MEASUREMENT OF ENERGY EFFICIENCY OF BUILDING ENVELOPES

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ABSTRACT

This report summarizes the work completed measuring and comparing the energy efficiency of highly insulated precast concrete sandwich panels. The work has been performed under a Demonstration of Energy-Efficient Developments (DEED) grant by the American Public Power Association. The project uses an adaptation of ASTM C177-85 and ASTM C976-85, *Standard Test Method: Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box*. Two five-walled test chambers are constructed, tested, and an analytical thermal model developed.

Test data is collected using the two chambers and a 96 channel data acquisition system to monitor system performance and test progress. Two samples of extruded polystyrene, with different R-values, are tested and submitted to the National Institute of Standards and Technology, (N.I.S.T.), for calibration traceability. A test procedure is developed and described for test result repeatability and verification. Results include thermal resistance values for the several panels tested. The measuired thermal resistance values were less than expected and explanations explored. Suggestions are made for further study investigating improvements in testing methods and panel construction.

1. INTRODUCTION

This paper summarizes the work completed for the project "Measurement of Energy Efficiency of Building Envelopes" financed under an APPA DEED grant. The grant has been made to provide the tooling and instrumentation required for the energy efficiency testing of several concrete sandwich panels developed at the Center for Infrastructure Research, University of Nebraska-Lincoln, Omaha campus. This research has been facilitated with funds provided by the Nebraska Energy Office and Wilson Concrete Co. of Omaha, Nebraska.

The testing procedure is a modification of ASTM C177-85[1] and ASTM C976-85, *Standard Test Method: Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box*[2]. The test specimens incorporate fiber reinforced plastic (FRP) connectors to improve both structural and thermal performance when connecting two concrete layers separated by a 3 inch (7.62 cm.) layer of insulation. The construction of the panels is illustrated in Fig. 1., on the following page. The development of pre-cast concrete panels with improved thermal performance will increase the energy efficiency of buildings designed and constructed using the new technologies.

The funding has been used to:

(1) construct two environmental chambers to be used in controlling the heat flow through the test specimens.
(2) assemble the necessary data acquisition system; including sensors, multiplexing and A to D conversion hardware, and operational software.
(3) provide the comparative analysis of heat transmission properties for the several prototype panels using the test results obtained.

The completed work includes the assembly of two envi-

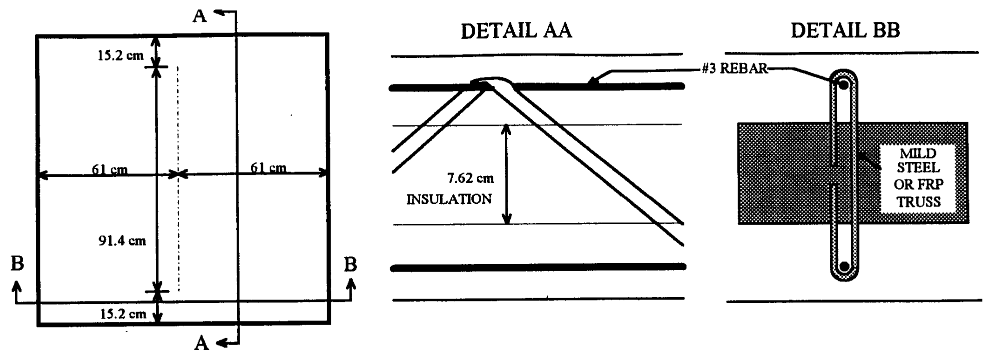

Fig. 1. Test Specimen Construction

ronmental chambers. Each chamber is provided with an air circulation manifold and heating/cooling equipment for temperature control. A 96 channel data acquisition system has been installed and used for the collection of test data.

The test analysis was performed using temperature differences and system input energy data. The submission of test samples to N.I.S.T. for verification of test results was judged a reliable and accurate method of system calibration.

2. HARDWARE

A summary diagram of the hardware constructed and assembled for this study is presented in Fig. 2., on the following page. Also included is a diagram of the data acquisition instrumentation purchased for the project. The two five-walled chambers (labeled Hot Box and Cold Box in Fig. 2) are constructed of several layers of extruded polystyrene (XPS). Each wall consists of two 3 in. (76.2 mm) R 15 ft^2-hr-°F/BTU (0.11X10^6 cm^2-sec-°C/cal) layers, two 1 in. (25.4 mm) layers with aluminum foil backing, and two layers of 0.5 in. (12.7 mm) plywood. This construction provides an approximate total R value of 43 ft^2-hr-°F/BTU (0.32X10^6 cm^2-sec-°C/cal) including static air film effects on the interior and exterior surfaces. This total R value was calculated from approximate values of the building materials used[3]. The calibration test confirmed this approximate R value.

