat Capacity (mm^2 /s^2K)
Steel	$7.833x10^{-9}$	$2.0x10^9$	0.29	$11.34x10\text{-}^{10}$	36.000	$4.6x10^8$
PCC Mortar	$4.004x10^{-10}$	$1.227x10^4$	0.18	$10.0x10^{-6}$	0.1298	$8.4x10^8$

In order for the simulation to output both the temperatures in the elements, as well as the stress and strain data, the simulation technique required was an Implicit coupled thermal-structural analysis. In order to run this simulation a *SET_SEGMENT card was created containing all of the faces on the exterior of the section of the member. The time-history temperature data from the site at the member in question was applied. The temperature is applied in the direction of the normal vector for each of the faces in the segment. It is important to note here that the normals are pointing inward along the radius of the member. This type of boundary condition that was applied establishes a changing ambient temperature matching the real recorded data at the exterior face of the member. The physical temperature data was pulled for a typical one day period.

The simulation will automatically generate ASCII data files that can be read by LS-PrePost for the changing temperature in each of the elements throughout the day. It will also generate stress and strain data, as well as the changing crack width over time.

CHAPTER III

RESULTS

Following the simulation run of the system in LS-DYNA some various results were outputted. We were able to develop a plot of the strain levels in the mortar as a function of the ambient temperature surrounding. The results are shown below for a one hundred second period of time corresponding to the real life data from the site.

