Why Do Green Building Enclosures Fail and What Can Be Done about It?

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ABSTRACT

Sustainable or "green" buildings are becoming increasingly popular. This is a positive trend, since buildings require the use of vast amounts of resources and energy. They are, among other things, responsible for approximately 39% of CO_2 emissions and 65% of waste outputs. Obviously, sustainable buildings require that their enclosure also be conceived and realized according to ecological principles. However, it appears that these green building enclosures are not always durable. Indeed, there are reports in North America of many green buildings having suffered major building enclosure failures after only a few years. This results in environmental, economical, and social impacts that can reduce or negate the positive impacts of those green buildings.

The questions then become: What are the potential traps in green building design that can lead to such failures? And what can be done to avoid them?

These questions are examined through examples of building enclosure failures in green buildings. These help identify potential pitfalls, which include

- *Disregarding building science principles when designing a green building*
- *Designing green buildings with a configuration that is not adapted to their actual exposure conditions and context*
- *Using materials in the wrong places and/or for the wrong purposes because they meet certain ecological criteria*

A durability plan, such as required in the LEED® Canada Credit MRc8 "Durable Building" (based on CSA Standard S478-95 [R2001], *"Guideline on durability in buildings"), can help minimize the risks of premature failure by addressing durability issues over the whole life cycle of the building. Although this does not guarantee that the building will be durable, it at least ensures that it has been designed and built to be durable. The basic elements of an actual durability plan are presented and discussed.*

In conclusion, some insights gained through the analysis of failures and the preparation of a durability plan are shared.

INTRODUCTION

Sustainable or "green" buildings are becoming more and more popular. This is a positive trend, since buildings have very significant impacts on the environment. According to the US Green Buildings (USGBC [no date]), buildings in the United States are responsible, among other things, for

- 39% of primary energy use
- 72% of electricity consumption
- 38% of all CO_2 emissions
- 40% of raw materials used
- 30% of waste output (136 million tons annually)
- 14% of potable water consumption

Looking at energy consumption per sector, buildings actually come first at 39%, followed by transportation at 32%, and then industry at 29%.

The building enclosure contributes directly to these environmental impacts in the following ways:

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- Energy consumption related to the R-value, airtightness, and configuration of the enclosure (e.g., amount and orientation of fenestration, thermal bridges)
- The embodied energy of materials included in the building enclosure (energy needed for the extraction and delivery of raw materials, and fabrication, delivery, and installation of the material or component)
- Use of resources (destruction of habitats, creation of pollution)
- Waste sent to disposal sites

It is thus clear that minimizing the environmental impact of buildings requires that their enclosure also be conceived and realized according to ecological principles. This may involve, for example, increasing the level of insulation and airtightness to improve energy efficiency, using materials with recycled content to minimize the impact related to resource use, or using materials manufactured locally to reduce greenhouse gas emissions. However, it appears that these green building enclosures are not always durable (Yost 2009). Indeed, there are reports in North America of many green buildings having suffered major building enclosure failures after only a few years. One example is the Philip Merrill Environmental Center, recognized as the first building to achieve the platinum rating under the USGBC LEED® rating system, which is cited extensively in the literature (e.g., Marshall 2006; McKay 2007; Kernan 2007; Armstrong and Flores 2008; Lemieux 2008).

The premature failure of building enclosures results in environmental, social, and economical impacts that can reduce or even negate the positive effects of those green buildings. The economic impacts, which are also related to social impacts, can be very significant. It is interesting to note that, according to Marshall (2006), although many moisture and mold problems could be stopped by measures costing typically less than $10,000 at the design stage, there are still cases in which premature failure of the building enclosure requires repairs costing $500,000 or more, not including the costs of lawsuits and tarnished reputations.

The environmental impact of premature failure of the building enclosure can also be measured in embodied energy and CO_2 emissions. For example, Lucuik (2007) estimated that for two buildings requiring major retrofitting work after 8 and 11 years, respectively, the impact of the premature failure could be estimated to represent between 10 and 20 years of operational effects for a single-family home and between one and three times the total embodied effects of a 2,200 ft^2 single-family home. When using CO_2 as a measure, he found that 80 to 100 tons of CO_2 was emitted to the atmosphere as a result of the increased material use associated with the building envelope failures. It is easy to conclude that buildings that require retrofitting of their enclosure before the end of their expected life expectancy can hardly be referred to as a sustainable buildings (Dixon 2008).

