USING AIRFLOW MODELLING SOFTWARE TO PREDICT AIRTIGHTNESS IMPROVEMENTS IN A HIGH-RISE RESIDENTIAL BUILDING: A CASE STUDY

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ABSTRACT

Energy loss through air leakage is an important component that can account for 30–40% of heat loss in buildings. Evaluating airtightness improvements can be a challenging problem, particularly in tall buildings. This study presents a modelling technique that can be used as a starting point for evaluating various airtightness retrofits in buildings. To illustrate the applicability of the proposed modelling technique, a building with both pre-retrofit and post-retrofit airtightness measurements was examined. A factorial sensitivity analysis was used to calibrate a CONTAM model using literature values for the pre-retrofit component air leakage rates. Next a series of models were tested to see whether the calibrated model could be used to predict measured post-retrofit whole-envelope air leakage rates. Construction specifications and literature values were used as the inputs in the series of tested models. Using this technique, the whole building post-retrofit air leakage rates were predicted to within 36% of the measured rate. However, on a floor by floor basis, the accuracy of the modelling was significantly less, with one of the floors having a predicted air leakage rate that was 58% higher than the measured rate. The predicted post-retrofit flow exponents are also discussed. The modelling methods used provided reasonable airtightness predictions that can serve as a good starting point for estimating the potential energy savings of retrofit options.

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INTRODUCTION

As energy costs rise and as awareness of our environmental responsibility grows, the need to improve the energy performance of existing buildings increases. Significantly improving the thermal performance of buildings often means considering major thermal retrofits. Such thermal retrofits can include over cladding, window replacement, and improvements in airtightness. Addressing the airtightness of a building can lead to significant energy savings. Researchers have found that air leakage can be responsible for up to 30–40% of the heat loss through a building enclosure (Fennell and Haehnel 2005, Younes et al. 2011). Addressing airtightness, in addition to saving energy dollars, can enhance the durability of the building envelope and improve indoor environmental quality (Fennell and Haehnel 2005).

However, before decisions about which airtightness measures should be implemented, designers need to weigh the potential energy savings of the various measures against the costs. This evaluation is normally carried out with the assistance of building energy modelling software. Unfortunately, modelling air leakage and estimating the potential effectiveness of retrofit measures, particularly in tall buildings, can be challenging. Designers often have to rely on reported leakage values found in databases or on default settings incorporated into modelling software. In their review of airtightness predictive models, Prignon and Moeseke (2017) suggested that the most promising models were those that were based on component air leakage values. Unfortunately, these authors also found that the currently available component air leakage data were largely outdated. Upon inspection of the available databases, it is found that a large portion of the data pertain to buildings built in the 1980s. While this is somewhat limiting, many buildings that were built in the 1980s are in need of retrofit, and therefore, these data are still very useful. Further, for other building vintages, this data can still be used as a starting point when models are calibrated.

The accuracy of predicting the effects of various airtightness retrofit measures can be improved if actual air leakage data are gathered prior to retrofit. In an effort to reveal the potential benefits of using actual air leakage data, this study examines the case of a 13 storey building located in Vancouver, British Columbia. In this case study, some pre- and post-retrofit airtightness data were available. The data were originally gathered and reported by Ricketts (2014). In the sections that follow, these data have been incorporated into a CONTAM, an airflow modelling software (Dols and Polidoro 2015). The CONTAM model was calibrated using existing airtightness data. Then the effect of the retrofit measures were incorporated into the model, and air leakage predictions were made. These post-retrofit predictions were then compared to the actual post-retrofit air leakage measurements.

THE STUDY BUILDING

Pre-Retrofit Building Description

A brief description of the residential building and the retrofit measures have been provided here. For more detailed information regarding the building and the retrofit measures, see Ricketts (2014). The residential building was built in 1986, and has a gross floor area of approximately 5,000 m^2 (53,819 ft^2) spread across 13 floors. The envelope has a surface area of approximately 3,800 m^2 (40,902 ft^2) and is composed of approximately 45% glazing, 44% opaque wall, and 11% roofs and decks. The original windows were double glazed insulated glazing units (IGUs) with a non-thermally broken aluminum frame. Most of the windows had an operable portion. The opaque portion of the envelope is cast-in-place concrete. The original roof was a protected membrane roof with a number of penetrations through it from the lower floors. The penetrations were found to be poorly sealed in the pre-retrofit building. For some of the penetrations running through the roof into the mechanical room, which is open to the outdoors through passive vents, the sealing was poor enough that it was possible to see daylight around the penetrations. The balconies on all floors are enclosed. The suites above the 8th floor all have gas fireplaces. Each fireplace does not have a damper and is separately vented by means of a B-vent through the roof. The suites on floors 12 and 13 have small areas that have glass curtain wall instead of windows; these suites also include small areas with skylights.

