Using a Heat and Moisture Transfer Simulation to Diagnose Moisture-Related Expansion/Contraction Problems in an Exterior Roof/Wall Assembly

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ABSTRACT

A pyramid-shaped structure was constructed along the South Carolina coast in 1995. The structure was designed for use as a restaurant facility. Within months of completion, the exterior cladding began to exhibit deformations that suggested excessive expansion of the synthetic stone veneer panels. The panels were tested to determine if the hot and humid environmental conditions produced the excessive movements. Testing did not indicate that environmental exposure was the cause of the deformation. A review of the construction drawings revealed that the roof/wall assembly incorporated an additional layer of insulation not indicated by the veneer manufacture's literature. The designer specified a 3.5-inch-thick layer of EPS to be installed between a layer of structural steel panels and a plywood fastening surface. The roof/wall assembly was modeled using WUFI Pro to simulate heat and moisture transport through the assembly. The WUFI data were exported to a spreadsheet so that coefficients of thermal and moisture-related expansion/contraction could be applied to study movement of the wall components. The data revealed that unanticipated contraction of the plywood substrate, as a result of drying, caused the exterior panel deformations. The results from computer modeling correlate closely to field measurements and anecdotal evidence collected by several investigators throughout the history of the building.

INTRODUCTION

Simple design changes to a structure can have unanticipated effects on the structure's performance. These changes can sometimes have catastrophic effects, such as the walkway collapse at the Kansas City Hyatt Regency. More often, these changes impact the durability and/or appearance of a structure. This case study summarizes investigations made into an exterior cladding failure at a pyramid-shaped facility in Myrtle Beach, South Carolina. It emphasizes the need to carefully consider the impact that design changes can have on the performance of building assemblies. Furthermore, it demonstrates the benefit of heat and moisture transfer modeling in this type of analysis.

Construction of a pyramid-shaped restaurant facility was completed in July 1995. The structure is located in Myrtle Beach, South Carolina, which has a warm, humid climate. The building is four stories tall with structural steel framing. The first level is mostly below grade with cast-in-place concrete walls and a concrete floor slab. The upper three floors have wide-flanged steel beams supporting corrugated steel decking and concrete floor slabs (see Figure 1).

The exterior walls are inclined at approximately 45° and thus have the dual function of walls and roofing. The wall structure consists of corrugated steel decking spanning between inclined, wide-flanged steel columns and purlins. Exterior of the steel decking were a 3.500 in. (88.90 mm) layer of expanded polystyrene (EPS) insulation, a 0.750 in. (19.05 mm) layer of plywood, a continuous bituthene membrane, a 0.375 in. (9.53 mm) air space, and 0.313 in. (7.95 mm) synthetic stone panels (see Figure 2). The panels are adhered to aluminum cleats, along the perimeter and across the center of each panel, with structural adhesive. The aluminum cleats are fastened to the plywood. The 0.375 in. (9.53 mm) wide

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Figure 1 *Overview of the subject facility. The synthetic stone panels extend approximately 75% up the building's façade from grade to a row of metal louvers.*

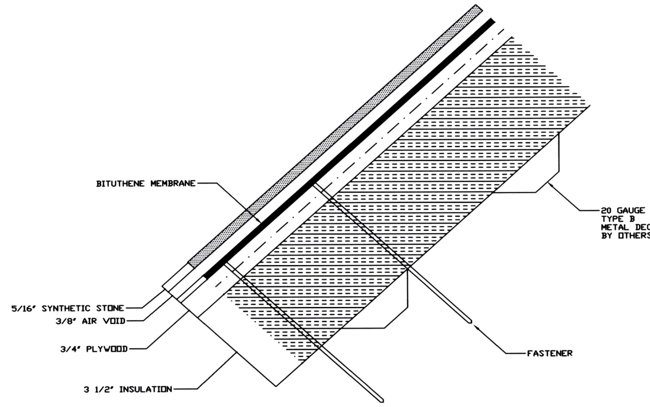

Figure 2 *The as-designed/as-constructed wall assembly.*

Figure 3 *View up the inclined face of the north wall showing curled panel edges and ruptured sealant joints.*

panel joints were sealed with silicone sealant having a ±50% movement capability.