The questions then become: what are the potential traps in green building design that can lead to such failures, and what can be done to avoid them?

In the following sections, these questions are examined through examples of green building enclosure failures and then possible strategies to minimize the risks are discussed.

IDENTIFYING POTENTIAL PITFALLS

There are elements pointing toward a correlation between new green building designs and observed failures (Odom et al. 2008a, 2008b). A look at examples of failures could therefore validate this relationship and help identify some common pitfalls.

The first issue to address is defining what actually makes a building green. Is it using only all "natural" materials (e.g., straw bale walls)? Integrating some complex and fancy high-tech gadgets to an otherwise conventional building? Installing a green roof? Also, do green buildings need to have a specific look, which would lead the designer to base important decisions solely on aesthetic criteria? It is hard to find an absolute and definitive definition that everyone will agree with. However, the way a team approaches or perceives a green building project has a significant impact on its long-term performance.

According to the US Environmental Protection Agency (EPA 2009), green building (or *green construction* or *sustainable building*) is defined as "the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life-cycle from siting to design, construction, operation, maintenance, renovation and deconstruction. This practice expands and complements the classical building design concerns of economy, utility, durability, and comfort." The general concept is that green buildings should have a lesser impact on the environment than non-green (i.e., conventional) buildings, over their whole life. But the questions remain as to how to actually do this and how to evaluate the greenness of specific projects.

Green Building Design Criteria

There are a number of environmental performance evaluation systems based on points or credits. For example, some of the systems available in Canada include Green Globes™, Built Green™, and GBTool. In North America, the rating system Leadership in Energy and Environmental Design (LEED), developed by the US Green Building Council (USGBC), has become somewhat of a reference over recent years and now appears to be one of the most popular system on this continent. Currently, there are different versions for different situations, such as new construction (NC), existing buildings: operations and maintenance (EB), core and shell (CS), commercial interiors (CI), and neighborhood developments (ND). The system has also been exported to other countries, including Canada. Since the LEED rating system in general is so widely applied, could it be playing a role in the observed green building enclosure failures? Some credits in

Table 1. Potential Impact of LEED Credits on Building Enclosure Performance

Credit Category	Credit Number and Title	Strategies	Potential Impacts
Sustainable sites	6.1 Stormwater Design: Quantity Control 6.2 Stormwater Design: Quality Control	- Reducing or eliminating impervious surfaces - On-site sub-grade piped drainage systems - On-site retention of stormwater	May result in larger volumes of ground water and therefore in water ingress if waterproofing is not adequate.
	7.2 Heat Island Effect: Roof	Use of green roofs or roof membranes with high reflectance	Relatively new in Canada; more complex than non-vegetated roofs. Issue with durability of high reflectance characteristics.
Energy and atmosphere	1 Optimize Energy Performance	Improving the thermal performance of the building enclosure (controlling heat and air movement)	Reduced drying potential. Increased potential for high RH levels indoor (if ventilation poor). May require modification of assembly to accommodate thicker insulation.
Materials and resources	1 Building Reuse	Maintaining specific percentages of key building systems	Potential for keeping components that are not functionally adequate.
	3.1 and 3.2 Resource Reuse	Reusing building materials	Remaining service life may be shorter than comparable new materials
	4.1 and 4.1 Recycled Content	Use of materials with recycled content	May affect durability when innovative but insufficiently tested materials used in building enclosure assembly.
Indoor environmental quality	2 Ventilation Effectiveness	Establishes a minimum ventilation rate	In some climates, may lead to more moisture inside the building.
	3.1 and 3.2 Construction IAQ Plan	Require the establishment of an IAQ plan that may include a flush-out prior to occupancy	In some climates, may lead to more moisture inside the building.
	4 Low Emitting Materials	Establishes limit for VOC emissions for certain materials (e.g., paints, adhesives, sealants, composite wood products)	Potential lower performance of these materials (e.g., lower adherence).

particular may have an impact on the long-term performance of building enclosures. Kernan (2007) and Odom et al. (2008) have identified some credits that may have a direct impact on building envelope performance. Table 1 presents a summary based on their analyses.

