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COMPARISON OF AIRTIGHTNESS, INDOOR AIR QUALITY AND POWER CONSUMPTION BEFORE AND AFTER AIR-SEALING OF HIGH-RISE RESIDENTIAL BUILDINGS

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SYNOPSIS

Air infiltration and ventilation has a profound influence on both the internal environment and on the energy needs of buildings. In most electrically heated high-rise residential buildings, in cold climates, during the peak winter conditions (below -18 deg C ambient temperature and above 15 km/hour wind velocity), the air infiltration component contributes to heating load by 10 to 18 W/m^2 - roughly 25 to 35% of peak heating demand. Any reduction in such uncontrolled air infiltration, without sacrificing indoor air quality, will have potential to reduce the peak heating demand. To evaluate the effectiveness of air-sealing measure, the air leakage rates through the building envelope were measured both before and after the air-sealing using the large vane-axial fan. Several air quality measurements (indoor temperatures, relative humidity, CO_2, formaldehyde, radon gas) were taken in each building to assess the practical implications of air sealing on the indoor air quality and thermal comfort.

The whole building airtightness tests showed that the air-sealing of the building envelope reduced the air leakage rate by 32% in one building and 38% in other. Energy monitoring for two buildings showed the reduction in heating demand by approximately 6 W/m^2 of floor space -- 12 to 15% due to air leakage control. Indoor air quality tests showed that the air sealing had no negative impact on the general conditions of comfort and air quality in both buildings. The field implementation of air leakage control has helped to remove some of the uncertainties and shown the potentials for conservation are indeed considerable. This paper presents the field tests and results, and suggest a procedure for the use by air-sealing practitioners to evaluate different air-sealing strategies.

1. INTRODUCTION

Concerned especially with reducing peak power demand, Ontario Hydro (the largest electric utility in Canada) is exploring various energy conservation strategies and their potentials. One way to obtain load reduction and energy efficiency is through improvements in the efficiency of electric space heating in high-rise residential buildings.

The energy audit and assessment of four high-rise residential buildings located in Ontario showed that the peak space heating demand varies from 35 to 65 W/m^2 of floor space. During peak winter conditions, the air leakage component contributes to the heating load by 10 to 18 W/m^2 - roughly 25 to 35% of the peak heating demand [Scanada 1991]. Therefore, the control of air leakage in buildings has become recognized as a key element in achieving energy conservation. Clearly, if high-rise buildings could be better air-sealed, the potentials for reductions in peak demand (plant capacity) and energy usage, and the associated costs, should be enormously attractive to building owners and the utility.

Despite the importance of the process of air leakage in high-rise buildings, it is still an aspect of building science about which there is considerable uncertainty. In part, this problem has been made difficult by the diverse range of buildings, each constructed according to widely varying construction practices. The quantification of air leakage flows is difficult due to the complexities of the flow mechanisms. It is this lack of design considerations in the building construction which has frequently resulted in higher heating consumption, and moisture and air quality problems. Clearly, good predictive design methods and demonstrations of air leakage control should assist in formulating programs relating to improve the energy efficiency of high-rise buildings. This paper describes a procedure to assess air leakage and field tests conducted to assess the effects of air-sealing on overall building airtightness, indoor air quality, and power consumption before and after air-sealing of two high-rise residential buildings.

2. PROCEDURE TO DETERMINE AIR LEAKAGE RATE

A simplified air leakage estimation procedure was developed, based primarily on equivalent air leakage area and local net pressure distribution [Scanada-1 1991]. The pressure difference at a given location depends on the infiltration driving forces (stack, wind and mechanical ventilation) and the characteristics of the opening in the building envelope. A simplified network of air-flow paths can be established using the following information: climate and exposure, building types, building form, building dimensions, surface to volume ratios, shafts, and envelope types, windows and doors, envelope crack lengths, openings, and make-up air strategies. The algebraic sum of air-flow through these paths must always be equal to zero. By applying the mass balance equation, the component of air infiltration which would be occurring during the peak winter condition can be determined. This air-flow rate is responsible for the space heating load due to uncontrolled infiltration. Any reduction in this infiltration flow should decrease the heating requirements for the building. The procedure has been simplified and developed into a practical application tool which will be utilized by assessors and air leakage control contractors.

