Comparing Collected Thermal Data with a Computer Model:
The Bradbury Building Atrium

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INTRODUCTION: HISTORY AND ORIGIN

The Bradbury Building was designed in 1893 by the architect George Wyman. The exterior of the building is slightly more ornamentally intricate than its contemporaries and shows Sullivanesque influences, but is otherwise similar to buildings built at the time. It is the interior atrium space that makes the building an architectural landmark worthy of its designation to the National Register of Historic Buildings. The large interior space has high levels of daylighting illuminating the delicate wrought iron filigree and terra-cotta interior. Hydraulic elevators with wrought iron cars almost appear to be freely floating in the air.

The central core atrium has been used as a set for movies such as Blade Runner, and is a regular stop for tourists in Los Angeles. The building has served as the offices of the L.A. Chapter of the American Institute of Architects, and currently houses a number of small offices including the urban design office of a faculty member of the USC School of Architecture. The atrium space has served as the location of countless cultural events for both the school and the city.

The building has five levels, with the atrium narrower at the lower floor and widening from the second floor. The circulation for the offices is around the perimeter of the atrium on all levels. The 4-sided enclosed atrium is oriented with its long dimension in the east-west direction. At the ground floor level, the atrium's 483 square meters (5,198 square feet) occupy approximately 28% of the floor area of the building, and the 9,955 cubic meters (351,560 cubic feet) of atrium volume occupy 26% of the total building volume. The building itself is primarily constructed withunreinforced brick masonry, clad with terra-cotta and stone tile. The floors of the interior circulation are ceramic mosaic, while the handrails and stairs are wrought iron. Because the building was built in 1893, it was not originally air conditioned. In recent decades, air conditioning has been added to the offices, but not to the atrium space.

Architects have used large, vertically dominant interior spaces in their buildings for many hundreds of years.'.' Atria

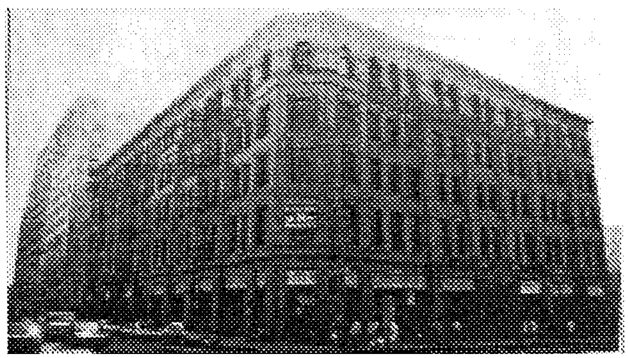

Fig. 1. Bradbury Building exterior view.

function as sources for light and air and have been sometimes been argued to be valuable in thermal control of building, though this is most often not the primary reason why atria are used in commercial architecture. With the greenhouse effect, short-wave solar radiation passes through the roof glazing and heats the interior surfaces of the atrium. The re-radiated long-wave radiation is not able to pass back though the glass, and the atrium is kept warm. The bouyancy of the heated air in the atrium results in a stack effect so that overheated air can escape through the top of an atrium and cooler air can be pulled in through the lower openings, cooling the atrium.' Finally, the thermal mass of a brick masonry atrium is argued to result in a thermal lag effect, buffering the atrium from extreme external temperature conditions.

In the Bradbury Building, we expect to see each of these natural phenomena in action. However, the atrium does not exhibit perfect interior conditions. In winter the stratification of temperature regularly results in excessively warm interior conditions at the upper floors of the atrium. In the summer, the cooling effect is not fully adequate to purge the atrium of the heat gained through solar radiation. Contributing aspects to these symptoms can be traced to a number of conditions in the current physical condition of the building.