Retrofit Measures

The enclosure retrofit was completed in December of 2013. The measures included the installation of a new protected membrane roof, the replacement of windows and doors, and the overclad of the concrete walls. As part of the retrofit, air sealing was carried out around windows, doors, and other penetrations. Although a new air barrier was not installed, sealing of cracks and transitions along the walls was performed using a liquid applied membrane. The retrofit on the roof included a new protected membrane and improved sealing around all penetrations. The replacement windows were triple-glazed IGUs with low-conductivity fiberglass frames. All operable windows were casement style windows. The gas fireplaces and the venting were not modified in any way.

Airtightness Testing and Results

Both pre- and post-retrofit air leakage testing were carried out on this residential building. The air leakage testing performed used the sequentially neutralized pressurization/depressurization test technique. In this technique, a zone in the building is chosen to be the "test" zone. Air leakage testing is then performed in this zone with the adjacent zones either at the same pressure as the test zone or unpressurized. This allows the tester to control the zones between which air can flow. If the test zone is adjacent to the exterior, the tester can measure the airtightness of the building envelope in that zone by testing with it and all the adjacent zones at the same pressure. This was the approach used to test the suite and whole floor envelopes in the case study building. A complete description of the test method used at the case study building is given in Ricketts (2014).

The building envelope was evaluated on floors 1, 3, 11, and 13. The envelope evaluation carried out on floors 1 and 13 involved the testing of individual suites as well as whole floor testing. This testing revealed that the whole floor test results were much higher than the aggregated suite-based results. It is possible that the whole floor testing measurements included air leakage that was not part of the envelope. For example, whole floor testing would necessarily include leakage through elevator doors, which are not part of the envelope. On floors 3 and 11, only suite based testing was completed. All of the testing was completed with the vents and other intentional openings unsealed.

To obtain a whole floor envelope leakage rate, the normalized suite test results given in Ricketts (2014) were averaged for each floor. This value was then multiplied by the entire envelope area of that floor to obtain the whole floor air leakage. Since whole building testing was not performed, a whole building envelope leakage rate was estimated using the whole floor leakage rates. The results of these calculations are shown in Table 1 for the pre-retrofit and post-retrofit building.

Table 1: Pre- and Post-Retrofit Air Leakage Results by Floor Based Upon Averaged Suite Measurements

	Pre-Retrofit			Post-Retrofit			
Floor	***n***	Q_{75} **[L/s]** ($Q_{0.3}$ **[cfm])**	q_{75} **[L/s·m²]** ($q_{0.3}$ **[cfm/ft²])**	***n***	Q_{75} **[L/s]** ($Q_{0.3}$ **[cfm])**	q_{75} **[L/s·m²]** ($q_{0.3}$ **[cfm/ft²])**	**Reduction**
1	0.61	879 (1862)	1.73 (0.34)	0.67	509 (1078)	1.00 (0.20)	42.2%
3	0.59	791 (1676)	3.34 (0.66)	0.66	373 (790)	1.57 (0.31)	52.9%
11	0.57	1047 (2218)	4.41 (0.87)	0.59	476 (1009)	2.01 (0.40)	54.6%
13	0.61	2283 (4837)	4.35 (0.86)	0.63	890 (1886)	1.70 (0.33)	61.0%
Whole Building	–	13,476 (28,554)	3.48 (0.67)	–	6,182 (13,099)	1.60 (0.31)	54.1%

Where: Q_{75} **(**$Q_{0.3}$**)** is the airflow at a pressure difference of 75 Pa (0.3 inH_2O), and q_{75} **(**$q_{0.3}$**)** is the airflow at a pressure difference of 75 Pa (0.3 inH_2O) normalized by the envelope area.

USING CONTAM TO PREDICT AIRTIGHTNESS

The pre-retrofit results shown in Table 1 were used to calibrate a pre-retrofit CONTAM model. Calibration began by breaking up the existing whole-floor envelope air leakage rate into its components. With the exception of the bathroom vents, envelope component leakage testing was not performed in the case study building. Therefore, literature values were used to estimate the component leakage rates. The main sources of component leakage rates used in this study were the databases provided by Orme et al. (1998) and by ASHRAE (2001). Much of the data provided in these databases have been compiled from component testing completed before 1990 on buildings constructed in the 1970s and 1980s.

Different techniques were attempted for assigning component air leakage rates, including factorial analysis and Monte Carlo simulation. However, only factorial analysis is discussed here. The factorial analysis was used to determine the combination of component leakage rates that would lead to the best approximation of the pre-retrofit air leakage rate.