This is not to say that these strategies should be avoided because they are too risky. On the contrary. For one thing, adopting the "business as usual" attitude clearly is not sustainable. As demonstrated in the introduction, buildings—and their enclosures—have significant impacts on the environment and therefore measures and practices to reduce these impacts have to be adopted. This is not possible without starting to do things at least a bit differently. Another issue is that the current way of doing things, with conventional designs, assemblies, and materials, is not without risks itself and in no way guarantees a good, durable building envelope. The prosperous building science consulting business can attest to that. What is important to keep in mind, however, is that the risks associated with more ecological choices have to be identified and taken into account for each project so they can be minimized and managed.

Below are a few actual examples of green building envelope failures encountered by the authors.

Examples of Green Building Enclosure Failures

Example 1. The implementation of some green strategies may require that standard components or assemblies be adapted, as this example illustrates. In this case, a green roof was incorporated into the design of the building, as shown in Figure 1. Within two years, water infiltration was reported. The investigation revealed that the aluminum base of the plumbing vents was perforated, at the junction with an extension sleeve. To accommodate the extra height due to the planting medium, it had been necessary to extend the plumbing vents. The problem is that the sleeves were made of stainless steel, which is a noble metal in comparison to aluminum. The combination of these two metals with a very moist environment (the planting medium) led to galvanic corrosion.

Other issues were also identified. As visible in Figure 1, there was no membrane in the system to inhibit root growth. The waterproofing membrane was then directly exposed to the roots, reducing its service life. Furthermore, all the mechanical

Figure 1 Roof case study: aluminum drains are perforated at the base (top pictures); lack of anti-root membrane leading to root growth and deterioration of the waterproofing membrane (bottom left picture); and mechanical equipment located in a cluster (bottom right picture).

Figure 2 High performance window case study: Bitumen streaks on the window frame (top); disintegrated flashing membrane but fairly intact sealant with water accumulation and infiltration at head of the window (bottom).

equipment was located close together, making it difficult, if not impossible, to achieve proper waterproofing and to maintain it in this area.

The implementation of a green roof, a popular strategy in green buildings, is by no means revolutionary. Systems with good performance records are available and have been installed successfully. However, there are specific considerations such as a potentially wetter environment, living components as part of the assembly, and, although the membrane is protected from UV rays, increased difficulty in accessing the membrane for maintenance and replacement. The selected components should therefore take these constraints into account. One can also see that coordination with the mechanical engineers and long-term vision are paramount.

Example 2. In the second example, an exterior cladding system with glass and metal shading fins in front of the windows was installed on a green building. In this particular case, it is impossible to remove the cladding system without damaging the other components of the assembly, and the shading fins also cannot be easily removed to give access to the windows.

High-performance windows were installed in this wall assembly. After a few years, unsightly bitumen streaks were reported at the window head. An exploratory opening performed at the head of the window revealed that the self-adhered membrane had been applied over a polyurethane sealant. The bitumen of the membrane was completely gone (parts of it were on the window frame, as shown in Figure 2), but the sealant was still in good condition. Eventually, the disintegration of the flashing membrane would have led to water infiltration. Although it had not gone inside, water was found to have accumulated at the head of the window.

In this example, building science principles, namely taking into account compatibility between materials, were not properly applied. The materials themselves and the issue are not specific to green buildings. However, maintenance and remedial work were greatly complicated by the configuration of the cladding system and shading fins, which had been selected as green features. Here, the improper application of building science principles is complicated by a lack of an integrated and long-term vision.

Example 3. The last example relates the case of a linoleum floor installed on a slab on grade with an adhesive without formaldehyde (Figure 3). After a few years, problems with the adhesion of the floor were reported, which were found to be caused by the presence of moisture under the flooring material. When portions of the flooring were removed to investigate, extensive mold growth was observed: the adhesive that had been used did not have formaldehyde but it also had nothing to inhibit the growth of mold.

