DESIGNING FOR PERFORMANCE: A CASE STUDY IN THE APPLIED SCIENCE OF AN ENVIRONMENTALLY RESPONSIVE HIGH-RISE DESIGN

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ABSTRACT

This paper explores the developing process and resulting features of an ultra high performance tower designed by Skidmore, Owings and Merrill through a multidisciplinary approach to building simulation and analysis. The 309 meter tall office tower for a new development in the Pearl River Delta region of Southern China, is an exemplar of the marriage of technical sophistication with a graceful form, featuring integrated renewable energy strategies and an active double skin facade coupled with a low energy building conditioning system. This landmark project is a statement to both China and the rest of the world that environmentally responsive design can be achieved on large scales in a challenging hot and humid climate. The solutions arrived at in its final form were only made possible through the quantification of the local macro-climatic characteristics coupled with multi-physics analysis early within the conceptual process.

KEYWORDS

Building design, Building thermal modeling, Heating, ventilation and air-conditioning systems, Renewable energy systems

INTRODUCTION

The emergence of a high-performance solution to the design and creation of the built environment requires both a restructuring and an abstraction to the current process of its development. The historical precedent of a design intelligence, concerned with local climatic, environmental and cultural constraints has given way to a modern global design, accompanied by an unprecedented potential for innovation. Yet, the current reality is in stark contrast with this ideal, as the modern tradition of definitive territories for art and engineering pervades. While computer simulation and optimization has provided the design community a means of extension to the very limits of our capacities, it has also reinforced the schism between fields, as the demands of complex theory force each respective group to disparate extremes. Contrary to this new tradition, in the Pearl River Tower the formal boundary between building and context is evolved into a concept of environment and an instrument for its augmentation to suit necessity. Through such a philosophy, building and environmental simulation becomes the necessary and sufficient condition for design.

Performative design for tall buildings

The tower has long served as icon of architectural achievement, necessitating innovative solutions for structural and mechanical engineering systems to insure efficiency and the economic viability of this spatial organization. While, it has been difficult at times to forecast the immediate economic returns on such massive engineering works in the past, ultimately the tower archetype has been crucial in serving the economic dynamism of the city. Today, fueled by explosive growth in population and the average standard of living, towers are now crucial elements to our cities survival but at a cost. The purveyance of such structures has diminished once naive creativity into a prescriptive process of codes and standards encased into aesthetically pleasing skin. In support of the thesis of this paper, that multi-physics analysis and energy modeling should allow for the conceptualization and application of innovative design strategies, the design for Pearl River Tower was able to be tuned to its external environment to improve the internal environmental performance, reduce the buildings loadings on the external environment and augment renewable energy systems to offset the remainder of the buildings energy, resulting in the congruency of both form and function.

SIMULATION TOOLSET

ECOTECT

ECOTECT is a comprehensive environmental modeling software package developed for utilization by both architects and engineers (Marsh 1996). Specifically catered to the conceptual stages of design, it allows for the efficient visualization of climatic conditions such as diurnal temperatures, prevailing wind directions, available direct and diffuse solar radiation and sun path. The tool also features internal analysis functions for rapid feedback on parameters such as sun penetration, potential solar gains, thermal performance, internal light levels, reverberation times and fabric costs.

eQUEST

eQUEST, developed jointly by the U.S. Department of Energy and the Electric Power Research Institute, is specifically designed for evaluating the energy performance of traditional commercial and residential buildings.

Fluent

Fluent is a general purpose computational fluid dynamics (CFD) simulation package. The software code is based on the finite volume method on a collocated grid, with which air flow, thermal and acoustics dynamics can be assessed for both steady-state and transient problems given prescribed boundary conditions and geometry.

CASE STUDY: PEARL RIVER TOWER

Conceptual Modeling

To enable the Pearl River Tower to utilize ambient energies in the wind and sun to generate power onsite for the buildings consumption, while minimizing its external environmental loadings though massing and a high performance fenestration system, a multitude of analytical tools were required such as: E-Quest, Fluent, and ECOTECT. Initial studies of the macro-climate were carried out through ECOTECT, which allowed for the efficient visualization and comparison of the local climatic conditions.