There are exterior windows in the office spaces on each of

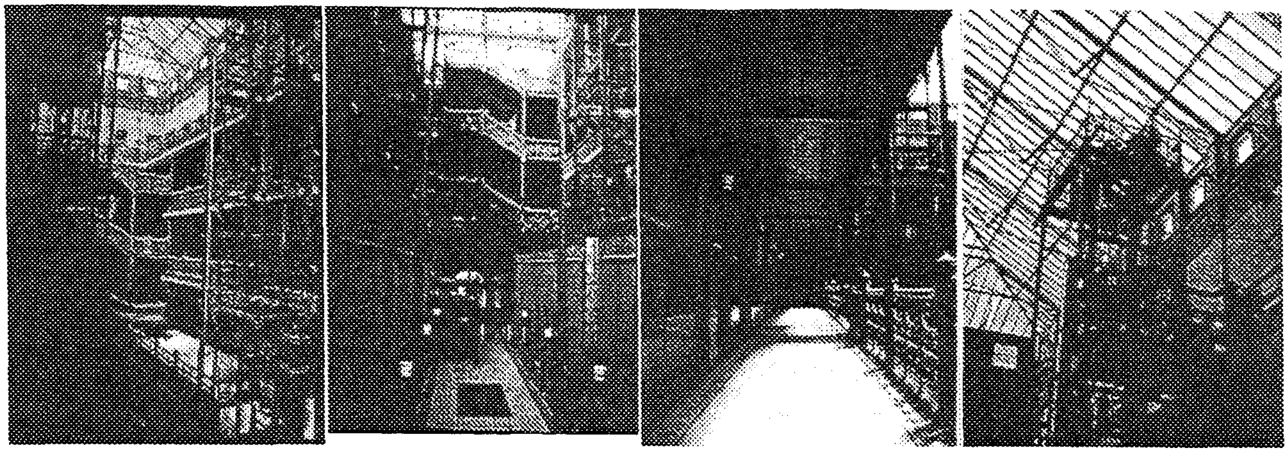

Fig. 2. Bradbury Building set of four interior views.

Fig. 3. Bradbury Building - During the filming of Blade Runner.

the levels, and glazed wood-frame interior doors from the offices into the atrium. The exterior windows are sealed as a result of an air conditioning system that serves the offices but not the atrium. All of the glazing is single pane. There are pivoting ventilation shutters above each of the interior doors, but these are also now sealed. The top of the atrium has a series of clerestory windows on all sides. These windows are closed in the winter, and opened during the summer months. Due to age and mechanical problems, only about 40% of the clerestory windows can be opened. The only source of inlet air is the two sets of doorways at the ground floor. These doors remain shut except when in use by individuals entering or exiting the building.

The goal of this study is to discover the interior temperature, air velocity and stratification conditions that would occur if the atrium were naturally ventilated so as to verify the architects original natural ventilation strategy. We hypothesize that thermal conditions would approach the comfort zone if the atrium was ventilated. The method involves a computational fluid dynamics (CFD) model and physical sensoring of the atrium space. The physical data of the unventilated atrium can be collected and used as a baseline to seed the CFD model. To validate the CFD simulation, a simulation is made of the unventilated condition as a check to see if it will correspond to the physical data. Then ventilated simulations can be run.

PHYSICAL DATA COLLECTION

Because the physical building already exists, it is possible to measure the conditions in the space. However, there are a large number of variables contributing to thermal comfort in the space. These include air temperature, surface temperature, air velocity, solar radiation, air pressure and external climatic conditions. As many of these variables would require expensive and time-consuming measurement techniques, it will not be possible to study all of the aspects. In order to provide data to the CFD model and to compare the results, it will be necessary to synchronously capture air temperature and surface temperature at regular intervals through the height of the atrium.

