SinBerBEST
Annual Meeting 2013

Progress Report Session

Thrust 5: Material, Design and Lifecycle

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9 January 2013

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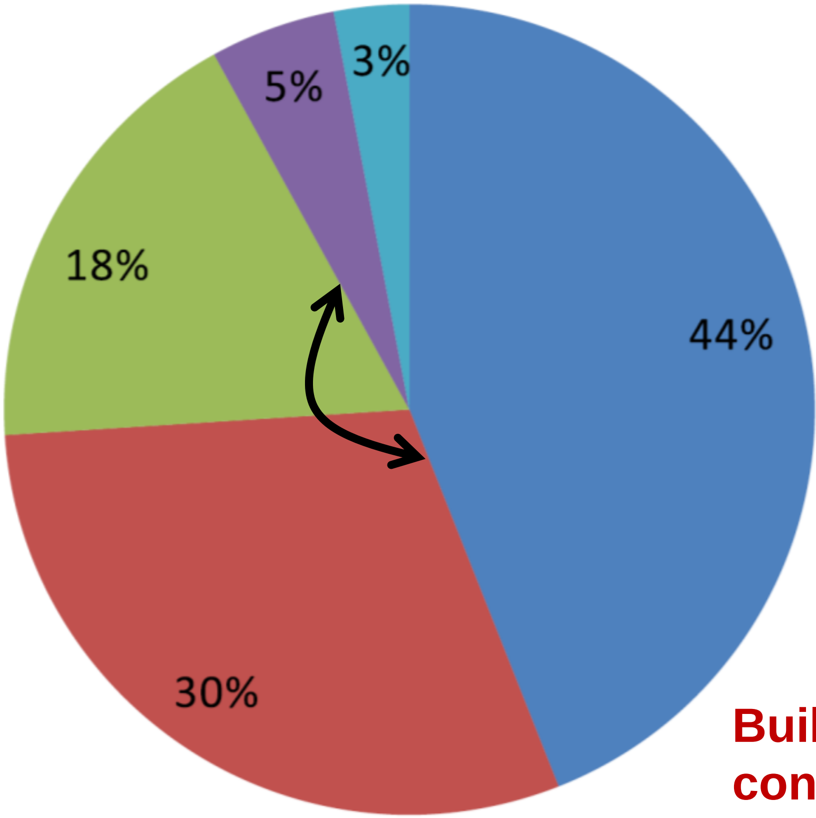
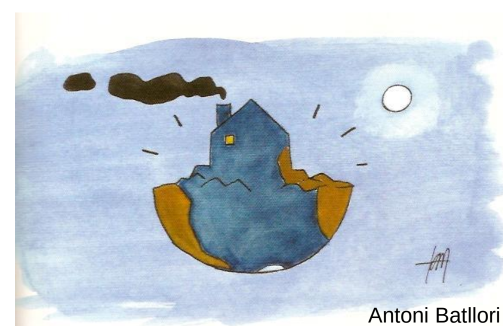
NATIONAL RESEARCH FOUNDATION

Building Efficiency and Sustainability in the Tropics (BEST)



Buildings & households consume almost <u>50%</u> of all electricity in Singapore

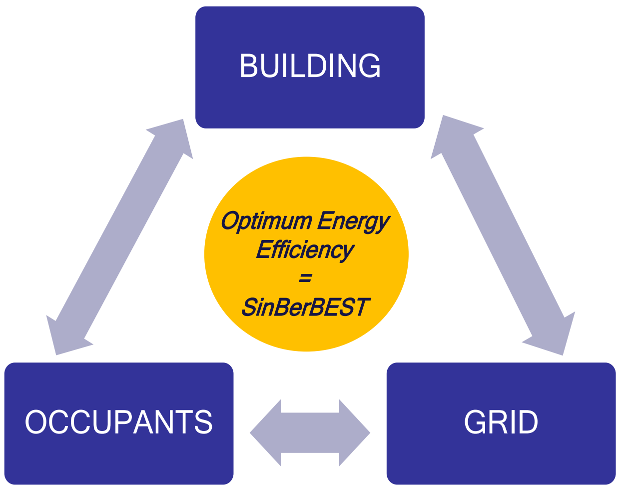


Antoni Batllori

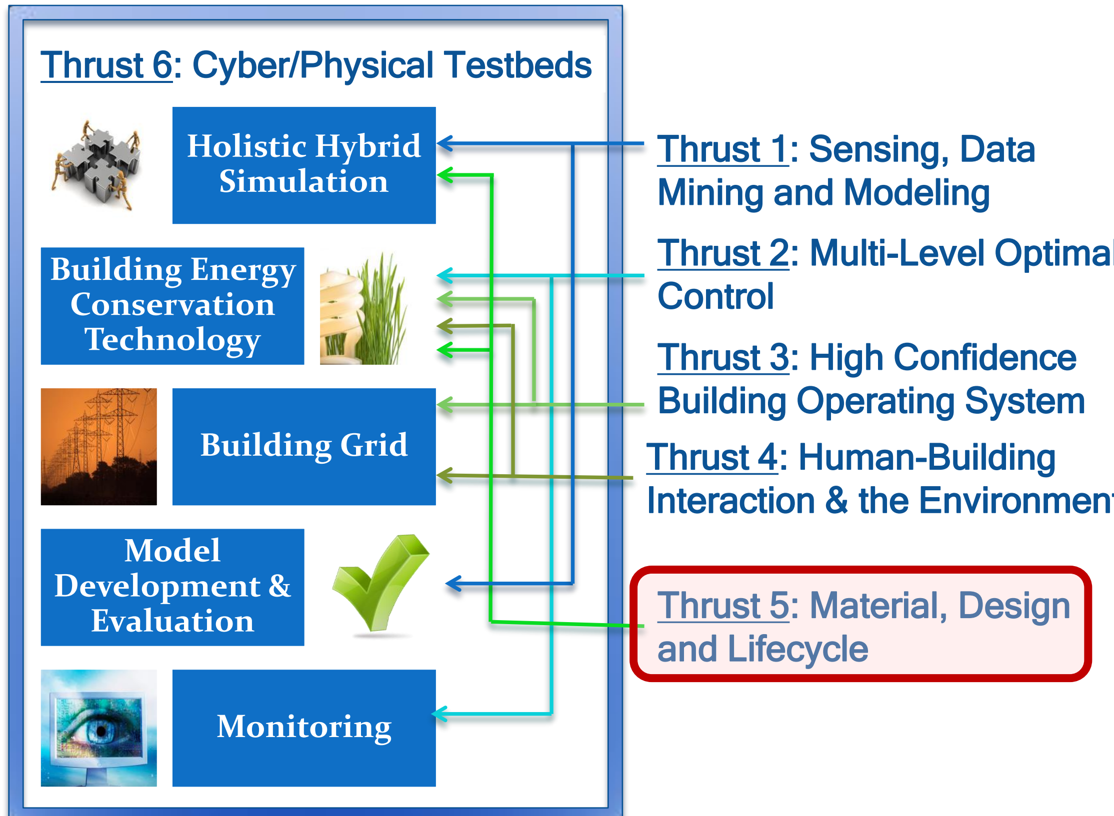
Electricity Consumption

Source: Energy Research Institute of Singapore (SERIS) Annual Report 2011 based on data from Building and Construction Authority (BCA), 2007

Dynamic Interaction for Optimum Energy Efficiency within SinBerBEST



Consumed energy in building construction and operation can be reduced by intelligent interaction between the grid, the building and its occupants/appliances. This requires a transformational paradigm-shift in designing, commissioning, & retrofitting.



Thrust 5: Mission Statement and Overarching Goal

Materials, Design and Lifecycle

Develop and demonstrate **optimal models** and **policies** to represent the **entire lifecycle** (ranging from the design of new buildings to the operation of new and existing ones) of the ***building materials and structural systems in the tropics***.

The sustainability performance criteria must simultaneously consider safety, energy efficiency, thermal comfort, occupant productivity, etc. This performance is tied directly to material selection and design, detailing and construction techniques, and lifecycle issues. We need an ***integrated design approach*** (from material to structure).

Thrust 5: PI's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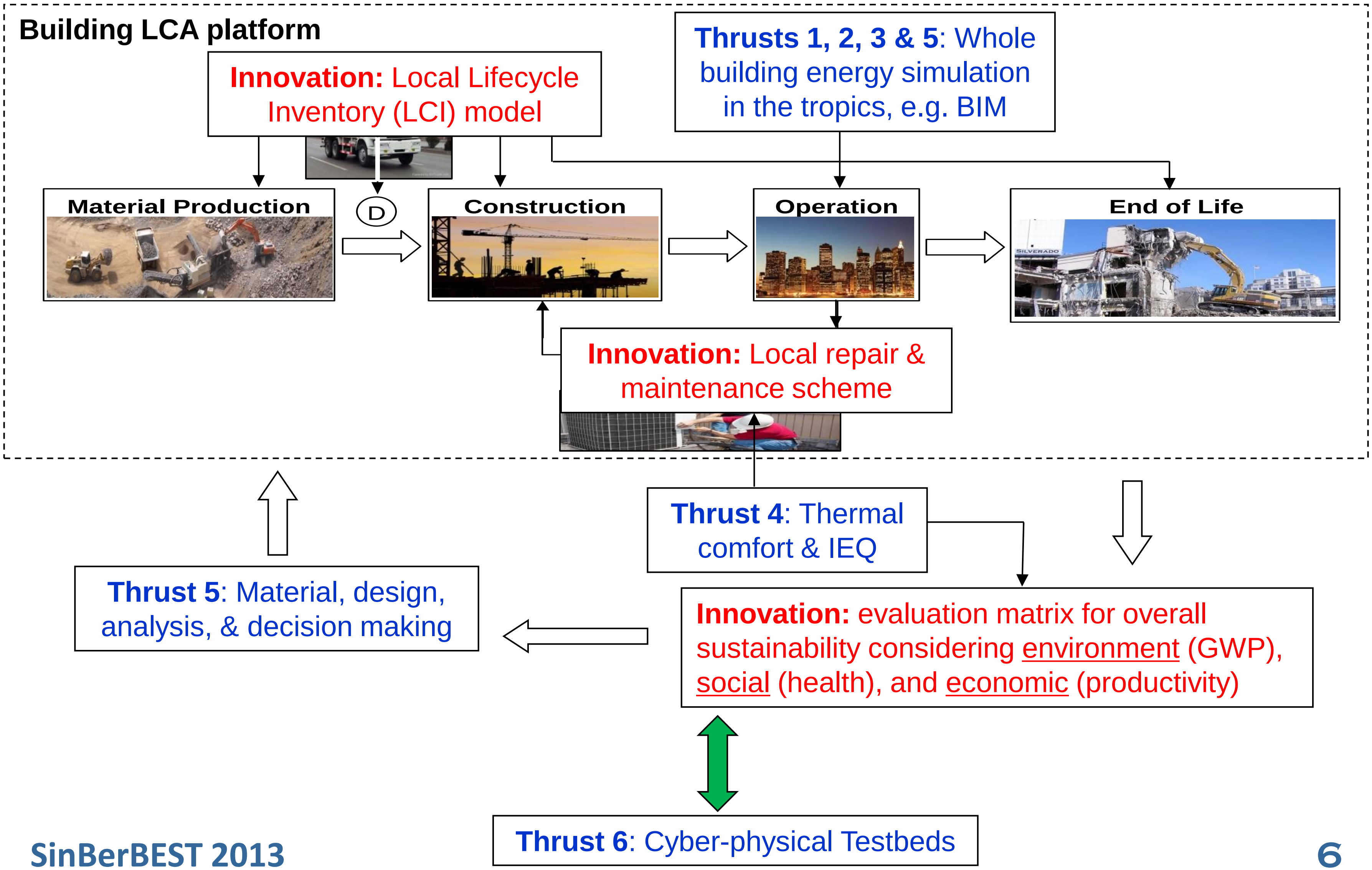
10) Liya Yu (Associate Professor, CEE, **NUS**, Co-PI)

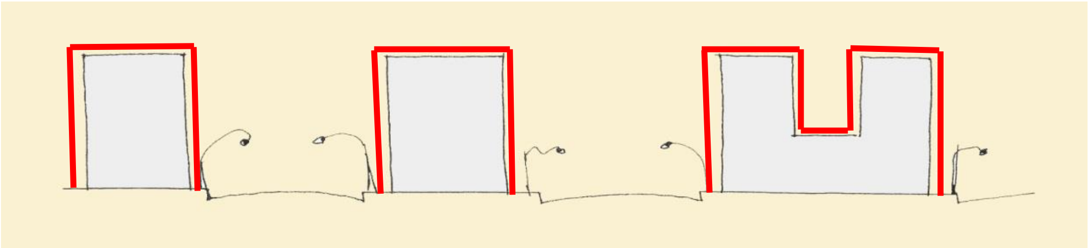
Building Lifecycle Assessment (LCA) in the Tropics



Building Envelope Study

Goal: A product which works efficiently during the "***solar time***" → It is necessary to understand the outdoor conditions of a building and the solar considerations.

We are focused on the **envelope** of the building:



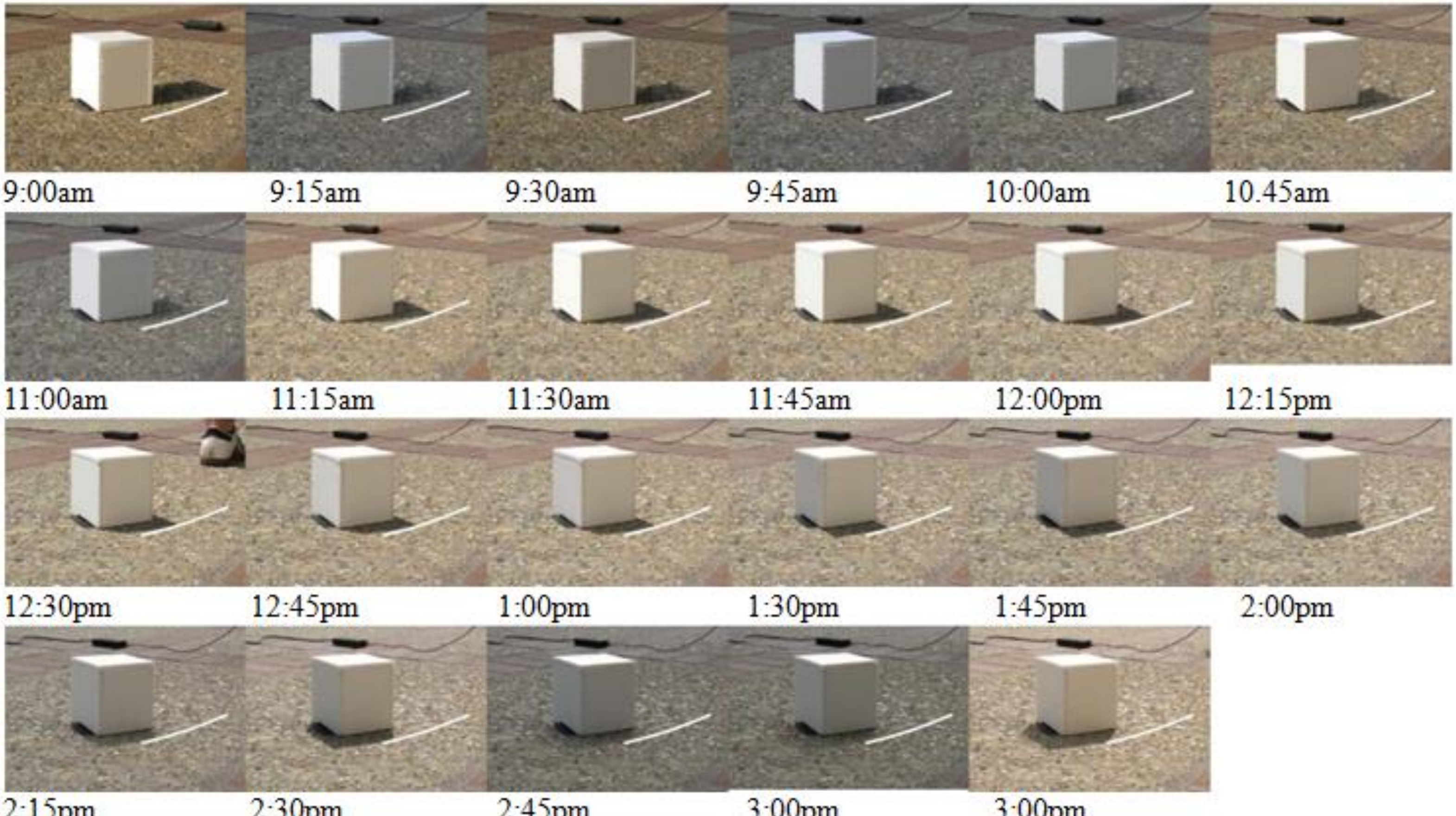
The following factors must be considered in the building design:

1. Building Location
To maximize the light transmission performance of the building envelope, it is necessary to consider the location of the building **to avoid shadows, trees, and adjacent buildings**

2. Building Materials
Select the **appropriate materials** for the building envelope → 1) Retain all energy the building saved during the day & 2) Avoid having excess energy accumulation in the building

3. Building Shape and Orientation
To optimize the sunlight coming into contact with the building envelope, the large openings of the façade must be oriented to the Equator to seize the passive solar energy

Preliminary Study of Shadows



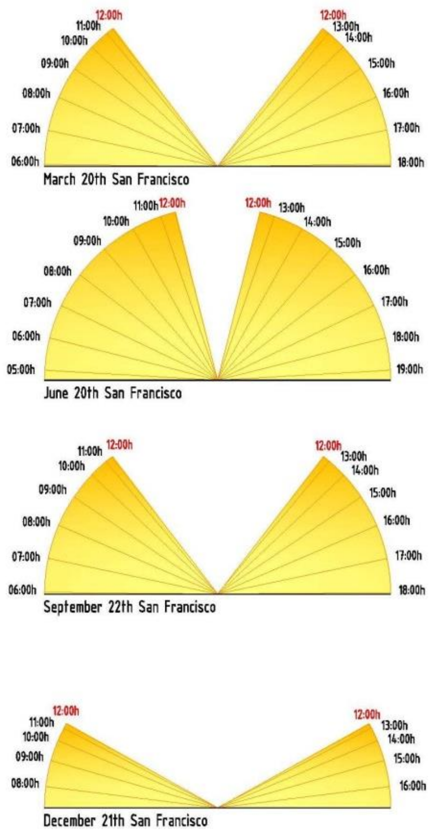
- **Goal:** Investigate the shadow tracking effect on a cube during a whole day sunlight exposure
- The shadow tracking test offers an idea about the **façade and roof efficient design conditions**
- It is important to test the shadow tracking of a building considering different elements located around it to **accurately analyze the light control of the building**

Study of Sun Inclination

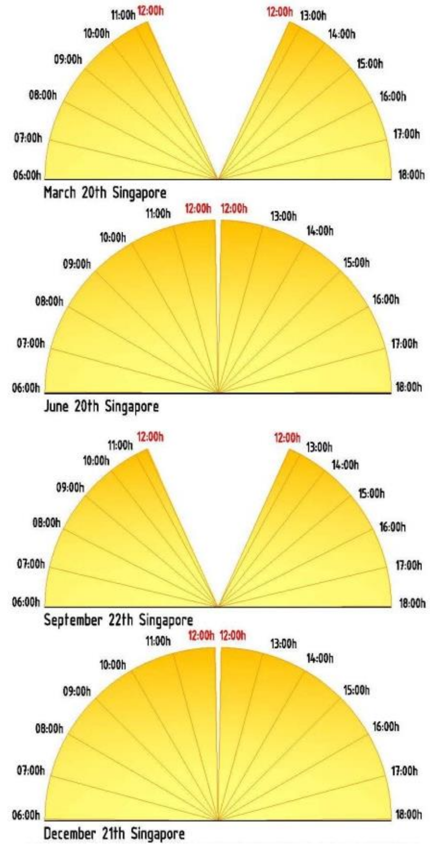
Sunlight incidence varies:

Solar angles during equinoxes and solstices

San Francisco



Singapore



March 20th

June 20th

Sept. 22nd

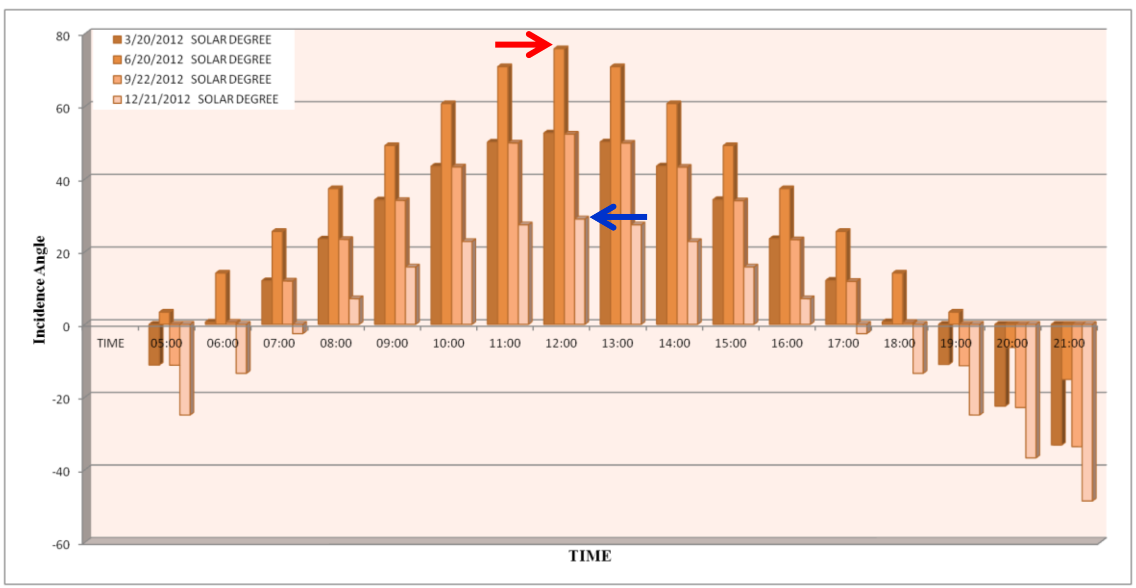
Dec. 21st

Parameters vary depending on which Hemisphere the building is located.
Important to design buildings considering sunlight incidence → Design external elements on *building envelope* (*e.g.* eaves) to stop or divert sunlight direct incidence during hottest period of the year → **saving energy!**

Study of Sun Inclination

San Francisco [noon]

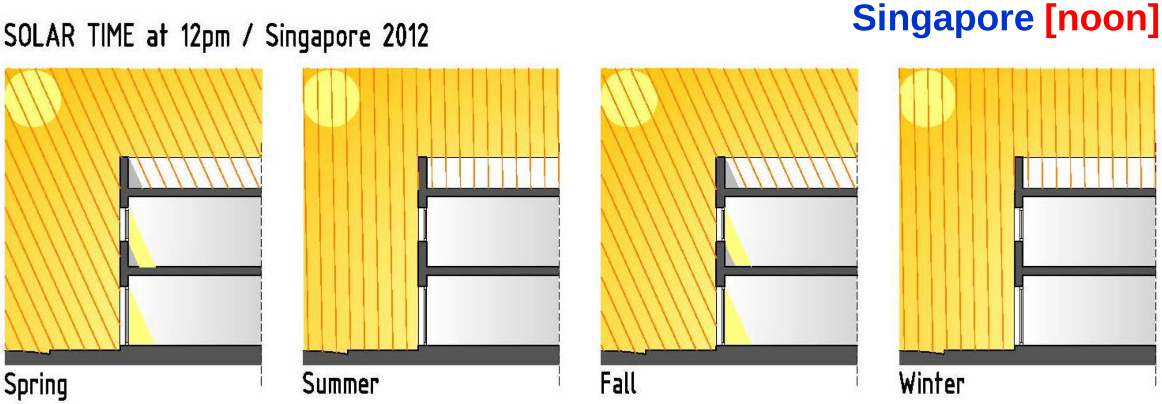
At the equinoxes and solstices:
Summer: sunlight incidence is almost ⊥
→ less light *inside the building*
Winter: sunlight incidence angle lower
→ letting light enter into the building



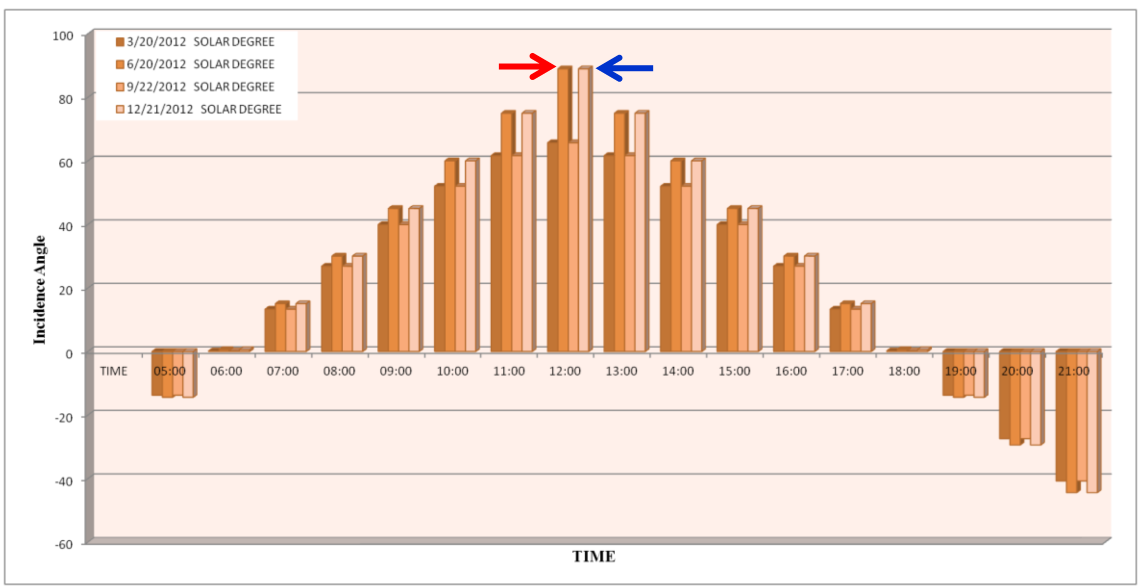
Solar time–angles for the equinoxes and solstices: Difference between summer and winter solar time angle is considerable

Study of Sun Inclination

Singapore [noon]



At the equinoxes and solstices:
Summer: sunlight incidence is almost ⊥ → less light *inside the building*
Winter: sunlight incidence is almost ⊥ → less light *inside the building*



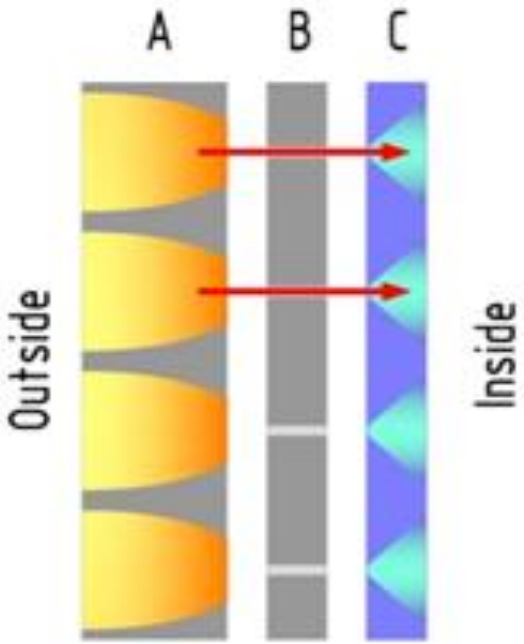
Solar time–angles for the equinoxes and solstices: There is no difference between summer and winter solar time angle.

Multi-layer Light Concentrating Structural Sub-system

- ✓ It has become ever increasingly important to harness the energy of sun and utilize it effectively.
- ✓ Features like microstructural rods or parabolic concentrators are capable of focusing large amount of sunlight on a small area.
- ✓ By functionalizing the outer surface of high-rise buildings with these features, we can use the photovoltaic energy for various purposes which includes replacing internal lighting.

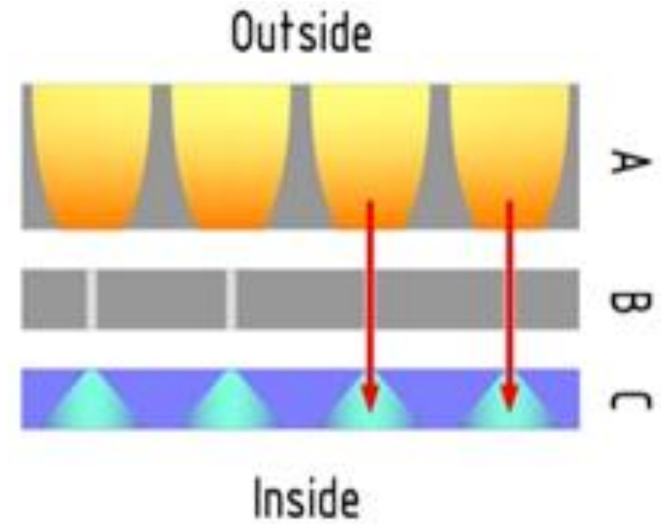
Multi-layer Light Concentrating Structural Sub-system

Building Envelope (Façade / Roof)



Vertical position of the panel

~ Façade



Horizontal position of the panel

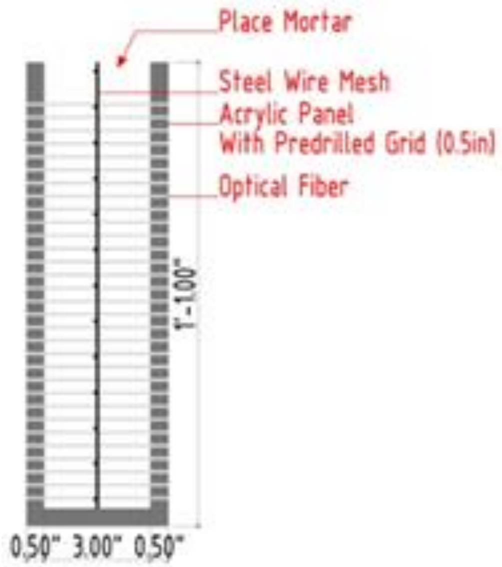
~Roof

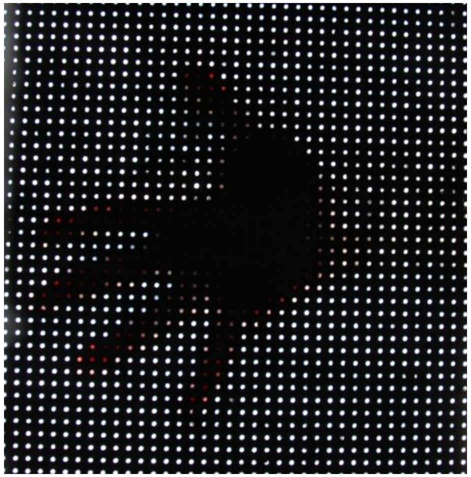
Panel Layers:
A: Light Concentrating Layer
B: Light Conduit Layer (& load-bearing structural element)
C: Light Scattering Layer

Multi-layer Light Concentrating Structural Sub-system

Translucent Concrete (TC) Panel with Embedded Optical Fibers (OFs)

