A New Paradigm for the Design of Sustainable Buildings

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ABSTRACT

Despite advances in building science technology, many buildings do not meet performance expectations, and in some cases, fail prematurely. Why do we continue to design and construct buildings that underperform? Is it simply a result of cost cutting, lack of skilled trades, or lack of awareness of all of the loads and system interactions?

By examining buildings with performance problems, we can learn how to improve the design of new buildings. This examination includes both detailed investigations to learn the reasons for the failure to meet the expected performance levels, as well as a more holistic review to determine the impact of the performance problems on the other building systems. Many of the problems fall outside of traditional building design team disciplines and responsibilities. A review of the causes for a sampling of building performance problems in multi-unit residential buildings is provided, including water ingress, ventilation, and energy consumption problems, as well as a discussion of the implications of these problems on other building systems. This review provides a basis for developing new approaches in building design and construction.

We have the ability to build buildings that meet our performance expectations. However, if we are going to meet our future energy efficiency and other building performance goals, there is a need for a new design paradigm. This new design paradigm utilizes actual building performance data along with a systems approach in order to consistently result in new buildings that meet our expectations, and provides the means to effectively improve our building stock in the future.

INTRODUCTION

The actual in-service performance of buildings is becoming a greater consideration in the design of new buildings. But how is the actual performance confirmed, and is this information being passed on to the original design and construction team? Considering that all buildings will experience some performance related problems over their service life, are these failure mechanisms and associated results being adequately investigated so that lessons can be learned to better design and construct buildings in the future? The authors have been involved in a number of building enclosure surveys to examine building performance issues. In these surveys, buildings commonly did not meet performance expectations.

One of these surveys of building enclosure performance problems (CMHC 1996) compared buildings with performance problems to control buildings that were performing adequately. Five

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design firms provided a list of thirteen suggested control buildings without problems. Upon reviewing the list, the authors of the survey recognized the names of some of the buildings from previous investigations, and found that ten of the thirteen buildings were buildings experiencing significant premature building enclosure performance problems. The project designers were unaware of these performance problems.

The following sections provide specific examples of how building problems became known, reviews the extent of the problems, and identifies some common factors relevant to the performance problems. By examining buildings with performance problems, we can find ways to improve both the design process as well as the specific details for new, more sustainable buildings.

IMPACT INVESTIGATION

A dramatic example of how the building owners and designers became aware of building enclosure failures is provided below.

The authors were asked to investigate the results of a tragic small plane crash at a residential tower complex in Richmond, British Columbia. The impact of the plane at the 9th floor, north elevation of one of the buildings caused significant damage to the building enclosure assemblies in this area. The impact also resulted in breakage of water pipes, flooding of the building units at and below the area of impact, and associated damage. Although the damage as a result of the impact was significant, it was much less extensive than the damage identified during the investigation as a result of ongoing water ingress problems.

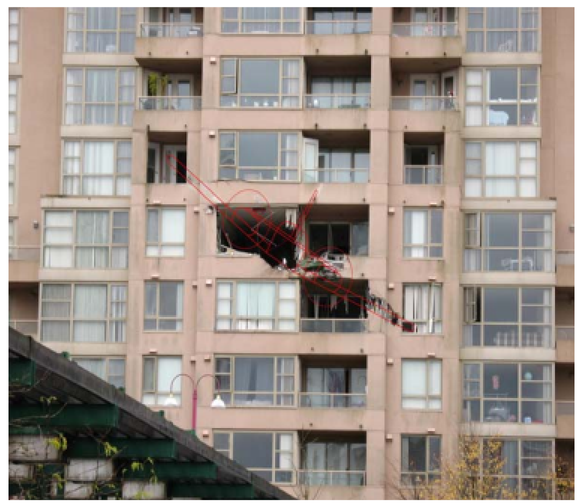

Figure 1: Partial elevation of building showing impact location of plane.

The exterior walls of the two buildings primarily relied on stucco cladding as shown in Figure 2. Poured-in place concrete walls, coated with an acrylic finish coat to match the stucco cladding also formed part of the building enclosure.

