THE USE OF LIGHT PIPES FOR DEEP PLAN OFFICE BUILDINGS
A case study of Ken Yeang’s bioclimatic skyscraper proposal for KLCC, Malaysia

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SUMMARY

The case study examines development work on the application of light pipe technology for a new bioclimatic high rise building in Kuala Lumpur, Malaysia. The paper outlines the architectural and environmental issues associated with the design of this building. It presents theoretical modelling and simulation work done to test the feasibility of using light pipes to increase daylight in the building and reduce the need for electric lighting. The benefits of this strategy are discussed.

INTRODUCTION

Waterfront House is a high-rise building proposed for Kuala Lumpur, Malaysia (Figure 1). It will be located in the commercial centre of the city and is sited adjacent to the world tallest building, Petronas Towers (Figure 2). The site has prominence in terms of its physical position and its architectural iconography. Trying to balance an economically driven commercial development with the environmental and social needs of the international move towards sustainability has created the intrinsic challenges of the design problem. This paper argues that this challenge can be met through innovation in the development of technical systems, appropriate technical synthesis with the integration of these technologies in the building design and the work of a multidisciplinary team. The first part of the paper explains the design problem, describes the design parameters and outlines the daylight strategy. This is followed by the science principles and experimental work to test the feasibility of the solution proposed. Finally, discussion on the general applicability of this solution is provided.

THE DESIGN PROBLEM

To meet the prescribed economic criteria there is a need to minimize a number of the physical parameters of the building, for example, external wall thickness, vertical support size, horizontal support, vertical circulation and floor-to-floor height (Yeang, 1996). These economic criteria result in a high-energy consumption solution and a building that relies on active systems for climate control. The bioclimatic building type, as defined by Yeang (Yeang, 1999) has a “passive low energy design approach that makes use of the ambient energies of the climate of the locality to create conditions of comfort for the users of the building”, and it challenges some of the economic criteria in favour of a reduced energy solution through mixed mode design- active and passive systems. A different strategy has been devised which seeks to make significant savings to the power demand from electric lighting and air conditioning.

Waterfront House design parameters are:

- floor to floor height of 4.6 m
- west located core (as a thermal buffer)
- ambient lighting level of 300lux with task lighting of 600lux
- deep plan floor plate of 2000 m²
- light directing shading to provide daylight to the edge of the floor plate
- light pipes to provide daylight in the centre of the floor plate
- natural ventilation through wind wall features
The focus of this paper is on the daylight strategy for natural lighting enhancement in the building. This strategy includes the use of light shelves to increase the passive illuminated zone, and the use of horizontal light pipes to decrease the dependence on electrical light of the active zone (centre of the floor plate). The paper will particularly discuss the proposal of introducing light pipes in the building, including experimental work performed at Queensland University of Technology (QUT). The technical design integration work will be carried out at University of Queensland (UQ).

PROPOSED LIGHT PIPES

For economic reasons (i.e. high land price in the inner city) the Waterfront House building has a large floor plate. A 20 m deep plan floor is not susceptible to good natural lighting, and therefore four light pipes per floor, coupled with laser cut panels have been proposed to improve the daylighting performance of office space in the building (figure 3). The light pipes are designed to channel sunlight into the deep zone of the office plan as sunlight falls on the western façade of the building.

Figure 3: Light pipes in plan (yellow), aligned to come through the westerly core, (source Greg Evans). Passive zone: spaces located on the perimeter that can benefit from the ambient environment (daylight, solar gain, ventilation, view), it is normally twice the floor to ceiling height (Baker and Steemers, 2000).
The light deflecting panel at the aperture of the light pipes enhances the performance by redirecting sunlight more directly along the axis of the light pipes (figures 4 and 5).

This report summarizes the theory of the light pipes, outlines the application of light pipe technology for the Water Front building, presents the scale modelling of the light pipes, the results and finally the conclusions.