Construction details are presented tomorrow by Mr. Baofeng Huang



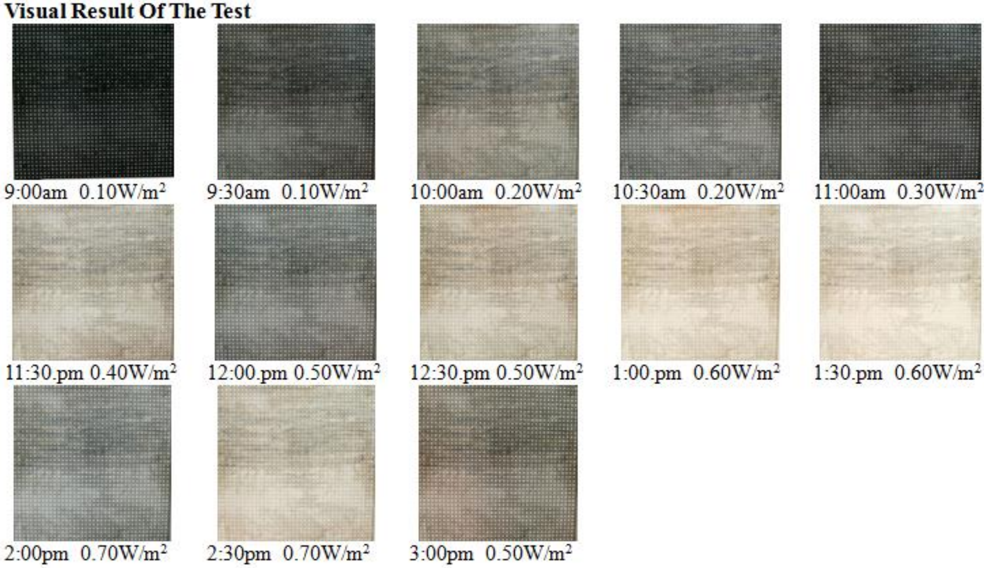


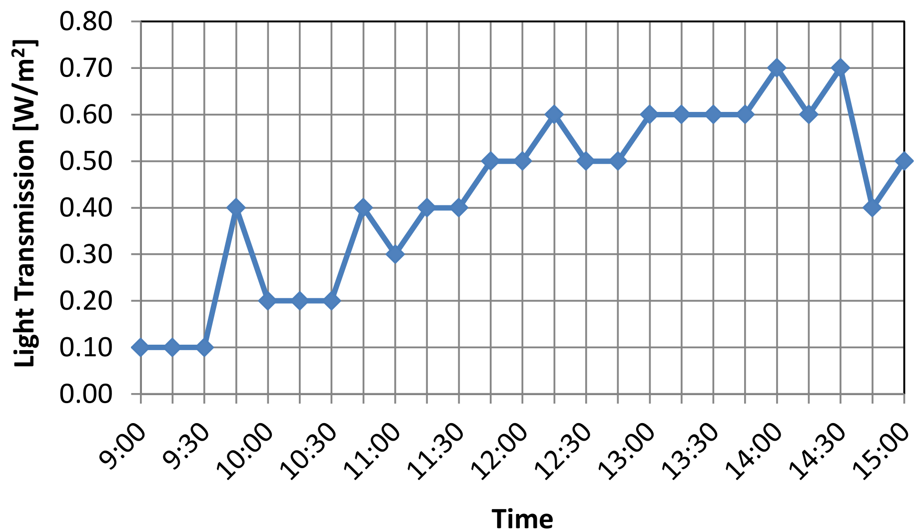
Multi-layer Light Concentrating Structural Sub-system

Translucent Concrete (TC) Panel with Embedded Optical Fibers (OFs)

- Light transmission of a panel & sun tracking in a *partial cloudy* day at Berkeley (**9:00 am to 3:00 pm**)
- Sun fully irradiating → the highest results were obtained from the TC panel
- Orientation of the panel is important for maximizing the light transmission from the TC panel

Visual Result Of The Test

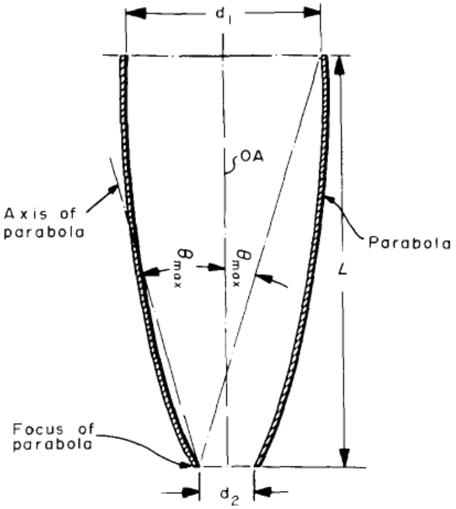




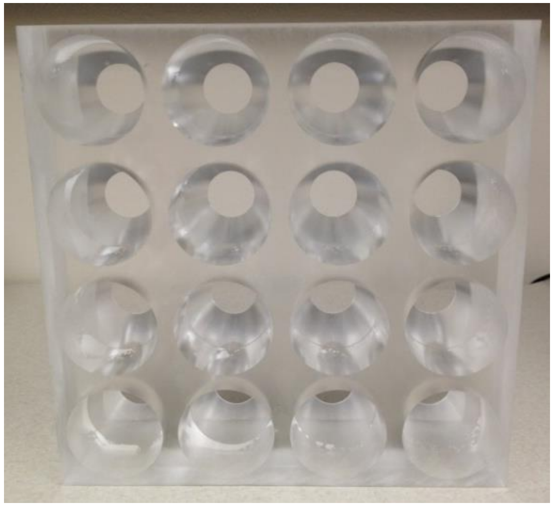
Multi-layer Light Concentrating Structural Sub-system

Light collecting using Winston Cones (WCs)

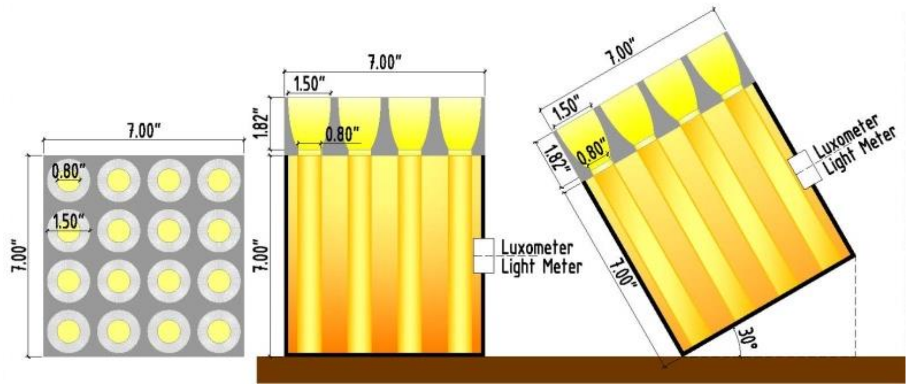
Simulation details are presented tomorrow by Mr. Baofeng Huang

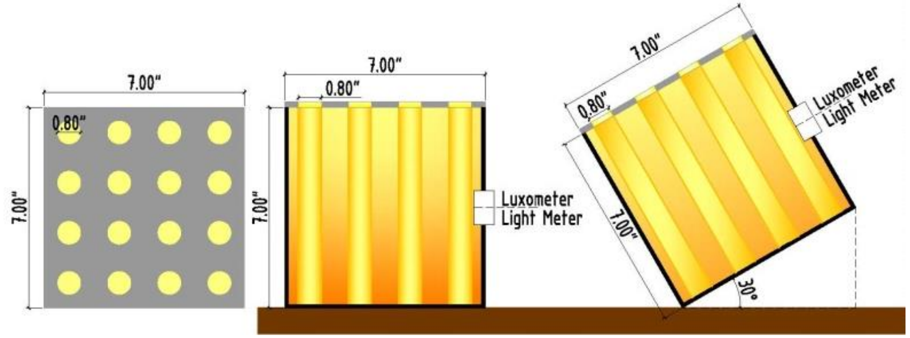


WC profile of ideal collector (axis of the parabola is inclined at an angle θ_{max} to the optical axis, OA)



Layer (A): Acrylic panel with 16 WCs

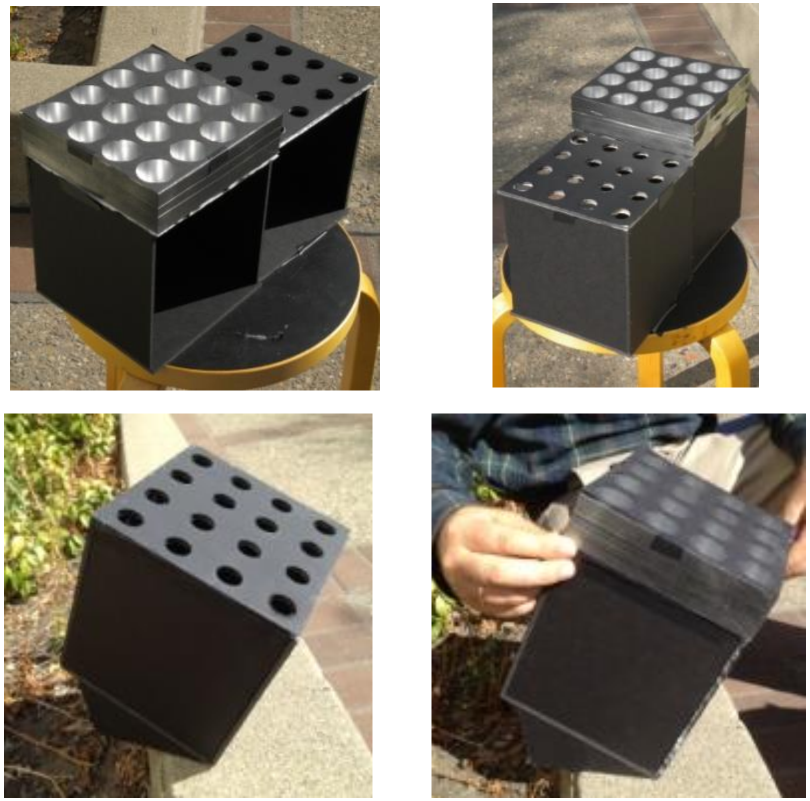


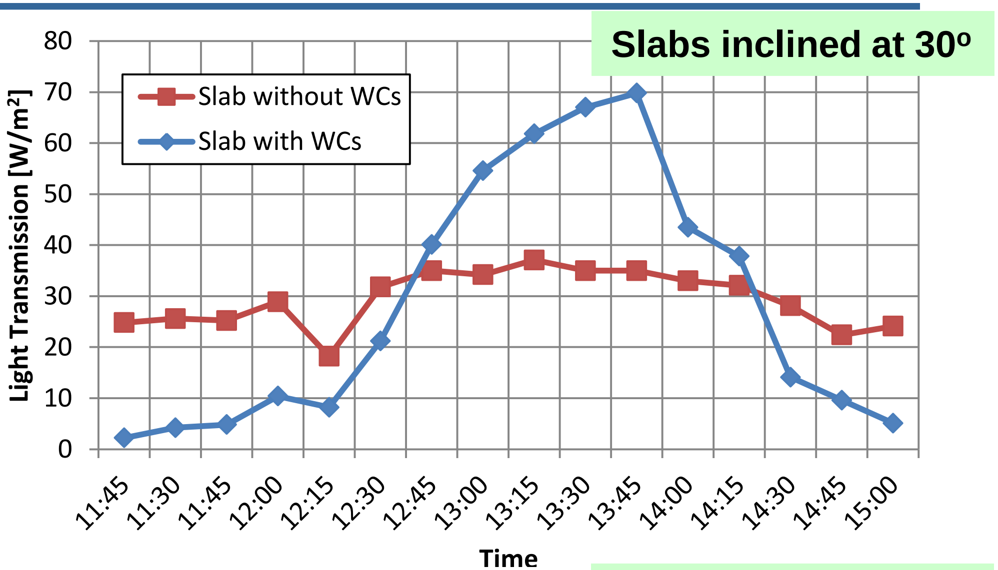


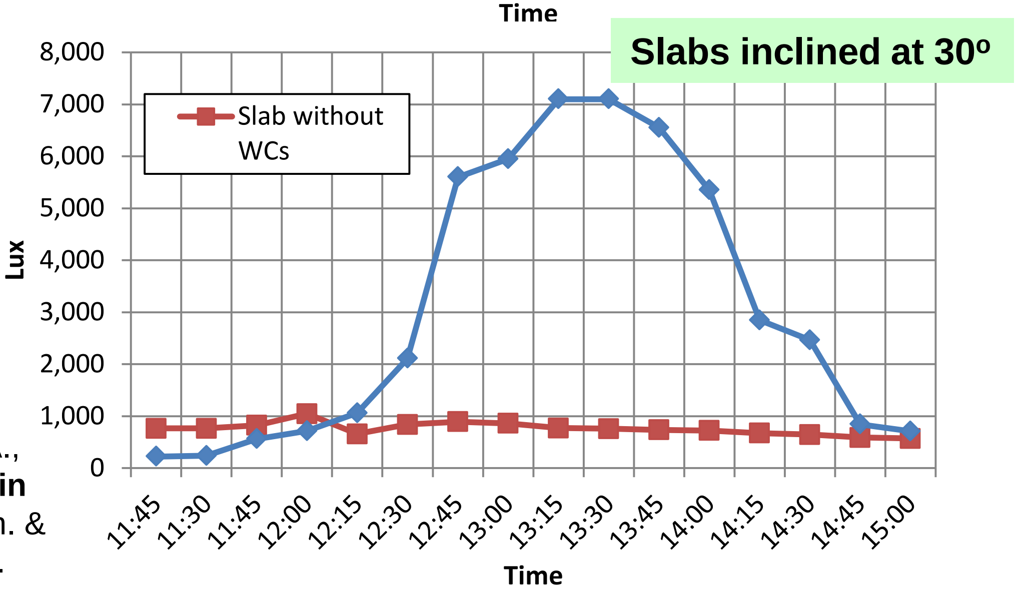
Slab with and without WCs

Multi-layer Light Concentrating Structural Sub-system

Light collecting using Winston Cones (WCs)







Mosalam K.M., Casquero-Modrego N., Armengou J., Ahuja A., Zohdi T., and Huang B., "**Anidolic Day-Light Concentrator in Structural Building Envelope**," 1st Annual Int. Conf. on Arch. & Civil Engineering (ACE 2013), 18-19 March 2013, Singapore.

Geometrical Ray Tracing

We assume that the features are at least an order of magnitude larger than the wavelength of incident radiation.

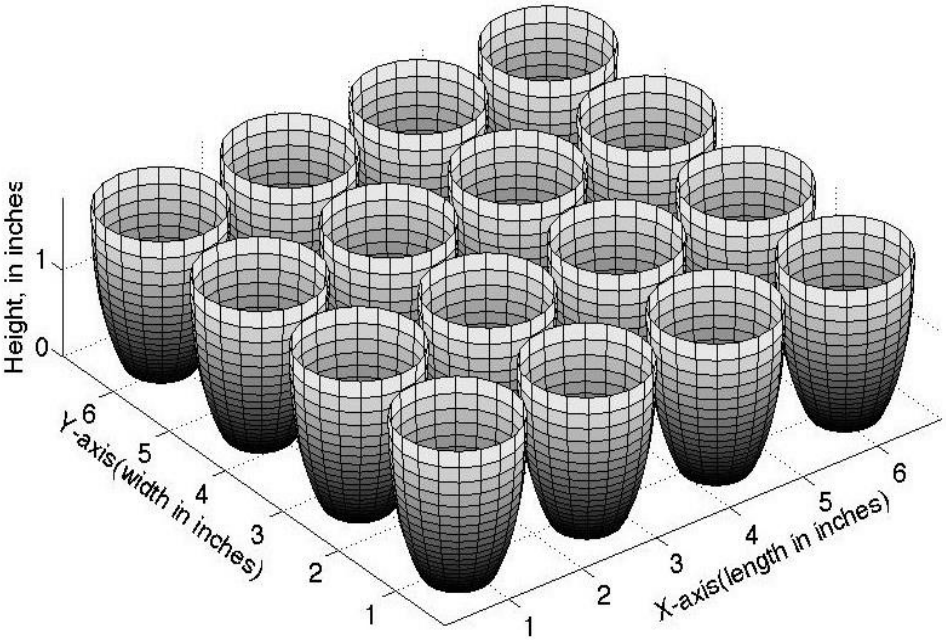
Initially, wave fronts are represented as an array of discrete rays. Geometrically, one proceeds by tracking each ray.

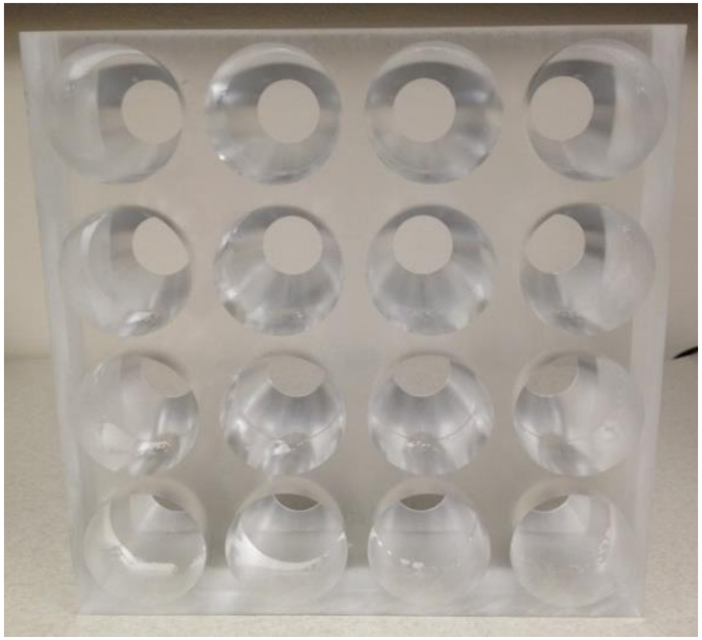
On encountering a surface, the ray changes trajectories and Fresnel conditions are applied at the point of collision.