The panels are composite sheets made by incorporating natural slate and stone fillers in a resin binder with chopped glass fibers for reinforcement (Petrarch 1994). The panels installed at the site measured approximately 10 ft × 4 ft (3048 mm × 1219 mm). Panels of the same size were used in the testing during this investigation. Several of the synthetic stone's material properties are listed in Table 1.

The exterior wall cladding was installed in early April 1995. Around the end of October 1995, the synthetic stone panels were visibly deformed (McCarty 1995). The deformations consisted of upward curling of the panel edges, outward pillowing of the panel centers, and combination pillowing/cupping in several panels (see Figure 3). In addition, many of the silicone sealant joints between adjacent panels had compressed beyond the designed minimum widths and some joints had ruptured.

INVESTIGATION

The purpose of the investigation was to determine the cause of the excessive deformations in the exterior synthetic stone panels and the failure of the sealant joints between panels. This investigation relied on information obtained from concurrent investigations performed by others.

During the course of the investigation, I considered two theories that seemed likely to explain the panel deformations. The first hypothesis was that the synthetic stone panels experienced moisture-related expansion beyond anticipated values. The second hypothesis was based on the possibility that unanticipated differential movement had occurred between the layers in the exterior wall/roof assembly.

Panel Expansion Hypothesis

The panel expansion hypothesis developed after liquid water was found in the air space behind the exterior cladding when a panel was removed during a field investigation (Ryan 1996). This hypothesis indicated that water either migrated through the panels via vapor diffusion or leaked inward at the metal louvers near the top of the building. The water collected between the panels and the bituthene membrane. It was theorized that the long duration of each panel's exposure to this interstitial moisture led to moisture absorption and moisture-related expansion beyond that anticipated for vertical wall assemblies using the synthetic stone panels.

Several tests were performed to examine this hypothesis. The first test was the installation of a single panel in an inclined rack that was placed at the site (Jordan 1998a). The panel was secured near its center and allowed to expand and

Table 1. Synthetic Stone Material Properties

Property	Value
Weight	3.2 lb/ft^2 (0.313 in. thick panel) 153.2 N/m^2 (7.95 mm thick panel)
Moisture absorption (ASTM D-570)	0.08% (by weight, short duration exposure), 0.20% (by weight, 24 hr immersion)
Thermal conductivity (ASTM C-177)	4.862 Btu in./hr ft^2 °F 0.702 W/m°C
Thermal expansion (ASTM D- 696)	10.8×10^{-6} in./in.°F 19.6×10^{-6} mm/mm°C
Permeability	0.02 perm 1.10 ng/Ns
Apparent porosity	1%

contract both vertically and horizontally. The length and width of the panel were measured one day per week in the morning and in the afternoon. After recording the afternoon measurements, the panel was sprayed with a hose for five minutes and remeasured. This testing was performed from May 19, 1998, to July 14, 1998. Data from this test indicated that the panel height and width were the same at the beginning and end of the test period. The panel width showed a slight decrease of 0.063 in. (1.59 mm) when measured in the afternoon. Wetting did not cause a change in the panel dimensions (Jordan 1998b). This battery of testing did not reveal unusual panel performance when placed at an incline in the site's climate.

The second test was to determine if the panels absorbed moisture in excess of the values (0.08% by weight short term, 0.20% by weight long term) provided by the panel manufacturer (Woods and Schmitt 1998). Three synthetic stone panels were subjected to ASTM D-570, *Standard Test Method for Water Absorption of Plastics*. The testing resulted in an average short-term moisture absorption rate of 0.09%. This result was 0.01% greater than reported by the manufacturer. The longer-term average result was 0.18%, which was 0.02% less than reported by the manufacturer. These results indicated that the panels performed nearly as expected with regard to moisture absorption.

Concurrent with the ASTM D-570 testing, the panel manufacturer tested a panel to determine if long-term moisture exposure caused excessive expansion in the panels (Heyes 1998). A small curb was fastened to the upper face of one panel so that water could be contained on that side. The curb was made of the aluminum used to manufacture the panel attachment cleats. The panel was mounted horizontally and allowed to expand in both length and width. Testing at room temperatures for several days did not cause measurable expansion in the test panel. A further condition was added with warm air, approximately 95°F (35°C) blowing beneath the panel for nine hours per day. After two days of exposure to combined heat and moisture, the panel expanded approximately 0.079 in. (2.00 mm) along its long axis. These results indicated that thermal expansion is more significant than moisture expansion in the panels. Furthermore, the magnitude of the expansion would only result in a 25% sealant joint movement. This was much less than the conditions observed at the site.