The leakage paths on the exterior building envelope and shafts are classified as following:

- the basement floor plus ground floor [A_G],
- typical floor [A_T], and
- top floor and penthouse [A_R].

Assuming that there is a neutral zone at the m^th floor as shown in Figure 1, the infiltration rate Q_i and exfiltration rate Q_o through the exterior wall can be expressed as the following with the inner/outer pressure differential ΔP (Pa) and leakage area A (m^2):

$$Q_i - A_G\sqrt{(2|\Delta P_G|/\rho)} + \sum_{j-2}^{M-1} A_{Tj}\sqrt{2|\Delta P_j|/\rho)} \tag{1}$$

and

$$Q_o - \sum_{j-M}^{N} A_{Tj}\sqrt{2|\Delta P_j|/\rho)} + A_R\sqrt{(2|\Delta P_R|/\rho)} \tag{2}$$

The airflow balance is

$$Q_i - Q_o \tag{3}$$

where, Q = Airflow rate, m^3/s *i* - in-flow, *o* - out-flow
A = leakage area, m^2
ρ = air density, kg/m^3
ΔP = pressure difference across building envelope, Pa

The solution to the above three equations can be obtained using the following steps:

1. Determine the leakage paths at each floor and assign the leakage class (visual inspection, thermography, and simple tests...)
2. Establish the stack pressure, wind pressure and pressure due to mechanical ventilation and determine the net indoor/outdoor pressure difference (ΔP) at each floor.
3. Calculate the air flows at each floor level using the above equations by assuming first that the neutral pressure plane (NPP) occurs at the mid height of the building.
4. Equate the air inflow and outflow ($Q_i = Q_o$). If inflow is greater than outflow, then move the NPP one floor below and repeat the calculations as in Step 3. If the inflow

is lower than the outflow, then assume the NPP one floor above and repeat the calculations. These steps should be repeated until at least three percent difference between inflow (Q_i) and outflow (Q_o) is obtained.

5. The air inflow (Q_i) to the building is the uncontrolled air infiltration. Reduction in this component will result in reducing the peak heating demand and energy consumption.

Based on the above method of determining air leakage rate, a field inspection procedure was developed to assess the potential reductions in peak heating demand [Scanada-2 1991]. The air leakage assessment procedure addresses four concerns: (1) What is the air leakage in the building? (2) How much reduction in peak demand is possible with air leakage control? (3) What will be the air sealing priorities and effectiveness for achieving maximum ratio of reduction in kW to the air sealing costs? and (4) How tight can buildings be and still supply adequate ventilation and maintain indoor air quality? Figure 5 shows the algorithm of the assessment procedure.

3. FIELD DEMONSTRATION AND RESULTS

Two buildings were selected for the demonstration of air leakage control. The following tests were conducted to characterize these buildings before and after the air-sealing work: (i) visual inspection and assessment of air leakage paths, (ii) whole building airtightness tests, (iii) indoor air quality, and (iv) monitoring of energy and power consumption. The buildings are as follows:

Building A: It is a fairly well maintained 21-storey apartment tower located in Ottawa in an open and flat terrain. Its 240 suites are fully occupied. The total heated floor space is 14,290 m^2 and the heated volume is 43,515 m^3. The exposed building envelope area is 7,470 m^2. A detailed energy audit of the building showed that the average annual space heating energy consumption was 105 $kWh/m^2/year$. The peak space heating demand during the winter months was 42 W/m^2. Ottawa has 4,634 heating degree days and the winter design temperature of -23 °C and wind speed of 12.5 m/s.

Building B: It is a ten-storey apartment building located in a suburban of Toronto. Its 95 suites are fully occupied. The total heated floor space is 9,825 m^2 and volume is 25,455 m^3. A detailed energy audit showed that the average annual space heating energy consumption was 98.6 $kWh/m^2/year$. The peak space heating demand during the winter months was 46 W/m^2. Toronto has 3646 heating degree days and the winter design temperature is -18 °C and wind speed of 11.5 m/s.

