Feature

Reviving the Concrete Giants: The Role of Structures as Building Enclosures

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THE VAST INVENTORY of existing buildings with exposed concrete framing will inevitably require repairs. For concrete-frame buildings where the exposed structure also serves as the building enclosure, deterioration can result in structural issues and fall hazards, in addition to unsatisfactory building enclosure performance, including water leakage. This article presents examples of deterioration mechanisms and repair approaches from both structural and building performance perspectives. The article also provides information regarding concrete construction techniques, exterior condition assessment best practices, discussion of building enclosure performance requirements and energy codes, and considerations for preventive maintenance and repairs.

Figure 1. *Building exterior walls consisting of concrete columns, concrete slab edges, windows, and sealant joints.*

CONCRETE EXTERIOR WALL SYSTEMS

Exterior walls for cast-in-place concrete-frame buildings typically consist of exterior concrete elements (for example, columns, slab edges, and walls), windows, and exterior sealant joints (**Fig. 1**). Collectively, these exterior walls are considered face-sealed barrier walls. Exterior wall insulation is typically located on the interior face of the exterior walls (**Fig. 2**). To resist water penetration, the exterior walls rely primarily on the weathertight integrity of the (sometimes coated) concrete surfaces and sealant joints. Face-sealed barrier walls only offer a single line of defense against water penetration and are considered by some as a "zero-tolerance" wall system. Water that penetrates beyond the exterior surfaces of the wall and sealant joints will likely result in water penetration into the building and/or deterioration of water-sensitive materials, including corrosion of embedded steel reinforcement and degradation of drywall and insulation on the interior side of the walls. Water is also able to penetrate cracks at skyward-facing surfaces unless a remedial solution, such as routing and sealing cracks and/or applying a waterproofing coating, is provided and the repairs are maintained over time.

In contrast, exterior wall system designs that include secondary lines of weather protection offer redundancy and are generally more effective at limiting water penetration compared with face-sealed barrier wall systems. Designs with secondary lines of weather protection often include a water management system consisting of a weather-resistive barrier, through-wall flashing, weeps, drips, and accessory components as required to manage and discharge water that enters the exterior wall drainage cavity.[25] Without overcladding the existing walls with an insulated rainscreen system, achieving a redundant exterior wall system for concrete-frame buildings is not practical. As such, preventive maintenance and repairs of the exterior wall systems are imperative to long-term durability and weathertightness of the concrete exterior wall system.

HISTORY OF CONCRETE BUILDING CONSTRUCTION PRACTICES

Concrete is the most commonly used construction material worldwide. In high-rise buildings, reinforced concrete construction provides stiffness, mass, and ductility that are ideal for tall and slender structures. Construction practices for concrete-frame high-rise buildings have evolved significantly over time. The first true reinforced concrete high-rise was the Ingalls Building in Cincinnati, Ohio, a 16-story structure completed in 1903 that is still in service today. The building utilized twisted steel bar reinforcement, patented by Ernest L. Ransome in 1884, establishing viability for concrete to be used in future high-rise buildings.[17] By the 1950s, high-strength concrete mixes ($f'c > 5000$ psi [3.4475 kPa]) began to emerge, allowing for more efficient and cost-effective construction. Ultra-high-strength concrete is now manufactured with compressive strengths over 20,000 psi (1.3779 kPa). Modern concrete buildings are constructed in a wide variety of shapes and sizes, owing to the material's versatility, and often utilize concrete as both the structural frame and architectural finish. Today, construction practices prioritize not only structural integrity but also efficiency and sustainability.

Although modern high-rise residential and commercial buildings provide more natural daylighting than older buildings, many modern structures are constructed with exposed exterior concrete. In these buildings, aluminum-frame curtainwall systems or other high-performing fenestration are typically arranged in a continuous ribbon window configuration at each floor. The concrete slab edges and some columns and shear wall components remain exposed to the building exterior (**Fig. 3**).