This example highlights how important it is to understand products' properties. Greener versions of existing products are available, but it is important to understand their properties and make sure they will be suitable for their exposure conditions.

Figure 3 *Floor case study: blistering of the linoleum flooring (top) and mold growth under the flooring material (bottom).*

In this case, the adhesive may be fine for an upper floor where there would be no danger of water, but was probably too sensitive for application on a slab on grade (which had a moisture problem to begin with). The specifier should have asked questions of the representative about installation, location, properties, adhesion, etc.

Some Lessons Learned

When looking at these failure examples, one observation is that the problems somehow involve exposure to moisture. This is not a surprise, since it has been known for a long time that the most common cause of building envelope problems at large is moisture (Lstiburek 2006). To quote Lemieux (2008), "uncontrolled water penetration, condensation and moisture ingress are three of the most common threats to the long-term durability, structural integrity and performance of the building enclosure." This remains true for both conventional and green buildings. In effect, another observation is that most of these failures that occurred in green buildings could have occurred in conventional buildings. However, the examples also show that the fact that they were designed as green buildings led to choices or exposure conditions that were potentially more problematic. Although one can presume the green strategies described were implemented with good intentions, the specific constraints and/or the characteristics of devices or materials used were obviously not fully understood or taken into account.

From the overview of the LEED credits and examples of failure in the literature as well as in the authors' own practice, problems can generally be linked to the following issues:

- Disregarding building science principles when designing a green building. The principles that apply to conventional building envelope should not be omitted because the building aims for sustainability objectives. It is not a "one or the other" type of issue.
- Designing a green building with a configuration that is not adapted to its actual exposure conditions (perhaps because of a preconceived idea of what a green building should look like, how complicated it should be, or how many gadgets it should have).
- Using materials in the wrong places and/or for the wrong purposes because they meet certain ecological criteria. There is not one "greenest" recipe, no assembly or material that could be used everywhere.
- Using new materials without knowing all their relevant characteristics. Materials should not be considered by themselves but always in relation to the other materials of the assembly and their exposure conditions.
- Lack of long-term vision. What is the life expectancy of each component? What maintenance will be required and in what sequence? If one component needs to be maintained or replaced, will it require the removal and discarding of other components that do not need to be replaced?
- Lack of quality control. If the design, installation, and performance of the building enclosure and its components are not validated at all stages of the project, how can we be confident they will perform over time?

ELEMENTS OF A POSSIBLE STRATEGY

So what can be done to minimize the risks of premature failure? From looking at some green building strategies and examples of failure, some potential pitfalls were identified. From this exercise, it stands out that taking into account the context and applying basic building science principles accordingly is crucial. The climatic context (i.e., the specific outdoor and indoor environmental loads) should obviously be at the core of the design decisions. In addition, those design decisions should be taken within a global vision. Checking items off a list or "point shopping" is not sufficient. It can actually lead to complete aberrations, not only in terms of building enclosure performance and durability but also, for example, in terms of energy consumption. A credit-based system can be—and is—very useful, with the condition that all decisions are always considered from a more global perspective and in relation to one another; in other words, that an integrated design process (IDP) be adopted. The IDP helps to avoid a fragmented design process, and allows development of the optimal solution for the specific project by identifying conflicts as well as opportunities. The traditional linear process, in which the engineers are stuck with decisions already taken by the architect and client, makes this virtually impossible. Finally, there should be a way to validate the design, construction, and performance of installed components, with the whole life cycle of the building in mind. The problems illustrated through the examples may have been avoided not only if building principles and basic knowledge of material behavior had been applied, but also if there had been a validation process at all stages for durability.

These elements of building science principles, integrated approach, and quality assurance process at all stages of a project actually constitute good practice, whether the building aims to be green or not. They can also constitute the basic elements of a comprehensive strategy for building durability. In fact, implementing such an approach, which considers the whole life cycle of the building and integrates context, building science, and quality control at all stages of the project, would result in a building with less environmental impact even if this is not the initial objective.

