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Methods for the illumination of multilevel buildings with vertical light pipes

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Abstract

This paper examines the feasibility of using vertical light pipes to naturally illuminate the central core of a multilevel building not reached by window light. The challenges addressed were finding a method to extract and distribute equal amounts of light at each level and designing collectors to improve the effectiveness of vertical light pipes in delivering low elevation sunlight to the interior. Extraction was achieved by inserting partially reflecting cones within transparent sections of the pipes at each floor level. Theory was formulated to estimate the partial reflectance necessary to provide equal light extraction at each level. Designs for daylight collectors formed from laser cut panels tilted above the light pipe were developed and the benefits and limitations of static collectors as opposed to collectors that follow the sun azimuth investigated. Performance was assessed with both basic and detailed mathematical simulation and by observations made with a five level model building under clear sky conditions.

Keywords: Multilevel daylighting; Light pipes; Extractors; Laser cut panels; Daylight collectors

1. Introduction

The need for energy efficient buildings and an appreciation of the physiological and psychological benefits of natural light for building occupants has encouraged the development of innovative daylighting technologies. These technologies-defined here as Daylight Guidance Systems (DGS) (CIE, 2006) – can increase daylighting levels and illuminate much deeper areas within buildings than is usually achieved by windows alone, reducing the need for electrical lighting, and consequent cooling load of a building. Thus, DGS potentially reduce overall building energy consumption and provide healthier environments for building occupants. Examples include mirrored or prismatic light pipes, fibre optics, lenses, etc. DGS usually comprise a light collection system (that captures daylight), a transport/guidance section (that transports the light over long distances into the building) and a system to distribute light and illuminate the space (Garcia-Hansen, 2006).

These new technologies have received a great deal of interest from researchers, designers, product developers and building industry (developers/builders/etc.). Their application in buildings ranges from the technically unsophisticated DGS in user-owned domestic buildings, to DGS in office, educational, industrial and health-care

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facilities (Al Marwaee and Carter, 2006), to avant-garde architectural DGS installations. Examples of the latter are Toyo Ito's Sendai Mediateque, Carpenter–Norris' light pipe in Morgan Lewis offices in Washington, and Peter Cook's light nozzles of Kunsthaus building in Graz, Austria.

Current research on DGS includes the following areas: new designs (Garcia-Hansen, 2006; Rosemann et al., 2008; Baroncini et al., 2010) and design optimization (Garcia-Hansen, 2006; Garcia-Hansen et al., 2009; Robertson et al., 2010; Nair et al., 2014); performance monitoring (Paoncini et al., 2007), prediction models (CIE, 2006; Lo Verso et al., 2011), simulation (Dutton and Shao, 2007; Kwok and Chung, 2008; Kocifaj, 2009) and comparative studies (Oh et al., 2013); monitoring of real building applications and glare analysis (Al Marwaee and Carter, 2006; Isoardi et al., 2012); user attitudes and user perception (Garcia-Hansen et al., 2010; Carter and Al Marwaee, 2009); integration with electrical lighting (hybrid systems) (Mayhoub and Carter, 2010); and finally, cost and life cycle analysis (Carter, 2008; Mayhoub and Carter, 2011).

Mirrored light pipes are the most popular of the DGS, as they are less complicated to build than other DGS (e.g. prismatic pipes, lenses) are currently cheaper than fibre optics, and potentially have a wide application in building design (Garcia Hansen et al., 2001; Garcia Hansen and Edmonds, 2003). Mirrored light pipes transport light by multiple specular reflections, and as a result their performance is affected by (1) light collection (amount of light at the input aperture), and (2) the dependence of luminous power transmission on solar elevation; both aspects can be improved by efficient daylight collectors. Performance monitoring of a simple light pipe over a year demonstrated the variation of performance throughout the day and the year and the need of improved simple daylight collectors (Paroncini et al., 2007). Latest examples to improved designs for daylight collectors for light pipes include shaped rods and Fresnel lenses (Ferrón et al., 2011; Nair et al., 2014).

