Energy Efficient Elementary School Design: Effect of daylighting on energy consumption and space illuminance in an existing elementary school

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ABSTRACT

This study investigated the effects of daylighting on building energy consumption and space illuminance for an existing elementary school in College Station, Texas, and is generic to similar school designs in hot and humid climates. Skylight and clerestory top-lighting options were analyzed to formulate balanced daylighting designs that provided for energy savings and increased interior daylight levels. Case study school spaces were analyzed using walk-throughs and daylight factor measurements to understand the potential for daylighting. Physical scale models of the study spaces with and without daylighting alternatives were built for daylight factor and daylight penetration analysis. Computer simulation models were created for the base case and all proposed daylighting designs for building energy performance evaluation using the DOE-2 building energy simulation program. One design each from the skylight and clerestory cases, and an overall design based upon specific performance criteria are proposed for the existing school building.

1. INTRODUCTION

The rising world population has a detrimental effect on the limited and constantly decreasing natural energy resources. Renewable energy sources have been neglected sources, with renewable power generation accounting for a very small percent of world primary energy production. Most energy produced today in the United States comes from fossil fuels. According to the U.S. Department of Energy, K-12 schools spend more than $6 billion a year on energy costs and at least a quarter of that could be saved through smarter energy management. The typical school district spends $400,000 each year on utility bills while those in huge metropolitan areas may spend $20 million or more. Daylight is a free, readily available renewable energy resource. A review of past literature on this topic indicates that daylighting can reduce building energy consumption and can lead to a significant increase in students' test scores and promote better health and physical development. This study is part of an M.S. Architecture thesis project undertaken at Texas A&M University that evaluates the effects of daylighting in an existing elementary school building.

2. THE CASE STUDY BUILDING

The school under consideration is one of five elementary schools under the College Station Independent School District (CSISD) administration, and has a total built-up area of 69,000 square feet.

The building is single storied and the front faces northeast. The building spaces considered for daylighting analysis consisted of 2 classrooms each on the north, south, and west side, and the central library space. The total area of the school under analysis was 10485 sq. ft. This area is approximately 15% of the total school building's built-up area.

3. METHODOLOGY

Three methods were used in this study. These consisted of: case study building analysis for actual interior daylight measurements, use of a physical scale model to study proposed top-daylit options, and use of the DOE 2.1e computer program for daylighting and building energy analysis.

3.1 Design information

Permission to conduct research in the CSISD was obtained from the Research Review Committee of the CSISD administration. The design information required to study the case study school spaces using physical models and computer simulation models was gathered. The as-built architectural drawings were obtained from the Architect for the school, and were used in construction of the physical model and also supplied required details for the computer simulation model input. The as-built mechanical drawings, measured hourly electricity use, and measured monthly natural gas use data was obtained from the Energy Systems Lab (ESL) at Texas A&M University. These were used to define the mechanical details in the computer simulation model. Figure 1 shows the plan of the school building.

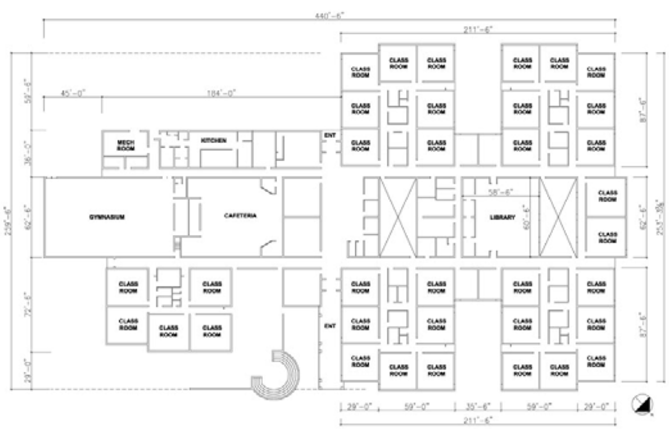

Fig. 1 Plan of the case study school showing classroom and library spaces.

3.2. Proposed daylighting options

Skylights and clerestories were proposed as the two daylighting options for this school building. The details of the proposed designs for a typical classroom are presented in Figure 2. A similar design was applied to the library space, except 4 skylights and 2 clerestories were used to serve the larger built-up area of the library. Skylight areas considered for analysis ranged from 1% to 10% of glazing to total roof surface area, and clerestories ranged from 2 ft to 6 ft of glazing height. All clerestories except the 2 classrooms on the south faced north.

