Parametric Design of Photo-catalytic Concrete Cladding Panels

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ABSTRACT: The paper documents the research conclusions, design methodology, and development of a prototype for an exterior wall paneling system which utilizes proprietary self-cleaning photocatalytic cement panels. The developed method of design is performatively modeled utilizing data from site conditions as a means of customizing each particular cladding panel variation to its location.
Buildings' energy demands are closely related to the building envelope, and can be decreased with efficient envelope design. As the building industry continues to be among the main accessories to the looming energy crisis, sensible envelope design and choice of exterior cladding are imperative. .

KEYWORDS: photo-catalytic concrete environmental design

INTRODUCTION

Today, environmental issues and political pressures for our industry to contribute more to sustainable development continue to intensify. While the architectural profession sees its future in the interplay and balance between the natural and built environments, it is increasingly poised to establish a functional interface between them. Influenced by the wide use and dependency on software and numerically-controlled fabrication technologies, complex forms are often evaluated through performance criteria that put an emphasis on the environmental and structural parameters that shape them.

Research into photocatalytic cements has been progressing for over ten years and this emerging technology offers building professionals a renewed opportunity to contribute toward sustainable goals while improving value. Photocatalytic cement uses daylight to react with and neutralize common air pollutants such as nitrogen and sulfur oxides, carbon monoxide, and VOC's – the reaction takes place on the surface of the concrete and the resulting inert nitrates can be washed off manually or by rain[1].

The environmental benefits of using photocatalytic cement are many – in addition to eliminating air-pollutants and its self-cleaning properties, reduced clinker content, comparable strength to Type I early-strength cements, and relatively high reflectivity make the use of this new admixture to concrete a sensible contribution to environmental protection and rehabilitation.

By pairing environment-based algorithmic design and innovative materials, the paper's bias is also that the mitigation of the adverse effects of energy transfer through the building envelope starts with the earliest possible incorporation of model data from site conditions into envelope design.

1.0. APPROACH

The developed method of design is performatively modeled utilizing data from site conditions as a means of customizing each particular cladding panel variation to its location. One type of data used comes from the site's longitude and latitude, which in turn is linked to data describing predominant wind directions, and hours of daylight. Another type of data describes the preferred orientation at a chosen site, which also corresponds with a predominant/desired view. As the parametric model is subjected to various data sets, such as geographic position and orientation and data linked to those two parameters, such as yearly solar stress, incident solar radiation[2], absorbed and transmitted solar energy[3] (based on the applied surface and material properties) and photosynthetically active radiation[4],a range of possible performative possibilities and optimized solutions arise.

Once the panel geometry is derived it is compared to a flat vertical panel of identical material and orientation and, lastly, a possible incorporation into a small building structure on the chosen site is illustrated.

1.1. Site

For the purposes of testing our design approach we have selected a medium density suburban location at latitude 40°39'50"N (40.66°), longitude 75°22'0"W (-75.37°), and altitude 116m (380'). The climate during the hot summer months form mid-June until mid-August is classified as warm humid and the weather station is less than a mile away, which makes the available weather data highly pertinent. The values are gathered from weather data available from U.S. Department of Energy[5] and formatted in Weather Tool 2011[6].

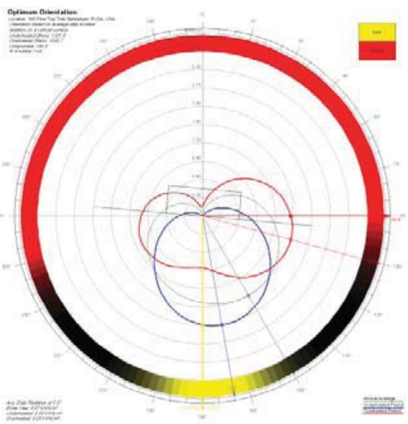

Figure 9: Optimum orientation, Weather Tool 2011, Autodesk Inc.

The most undesirable orientation for glazing is towards those portions of the sky in which the sun is low in its daily path, usually towards the East and West. The best orientation for a vertical surface is when there is the most solar radiation during the under-heated period (Fig. 1, blue line) and least during the overheated period (Fig.1, red line). An analysis of the case study location leads to the conclusion that the worst case scenario is for east-facing glazing at 15 degrees from the East, based on average daily incident radiation on a vertical surface. A façade 80.25° degrees from the East is identified it as most exposed to solar radiation and as such an obvious choice for use of photocatalytic cement products.