Planning for Durability

Durability will not happen by magic, and a specific plan of action is needed (Totten 2008). The Canada Green Building Council (CaGBC) version of the LEED system for new construction, LEED Canada-NC 1.0, addresses the issue of durability by including a durable buildings credit, #8 in the materials and resources category (referred to as MRc8). MRc8 was established to avoid premature failures of building enclosures such as those experienced in Vancouver, British Columbia, known as the "leaky condo crisis". The intent of this credit is to "minimize materials use and construction waste over a building's lifetime resulting from premature failure of the building and its constituent components and assemblies," namely the building enclosure. The requirement for MRc8 is to "develop and implement a Building Durability Plan, in accordance with the principles in *CSA S478-95 (R2001)—Guidelines on Durability in Buildings*, for the components within the scope of the Guideline, for the construction and preoccupancy phases of the building." This standard requires that the expectations for quality be defined for each project. It also states the three main elements to achieve quality:

- Provide the required quality of design
- Use the required quality of materials throughout
- Provide the required quality of workmanship throughout

The standard, and thus the LEED durable buildings credit, requires that a table presenting all the information relevant to the project and about each component be completed. This tables is called "Table B, Service Life and Maintenance of Components"; a table template created by the CaGBC is available, in which the required information, such as design service life, predicted service life, failure category, effects of failure, maintenance frequency, and maintenance access, can be entered. Although the development and implementation of such a building durability plan cannot guaranty that the building will be durable, it at least provides some assurance that it has been designed and built to be durable and that the whole life cycle of the building enclosure and its components has been considered.

In Canada, it is estimated that approximately 25% of buildings seeking LEED Canada certification are striving to achieve the durable building credit (Marshall 2008b). One explanation for this low number is that the credit is perceived as being expensive to achieve. This can be especially true in projects where the capital costs for construction and operation/maintenance costs are managed by different departments or entities. In those cases, there is the temptation for the team responsible for initial construction to reduce their costs, even if it means increased costs later on. In reality, however, a durability plan has the potential to save a lot of problems as well as money at all stages of a building's life cycle.

In the province of Quebec, no buildings have obtained the credit so far. However, the authors are currently involved as building envelope consultants in two LEED projects going for MRc8: one in Montreal, Quebec, and the other in Ottawa, Ontario. The construction of both buildings was set to begin in the spring of 2010. The general methodology being implemented at the various phases of these projects is described below. It should be mentioned that these elements have already been applied to numerous projects outside the context of LEED certification. They were simply adapted and coordinated to meet the requirements of MRc8 and *CSA Standard S478-95 (R2001)*. Such quality control measures have proven invaluable in identifying potential problems at a stage when they could easily be fixed. This way, the odds for increased durability are improved and costs may be minimized.

Design Phase. At the beginning of the design phase of the projects, meetings and discussions were held with the project team. These meetings were used to gather information such as the needs and intentions of the client, validation of the overall context (environmental loads, economic, occupancy, etc.) and objectives, identification of opportunities for synergy with other credits sought, etc.

The assemblies and components were then reviewed and evaluated against the criteria set out in *CSA Standard S478-95 (R2001)*, for synergies with other LEED Canada-CS credits, as well as for potential problems related to air leakage, water infiltration, condensation, sequencing, ease of access, required maintenance, etc. Also, the fit between the global context and the proposed assemblies and details was validated. The comments were submitted to the architect and the client.

The quality control measures to be implemented during construction were also defined at this stage (e.g., number of visits; number, types, and location of field tests; mock-ups to be built).

Note that, at this stage, hygrothermal performance computer simulations may be performed if the conditions or requirements are particularly challenging. They were not required for either of the two projects.

Construction Phase. The implementation of the durability plan involves quality control during the construction of the building to ensure that the components and assemblies have been built and perform according to the specifications and requirements of the durability plan. This is done through punctual visits during construction, field testing and mock-up construction.

During the visits, any variation of the building envelope from the elements of the durability plan is reported promptly to the architect, who then communicates corrective measures to the contractor. If necessary, consultations are conducted jointly with the consultant, architect, client, and contractor, in order to find a solution consistent with LEED MRc8.

