An Artistic Analysis to Guide Trustees Preserving An Artistic Vision for Building Simulation 2017 Conference

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Abstract

A typical museum environment can be a challenging design task. When an existing building and site conditions are included as part of the artistic experience, the challenges become highly unusual. We used EnergyPlus for an initial phase of work to model a building with no mechanical systems and included a piece of art as a building zone. We discovered that the slab on grade model for ground heat loss was unable to simulate the actual heat storage capacity of the soil and prevented correlation of model to measured interior temperature conditions we were given. Once past this hurdle, we were able to evaluate the effectiveness of various art preservation strategies and advise our client of the limitations and costs of various building modifications.

Introduction

Two single-story concrete and brick buildings constructed at Fort D. A. Russell in Marfa, Texas in 1938 are now known as the Artillery Sheds. They house internationally important works of art by the renowned minimalist artist Donald Judd (1928 –1994). In 1979, Judd purchased the then-derelict structures, made significant architectural modifications to the buildings, and installed 100 aluminum works of art together as one vision. Judd's installation of 73 story-high glass and aluminum windows create nearly fully transparent facades. The transparency, in turn, creates an important contextual relationship between the works of art and the landscape, and admits enormous amounts of natural light, the nature of which changes continuously from sun up to sun down. Judd also transformed the exterior appearance by installing barrel arches on the once-flat roofs, known in the vernacular as Quonset huts.

Figure 1: An Artillery Shed in Marfa, Texas.

The Chinati Foundation cares for the Sheds and their works of art, and opens the space to the public. The buildings remain preserved as Judd created them: building elements and materials bare and exposed; interior environment unconditioned and unlit by artificial light; and experience in the space acoustically unaltered by building mechanical and electrical systems.

Figure 2: Donald Judd's Vision

As curators of this collection, the Chinati Foundation approached our company to assist them with evaluation and repair of the building and preservation of the aluminum art works. As well as typical aging building issues such as deteriorated structural components and air/water leakage, the Foundation was concerned with the aluminum art works because they "walk" out of position over time, audibly ping with changing solar exposure, and some of the joints that were originally tight have opened. While our collective building envelope experience could easily be applied to structure, the interior environment and movement of the aluminum art works requires more advanced analytical study. EnergyPlus and finite element method analysis (FEM) were used to evaluate the aluminum artwork environment.

Background

A typical energy model simulates internal and external loads on a building envelope system with a schedule of use and occupancy and calculates the energy use to maintain acceptable temperature conditions for the occupants. A museum environment strives to maintain stable temperature, humidity, and lighting conditions for the preservation and viewing of the artwork. A museum energy model calculates the energy cost of design decisions made for the structure. The Artillery Shed analysis requires a completely different approach. A baseline simulation of the unconditioned space is required first so that the effectiveness of each modification intended to improve conditions for the art is measured. Since a primary concern of the curators is preservation of the aluminum art constructions, simulating an artwork as a part of the building generates direct data about how stable the art environment actually becomes as various improvements are implemented.

The single pane, clear glass of the windows allow for tremendous solar radiation into the space. The aluminum works, comprised of rectangular aluminum plates creating box-like sculptures, are struck by sunlight and the surface temperatures of the aluminum in the direct light are much higher than other parts of the given work creating thermal gradients that migrate throughout the day and stress the aluminum. The diurnal and annual temperature fluctuations of the space are well outside ranges commonly sought for the preservation of art. Paradoxically, common strategies to affect the indoor climate, for example sun screens, window shades, coated glass and HVAC systems, all alter the architecture and arguably change the observer's intrinsic experience with the installation.

We used EnergyPlus to model the building and included an aluminum box as an internal zone to represent artwork to study temperatures in the space as we made changes to building envelope. EnergyPlus temperature predictions were subsequently fed into a more detailed (FEM) model of the aluminum box as a preliminary study of actual stresses and movement occurring in the pieces due to the environment.

Baseline EnergyPlus Model

For this initial study we modelled only one of the two Artillery Sheds using an actual year weather file. Figure 3 is a view of the building generated by Sketchup, the geometry tool we used for generating this model. The original shed is about 61' x 285' x 17' high (18.6m x 86.9m x 5.2m) to the flat roof. A concrete slab on grade floor supports concrete columns and a concrete roof. End walls and partitions are brick. Aluminum framed storefront windows replaced garage doors on the long sides of the building. The galvanized steel barrel roof increases the building height to 35' (10.7m) and encloses an empty, unused space.