These buildings continue to be constructed with insulation placed on the interior face of the concrete exterior walls. However, due to thermal bridging of the slabs and balconies where no insulation can be provided, the interior insulation

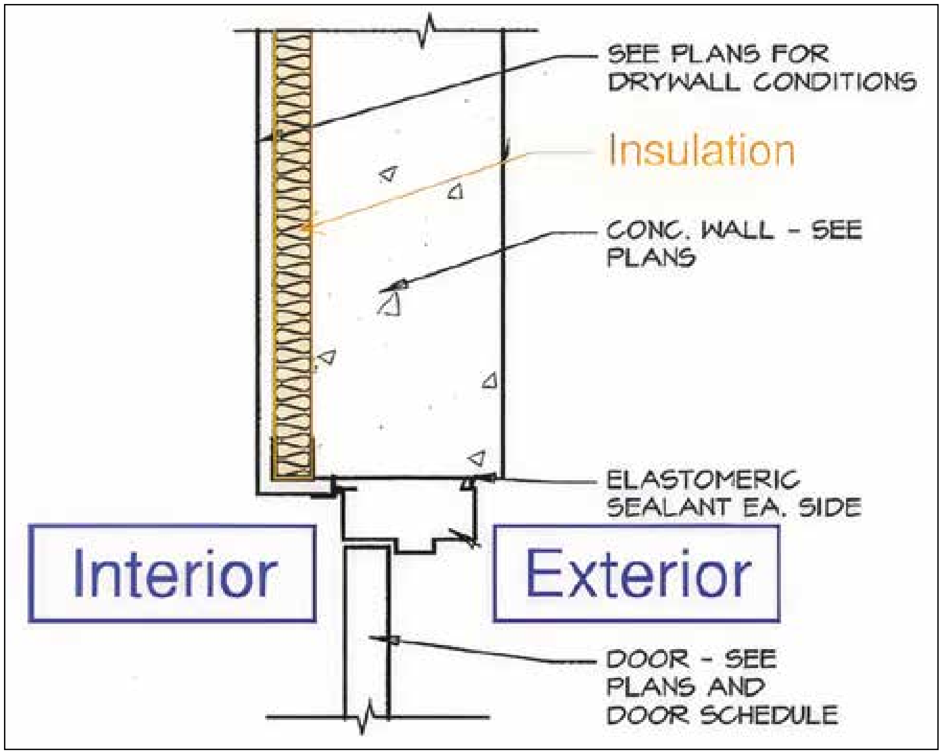

Figure 2. *Concrete exterior wall design with insulation on building interior.*

Figure 3. *Modern building (circa 2018) with exposed concrete beams, wall areas, columns, slab edges, and balconies.*

at wall locations may only provide limited thermal benefit with respect to the entire structure.

Although providing fibrous insulation on the interior side of concrete exterior walls theoretically improves thermal resistance and offers increased energy performance, the presence of this insulation increases the risk of condensation in cold climates. The presence of fibrous insulation results in colder surfaces on the interior face of the concrete but does not prevent warm, conditioned interior air from passing through the insulation to the cold concrete surfaces. Additionally, placing insulation on the building interior typically results in discontinuous insulation at window and door locations, thus resulting in localized thermal issues where fenestration is located outboard of the insulation plane.

Some modern buildings are constructed with precast concrete panels with insulation placed between an interior and exterior layer of concrete (that is, insulated concrete sandwich panels). With proper detailing, these buildings can offer improved thermal performance with respect to cast-in-place concrete structures. However, thermal modeling is typically recommended to allow for the evaluation of conditions at floor slabs, fenestration interface details, and locations of reduced insulation, such as at steel embed plate locations.

DISCUSSION REGARDING BUILDING SCIENCE AND CONDENSATION

Continuous exterior insulation is now required by many energy codes for new buildings, especially in cold climates. For existing buildings, achieving a redundant exterior wall system with continuous exterior insulation is not practical unless the concrete walls are overclad with an insulated rainscreen system or as part of a deep retrofit program. As such, improved thermal performance of concrete exterior wall systems is often achieved locally by means of condensation mitigation efforts.