Thermally broken aluminum framed windows, window-wall, and doors were typically incorporated into the buildings. Head and sill flashings, along with subsill drainage consisting of self adhered membrane were typically incorporated below the glazing assemblies.

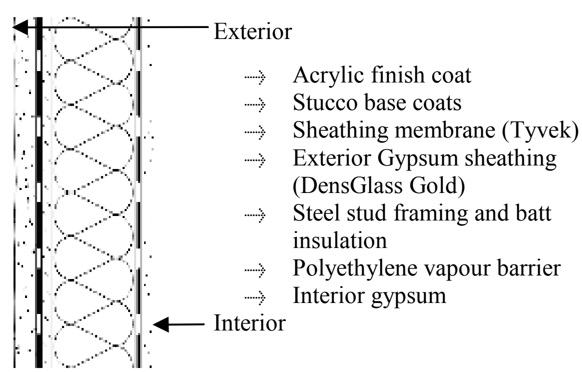

Figure 2: Section through typical wall assembly

Figure 3: Cut section of punch window sill at crash location

Figure 4: Cut section of a window sill at impact location

Widespread rain water leakage problems were identified, which resulted in damage to the interior finishes, steel stud framing, and other wall components. Examples of the damage are shown in Figures 5 and 6 below.

Figure 5: Corrosion of the exterior wall steel studs and deterioration of the exterior gypsum sheathing

Figure 6: Fungal growth on the interior finishes below a window at an exterior wall.

Rehabilitation of the exterior wall and glazing assemblies is required to correct the water ingress problems at the building.

Following the investigation, the project manager from the original design team offered to assist an owners group with the rehabilitation of another complex. He was unaware of the extent of the performance problems at the above project, or the extent of similar problems at several other similar projects he was originally involved with.

CURTAINWALL GLAZING FAILURE

The owners of a prominent high-rise complex in Vancouver, British Columbia requested a pro-active maintenance and renewals plan to ensure the long-term performance of their complex. The building primarily relies on a four sided structurally glazed curtainwall clad assembly as the exterior walls. The glazing system utilizes the rainscreen principle to control rainwater penetration. During the gathering of information for the plan, spots were identified within the glazing units of the curtainwall assembly, which required further investigation.

Figure 7: Visual condensation and severe corrosion of the low-e coating visible from the interior

Figure 8: Large spots within the insulated glazing units

The curtainwall assembly relies on a proprietary three element insulated glazing unit (IGU) consisting of an optically clear polyethylene terephtalate (PET) film, suspended between two lites of glass to increase the thermal insulating performance. Soft coat low-e coatings are located on surfaces 2 and 5 within the IGU. The hermetic seal around the perimeter of the IGU consists of a stainless steel foil band set into a thin layer of a butyl based thermoplastic sealant. This glazing unit arrangement is intended to result in a curtainwall assembly with significantly improved R values compared to conventional curtainwall systems.

A unique characteristic of the IGU's is that they are allowed to vent and pressure equalize to the interior of the building. The venting is achieved by means of a small breather tube that is attached to a spigot that penetrates through the stainless steel edge band to the interior of the IGU. The breather tube is attached to a large aluminum tube filled with desiccant on the interior of the building. When temperature variation, wind pressure and atmospheric pressure change the volume of air inside the IGU, it is intended that small volumes

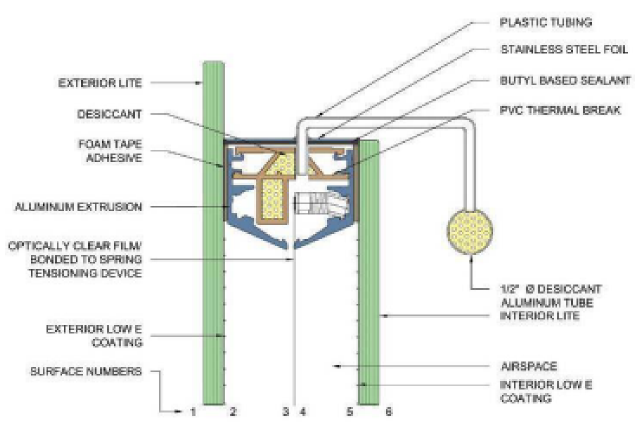

Figure 9: Typical insulated glazing unit

of air will flow in and out of the unit and any moisture will be absorbed by the desiccant in the tubes, which can be replaced when necessary. Any other moisture would be absorbed by the desiccant within the PVC spacer bar.

