Simulations of Innovative Solutions for Energy Efficient Building Façades

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Outline

• Introduction

• Proposed Technology

• Methods and Simulation Results

• Future Work
Introduction
Introduction

1. Working on a multi-disciplinary project called SinBerBEST.
2. Seeks cooperative interaction between the grid, building and occupants.
3. Optimizing energy consumption, productivity, emissions, comfort, productivity and the entire building lifecycle.

4. My work: Analyze new energy efficient building material for façades.
SinBerBEST Research Thrusts

Thrust 6: Cyber/Physical Testbeds
- Holistic Hybrid Simulation
- Building Energy Conservation Technology
- Building Grid
- Model Development & Evaluation
- Monitoring

Thrust 1: Sensing, Data Mining and Modeling
Thrust 2: Multi-Level Optimal Control
Thrust 3: High Confidence Building Operating System
Thrust 4: Human-Building Interaction & the Environment
Thrust 5: Material, Design and Lifecycle
Proposed Technology
Energy Usage

a) Sources of energy use

- Industrial: 30%
- Commercial: 19%
- Residential: 22%
- Transportation: 29%

b) Energy consumption in commercial buildings

- Lighting: 20%
- Others: 21%
- Space heating: 16%
- Ventilation: 9%
- Air conditioning: 15%
- Hot water supply: 4%
- Refrigeration: 7%
- Plug Loads: 8%

Images Source: DOE 2011
Sunlight in buildings

Sunlight (positive)
Substitute indoor lights

Primary Energy Use of Commercial Buildings (By Category)

- Lighting, 20%
- Others, 21%
- Plug Loads, 8%
- Space heating, 16%
- Air conditioning, 15%
- Ventilation, 9%
- Refrigeration, 7%
- Hot water supply, 4%

Source: DOE 2011 Buildings Energy Data Book
The proposed building element is referred to as ‘Translucent Concrete Panel’
Features of TC panels

- Structural panels that can support buildings.
- Fibers channel diffused daylight into the room.
- Sunlight into room can be controlled by varying volumetric ratio of fibers.
- The panels can be coupled with other technologies [Mosalam13].
Construction Procedure: Part A

a) Preparing the acrylic formwork

b) Greasing the formwork

c) Roughening fibers for Better bonding
Construction Procedure: Part A

d) Inserting fibers and clamping them

e) Casting concrete

f) Cutting concrete blocks into panels
Translucent Concrete

Sample of TC panel held against Sun
Methods and Results:
Optical and Thermal Behavior
Optical behavior: Ray tracing

• Ray tracing tracks light rays across different media.

• Trajectory followed by rays is continuous. Expressed in form of differential equation.

\[ \frac{d}{ds} \left[ n(x, y, z) \frac{dR}{ds} \right] = \nabla n \]

Eikonal equation

where: \[ \frac{dR}{ds} = [\cos \alpha, \cos \beta, \cos \gamma] = \mathbf{A} \], \( n(x, y, z) \): Refractive Index at (x, y, z)
Marching rays

- For each ray, the equation is discretized spatially.

- Algorithm developed in Fortran and Python.

- At each time step, the location and velocity of ray is updated.
Light interaction with fibers

Fresnel’s Laws

Reflection and Refraction

Total Internal Reflection

Other losses:
1) Light scattering
2) Absorption
3) Surface roughness of fibers
Light interaction with concrete

\[ \theta_i = \theta_r \]

Concrete part of TC
Sunlight distribution model

Perez Sky Distribution Model [Perez87]
Sky cover for Berkeley

Variation of the solar flux with sun’s position.
{1: least clear; 8: most clear}
Illumination Calculations

Ray Tracing

Database

Start

Calculate the external weather conditions

Compute light entering the room

Store data in *.csv

Load *.csv in Radiance

Stop

Simulate illumination in room

Import material & reflectivity data for surfaces

Model OFs as luminaires

Model a room and designate a wall as TC
Illumination Calculations

Start

- Calculate the external weather conditions
- Compute light entering the room
- Store data in *.csv
- Load *.csv in Radiance

Stop

- Simulate illumination in room
- Import material & reflectivity data for surfaces
- Model OFs as luminaires
- Model a room and designate a wall as TC
1) Optical fibers are modeled as light emitting luminaires [Ahuja14, Ahuja151].

2) Illumination can be calculated at any point inside the room.
Energy calculations

• Illumination calculations are further extended to include occupant behavior.

• The occupant behavior decides light switching activity.

• For the times light is switched off, electrical energy is conserved.
Algorithm for Energy Calculations

Start

Ray Trace through Translucent Concrete
Algorithm for Energy Calculations

Start

Ray Trace through Translucent Concrete

Model a room

N
Algorithm for Energy Calculations

Start

Ray Trace through Translucent Concrete

Model a room

Monday occupancy profile between 8am and 6pm

Markov chain Occupancy Profile

Graph showing Monday occupancy profile between 8am and 6pm with different lines for average profiles for different groups.