Windows and doors are typically anchored directly to and supported by concrete framing and, thus, are in direct contact with the building's structural concrete frame. Exterior walls for high-rise towers are not anticipated to be high performing because of the thermal bridging that occurs as a result of the concrete structure being exposed directly to exterior conditions. Cantilever conditions, such as at balconies, exacerbate potential issues associated with thermal bridging (**Fig. 4**). Additionally, solid concrete has high thermal mass. In winter months, when the outside air temperature is colder than the indoor air temperature, the surface temperature of the inside face of the concrete wall will typically remain lower than the indoor air temperature. The window and door frames, therefore, are typically supported by and attached to a cold concrete substrate during winter months. Condensation can occur on the cold interior surfaces, including concrete, window and door frames, and glass.

Figure 4. *Concrete-frame balconies cantilever beyond the building exterior wall.*

When the surface temperature of the window frames or interior face of the concrete walls falls below the dew point temperature, water vapor in the air condenses on the cool surfaces in the form of liquid water. Similarly, when the surface temperature of the window or concrete surface falls below the frost point temperature, water vapor condenses in the form of frost. Although calculated differently, both the dew point and frost point temperatures are functions of the ambient temperature and relative humidity within the building interior. Assuming the interior air temperature is fairly constant, the interior dew/frost point temperature will rise with increasing values of interior relative humidity. This phenomenon is more likely to occur in "heat-starved" spaces that do not receive direct heat from the interior, such as windows located behind closed curtains, concrete structural components located behind drywall finishes, and other interior surfaces far from heat sources.

Condensate on windows and doors can result in water runoff onto window stools and floor surfaces, resulting in deterioration and/or buckling of moisture-sensitive finishes (**Fig. 5**). Condensation within concealed spaces, such as behind drywall finishes, can result in deterioration of the finishes and/or biological growth.

If condensation becomes a nuisance or health issue for building occupants, thermal modeling can be used to analyze the thermal performance of the fenestration in combination with the surrounding construction, including the concrete exterior walls, interior insulation, and interior finishes. Models of existing construction can then be modified to assess options for improving the thermal performance of the fenestration and surrounding construction to limit the possibility of condensation during periods of cold exterior temperatures.

When performing thermal modeling and evaluating options for condensation mitigation, it is advisable to make interior investigative openings at representative areas to verify in-place conditions and monitor interior temperature and relative humidity values to establish a range of interior conditions during winter months. In some cases, condensation potential can be mitigated by means of slight adjustments to interior relative humidity controls during periods of cold temperatures.

CONCRETE EXTERIOR WALL DETERIORATION MECHANISMS

Though concrete high-rise buildings are often designed for long service lives, deterioration will occur due to various environmental factors. Concrete durability is defined by the American Concrete Institute (ACI)[20] as "the ability … to resist weathering action, chemical attack, abrasions, and other conditions of service."