The methods for daylighting multilevel buildings described in this paper are based on a case study of using vertical light pipes to naturally illuminate five floors of a library building in sub tropical Brisbane, latitude – 27°, (Garcia-Hansen, 2006). There are significant technical challenges in daylighting a deep plan, multilevel building. These include adequate collection of ambient light, transmission of the light and distribution of the light to each level of the interior. An outline of, and the basic approach taken to meet each of these challenges is given in Section 2. Section 3 outlines the performance of vertical light pipes at different latitudes. Sections 4 and 5 describe the design and performance of extractors in a model multilevel building. Section 6 outlines the design and performance of collectors for use with light pipes. Section 7 presents observations of the performance of a combined DGS in a model multilevel building. Section 8 draws some conclusions on feasibility of the proposed design.

2. Basic approaches to multilevel natural lighting via vertical light pipes

In a case study of a five level, 100 m × 60 m floor plan building the shortest distance to capture and pipe natural light to the inner (80 m × 40 m) zone was from the roof. It was proposed that the inner zone, which would normally depend entirely on electrical light for illumination, be illuminated by natural light piped from the roof via 32 light pipes, Garcia-Hansen (2006). The question posed by the case study was whether there is enough light available to adequately illuminate a multilevel building via vertical light pipes and whether the light pipes occupy a reasonable fraction of the floor area. Fig. 1 is a simplified schematic of the proposed lighting system. Light pipes collect ambient light at the roof and transmit the light to the various levels of the building where the light is extracted to illuminate each floor level. The required illuminance of an interior is, typically, 500 lux. The interior illuminance on the floor in lux, E_{INT}, can be estimated if the light output to the interior in lumens, Lo, is known.

$$E_{\mathrm{INT}} = L_o/[A_F(1 - R^2)] \qquad (1)$$

where A_F is the area of the floor and R is the average reflectance of the ceiling and floor. Here it is assumed that the interior zone is sufficiently wide plan that the walls can be neglected. Eq. (1) is based on a well known relationship concerning radiant heat transfer between two parallel planes, Holman (1992). Eq. (1) applies reasonably well to the illumination of rooms provided R is not close to 1. In office buildings typical values of R range between 0.3 and 0.5. For a room illuminated via light pipes and assuming no losses, $L_o = E_H \cdot A_P$ where E_H is the external horizontal illuminance and A_P is the total cross sectional area of the

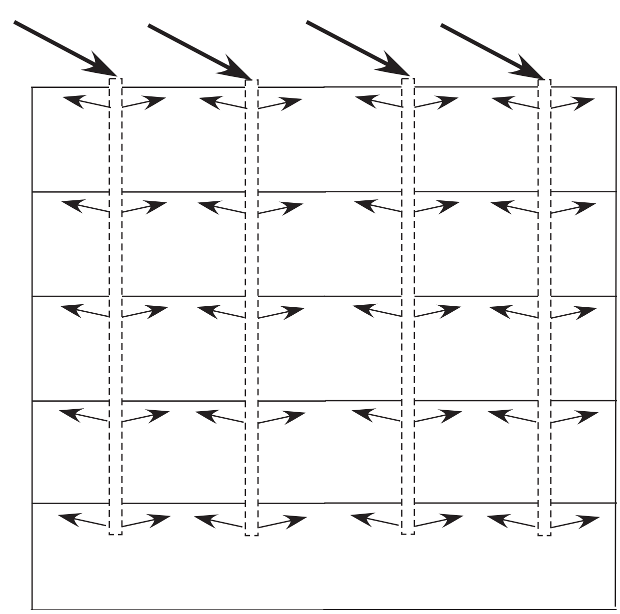

Fig. 1. Basic concept of a system to deliver natural light via light pipes to a five level building.