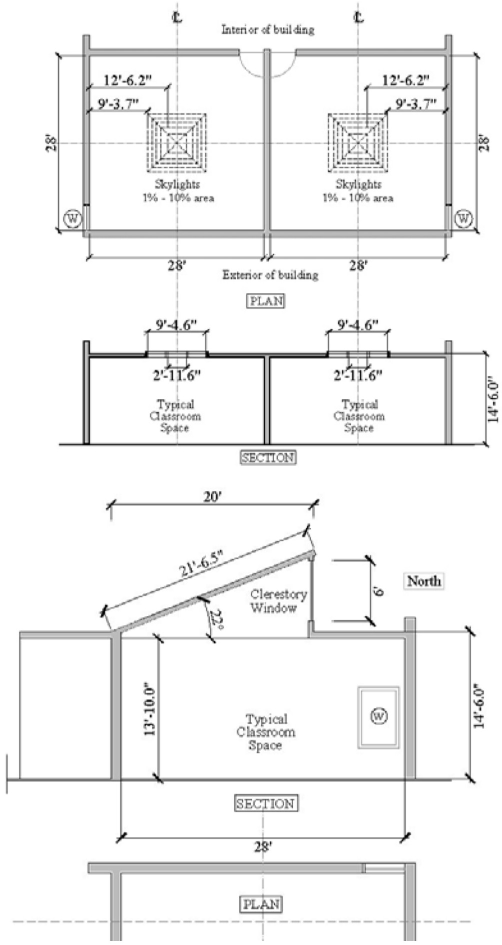

Fig. 2 Plan and section of typical classroom showing proposed skylight and clerestory cases. The dotted lines in the skylight cases indicate the varying sizes of skylights.

A physical scale model of the analysis spaces was built to a scale of 1 inch = 1 foot. Interior model reflectances were matched with their respective actual surface reflectances from the case study site. Flexible model materials were selected in order to experiment with different daylight openings. The window openings were treated with 1/8" glass to correspond with the glass openings in the actual space. Similar treatment was used for all the top-lighting solutions that were experimented with in the model. The model roof was not fixed, and could be substituted for different combinations of skylights and clerestories. Adequate openings, other than the windows, were provided in the walls to insert the cables for the light meters, and also for taking interior photographs using a digital camera. Figure 3 shows the base case model without a roof, a modified 2 feet glazing height clerestory case, and a modified 7% skylight case.

Fig. 3 Physical model photographs: base case with no roof, 2 ft glazing clerestory, and 7% glazing skylight cases.

The DOE-2.1e computer simulation model was built using available architectural and mechanical data. Figure 4 shows a DrawBDL representation of the base case model, a 2 ft glazing height clerestory and a 3% skylight case as modeled in DOE-2. Daylighting commands were added to the DOE-2 daylit base case input file in order to perform daylighting calculations. Skylight and clerestories were added to the analysis spaces, and their effect on daylight illuminance and building energy consumption was analyzed.