As part of the quality control, in-situ testing is performed to determine whether the selected component and/or assembly meets the specified performance requirements, particularly in terms of vulnerability to water and/or air infiltration. Corrections can be implemented right away if necessary, avoiding problems after completion of the building. Mock-ups of specific building envelope sections are also built to identify any problem and make sure all workers involved understand what has to be done.

Operation phase. A maintenance program, mainly in the form of Table B, Service Life and Maintenance of Components, is prepared and submitted to the client. This way, there are no surprises and the client knows what maintenance work has to be done to ensure that the building enclosure and its components perform over time.

It is important that each step be fully documented and also that all relevant information be circulated through the defined communication channels for the whole duration of the project. At the end, all this information, including the description of the various steps, their results, and analysis, is put together and provided to the client.

It should be noted that these steps should not be seen as a recipe. The plan and methodology presented here would need to be adapted according to the complexity of the project, severity of the loads, or any other particular constraint.

CONCLUSION

There is a growing consensus that it is desirable, even necessary, to at least minimize the environmental impact of buildings on the environment. However, we have seen that some green building strategies can increase the risk for premature failure of the building enclosure, and that such failures do indeed occur. This actually increases the environmental impact of the building on the environment.

The first question this paper attempted to answer is why green building enclosures fail. From a literature review and a look at some examples, it was found that failures were linked to a poor understanding or application of basic building science principles, a lack of an integrated and long-term vision, no plan for durability that would involve third-party revision of the building enclosure design and construction, and lack of planning for the required maintenance. These problems are not limited to green buildings. However, the fact that they were designed as green buildings led to choices or exposure conditions that were potentially more problematic.

Durability is important for all buildings, but especially if sustainability is stated as a goal. The second question then is what can be done to minimize the risks of premature failure. Basic elements of a strategy for building durability, namely building science principles, integrated approach, and quality assurance process at all stages of a project, were identified. These actually constitute good practice regardless of whether the building aims to be green, and implementing such an approach would actually result in a building with less environmental impact even if this is not the initial objective.

To achieve durability, a durability plan incorporating specific steps at all stages of the project is needed. The LEED Canada-NC 1.0 durable building credit (MRc8) provides a framework on which such a durability plan can be built. Elements of durability plans being implemented in actual projects at the design, construction, and operation phases have been presented. Experience with a similar methodology, based on quality control measures at all stages of a project, has demonstrated that it can help avoid problems and minimize costs, even outside the scope of green building or LEED certification. It is therefore surprising that there is so much hesitation in seeking MRc8 credit. Since durability of the building envelope is essential to its sustainability, a durability plan should actually be a prerequisite. Such a plan cannot guaranty durability, but at least it provides some assurance that the building has been designed and built to be durable and that the whole life cycle of the building enclosure and its components has been considered. This type of approach is taken for mechanical systems, for which commissioning is required under the LEED rating system. Why not the building envelope?

This being said, the success of a green project is also a question of how a team approaches such a project. An important issue is that green buildings and performing, durable buildings should not be seen as opposite goals but rather as complementary and indivisible objectives. It is not a choice between the two; it is not because a building is to be green that building science principles should be forgotten or neglected. The understanding and application of building science principles should always be integral to the design, construction, and operation of sustainable buildings. In fact, this should come before green design criteria.

Furthermore, being green does not depend strictly on looks or technological gadgets, or even the number of points achieved under a specific rating system. Rather, a holistic, integrated approach, with the building and its systems designed specifically for its global context, is required. This implies applying building science to evaluate and find well-adapted solutions. This also means that there is no one-size-fits-all solution. And there is no single, ideal product that can be used everywhere. Buildings in Vancouver, Edmonton, Montreal, and Yellowknife, for example, need to be designed differently, as each climate has its own challenges.

In closing, many green buildings are success stories, and the fact that some problems were encountered should not deter us from trying to design and build buildings that use resources in a more responsible manner. Knowing what we know now, it becomes obvious that all buildings should be sustainable and that therefore, green strategies should be integrated to conventional practices while respecting building science principles and good practices.

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