Each chamber contains an air circulation manifold. The manifold mounted in the hot chamber contains a small heating element connected to a proportional temperature controller. The output of the controller is monitored with a wattage transducer with a linear 0-5 Volt output over the range of 0-500 Watts input. The output voltage is integrated with a voltage to frequency converter-integrator for monitoring the total energy input. The integrator output pulses are counted with a 12 bit counter installed on an expansion card mounted in an expansion slot on the 386 PC. This counter was specially designed and assembled for this project. The cold side manifold contains a heat exchanger coil which is supplied with a mixture of water and automotive anti-freeze. This mixture is cooled and circulated from a compressor and pump mounted external to the test chambers.

Both manifolds have air circulation fans mounted on the interior with the heating/cooling elements. The hot side fans are connected through a power transducer so that the circulation fan power (approximately 57W) can be included in the total energy data. During the initial calibration tests, the input energy of the hot side circulation fans was found to be sufficient to develop a temperature differential of 60 °F (33 °C) or more across a sample panel of R 5 ft^2-hr-°F/BTU (0.037X10^6 cm^2-sec-°C/cal). In subsequent tests only the fan wattage was used as total power input. The heater coil was used only as a "booster" to reduce the time to reach a steady state condition.

The data acquisition system used includes a 12-bit analog to digital converter placed on an ISA bus expansion card. The expansion card also includes a programmable

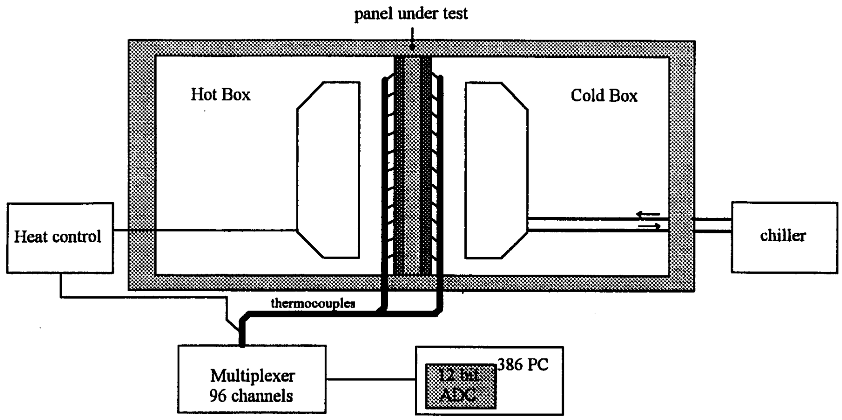

Fig. 2. Environmental Test Chambers

gain amplifier and an 16-channel analog multiplexer. The several sensor signals used to gather test data are further multiplexed via three signal conditioning boards installed in a chassis external to the 386 PC. Each of these external boards provides input signal conditioning channels for 32 sensors.

Copper-constantan (Type T) thermocouples are used to monitor the sandwich panel surface temperatures, the chamber air stream temperatures, and the chamber and room ambient temperatures. Another thermocouple is used to monitor the cooling fluid temperature. A humidity sensor is used to monitor the humidity of the hot chamber and the total input energy input adjusted to compensate for the loss due to vaporization.

3. SOFTWARE

The test monitoring and data acquisition software written for this project provides a display of the test progress. Four scrolling windows display a history of the latest 24 hours of the test. These windows contain the average air stream temperature for each manifold and the average surface temperature for the hot and cold sample surfaces. Also a text display of the maximum and minimum readings for each set of thermocouples alerts the operator of any open thermocouple or radical air leak by displaying major temperature anomalies.

The ambient room temperature and the temperature of each chamber is displayed. The relative humidity of the hot chamber is displayed and monitored according to ASTM recommendations. The temperature of the cold side air should remain above the dew point of the hot side air in order to prevent moisture migration through the sample[2]. The thermocouple cold junction compensation, approximate heater wattage, and a running total of energy input is also presented in the on-screen display. An approximate calculation of sample R-value is given on this main screen along with data file statistics. Test data is collected and displayed at intervals of six minutes. For each sensor, readings were taken 1024 times within 500 msec. and a mean recorded. This oversampling reduced noise influences.

Software written for the project included a 3-D finite element model for the specific chamber configuration used. This program used homogeneous elements to approximate the heat losses through the chamber walls to ambient conditions and the losses through edge effects around the specimen under test. The number of elements was then reduced to save analysis time after the correlation between the models was studied. The smaller model provided results within 5% of the larger model for sample R values over the range of 1 to 20 (ft^2-hr-°F) /BTU ($7.4X10^3$ to $0.15X10^6$ cm^2-sec-°C/cal).