A testing protocol for the IGUs was developed to determine the extent of the problems. This protocol included:

- Visual review
- Dewpoint testing (ASTM E 576)
- Pressure Decay Tests (including submerged pressure tests).

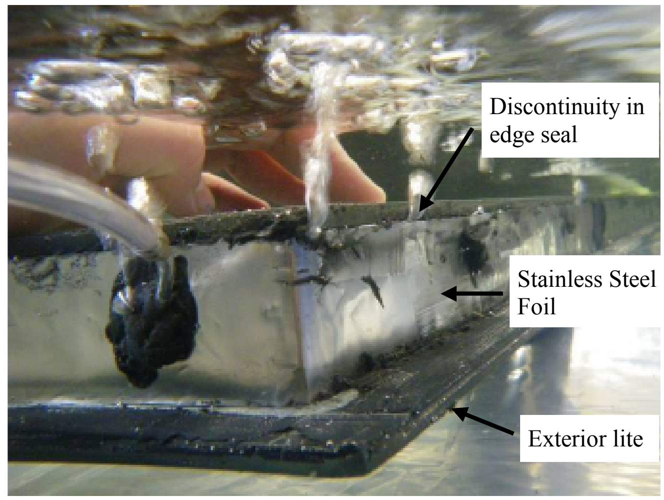

Figure 10: Air leakage during a pressure test of a submerged IGU with evidence of corrosion of the low-e coating

Over the course of the investigation, visual clarity of the insulating glazing units was found to be progressively deteriorating to unacceptable levels on the majority of the building glazing panels. It was found that deterioration of the visual quality is a result of premature condensation forming inside the insulating glass unit and causing corrosion of the low-e coating on the glass. The condensation was caused by an excessive building up of moisture in the desiccant as a result of airflow through discontinuities in the perimeter seals. The discontinuities are a result of defects in the design and manufacturing of the insulating glass unit.

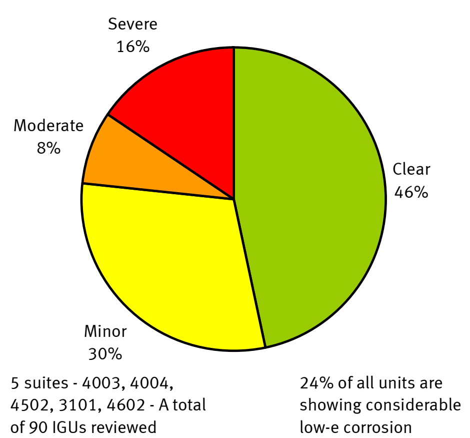

Figure 11: 2006-2007 visual review summary. Corrosion of the low-e coating within the glazing units (Review of IGUs at 5 Suites)

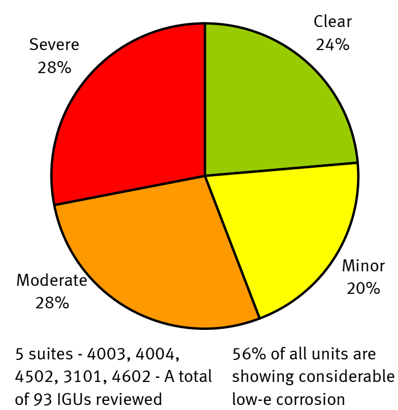

Figure 12: 2008 visual review summary. Corrosion of the low-e coating within the glazing units (Review of IGUs at the same 5 Suites)

The majority of the insulating glass units (IGUs) reviewed exhibited moderate to severe corrosion of the low-e coating after several years of service. Many of the units where minor deterioration was observed were previously found to be clear only a couple of years earlier. The corrosion level on insulating glass units reviewed over multiple years indicates that these units have failed and are continuing to degrade. Test results indicate that the majority of the clear IGUs are near, or at the point where condensation and corrosion will start to occur.