3.1 Estimation of Potential for Air Leakage Control

The air leakage assessment procedure was used to determine the potential for air leakage control in these buildings. The field inspection showed that the total leakage area in the Building A was 2.72 m^2. The air leakage rate at the peak winter conditions was calculated using the above Equations 1, 2 and 3. Figure 2 shows the air leakage rates at the peak winter design condition. The air leakage rate in Building A was 5,990 L/s, resulting in a heating demand of 265 kW - approximately 42% of peak space heating load. By assuming that the air sealing can reduce the uncontrolled air leakage by 32%, the resulting in peak heating demand would be approximately 92 kW. Similar approach was used to assess the Building B. The air leakage control could potentially reduce the peak demand by approximately 33 kW in the Building B.

3.2 Airtightness Tests

A test procedure "*Establishing the Protocols for Measuring Air Leakage and Air Flow Patterns in High-Rise Apartment Buildings*" was used to conduct the whole airtightness tests in both buildings [Magee and Shaw 1990].

Building A: A large axial vane fan with maximum capacity of 23,600 L/s was used to depressurize the building. The fan inlet was connected by 12 m of 0.9 m diameter ducting to a plywood panel temporarily installed in the double doors. Airflow rates were measured upstream of the fan intake using a pair of total averaging tubes. Flow rates are accurate within 5% of the measured values. As shown in Figure 3, this building had a net uncontrolled air leakage rate of 4,740 L/s at 10 Pa pressure difference before air-sealing retrofit. The second test conducted after the air-sealing retrofit showed that the air leakage rate reduced to 3,220 L/s at 10 Pa pressure difference. As shown in Figure 4, the improvement in airtightness was 32% after air-sealing.

Building B: The airtightness results showed that the air leakage rate was 1,885 L/s at 7 Pa pressure difference before air-sealing retrofit. The air-sealing of the building envelope reduced the air leakage rate to 1,165 L/s at 7 Pa pressure difference. The improvement in airtightness was 38% after the air-sealing.

3.3 Indoor Air Quality

Air quality in residential buildings is an area of great concern. With the trend to conserve energy, the effects on air quality should be evaluated to avoid potential health problems which may result from the drastic reduction in air change. Therefore, during this study, air quality tests to monitor the effects of air sealing work were done before and after the air sealing using a test protocol developed by CMHC [CMHC 1990]. The following air quality indicators were chosen for these buildings: formaldehyde, radon, carbon dioxide, relative humidity and indoor temperature. In the Building B, carbon monoxide samples were taken at the ground and underground parking level.

Formaldehyde: The formaldehyde readings did increase slightly in some apartments while remained relatively same in other apartments. However, the upper levels of formaldehyde concentration were well below acceptable limit of 0.1 ppm for residential occupancies.

Radon: Radon samples were taken at the basement, ground and first floor levels. There was not any significant change in the radon level after the air sealing retrofit. The maximum level recorded in these buildings was 20 Bq/m^3 (0.54 pCi/L) which is well below the acceptable level of 148 Bq/m^3 (4 pCi/L).

Carbon Dioxide: The carbon dioxide levels either remained the same or increased in some apartments after the air sealing. However, the upper levels of CO_2 were less than 1000 ppm.

Relative Humidity: The relative humidity levels increased in the lower floor apartments and decreased in the upper storeys. The average RH was at 29% before and 32% after air sealing. The measured data RH readings were within the human comfort zone.

Carbon Monoxide: CO samples were taken at the underground parking and ground floor level at the Building B. Comparison of samples showed no significant difference. The CO levels were well below the accepted limit of 11 ppm.

In both these buildings, it was also observed that the air sealing had reduced the movement of stale odours. In fact, the sealing allowed for more consistent adjustment of air supply to the apartments. The air sealing had no negative impact on the general indoor air quality in the test buildings. Variations and divergent trends observed from apartment to apartment were quite representative of what could be expected due to occupants' lifestyle and habits.

