Orders of Failure in Building Skin Design and Construction

Jeffrey C.F. Ng, AIA, LEED AP
INTERTEK
311 W. 43rd Street, New York, NY 10036
Phone: 203-556-0116 • E-mail: jeffrey.ng@intertek.com

Jennifer Keegan, AAIA

AND

Matthew Ridgway, PE, LEED GA
INTERTEK
350 Sentry Parkway, Bldg. 670, 2nd Fl., Blue Bell, PA 19422
Phone: 610-306-7199 • jennifer.keegan@intertek.com
**Abstract**

The design of high-performance building skins in a 21st-century city demands more forethought than building codes or zoning ordinances can anticipate. This session will explore, through forensic case studies, why newly built high-performance skins fail with the lens of an analytical tool called the “Orders of Failure.” These orders of failures organize conventional typologies of building skin failures, such as air, water, thermal, structure, glass, finish, and acoustics, by correlating them with three spatial dimensions and the fourth dimension of time. Using the information developed by these matrices, the speakers will discuss common myths of building skin design and the need for alternative bidding and value-engineering approaches that maintain building skin design integrity and utilize state-of-the-art prefabrication technologies to assure delivery of durable, high-performance building skins that enhance comfort and adapt to the seasons in the 21st-century city.

**Speaker**

**Jeffrey C.F. Ng, AIA, LEED AP — Intertek**

JEFFREY NG is an architect with over 35 years of experience integrating art and science in adaptive high-performance building skin designs. He has consulted on innovative award-winning national and international architectural projects. He has presented at numerous conferences, including the 2017 AIA National Convention, the 2013 Façade Design and Delivery Conference, and the 2010 BESS Symposium at Cal Poly in Pomona. Prior to joining Intertek, Ng was VP and lead building skin consultant at Thornton Tomasetti. He has been associated with leading architectural firms Ehrenkrantz & Eckstut, Davis Brody, Cossutta Associates, I. M. Pei & Partners, and S.O.M.

**Jennifer Keegan, AAIA — Intertek**

JENNIFER KEEGAN has 18 years of experience as a building enclosure consultant specializing in assessment, design, and remediation of building enclosures. She has investigated failures and provided construction administration, condition surveys, and design peer reviews of residential and commercial façades; has served as an expert witness; and offered litigation services. Utilizing her expertise in the built world, Keegan brings depth and focus to building enclosure commissioning and a proactive team approach to meet project performance requirements.

**Nonpresenting Coauthor**

**Matthew Ridgway PE, LEED GA — Intertek**
**INTRODUCTION**

This paper introduces an alternative way of organizing data of building skin failures that may facilitate scientific inquiry to bridge the many disciplines within building skin science. The intent of this classification methodology is to help building skin designers, engineers, and consultants to clearly communicate scientific findings to their project teams in order to clarify project requirements, promote holistic decision-making, and assure long-term performance and reliability of building skin systems.

Common forms of building skin failures can be correlated with the four dimensions of space and time by organizing failures with dimensional discontinuities, spatial overcapacity, and degradation due to time. These Four Orders of Failure create a hierarchical organization of failures across conventional building skin performance typologies. This methodology can be applied in building skin design, construction, and forensics to highlight key common characteristics of building skin failures across each of the orders, regarding causation, diagnostics, and repair. Lessons drawn from these illustrations of the Orders of Failure can be used to explore alternative methods for evaluating building skin designs, value engineering, procurement, fabrication, and delivery.

**BUILDING SKIN FAILURES**

The purpose of a building skin is to filter, moderate, or control the outside natural environment within which the building is situated. Building skin failures generally stem from noncompliance of materials, components, and assemblies with specified project performance requirements, manufacturers’ installation instructions, applicable building codes, and industry standards. These failures become evident in the course of the actual use and operation of the building skin. They can also become evident through testing under controlled conditions, intended to simulate some or part of the natural environment.

The study of building skin failures is a physical science. Building skin failures are objective and generally observable, measurable, and verifiable by established testing methods. Failures are effects that result from particular causes. Failures often are predictable through analysis and investigation. The environmental conditions that result in failures are typically discoverable and repeatable. Similar to any science, there will be anomalous events that will be challenging to measure, analyze, test, or recreate. These anomalies may be difficult to explain, based on the conventional paradigm. Studies in these anomalies may offer insight to the need of a paradigm shift. The evolution of the study of air barriers is an example of such a paradigm shift. The practice of locating the vapor barrier behind the interior insulation has been superseded by exterior water-resistant barriers and continuous insulation.