Table 1: Results from the 2006 and 2008 visual review and dewpoint testing at a sample suite

Suite 4502 -				
Glazing Unit Serial #	Feb 13/2006 Visual Condition	Aug 7/2008 Visual Condition	2006 Dewpoint	2008 Dewpoint
43205	Clear	Clear		-12
43238	Clear	Clear		1
43239	Clear	Clear	-55	-4
45157	Clear	Clear		-1
45458	Clear	Minor		2
45474	Clear	Minor		2
45470	Minor	Severe		3
45466	Minor	Moderate		4
45357	Minor	Moderate		
45459	Minor	Severe		
45456	Minor	Moderate		
45150	Minor	Severe		2
45153	Minor	Moderate		2
45367	Clear	Severe		8
44900	Clear	Severe	-10	4
45484	Severe	Severe	-5	6

During the investigation, other problems were also identified including overheating of the air conditioned suites.

Figure 13 shows the temperature readings near the glazing panels in a sample suite on three sunny days in September. The suite heating, ventilation and air conditioning system was set to 21 degrees Celsius. The interior air temperatures at these locations reached 40 degrees Celsius during this time period.

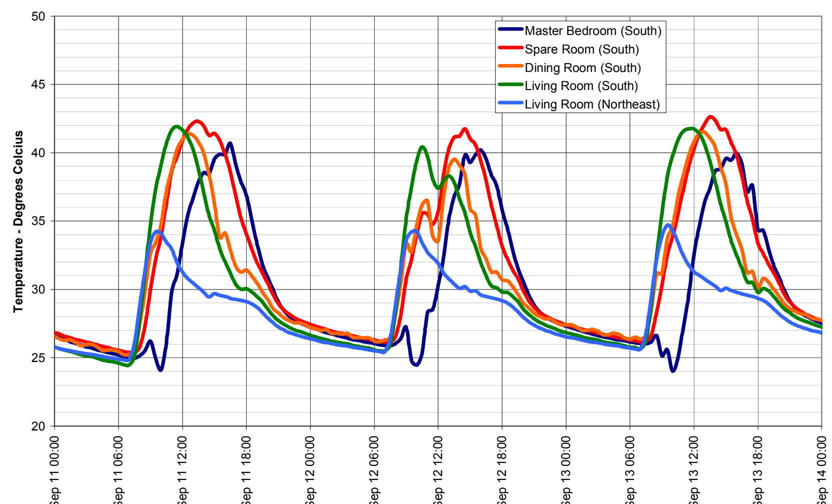

Figure 13: Suite Temperatures, September 11 through 14, 2008

In-situ repairs such as desiccant tube replacement and sealant injection at the IGUs were previously attempted by the manufacturer and have not been effective at mitigating the problem. Replacement of the glazing units will be required, as well as adjustments to other building systems.

The above example highlights the need for product testing and monitoring of new systems, including new systems intended to reduce energy consumption in buildings.

MAKE-UP AIR INVESTIGATION

Our firm was asked to undertake a detailed investigation and analysis of condensation related problems at a newly constructed building in Portland, Oregon. The condensation was occurring at the window-wall assemblies and it was initially suspected that the glazing systems were inadequately insulated. The investigation involved monitoring the environmental and mechanical system conditions in 6 sample suites during a period of cold weather when condensation was likely to occur. The sample consisted of 2 control suites, which were not experiencing condensation problems, and 4 suites that had reported significant condensation on the windows.

The monitoring system recorded environmental factors such as temperature, relative humidity, and carbon dioxide levels at various locations throughout the interior and exterior of the suites. In addition, the operation of the mechanical equipment was monitored, including the heat pump, clothes dryer, kitchen exhaust and bathroom exhaust fan. The volume of exterior hallway air entering the suite under the main entry door with and without various combinations of mechanical exhaust fans operating, and the supply air speed from the heat pump was also measured during the installation of the equipment. All of the results were graphically presented to allow a comparative analysis of the differences between the control suites and the condensation suites.