A convenient time step size to march rays would be: $\Delta t \propto \frac{\xi b}{\|v\|}$

where b is the smaller radius of the aperture, $\|v\|$ is the speed of light rays and ξ is a suitable scaling factor.

Geometrical versus Physical Models





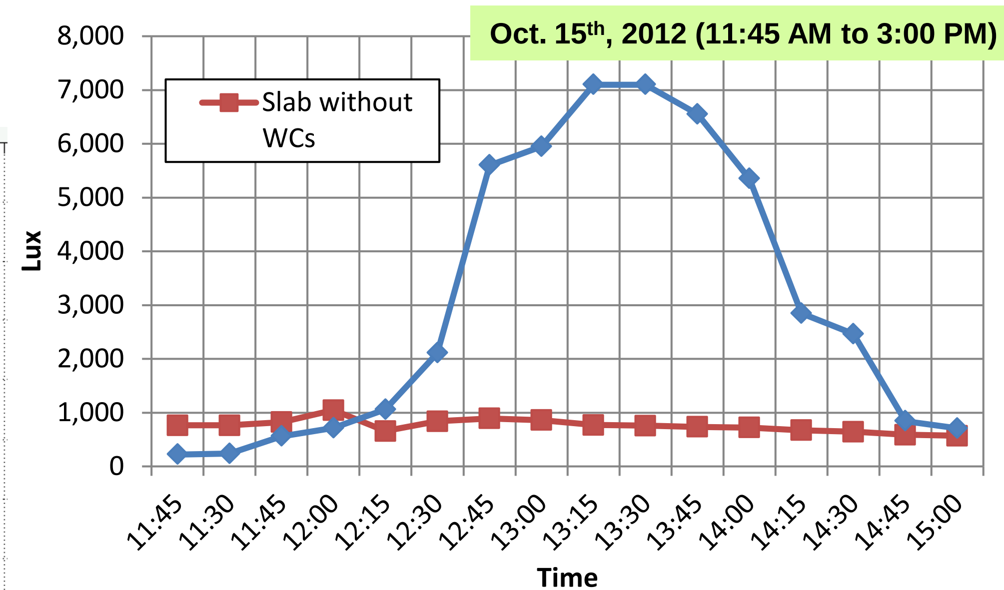
Assumptions:

Acceptance angle = 32.23°, d_{max} = 1.5 in., d_{min} = 0.8 in.

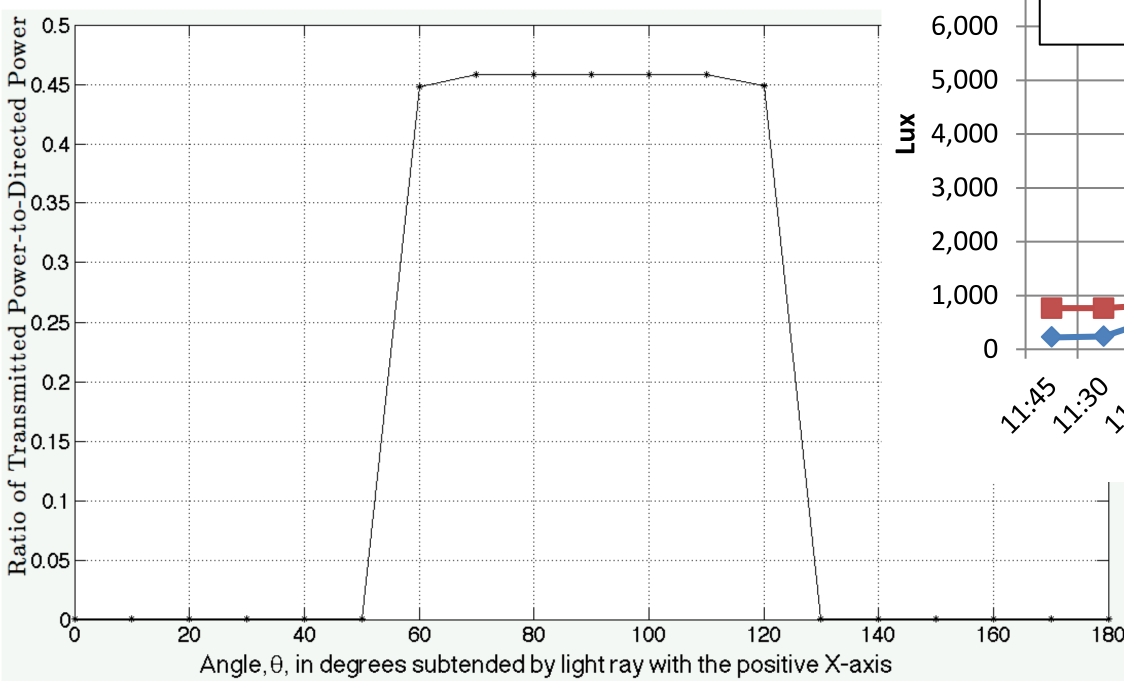
1) Inside of Winston cones is totally reflective (mirror effect).
2) Light rays falling outside the boundary of cones is absorbed completely and not transmitted.
3) Small energy losses are ignored, i.e. roughness of the surface that causes scattering is not taken into account.

Simulation Results

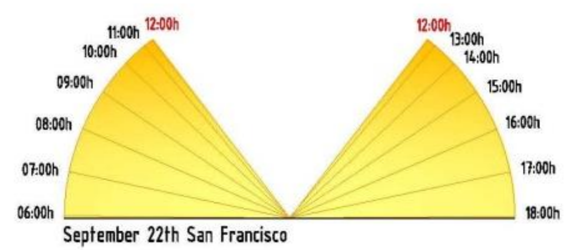
- Experimental results correlate well to computational ones
- The specimen is most effective for sunlight incident angles of **62º to 118º** with the horizontal, i.e. **28º to -28º** with the vertical.



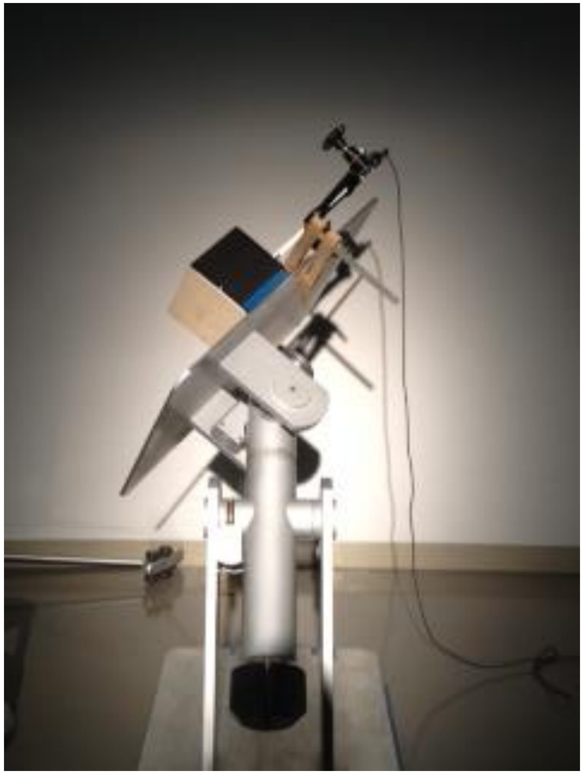
Amount of light recorded with panel inclined at **30º** to vertical

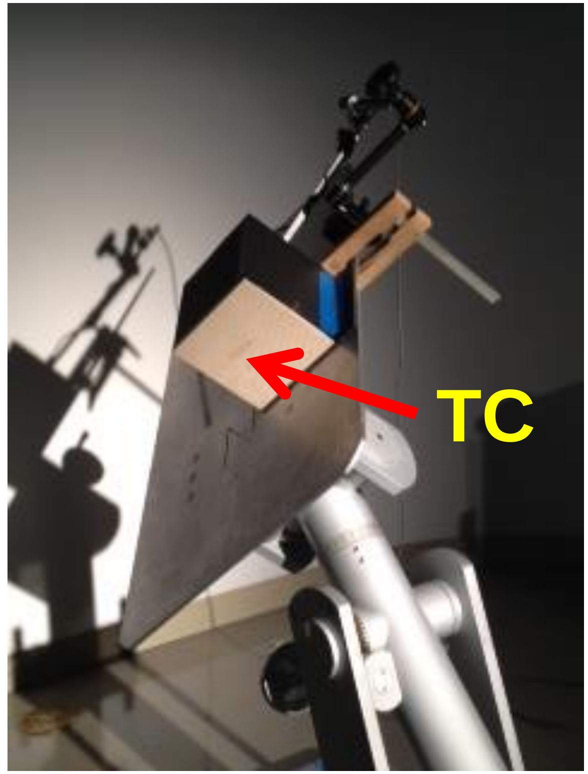


Ratio of light transmitted to directed energy for **2600** rays



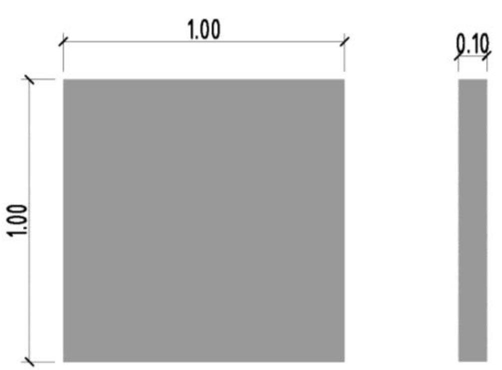
Future Extension: Heliodon Experiments @ PG&E



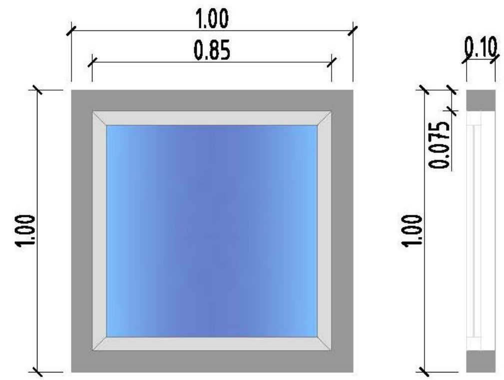


By placing a **model building** (at an assumed latitude) on the heliodon's flat surface & making adjustments to the light/surface angle, we can see how the building would look in the 3D solar beam at various dates and times of day.

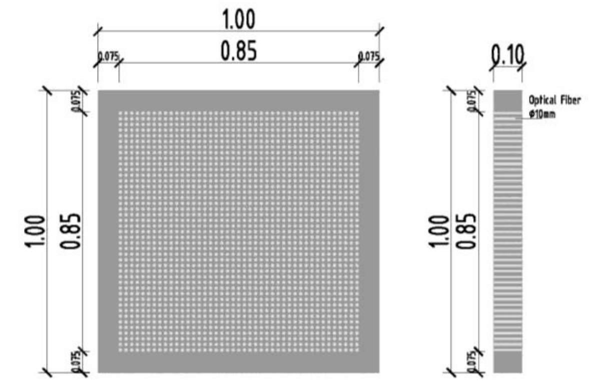
Future Extension: Multi-layer Building Envelope Proposal



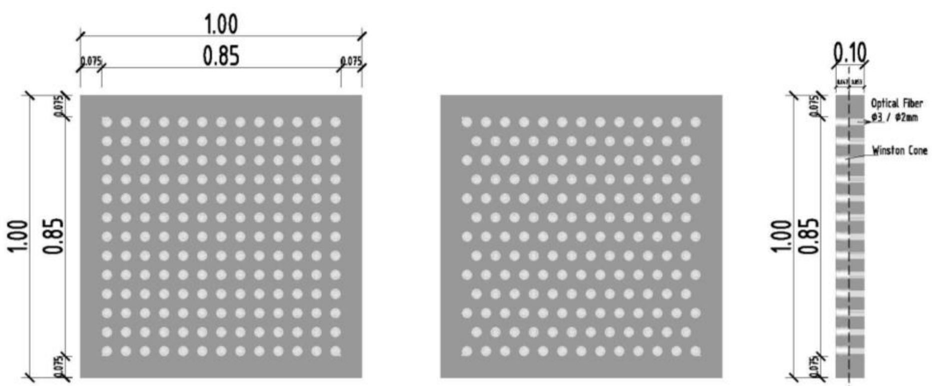
Module: solid panel



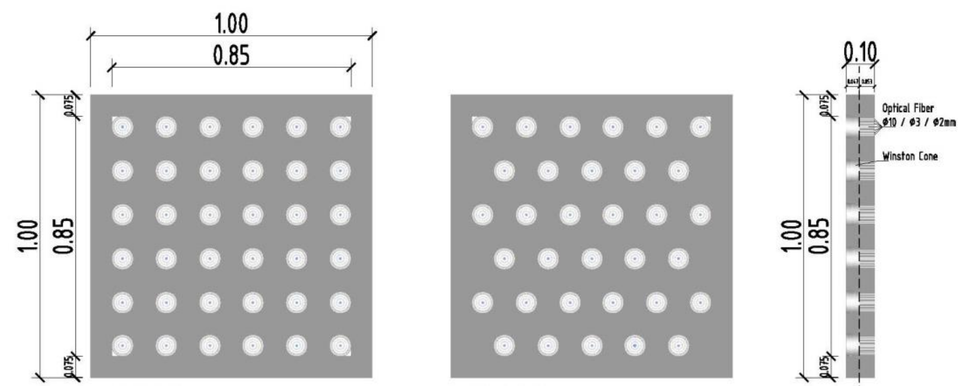
Module: window panel



Module: TC panel



Module: TC+WC panel (Fine)