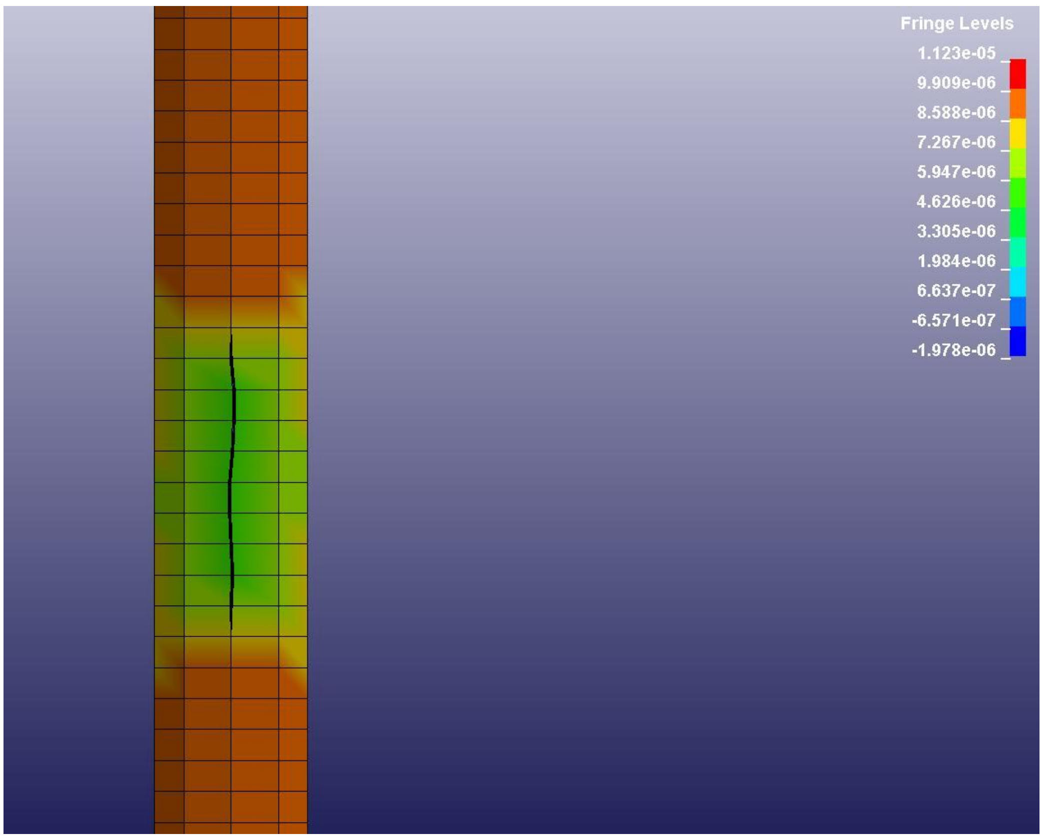

Figure 3: Strain in the system at time=50secs

Figure 3 above shows the plastic strain in the tubular system at 50 seconds into the run. As expected the strain levels around the crack opening are much lower than the surrounding strain levels. Once the cracks form or propagate further, more of the local strain in that region can be dissipated.

Another interesting observation that can be discerned from this simulation is pictured below in *Figure 4.*

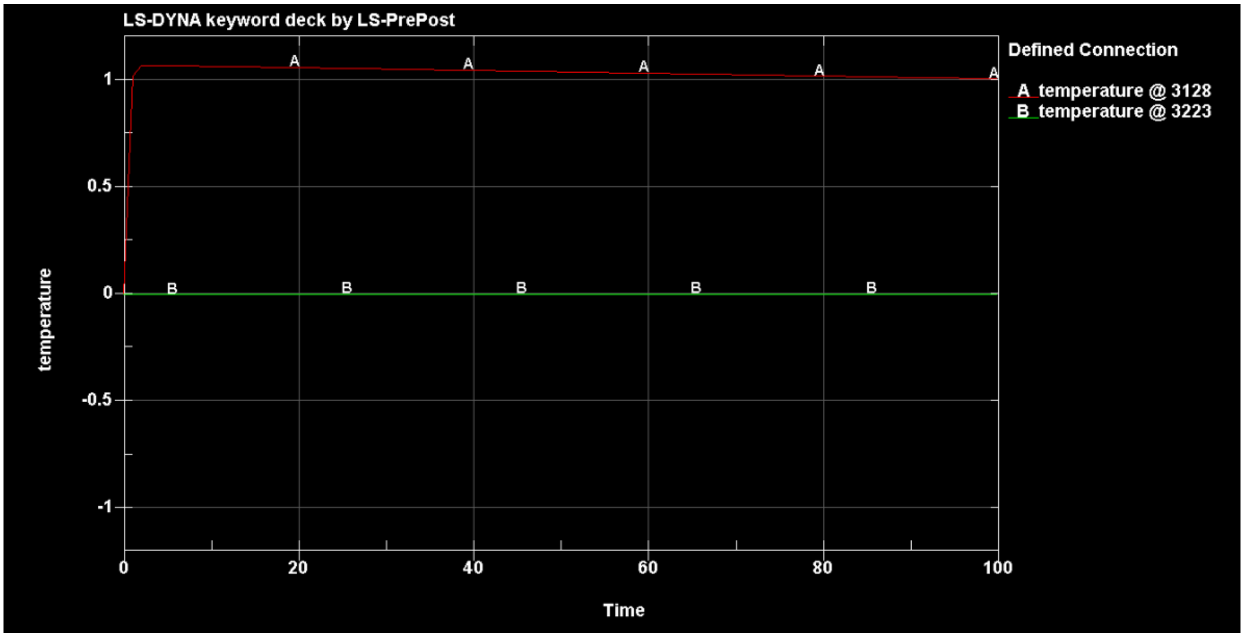

Figure 4: Element Temperatures over time

The figure displays the temperature as a function of time in two different Solid elements denoted A and B. Element A can be bound on the outer face of the tubular section getting direct sunlight. Element B on the other hand is on the interior face of the section receiving none of the direct sunlight. The figure clearly shows that the temperature effects from the sunlight are much less as you go deeper into the structure.

This function of ambient temperature vs. element temperature as you move radially into the structure is reflected in the element plastic strain levels as well. *Figure 5* below shows a top view of the tubular

section with plastic strain levels plotted.