Based on the monitored results, the condensation resistance index (I value) was calculated for comparison of the window wall assemblies between the suites. The measured I values did not identify significant anomalies with the glazing assemblies or significant differences between the control suites and the suites experiencing condensation related problems.

Table 2: Condensation potential at window wall assemblies.

Average Window Wall I Value

Based on Data Logged Values Calculated Every 5 Minutes

(N601, 301 - Mar 11 0–5 am), (W602, E902, W302, Mar 9, 0-5 am), (W601 Feb. 27 0-5 am)

	Zone 1		Zone 2		Zone 3	
Suite	Glass	Frame	Corner	Frame	Glass	Frame
N601	63	63	47	58	81	73
N301	66	63	51	55	70	69
	Glass	Corner	Operable	Frame	Glass	Frame
W602	70	55	78	74	89	79
E902	60	50	80	66	75	66
W302	71	59	78	70	91	76
	Glass	Corner	Jamb	Sill	Glass	Frame
W601	76	49	74	61	81	67

Control Suite

Condensation Occurred During Sample Time

The results confirm that there are several factors that influence the probability of condensation. The key factors affecting the condensation potential in the building are categorized as follows:

1) Occupant Use / Lifestyle
2) Heating Ventilation and Air Conditioning (HVAC) system.

The occupant use and lifestyle issues were primarily related to the operation and use of the heat pump (furnace) and the exhaust fans. In a number of the suites experiencing condensation the furnace was either not turned on for the entire cold monitoring period, or the suites were maintained at temperatures below degrees 70 Fahrenheit resulting in colder perimeter temperatures. In addition, all of the suites used exhaust fans only intermittently during humidity generating events or fans were only utilized for very short periods during showers and were not operated after afterwards to evacuate the moisture from the suite.

The significant HVAC issues are related to supply air. The design of the mechanical system relies on natural ventilation to supply fresh air to the suites. The exterior walls were found to be very airtight unless operable windows are opened. During periods of cold weather, particularly when the wind is relatively calm the main source of supply air for the suites is pressurized air from the hallways that infiltrates into the suite under the entry door. The data showed that in general, the control suites received more dry supply air under the entry door than the condensation suites. In fact, it was found that even though the furnaces in one of the control suites was not turned on, and the bathroom fans were not consistently used during the monitoring period, the suite did not experience condensation problems since increased supply air was provided relative to the other suites. In all units the mechanical supply of fresh air to all suites was significantly below the ASHRAE recommended amounts in all suites tested.

Table 3: Measured make-up air below suite entry door thresholds.

	Unit					
	N601	N301	W602	E902	W302	W601
	Airflow (cfm)					
Baseline	24	0	10	7/53*	13	20
Master Bathroom	55	8	14	21	12	31
Guest Bathroom	53	11	15	20	12	31
Common Bathroom	55	14	18	21	13	24
Kitchen Level 1	55	11	24	24	18	27
Kitchen Level 2	55	16	28	27	21	31
Kitchen Level 3	59	29	43	39	29	39
Dryer w/ Booster Fan	55	14	18	53	18	20
ASHRAE Recommended (based on suite size = 0.3 ACH)	82	82	86	86	86	93
% of ASHRAE Recommended @ Baseline	29%	0%	11%	8%	15%	21%
% of ASHRAE Recommended with Continuous Master Bath Fan	67%	10%	16%	24%	14%	33%
ASHRAE Recommended (based on # of occupants, 15cfm/person)	30	30	45	30	30	30
% of ASHRAE Recommended @ Baseline	79%	0%	22%	23%	43%	66%
% of ASHRAE Recommended with Continuous Master Bath Fan	183%	27%	31%	70%	40%	104%

* Booster fan was found to be operating intermittently without dryer use elevating the actual baseline. The baseline used for report's graphs was the measured value with booster fan off (7 cfm)

Air flow measurements had no increase when fans were activated, the hallway pressurization inadequate to counteract wind

Control suite

ASHRAE recommendations based on suite area (5-6 occupants based on the suite area)

ASHRAE recommendations at 15 cfm per person for actual occupant loads

The investigation also found that the heated supply air from the heat pump is exhausted from the center of the room towards the windows at the perimeter. As a result, the speed of the air wash at the perimeter of the building is very low and the duration of a typical heating/fan cycle is very short. This has the net effect of reducing the surface temperatures of the windows and glazing and increasing the potential for condensation.

