

ENERGY-EFFICIENT DESIGN OF BUILDING ENVELOPES FOR HIGH-RISE RESIDENTIAL BUILDINGS

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ABSTRACT

The building envelope significantly affects the energy consumption in high-rise residential buildings. In designing new buildings, it is not always easy to visualize how the building is going to perform under various conditions. A thorough energy audit of six similar public housing projects in four different cities in Iowa furnished a wealth of information on how these buildings performed and what role the building envelopes played in the total energy balances. All six buildings were of similar construction materials, primarily of concrete frame, either exposed or partially covered with brick, and had double-glazed windows, insulated exterior wall panels, and central heating with individual window air-conditioners.

The floor plans and orientations differed. Five buildings had primarily central corridors with apartments on both sides, while one had balconies that were used in place of interior corridors. All but one had been built in 1973-75; one was designed to ASHRAE 90-75 standards. The number of apartments varied from 160 to 200 per building.

Energy conservation opportunities were indicated in three conceptual areas: the building envelope, mechanical and electrical systems (and their interfacing with the envelopes), and operations. While heating controls and mechanical supply and exhaust ventilation were available in all cases, the amount of window ventilation and infiltration varied extensively. Many occupants of the apartments mishandled temperature controls and were generally ignorant of proper operating procedures. Windows were kept open indiscriminately. The structural design did not provide thermal breaks at exposed structural frames. The design of mechanical and electrical systems was not always appropriate, and controls were often inadequate. One building was not individually metered. Malfunctioning of equipment was found to be resulting from tampering by the maintenance personnel. Relatively simple corrective measures were recommended for an improved energy profile, as described in this paper.

INTRODUCTION

Energy-efficient design of building envelopes for high-rise residential buildings did not receive much attention prior to the development of ASHRAE Standard 90-75. Since then, the establishment of a Model Energy Code has done much to improve the designs as architects and building engineers have had to consider energy conservation as one of the important aspects of building design. The ASHRAE 100.2 retrofit standard for high-rise residential buildings goes further in suggesting improvements that can be made, depending on the cost/benefit ratio and life-cycle costing. And although the ASHRAE 90A-80 revision of Standard 90-75 did not change much the high-rise and commercial building standards, the anticipated ASHRAE 90.1 standard will take a completely new look at how buildings should be designed for energy conservation. While these new standards for the design of the building envelope and the internal systems are still being developed, the author is bringing up points to consider, based on extensive energy studies of six typical high-rise residential buildings built in Iowa. The energy performances of these sample buildings have been measured and their energy consumptions have been analyzed in detail. Judging from this experience, the direct share of the building envelope of the energy losses is only one third of the total, by heat transmission. This takes into consideration both

heat gains and losses, solar radiation, and energy storage in building masses. Another one third of energy losses occurs through infiltration through windows, doors, and other openings. The third portion is lost through inefficiencies of boilers and other equipment, and in the heating of domestic hot water, cooking, lighting system, fans and other miscellaneous equipment.

The building materials involved are typical of the trade. The designers of the six buildings came from outside of Iowa, primarily from the Midwest. Prior to 1975, the structural concrete frames were left at least partially exposed. The thermal bridges thus created were generally ignored. Double-glazed windows were provided at least for the living units. Central heating and air-conditioning units were provided for most of the public portions of the buildings, but individual window air-conditioners appeared in living units. All six buildings utilize natural gas boilers and water heaters. The number of open windows varies depending on the time of day and the season, but the effect of open windows on infiltration is tremendous. Elderly people specially seem to enjoy open windows, summer or winter, and particularly in the public housing units, apparently ignorant of the effect on energy consumption.

DESCRIPTION OF THE SIX BUILDINGS

Four of the sample buildings are similar by building design characteristics and by energy consumption. They all have central corridors, apartments facing mostly south and north, but also with east/west exposures, and having at least a portion of the structural concrete frame exposed. One of them is a nine-story, three-point-star-shaped building with one of the building faces toward the north, the others due southeast and southwest, respectively. On the first and second floors, the north area is unexcavated. The building was completed about 1973. Its structure is poured concrete framing, including a fair amount of exterior poured concrete walls. The entire exterior wall has 3/4" rigid insulation, covered inside by plaster board. The windows are double-glazed, aluminum framed, and not very tight, allowing some infiltration even when closed. There is a minimum of 1" of rigid insulation on roof. Ceilings are plaster board, suspended. Concrete floors are generally covered by carpeting.