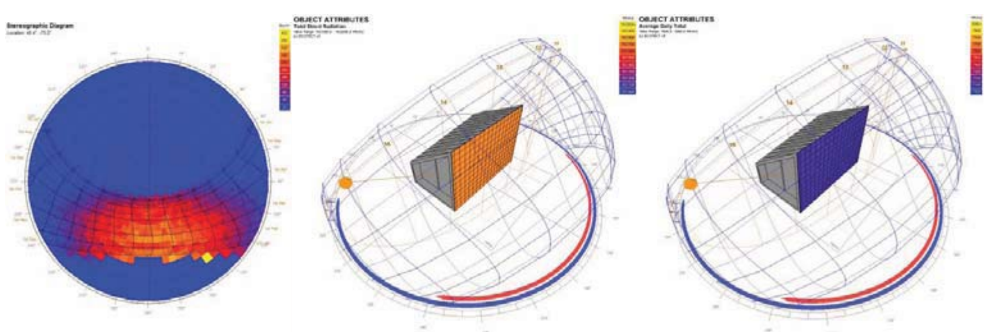

Figure 10: Left: total monthly stress south-facing façade (sun-path diagram); Middle: annual cumulative incident solar radiation (direct only); Right: annual cumulative photosynthetically active radiation (direct only). Source: (Author 2013).

The annual cumulative incident solar radiation (direct only), annual cumulative photosynthetically active radiation (direct only), and total monthly stress south-facing façade (sun-path diagram), provide a good insight about what time of year is most critical for a vertical facade with southern orientation and how inefficient a vertical flat façade is in capturing the available photosynthetically active radiation (Fig. 2).

1.2. Cumulative solar radiation

For the purpose of maximum exposure to solar radiation a plane needs to be in perpendicular orientation to the direction of the sun[7]. Over the movement of the sun such a plane will continually revolve like the head of a sunflower, continually inscribing a spherical polyhedron (the size of its side can be thought of as either infinitely small to approximate a sphere or of a given dimension to reflect available solar radiation data). Using a modified code ported into vb.net and integrated into a Grasshopper[8] by Ted Ngai[9] we visualize the yearly incident solar radiation[10]. We determine that over the year[11], 90% of annual accumulated amount of solar radiation[12] occurs at Azimuths ranging between 121.73° and 235.94° and Solar Altitude angles ranging between 8.72° and 57.41° (Fig. 3).

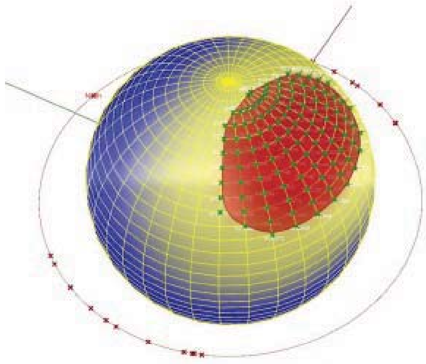

Figure 11: Incident Solar Radiation on a sphere, area of 90% of total annual radiation amount shown in red. Source: (Author 2013)

The further design is based on the premise that the spherical surface from Figure 3, in red, represents the collection of all normals parallel to the sun position within the above mentioned range and, more importantly, its constant curvature (being spherical) enables even distribution of solar stress. This surface optimally faces the sun year-round and represents the geometry with maximum exposure to 90% of the solar radiation. Its inverse clone, made by polar symmetry, is equally suitable. We have two reciprocal surfaces which can serve as the basis for surface generation as long as their curvature and range of normals are maintained.

2.0. Panel design

Developed in grasshopper surface is comprised of developable surfaces with horizontal inclination between 121.73° and 235.94° and vertical inclination between 8.72° and 57.41°. This corresponds to the previously identified limits for solar elevation and azimuth. Having all surface normal within these ranges of inclination ensures that for any given sun position from the design orientation there is fully performing portion of the surface (Fig.4). Each surface has an equal amount of normal oriented within the above range in both concave and convex position - the produced pattern is mirrored relative to a central horizontal axis to generate a surface which is topologically equivalent in both short and long axes.