Based on the results of the investigation, improvements to the heating and ventilation systems are required in order to better reflect the occupant use of the building.

The findings in the above example confirm the need for actual operation data of buildings during the design process, and integration of the building systems.

BUILDING 19 OF THE ENERGY CONSUMPTION AND CONSERVATION STUDY

The Research Study: Energy Consumption and Conservation in Mid and High Rise Residential Buildings in British Columbia (the Study, RDH 2009) included numerous examples of buildings that did not meet the performance expectations of the original designers. Exterior moisture management, energy consumption, heat transfer characteristics, condensation potential, occupant comfort, and durability and other actual performance characteristics consistently did not meet the original design intent at these buildings. Although the sample set of buildings is limited, the findings show a trend of increased energy consumption for newer buildings.

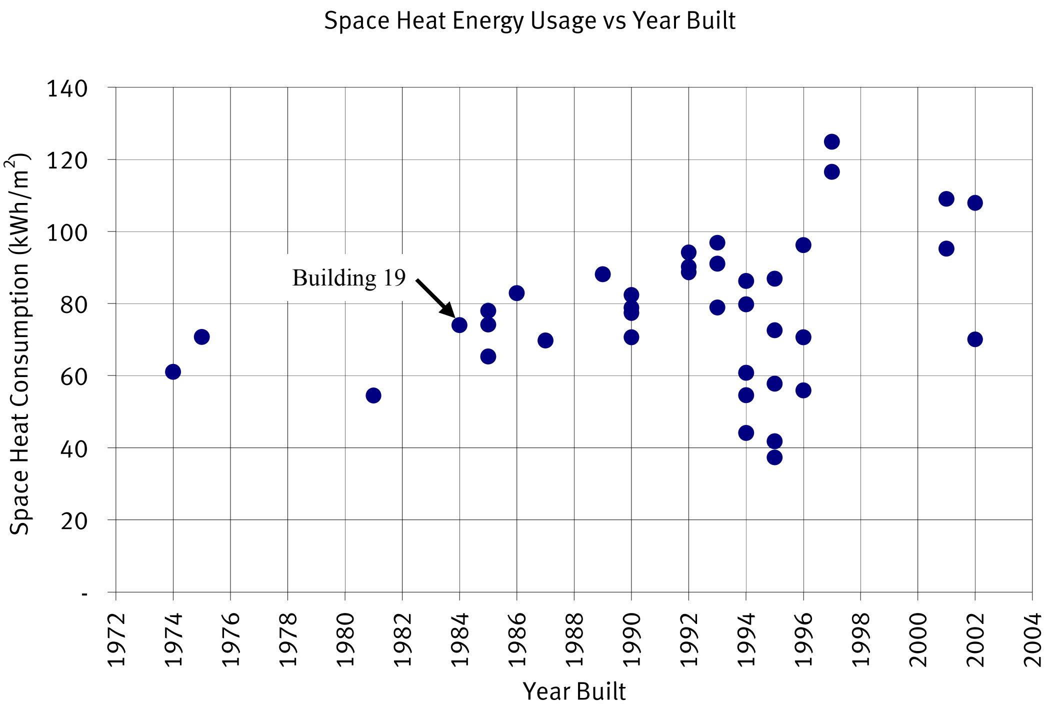

Figure 14: Space heat energy consumption per floor area of 39 buildings verses year built.

Building 19 of the Study is an example where the building failed to meet expectations. It is a 10 storey mid-rise residential building. It was originally intended that the building incorporate improved building enclosure, with the use of higher performance ‘Thermo Stucco’. The use of the improved stucco cladding, along with the incorporation of a relatively low window percentage was expected to increase the overall R-value of the building enclosure. However, the actual overall building enclosure R-value was less than 3, and the as-built arrangements resulted in extensive water ingress related damage including severe corrosion of the supporting steel stud framing as shown in the Figures 15 and 16.