Factorial Analysis Using Literature Values for Pre-Retrofit Model Calibration

Two distinct models, based on the underlying assumptions, were created: Model 4 and Model 5. It was assumed in the first model, Model 4, that the fixed windows were airtight and that the concrete roof leakage rate was the same as the concrete wall leakage rate. This first assumption was tested because the component air leakage rate for fixed windows was not found in either of the two databases, Orme et al. (1998) and ASHRAE (2001). The second assumption was made to reduce the number of variables used in the factorial sensitivity analysis. However, upon completion of the first model, a second model, Model 5, was developed. In Model 5, air leakage rates were assigned to the fixed windows using values from Weidt and Weidt (1980) and the roof air leakage rate was separated from the wall air leakage rate.

The factorial analysis for both models assigned three values to each variable (see Table 2). When the values

were obtained from Orme et al. (1998), the three values that were used were the upper quartile, median, and lower quartile. When the values were obtained from ASHRAE (2001), then the three values used were the maximum, best estimate, and minimum. Since the variables were varied independently, the number of iterations increased to the power of the number of variables. For example, because three values for each variable were used, if *k* variables are used, then there will be 3^k model trials or iterations. Minimizing the number of variables is therefore beneficial, since it significantly reduces both the number of iterations and the computing time. This approach was taken for both models, although the second model introduced two new variables. To reduce the number of variables, in the pre-retrofit models, it was assumed that the frame leakage rates and the interface leakage rates were all upper quartile or maximum, depending on the source database (see Table 3). This assumption is consistent with the guidance provided by Orme et al. (1998). Note that the bathroom vent leakage rate was also not used as a variable in the factorial analysis, since it was measured.

Table 2: Inputs Used for the Pre-Retrofit Model Factorial Analysis

	Max Value		**Mid Value**		**Min Value**		**ELA_4 Units**	
Component	**ELA_4**	***n***	**ELA_4**	***n***	**ELA_4**	***n***		**Reference**
Dryer Vent	34 (5.27)	0.65	15 (2.33)	0.65	12 (1.86)	0.65	cm^2 (in^2)	ASHRAE (2001)
Kitchen Vent	72 (11.16)	0.65	40 (6.20)	0.65	14 (2.17)	0.65	cm^2 (in^2)	ASHRAE (2001)
Sliding Door Opening	15 (0.216)	0.65	5.5 (0.079)	0.65	0.6 (0.009)	0.65	cm^2/m^2 (in^2/ft^2)	ASHRAE (2001)
Swing Door Opening	7.487 (0.354)	0.6	2.407 (0.114)	0.6	0.731 (0.035)	0.6	cm^2/m (in^2/ft)	Orme et al. (1998)
Concrete Wall	1.316 (0.019)	0.75	1.215 (0.017)	0.75	0.587 (0.008)	0.8	cm^2/m^2 (in^2/ft^2)	Orme et al. (1998)
Concrete on Roof*	1.316 (0.019)	0.75	1.215 (0.017)	0.75	0.587 (0.008)	0.8	cm^2/m^2 (in^2/ft^2)	Orme et al. (1998)
Fireplace	90 (13.95)	0.65	65 (10.08)	0.65	40 (6.20)	0.65	cm^2 (in^2)	ASHRAE (2001)
Curtain Wall: Operable and Fixed	1.517 (0.022)	0.74	1.316 (0.019)	0.75	0.999 (0.014)	0.77	cm^2/m^2 (in^2/ft^2)	Orme et al. (1998)
Window: Operable	3.654 (0.173)	0.6	1.159 (0.055)	0.6	0.767 (0.036)	0.6	cm^2/m (in^2/ft)	Orme et al. (1998)
Window: Fixed**	0.255 (0.012)	0.6	0.123 (0.006)	0.6	0.035 (0.002)	0.6	cm^2/m (in^2/ft)	Weidt and Weidt (1980), assumed n from Orme et al. (1998)

Where: ELA_4 is the equivalent leakage area at a 4 Pa (0.02 inH_2O) pressure difference with a discharge coefficient of 1.0.
*For Model 4, Concrete on Roof = Concrete Wall for each iteration (in other words, it is not a separate variable).
**Not used in Model 4

Table 3: Remaining Inputs for the Pre-Retrofit Model

Component	ELA_4	*n*	ELA_4 Units	Reference
Bathroom Vents	19.35 (3.00)	0.65	cm^2 (in^2)	Measured. See Ricketts (2014)
Chimney Penetration Interface	6.952 (0.328)	0.6	cm^2/m (in^2/ft)	Orme et al. (1998)
Plumbing Penetration Interface	7.487 (0.354)	0.6	cm^2/m (in^2/ft)	Orme et al. (1998)
Sliding Door Frame	1 (0.014)	0.65	cm^2/m^2 (in^2/ft^2)	ASHRAE (2001)
Swing Door Frame	0.107 (0.005)	0.6	cm^2/m (in^2/ft)	Orme et al. (1998)
Floor Open to Parking Garage	0.15 (0.002)	0.65	cm^2/m^2 (in^2/ft^2)	ASHRAE (2001)
Curtain Wall Frame	0.107 (0.005)	0.6	cm^2/m (in^2/ft)	Orme et al. (1998)
Window Frame	0.107 (0.005)	0.6	cm^2/m (in^2/ft)	Orme et al. (1998)

Where: ELA_4 is the equivalent leakage area at a 4 Pa (0.02 inH_2O) pressure difference with a discharge coefficient of 1.0.