The third test used to evaluate the panel expansion hypothesis was to replace a row of panels on the building. The purpose of this test was to determine if installation techniques had impacted the performance of the panels. The second row of panels on the north elevation was removed and replaced on May 12 and 13, 1998. The installation was monitored to ensure compliance with the manufacturer's instructions. Observations done on July 17, 1998, indicated that the panels did not exhibit visible deformations similar to the original panels despite exposures to high temperatures and humidity (Jordan 1998c). By late fall, this row of panels exhibited low severity deformations and excessively compressed sealant joints (Jordan 1998d). These results confirmed that panel installation techniques were not responsible for the deformations. The results also seemed to indicate that panel deformations may be related to seasonal changes as both the original panels and the replacement row exhibited deformations around October or November.

Overall, the data did not support the panel expansion hypothesis.

Differential Expansion Hypothesis

The differential expansion hypothesis developed when it was discovered that the as-built/as-designed wall did not conform to the installation details recommended by the manufacturer. The manufacturer's literature indicates that the exterior sheathing substrate should be fastened directly to the structural supports. Figure 2 shows that a 3.500 in. thick layer of EPS insulation board was installed between the plywood sheathing and the corrugated steel decking. It seemed likely that the long fasteners that extended from the plywood to the steel decking would be subjected to bending loads that could cause the fasteners to deflect. The recommended construction places only shear loads on the fasteners and would result in a more stable assembly (see Figure 4).

An analysis of the assembly's performance over several months was required to study the differential expansion hypothesis. A computer-based simulation of the likely expansion/contraction in the assembly was more practical and less expensive than laboratory testing. This type of simulation was not readily available at the time when the structure was designed. The simulation consisted of two phases. First, heat and moisture transport effects were calculated using a commercially available software package. Temperature, humidity, and moisture content values were calculated on an hourly basis for the materials that composed the wall assembly. These results were exported to a commercially available

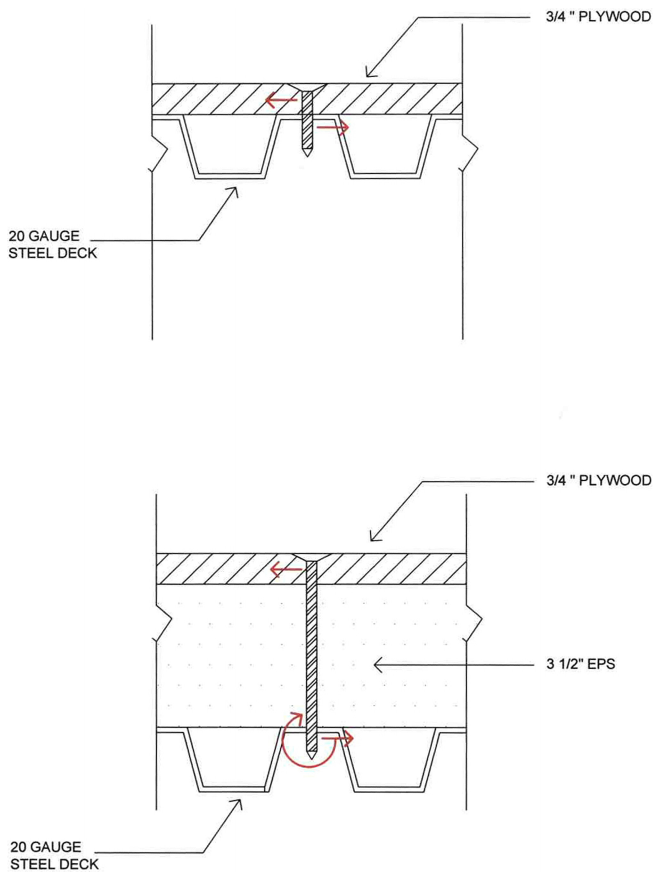

Figure 4 *Top, manufacturer's recommended installation with the exterior sheathing fastened directly to the steel structure. Bottom, the assembly used at the subject facility. The thick layer of EPS required much longer fasteners.*

spreadsheet program so that coefficients of thermal and hygroscopic expansion could be applied.