The heating system includes two boilers and a central air-handling system, which supplies about 1.2 air changes per hour into the building. A similar amount of air is exhausted from the apartments by roof ventilators. However, while the original design intended the air to be circulated through a 3/4" high opening under the doors from the corridors into the apartments, these openings have been closed by the carpeting. As a result, the central air escapes through other routes, such as the elevator shafts, and the exhaust air from apartments is primarily air coming in through open windows. The roof fans ran continuously at the time of the energy audit.

Another sample building is an 11-story rectangular building, oriented with its long axis north-south, and having thus one-half of its apartments facing east, the other half facing west. Because the edges of the floor slabs are exposed, the designers did anticipate water problems and provided weep holes through the brick panels at the floor line. The edge of the floor is set back about an inch from the face of the brick. The inside of the exterior wall is covered by plaster board installed on nailing strips. Electrical conduits run in this space, and some of the conduits penetrate through the floor slab to the floor below. This detail of the floor edge turned out to be a continuous problem. Hard-driving rain water entered at the ceiling level and ran down inside the brick wall, spreading into the room below the window panels, eventually spoiling the carpet. Condensation of indoor humidity similarly formed at the cold ceiling edge and ran down in the wall cavity. The condition did not occur uniformly in all units, but affected those units in which brick panels did not close tightly in the ceiling contact.

This building is part of a six-building group in which the other buildings are one-story units. Central heating is provided to the smaller buildings from the high-rise building, but there is only central metering. As a result, leaks in the system are difficult to discover and energy consumption in individual buildings hard to analyze. The efficiency of the central system was tested by separating the supply lines to the other buildings and running the system without the extra loads. The high-rise building was found to perform similarly to the No. 1 building listed in Table 1.

Three buildings in another city were built in succession, about 1973, 1975, and 1977. They are six to nine stories high, with about 160 units in each. Experience from earlier construction was used to improve designs. In the first of the three, both vertical and horizontal concrete frames are exposed (Figure 1). The initial single-pane windows were eventually replaced with double-glazed windows for the living units only. This building is listed as No. 1 in Table 1. A slight improvement was made in the design of the 1975 building, as the floor edge was covered. This made about a 2% improvement in the total energy profile. Better quality windows were also initially installed. The orientation was same, with the long axis running east to west.

The apartments facing north appeared to have slightly fewer windows open than the south-side apartments. The overall energy figures were still similar to the 1973 building, because part of the first floor area was open, and the second floor above that portion was poorly insulated (Figure 2).

In the newest of these three buildings, the structural frame is covered and the exterior walls and roof are better insulated than the previous models. Also, there are fewer windows and insulated wall panels. The orientation is still the same, east to west, but the occupants are perhaps a little more energy conscious, as the percentage of open windows seems to be less (although some are still wide open, regardless of the season, see Figure 3). This building is listed as No. 3 in Table 1.

The sixth sample building is located in the southern-most city of Iowa. It is curvi-linear, following the sun from east to west and also the river on which it fronts. The design of its plan is drastically different, as it discards the central corridor idea and provides instead open concrete balconies on the south side for circulation. As a result, the apartments have two exposures and enjoy cross ventilation (Figures 4 and 5). For this building, solar contribution was estimated as about 14% of the energy demand during the heating season. The natural ventilation is much utilized during the cooling season, particularly during the fall and spring when practically no space conditioning is otherwise needed. As a result, the owners of the building have been pleased with the relatively low energy cost per apartment but have been unaware of the higher energy losses and costs on an area unit basis. As Table 1 shows, this building (No. 2) has an identical energy budget as the No. 1 building, which was the poorest of the three in the other city based on energy use per area unit. Not only is the structural frame without a thermal break, but the HVAC-system was designed to the lowest initial cost. On the north side of this seven-story building, the hot water baseboard heating runs continuously to each end from the center of the building with two risers at center and one at each end. The south side is similar, except the piping has to underpass the doors to the balconies. A total of four thermostats controlled the entire 160 units, located at two top-floor apartments for south and north side piping. The loss of energy through the thermal bridges is compensated by the ample solar contribution during heating season and by shading provided by balconies during cooling season.

At all six buildings, the ventilation systems were found to be out of balance, causing additional open windows for ventilation. In some cases the rooftop exhaust ventilators were incapacitated, and one had a broken damper arm for more than a year without the maintenance personnel being aware of it. In central public areas, imbalancing caused excessive distribution of cooling air to some areas, while in other areas doors were kept open for better ventilation.