Figure 5. *Condensation at a concrete-frame building in a cold climate.*

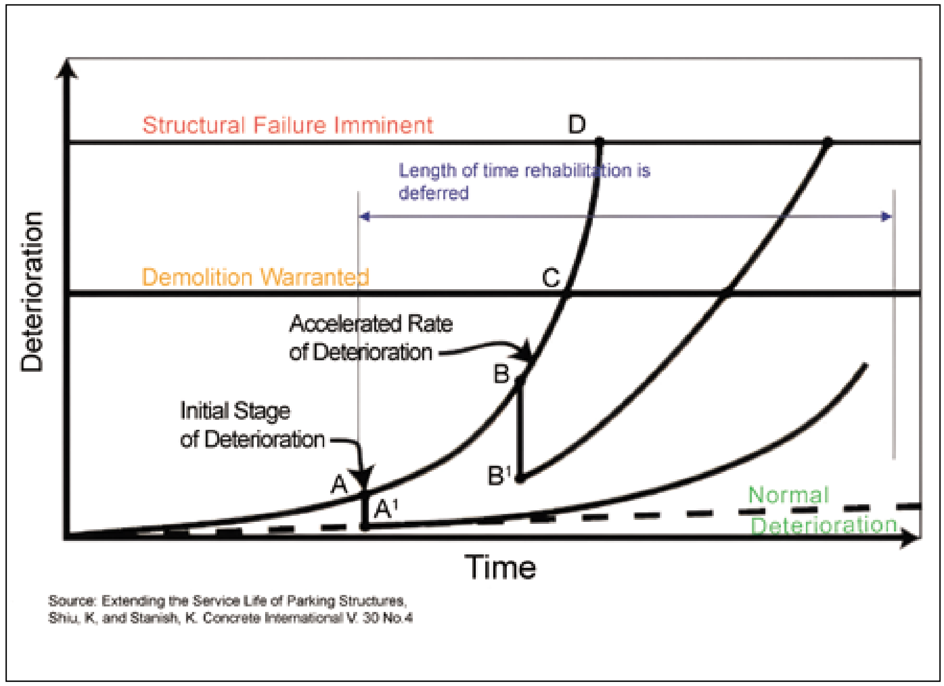

Figure 6. *Schematic representation of the relationship between deterioration and time of a concrete structure exposed to environmental factors.*

Properly designed and constructed concrete structures are resistant to most natural environments; however, they can be exposed to conditions that initiate chemical and/or physical deterioration mechanisms. Following the onset of initial stages of deterioration, the deterioration tends to accelerate exponentially over time.[22] Due to these factors, even the most durable concrete structures require periodic evaluation and routine maintenance throughout their design life to ensure safety and functionality. If maintenance and repairs are deferred indefinitely, structural failure can occur (**Fig. 6**).

Several variables that increase the risk of deterioration of exterior concrete structures include the following:[23,24]

- **Permeability and diffusivity:** The ease with which fluid/gas can penetrate and migrate through concrete (permeability) and the ease with which dissolved ions (for example, chlorides) move through concrete (diffusivity) are vital characteristics that are controllable through proper concrete mix design, such as the use of a low water-to-cement ratio and inclusion of supplementary cementitious materials. Higher permeability and diffusivity reduce the ability of concrete structures to resist most forms of deterioration.
- **Deleterious mix constituents:** Some forms of deterioration can be sourced back to the original concrete mixture constituents. Alkali-silica reaction occurs when reactive forms of silica within some aggregates are mixed with a high-pH pore solution and sufficient moisture, resulting in the formation of an expansive gel product, which can manifest as concrete cracking. Concrete mix constituents can also influence the corrosion of embedded steel reinforcement. Admixtures, aggregates, and mix water cumulatively containing chlorides in excess of approximately 0.15% by weight of cement can result in corrosion initiation at the reinforcement without external chloride exposure (see the discussion of chlorides later in this section).
- **Cracking:** Regardless of the concrete quality, extensive cracking in concrete structures, no matter the cause, allows water to enter the concrete, which can initiate deterioration mechanisms.
- **Freezing and thawing:** In colder climates, concrete elements exposed to weathering are susceptible to freeze-thaw deterioration. Pressure within pores of the cement paste and aggregate develops as wet concrete freezes. If this pressure exceeds the concrete tensile strength, these cavities will dilate and rupture. Repetitive cycles of this phenomenon may cumulatively result in the manifestation of visible cracking, delaminations, and spalling. Freeze-thaw exposure is typically considered moderate for concrete exterior wall elements, which are only occasionally exposed to long-term exposure to water accumulation. However, freeze-thaw deterioration can be particularly severe for skyward-facing surfaces, such as at exposed unprotected slab edges, balconies, and railing post pockets, which are more consistently exposed and prone to water ponding.
- **Carbonation:** During the hydration of cement, the pore solution in concrete becomes highly alkaline (pH $>$ 13). In this environment, ordinary, uncoated steel reinforcement will form a thin, protective oxide film, preventing the formation of expansive corrosion products. The natural diffusional ingress of carbon dioxide through concrete over time results in the neutralization of this alkalinity, lowering the pH of the pore solution and destabilizing the protective film. Carbonation leads to the complete dissolution of the protective layer and corrosion of the reinforcing steel.
- **Chlorides:** The presence of chloride ions in the pore solution at steel reinforcement locations can result in the depassivation of the steel's protective layer at certain concentrations, initiating corrosion. Chlorides can be internally sourced as part of the original mix or externally sourced from exposure to seawater, airborne chlorides in coastal regions, or deicing salts. The risk of external chloride exposure is typically considered low to moderate for concrete exterior wall elements but can be severe in localized areas, such as seawater splash zones and lower levels adjacent to roadway traffic in colder climates.
- **Corrosion of reinforcing steel:** Whether due to carbonation, chloride contamination, or other means, corrosion of embedded reinforcing steel forms expansive corrosion