Rehabilitation of the building enclosure assemblies was required to correct the damage.

Figure 15: Overall corrosion of the exterior steel stud wall assemblies at Building 19.

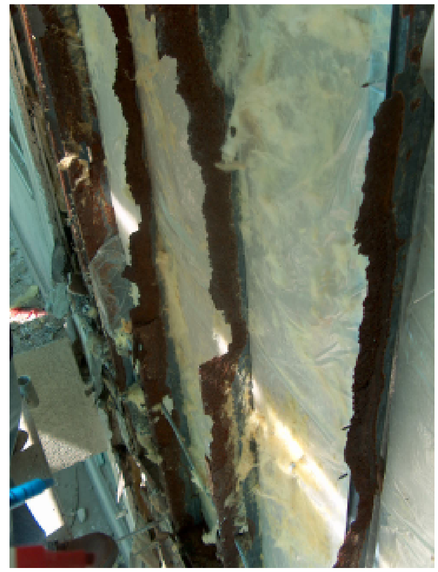

Figure 16: Typical corrosion of the exterior steel studs behind the cladding at exposed portions of the south elevation.

All of the above projects include examples of failures resulting from the desire to improve an aspect of the design and construction (commonly the desires to reduce energy consumption as well as initial cost), without adequate consideration of all of the loads imposed on the buildings. In each of these examples, the extent of these problems was not apparent to the building owners until an event or maintenance activity triggered the need for further investigation.

NEED FOR A NEW PARADIGM TO THE DESIGN OF SUSTAINABLE BUILDINGS

Green building programs have recognized the need for a new design approach. The Integrated Design Process (Bunting Coady) is a good example of a new approach resulting in positive results. The building enclosure (or envelope) is central to the design process in this approach, while considering the other key design elements. The Integrated Design Process also considers quality assurance and life cycle costing and commissioning. However, this approach does not readily provide designers with feedback on the actual performance of the buildings.

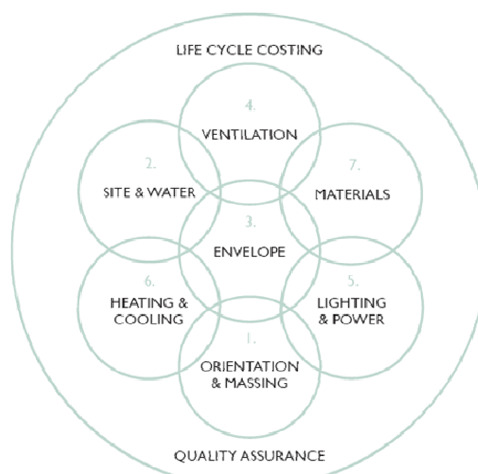

Figure 17: Integrated Design Process

Previous studies (NRCan 2005) have found that there is a direct correlation between a building user's awareness of the energy consumption, and the actual energy consumption. When consumers regularly see and have to directly pay for energy costs, energy consumption is less. Can the designers and builders also be made aware of the actual performance characteristics of their buildings? This information is essential in order to make informed decisions when designing new buildings, and exploring cost saving.

A feedback loop that provides actual building performance characteristics to the developers, designers, and constructors of new buildings is needed. This feedback loop should include data collection of the following performance characteristics:

- Moisture control
- Energy consumption
- Interior operating conditions (temperatures, relative humidity, ventilation rates, etc.)
- Heat transfer characteristics
- Air movement characteristics (air pressure differences, air exchanges, etc.)
- Service life data of materials used
- Building movement and deflections
- Occupant behaviour and satisfaction.

Advancements in metering and monitoring equipment can now readily allow the measuring of the above performance characteristics and much other data. This information could be made available online to the building occupants, designers and builders. By gathering information from each project, our collective knowledge base and ability to advance building technologies will increase dramatically.