Ten (10) Stowaway XTI temperature data loggers were used to collect the temperature data (Stowaway Data Loggers manufactured by the Onset Computer Corporation, Pocasset, MA). The compact data loggers are convenient for this purpose, since they are inconspicuous, can be launched with a time delay and all of the units can be synchronized to

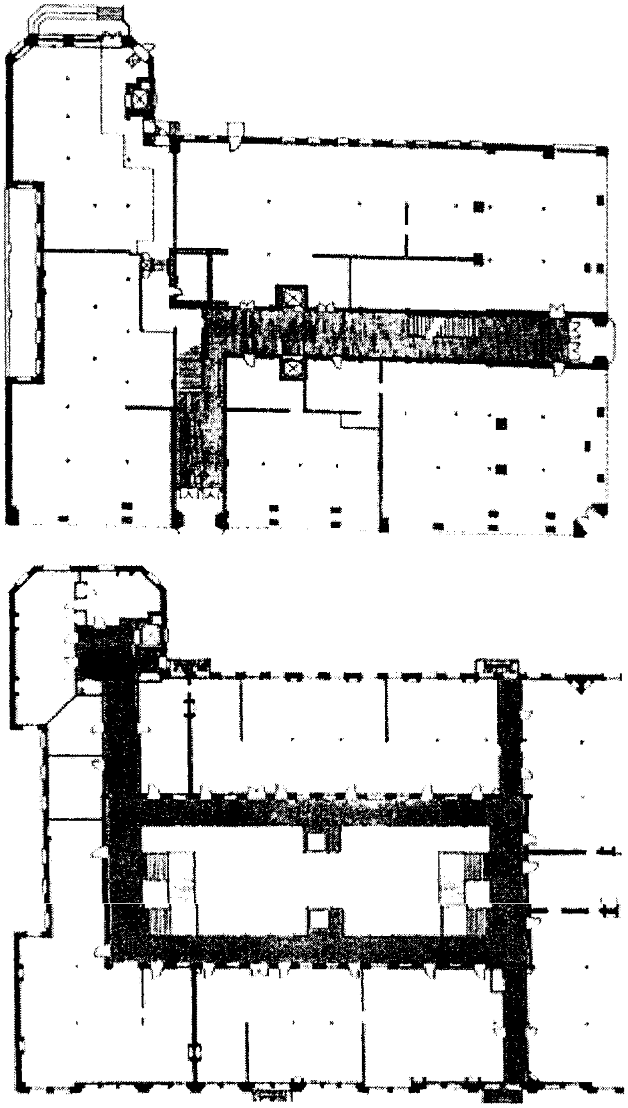

Fig. 4. Bradbury Building first floor plan and typical floor plan (north is up in the drawings).

be active at the same time. They do not require an external power source. These units come with the "LogBook" software to allow download in spreadsheet format to ordinary desktop PC's. Each data logger is capable of logging 8000 data points between -40 degrees C and +75 degrees C, and the intervals can be set within a large range of allowed values.

Nine of the data loggers were placed to collect data at different levels in the atrium (Fig. 5). A series of dry run data sets were collected in order to test the data loggers and to confirm the existence and magnitude of the temperature stratification. One of the data loggers was placed on the ground floor, and four each were placed on the north and south sides of the atrium at each floor level. The tenth data logger was placed on the north exterior face of the building to synchronously collect outdoor temperature conditions.

As expected, the data show extreme temperature stratification in the atrium. Also expected was that the temperature