Figure 7. *(a) Potentially hazardous delamination and cracking at concrete slab edge soffit; (b) corroded reinforcing steel exposed following removal of spalled concrete.*

products that increase the internal stresses in the concrete, eventually resulting in cracking, delamination, and/or spalling (**Fig. 7**).

CONCRETE SKYWARD-FACING SURFACES

Although not required by most building codes, concrete exterior walls are often coated for aesthetic purposes. A properly designed and applied coating system can also improve exterior wall performance and durability by limiting water penetration, thus delaying the onset of several forms of deterioration. Typical concrete exterior wall coatings are often highly permeable such that moisture within the concrete pore structure can evaporate to the exterior, even following coating application.

While a highly permeable acrylic coating may be appropriate for most concrete exterior wall surfaces, design at skyward-facing surfaces warrants further consideration with respect to waterproofing because water, snow, and ice can accumulate on these surfaces. Concrete cracking may occur on skyward-facing surfaces, and water that penetrates into the cracks will result in concrete deterioration and potential leakage into the building. At balcony locations, where deicing salts may be utilized, the salts may also penetrate into the cracks, accelerating corrosion of the embedded reinforcing steel.

Fenestrations are typically integrated with exterior concrete surfaces using sealant joints. Depending on the material utilized, exterior sealant joints may have a useful service life of 5 to more than 20 years. Even if these sealant joints are appropriately designed, installed, and maintained, water infiltration through concrete cracks at ledge conditions can bypass the joints, resulting in interior water penetration (**Fig. 8**).

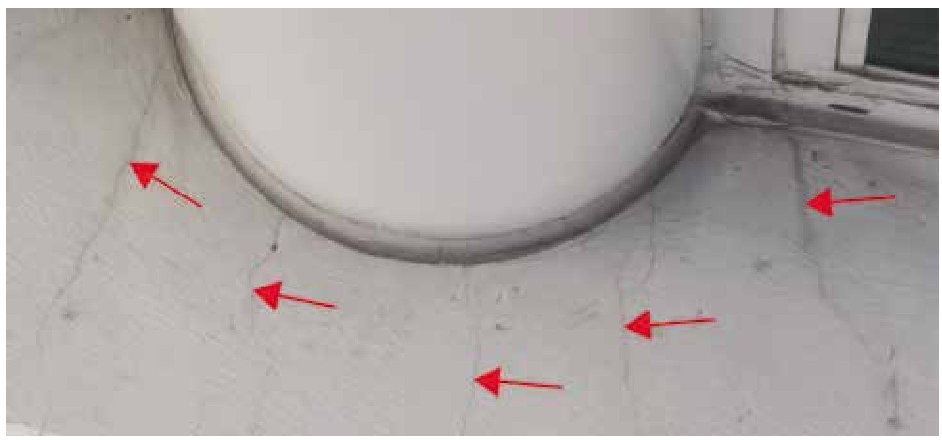

Figure 8. *Cracks at concrete skyward-facing surface extend below sealant joints.*

CONCRETE EXTERIOR WALL CONDITION ASSESSMENTS

Concrete deterioration can affect structural integrity and durability, and it also has the potential to impact the health and safety of the public. Concrete delaminations can result in spalls and fall hazards, posing safety risks. Unrepaired spalls reduce concrete cover and may expose embedded steel reinforcement, accelerating the deterioration. Addressing concrete degradation requires periodic repairs and maintenance; deferring these issues can lead to more extensive deterioration over time and higher long-term building maintenance costs. To mitigate these issues, regular condition assessments and timely maintenance are essential.