Heat and moisture transport were modeled using WUFI Pro 3.2. WUFI considers the effects of vapor diffusion and capillary suction in one dimension through an assembly (Kuenzel et al. 2001). It does not include the effects of air leakage. The subject building has a continuous layer of bituthene membrane extending behind the synthetic stone panels. Also, only one small area of windows and one section of doors penetrate the pyramid portion of the building. The large wall areas with few penetrations and the continuous membrane make the use of this type of model exceptionally favorable as air leakage is relatively insignificant. WUFI considers heat and moisture transport in only one dimension. However, the large, uninterrupted wall areas on the subject building decrease the importance of edge and corner effects. A one-dimensional simulation would adequately characterize the performance of much of the wall area.

WUFI has the capability to use moisture-dependent property data to enhance the accuracy of an analysis. The properties of most of the wall's materials were already present in the database provided. Only data for the synthetic stone panel and the corrugated steel deck layers had to be generated.

The synthetic stone panels have low moisture absorption and low vapor permeability. These characteristics indicate that the material property data are nearly constant and not subject to significant changes based on changes in moisture content.This condition is similar to the properties of polyethylene membranes. The minimum required data could easily be derived from the manufacturer's printed literature.

The corrugated steel layer had to be modeled as a representative homogenous layer with combined steel and air properties. A model of the steel layer alone would be virtually impermeable to air and water. In practice the steel has laps and fastener holes that allow some moisture to move across this layer. The sizes of the gaps created by the laps and fastener holes were estimated from field measurements so that the total area of air space could be approximated for a typical sheet of corrugated decking. The properties of the synthetic steel/air layer were then created by applying an area-weighted averaging system to the properties of steel and air. Equation 1 shows how the properties were combined.

$$Representative\ Property = \frac{(Area_{air} \cdot Property_{air}) + (Area_{steel} \cdot Property_{steel})}{(Area_{air} + Area_{steel})} \quad (1)$$

Initial conditions for the WUFI simulation were based on historical weather data. Actual weather data from 1995 were not available from the National Climatic Data Center. Historical weather data for March in Myrtle Beach indicate that the mean dry-bulb temperature is approximately 55°F and the mean dew-point temperature is approximately 45°F (USAF 2000). These conditions result in an equilibrium wood moisture content of around 12% (FPL 1987). The remaining initial conditions were based on the mean relative humidity of approximately 63%.

Figure 5 shows the results of the combined hygrothermal analysis and expansion/contraction analysis. The gray data show the width of a typical panel joint over two years when only thermal expansion and contraction are considered and the assembly's layers are free to move with respect to each other. The dashed lines above and below the gray data show the allowable joint movement based on ±50% joint movement.

The black data in Figure 5 include the effects of moisture-related movement in the plywood. The average coefficient of hygroscopic expansion in plywood is 0.000002 in./(in. %RH) (O'Halloran 1975). The structural steel would not exhibit significant movement as a result of moisture exposure. Also, the testing discussed above did not reveal significant moisture-related movement in the synthetic stone panels. The data in Figure 5 reflect free movement of the wall components with respect to one another; in other words, no fastening or bonding

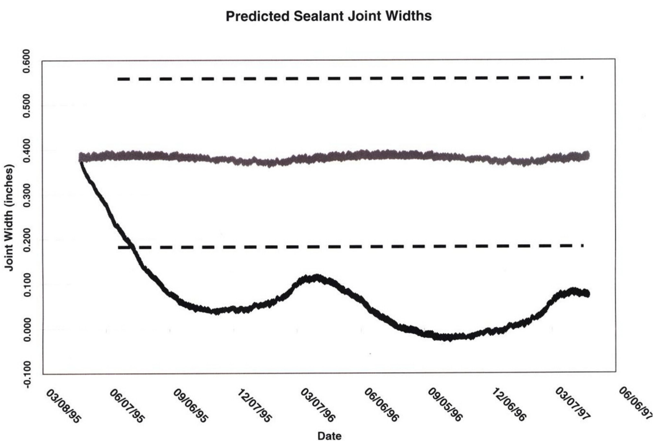

Figure 5 *Shows the expected performance with consideration of only thermal movements as compared to the performance considering both thermal and moisture-related movements. The assembly layers are unrestrained by bonding or fastening in this figure. The dashed lines represent ±50% acceptable movement range.*