As physical phenomena in a spatial world, building skin failures can be understood and categorized in relation to the three spatial dimensions and the fourth dimension of time. This form of categorization of building skin failures into four orders can be used as a methodology to organize building skin failures and to reveal common “dimensions” or norms in phenomena, causation, diagnostics, mitigation, remedies, and repair of building skin within each of the four orders.

Building skin failures are typically studied as deficiencies within discrete typologies of building skin performances, as noted below:

1. Water penetration
2. Air infiltration
3. Thermal performance
4. Condensation resistance
5. Structural performance
6. Glass performance
7. Finish performance
8. Acoustic effectiveness
9. Fire protection continuity

This conventional organization of common building skin failures can result in a large compendium of information, myriad industry standards, product literature, and lengthy checklists that we as building designers, engineers, and consultants must refine to be useful communication tools during design or as quality control or quality assurance programs during construction. This paper offers another approach to educate and communicate with project teams during the design and construction process, so that decisions made in fast-track, cost-driven projects are, at least, fully informed.

When building skin systems are designed, installed, and then fail, camps are often divided between those claiming systemic improper construction and those claiming improper design. The truth is often a combination of these two. Building skin systems, such as cavity walls, double skins, pressure-equalized cavities, and continuous exterior insulation, fail due to poor installation and improper design. These failures have been compounded by poor communication and poor contractor coordination. Building skin professionals must continue to evaluate extensive historical and available test data to develop technical refinements to better adapt these building skin systems to their specific building locations and use.

**THE FOUR ORDERS OF FAILURE**

The Four Orders of Failure is a taxonomy or classification system of building skin failures based on four dimensions of space and time, as related to component interfaces, system capacity, and temporal degradation.

**First-Order Failures**

First-order failures consist of a linear opening, discontinuity, or nonuniformity within a component of the building skin assembly that is either in noncompliance with product specifications or may result in failure of the assembly. Generally, a first-order failure is a local defect resulting in the failure of the building skin component. The location of a first-order failure can be identified as a local discrete point in the surface of the component(s) that can be geometrically described by a line segment associated with a starting point on the exterior surface of the component and an end point.
point on the interior surface of the component. A first-order failure in terms of water infiltration is a penetration or gap that allows a linear stream of water to enter the building skin assembly in an uncontrolled manner, such as an unsealed penetration in the weather-resistive barrier membrane (Figure 1).

First-order failures are localized component defects or deficiencies. They are generally noncompliant with installation, manufacturing, or design requirements caused by poor workmanship or improper quality control, such as gaps in sealant application or improper depth sealant joints. First-order failures can be repetitive, such as penetrations through exterior insulation with thermally conductive fasteners. First-order failures can also be a result of accidents on site or in the fabrication plant, such as cuts in a membrane or damage to finished work.

First-order failures could be observed during the installation of the components by on-site inspections, or during plant manufacturing by in-line inspections. They may become progressively more difficult to discover after installation, without probes and diagnostic testing. Repetitive first-order failures could be identified during shop drawing reviews, prior to installation. Accidental first-order failures could be prevented with proper sequencing of work by adjacent trades, QA/QC programs, and protection of finished work.

First-order failures can be managed or remediated by using specified and approved components, observing manufacturers’ requirements, implementing project-specific quality control programs, proper training and checklists of critical installation requirements, and third-party inspections.

Second-Order Failures

Second-order failures consist of a planar gap or joint discontinuity between components of the building skin assembly. Generally, a second-order failure is a defect or deficiency in the assembly of components within the building skin assembly. The location of a second-order failure can be identified at the interface between adjoining components that can be geometrically described by the shape of the planar area of discontinuity between components.

Second-order failures in terms of water infiltration consist of a planar gap within the water management system that allows water to enter the building skin assembly in an uncontrolled manner, which may be caused by poor substrate preparation for sealant applications (Figure 2).

Other examples of second-order failures include improper sequencing of flashing materials and failed weld joints in metal fabrications.

Second-order failures are defects or deficiencies in the assembly of components within the building skin system. They are generally noncompliant with design documents, shop drawings, manufacturers’ assembly requirements, or industry standards.

For field-installed assemblies, second-order failures can be managed or
remediated with retaining qualified installers, pre-installation meetings, construction supervision, coordination of work between trades, field mock-ups, field testing of first installations, and third-party inspections. For plant-fabricated assemblies, second-order failures can be managed or remediated by observance of the engineered shop drawings; use of proper, well-maintained equipment; staff training; and in-line inspections with state-of-the-art testing methods. Coordinated design details and specifications and field verification of as-built conditions will facilitate the development of accurate shop drawings by the contractors for assembly of the building skin system. Active clarification of details and ongoing review of work between trades by contractors, manufacturers, architects, engineers, and consultants can play a key role in mitigating second-order building skin failures.