4. TESTING METHODS AND PROCEDURES

In order to establish a comparative (or secondary) measurement method of sample thermal conductivity, it was necessary to calibrate the apparatus with specimens of known thermal transmission properties. This was facilitated through the assistance and advice of Mr. Robert Zarr of N.I.S.T. Two XPS specimens of Dow Styrofoam® (R-5 and R-15) were tested using the project apparatus and then submitted to N.I.S.T. for calibration traceability. The work to develop an analytical model of the test chambers was also greatly enhanced by Mr. Zarr's donated involvement.

Each test specimen, including the calibration samples, was installed between the two five-walled chambers. The surface temperature thermocouples were installed on a 6X6 grid, with a grid spacing of 6 in. (152 mm). The thermocouples were secured using duct tape attaching at least 4 in. (102 mm) of the leads to the surface before the junction. This assured that the thermocouples accurately read the surface temperature without the effects of lead thermal conductivity. Nine thermocouples were also placed in each manifold air stream to monitor the uniformity of the air stream temperature.

The remaining channels of the data acquisition system were then connected to thermocouples used to monitor hot and cold chamber temperatures, room temperature, and the cooling bath temperature. Channels were also used to monitor the hot chamber relative humidity and the output of the power transducer-integrator.

Several techniques were used to minimize infiltration leaks to room ambient conditions. Gaskets were constructed of 2 in. (51 mm) pipe insulation to reduce infiltration on the physical bottom of the chambers. Expandable foam was used to thermally seal the top and sides of the chamber-sample junction. Finally a fogger was used to generate a small amount of smoke and positively pressurize the hot chamber. Any remaining massive air leaks became immediately obvious and were sealed with expandable foam and/or duct tape.

Three steady-state conditions were used to generate test data.

(1) Full circulation fan power and full cooling was used to generate a large temperature difference between the two monitored sample surfaces.

(2) The cooling was turned off and the circulation fan power lowered in both chambers to maintain both chambers at the temperature reached by the hot chamber in the first test. The second test minimizes the heat flow through the test sample and was used to model losses to ambient conditions.

(3) The temperature of the hot chamber was maintained as close as possible to room temperature and the cold chamber cooled to the temperature reached in the first test. The third test minimizes losses to ambient in order to model the combined effect of hot to cold infiltration and though-sample heat flow.

For each test, the chambers were maintained at a steady state condition for a minimum of 24 hours. The data used for R value calculations was the average of all conditions for this 24 hour period. The equipment room conditions possessed a plus and minus five degree diurnal cycle; so the length of time for steady state readings was increased from the ASTM recommended 8 hours.

5. RESULTS

The N.I.S.T. tests run on two XPS specimens were used to establish a calibration standard for the test chambers. The results of tests (2) and (3) on each specimen were used to improve the accuracy of the finite element model of the test chambers. The results of tests (1), (2), and (3) on each XPS specimen were used in conjunction with the N.I.S.T. test results to generate the least squares best fit plane for Q_{err} of Fig. 3., on the following page, and establish a calibration standard between values of R = 5.23 and R = 14.98 ft^2-hr-°F/BTU ($38.7X10^3$ and 111 $X10^3$ cm^2-sec-°C/cal).

The best fit plane is displayed in the 3 space of ΔT_{hc}, the difference between the two surface average temperatures; ΔT_{hr}, the difference between the hot chamber and room temperatures; and Q_{err}, the total heat losses unaccounted for by the finite element model. All system calibration test results fall within a 5.5% band of this plane. The sources of Q_{err} losses include air migration around the test specimen and exfiltration losses to ambient.

The equation of this least squares plane is:

$$Q_{err} = 0.3689*\Delta T_{hr} + 0.2514*\Delta T_{hc} \qquad \text{(Eq. 1)}$$

Using Q_{err}, the energy balance equation, Eq. 2, can be used to calculate Q_s, the energy passing through the panel under test.

$$Q_{in} = Q_s + Q_b + Q_{err} \qquad \text{(Eq. 2)}$$

where:

Q_{in} is the total energy input to the hot chamber (including energy delivered by the chamber circulation fans).

Q_s is the energy passing from the hot chamber to the cold chamber through the test sample.

Q_b is the energy passing from the interior of the hot chamber to room ambient. These conduction losses are calculated using the finite element model program described in section 3.

Q_{err} is described above. All other losses including: infiltration/exfiltration, radiation, convection, etc.

Q_s can be used in Eq. 3 to then calculate the R value of the test sample.

$$R = (\Delta T_{hcs} * A_s) / Q_s \qquad \text{(Eq. 3)}$$

where:

ΔT_{hcs} is the temperature difference between the hot and cold surfaces of the test sample.