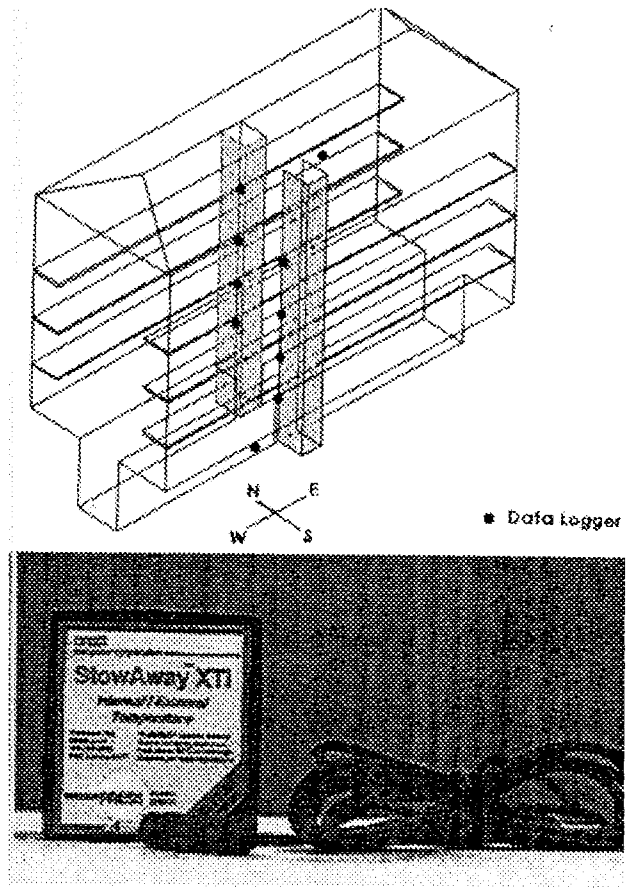

Fig. 5. The Data Loggers and their locations in the atrium.

differential increases sharply at the upper floors, due to direct solar gain through the roof glazing and clerestory windows. However, what was not expected was the discovery that there was virtually no thermal lag between indoor and outdoor temperatures (in fact, the indoor temperature peak between 11:00 and 12:00, well before the outdoor peak).

COMPUTATIONAL FLUID DYNAMICS ANALYSIS

CFD is a computer tool that uses physical principles to simulate fluid flows and non-linear conditions associated with it. In addition to fairly widespread uses in non-architectural fields, CFD techniques have been used to model fire spread and air contamination in architecture. One advantage of CFD procedures is that the numerical descriptions of fluid flow can be easily converted into a graphical format.

In selecting a program for use in this analysis, four initial criteria were considered.[4,5,6,7] These included a reasonable simple input method for establishing the base case, a method for graphic output, the ability to run on desktop computers, and reasonable computation time. A fifth criteria, cost of the software, was also considered.

The program we selected was PHOENICS: Parabolic, Hyperbolic or Elliptical Numerical Integration Code-Series.[8] The software has a relatively simple input language and it runs on PC's, performing well on Pentium-based computers. PHOENICS consists of two essential modules, a pre-processor called SATELLITE and a processor called EARTH. It also includes a post processor called PHOTON and a self-instruction program called POLIS. SATELLITE is the interpreter that supplies the problem defining data. EARTH is the iterative equation resolver. It incorporates code for the relevant laws of physics applied to elements of the material distributed in time and space. EARTH reads the data file created in SATELLITE and creates two output files; a readable file called "Result" and a file called "PHI" which can be read by the graphic display module PHOTON.

We chose to model a2-dimensional section of the Bradbury building for two reasons. The data collected in the physical data collection phase also represents a 2D section, and the calculation time of a 3D model is orders of magnitude larger. The key dimensions of the space are the width and height of the atrium space, the floor-to-floor heights, the location of the roof glazing, and the location of the walkways. These are listed in Table 1:

Table 1: Atrium Dimensions:

Width	14.0 meters
Width at Ground floor	4.0 meters
Floor-to-floor height	
Ground Floor	6.0 meters
2nd through 4th floors	4.0 meters
Top floor	7.0 meters
Glazed Roof	3.5 meters, sloped from 7.0 meters above the top floor
Walkways	2.25 meters wide, 0.10 meters thick

An advantage of the 2D model is that the cell mesh grid can be relatively fine without excessive computing time. Using 42 cells vertically and 56 cells horizontally results in 2,352 total cells. Some of the cells have been assigned a porosity of zero to maintain the internal geometry of the building (lower level and walkways). Thus there are 1,720 total cells. The cell sizes vary in hieght and width to allow more detailed analysis at the upper levels. The cell sizes are:

General cell size	1.0 meter by 0.25 meter
Slab/Walkway	0.1 meter by 0.25 meter
Gabled roof	0.25 meter by 0.25 meter

The PHOENICS program requires as input the surface temperature conditions of the boundary layer.