APPLICATION OF LIGHT PIPE TECHNOLOGY TO THE WATER FRONT HOUSE BUILDING

The design for the Water Front house building places the utilities zone of the building against the windowless West wall with the workplace zone extending three quarters of the way across the building from the Eastern side of the building as illustrated in Figures 3 and 6. As it is expected that the Eastern perimeter zone will be well illuminated during the morning and less adequately illuminated during the afternoon the objective of the light piping system is to illuminate the inner zone of the work area- more particularly in the afternoon. The light pipe takes light incident on the Western facade through the plenum area above the utilities zone and distributes light into the inner zone of the building. The performance of the long light pipes (24 metres long and 4 per floor) is enhanced with: 1) a laser cut panel light deflector at the input aperture to deflect high elevation light more directly along the axis of the pipe, 2) a light extraction system to extract the required proportion of piped light into the inner zone and 3) a light spreading system (shown in Fig. 12 and Fig.14) to distribute the light away from the area directly below the light pipe and more evenly over the zone.
Laser cut panel (Edmonds, 1993) is produced by making parallel laser cuts in transparent acrylic panel – each cut becoming a thin mirror, which provides powerful deflection of off-normal light as illustrated in Fig. 7. The fraction of light deflected, \( f_d \), depends on the angle of incidence, \( i \), and the cut spacing to cut depth ratio, \( D/W \), as shown in Fig. 8 for three nominal \( D/W \) ratios.

![Figure 7: Laser cut panel section. Incoming light deflected and transmitted.](image1)

![Figure 8: Fraction of incident light deflected for different spacing to depth ratios, D/W.](image2)

For effective light collection and deflection of incident sunlight into the light pipe the laser cut panel is placed at an angle to the input aperture as shown in Fig. 9. Incident sunlight is split into a deflected beam, \( f_d \), and an undeflected beam, \( f_u = 1 - f_d \). High elevation sunlight is deflected more axially down the pipe and therefore makes fewer reflections in traversing the pipe than the undeflected beam. The transmission of light through the pipe is given by \( T = r^N \), where \( r \) is the reflectance of the pipe surface and \( N \) is the number of reflections along the pipe which bring the light to the point of interest. In the model used in this work the reflectance of the pipe material (aluminium) was 0.85. For example, if the deflected beam makes two reflections before reaching an output aperture, the transmission is \( T = 0.85^2 = 0.72 \), while for the undeflected beam, for example, making 12 reflections before reaching an output aperture, the transmission is \( T = 0.85^{12} = 0.14 \).

![Figure 9: Detail of the laser cut panel as light collector, and deflection of incident sunlight into the light pipe.](image3)
In the present application the pipe input apertures are on the Western façade and sunlight enters the apertures from 12 noon through the afternoon as illustrated in Fig. 10. It is evident from this illustration that the amount of light incident on the apertures and transmission of this light through the pipes depends in a fairly complicated way on the sun elevation angle and, therefore, on time of day.

![Diagram of light pipe and deflected beam of light](image)

**Figure 10:** Transmission of the light through the pipes for the deflected and undeflected beam of light at different times of the day.

As the light traverses the pipe specified proportions of the light must be extracted at intervals along the light pipe to provide the desired light distribution (usually uniform distribution) below the light pipe. The principle of a light extraction system is illustrated in Fig. 11. In this example the same amount of light is extracted at each aperture. To achieve this the first extractor panel is made sufficiently reflecting to deflect one quarter of the light. The second deflects one third of the remaining light, the third panel deflects one half and the final extractor deflects all of the remaining light. More complicated ratios may be derived to account for transmission loss in the pipe that occurs between each extractor (Edmonds et al., 1997). As is evident in Fig. 10 the transmission loss will vary with incidence angle of the light and hence with time of day. Therefore it is expected that the distribution of light from the light pipe will also vary with time of day.