For Model 4, eight variables were tested with 3 different values each as shown in Table 2 (Note that 'Window: Fixed' is not used in this model and that 'Concrete on Roof' is varied with 'Concrete Wall', i.e. their values are the same for each iteration). For Model 5, the values of all ten variables given in Table 2 were varied. Therefore, there were 6561 combinations tested for Model 4, and 59,049 combinations tested for Model 5. A separate file for each of the combinations was generated using a computer program written specifically for this study. A similar program is available from the CONTAM group on Yahoo! (Dols 2016). These models were then evaluated in batch mode using ContamX, the numerical solver of CONTAM.

Although there were a large number of combinations, only a select few matched well with the measured values. For an iteration to 'match well,' the percentage difference between the modelled and measured value calculated using Equation 1 for each floor had to be within ±10%. As well, the range in calculated percentage differences of the floors, as determined by Equation 2, had to be within ±10%. These conditions were chosen to ensure reasonable agreement between modelled and measured values on a per floor basis and to reduce the spread in percentage difference of the floors. Without adding the second condition, the maximum spread in percentage difference would have been 20%. Equation 3 shows the two conditions combined in a single equation that could be used in an analysis software.

$$\%\text{Diff(Floor)} = \frac{Q_{75(\text{modelled})} - Q_{75(\text{measured})}}{Q_{75(\text{measured})}} \times 100 \tag{1}$$

$$\begin{aligned}\%\text{Diff Range} = {} & \text{MAX}[\%\text{Diff(Floor 1)}, \%\text{Diff(Floor 3)}, \%\text{Diff(Floor 11)}, \%\text{Diff(Floor 13)}] \\ & - \text{MIN}[\%\text{Diff(Floor 1)}, \%\text{Diff(Floor 3)}, \%\text{Diff(Floor 11)}, \%\text{Diff(Floor 13)}]\end{aligned} \tag{2}$$

$$\text{Matched Combination} = [\%\text{Diff(Floor 1)} \;\&\; \%\text{Diff(Floor 2)} \;\&\; \%\text{Diff(Floor 11)} \;\&\; \%\text{Diff(Floor 13)} \;\&\; \%\text{Diff Range}] < 10\% \tag{3}$$

For Model 4 and Model 5, there were 10 and 195 iterations, respectively, that met the 'match well' criteria established above. The measured results for the pre-retrofit building and the range in modelled results for both models are shown in Figure 1. Note that, as expected, the range in results for Model 5 is slightly larger because of the larger number of iterations. However, for all of the floors, the modelled range is within 10% of the measured value.

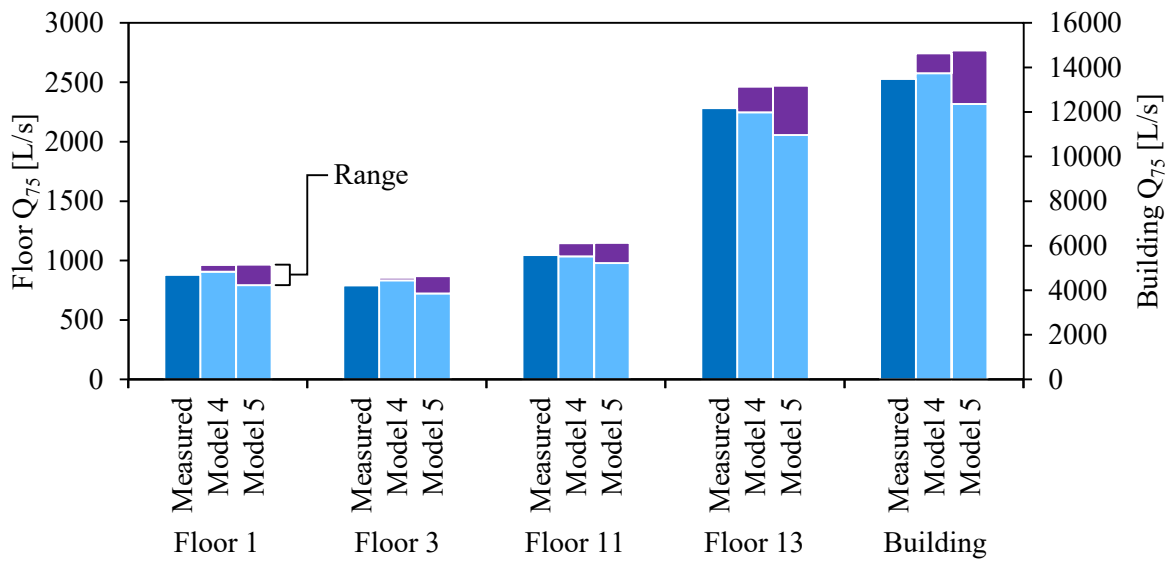

Figure 1: Pre-Retrofit Modelled and Measured Leakage Rates for Each Floor and for the Whole Building (Conversions: 1 L/s = 2.119 cfm; 75 Pa = 0.3 inH_2O)