A_s is the surface area exposed on each side of the sample.

The test results demonstrate the relative R value of the different construction types. The concrete sandwich panel results are summarized in Table 1: Concrete Panel Measured Thermal Resistance. The highest thermal conductivity (lowest R value) was measured on specimen UN2. This panel uses concrete to connect the two surface layers of the specimen. The lowest thermal conductivity was measured for sample UN3. This panel incorporates one FRP (fiber reinforced plastic) truss as a connecting element.

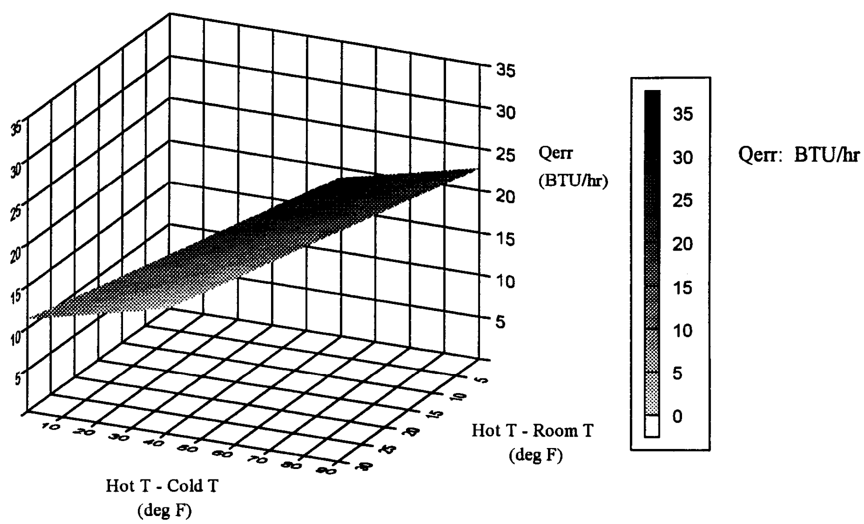

Fig. 3. Heat Losses vs. Temperature Differentials

TABLE 1: CONCRETE SANDWICH PANEL MEASURED THERMAL RESISTANCE

Panel Designation	R Value (ft²-hr-°F)/BTU	Reinforcement Tie
UN1	2.85	concrete
UN2	4.51	mild steel
UN3	5.36	1 FRP
UN4	4.99	2 FRP

6. CONCLUSION

The measured thermal resistance of the concrete sandwich panels is much lower than originally postulated. A 3 in. (76.2 mm) layer of XPS insulation alone would contribute an R value of approximately 15 ft^2-hr-°F /BTU (111 X10^3 cm^2-sec-°C/cal). While some losses were expected from the bridging of the insulation by the trusses and/or concrete, the significance of these losses is much greater than anticipated. Other sources of heat conduction include the steel lifting inserts used to transport the panels and air migration around the edges of the panels during the test procedures. Because the actual R value of the specimens is at or below the low end of the calibration scale established by the N.I.S.T. traceability tests, further development of a lower calibration scale will be necessary to develop a test absolute error specification.

The major finding of the project is therefore:
Thermal losses are dramatically increased with introduction of truss elements bridging an insulation layer. While the lower thermal conductivity of FRP (vs. steel) reduces these losses, the final result is to decrease the total R value of the building envelope by 60% to 70%.

Other findings of the project are summarized.

(1) The measurement of surface temperatures, the use of a 3-D finite element model of the test apparatus, and the least squares best fit estimation of heat losses provide valid and useful tools in a comparative study of building envelopes.

(2) There are significant comparative thermal advantages in the use of structural truss members as connection elements in concrete "sandwich" panel construction versus the use of concrete bridging techniques.

(3) The methods employed in this project can be refined and an absolute calibration standard developed with the testing of R value calibration standards.

Some suggestions for continuing study include:

(1) The development of an absolute calibration scale over the range of R 1 to 5

(2) Determination of local thermal conductivity. Observation of smaller surface temperature and heat flow variations will further facilitate improvements in panel design.

(3) The incorporation of air circulation velocity effects into the calculation of actual test sample thermal resistance. This will be necessary to complete 1) to an absolute accuracy of ±5%.

Some suggestions for test hardware improvements include:

(1) Improvements in the sealing mechanisms of the chambers to reduce infiltration/exfiltration losses.

(2) The development of a guarded hot box apparatus to reduce the energy losses to ambient.

(3) The introduction of heat flow sensors with the sensitivity to detect and monitor local surface temperature variations would refine the 3-D finite element model of the test chambers and improve the measurement of sample conductivity.

7. REFERENCES

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