Third-Order Failures

Third-order failures are failures of size, volume, or design capacity of the building skin system. Generally, a third-order failure is a failure in compliance with performance requirements of the building skin system that may be a result of improper engineering or design.

A third-order failure in water infiltration consists of an overload of the capacity of the building skin water management system resulting in uncontrolled water intrusion, such as employing a 1-inch-high sub-frame flashing assembly, designed for 6.24-psf water resistance, for a window system that encounters regular severe rain events with wind speeds in excess of 50 mph. Other design defects that can lead to third-order failures include the improper spacing and sizing of weeps and the omission of vents for mitigating pressure differential in the air space of a masonry cavity wall.

A third-order failure may be due to forces that cause an overload of the design capacity of the building skin that was not anticipated by prescriptive building codes, such as extreme wind loads at the corners of high-rise building skins with complex geometries. A third-order failure can also be the result of conflicting performance requirements, such as ADA-compliant doors installed within a curtainwall system that requires 15-psf water resistance.

First- and second-order failures can appear to be a third-order failure in the water management system. Failures such as improper flashing material, improper application of barrier membrane, the obstruction of weep holes (first order) or the improper lapping, configuration, and termination of flashing (second order) can initially appear as a capacity issue. These apparent escalations of the Orders of Failures can generally be remediated by compliance with the system design documents. However, a third-order failure is a failure of a system that was installed in accordance with design documents, whose capacity or performance capability is exceeded by actual environmental conditions, user expectations, or regulatory requirements. Third-order failures can also be a result of limitations in capacity or performance caused by aesthetic requirements, such as low or no curb height for proper termination of roof membranes, oversized panels, and complex geometries.

Third-order failures can be managed or anticipated by computer simulation modeling, physical scale model testing, laboratory mock-up testing, and field performance verification testing (Figure 3). Remediation of third-order failures will become progressively more difficult as the project moves from the design phase and further into the construction phase. Solutions may require alternative designs and applications of innovative materials, assemblies, and fabrication technologies. Peer review of design documents can assist in assuring consistency in performance requirements for different building skin system and related components. Single-source responsibility of the building skin assembly can be key in assuring compatibility of all components, compliance with performance requirements across all the interfaces of the entire building skin, and comprehensive, project-specific warranty of assemblies and components.

Figure 3 – Third-order failure: field-testing storefront that had water intrusion.
Fourth-Order Failures

Fourth-order failures are failures due to degradation of components and assemblies over time. Generally, a fourth-order failure is a progressive decline in performance of the building skin system, caused by repeated usage; exposure to vapor, moisture, UV or airborne debris; seasonal change; freeze/thaw cycles; severe weathering; or extreme environmental conditions. A fourth-order failure in water infiltration consists of degradations of sealant or gasket materials from UV exposure, limiting joint movement and causing failure of flashing membranes due to extreme temperature variations, such as within parapets and copings. Another form of fourth-order failure can be due to the limitations of the building skin system to adapt to changing building codes and industry standards. Building code changes may require a completed building to add insulation, change windows and glass types, or improve the air barrier system to meet the revised R-value requirement of building skin.

Fourth-order failures can result in the occurrence of lower-order failures. Long-term exposure of the roof coping to ultraviolet light can result in first-order cohesive failure and second-order adhesive failure of the sealant joints. Freeze-thaw cycles can cause second-order cracking in the mortar joint below the coping. Weathering and movement can cause third-order cracking and displacement of the coping. High temperature variations, combined with radiant energy reflected from neighboring structures, can cause deterioration of the through-wall flashing, which can result in first-order water intrusion around the reinforcing bars supporting the coping. Similarly, deterioration of a concrete coping can result in corrosion and failure of structural steel reinforcing bars. This can lead to second-order separation of the concrete from the reinforcing bars and first-order water intrusion (Figure 4). These de-escalations of the Orders of Failure can be characterized as a “cascade of the Orders of Failure.”

Conversely, lower-order failures can result in the appearance of fourth-order failures. First- and second-order water infiltration in laminated glass can cause third-order delamination. This can result in fourth-order yellowing or bubbling of the interlayer.