Using the Calibrated Pre-Retrofit Model to Estimate Post-Retrofit Air Leakage Reduction

Having found the combination of variables that matched well with the pre-retrofit air leakage, the next step was to use these calibrated models to predict the post-retrofit air flows. The number of iterations that had to be carried out for the post-retrofit models was greatly reduced because only those variables that had been affected by the retrofit measures needed to be tested. The other variables remained the same as the pre-retrofit model. Therefore, only unique combinations of untested variables from the pre-retrofit models were used for the post-retrofit models. The number of unique combinations for Model 4 was four and for Model 5 it was nine.

In these post-retrofit trial iterations, the air leakage values used for the retrofitted components were the values specified in the construction documents. The specifications provided values for the windows, doors (sliding and swing), and curtain wall. However, the specifications did not provide any flow exponent values. Since all of the specifications were based on crack length, a flow exponent value of 0.6 was assumed, as suggested by Orme et al. (1998). The retrofit also included a roof replacement, for which an airtightness specification was not provided. Therefore, a sensitivity analysis was performed using reasonable literature values (Table 4). The roof replacement included improving the sealing of penetrations and the replacement

of the membrane. Since no protected membrane values were available, it was assumed that the retrofit would result in an air leakage rate that was similar to a wall with a continuous air barrier. Therefore, the ASHRAE (2001) maximum, best estimate, and minimum values for this type of wall were used for the protected membrane roof. However, the original roof inputs used in the pre-retrofit model were also tested (Table 4). Introducing this air leakage variable for the roof resulted in a total of 12 and 27 post-retrofit iterations for Model 4 and Model 5, respectively.

Although Model 4 did not include fixed window air leakage for the pre-retrofit model, it was included in the post-retrofit model, since it was included in the specifications. For Model 5, three post-retrofit versions were created to test variations of the post-retrofit inputs. The three models are labelled Model 5A, Model 5B, and Model 5C. Model 4 and Model 5A use median/best estimate values for the frames and interface seals (

Table 5). Model 5B and Model 5C use lower quartile/minimum values for the frames and interface seals (

Table 5). Model 5C also uses the pre-retrofit values for 'Concrete on Roof' to see the effects this will have on the estimation.

Table 4: Retrofitted Roof Inputs for the Post-Retrofit Model Factorial Analysis

	Max		**Mid**		**Min**		**ELA_4 Units**	
Component	**ELA_4**	***n***	**ELA_4**	***n***	**ELA_4**	***n***		**Reference**
Concrete on Roof*	0.21 (0.003)	0.65	0.15 (0.002)	0.65	0.055 (0.001)	0.65	cm^2/m^2 (in^2/ft^2)	ASHRAE (2001)
Concrete on Roof**	1.316 (0.019)	0.75	1.215 (0.017)	0.75	0.587 (0.008)	0.8	cm^2/m^2 (in^2/ft^2)	Orme et al. (1998)

Where: ELA_4 is the equivalent leakage area at a 4 Pa (0.02 inH_2O) pressure difference with a discharge coefficient of 1.0.
*Used in all models except Model 5C
**Used in Model 5C only

Table 5: Remaining Inputs for the Post-Retrofit Models

	Model 4 & 5A		Model 5B & 5C		ELA_4 Units	
Component	**ELA_4**	***n***	**ELA_4**	***n***		**Reference**
Chimney Penetration Interface	1.248 (0.059)	0.6	0.241 (0.011)	0.6	cm^2/m (in^2/ft)	(Orme et al. 1998)
Plumbing Penetration Interface	6.596 (0.312)	0.6	5.615 (0.265)	0.6	cm^2/m (in^2/ft)	(Orme et al. 1998)
Sliding Door Frame	1 (0.014)	0.65	0.3 (0.004)	0.65	cm^2/m^2 (in^2/ft^2)	(ASHRAE 2001)
Sliding Door Opening	0.102 (0.005)	0.6	0.102 (0.005)	0.6	cm^2/m (in^2/ft)	Specifications
Swing Door Frame	0.022 (0.001)	0.6	0.003 (0.0001)	0.6	cm^2/m (in^2/ft)	(Orme et al. 1998)
Swing Door Opening	0.102 (0.005)	0.6	0.102 (0.005)	0.6	cm^2/m (in^2/ft)	Specifications
Curtain Wall Frame	0.022 (0.001)	0.6	0.003 (0.0001)	0.6	cm^2/m (in^2/ft)	(Orme et al. 1998)
Curtain Wall: Operable and Fixed	0.102 (0.005)	0.6	0.102 (0.005)	0.6	cm^2/m (in^2/ft)	Specifications
Window Frame	0.022 (0.001)	0.6	0.003 (0.0001)	0.6	cm^2/m (in^2/ft)	(Orme et al. 1998)
Window: Operable	0.102 (0.005)	0.6	0.102 (0.005)	0.6	cm^2/m (in^2/ft)	Specifications
Window: Fixed	0.046 (0.002)	0.6	0.046 (0.002)	0.6	cm^2/m (in^2/ft)	Specifications