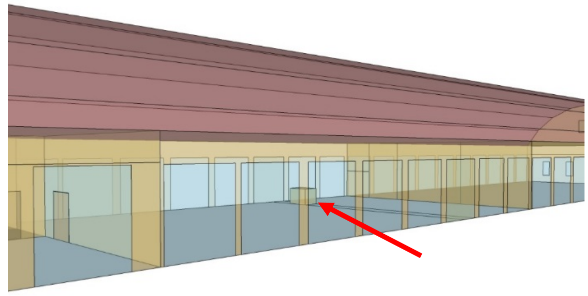

Figure 3: Artwork As A Zone In The Model.

Once the basic geometry was generated, we performed the remainder of our work using text and IDF editors. We simplified the windows by neglecting the frames and only changing glass properties for the simulations. The roof is also simplified as a series of flat plates forming a circular arch. We had to approximate solar properties for the roof because the actual shape of the ribbed metal (Figure 4) does not perform like a flat plate of galvanized steel.

Because the attic space also has air louvers at each end, we simulated the building with a simple airflow network in the attic and actual year weather data to generate an air exchange rate. Rather than constantly recalculate the attic airflow, we used the airflow network results to schedule attic ventilation for the remaining model runs.

Figure 4: Ribs of the Quonset Huts Roof.

Calibrating The Baseline Model

An important part of any simulation effort is generating confidence in the model through a calibration exercise. In this case we were given data on recorded interior temperatures for a given period of time, but little information about the actual location of the sensor. A study of the recorded data revealed temperature spikes that would be consistent with direct beam solar exposure on the recording device. We also assumed the sensor is located on an interior brick partition wall, so any air temperature reading would be highly influenced by the adjacent wall temperature. We located an interior partition spot with a similar direct beam solar radiation pattern, created an isolated surface patch at the location (Partition East Surface), and proceeded to calibrate the model not to the peak recorded readings, but to the temperatures recorded when direct solar gain was not present.

The calibration effort turned out to be extremely important. We initially used SLAB to calculate heat exchange with the ground. While the SLAB program may be verified for buildings that are temperature controlled with mechanical systems, it performed poorly for an uncontrolled building subject to only environmental exposure and solar gains. Our initial calibration runs using recorded average temperatures for the space as inputs to SLAB correlated consistently under target in the warm weather (Figure 5), but acceptably close in the winter weather (Figure 6). The inconsistent summer result in Figure 5 is likely due to the extremely high solar gains from the windows that warm the floor creating a thermal storage system rather than a ground heat loss mechanism calculated by SLAB.

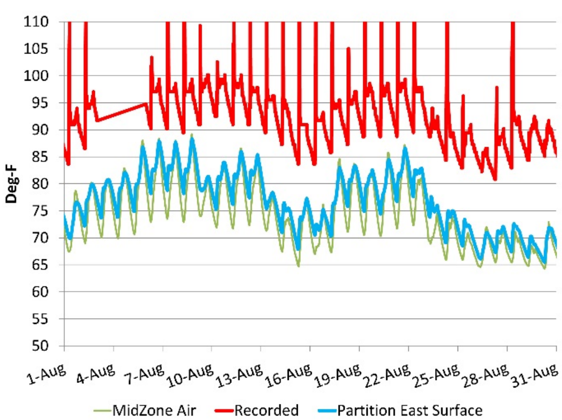

Figure 5: Poor Summer Matching Recorded Temperatures To A Calculated Model Surface Using SLAB

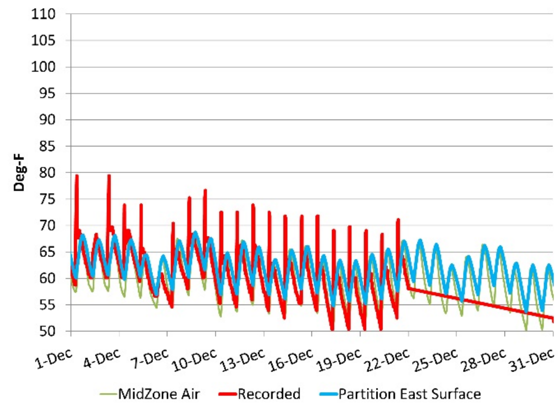

Figure 6: Closer Winter Matching Recorded Temperatures To A Calculated Model Surface Using SLAB

To better calibrate the model we manually adjusted the ground temperature inputs and iterated the model until we were confident that there was an acceptable correlation of recorded and calculated temperatures. We started by using the average high temperatures for the month as the ground temperature and then adjusted up or down as necessary to create a match. The problem with this approach is that subsequent performance changes from building modifications cannot be reliably carried into new ground temperature conditions. Using predicted average high temperatures from an altered simulation to modify the ground temperature of a next iteration of that simulation does not reliably result in a converging temperature condition. A more extensive study of ground solar storage needs to focus on generating reliable ground temperature prediction routines like SLAB for models with significant ground heat storage potentials from solar gains.