While fourth-order failures, in general, cannot be completely avoided, they can be

<table>
<thead>
<tr>
<th>Order</th>
<th>Air Infiltration</th>
<th>Water Penetration</th>
<th>Thermal</th>
<th>Structural</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gaps in corner or in improperly installed gaskets</td>
<td>Unsealed gaps or penetrations; holes in WRB membranes</td>
<td>Conductive fastener; damaged insulation</td>
<td>Damaged fasteners or members</td>
</tr>
<tr>
<td>2</td>
<td>Improperly sized or missing gaskets; improperly installed doors</td>
<td>Unadhered sealant to substrate; improperly lapped WRB membranes</td>
<td>Gaps between insulation batts</td>
<td>Failed connections; adjustable anchors</td>
</tr>
<tr>
<td>3</td>
<td>Improperly designed weatherstripping at doors/windows</td>
<td>Low flashing height</td>
<td>Insufficient insulation thickness</td>
<td>Excess deflection of members</td>
</tr>
<tr>
<td>4</td>
<td>Gasket UV degradation</td>
<td>Sealant UV degradation</td>
<td>Insulation sagging or degradation</td>
<td>Corrosion of members</td>
</tr>
</tbody>
</table>

Table 1 - Typologies of building skin failures.
mitigated by the use of durable materials and high-performance assemblies, design redundancy, post-installation performance verification testing, proper maintenance programs, and timely repairs. Maintainability can be improved with custom window washing systems, modular panels, and providing for accessibility. Designing for adaptability or exceeding current industry standards and building codes can contribute significantly to the long-term performance of the building skin system. Nature can be a source of inspiration for innovative design such as simulating a natural ventilated system, developing self-cleaning surfaces, and using self-crystalizing concrete aggregate that may stand the test of time.

### Applications of the Four Orders of Failure

The Four Orders of Failure in building skin can be used as an analytical tool for presenting information in matrices to assist decision-making during design, value-engineering, bidding, and construction phases of a project.

#### Design Phase

The Orders of Failures can also provide insights in developing and analyzing building skin design solutions that bridge across individual modes of building skin failures within a common order, such as providing an air cavity that mitigates pressure differentials to manage water and air infiltration in the building skin assembly.

Table 2 shows a design solution matrix developed for a 12-story luxury condominium project with a 13,000-sq.-ft. building skin that was designed to include articulated limestone walls and a window-wall system with alternating glass planes. The matrix identifies the performance requirements and proposes design options for mitigating first-, second-, third-, and fourth-order failures.

### Table 2 – Design solution matrix.

<table>
<thead>
<tr>
<th>Order</th>
<th>Air Infiltration 0.060 cfm/sf</th>
<th>Water Penetration 12 psf</th>
<th>Thermal Opaque: 15-R Window: 0.38 U</th>
<th>Structural 50-psf Wind Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Self-healing WRB membrane</td>
<td>QC sealant joint installation to assure proper geometry.</td>
<td>Nonconductive fasteners. Sealed penetrations</td>
<td>Observe edge limit dimensions</td>
</tr>
<tr>
<td>2</td>
<td>Vulcanized corner gaskets; seal all gaps</td>
<td>Manufacturer-approved flashing assembly; adhesion testing and use of primer, if needed</td>
<td>T&amp;G insulation; seal all gaps</td>
<td>Engineered adjustable anchors to slab</td>
</tr>
<tr>
<td>3</td>
<td>Continuous WRB membrane with interior air seal</td>
<td>Field-test sealant; proper height window gutter</td>
<td>4-in. continuous insulation</td>
<td>Structural window calculations per ASCE-7</td>
</tr>
<tr>
<td>4</td>
<td>Air-permeable WRB membrane; silicone gaskets</td>
<td>Two-stage silicone seals with closed-cell backer rods</td>
<td>Hydrophobic insulation</td>
<td>Separation of dissimilar metals</td>
</tr>
</tbody>
</table>