Figure 1 Pearl River Tower rendering

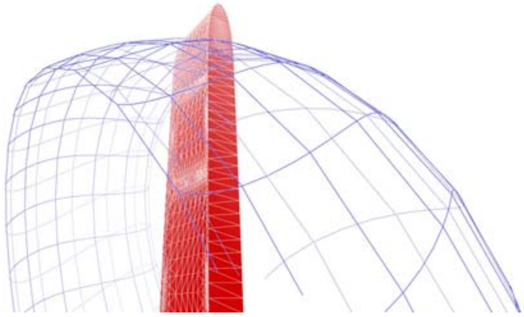

Figure 2 Environmental boundary conditions such as sun path informed the design for the tower

Continuing the process, a set of building geometries generated through a variety of CAD packages were imported into the software, their performance quantified and compared by mapping the annual average and peak incident solar radiation onto the building envelopes. Through a rapid and efficient means of visually cross-correlating these environmental boundary conditions, a tower form was able to be developed in response to solar loading by minimizing east and west exposures, which in turn exposed the broad faces to the prevailing wind directions. Taking advantage of the pressure difference across the windward and leeward facades, wind turbines would be located in orifices formed through the tower.

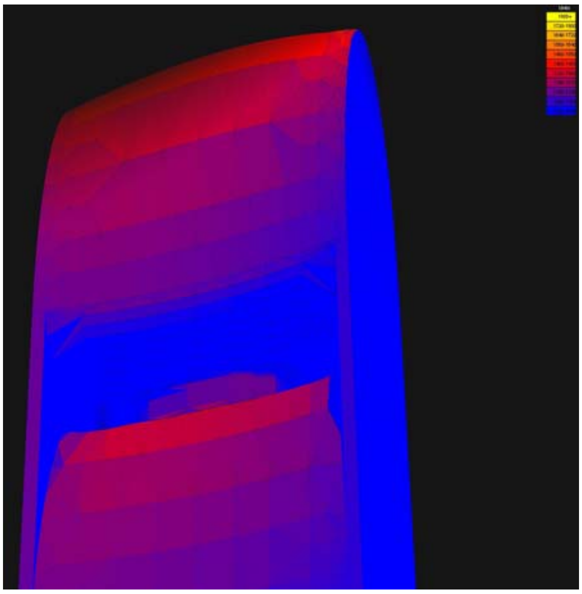

Figure 3 Mapping incident solar radiation to the building envelope via ECOTECT

Double Skin Facade Simulation and Design

The tower’s fenestration system was conceived as a double skin facade to reduce the buildings cooling demand and to further allow for the coupling with an efficient radiant space conditioning system. Such a system would allow for greatly diminished air volumes, reducing the associated fan energy consumption; however, had to be carefully modeled concurrently with the internal environment to ensure an adequate amount of air was being delivered to the space and thus through the facade. In collaboration with RWDI of Canada, a multitude of design scenarios were tested varying glass properties and ventilation dynamics. As initial studies required a multitude of scenarios to be analyzed quickly and efficiently, a simplified mathematical model based upon the heat balance method (HB) as described in ASHRAE Fundamentals was developed. The model, accounting for the inward flowing fraction of long and short wave radiation, convective and conductive gains to the cavity and room allowed a subset of potential typologies to be ascertained. As daylight harvesting was another integral aspect of the low energy concept, the facades' thermal performance also had to be carefully weighed again its visible transmission, achieved using ECOTECT by mapping characteristic daylight factors to the internal space.

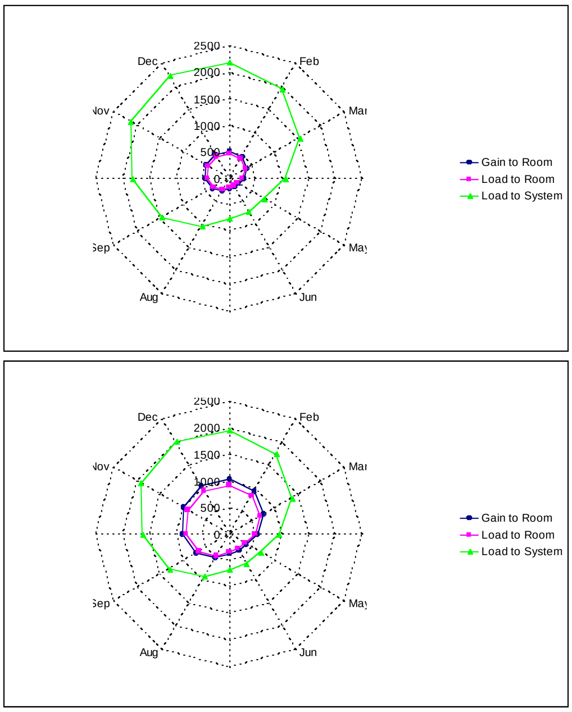

Figure 4 Comparison of annual space gains and total loads to space and cavity (a) 120 m3/hr (b) 40 m3/hr