Where: ELA_4 is the equivalent leakage area at a 4 Pa (0.02 inH_2O) pressure difference with a discharge coefficient of 1.0.

The results of the iterations for each model are shown together in Figure 2. All of the models over-estimated the leakage rate for the whole building and for floors 1, 3, and 11. The measured leakage rate of floor 13 is within the range of predicted values for Model 4, Model 5A, and Model 5B. However, Model 5C over-estimates the leakage rate of floor 13, as shown in Figure 2.

From Figure 2, it can be seen that floor 11 is the least accurately predicted floor for all of the models, followed closely by floor 3. In the best model, Model 5B, the air leakage on floor 11 is over-estimated by 57 to 104% and floor 3 is over-estimated by 46 to 85%. The model with the poorest predictions, Model 4, over-estimated floor 11 by 86–109% and floor 3 by 83–88%. The air leakage on floor 1 was also consistently over-estimated. Model 5B over-estimated floor 1 by 4 to 37% and Model 4 over-estimated floor 1 by 38 to 43%. In Model 5C, floor 13 is over-estimated by 27 to 96%, while all the other models correctly predict the leakage rate of floor 13.

Figure 2 shows that for the whole building air leakage, Model 5B has the least error. Model 5B over-estimated the building air leakage by 36 to 70%, whereas Model 4 over-estimated the building air leakage by 68 to 78% and Model 5C over-estimated it by 44 to 84%. Since the only difference between Model 5A and Model 5B is the frame and interface leakage rates, these two models could be combined to provide the full range of possible air leakage predictions.

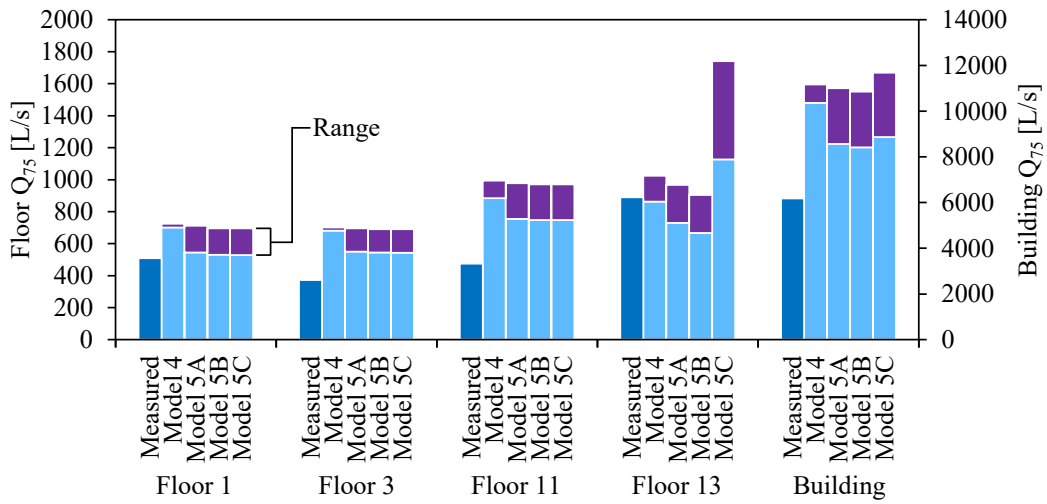

Figure 2: Post-Retrofit Modelled and Measured Leakage Rates for Each Floor and for the Whole Building (Conversions: 1 L/s = 2.119 cfm; 75 Pa = 0.3 inH_2O)

Another way of examining the measured and modelled data is to examine the percentage of reduction in air leakage. It is this latter quantity that can be used to estimate the amount of energy saved through retrofit measures. Figure 3 shows the results of the calculation. For the whole building and floors 1, 3, and 11, all of the versions of Model 5 have a predicted reduction range that is more accurate than Model 4. This suggests that, overall, the assumptions made for the pre-retrofit model of Model 4 likely led to the larger error in estimating the percent reduction in air leakage. Model 5B was found to predict the building leakage reduction most accurately, with a predicted reduction of 22 to 38%, although this is still less than the 54% that was measured. Further, since the quality of workmanship is an unknown in any retrofit, a range of values for the frame and interface leakage rates is justifiable. Since both Model 5A and Model 5B account for this range, the two models could be combined to give a full range of possible post-retrofit air leakage reductions, since the only difference between these two models is the frame and interface air leakage rates. When the two models are combined, the resulting range in air leakage reduction is 21 to 38%.