ASTM International standard E2018, *Standard Guide for Property Condition Assessments: Baseline Property Condition Assessment Process*,[1] defines professional practices, establishes reasonable expectations for those requesting the condition assessment, and suggests a baseline level of standard of care and recommended protocols for professionals performing the assessment.

ASTM also provides standards specific to condition assessments of exterior walls. ASTM E2270, *Standard Practice for Periodic Inspection of Building Facades for Unsafe Conditions*,[2] defines "methods and procedures for periodic inspection of building facades for unsafe conditions" in order to establish "minimum requirements." ASTM E2841, *Standard Guide for Conducting Inspection of Building Facades for Unsafe Conditions*,[3] is intended to provide "explicit knowledge gained from experience in conducting periodic facade inspections." ASCE/SEI 30, *Guideline for Condition Assessment of the Building Envelope*,[4] provides similar guidance.

In many municipalities, including Boston, MA; Chicago, IL; Cincinnati, OH; Cleveland, OH; Columbus, OH; Detroit, MI; Jersey City, NJ; Milwaukee, WI; New York, NY; Philadelphia, PA;

Question	No		Not Sure		Yes	
	Responses	Percent	Responses	Percent	Responses	Percent
Does the traffic coating on your balcony exhibit deterioration?	28	54%	13	25%	11	21%
Have you observed cracked concrete on building exterior walls?	31	60%	5	10%	16	31%
Does drywall on the interior side of exterior walls exhibit cracking?	43	83%	3	6%	6	12%
Does drywall on the interior side of exterior walls exhibit water staining?	49	94%	2	4%	1	2%
Has drywall or flooring been removed in your unit due to exterior wall leaks/repairs?	41	79%	5	10%	6	12%
Does your unit experience issues related to leakage (windows, walls, etc.)?	38	73%	3	6%	11	21%
Does your unit experience issues related to condensation?	25	48%	4	8%	23	44%
Does your unit experience issues related to air leakage (including drafty windows)?	42	81%	3	6%	7	13%
Does your unit experience issues related to temperature control?	41	79%	5	10%	6	12%
Are your windows or balcony doors difficult to operate?	33	63%	1	2%	18	35%
Have your windows or balcony doors been repaired in the last 5 years?	30	58%	12	23%	10	19%

Figure 9. *Example of results from an occupant questionnaire for a concrete-frame building.*

Pittsburgh, PA; San Francisco, CA; and St. Louis, MO, periodic exterior wall condition assessments are required by means of local ordanances.[21]

The first steps of a condition assessment should include background review of existing documents and discussions with facility managers, building engineers, building occupants, and/or contractors who have been involved in maintaining the property. Ideally, the background review should include an occupant questionnaire to assist in identifying known issues, such as concrete cracking and areas of water leakage. While results from these surveys should not be considered absolute, completed surveys will assist the investigator in establishing patterns of reported issues (**Fig. 9**).