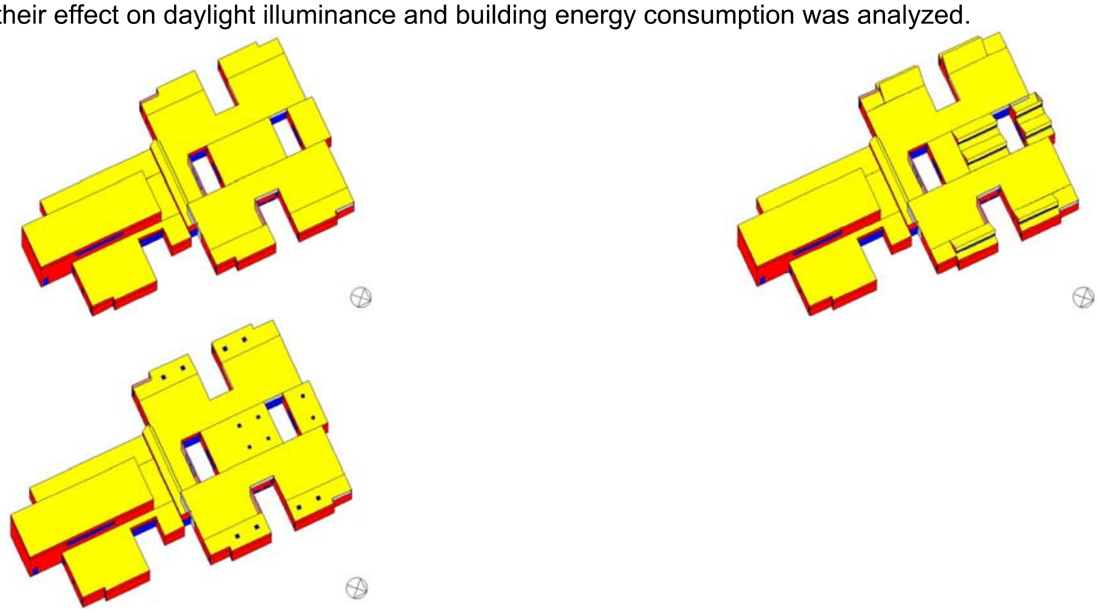

Fig. 4 DOE-2 models showing base case, 2 ft glazing clerestory, and 3% glazing skylight cases.

4. ANALYSIS AND RESULTS

4.1 Daylighting analysis

Calibrated DOE-2 and physical scale models were used for daylighting analysis. The DOE-2 model was calibrated to the measured hourly electricity use and monthly natural gas use. The physical model was calibrated using actual space illuminance and luminance values. Daylight factors measured in the analysis spaces, measured in the physical model and calculated by DOE-2 were compared. Daylight factors from the physical model and DOE-2 were found to be lower than the actual site values. This discrepancy was attributed to various factors, the main being the presence of ceiling-hung television sets near the windows in classrooms. Other factors could be the actual window transmittances, internal light reflections due to furniture and blackboards inside the classrooms, and the presence of trees outside the spaces.

The second part of the daylight factor analysis involved a comparison between the DOE-2 values and the physical model values for the proposed skylight and clerestory designs. Minimum and maximum skylight and clerestory cases (1% and 10% for skylights and 2 ft and 6 ft for clerestories) were considered for comparison. The daylight factors obtained from the physical model were found to be more than the factors from DOE-2 in both the skylight cases. The difference was approximately 2 times in the 1% case and approximately 4 times in the 10% case. In the minimum (2 ft) clerestory case, DOE-2 values were consistently higher for all the spaces, whereas they showed an irregular trend for the maximum (6 ft) case. DOE-2 calculated daylight factors were found to be inaccurate and hence daylight factors from the physical model were considered for further analysis.

A FUNCTION input was added to the DOE-2 input file in order to replace the daylight factors calculated by DOE-2 with user-defined daylight factors (in this case, physical model daylight factors). The functional input used for this study is similar to the one developed by M. Steven Baker from the Oregon Department of Energy. For actual input details, please refer to the publication in the *Proceedings of the Solar Energy Society Conference, Denver, Colorado, 1989*. A comparison of the DOE-2 output before and after the use of the FUNCTION command showed a distinct difference in energy use and space illuminance values in all the spaces (reduction in energy use and increase in illuminance).

4.2 Space daylighting summary

The space daylighting reports from the DOE-2 output were analyzed to understand the effect on lighting energy reduction and space illuminance values in all the analysis spaces through the use of daylighting.

Comparisons were made between all the proposed cases with reference to a daylit DOE-2 base case.

Average lighting energy reductions of 48% and 57% were observed for the skylight and clerestory cases respectively. The lighting energy reductions as compared to the daylit DOE-2 base case were 26% and 33% for the skylight and clerestory cases respectively.

Average space illuminance values of 76 footcandles and 80 footcandles were observed for the skylight and clerestory cases respectively. The increase in the average space illuminance (all spaces included) was 44 and 47 footcandles for the skylight and clerestory cases respectively as compared to the daylit base case.