![Diagram of light extraction system](image)

**Figure 11:** Light extraction in the light pipes

![Diagram of laser cut light spreading panel](image)

**Figure 12:** Laser cut light spreading panel.
As the light is directed near axially and is extracted by reflection off planar extractors it follows that the extracted light is emitted into the room as an approximately vertical and fairly well collimated beam (figure 13). In this case, only the area directly below the apertures is well illuminated. To distribute the light more widely a light spreading system comprising a triangular arrangement of laser cut panels was used. Fig. 12 shows a cross-sectional view of the light pipe and light spreading arrangement. A high proportion of downwardly directed light is deflected by the panels over the ceiling to either side of the light pipe thereby improving the distribution of light in the room by spreading the light more evenly over the interior, and approaching more closely the design target of a uniform 300 lux illuminance (Fig.14).

**Figure 13**: Distribution of the light without emitters.

**Figure 14**: Light redirected to the ceiling by LCP emitters.

**SCALE MODELING OF THE LIGHT PIPING SYSTEM**

A 1/20 th scale model of the system was fabricated, figure 15, and measurements made under direct sunlight conditions. While only one light pipe was modelled the effect of multiple light pipes was simulated by making the vertical sidewalls of the model reflecting. The grid of measurement points within the model interior is shown relative to the light pipe in fig. 16.

**Figure 15**: scale model testing

**Figure 16**: Measurement grid

Measurements of workplace illuminance made at various sun elevations are shown in Figures 17a to 17d. It is evident that the amount of light delivered, ranging between about 200 and 300 lux over the time period from 12 noon to 4 pm contributes significantly to the illuminance level (design level 300...
lux) required in the building. That the area directly below the light pipe receives up to 3 times as much light as areas to the side is due to a less than optimal design of the light spreading system. This will be improved by using laser cut panels with cut spacing to provide maximum deflection of light to the side. The emitted light shows a moderate reduction in strength with distance along the light pipes. This is due, primarily to the fact that the proportions of light extracted by the extractor panels cannot be varied to adjust for varying transmission in the light pipe as the sun elevation and time of day change. However the reduction is moderate and it is expected to be compensated by a fall off in illumination from the window walls on the Eastern façade of the building.

Figure 17a: measured values for 81° sun elevation
Figure 17b: measured values for 57° sun elevation
Figure 17c: measured values for 45° sun elevation
Figure 17d: measured values for 27° sun elevation

The elementary theory of light pipe performance outlined above may be summarised as follows. Calculate:
1) the number of lumens incident on the input aperture,
2) the fraction of incident light deflected and undeflected,
3) the transmission of both components to each of the four light pipe apertures,
4) the average workplace illuminance by dividing the lumen output from each aperture by the area of workplace associated with each aperture, 30m².

The calculations are compared with the average measured values in figure 18 for the four different solar elevations for which measurements were made. Given the simplified theory used the fair agreement between theory and measurement is encouraging.
Figure 18: Comparison between measured values and theoretical calculations

DISCUSSION

The study showed that light pipes coupled with laser cut panels have a good performance for deep plan buildings, reaching illuminance values ranging from 200 to 300 lux over a period from 12pm to 4pm thereby contributing to the 300 lux required for the Water Front House Building.

The best performances were obtained for the higher sun angles where the deflected fraction of the incoming light is greater, and is transported through the pipes with fewer reflections. For lower angles the performance diminished as a consequence of the reduction of the light deflected and the increase in the number of reflections suffered by the off axis beam. It appears that the 55º tilt angle of the input LCP is near optimum for a fixed system, however some form of tracking which adjusts the LCP angle could improve the performance of the system.

Thus the analysis indicates the use of the light pipes will increase the passive zone in the building and hence reduce energy consumption by the use of daylight, but further study needs to be done in other to obtain a better distribution of the out coming light in the space, and also the integration of the system with electrical light. The design integration may include use of a reflective lighting ceiling in a similar manner to the Johnson Wax building.

REFERENCES


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