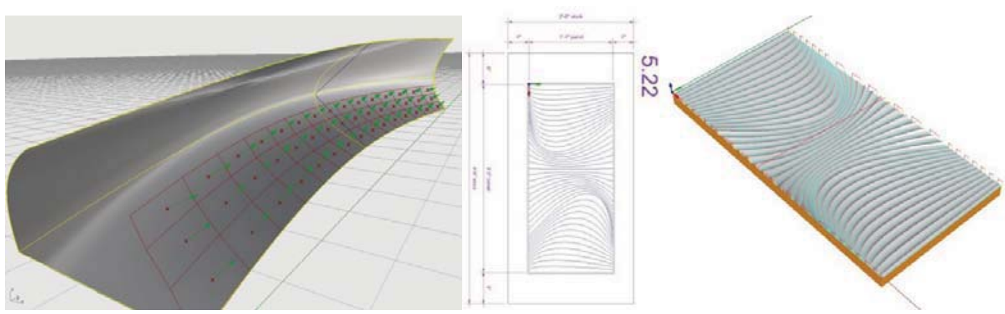

Figure 12: Left: Developable surface constrained by face normal angles, modeled in Rhinoceros; Middle: tool paths exported for use by RhinoCam; Right: Simulation of panel surface stock for CNC routing. Source: (Author 2013)

2.1 Comparison to a generic flat concrete vertical panel

A new concrete panel with the above surface is simulated in Grasshoper and compared against a vertical flat surface of equal overall height, width, and depth, and in identical south orientation. The comparison shows an 11.26% increase of surface area of the proposed panel compared to that of the flat panel, which leads to an overall increase of total surface available for photocatalysis. In addition, 55.28% of surface area of proposed panel has higher exposure to radiation than the flat panel. 9.99% of proposed surface is exposed to 90% of total accumulated annual radiation[13] (Fig. 5).

Figure 13: Color-coded comparison of amount of total annual incident radiation of proposed panel (left) to a flat panel (right). Source: (Author 2013)

2.1. Scales

An interesting observation can be made that the panel's performance is not related to its scale. Comparisons of a number of different scales produce density patterns with varying aesthetic readings and fabrication implications. Most importantly, all of them result in identical total areas of surface available for photocatalysis and with same large amount of surface area with higher exposure to radiation than that of a flat panel. The final size and scale of the panel is derived from typical construction material dimensional module of 120cm x 240cm (4'x8'), (Fig. 6).

Figure 14: Close-up of proposed photocatalytic concrete panel. Source: (Author 2013)

3.1. Building design

The building design follows the general rules of environmental design: the footprint is a rectangle with the long sided facing North-South and short sides facing East-West. The east- and west-facing facades are glazed and set back with 120cm (4’) overhangs. The west roof rake is pitched at 25.9° to the South toward the lowest solar altitude at 12pm on December 23 to minimize incident radiation exposure on the roof. For similar reasons, the North eave is pitched 9° toward the highest Sun position to the West (Fig. 7). The roof pitch values are taken from tabulated daily solar tables formatted in Solar Tool 2011, (Fig. 8).

Figure 15: Design Development, Parti model. Source: (Author 2013)