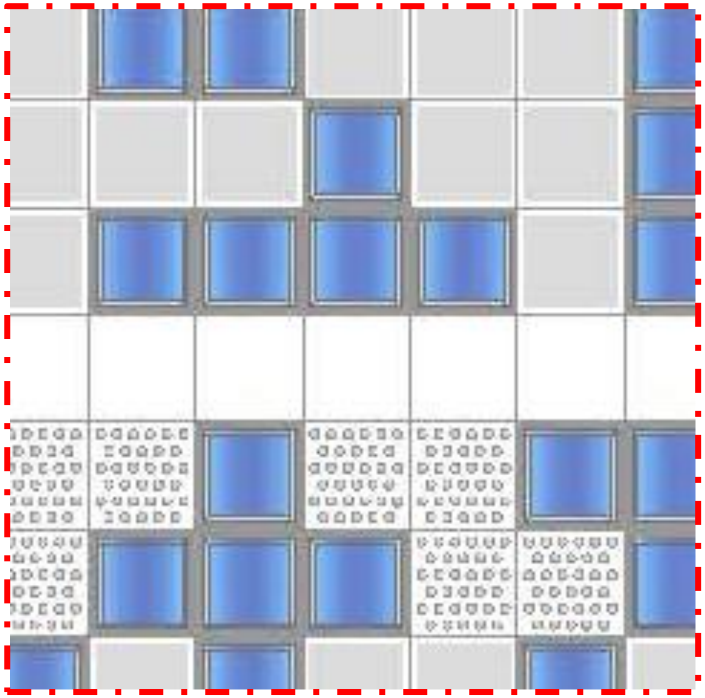


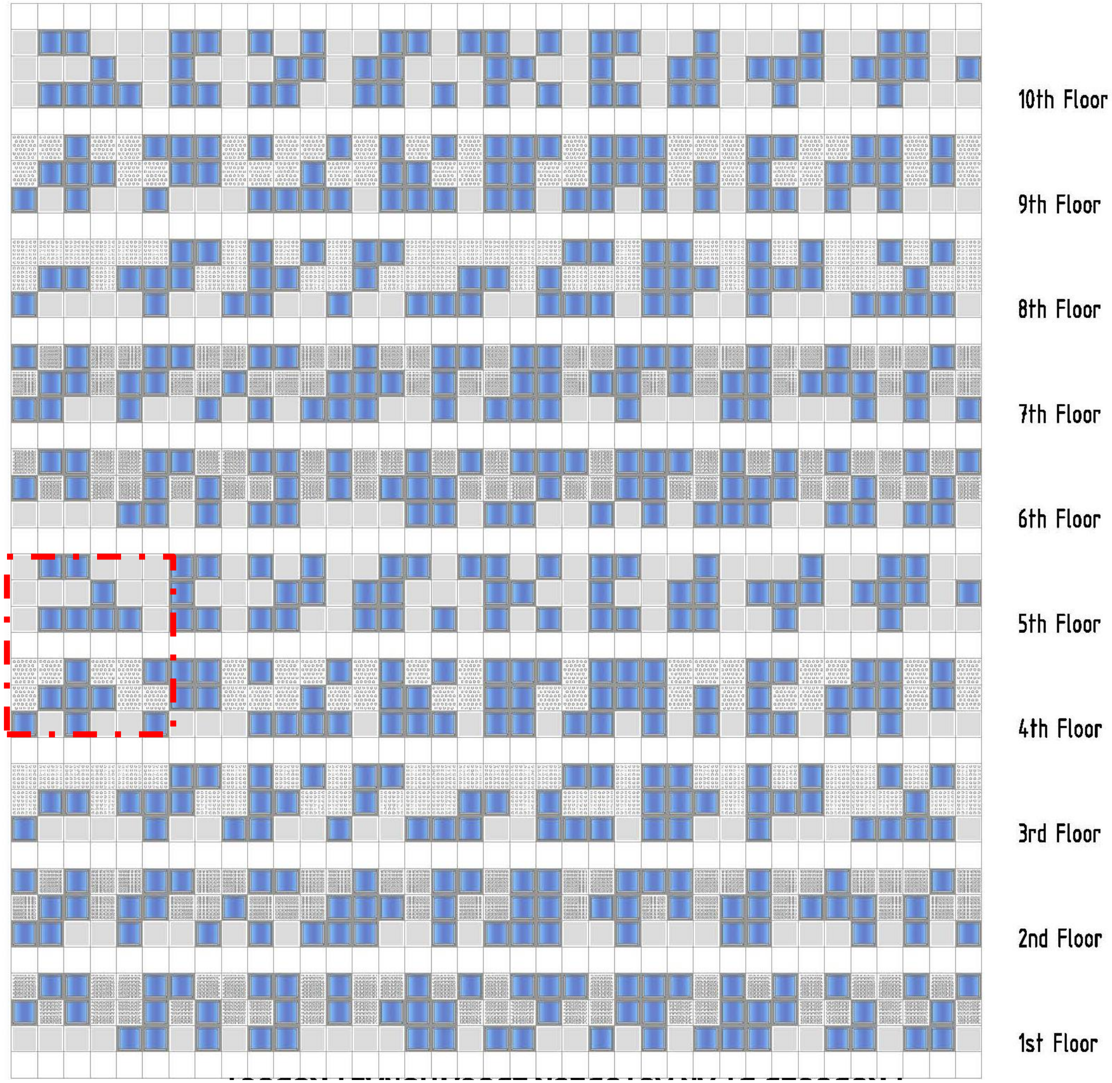
Module: TC+WC panel (Coarse)

_ Modular façade
_ Reinforced concrete frames 1 x 1 x 0.10 m (7.5 cm member height)
_ Each module is structural

Future Extension: Multi-layer Building Envelope Proposal (A Futuristic Look!)

- Replace RC walls for TC panel with embedded OFs + WCs
- Modular façade following Agbar Tower design (**next slide**)
- Connection between precast elements
- Design & testing of standardized modules
- Structural model of the whole façade





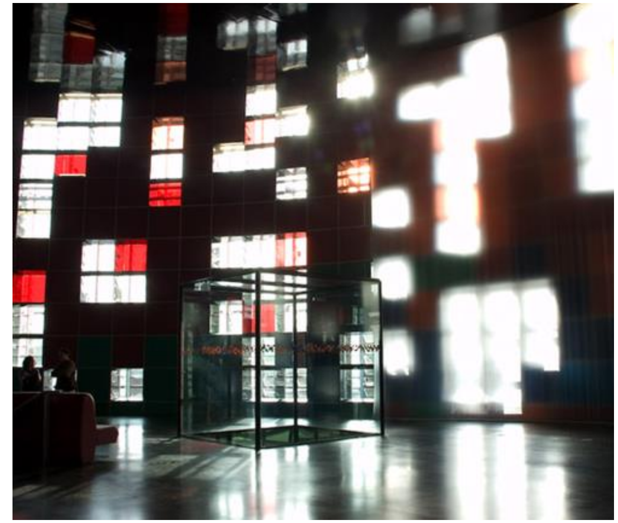
Proposed façade

Future Extension: Multi-layer Building Envelope Proposal

Agbar Tower (2005) – Barcelona (Spain) / Architect: Jean Nouvel

General view

Construction process



Inward view

Façade quartering

- Office building
- **Structurre:** Load-bearing reinforced concrete walls
- 31 Floors
- Random openings (**Puzzle or Tetris**)

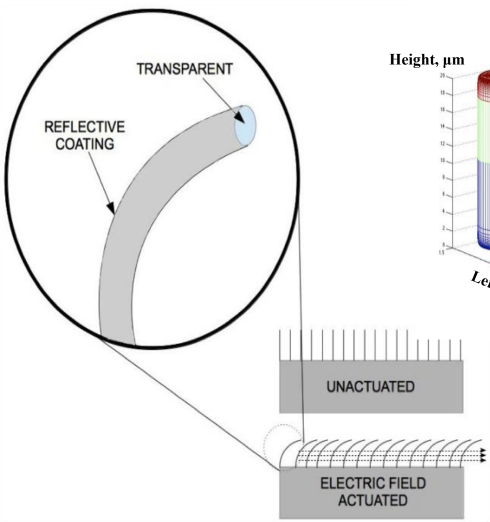
Future Extension: Multi-scale Light Absorbing Tiled–coating System

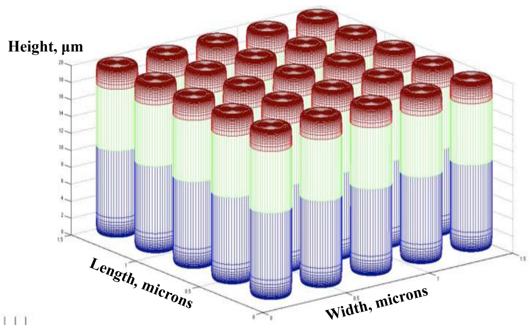
The micro-array rods are modeled as **superquadrics** given as:

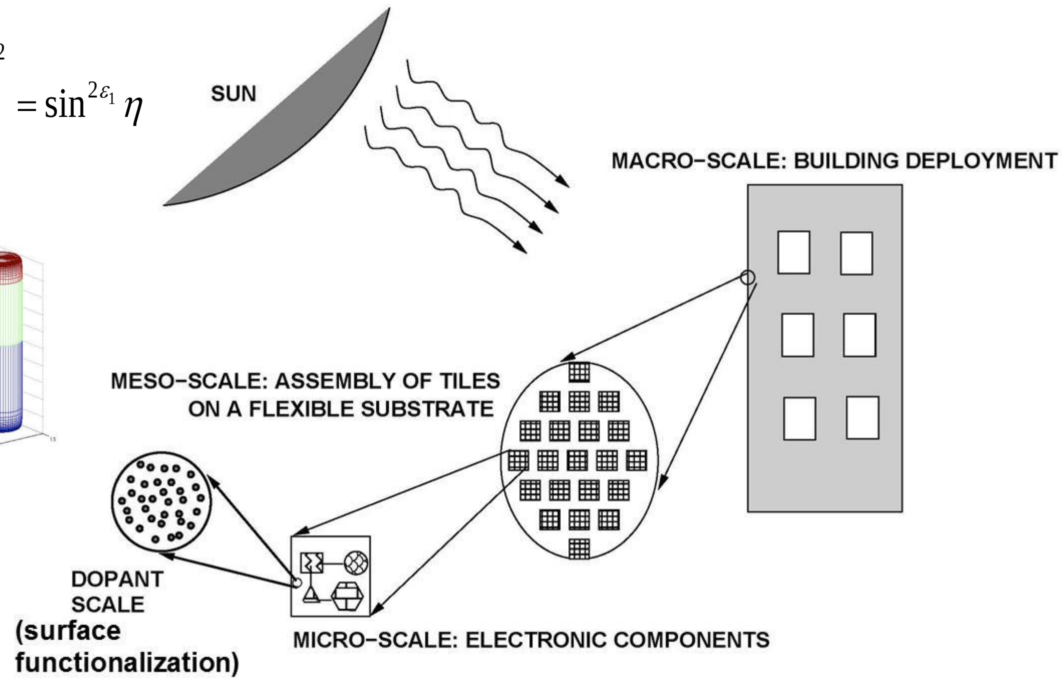
$$F(x,y,z) = \left(\left(\frac{x}{a_1} \right)^{\frac{2}{\varepsilon_2}} + \left(\frac{y}{a_2} \right)^{\frac{2}{\varepsilon_2}} \right)^{\frac{\varepsilon_2}{\varepsilon_1}} + \left(\frac{z}{a_3} \right)^{\frac{2}{\varepsilon_1}} = 1$$

where a_1, a_2, a_3, ε_1, ε_2 are variables that control the cylindrical geometry; η and ω are azimuth and polar angles, respectively.

$$\left(\frac{x}{a_1} \right)^2 = \cos^{2\varepsilon_1}\eta \cdot \cos^{2\varepsilon_2}\omega; \left(\frac{y}{a_2} \right)^2 = \cos^{2\varepsilon_1}\eta \cdot \sin^{2\varepsilon_2}\omega; \left(\frac{z}{a_3} \right)^2 = \sin^{2\varepsilon_1}\eta$$







1) Develop a code to calculate light transmission for rods that ***sway*** with electric field application.

2) Optimizing shape and topology of microstructures to ***quickly act*** under electric field actuation.

3) Selecting the right type of materials for ***light reflective and absorptive*** properties.

Engineered Cementitious Composites Incorporating Recycled Concrete Fines

- Motivation
  - Shortage of natural aggregates in Singapore
  - RCF has no reusable value & applications; to deviate RCF from landfill to extend Pulau Semakau's lifespan

- **Objective:** Reuse of RCF in production of high performance fiber-reinforced cementitious composite

Source: Straits Times, 25 Jan. 2007

Jakarta bans sand exports, cutting off S'pore's main supply

By Azhar Ghani
Indonesia Bureau Chief
In Jakarta

INDONESIA has banned the export of some sand and soil products in what it says are efforts to prevent further damage to its environment and to protect its boundaries.

The move would cut off the main supply of land sand – which is used to make concrete for buildings – to Singa-

ties, especially in the outer islands of Indonesia, and preserve the ecosystem, as well as the boundaries of Indonesia," he said.

Exporters have until Feb 5 to sort out their contracts before the full ban kicks in. They will be allowed to fulfil existing obligations.

In a joint statement, Singapore's National Development Ministry and Building and Construction Authority (BCA) expressed disappoint-

six to eight million tonnes of sand a year, almost all of it from Indonesia, since 1997, when Malaysia banned exports to the Republic.

To counter ... shortfall ... sian ... term, it will release sand from its stockpile to meet any shortfall. Other sources in the region

to deal with the shortfall is to reduce ... need for sand in ... ment is en... use of steel, ... more com... buildings, ... types, and ... is working with the industry on this.

However, though construction will not be slowed, it will get more expensive, as the price of sand is expected to go up from the current $20 per tonne.

cerns over the possibility that Indonesia's neighbours might try to expand their maritime boundaries if some of its unmapped small outer islands were to disappear under extensive sand quarrying.

But Singapore has always maintained that its reclamation works are carried out entirely within its territorial waters and will not, in any way, alter its maritime boundaries with Indonesia.

According to official

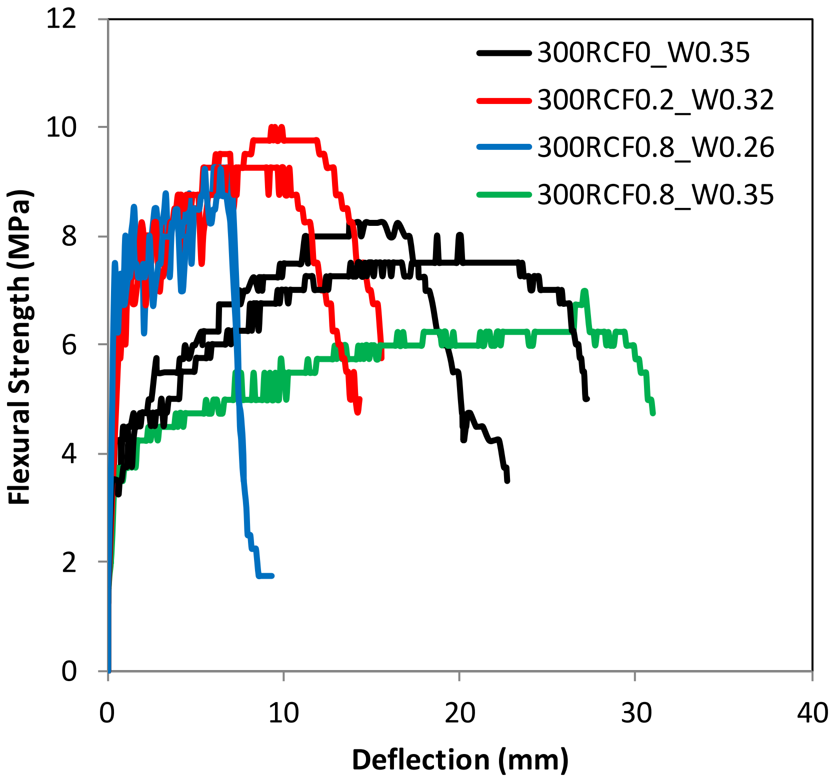
US$6 million. China was a distant second with US$2.4 million.

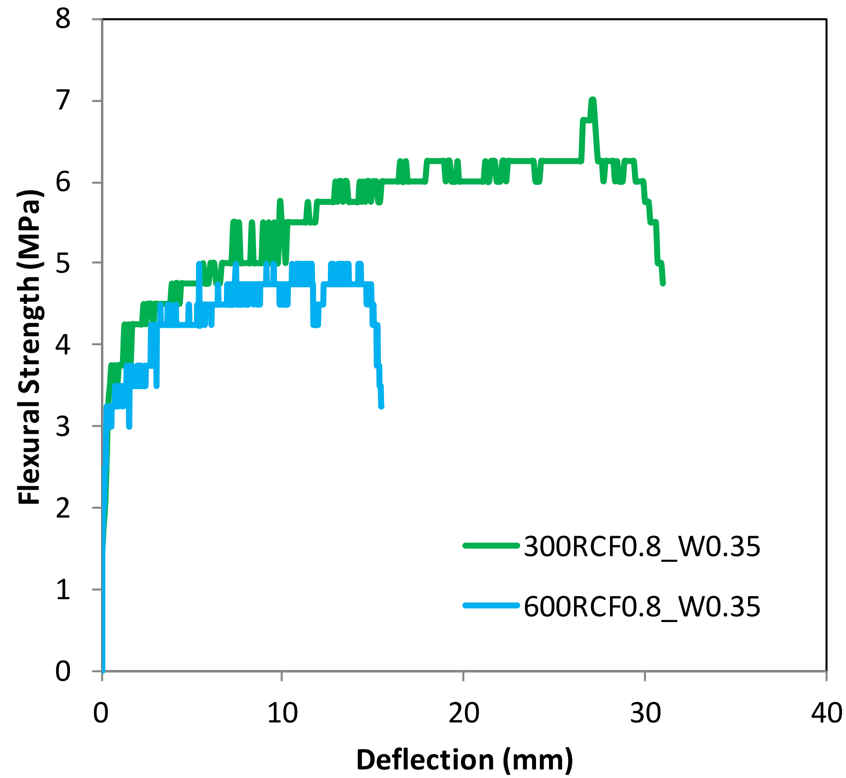
But in the first five months of last year, the roles were reversed – China imported some US$8m worth, while Singapore's imports totalled $2.93 million.

Mr Chang Meng Teng, chairman of the Construction Industry Joint Committee, said developers will have to accept the fact that the industry must move away from relying on sand.

Price of aggregate increases 3 times!