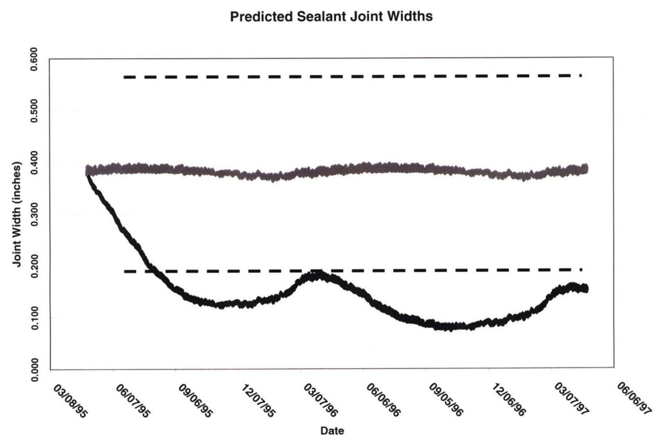

Figure 6 *Shows estimated actual movement considering both thermal and moisture-related movement based on a reduced coefficient of hygroscopic expansion. The reduction of the coefficient accounts for fastening between the wall layers. The dashed lines represent ±50% acceptable movement range.*

between the layers is considered. The following can be determined from examining the data.

1. The data have a clear sinusoidal pattern with peaks around April and troughs around November. The data also appear to be decaying to an asymptotic average of approximately 0.040 in. (0.10 mm).
2. The data trend closely to the reported observations; however, the magnitude of the movement is greater than what was reported. Note the following:
   - The initial complaint about the joint width was reported around the end of October 1995. The data show a local minimum occurring at this same time.
   - The joints had closed to around 0.063 in. (1.59 mm) on October 23, 1996 (Lambrix 1996). The data show that the panels would have been overlapped had free expansion occurred. The free movement analysis overestimates the actual movement between the layers.
   - A row of replacement panels was installed in May 1998. The row reportedly appeared acceptable during the summer of 1998 but exhibited evidence of deformations by late fall of the same year. These observations, two years later than the analysis, correlate well with the predicted seasonal movements shown by the data.

As installed, free expansion is not possible between the layers. The long screws that secure the plywood to the steel deck through the EPS provide some resistance to the movement of the plywood. The attachment of the synthetic stone panels provides additional resistance to movement in the plywood. The effective coefficients of thermal and hygroscopic expansion in the plywood are reduced as a result of bending resistances in the screws and compression/tension in the synthetic stone panels. The two known joint widths are 0.375 in. at installation in April 1995 and 0.063 in. measured on October 23, 1996. Fitting the curve to these two points results in an effective coefficient of hygroscopic expansion in plywood of 0.000016 in./(in. %RH). Using this value for hygroscopic expansion yields more realistic results for expansion and contraction. Figure 6 shows the predicted joint widths during the period of analysis using this reduced value.

CONCLUSIONS

An exterior cladding failure occurred at a Myrtle Beach, South Carolina, structure. The cladding exhibited cyclical movement on the expansion joints. Two hypotheses were explored. The first hypothesis was that the cladding panels expanded excessively. A variety of tests intended to simulate the warm, humid climate did not yield results that explained the observed movements.

A second hypothesis was that differential movement between the wall assembly layers caused the expansion joints to close excessively. Computer-based hygrothermal modeling of the wall assembly was used to analyze the wall performance. The analyses show that unanticipated, moisture-related contraction of the plywood substrate caused the deformations in the exterior cladding. As the plywood dried and shrank, the spacing between the attachment cleats decreased. This created compression along the length and width of each panel that resulted in inward and out-of-plane deflections of the panels. It also caused the joints between the panels to close tighter than the minimum allowable joint width. This, in turn, led to rupturing of some sealant joints. Water penetrated through the failed sealant joints and accumulated behind the panels.

The addition of the exterior insulation resulted in a condition that allowed the plywood to contract excessively. The manufacturer's recommendations showed plywood sheathing attached directly to the structural framing with the cleat fasteners also extending into the framing. The thick layer of EPS insulation allowed the long fasteners to deflect under the forces created by the contracting plywood. This did not adequately resist drying-related shrinkage in the plywood.

A heat and moisture transfer analysis during the design of the structure could have identified the potential for this problem. The input data for this work existed at the time of the design. Unfortunately, a program to perform the computations used in this analysis was not commercially available then. As heat and moisture transport programs become even more available and understood by the design community, problems such as the one discussed in this paper should become less frequent.

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