THE CFD SIMULATION

The first sets of simulations are run to confirm that the CFD model produces output consistent with the measured data of the atrium.

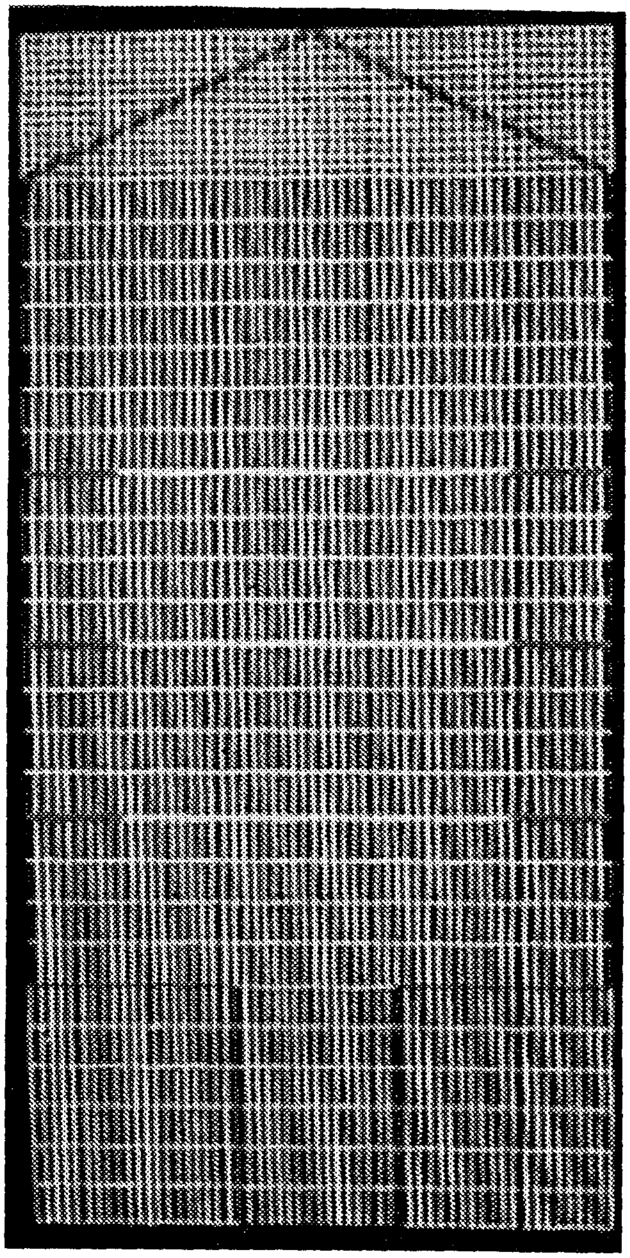

Fig. 6. Cell distribution for the PHOENICS program.

Unventilated Simulations

In the unventilated CFD simulation, the temperature contours exhibit a maximum internal temperature of 41.0 degrees C (105.8 degrees F), satisfactorily close to the maximum recorded temperature. The net vertical temperature differential in the simulated model is 16.5 degrees C, comparable to the 17.3 degrees C measured in the building. At each of the levels for which physical data were collected, the CFD model compare reasonably with the recorded physical data. While the CFD model does not exactly match the recorded data, there is enough similarity in the results to give some measure of confidence in the technique.

In addition to the temperature contours, the output variables from the PHOENICS program include velocity vectors, horizontal direction velocity vectors, and vertical direction velocity vectors. Although we cannot compare the results to measured data, since we did not have the resources to measure each of these variables, the results are much as would be logically expected. There is very little air movement, the maximum air velocity being 0.026 meter/second, and air flow patterns exhibit no clear paths of flow.

Ventilated Simulations

To simulate possible improvements for the atrium, the CFD model is used to simulate a ventilated atrium. A moderate air change rate is assumed (2.8 changes per hour). An air inlet 2 meters wide is assumed at the bottom of the atrium (to simulate door openings) and two outlets, each one meter wide, are provided at the clerestory level at the top of the atrium.