Investigations should be performed by experienced professionals. Many municipal ordinances require the condition assessment to be performed by a licensed architect, professional engineer, or structural engineer. Investigations should be tailored to the specific building and site conditions and may include the following:

- **Visual survey:** Visual surveys can be performed from various vantage points, including the ground, balconies, roof, and adjacent rooftops and parking decks, using binoculars and high-resolution cameras. Such "binocular" surveys are limited in their efficacy by the resolution and magnification capacity of the binoculars and cameras used and the inability of the investigator to closely review all exterior wall surfaces. Unmanned aerial vehicles (UAVs) equipped with cameras and video recorders can supplement visual surveys by documenting large areas of the exterior walls. Such photographs and videos can be taken perpendicular to the exterior wall surfaces, thus providing images that otherwise would not be possible. UAV surveys are still limited, however, in that the investigator is unable to review concrete building components up close. As such, data obtained during visual surveys are most useful in allowing the investigator to identify areas for a supplementary up-close examination using traditional access methods.
- **Up-close examination:** In certain municipalities, exterior wall ordinances may only require a visual survey; however, the authors often recommend that up-close examination of representative exterior wall areas be performed in conjunction with a visual survey, especially if areas of potential concern have been identified. In other cases, a more comprehensive up-close examination may be required by the authority having jurisdiction or recommended by the investigator in order to develop scopes for repair. Access to the exterior walls is typically accomplished using swing stages, fixed scaffolding, articulating boom lifts, and/or industrial rope access. Evaluation of concrete exterior walls should utilize hammer sounding techniques described in ASTM D4580, *Standard Practice for Measuring Delamination in Concrete Bridge Decks by Sounding*,[5] and International Concrete Repair Institute (ICRI) 210.4R- 2021, *Guide for Nondestructive Evaluation Methods for Condition Assessment, Repair, and Performance Monitoring of Concrete Structures*,[6] to mechanically sound areas of the exposed concrete to identify delaminations.
- **Investigative openings:** If loose or delaminated concrete is identified during an up-close examination, removal of the loose concrete should be performed to address the potentially hazardous condition. The authors recommend that up-close examinations be performed by an experienced professional in conjunction with a concrete restoration contractor so that the contractor can perform "make-safe" repairs if directed to do so by the professional. At a minimum, representative investigative openings should be made to verify the concrete cover at steel reinforcement locations, as the extent of concrete cover will influence repair design considerations.
- **Nondestructive testing:** Nondestructive evaluation techniques require a trained and experienced technician. Findings from such testing should typically be verified via a sufficient number of investigative openings. For some projects, it may be beneficial to extract cores from balconies or other projecting elements in accordance with ASTM C42, *Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete*.[7] The contractor should utilize ground-penetrating radar to select core locations free of steel reinforcement, conduit, etc. In addition to concrete considerations,

additional investigation should typically be performed to verify sealant joint adhesion and joint geometry, as well as exterior wall coating adhesion and thickness.

- **Laboratory testing:** Prior to specifying repairs, it is useful to verify the chemical composition of existing exterior wall coatings and sealants. In addition, laboratory analysis can be performed to evaluate the concrete chloride concentration and carbonation depth to better understand the condition and properties of the concrete. Such laboratory testing is typically performed in accordance with ASTM C1152, *Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete,*[8] and/or ASTM C1218, *Standard Test Method for Water-Soluble Chloride in Mortar and Concrete* (chloride depth profile),[9] and ASTM C856, *Standard Practice for Petrographic Examination of Hardened Concrete* (carbonation depth).[10] Results from the laboratory testing will help to inform future repair strategies.

Minimum requirements for exterior wall examinations per ASTM E2270[2] are summarized in **Fig. 10**.

Following the condition assessment, the investigator may be tasked with preparing a report, and licensed professionals may be requested to develop drawings and specifications for repair. In some cases, depending on the scope of the original assignment, the report may include additional recommendations, including investigative openings and/or laboratory testing. If water leakage has been reported at the property, forensic water testing may be recommended. ASTM E2128, *Standard Guide for Evaluating Water Leakage of Building Walls,*[11] can be utilized as a guide when developing a project-specific forensic water testing protocol. Thermal analysis may also be recommended if condensation-related issues have been reported or are revealed during the investigation.