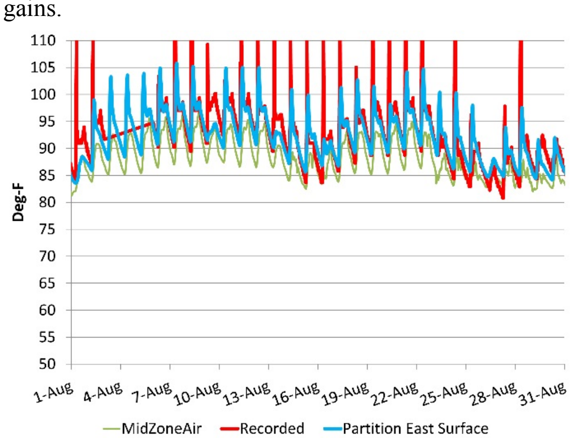

Figure 7: Manually Adjusting Summer Ground Temperatures To Match Recorded Data

Evaluating Building Modifications

The calibrated baseline model gave us zone air temperatures and aluminum box surface temperatures (Figure 7) to compare with simulations of the various building modifications. The baseline simulation shows that there will be large daily as well as seasonal temperature changes and that there are temperature differences between different sides of the box.

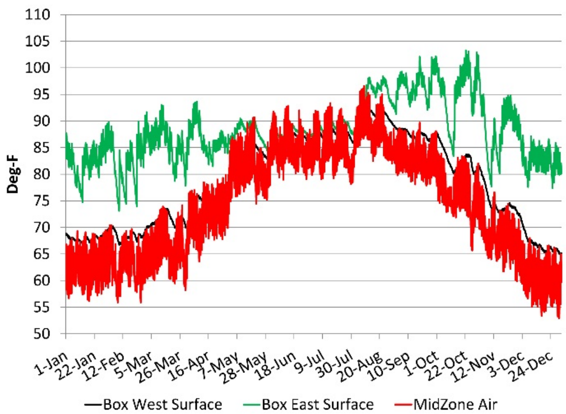

Figure 8: Calibrated Baseline Temperatures

Our initial study was to evaluate the relative impact of various building modification. We concluded that the ground temperature issue would make our performance improvement predictions conservative, but appropriately comparative in nature. We proceed to simulate 45 variations with the following model changes:

- Attic Insulation
- Glazing Changes
- Interior Shades
- Exterior Shades
- Night Ventilation
- Full Mechanical Conditioning System
- Combinations of Individual changes

We looked at both daily and seasonal temperature variations with a goal of reducing the variation. No single change was able to create a completely stable thermal environment for the artwork. The simulations indicated the following trends:

- Adding insulation to the attic tempered the occupied space slightly, and given unobtrusive nature of this modification, it was added to all subsequent changes in the models. We did model different insulation thicknesses to identify a practical, efective thickness.
- Glazing system changes had minimal effect with the clearest glass and did not show significant benefit until the simulation used dark reflective glazing.
- Interior shades did not perform as well as exterior shades. To be effective, the shades require automated activation depending on curent soalar conditions at each window.
- Night ventilation was not very effective. We limited the night ventilation to 2 air changes per hour based on a design criteria that called for extracting air from the occupied space through existing control joints in the concrete ceiling. To generate more air flow would require additional openings in the existing ceiling.
- Full mechanical systems can control the space air temperature (Figure 9). We used setpoints of 75°F cooling and 65°F heating. However, mechanical systems needed improved glazing or shades to both reduce the size of the systems and reduce the fluctuations of artwork temperature changes. The total system airflows also required additional ceiling penetrations, even when considering high pressure, high velosity distributions systems.

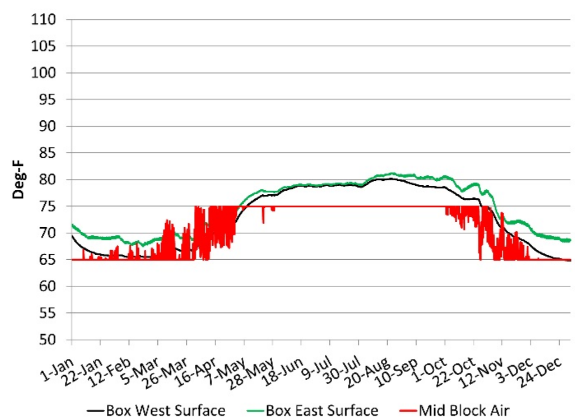

Figure 9: Dark Reflective Glass And A Full Mechanical System Does The Most To Stabilize Temperature Conditions

In addition to temperature performance data, we generated cost and appearance comparisons for each modifications.