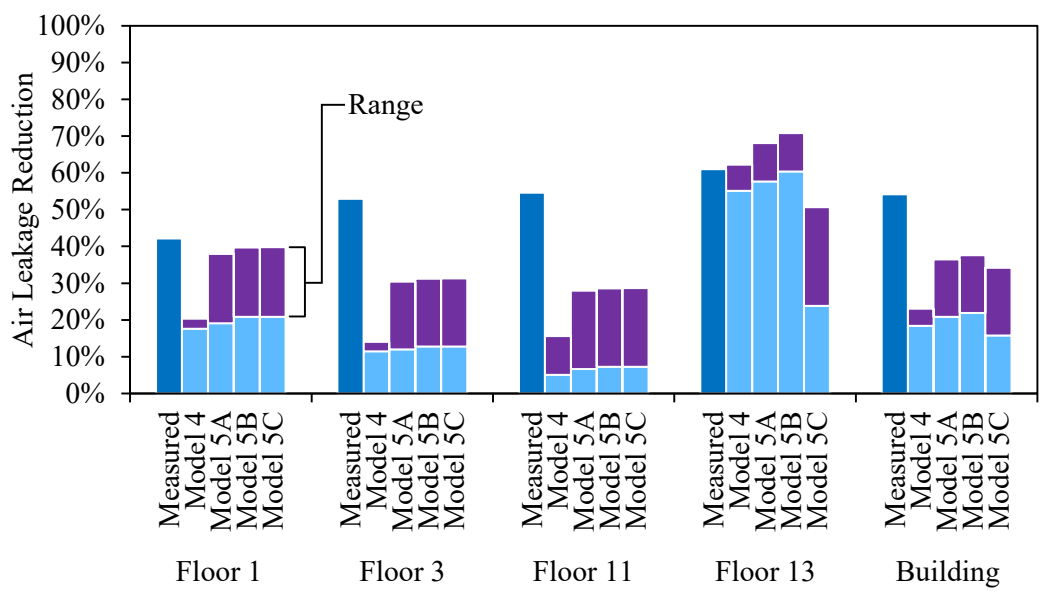

Figure 3: Post-Retrofit Air Leakage Reduction for Each Floor and for the Whole Building

ESTIMATED POST-RETROFIT FLOW EXPONENTS

The quantity of air leaking from a building is a function of the leakage area, the resulting net pressure difference, and the roughness and geometry of the leakage opening. Air leakage can be described by a basic flow equation that takes a power law form. The value of the flow exponent is a function of the flow regime and ranges in value from 0.5 for turbulent flow to 1.0 for laminar flow (ASHRAE 2001). Of importance with the exponential flow equation is that an incorrectly estimated flow exponent can lead to significant errors in flows calculated for pressure differences other than the test pressure, such as the pressures experienced under normal building operation.

Generally, the flow exponents for buildings fall within the range of 0.6–0.7, and a commonly assumed value of 0.65 is used for buildings and building components for which a flow exponent is not given. This is the approach used by modellers when using the component leakage rates given in ASHRAE (2001), since no flow exponents are given for these rates. This, however, provides a rather predictable whole envelope flow exponent of 0.65. On the other hand, Orme et al. (1998) provides leakage rates with flow exponents that are determined using one of two possible routes. The first route is for leakage rates that are crack length based. These all get a flow exponent of 0.6. The second route is for leakage rates that are area based. The flow exponent for these is calculated using a regression equation given in the report. Since Orme et al. (1998) was used to obtain the majority of the component leakage information, the flow exponents predicted by the models are not obvious or assumed. Therefore, the predicted flow exponents are compared to the measured flow exponents and the commonly assumed flow exponent of 0.65 to determine the applicability of the flow exponents used in this study.

Figure 4 shows the modelled and measured flow exponents and the commonly assumed flow exponent of 0.65, which is also the exponent that would have been predicted if ASHRAE (2001) had been used. None of the predicted flow exponents match the measured values. Further, Model 5C significantly over-estimates the flow exponent for floor 13. This is due to the higher leakage rate and flow exponent given in Orme et al. (1998) for the roof leakage used in this model. Although none of the flow exponents match, the flow exponents for floors 1, 3, and 13 are reasonably well estimated. However, floor 11 is not estimated well. It is worth noting that the measured flow exponent for floor 11 is below 0.6, whereas none of the component leakage rates given in the databases have a flow exponent below 0.6. It would therefore be impossible to predict the floor 11 flow exponent using the leakage data given in Orme et al. (1998) and ASHRAE (2001). From Figure 4, it is apparent that neither ASHRAE (2001) nor Orme et al. (1998) would correctly predict the flow exponents. It does, however, appear that ASHRAE (2001) (or assuming a flow exponent of 0.65) would have provided a slightly better flow exponent prediction.