Preliminary Results and Conclusions

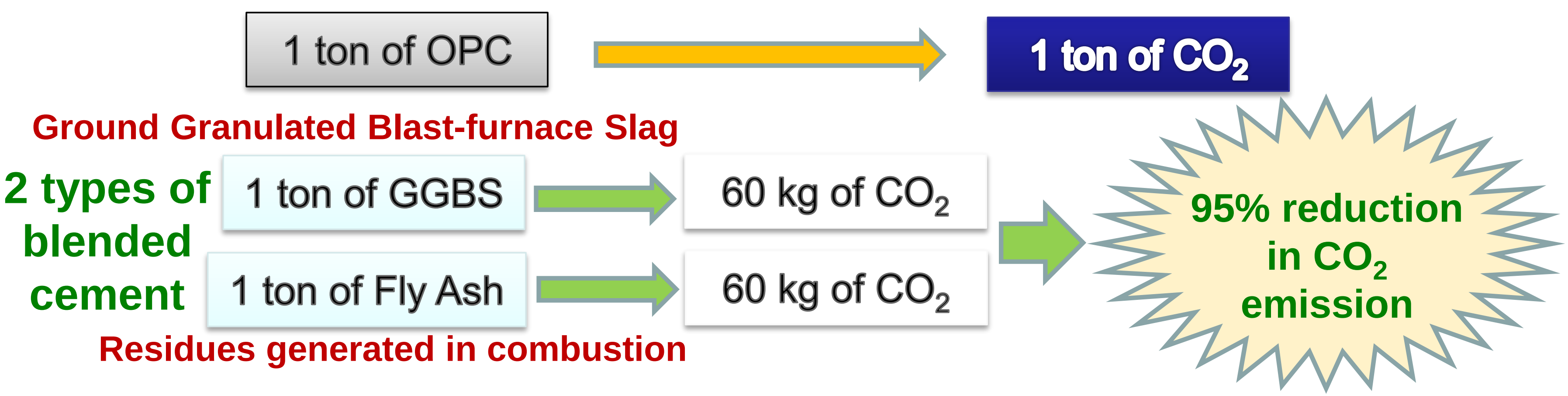




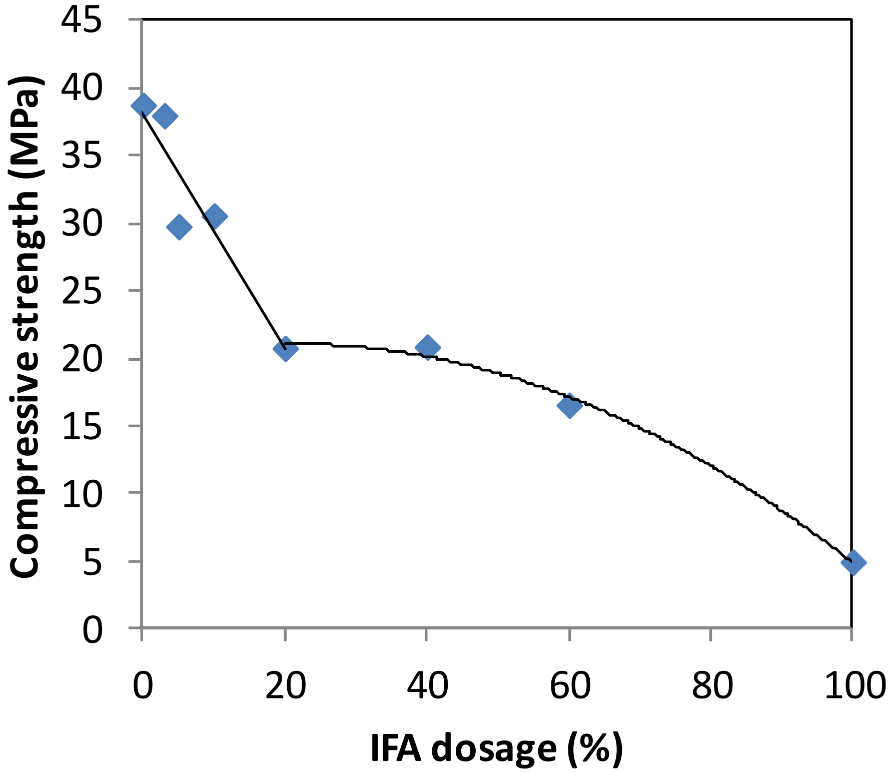
- RCF can be used in the production of ECC with more than 3% tensile ductility
- Higher RCF content and smaller particle size are in favor of ECC tensile ductility
- Increase of RCF content reduces ECC compressive strength
- Smart greening (guided by micro-mechanics) is key to incorporate recycled wastes

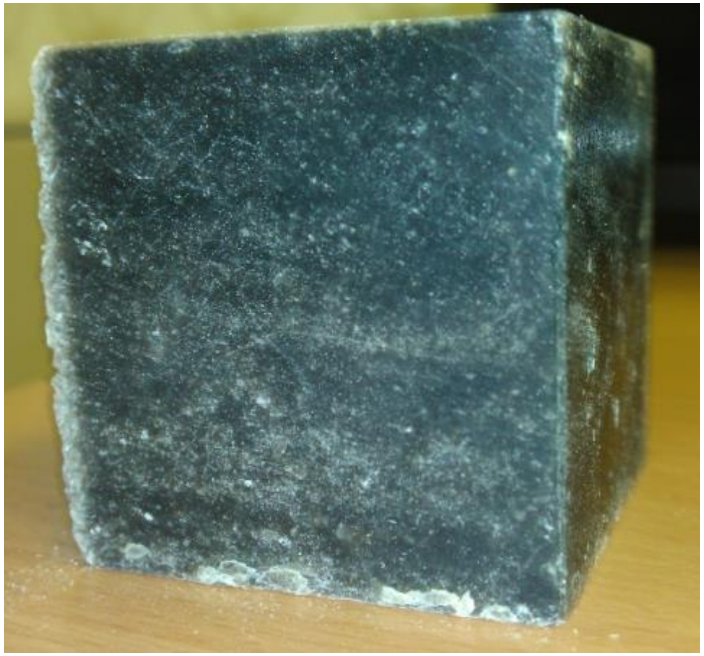
Ground Granulated Blast-furnace Slag Geopolymer with Municipal Solid Waste Incineration Fly Ash

- Motivation:
  - To reduce embodied energy of building materials
  - MSWI fly ash has no reusable value & applications; to deviate MSWI fly ash from landfill to extend Pulau Semakau's lifespan
- Objective: GGBS + MSWI fly ash w/ zero OPC



Preliminary Results and Conclusions





- From leaching analysis, GGBS geopolymer binder can effectively immobilize heavy metals in IFA for non-hazardous landfill
- GGBS-IFA geopolymer with compressive strength above 15 MPa (replacement ratio 60%) has the potential use as a non-structural construction material
- Further study on chemical bond of heavy metals in GGBS-IFA geopolymer is needed

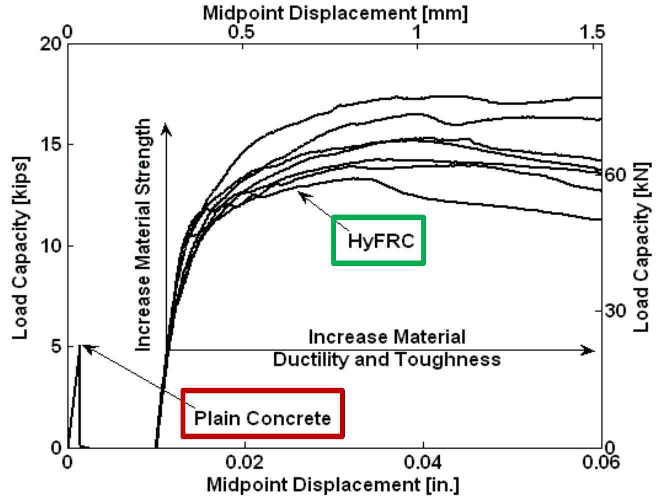
High Performance Green Concrete

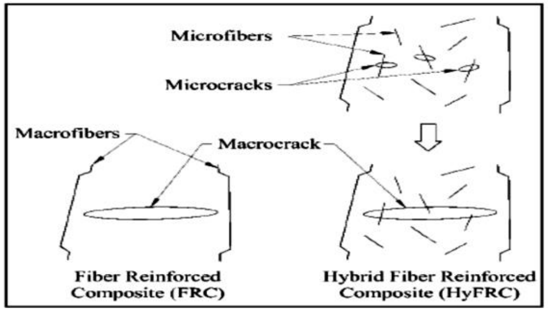
High Performance

- Ductile behavior
- Crack resistance
- Durable (damage resistant when exposed to environmental loading conditions)
- Damage resistant (when exposed to mechanical loading conditions)
- Self-healing & sensing capabilities

- Deflection hardening behavior in bending
- Strain hardening behavior in pure tension
- Crack control on multiple scales

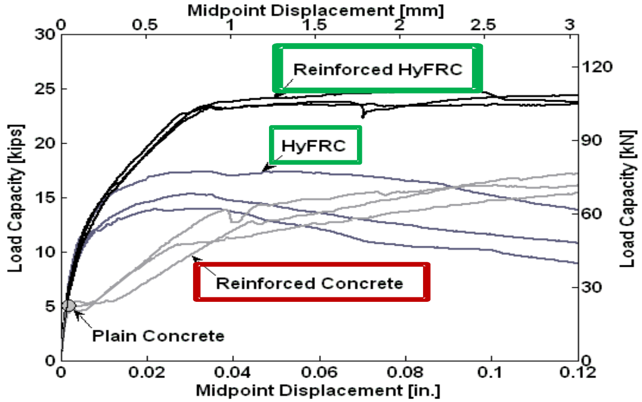
High Performance Hybrid Fiber Reinforced Composites (HP-HyFRC)

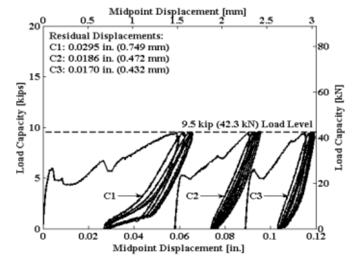


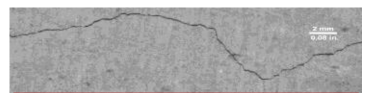


High Performance Hybrid Fiber Reinforced Concrete Composites (HP-HyFRC)

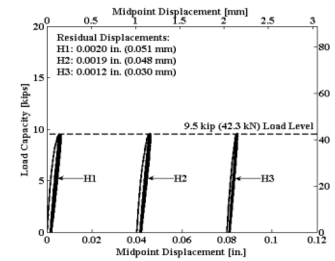
Crack Resistance (when exposed to service load)

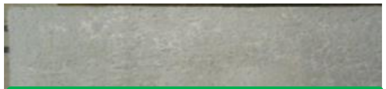






Reinforced concrete

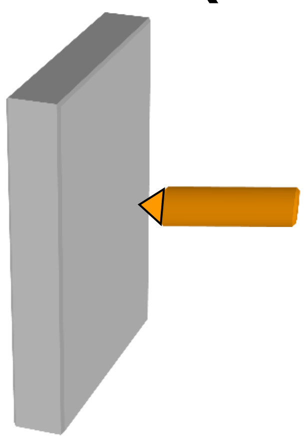


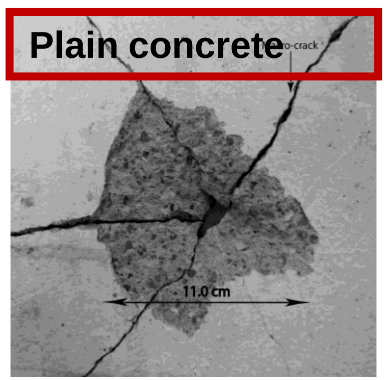


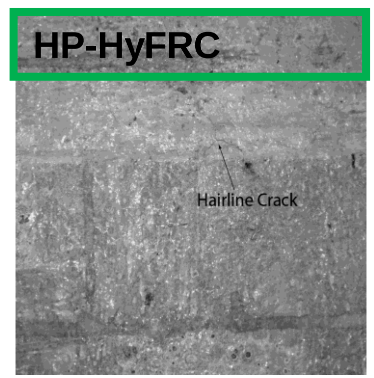
Reinforced HP-HyFRC

Damage Resistance (when exposed to impact loading)

25mm thick panels subjected to steel projectile





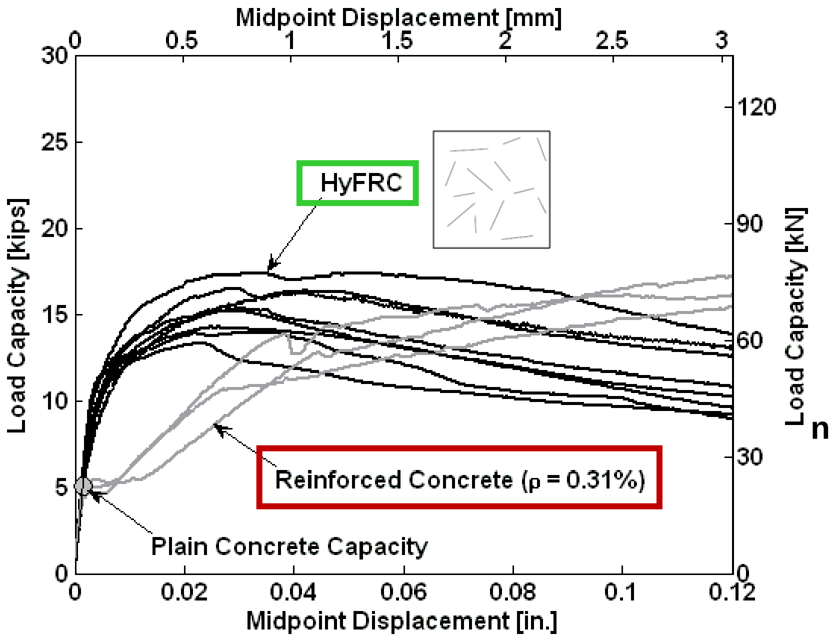


127 m/s   167 m/s

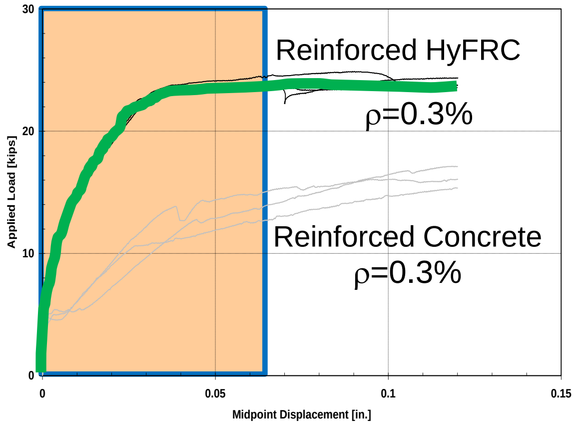
Projectile velocity

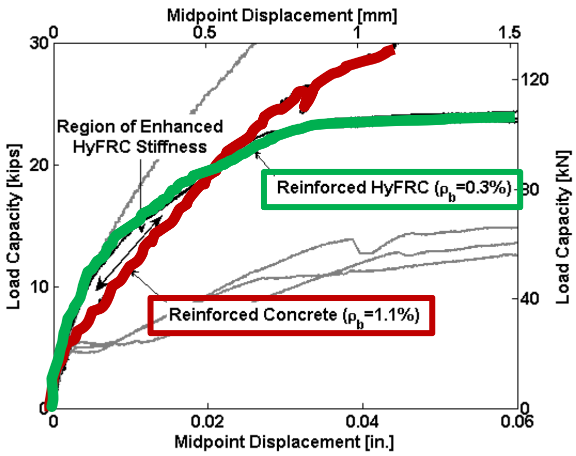
HP-HyFRC: New Design Possibilities

Reduction in section thickness and in conventional steel reinforcements due to enhanced performance



RC walls benefit from HP-HyFRC due to its enhanced cracking strength and stiffness





Reinforcing ratio of conventional RC needs to be increased by **73%** to reach similar flexural stiffness as a reinforced HP-HyFRC at ρ=0.3%.