4.3 Building energy analysis

A comparison of energy consumption between the daylit and non-daylit DOE-2 base cases showed a decrease in lighting energy throughout the year for the daylit case, whereas the cooling energy also decreased, especially in the hot season between the months of April to October. The base case daylit model indicated a decrease in whole building electrical energy throughout the year, but the heating energy showed negligible increase or decrease for any of the months. The base case daylit model performed better than the non-daylit base case model.

4.3.1 Lighting energy analysis

To better understand the effect on lighting energy use, the different daylighting cases (skylights and clerestories) were analyzed for March 21, June 21, September 21, and December 21 (vernal equinox, summer solstice, autumnal equinox, and winter solstice). The lighting electricity energy consumption was seen to be consistently lower than the base case in all the cases for all the four typical days, with a maximum of 16.5% reduction for the 10% skylight case, and a minimum of 11.5% for the 1% skylight case. The most savings were observed on the day of March 21. The clerestories showed a similar trend, with a maximum of 16% reduction for the 6 ft case, and a minimum of 14.9% for the 2 ft case. The most savings were observed to be on the day of September 21, followed by March 21.

4.3.2 Cooling and heating energy analysis

Hourly cooling and heating analyses were performed on September 21 and December 21 respectively, being the hottest and coldest days of the year. Though the cooling energy showed a clear decrease in the daylit base case, there was a consistent increase in the cooling energy between the daylit base case and the different skylight and clerestory cases. This effect was attributed to heat transfer through the glazing materials of the skylights and clerestories. The absence of additional glazing during the base cases comparison might have led to the decrease in the cooling electricity energy consumption. The cooling electricity use increased with increasing skylight to roof ratio and higher clerestory glazing size. No noticeable trend (increase or decrease) was observed in any of the cases during hourly heating energy analysis. The heating energy remained almost constant for all cases studied.

4.4 Energy Savings and energy cost savings due to proposed designs

The 1% and 3% skylight cases and the 2 ft clerestory case were the 3 cases that provided some cooling energy savings whereas all other cases showed a loss. Lighting energy savings were the highest at 14.70% for the 6 ft clerestory glazing, followed closely by the 10% skylight case at 14.52%. These two cases performed the worst though in terms of cooling energy saving. Clerestory cases performed better than skylight cases in terms of heating energy (natural gas use) savings, with all clerestory cases showing positive, though minimal savings. Total electricity use was best in the 3% skylight case and the 2 ft

Skylights	Energy	Energy cost	Clerestories	Energy	Energy cost
	Savings (%)	savings($)		Savings (%)	savings($)
1% Skylight Area	2.65	2311.51	2 ft glazing	3.17	2742.97
3% Skylight Area	2.95	2569.53	3 ft glazing	2.99	2577.23
5% Skylight Area	2.65	2295.38	4 ft glazing	2.77	2374.13
7% Skylight Area	2.39	2063.72	5 ft glazing	2.53	2157.23
10% Skylight Area	1.76	1536.98	6 ft glazing	2.29	1934.93

Fig. 5 Energy savings and energy cost savings from the proposed daylighting options

clerestory case, the 2 ft glazing case performing slightly better than the skylight case. The 3% skylight case was the best among the skylight cases, while the 2 ft glazing performed best in the clerestory category. In all, the proposed cases perform better than the base case in terms of total energy savings.

Total average annual energy savings of 2.6% and total average annual cost savings of $2500 were achieved through the application of any of the proposed designs.

An important factor to be considered is the area of the spaces under analysis. The sum of the built-up areas of all analysis spaces was just 15% of the total built-up area of the school. The proposed daylighting options have been limited to this 15% area, and the estimated energy and cost savings reflect the effect of the modifications made to this 15% area on the entire school building. Under the circumstances that the entire school building is daylit through the use of skylights or clerestories, the projected savings would be much higher than the present calculated value.

6. CONCLUSIONS

Daylighting has a direct effect on building energy consumption and interior daylight illuminance levels. Use of daylighting reduces the total building energy consumption and has a high potential for lighting electricity savings. Assuming that about 80% of the total built-up area of the school can be daylit, if the savings for the 15% analysis area can be used for the whole school, simple extrapolated savings would be:

Total average annual energy savings of 14%, corresponding to around $13000 in annual cost savings; and

Total average annual lighting electricity savings of 66%, corresponding to around $7500 annual cost savings.

7. ACKNOWLEGDEMENTS

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