#### Table 3 – Building skin fabrication alternatives.

<table>
<thead>
<tr>
<th>Order</th>
<th>Conventional Field-Installed Window and Veneer Stone</th>
<th>Prefabricated Windows and Cubic Stone</th>
<th>Unitized Curtainwall</th>
<th>Prefabricated Stone and Windows</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Susceptible to poor workmanship</td>
<td>Fewer joints with large cubic stone; field-installed windows and flashing assemblies</td>
<td>Fewer joints in factory-fabricated CW panels; separate unitized stone panels</td>
<td>Factory-fabricated composite stone panels and window panels</td>
</tr>
<tr>
<td>2</td>
<td>Field-installed joints between stone/stone and window/stone</td>
<td>Field-installed joints between stone/stone and windows/stone</td>
<td>Field-installed joints between CW/stone panels</td>
<td>Field-installed joints between panels</td>
</tr>
<tr>
<td>3</td>
<td>No assembly test; stone wall cannot be field-tested; field-performance verification tests on limited windows</td>
<td>Lab test of similar windows only; stone wall cannot be field tested; field-performance verification tests on limited windows</td>
<td>Pre-engineered lab tested CW and stone panels; field-performance verification test on field-installed joints</td>
<td>Single source pre-engineered, tested total stone/window assembly; field-performance verification test on field-installed joints</td>
</tr>
<tr>
<td>4</td>
<td>Long installation time &gt;12 months; 5-20 years life expectancy</td>
<td>Lead time &gt; 6 mos.; installation &lt;8 mos.; 10-20 years life expectancy</td>
<td>Long lead time; installation &lt;4 mos.; 20-50 years life expectancy</td>
<td>Longest lead time; installation &lt;4 mos.; 50-year life expectancy</td>
</tr>
</tbody>
</table>
Building skin performance but can have cost reduction can not only compromise piecemeal fashion. This singular focus on built alternatives and often performed in a generally based on standard conventionally adjacent systems. Value engineering is generally native to facilitate an informed decision-making process that will not compromise performance and adversely affect the project schedule and long-term durability of the building skin. Organizing relevant information about potential building skin failures in a clear, succinct, and hierarchic way would significantly contribute to limiting short-sighted cost savings at the expense of long-term performance.

Value engineering requires a more comprehensive organization and presentation of the cost and consequences of each alternative to facilitate an informed decision-making process that will not compromise performance and adversely affect the project schedule and long-term durability of the building skin. Organizing relevant information about potential building skin failures in a clear, succinct, and hierarchic way would significantly contribute to limiting short-sighted cost savings at the expense of long-term performance.

The example below relates to a project, where midway into construction, in order to reduce construction costs, it was proposed to install ribbon windows with horizontal precast concrete spandrels on the three-story penthouse in lieu of the original unitized curtainwall system.

The matrices in Tables 4 and 5 compare the potential first-, second-, third-, and fourth-order failures for this value engineering option and the original unitized curtainwall. The tables illustrate the significant risks in third-order failure through performance requirements with this value engineering option. They highlight the need for proper redesign of the exterior wall system to address these potential deficiencies. Particularly, the entire water management system needs to be modified to provide for a proper WRB membrane, flashing assembly, and two-stage sealant system to reduce the risk of first- and second-order water and air leakage. The impact of thermal bridging on thermal performance needs to be addressed. Alternatives to the proposed addition of interior building insulation must be considered. These matrices also inform the owner of the requirement for annual inspections and maintenance.

**CONSTRUCTION CASE STUDIES**

The orders of failure reveal themselves during the construction phase and present inherent risks when best practices are bulldozed by cost and schedule-focused projects. Fabrication before shop drawings, installation prior to successful mock-ups, and projects without enclosure consultants are three scenarios that result from low-cost and schedule-driven projects, which, in turn, create opportunities for failure. The following case studies will discuss the risks associated with each of these scenarios.

Owners are pulled in many directions, and advice received from their architect, façade consultant, general contractor, sub-contractor, and fabricator is often biased. While we are all working towards the same objective, we all have different priorities and ideas on what is necessary to complete the project. There is tremendous pressure

<table>
<thead>
<tr>
<th>Order</th>
<th>Air Infiltration 0.10 cfm/sf</th>
<th>Water Penetration 12 psf</th>
<th>Thermal 15 R-value</th>
<th>Structural 50-psf Wind Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gaps in field-installed weather and air seal</td>
<td>Water intrusion at intersection of gasketed vertical and field-installed window joints</td>
<td>Thermal-bridged interior building insulation</td>
<td>Check for load imposed by windows on concrete spandrels</td>
</tr>
<tr>
<td>2</td>
<td>Leaks at field-installed window/concrete spandrel joints</td>
<td>Damage to WRB membrane during installation</td>
<td>Discontinuity of insulation at floor slabs</td>
<td>Field-installed adjustable anchors; check spandrels are within tolerances</td>
</tr>
<tr>
<td>3</td>
<td>Continuity of air barrier difficult to install and and properly terminate</td>
<td>Primary seal has no backup; flashing difficult to install.</td>
<td>Difficult to install continuous insulation in concrete spandrels</td>
<td>Check structure for load imposed by concrete spandrels</td>
</tr>
<tr>
<td>4</td>
<td>High maintenance cost of air/weather seals; &lt;10 years life expectancy</td>
<td>High risk of water intrusion and damage to interior finishes and structure; &lt;10 years life expectancy</td>
<td>Interior insulation may condensate; risk of mold and corrosion to structure; &lt;20 years life expectancy</td>
<td>Concrete may require spall repair in 10-20 years; &lt;20 years life expectancy</td>
</tr>
</tbody>
</table>