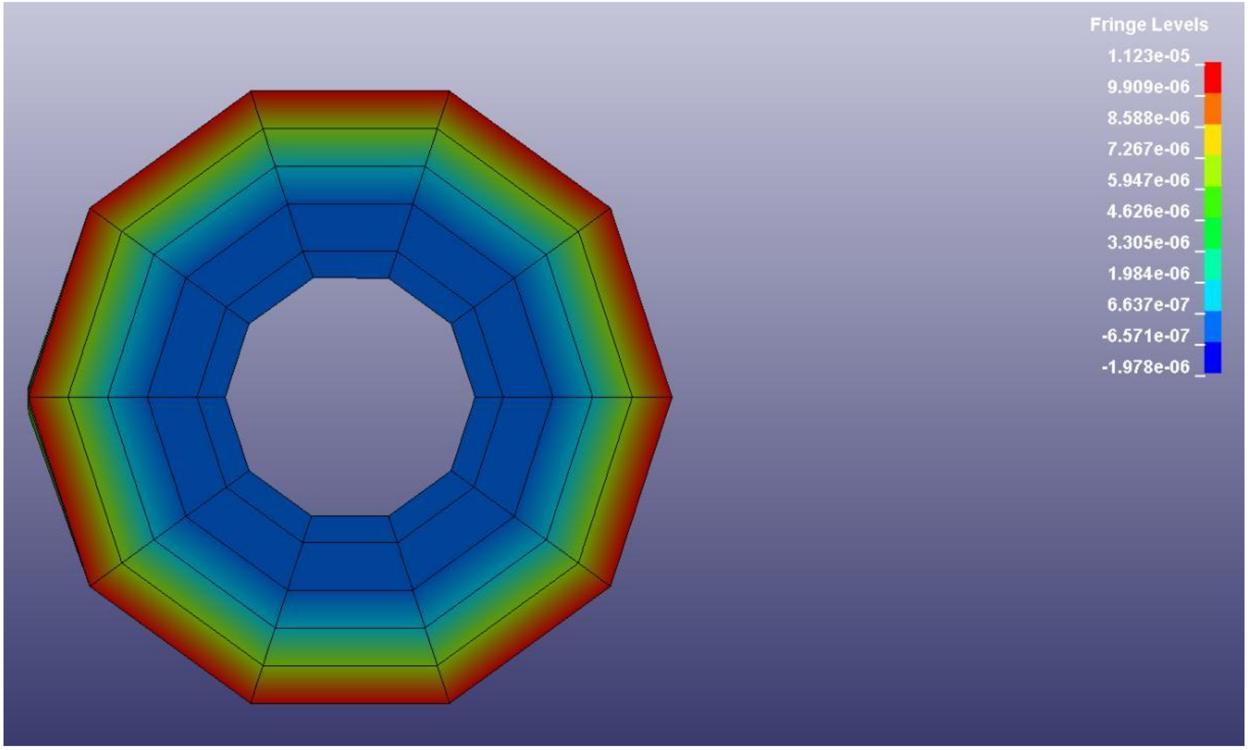

Figure 5: Top View Plastic Strain at 50ses

As you can see in the figure the strains in the brick elements are much higher where the temperature effects are the greatest. This would seem to fit with the mathematical model used in this system, where the elements thermal stress can be related to the directly to the temperature and coefficient of thermal

expansion.

CONCLUSIONS

After performing both on site physical testing and computer simulations, several conclusions can be drawn. It is clear that an inverse relationship exists between the crack gap opening and the ambient temperature surrounding the structure. In both the instrumented testing and simulated results, the width of the crack opening got much larger as the surrounding temperatures began to fall.

If it is true that the crack opening changes with the temperature throughout the day, and a direct relationship exists between the temperature and the strain values in the elements, then it must be true that the daily thermal cyclical loading plays a significant role in the formation and propagation of cracks in the structure.

In the future it is recommended that further analysis is performed to develop an accurate mathematical relationship between the local element stresses and the surrounding crack gap opening. This relationship can be used to develop a proper filler material to make lasting repairs to the Watts Towers.

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