After analyzing a number of potential construction iterations and with consideration to the associated costs, the final design would include a 300mm internally ventilated cavity wall on the southern facade, the East and West facades would feature a triple glazed unit with integral blinds and 750mm fixed external shading, the design of which was informed by sun path information and shading masks generated within ECOTECT. For the double skin facade a low-e coated, insulating glass unit forms the exterior, with a monolithic unit adjacent to the interior occupied space from which air is mechanically drawn from low-level on at a rate of 45 m3/hr per linear meter. The warmed air brought from the facade would mitigate the necessity for reheat and ventilation air heating energy expenditures. Operation of the blinds was essential for the low-energy HVAC system to maintain an acceptable operative temperature and therefore thermal comfort at the perimeter zone as demonstrated in figure 5.

Table 1 Parameters of final ventilated facade design

Case	**U-Value (W/m2K)**	**SC**	**VT**
Interior	5.60	0.92	0.73
Exterior	1.76	0.34	0.53
Combined (no air)	1.2	Dynamic	0.32

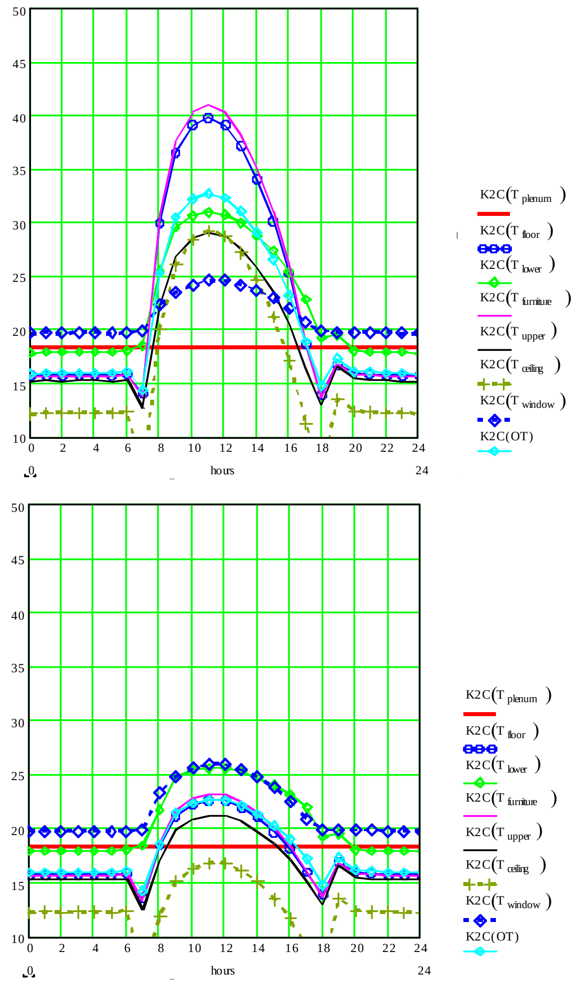

Figure 5 Demonstration of the effectiveness of blinds at reducing perimeter temperatures with 85 W/m2 chilled ceiling (a) no blinds (b) blinds deployed

To verify the final design for the ventilated façade, the Computation Fluid Dynamic (CFD) software package Fluent was implemented. Through analysis it was discovered that thermal buoyancy in the cavity was great enough to induce a stack-effect between the cavity and internal space, resulting in warmed return air reentering the space from the top of the façade. To mitigate this effect, seals between the internal glass panels were improved for the final design. An additional modification was to incorporate a mesh filter into the lower intake slot, a small pressure drop would serve to improve flow uniformity and thus the heat transfer from the façade to the exhaust air. The final performance of the façade, coupled with the radiant cooling and hybrid displacement ventilation system was then verified by a multi-physics simulation carried out within Fluent to ascertain operative temperatures and air change effectiveness for the internal space.