**Table 4 – Risks associated with ribbon windows with horizontal precast panels (value-engineered option).**

**Fabrication Alternatives**

The same 12-story condominium project has an aggressive eight-month installation schedule. The matrix in Table 3 compares four options for installation of the window and stone panel wall systems. The matrix highlights the different risks in the Four Orders of Failure associated with each of the four fabrication options. The prefabricated and unitized options minimized the risk of failures, reduced installation time, and provided the best assurance for long-term performance.

**Value Engineering**

Value engineering is a necessary form of cost control in most projects—large or small. These value-engineering exercises are generally conducted by the construction manager or general contractor and not led by the project building skin design team who initiated, developed, and coordinated the integrated building skin system design. These sessions are often conducted under high-stress conditions when the project is either about to go out to bid or is in the middle of construction. Consequently, there is often not sufficient time and priority to fully understand the impact on the performance requirements of the project, or the “ripple effect” on the design and performance of adjacent systems. Value engineering is generally based on standard conventionally built alternatives and often performed in a piecemeal fashion. This singular focus on cost reduction can not only compromise building skin performance but can have a major unexpected impact on the project schedule due to out-of-sequence work, conventional field-installed assemblies, use of less-durable materials, and modifications of adjacent systems. The quality control and assurance programs that were an integral part of the original single-source wall assembly, specified by the design architect, are often foregone by piecemeal value engineering.

While we are all working towards the same objective, we all have different priorities and ideas on what is necessary to complete the project. There is tremendous pressure
to turn buildings over on schedule and on budget. Therefore, many decisions are made from a time-and-cost perspective, increasing the risk of poor performance and inefficiency. In the long run, many of these decisions result in additional time and cost to compensate for proceeding out of sequence.

**Case Study 1 – Fabrication Prior to Approved Shop Drawings**

Almost 30% of nearly 300 architects, owners, and consultants polled in a number of symposia at which we have recently presented along the East Coast of the United States have admitted to falling victim to this practice on at least one project. This is a disturbing trend that speaks to the prioritization of schedule and the willingness to take on the risks caused by out-of-sequence work.

The project in this case study began with a failed laboratory mock-up. The large window assembly, which was approximately 14 feet wide and 10 feet tall, could not properly manage water. The window assembly was redesigned into a curtainwall assembly. The first set of shop drawings was produced within four months. Four months later, as the shop drawing revision process continued to resolve the identified failures, including a lack of weeps (first-order failure), discontinuity in the plane of airtightness between the window assembly and adjacent metal panel (second-order failure), and a water capacity issue (third-order failure), the manufacturer convinced the owner to release fabrication, promising to make up lost time in the schedule due to the redesign process. Despite our recommendations and continued identification of potential first-, second-, and third-order failures, fabrication was released with no approved shop drawings or valid laboratory test data.

Despite the promises of improving the schedule, fabrication was continually delayed. After one year of waiting for units, the first fabrication plant visit revealed first-, second-, and third-order failures including:

1. First-order failures: Gasket failures
2. Second-order failures: Gaps and discontinuities in the insulation
3. Third-order failures: Glass roller wave distortion and omission of insulation

The manufacturer promised to make up lost time in the schedule and recommended on-site fabrication in lieu of plant fabrication. Despite our recommendations to the contrary, the owner agreed to allow shipment of crates of parts to the project for on-site fabrication, still without approved shop drawings.

Four months later, a small crew was on site to fabricate the first unit. Fabricating a unit on site without shop drawings proved more difficult than anticipated. It took two months to fabricate the first window, which was to be a “first-install” mock-up. Over the next three months, the mock-up failed three times before another installer was hired to fabricate on site and install the next mock-up.

One month later, the new first-install mock-up was tested and failed. The mock-up unit was retested three times over the next five months, and the following failures were identified: leaks at fasteners (first-order failure), sealant joint adhesion failure (second-order failure) and excessive air leakage (third-order failure). However, in an effort to make up some of the lost time in the schedule, unit installation continued. Through a series of isolated testings, an issue with the gaskets was identified on the operable windows that required fabrication of custom gaskets, which resulted in another three-month delay. When the custom gaskets arrived, nearly 80% of the units were fabricated and installed. All of the operable lites needed to be retrofitted and reinstalled. The laboratory mock-up test will be scheduled after all 550 units are installed in the condominiums, more than two years behind schedule.