Diagram of a room with ray tracing through translucent concrete and a Markov chain model for occupancy profile.
Algorithm for Energy Calculations

Start

Ray Trace through Translucent Concrete

Model a room

Light Switching Events

Light Switch-on at arrival

Markov chain
Occupancy Profile
Algorithm for Energy Calculations

1. Start
2. Ray Trace through Translucent Concrete
3. Model a room
4. Markov chain
5. Occupancy Profile
6. Light Switch-on at arrival
   - Light off; Energy saved
   - Light on; Energy spent

Flowchart:
- Start
- Ray Trace through Translucent Concrete
- Model a room
- Markov chain
- Occupancy Profile
- Light Switch-on at arrival
  - Light off; Energy saved
  - Light on; Energy spent
Results

- For fiber density of 5.59%, lighting energy saved is about 50% compared to constant use of T8-tubes.

- The energy saved increases to 65% for a fiber density of 10.6%.
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Results

- For a fiber density of 5.59%, the lighting energy saved is about 50%.
- The energy saved increases to 65% for a fiber density of 10.6%.

1) Occupancy schedules for NREL, DOE-2 gives lower energy savings
2) Does not account properly for occupancy during weekends.
Thermal Behavior

Solar Radiation

Outside Convection

h_{outside} = \text{outside convection}

Ambient Temp = T_{outside}

Inside Convection

h_{inside} = \text{inside convection}

Solar Radiation

Radiation exchange from walls

ROOM CONDITIONS

Total Heat Flux = Q
Comfort Temp. = T_{inside}
Composition of wall

Model a room

Different layers of the wall,
R-value of opaque wall = 16
Representative Vol. Elem. (RVE)

- Thermal behavior of opaque walls is easy and can be solved as a 1D problem.

- Thermal behavior of TC panel requires a 3D algorithm as the fibers passes through all layers.

- But 3D simulations are slow...divide the TC panel into repeating blocks or RVE.
Heat Contribution

• Three sources of heat are considered in the room:
  
  – Heat Conduction through walls
  
  – Solar radiation through optical fibers
  
  – Heat dissipation by Fluorescent tubes
Radiation and Lighting loads

- Radiation loads depend on the fiber density ratio of the TC panels.
- Lower density of fibers is bad and so is higher density. Optimal density required.
- When solar radiation contribution is large, less artificial lighting is needed.

Radiation and heat dissipation loads for TC panels with 1.4% fiber density ratio.
1) Heat added into room by conduction was small.

2) Cooling loads were majorly from solar radiation.

3) Heating loads due to conduction were substantial.

4) Heat dissipation from artificial lighting decreased as the fiber density increased.

Parameters for simulation:
R-value of wall = 16; R-value of fibers = 5.7;
Dissipation factor for tubes = 0.77; HVAC operation time: 8am-6pm
1) Heat removal due to conduction was large.

2) Most of the heat from room was removed during start of HVAC operation schedule (8 am-6 pm).

3) The initial temperature at start of simulations (i.e. 8 am) were set to temperature at 7 am

4) Temperature at 7 am << 22°C
Results: Net savings

1) Combining the loads on HVAC with lighting requirements.

2) A fiber density ratio of 5.6% performs best in saving about 26% costs [Ahuja152].

3) Small fiber density makes TC fabrication process easier.

4) High fiber density leads to monetary loss as solar radiation loads are high.

Parameters:

- Heater \(\text{COP}: 3.5\); Air-conditioner \(\text{COP}: 4.0\)
- Utilities prices for SF Bay Area
  - Electricity: 23.3 \(\text{¢/kWh}\); Natural gas: 5.4 \(\text{¢/kWh}\)
Results: Net savings

1) Lightweight composites used as building material.

2) Uses cenospheres which are hollow glass spheres and are produced as byproducts of coal combustion.

3) Cenospheres also enhance the thermal conductivity.

4) Expenditure reduces by 4% for fiber density of 5.6%.

Parameters for TC w/cenospheres:
Thermal conductivity: 0.4 W/mK
Density: 1303 kg/m³
Specific heat: 788 J/kgK
Conclusions

• Developed algorithms to analyze the thermal and optical behavior of translucent concrete.

• Translucent concrete shows promising results in saving energy.

• A fiber density of 5% can save ~50% on lighting energy.

• A fiber density of 5% can save ~24% total energy.

• Interfacing the algorithms with EnergyPlus to model complex situations.
Future Work
Tilted Panels

Avg. sunlight influx for whole year

A TC wall with a tilt of 30° with horizontal transmitted maximum sunlight.
Capturing more daylight

Modifying fiber shape

Using sun-tracking beams
Coating optical fibers

1) Potential in reducing energy usage by coating fibers to eliminate UV and infrared transmission.

2) Cuts down on solar radiation and increases savings to almost 40%.
References


References


Thank you.
Questions?

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