Tabulated Daily Solar Data

Latitude: 40.6°
Longitude: -75.4°
Timezone: -75.0° [-5.0hrs]
Orientation: 0.0°

Date: 23rd December
Julian Date: 357
Sunrise: 07:27
Sunset: 16:33

Local Correction: -0.5 mins
Equation of Time: 1.1 mins
Declination: -23.5°

Local	(Solar)	Aziumuth	Altitude	HSA	VSA	Shading
07:30	(07:29)	122.0°	0.3°	122.0°	179.4°	[Behind]
08:00	(07:59)	127.0°	5.0°	127.0°	171.7°	[Behind]
08:30	(08:29)	132.4°	9.4°	132.4°	166.2°	[Behind]
09:00	(08:59)	138.1°	13.4°	138.1°	162.2°	[Behind]
09:30	(09:29)	144.2°	17.0°	144.2°	159.3°	[Behind]
10:00	(09:59)	150.7°	20.1°	150.7°	157.3°	[Behind]
10:30	(10:29)	157.5°	22.5°	157.5°	155.8°	[Behind]
11:00	(10:59)	164.8°	24.4°	164.8°	154.8°	[Behind]
11:30	(11:29)	172.3°	25.5°	172.3°	154.3°	[Behind]
12:00	(11:59)	179.9°	25.9°	179.9°	154.1°	[Behind]
12:30	(12:29)	-172.5°	25.5°	-172.5°	154.3°	[Behind]
13:00	(12:59)	-165.0°	24.4°	-165.0°	154.8°	[Behind]
13:30	(13:29)	-157.8°	22.6°	-157.8°	155.8°	[Behind]
14:00	(13:59)	-150.9°	20.2°	-150.9°	157.2°	[Behind]
14:30	(14:29)	-144.4°	17.1°	-144.4°	159.3°	[Behind]
15:00	(14:59)	-138.3°	13.5°	-138.3°	162.1°	[Behind]
15:30	(15:29)	-132.6°	9.5°	-132.6°	166.0°	[Behind]
16:00	(15:59)	-127.2°	5.2°	-127.2°	171.5°	[Behind]
16:30	(16:29)	-122.2°	0.5°	-122.2°	179.1°	[Behind]

Tabulated Daily Solar Data

Latitude: 40.6°
Longitude: -75.4°
Timezone: -75.0° [-5.0hrs]
Orientation: 0.0°

Date: 23rd June
Julian Date: 174
Sunrise: 04:36
Sunset: 19:30

Local Correction: -3.6 mins
Equation of Time: -2.0 mins
Declination: 23.4°

Local	(Solar)	Aziumuth	Altitude	HSA	VSA	Shading
05:00	(04:56)	62.2°	3.9°	62.2°	8.3°	0%
05:30	(05:26)	66.8°	9.0°	66.8°	22.0°	6%
06:00	(05:56)	71.2°	14.4°	71.2°	38.5°	15%
06:30	(06:26)	75.6°	19.8°	75.6°	55.4°	27%
07:00	(06:56)	80.0°	25.4°	80.0°	69.9°	48%
07:30	(07:26)	84.5°	31.0°	84.5°	80.9°	61%
08:00	(07:56)	89.2°	36.7°	89.2°	88.9°	66%
08:30	(08:26)	94.2°	42.4°	94.2°	94.6°	[Behind]
09:00	(08:56)	99.8°	48.0°	99.8°	98.7°	[Behind]
09:30	(09:26)	106.2°	53.6°	106.2°	101.6°	[Behind]
10:00	(09:56)	114.1°	58.9°	114.1°	103.8°	[Behind]
10:30	(10:26)	124.0°	63.9°	124.0°	105.3°	[Behind]
11:00	(10:56)	137.3°	68.3°	137.3°	106.3°	[Behind]
11:30	(11:26)	155.1°	71.4°	155.1°	106.9°	[Behind]
12:00	(11:56)	177.2°	72.8°	177.2°	107.2°	[Behind]
12:30	(12:26)	-160.1°	72.0°	-160.1°	107.0°	[Behind]
13:00	(12:56)	-141.1°	69.1°	-141.1°	106.5°	[Behind]
13:30	(13:26)	-126.9°	65.0°	-126.9°	105.6°	[Behind]
14:00	(13:56)	-116.2°	60.2°	-116.2°	104.2°	[Behind]
14:30	(14:26)	-108.0°	54.9°	-108.0°	102.2°	[Behind]
15:00	(14:56)	-101.2°	49.4°	-101.2°	99.5°	[Behind]
15:30	(15:26)	-95.5°	43.8°	-95.5°	95.7°	[Behind]
16:00	(15:56)	-90.3°	38.1°	-90.3°	90.4°	[Behind]
16:30	(16:26)	-85.6°	32.4°	-85.6°	83.1°	58%
17:00	(16:56)	-81.1°	26.7°	-81.1°	72.9°	48%
17:30	(17:26)	-76.7°	21.1°	-76.7°	59.2°	39%
18:00	(17:56)	-72.3°	15.7°	-72.3°	42.7°	27%
18:30	(18:26)	-67.9°	10.3°	-67.9°	25.8°	16%
19:00	(18:56)	-63.3°	5.1°	-63.3°	11.3°	8%
19:30	(19:26)	-58.5°	0.1°	-58.5°	0.3°	0%

Figure 16: Tabulated Daily Solar Data for Dec23 and June 23. Solar Tool 2011, Autodesk, Inc. 2010

The building utilizes a standard light-wood balloon construction with 5x20 (2x8) wall studs, 5x35 (2x14) floor joists, 2x30 (2x12) roof joists, plywood floor and roof deck, plywood sheathing at north and south wall, let-in braces and translucent polycarbonate panels at east and west walls, standing seam metal roof and flashing, photocatalytic concrete panels adhered to structural substrate (Fig. 9).