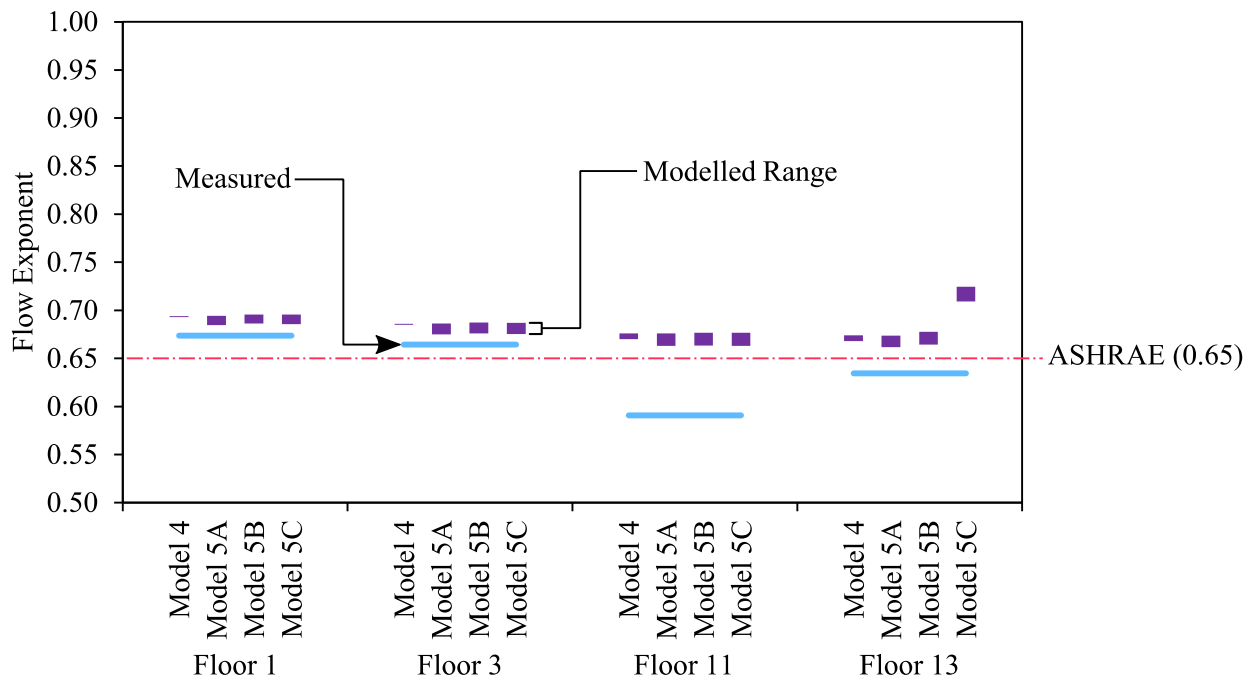

Figure 4: Post-Retrofit Flow Exponents for Each Floor

CONCLUSIONS AND RECOMMENDATIONS

The improved prediction accuracy of Model 5 suggests that the inclusion of fixed windows and the varying of the roof leakage separately from the wall leakage is beneficial. However, Model 4 requires less computing time and has fewer iterations than Model 5 and is, therefore, still a reasonable approach. It should be noted that on a floor-by-floor flow basis, none of the models accurately predicted the air leakage for all of the floors. Of all the models, Model 5A and Model 5B produced the most accurate estimates. For the purposes of energy modeling and design, Models 5A and 5B could be combined to include the full range of possibilities, since the only difference between Models 5A and 5B is the quartile used for interface and frame leakage rates. Estimating these latter quantities can be highly dependent on construction quality, and therefore, the range of the actual air leakage may be rather large.

Although the models predict what may be considered an upper bound for the post-retrofit airtightness, the use of the predicted airtightness to estimate infiltration must be done with caution, since the models do not accurately predict the flow exponents. They therefore do not necessarily provide an upper bound for post-retrofit infiltration. Depending on the method used to estimate component flow exponents and the source used to obtain component leakage information, the predicted infiltration rates may be over- or under-estimated.

For future research, it is recommended that component and whole-envelope air leakage testing be completed pre-retrofit. This will provide pre-retrofit component air leakage rates that are representative of the building and can be used to more accurately estimate the pre-retrofit leakage rates and the post-retrofit airtightness improvement. Further, there is a need to develop and publish a database of component leakage values based

on pre- and post-retrofit testing. Such a database would be invaluable for improving air leakage modelling and ultimately energy savings predictions.

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