The decision to fabricate without shop drawings, which became further complicated by the decision to fabricate on site, resulted in a project delivered nearly two years behind schedule at an undisclosed financial loss. This project will be completed without approved shop drawings and with a laboratory mock-up test that will hopefully be successful upon completion of the project.

**Case Study 2 – Installation Prior to Approved Mock-ups**

Another scenario that results from low-cost and schedule-driven projects is installation prior to successful mock-ups. This scenario is a more common occurrence and was touched upon in the previous case study.

Freestanding mock-ups are often excluded from fast-track schedules and budget-focused projects, leaving project teams to rely on the first-install mock-up.
Delays due to fabrication, weather, cure times, and mock-up failures often result in installation prior to the completion of a successful mock-up.

As is common for many projects, the first-install mock-up in this example failed. While the team took the time to understand the failure mode, identifying first-, second-, and third-order failures, the contractor continued to install the windows while the diagnostic evaluation continued.

After the second failed mock-up test, the window was removed so the team could more closely scrutinize the installation. Upon review, it was noted that an errant hole was drilled through the thermal break during fabrication, which resulted in the leak. Unfortunately, 50% of the windows were already installed and needed to be removed, repaired, and reinstalled.

If the project team agreed to work through the failed mock-up and identify the first-order failure, all of the windows could have been repaired prior to installation. Better yet, if a freestanding mock-up had been tested prior to fabrication, the machining error could have been corrected in the factory.

**Case Study 3 – Design and Construction Without a Building Skin Consultant**

A third outcome resulting from low-cost and schedule-driven projects is the exclusion of the building skin consultant from design projects or delegation of responsibility for the enclosure to the wrong team member. All inherent responsibility and risk for the enclosure are delegated to the architect. At times, this leads to the need for an enclosure consultant to resolve performance issues after the project is complete. One example of this scenario is a 12-story condominium that was completed just two years prior to our engagement. Claims of tenant comfort issues and high utility bills resulted in a preliminary assessment. Results of a whole-building air leakage test in conjunction with an infrared scan validated their concerns. For example, a mock-up of an exterior wall system designed to be a perfect barrier may pass water infiltration criteria during initial performance verification testing, only to later reveal the same fully installed system performs poorly over time. More often than not, such problems can be traced back to lower-order failures. Failed or improperly installed sealants (first order) will become point sources for water infiltration, while linear discontinuities at expansion/ control joints (second order), which were not tested during initial mock-up phases, can further contribute to water infiltration. These unanticipated water infiltrations can significantly increase the rate of deterioration if unmitigated. Corrosion of internal reinforcing steel might advance deterioration of exterior walls to the extent that spalling or distortion occurs or causes mold on interior framing/ finishes (fourth order). A barrier wall system does not provide any drainage capacity and, therefore, would fail to meet the design criteria for water resistance. This lack of redundancy in the water management system is one reason barrier wall systems generally do not meet criteria for industry best practices. When similar failure modes are applied to a rainscreen system, a properly designed and implemented drainage plane and flashings will be capable of managing water leakage. However, if these components are undersized or improperly sloped, they could be overwhelmed during normal operation and permit third-order water intrusion to the interior of the building.

Of primary importance to the higher-order failures is issues that are often sorted out early in the design process via identification of the owner’s project requirements and design intent. While cost and schedule may dominate the construction process, it is recommended that the project requirements and design intent be referenced. Efforts to drive cost and schedule may adversely affect previous decisions related to service life, durability, and redundancy. Designers and fabricators have a responsibility to understand how building skins will fail or at least anticipate how decisions might affect performance requirements and other failure typologies.

Unanticipated performance and/or serviceability requirements often result in cascading Orders of Failure defined by a compounding effect that lower Orders of Failure might have in causing higher order failures such as decreasing the service life of enclosure components and assemblies. When failures cascade, characterization of deficient conditions may be complicated, as the relationship between cause and effect of related assemblies and failures can be convoluted. It may be useful to summarize symptoms in a matrix in order to help identify root causes.