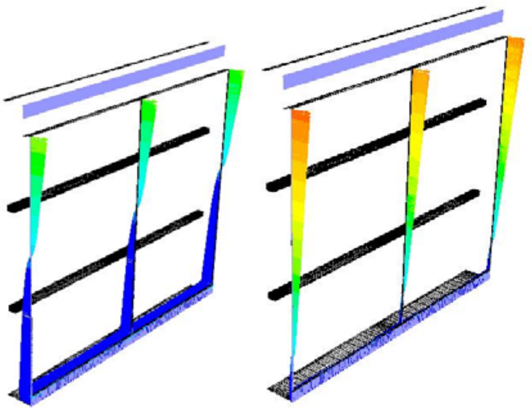

Figure 6 Outflow from the facade as a result of the stack effect (a) 120 m3/hr/m (b) 40 m3/hr/m

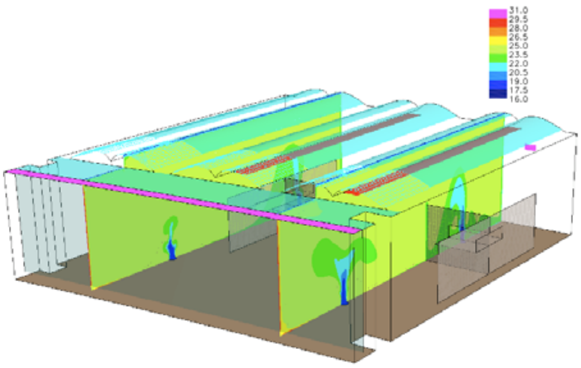

Figure 7 3-dimensional verification of final design performance: Air Temperature (C)

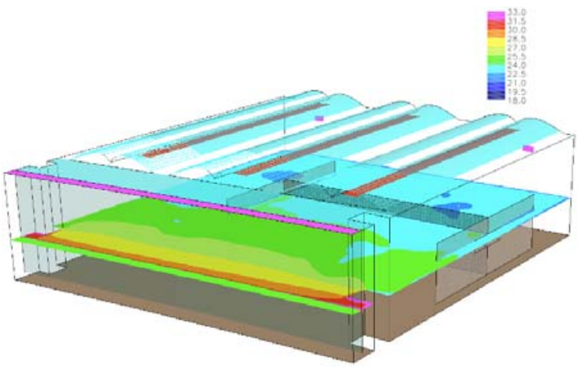

Figure 8 3-dimensional verification of final design performance: Operative Temperature (C)

Design for the Photovoltaic System

Another unique feature of the façade was the integration of a photovoltaic system to generate power for the automated sun tracking blind system. Using the incident solar radiation map generated in ECOTECT, mechanical rooms were to be located on the floors directly below the wind turbine inlets whose normals characteristically faced towards the sky. As views were not required for these floors, the facades are designed to maximize photovoltaic cell coverage. Additionally, photovoltaic cells were integrated into the glass roof of the upper level which additionally served to minimize heat gain to the space. A total active area of 3000 m2 will produce in excess of 300,000 KWh annually.

Design for the Wind Energy System

The most iconic feature of the tower are the four integrated wind turbines located at 120 meters and 210 meters in elevation respectively. In order to determine the feasibility of implementing wind turbines for power generation in Guangzhou, an analysis of remote sensing data acquired by NASA satellites was undertaken. While the wind speeds were of a moderate class, by taking advantage of higher elevations and the associated greater wind velocities, integration within the building was therefore considered.