Figure 17: South-West, Bird's Eye, and North-West Exterior Views. Source: (Author 2013)

CONCLUSION

Buildings can consume up to 40% of primary energy and 72% of electricity consumption - each of building's energy demands is closely related to the building envelope and can be decreased with efficient envelope design. In climates where the exterior temperatures exceed the desired indoor temperature for extended periods of time, the sensible envelope design and choice of exterior cladding is imperative.

The proposed panel design is intended to augment existing building materials and technology and their interface with any particular construction method is generic. In addition to linking environmental parameters to formal design criteria applicable to an innovative material, this research project so far has led to the interesting discovery that the increase or decrease in the surface area of the panels does not affect their performance. In order to go beyond the critique of functionalist parametricism the author's indent is to test through both mockups and simulations panels of varying scales for aesthetic and stylistic interpretations as well as empirically verify the proposed panels' effect on the performance of the façade system.

ENDNOTES

[1] The cement contains titanium dioxide, which is a photocatalyst activated by daylight. The photocatalytic reaction results in oxidizing reagents converting hazardous NOx into harmless NO3- . On a bright and clear day the process can eliminate up to 90% of nitrogen oxides, aldehydes, benzenes and chlorinated aromatic compounds. When the sun is not directly shining and the UV radiation is low up to 70% of the pollutants can still be eliminated. The photocatalytic reaction does not consume the photocatalyst. Source: "TioCem® – High Tech Cement for the reduction of air pollutants." Accessed January 18, 2013. http://www.heidelbergcement.com/de/de/country/zement/lieferprogramm/spezialzemente/tiocem_en.htm

[2] A process by which electromagnetic radiation is propagated through space. This process is to be distinguished from other forms of energy transfer such as conduction and convection.Source: Glossary of Meteorology. Accessed January 19, 2013. http://amsglossary.allenpress.com/glossary/search?id=radiation1

[3] Absorption is the process by which solar energy is captured by a building material, reducing its available amount. Transmittance is the fraction or percent of a particular frequency or wavelength of electromagnetic radiation that passes through a building material without being absorbed or reflected. Source: Glossary of Solar Radiation Resource Terms. Accessed January 13, 2013. http://rredc.nrel.gov/solar/glossary/

[4] Photosynthetically active radiation designates the spectral range of solar radiation that photosynthetic organisms are able to use in the process of photosynthesis, mostly overlapping with the spectrum of light visible to the human eye. Photons at shorter wavelengths tend to be damaging to cells while photons at longer wavelengths do not carry enough energy to initiate photosynthesis.

[5] http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_about.cfm

[6] Weather Tool ™ 2011, © 2010 Autodesk, Inc.

[7] The sun imparts more of its energy on a surface when it strikes it directly front-on than if the radiation strikes at an angle. Source:" Shading: Solar Incidence". Accessed December 22, 2012. http://wiki.naturalfrequency.com/wiki/Solar_Incidence

[8] Grasshopper™ is a graphical algorithm editor integrated with Rhinoceros' 3-D modeling tools. Rhinoceros, also known as Rhino, is a 3-D modeling software.

[9] Ted Ngai, "incident solar | analemma." Posted on February 1, 2009. Accessed June 22, 2012. www.tedngai.net

[10] The algorithm is based on National Oceanic and Atmospheric Administration's Solar Position Calculator. http://www.srrb.noaa.gov/highlights/sunrise/azel.html

[11] at the time of writing 2011 data was used

[12] direct light only, not accounting for ground reflections

[13] This solar irradiance is calculated using code ported into vb.net and integrated into Grasshopper by Ted Ngai Jan 30, 2009 http://www.tedngai.net/experiments/incident-solar-analemma.html . In it, he states that the calculation of solar irradiance is based on algorithm by University of Oregon Solar Radiation Monitoring Laboratory http://solardat.uoregon.edu/SolarPositionCalculator.html, and does not account for radiation reduction through various kinds of scattering (vapor, particle, ozone...etc).