3.4 Comparison of Energy Consumption Before and After Air Sealing

Energy consumption in both the buildings was continuously monitored at every 15 minute interval. The total electric supply to the building and the hot water loads were monitored from the month of November 1990 to June 1991. Similar weather periods, before and after air sealing, were selected to compare the energy consumption. The analysis was performed using the hourly energy simulation program to develop appropriate correction factors to account for solar gains, weather effects and occupancy using the building description. The results are summarized as follows:

Building A: The comparison of similar weather periods showed that the difference in electric load before and after air-sealing was 64 to 84 kW depending on the ambient conditions. Using the building characteristics, and an assumed weather profile for a peak day (ambient temperature varying from -18 to -21 °C and average wind speed of 12.5 m/s) simulation was performed to predict the potential reductions in heating load. Results showed that the reduction in heating load due to air-sealing would be 85 kW on a peak day -- a reduction of 14% of the peak space heating demand. The space heating energy consumption during the heating season reduced by 12%.

Building B: The comparison of similar weather periods showed that the difference in electric load before and after air-sealing was 24 to 35 kW depending on the ambient conditions. Analyses using the building characteristics and an assumed weather profile for a peak day (ambient temperature varying from -15 to -18 °C and average wind speed of 11.5 m/s) were performed to predict the potential reductions in heating load. The reduction in heating load due to air-sealing was 38 kW on a peak day -- an 18% of the peak space heating demand. This reduction in space heating load represents 10.5% of the total electric load for the building. The energy consumption during the heating season reduced by 15%.

4. CONCLUSIONS

- Based on the successful demonstration of air-sealing work and the use of assessment procedure, it can be concluded that the air leakage control offers a potential to reduce the peak electric demand by 4 to 10 W/m^2 of floor space depending on the location and building characteristics.

- A method has been developed to determine the air leakage rate for high-rise buildings. This assessment procedure has been validated with the field demonstration of air leakage control in two high-rise buildings.

- Indoor air quality tests showed that the air sealing of the building had no negative impact on the general conditions of comfort and air quality in both buildings. In both these buildings, it was also observed that the air sealing had reduced the movement of stale odours. In fact, the sealing allowed for more consistent adjustment of air supply to the apartments.

REFERENCES

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2. Magee R.J. and Shaw C.Y. 1990: "*Establishing the Protocols for Measuring Air Leakage and Air Flow Patterns in High-Rise Apartment Buildings*", Report prepared for Canada Mortgage and Housing Corporation, Ottawa, Ontario.
3. Scanada-1 1991: "*Development of Design Procedures and Guidelines for Reducing Electric Demand by Air Leakage Control in High-Rise Residential Buildings*", Scanada Consultants Limited. Report prepared for Ontario Hydro, Toronto, Ontario.
4. Scanada-2 1991: "*Multi-Storey Residential Buildings Weatherization Project - High-Rise Residential Weatherization: Procedure for Assessing Air Leakage and Potential Control in Electrically Heated Residential Buildings of Eight Storeys and Higher*", Scanada Consultants Limited. Report Prepared for Ontario Hydro, Toronto, Ontario.

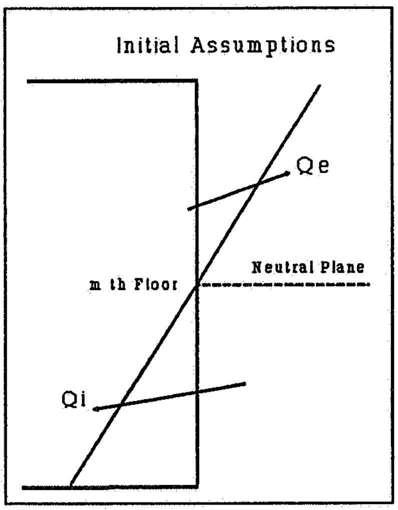

Figure 1: Initial Assumptions.