PROPOSED IMPROVEMENTS

For the six sample buildings, proposed improvements are being carried out slowly. For the first one mentioned, central air-handling is being re-instituted by providing supply air to the apartments for both heating and cooling, through fire-dampened louvres in corridor doors. Equipment efficiencies are also being improved. At windows, white drapes are used for reducing sun radiation during the cooling season. Occupant education was recommended for the use of drapes.

For the second building, separate metering was recommended. At floor edges 1" thick rigid insulation thermal breaks were proposed. While requiring about a fifteen year payback, the insulation with a flashing will also take care of the water problem.

The two older buildings of the group of three can be improved by adding inside insulation, but it is somewhat of a costly improvement. By using one-inch phenylic insulation boards, u-values can be significantly lowered. The thermal bridges at the structural frame will continue to cost energy, and corrective measures are expensive. The newest of the three buildings continues to lead the way to energy conservation.

For the curvi-linear building with exposure to both south and north in its apartments, improvements to the control system include separate thermostats for each apartment on the south side and zone thermostats at the center of each floor section on the north side. Additional insulation by phenylic wall panels is a possibility. The thermal bridges will be difficult to eliminate. Windows can be improved by demountable plastic panes, mounted with magnetic strips.

Thermal breaks and covering structural frames in high-rise residential buildings are two of the main improvements for future design that resulted from the study of these six buildings. Adequate insulation, particularly by utilizing such superinsulating materials as phenylic interior panels inside the exterior walls, should be considered. On the roof, more insulation than has been traditionally used should be considered, and existing roofs reinsulated when reroofed.

For fenestration, better glazing materials are now available, and new ones are under research. Multiple panels of glass, some with a vacuum between them, and low-emittance coatings can reduce the u-values. Where feasible, the use of airflow windows should be investigated. Airflow windows extract the heat from window areas and redistribute it or exhaust it depending on seasons. Excess of heating energy can be stored in the building masses and reused and distributed where needed. Similarly, airflow windows reduce the effect of sun radiation during the cooling season. Also, night cooling can be utilized from building masses. New types of glass, with radiant barriers, look promising when cost-effective.

While the improved materials and technologies help improve the quality of building envelopes, and the efficiency of HVAC and electrical equipment and lighting systems keeps improving, operational improvements are critical. Maintenance continues to be an important aspect, as the efficiency of equipment needs to be maintained and the condition of roofs and exterior walls kept up to standard. Education of both the maintenance personnel and the occupants will help them understand better how the building systems work and how they can help conserve energy. A system of "commissioning" a building is being proposed as one solution along this line, by providing the owner appropriate documentation and instruction for the operation of the building systems, including the building envelope, and for facilities management. Computer-based energy design and management systems are becoming increasingly available, and some of them consider adequately the role of the building envelope in developing software.

CONCLUSION

Architectural design affects the performance of the building envelope more than is usually recognized. Failure to understand the correct use of materials and technologies will result in energy losses, moisture problems, degradation of materials, costly maintenance problems, and personal discomfort of the occupants. The solution may be by way of improved and modified designs, by new design concepts, and by utilizing new materials and technologies that become available. Thermal breaks are needed to reduce thermal conductivity, reduce bridge cross sections, and increase thermal resistance. Better glazing materials need to be considered, combined with reduced infiltration, and utilizing exterior or interior shading. Understanding of the interfacing of the building envelope and the HVAC and lighting systems is necessary for energy conservation. Daylighting can reduce the use of electricity and of total energy, as long as the amount and orientation of fenestration is appropriately designed.

Of the six sample high-rise residential buildings, the author has selected three for comparison of energy uses and costs, in Table 1. Building No. 1 is representative of four of the samples. For all of the three buildings, Btu/sf.yr. figures show accumulation of heating + cooling.

REFERENCES

- Kainlauri, E.O., 1985. "Architectural Design Considerations in Energy Retrofitting Three High-Rise Residential Buildings in Iowa, USA." Proceedings of CLIMA-2000 World Congress on Heating, Ventilating and Air-Conditioning, Volume 2: Building Design and Performance, pp. 179-184.