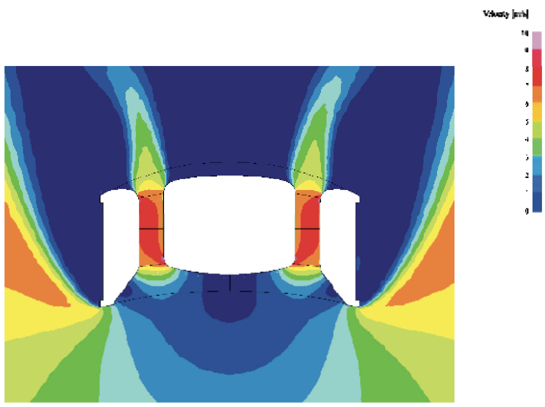

Figure 9 Contours of velocity at mid-elevation

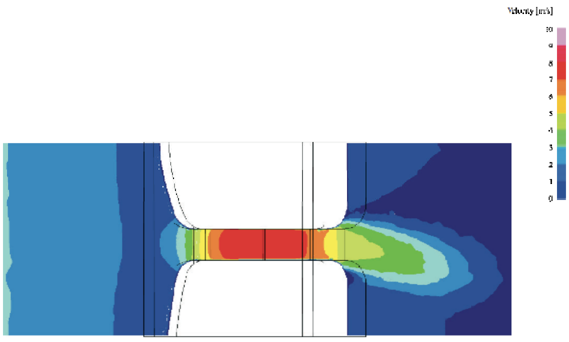

Figure 10 Contours of velocity at mid-section

For a turbine in the free-stream, the air directly behind the actuator is sub-atmospheric while the air in front is greater than atmospheric pressure. By taking advantage of the buildings characteristic pressure difference across the windward and leeward faces, turbine acceptance angles and overall performance could be improved. Maximum power would be achieved when the air velocity was uniformly decreased upon entering the duct, therefore the characteristic facade is designed as a slowly converging nozzle. For an initial estimate of performance, a flat plate concentrator model was utilized (Mertens 2006). The results of this preliminary analysis were then compared with the results from a small scale wind tunnel test. In the absence of the turbines, winds would be accelerated by a magnitude of 2-3 from what would typically be encountered. By ducting the turbines through the building the 59.4% physical limit to the turbines' power extraction efficiency, known as the Betz limit, would no longer apply. The final design for the turbines was analyzed in Fluent and verified by large scale wind tunnel tests which indicate the turbine power extraction efficiency at around 90%, a significant improvement from the documented 34% efficiency without building augmentation.

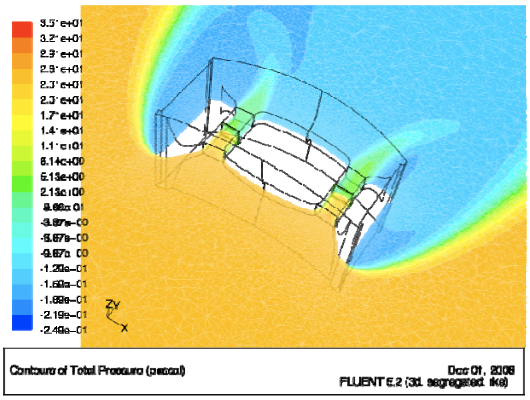

Figure 11 Contours of total pressure

PERFORMANCE RESULTS

A detailed energy simulation of the final design for the Pearl River Tower project was performed using the eQUEST building energy simulation program. As eQUEST was intended for evaluating the energy performance of traditional commercial and residential buildings several modeling approaches were required to quantify the performance of the systems incorporated in the design for the Pearl River Tower. In order to accurately account for the double skin facade performance, the gains and losses for the perimeter zone as well as the cavity zone were calculated for 8760 hours on an hourly time step using the model developed for the initial comparison of facade typologies. This data was used along with the following definitions in order to model the whole building energy performance:

- The discritized load profile was scheduled as a process load in the perimeter zone as it would not create a utility load on the central plant, but appear as a zone heating or cooling load.
- Similarly, a process load was defined for the plenum to account for the loads to the return/exhaust air drawn through the double skin facade.
- 25% of the occupant load, 33 % of the equipment load and 33% of the lighting load was assigned to the plenum spaces to model the resulting fan energy reduction from the hybrid UFAD/radiant system
- The supply setpoint temperature was elevated to 17.8C
- Energy recovery and daylight responsive controls were enabled

From the eQuest model a total energy savings of 31% is estimated with a 46% energy reduction associated with HVAC and lighting for the office floors of the tower as compared with the minimum requirements of the "Design Standard for Energy Efficiency of Public Building in China". The model has the same gross square footage and space area distribution as the actual Pearl River Tower design case.

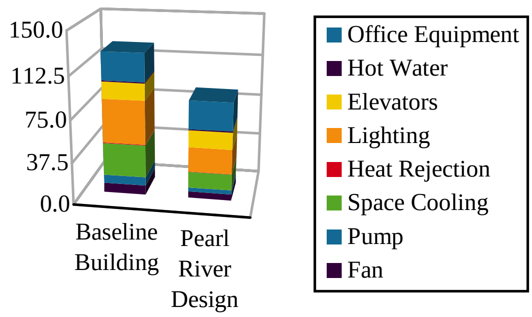

Figure 12 Energy Usage Density kwh/m2

CONCLUSIONS

Reflecting the growing awareness of the environmental and economic implications of a growing urban environment and the necessity the evolve our current practice to keep pace, the design for the Pearl River Tower project resulted from a multidiscipline digital built environment synthesis. Early within the conceptual stage, local climate was analyzed for annual trends in: temperature and humidity; rainfall; available solar radiation and sun path; wind directions and speeds, establishing a weighted criteria for an environmentally responsive design. Furthering the conceptual process, incident solar radiation and wind pressures may be mapped to a multitude of imported shell geometries, available daylight levels and wind behavior were then assessed for a limited subset of geometries, the quantification of these boundary conditions directly informed the final design for the tower. Thus, by adopting a concurrent design process, as opposed to a linear system of design followed by verification and post-rationalization, a new means towards sustainable development was possible within a rapid project development schedule.

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