FEM Analysis

Finite element modeling divides the simulated object into numerous smaller cells that can interact with each other to calculate energy exchange, dimensional change, and stresses. Although the physical properties of the materials for the aluminum artwork can be reasonably determined, the environmental inputs of temperature, solar gain, and energy exchange with surrounding objects is more dificult to determine and calculate within FEM software. Fortunately, one of the fundamental calculations of EnergyPlus is the interaction of surfaces with their environments, including direct and indirect energy exchanges with surrounding objects. A FEM simulation can be greatly simplified by inputing surface temperature or solar gains rather than calculating them from within the FEM simulation. Given the uncertainty of our EnergyPlus calculation of artwork surface temperatures, the our initial FEM simulations were simplified to calculate only expansion and contraction. The EnergyPlus uncertainty stems from uncertain material properties for aluminum, lack of data for measured conditions for calibration, and the averaged calculation EnergyPlus performs over and entire surface without regard to variations due to shading and three dimensional thermal conductance effects.

Although simplified and uncalibrated, the FEM models replicated dimensional changes consistent with movement that could explain the "walking" of artwork over time if appropriate friction were applied to the model.

Interpreting Results

Although delivering positive results and definitive answers is a consultant's ultimate goal, verification of the truth of a situation can be just as useful to the client. In this case, the truth is an ultimate preservation remedy, stable themperature conditions for the art objects, is also an artistic vision nightmare.

Repairs for water leakage, envelope deterioration, and the installation of some attic insulation to moderate occupied space conditions are simple to implement. Other energy related changes to the building come with limited effectiveness, complex implemetation, increased maintenance and operating costs, or detrimental changes to the original artistic vision that married the interior to the exterior. Of value is providing cost and effectiveness data for various options modeled with EnergyPlus, even if they could be judged artistically unacceptable. For instance, to ballpark the cost of an ultimate mechanical conditioning system by roughly sizing systems and conceptually designing them is useful information for a nonprofit foundation that needs to raise funds for the most basic of improvement and preservation work. While not identifing a clear path forward yet, our client became empowered by information about wasteful and infective courses of action we modeled.

The ultimate objective of the Chinati Foundation is the preservation of Judd's entire artistic vision, our ability to provide solid envelope repair recommendations ment that the remaining Foundation concerns could focus on the aluminum artwork pieces. The curators need to know what conditions, including existing site conditions, are acceptable for preservation of the aluminum artwork pieces. Currently there are no science based or experienced based expertice to make this kind of determination for aluminum plate sculptures with friction pin and screw fastener connections. Our preliminary work shows that a combination of EnergyPlus analysis for input into more detailed FEM modeling of the artistic pieces should be able to predict stresses and fatigue in the joints and fastening of the aluminum objects, and shine an objective light on the relative importance of moderating the environmental temperature conditions. To that end, the Chinati Foundation implemented a program to instrument some of the artwork in order to develop and calibrate a more complex EnergyPlus model with multiple art objects to create a more detailed environment around a subject artwork. The goal this additional study is to make EnergyPlus reliably predict artwork temperatures as inputs to more detailed FEM models of actual artwork construction. An EnergyPlus model calibrated actual artwork temperature measurements allows generation of a more complete picture of environmental conditions during other extremes of weather for input into FEM models that can evaluate attachment stresses and connection fatigue. This work should answer the question of whether "walking" art objects just need repositioning and adjusting now and then or if such movement is a precurser of significant damage to the pieces.

EnergyPlus Analysis

This project demonstrates once again that the detailed computations and reporting capability implementated in EnergyPlus for building energy simulations are also useful for situations where energy use is not the primary focus. Unlike software focused on load analysis and mechanical system performance, EnergyPlus can reasonably predict performance in unconditioned spaces. This project highlighted a weakness in EnergyPlus related to dealing with ground storage of solar gains. This is potentially a serious issue for designs focused on net-zero solutions to energy usage that incorporate such storage mechanisms. Hopefully this will inspire further research into predicting ground heat flow for less conditioned buildings or at least inform simulators of a limitation they may not be aware of.