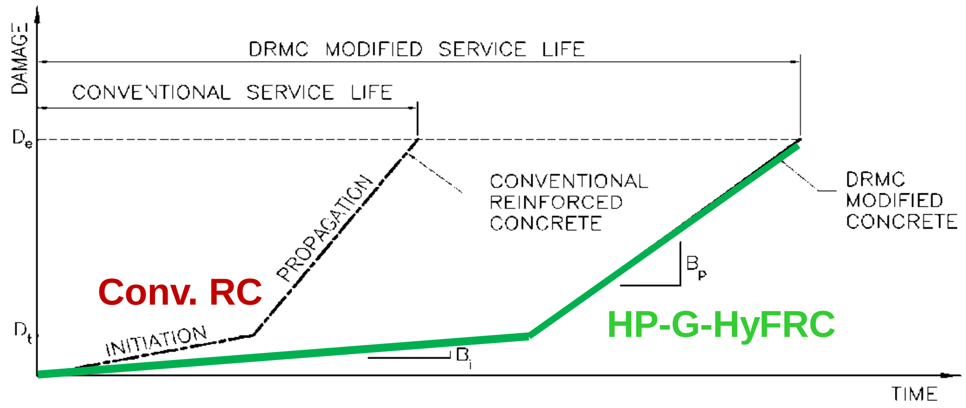
High Performance Green Concrete

Green

- Reduction in energy consumption
- Reduction in green house gas emission
- Preservation of resources
- Long-term durability
- Damage tolerance and extended service life
- Recycle/Re-use

- Replacement of cement by up to 60% of waste materials
- Replacement of Aggregates by recycled concrete

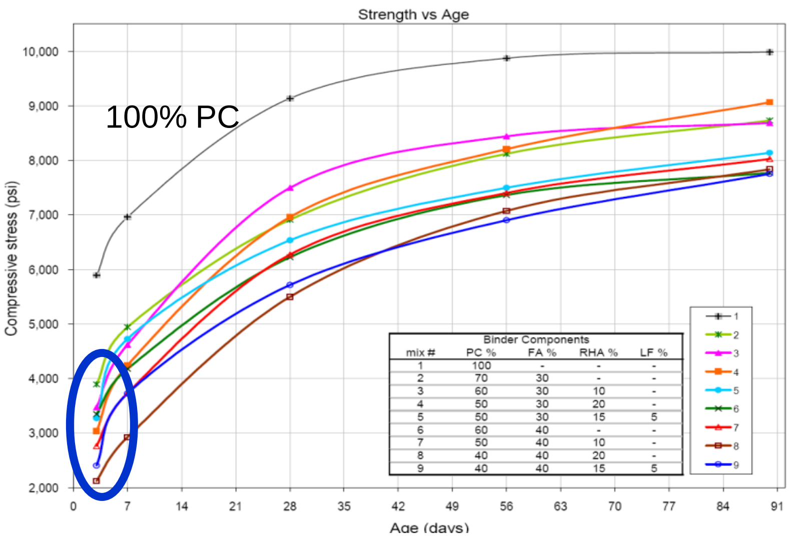
High Performance Green Hybrid Fiber Reinforced Composites (HP-G-HyFRC)



HP-G-HyFRC extends the service life of buildings (extending damage ***initiation phase*** & slowing down damage ***propagation phase***)

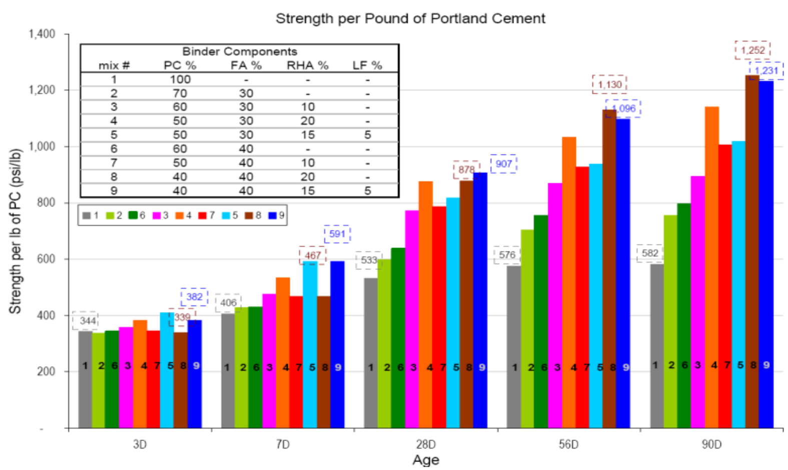
Mechanical Properties of HP-G-HyFRC

Early strength reduction due to waste materials



Up to **62%** reduction in energy consumption & green house gases due to cement replacement by waste materials.

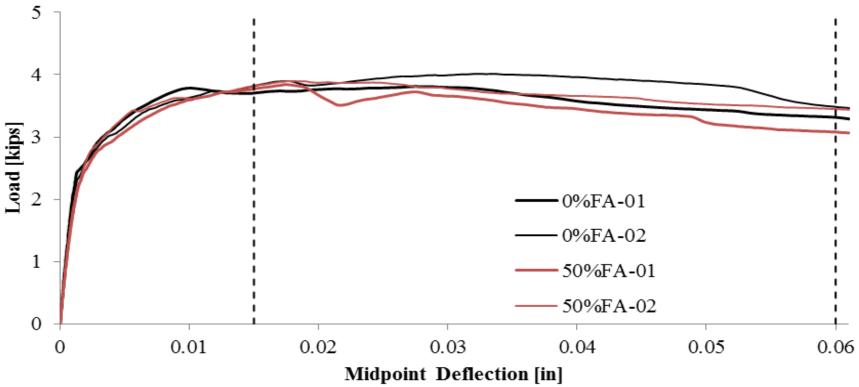
Strength development continues & eventually approaches the **100%** PC strength level.



Waste materials are ***not inert*** materials and do contribute to strength development.

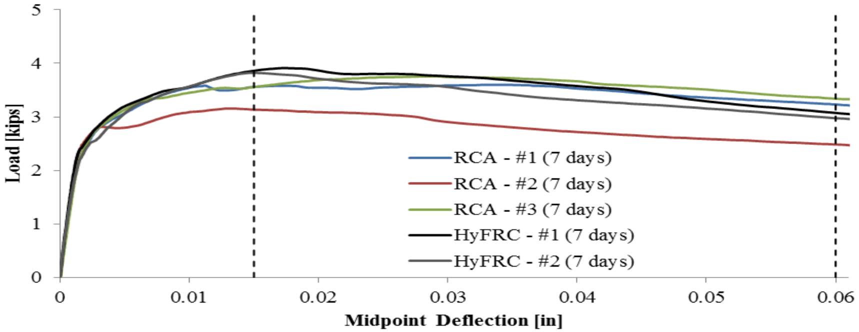
Mechanical Properties of HP-G-HyFRC

Deflection with <u>50% fly ash replacement</u>



HP-G-HyFRC (with **50%** reduction in energy consumption & green house gas emission) exhibits the same flexure performance as HP-HyFRC after **6 months**.

Deflection with 100% coarse aggregate replaced by <u>recycled concrete</u>



Deflection hardening behavior not compromised due to replacement of aggregates by recycled concrete.

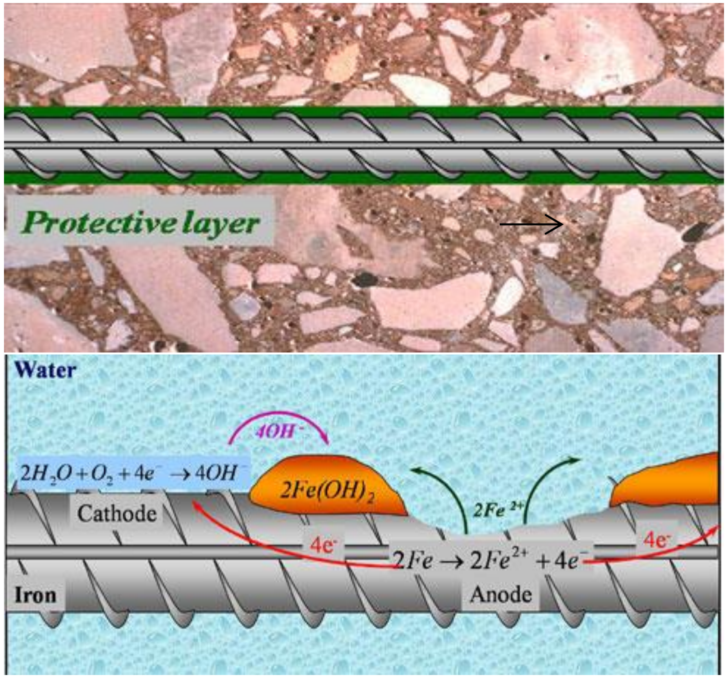
HP-G-HyFRC (recycled concrete as aggregate & 50% cement replaced by fly ash)

Deflection hardening behavior and hence ductility, crack resistance, and damage resistance preserved despite **40 wt%/yd^3** of concrete replaced by waste materials.

Future Extension: Durability of HP-G-HyFRC

Corrosion: How stable is protective layer in green concrete?

- Microstructural analysis
- Accelerated corrosion tests
- Electrochemical measurements to determine corrosion rate:
  - Corrosion potential measurements
  - Polarization resistance measurements
  - Galvanic current flow measurements



Future Extension: High Performance Green Concrete in Building Design

Development, Characterization and Lifecycle Assessment of High Performance Green HyFRC Composites for Sustainable Buildings

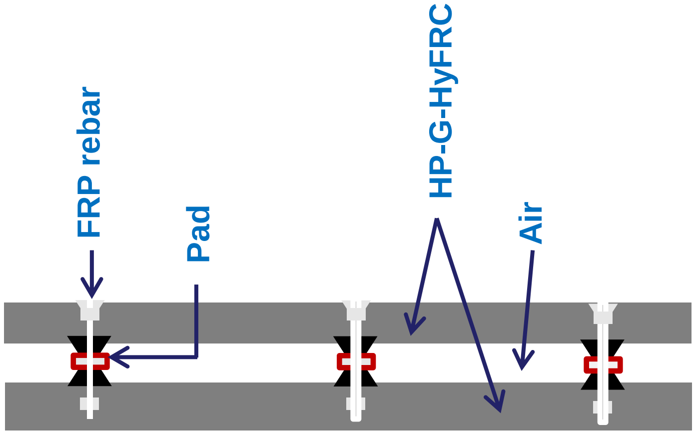
Mechanical Properties

Long-Term Durability Assessment

Dimensional Stability Assessment (Shrinkage and Creep)

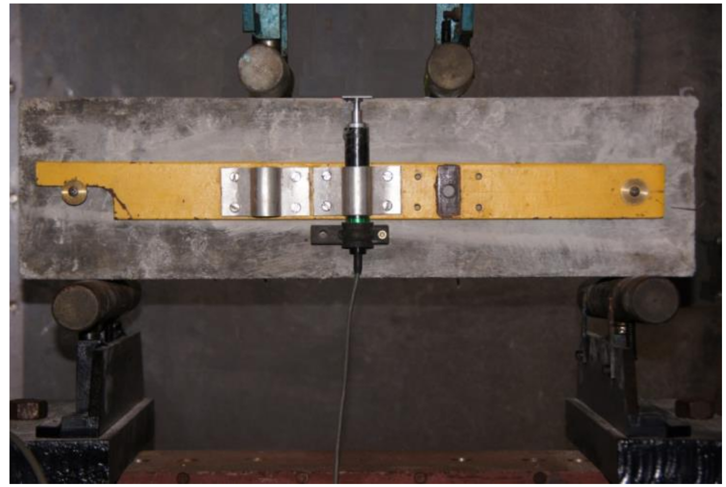
HP-G-HyFRC Product Design & Development for Reduction in Operational Energy of Buildings

Large Scale Testing



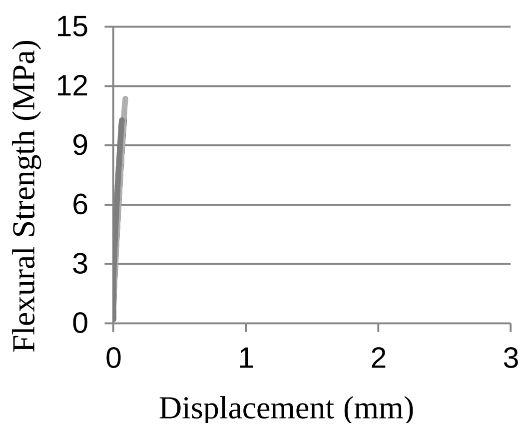
Insulating HP-G-HyFRC Wall Panel

Properties of Sustainable–Ultra High Performance Fiber-Reinforced Concrete (S-UHPFRC)

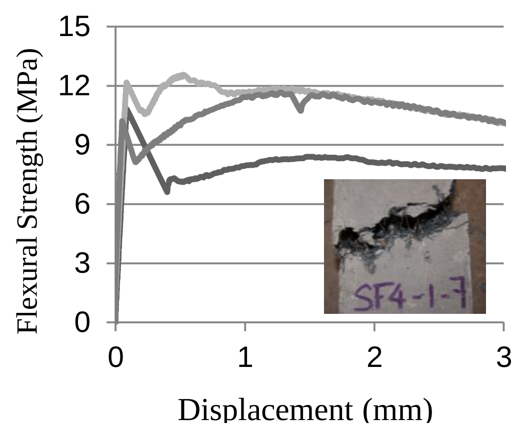


Flexural Tests: 150x150x600 mm prisms tested according to ASTM using displacement control

Fibers = 0.0%

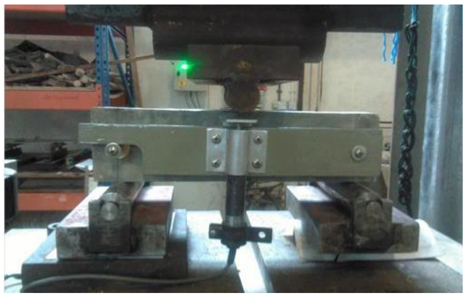


Fibers = 0.9%



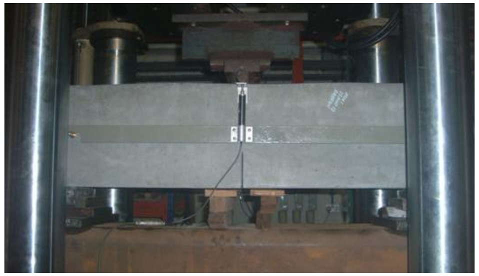
Properties of Sustainable–Ultra High Performance Fiber-Reinforced Concrete (S-UHPFRC)

Fracture Energy Tests: f'_c = 100 MPa; Geometrically similar concrete prisms with different notch depths (0, h/6, h/3, and h/2) tested under three-point-bending



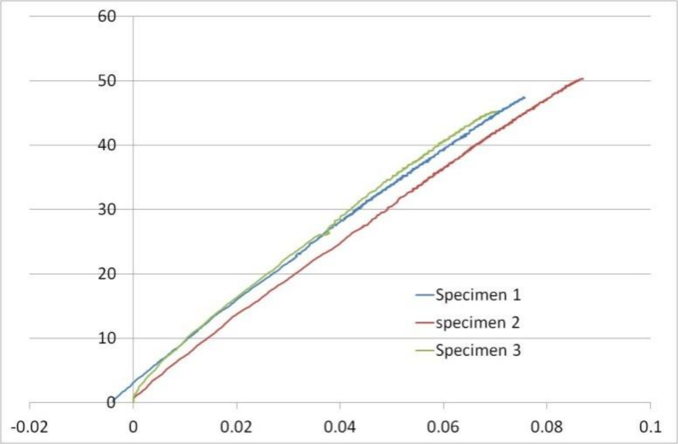
75x75x250 mm beams

150x150x500 mm beams

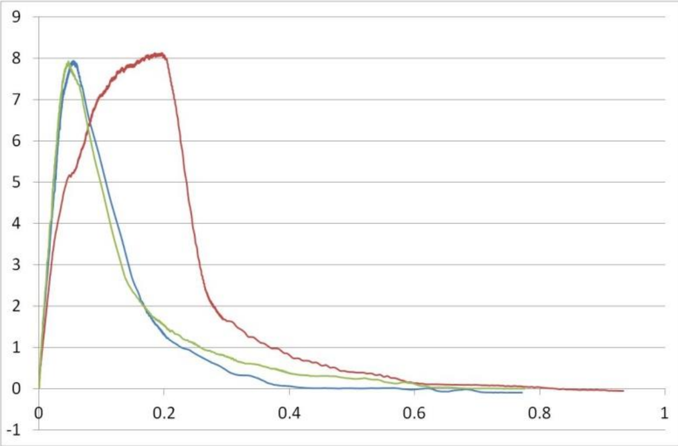


150x300x1000 mm beams

Tested Specimens



Notch depth = 0



Notch depth = h/2

Results of Load (kN) – Deflection (mm) curves for 150x150x500 mm beams with different notch depths

Future Extension: Sustainable–Ultra High Performance Fiber-Reinforced Concrete (S-UHPFRC)

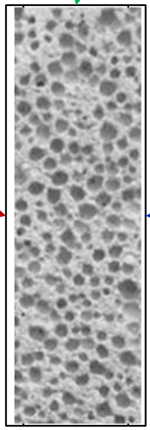
1. Mix design for higher strength (Grade 150 MPa) for S-UHPFRC
   - Investigation of different percentages of GGBS and silica fume.
   - Use of recycled concrete (not recycled aggregates)
2. Creep and Shrinkage tests for S-UHPFRC
3. Durability tests for S-UHPFRC
4. Applications of Grades 100 and 150 S-UHPFRC to large structural beams, slabs, and walls.