**Case Study – 15-Year-Old Institutional Building**

An institutional building has had significant leaks since the day it opened approxi-
approximately 15 years ago. The building enclosure consisted of traditionally built masonry cavity walls and EPDM roofs that were topped with an integrated 3½-acre unitized skylight system with a clear span over the interior space. The system is framed over 5-in. steel tubes to form the primary support structure for the glazing. Preassembled unitized glazing panels are set on an extruded aluminum sub-frame installed over the steel, and typically include four lites of ¾-inch, stacked and then captured by extruded aluminum ribs. Individual lites were originally factory-glazed with structural silicone sealant to intermediate aluminum frames. Field-applied perimeter sealant joints were installed at the joints between adjacent unitized panels and the extruded aluminum capture system. At end conditions, the unitized panels turn 90 degrees from vertical to horizontal where the skylight terminates at a structurally supported horizontal extruded aluminum frame that is installed over horizontal EPDM roofing.

An initial post-occupancy evaluation attributed leaking of the building primarily to improperly installed sealant joints at locations within the skylight, which had over 125,000 linear feet of sealant. Subsequent analysis years after the completion of the building revealed more systemic water infiltration issues that are all interrelated:

1. First-order failures: Several joints at shallow setting blocks and a few adhesion issues of the sealant joints related to workmanship were noted.

2. Second-order failures: The extruded aluminum capture system butt joints and panel end-cap butt joints were sealed to one another such that the primary weather seal had very little (approximately <¼-inch) bite when installed in accordance with the manufacturer requirements, which was found to create linear sealant joint failures in situ.

3. Third-order failures:
   a. A value management exercise during construction changed skylight end units from an offset sloped panel to a horizontal panel. This caused the weep system to be unable to manage water infiltration cascading down from the large field of the skylight.
   b. The sub-frame was designed to anticipate drainage of condensation but did not anticipate future failures of sealant joints and bulk water infiltration.

4. Fourth-order failures: Unanticipated water infiltration within the skylight system has led to the premature degradation of the PVB interlayer at the laminated glass edges.

The above list is not comprehensive to this case study, but is an accurate representation of how issues can be interrelated. Following characterization of the leak activity, it was determined that the second-order failures were causing the most systemic problems related to the volume of water infiltration. Addressing the issues of transition joints resolved approximately 95% of the most significant leakage. However, the damage sustained on the interior of the building steel, drywall, and other finishes remains an ongoing operations and maintenance problem, due to the inability of the weep systems to facilitate serviceability requirements of the aging skylight seals.

Anticipating durability and serviceability requirements is necessary for any building to be sustained into the future. When possible, it is useful to design and construct buildings of components and assemblies with similar maintenance and service cycles, but it is not unusual in modern construction to use materials of varying service requirements adjacent to one another. Third- and fourth-order failures can be mitigated by providing formal separation between systems, creating efficiencies for future maintenance and capital projects.

For example, a modern tower was constructed of a combination of a custom unitized curtainwall, along with prefabricated EIFS panels at a podium deck. There is available service history of the prefabricated EIFS panel system to anticipate the maintenance requirements for the EIFS panel joints. However, the lack of service history of the custom unitized curtainwall precludes fully anticipating its future maintenance requirements. In this case, a formal articulation and flashing between adjacent EIFS and curtainwall systems would serve to reduce the risk of cascading Orders of Failure between the systems.

It is also important to note that aging buildings exist in a world of changing requirements where building code is often the lowest common denominator. In the restoration of older stock or historical buildings, designers can be faced with resolving issues related to air infiltration, thermal resistance, and condensation risk. A review of NY State Building energy code requirements for a historical building where an energy code variance was not available, revealed the following fluid changes in the thermal performance requirements for exterior walls:

1. 1959 NYS BC:
   a. Vapor barrier required between floor and sub-floor
   b. No insulation requirement
2. IECC 2009: R-20ci
3. NYS ECC 2010: R-20c
4. IECC 2012: NYS ECC 2015: R-25ci
5. IECC 2015: R-30ci

In our drive for energy efficiency, an under-insulated building would be considered a fourth-order failure. More generally, serviceability requirements of building skins are changing. Just as a building constructed in a flood plain would be deemed unacceptable if it did not anticipate future floods, our building skin designs need to address our rapidly changing environments.

CONCLUSION

The Four Orders of Building Skin Failure is a classification system that spatially correlates the multi-dimensional interfaces of building skin components with the building skin failures. This classification system can assist building skin professionals in presenting relevant information about project requirements and potential failures in a clear ordered form to our owners, contractors, and project teams, and thereby contribute to holistic decision-making to assure long-term performance. This methodology can be used as an analytical tool to promote innovative, adaptable, high-performance building skins that can address changing environmental and regulatory requirements.