TABLE 1
Comparison of Energy Performance in
Three Hig-Rise Residential Buildings

Building	Btu/sf.yr. ($\times 10^3$)	Mj/m ³ yr.	Btu/Apt.yr. ($\times 10^6$)	Gj/Apt.yr.	\$/Apt.yr.
No. 1 (1973)	64.6 + 24.4 = 89.0	8.72	66.6	70.3	\$442.48
No. 2 (1975)	66.1 + 18.2 = 89.0	8.72	48.4	51.1	\$274.39
No. 3 (1977)	44.4 + 14.3 = 58.7	5.75	36.6	38.6	\$259.46

Building design No. 3 performs best of the three, with more insulation, less windows, and with adequate thermal breaks. Design No. 2 appears to be as good on the basis of fuel and electricity costs per apartment per year, but it is only because of the elimination of the central corridors and the resulting smaller total indoor floor area. By better design of the building envelope for energy conservation, the No. 2 design could produce the best all around building for comparison, as long as outdoor balconies are acceptable to occupants for access circulation.



Figure 1. Exterior wall of Building 1 showing exposed concrete frame

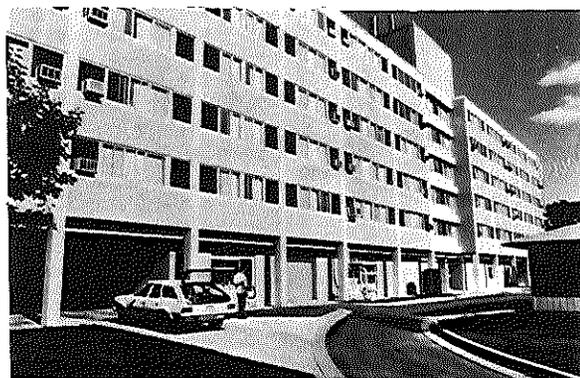


Figure 2. Slightly improved design of exterior wall with floor edges covered



Figure 3. North wall of Building 3 with structure covered and with less window area



Figure 4. South side of Building 2 with balconies and exposed concrete structure

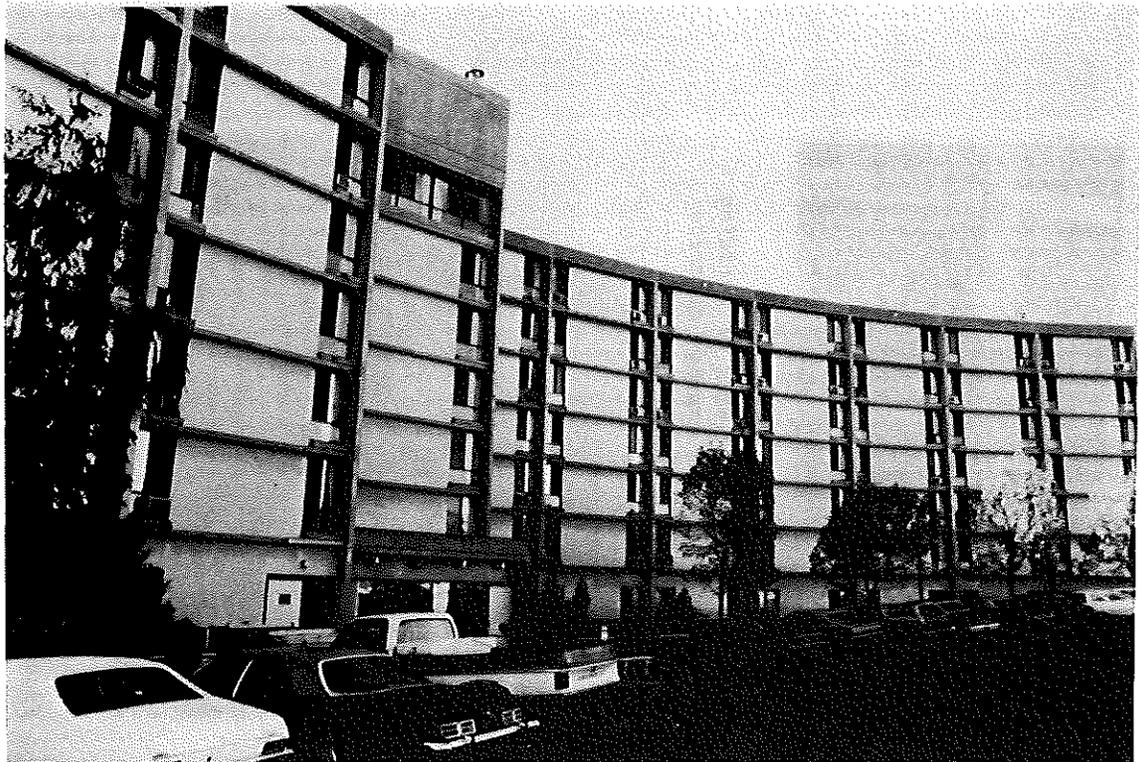


Figure 5. North side of Building 2