Above topics are in collaboration with an on-going NRF-funded project (NRF-CRP† Underwater City and Infrastructure for the Future)

†**Competitive Research Program**

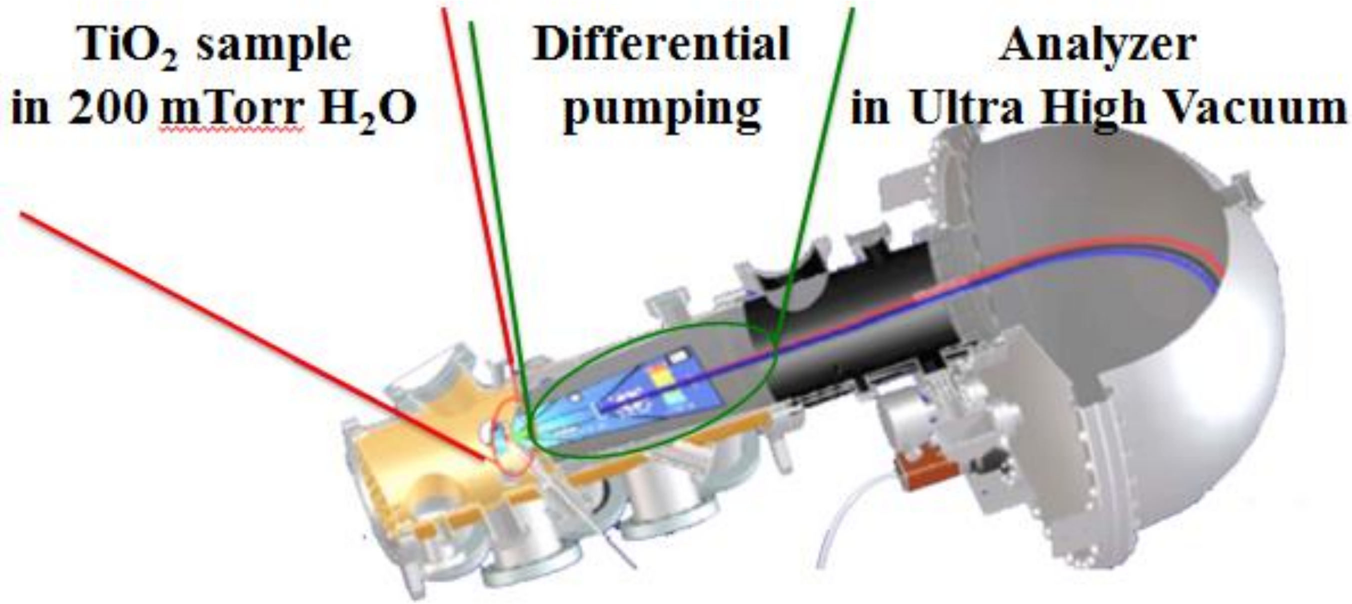
Multifunctional Energy-Efficient Structural Materials

- **Goal:** Develop multifunctional energy efficient structural materials for buildings
- **Approach**
  - Energy efficient structural material
    - Lightweight
    - Low thermal conductivity
    - Sufficient strength & E modulus and low shrinkage/creep for structural applications
  - Environmental sustainable material
    - Renewable abundant tropical light source
    - Removal of airborne pollutants and self cleaning
    - Enhanced durability through mechanistic studies



Multifunctional Energy-Efficient Structural Materials: Research at UC-Berkeley

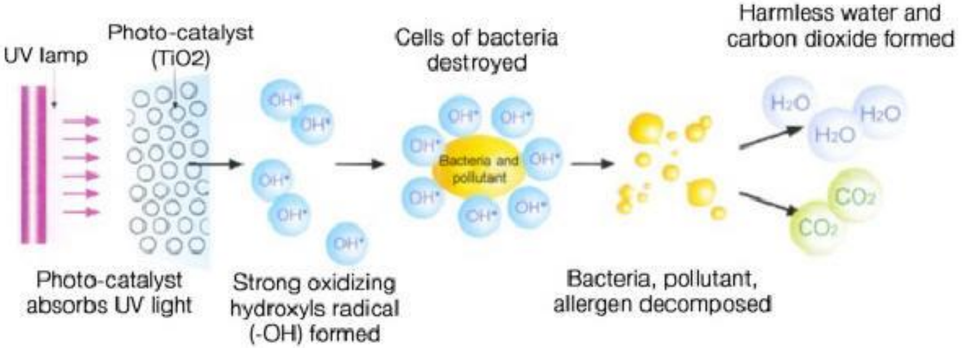
Ambient pressure x-ray photoelectron spectroscopy (**XPS**)



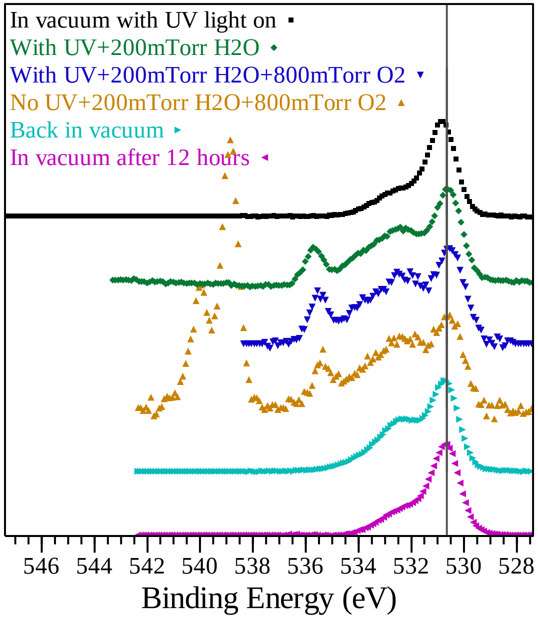
Goal: Study details of the reaction:

UV + TiO_2 ➔ TiO_2 ($h^+ + e^-$)

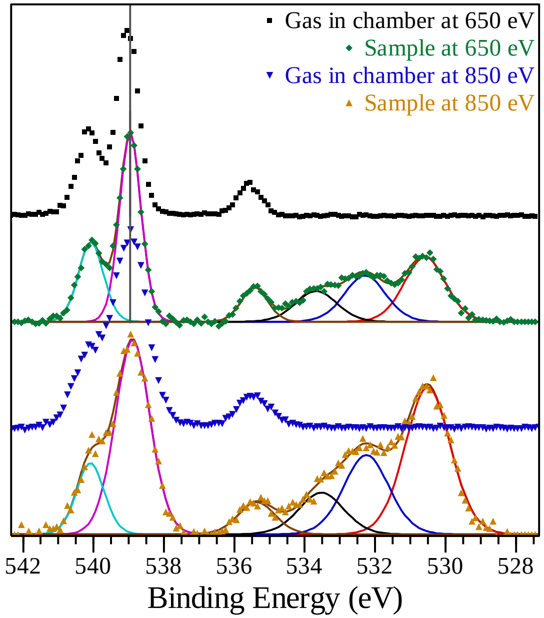
$h^+ + H_2O$ ➔ H^+ + •OH



Multifunctional Energy-Efficient Structural Materials: Results



In-situ evolution of O1s XPS peak upon exposure to gases. Photon energy 650 eV. Background subtracted & spectra normalized by intensity of peak at 530.5 eV.

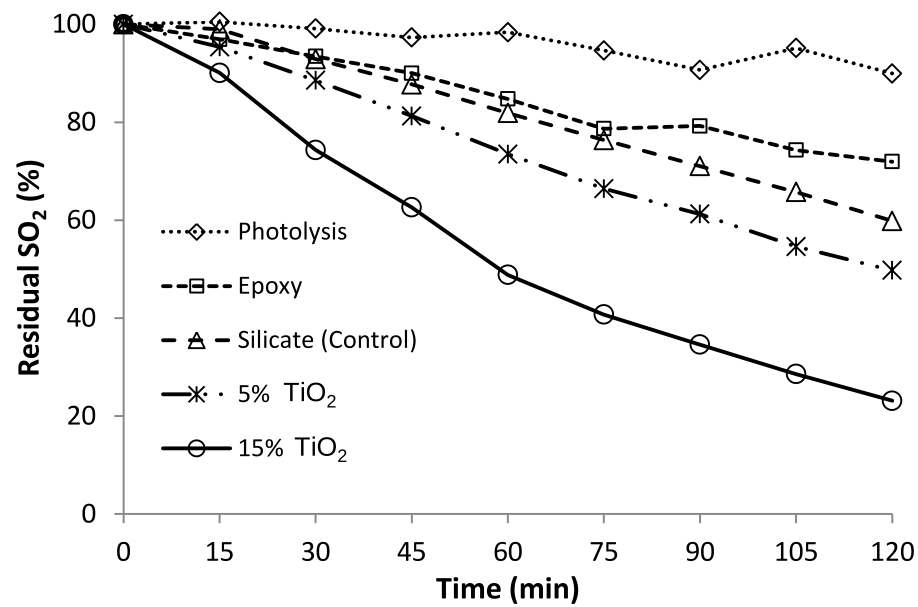


O1s XPS peak in 200 mTorr H_2O & 800 mTorr O_2. **Spectra from top to bottom**: gas in chamber at 650 eV, TiO_2 powder at 650 eV, gas in chamber at 850 eV, and TiO_2 powder at 850 eV.

- Peak at 536 eV appeared with introduction of water in the chamber.
- Peaks at 539 and 540 eV appeared with introduction of oxygen.
- Leaking 200 mTorr water in the chamber, Hydroxyl groups appeared & remained at the same intensity when O_2 is added even when back in vacuum for **12 hrs**.

Photocatalytical Material to Mitigate Airborne Pollutants: Research at NUS

– Applicable to existing and future building surface
– Decrease in temperature over building surface
– Mitigation of airborne pollutants (SO_2, CO, and NO_x particulate)

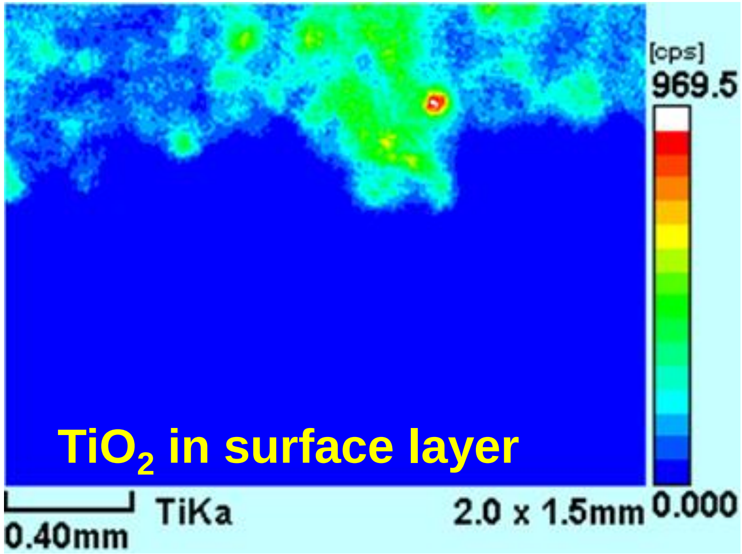


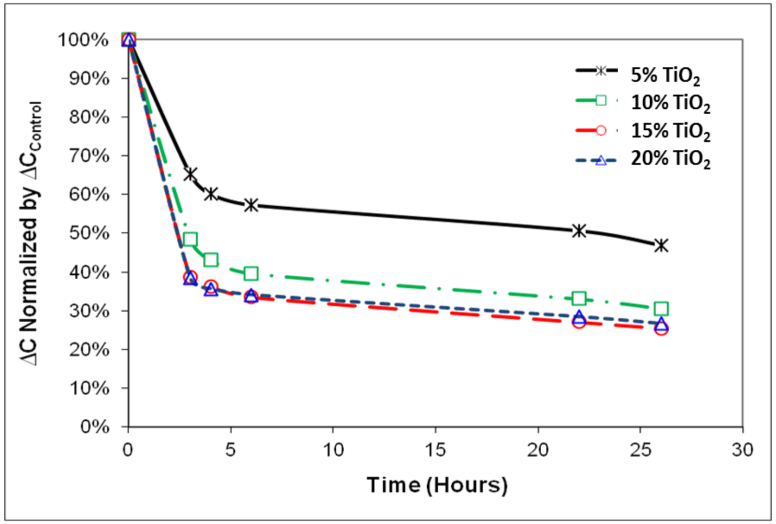
Funded by A*STAR's Science & Engineering Research Council (SERC)

Photocatalytical Material to Self-Clean Building Surface: Research at NUS

- Silicate coating with 15% TiO_2 is most effective in photocatalytic degradation of RhB – a surrogate of particulate pollutants – compared to other silicate coatings.

- Specimens coated with silicate containing 15% TiO_2 showed satisfactory degradation efficiency in lab accelerated tests up to **2500 hrs of simulated UV irradiation**, indicating durable performance.



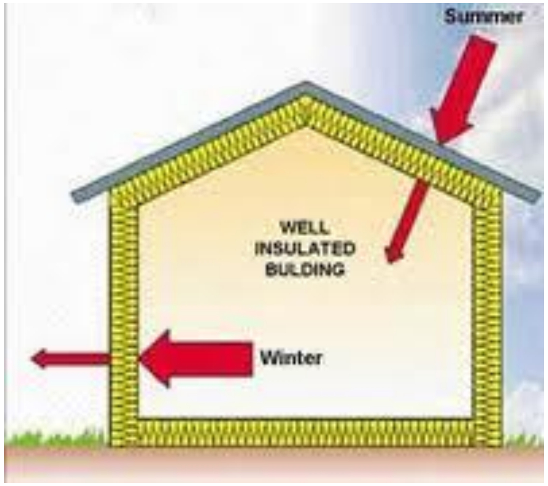


Funded by A*STAR's Science & Engineering Research Council (SERC)

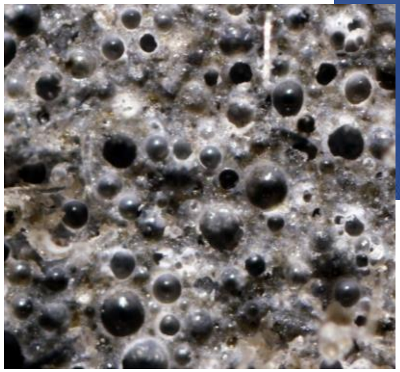
Future Extension: Developing Energy Efficient Structural Material

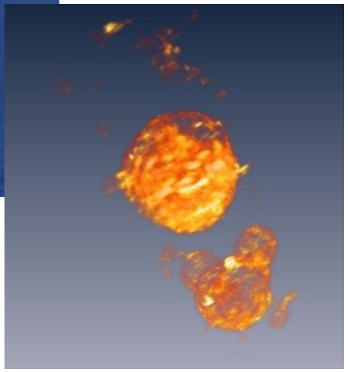
Characteristics:

- Low thermal conductivity
- Lightweight
- Sufficient strength, elastic modulus, and low shrinkage/creep for structural applications (**Integration between many researchers**)



Approach: Develop energy efficient structural materials by optimizing the nano, microstructure, and packing of the material





Optimized air void system

Future Extension: Durability and Long–term Efficiency of Photocatalyst–containing Building Materials

Sustainable energy-efficient structural materials:

- Consistent & long-term performance
- Withstand tropical warm humid weather
- Understanding of mechanisms of compromising light scattering efficiency

Building with photocatalysts

Thank You!

Questions? Comments?