In the ventilated simulation, horizontal stratification virtually disappears, air velocity is significantly increased, and direction velocities and temperatures are not symmetrical.

Night Simulation

An additional simulation was run to test the night-time conditions of the atrium. The results showed an absense of stratification (as the measured physical data suggested), and very low internal temperature differential. The characteristic swirling airflow pattern results from warm internal air rising until it hits the cool glazing, and from the horizontal projections of the walkways. In spite of the drama of the graphic visualization, it must be remembered that the maximum temperature differential is very low under nightime conditions.

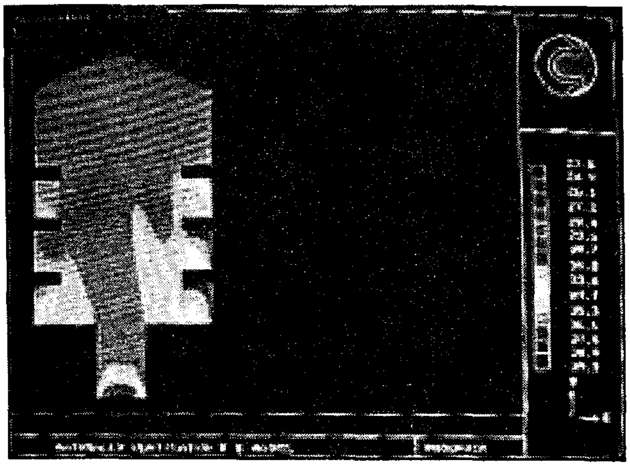

Figure 7. Temperature contours in the ventilated CFD model

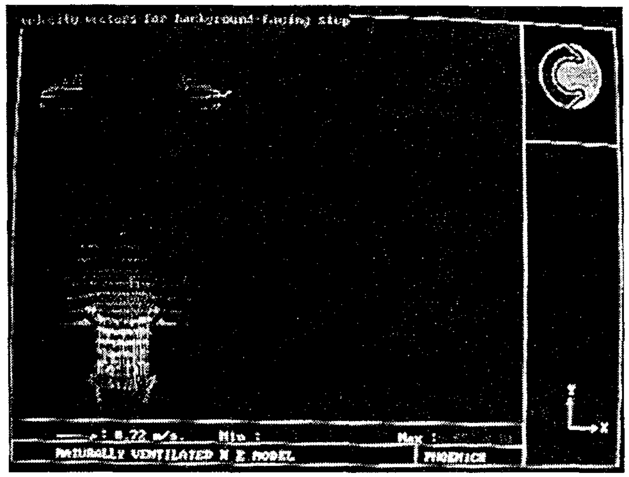

Figure 8. Velocity vectors in the ventilated CFD model

CONCLUSIONS

This experiment into a practical application of CFD modeling for building atriums has demonstrated that the method initially appears to be reliable, has reasonable requirements for input data, and provides very good graphical output to help designers. The CFD model provides data that would otherwise be prohibitively expensive to collect in an existing atrium, and extremely difficult or impossible to calculate with other analysis tools, such as DOE2.IE, Blast, PI-Model, Fres, Trnsys, and Modpas. Most of these simulation programs are not capable of accounting for prediction of air flow rates in multi-zone models. They also do not account for interaction between mechanical and natural ventilation/infiltration as well as dependence on height and pressure gradients in space.

Regarding the atrium in the Bradbury Building, the results are too preliminary to draw conclusions about the complex interaction of the variables involved in comfort in the atrium or to make any serious recommendations. For the sake of continued explorations, it would be valuable if the clerestory windows could be made fully operable again, but with the air inlet from the office windows, it is not clear that there would be a substantial improvement.

The Building Science Croup in the School of Architecture has carried out explorations of atria and courtyards including lighting. We plan to continue this experiment in particular and other atria-related experiments in the future.

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