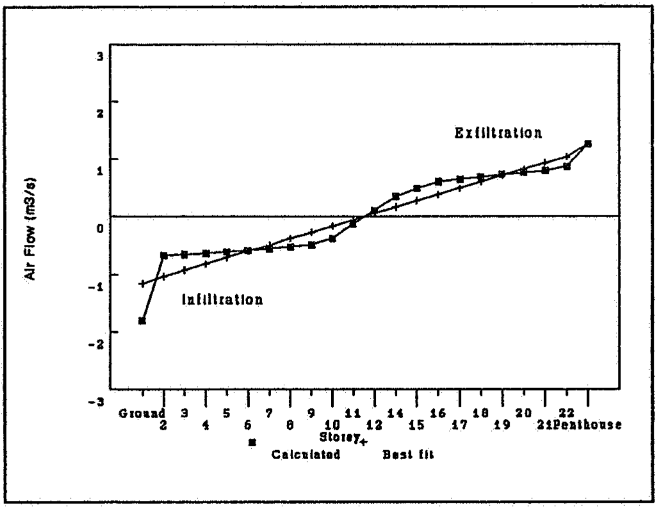

Figure 2: Estimated profile of air in-flow and out-flow at the peak winter conditions for the Building A.

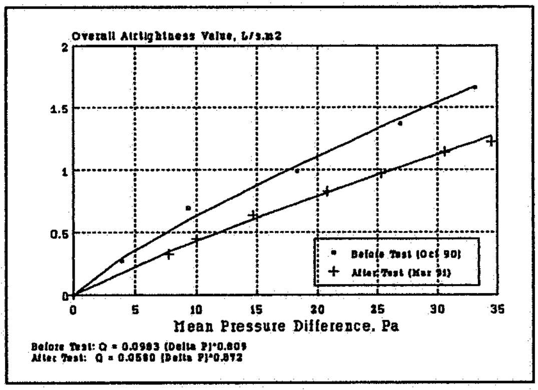

Figure 3: Effect of air-sealing on airtightness of Building A.

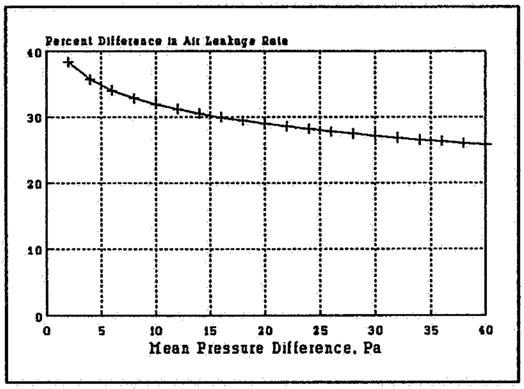

Figure 4: Difference in air leakage rate before and after air sealing of Building A.

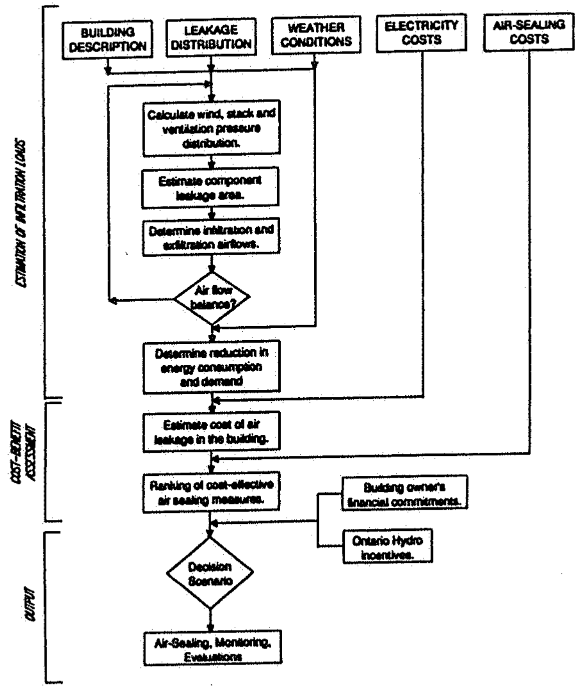

Figure 5: Procedure for Assessing Air Leakage and Potential Control in Electrically Heated Residential Buildings of Eight Storeys and Higher.