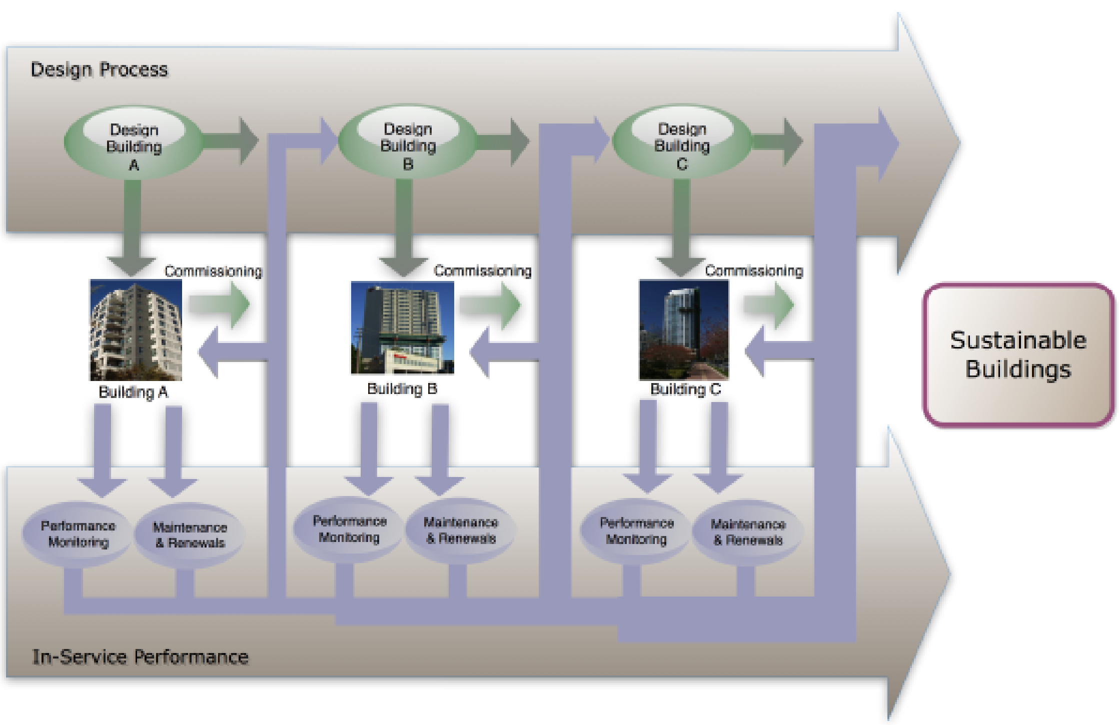

Figure 18: A new design approach based on knowledge gained from in-service data.

Considering the costs of these buildings assets often range from $10 million, to $300 million and more, the incorporation of metering to measure actual energy consumption as well as monitoring equipment to measure other performance characteristics is trivial. However, the information gathered by adopting this new approach would be of unlimited value for both new and existing building design.

By adopting this feedback approach, the designers of the building impacted by the airplane and Building 19 of the Study would likely have incorporated exterior insulated rainscreen wall assemblies. Monitoring of the desiccant filled breather tubes in long-term trial mock-ups and previous projects would likely have identified failures of the curtainwall IGUs and need for improved perimeter seals on the glazing units. Finally, monitoring of the interior conditions at the building clad with window-wall glazing assemblies would have identified the need for improvements to the heating and make-up air systems and better informed the occupants on how to control the interior conditions during the cooler winter months without opening their windows and wasting space heat energy.

The adoption of this new approach based on in-service data will better allow us to learn from our efforts, and eventually work, live and enjoy sustainable, near net zero buildings.

Figure 19: Dashboard display providing feedback to those driving new building development, design and construction.

REFERENCES

CMHC 1996. Survey of Building Envelope Failures in the Coastal Climate of British Columbia

RDH 2009. Energy Consumption and Conservation in Mid and High Rise Residential Buildings in British Columbia Report #1: Energy Consumption and Trends. RDH Building Engineering Ltd. Report to Study Partners. February 2009.

Bunting Coady. Bunting Coady Architects, http://www.buntingcoady.com/integrated-design.html

NRCan 2005. 2003 Survey of Household Energy Use (SHEU) Summary Report