10.4.1 Viewing horizontal surfaces that can pond water (such as sills, ledges, cornices, water tables, and other such horizontal bands) from above wherever possible,

10.4.2 Checking for out-of-plane displacement of facade elements while scanning the facade horizontally and vertically,

10.4.3 Checking for signs of staining, spalling, water or moisture damage, weathering or distress of facade components,

10.4.4 Sounding of the facade surface with a hammer[3] if material delamination of facade components is possible,

10.4.5 Pushing against or pulling on facade elements, or both,

10.4.6 Pull test on adhesively attached components at building corners and in the field of the wall,

10.4.7 Evaluating sealant adhesion by NDT,

10.4.8 Probing (exterior or interior, or both) and NDT to observe concealed facade components such as anchors, inserts or support of facade components,

10.4.9 Removing loose or fractured components to reveal cause of distress, where safe to do so, and,

10.4.10 Sampling of material obtained from probes for visual examination and laboratory testing as required.

Figure 10. *Excerpt from ASTM E2270.*

STRUCTURAL MAINTENANCE AND REPAIR

ASTM E2018[1] describes deferred maintenance as deficiencies that could have been remedied with normal routine maintenance but are overlooked or otherwise not addressed due to budgetary limitations. As maintenance is deferred, the eventual repair typically becomes more expensive, especially if hazardous conditions develop that require emergency repairs that limit owners' ability to obtain competitive pricing for repairs. The best way to avoid this situation is for building owners to budget for and be proactive regarding preventive maintenance.

Where concrete distress has been identified via a condition assessment, the distressed regions should be evaluated and remediated using industry-standard practices and guidelines. Resources for proper repair and maintenance of concrete distress include ICRI 310.1R, *Guideline for Surface Preparation for the Repair of Deteriorated Concrete Resulting from Reinforcing Steel Corrosion,*[12] ICRI 320.1R, *Guideline for Selecting Application Methods for the Repair of Concrete Surfaces,*[13] ACI 546R, *Guide to Concrete Repair,*[14] ACI 562, *Assessment, Repair, and Rehabilitation of Existing Concrete Structures,*[15] *and* ACI 563, *Specifications for Repair of Concrete in Buildings.*[16]

Every building is unique, and there is no one-size-fits-all concrete repair strategy. Industry-standard details and specifications should be adapted to meet project-specific needs. Repair projects should consider the geographic location of the project, exposure to freeze-thaw cycles, exposure to deicing salts in cold regions or saltwater in coastal regions, and the materials used during original construction (**Fig. 11**).

WATERPROOFING AND BUILDING ENCLOSURE CONSIDERATIONS

ASTM E2018[1] describes the building envelope as the enclosure of the building that protects the building interior from outside elements. Because concrete-frame buildings are barrier wall systems, deterioration of the exterior concrete structure compromises building enclosure performance. Building enclosure design considerations during a concrete repair project can limit future water leakage and slow concrete deterioration mechanisms.

Various protective coatings are available to extend the service life of concrete structures. Acrylic coatings are frequently selected due to their permeability, which allows them to be applied over concrete surfaces that include high relative humidity values within the open pore structure. Although concrete is expected to cure and gain strength relatively quickly, concrete structures will never be completely dry, even in warm, dry environments. However, acrylic coatings are typically not appropriate for use on skyward-facing surfaces. Warnings against using acrylic coatings on skyward-facing horizontal surfaces are often included within product data (**Fig. 12**).

Horizontal surfaces can be treated using silicone waterproofing membranes or urethane traffic coatings (**Fig. 13**). The waterproofing membrane color can often be matched to that of the exterior wall coating to achieve consistency of aesthetics.

Given that many concrete repair projects will include sealant joint repairs at cracks and interface conditions, the choice of sealant is also important to ensure compatibility and

Figure 11. *In-progress concrete exterior wall repairs.*

sequencing considerations. As an example, silicone sealants should typically not be utilized at route-and-seal repair locations if an acrylic coating is applied over the concrete surfaces. However, a compatible silicone sealant should typically be applied at fenestration perimeter locations, especially in cases where silicone waterproofing coatings are applied at horizontal projections below the windows (**Fig. 14**).

Even for a project that includes predesign testing and analysis, a comprehensive design, complete specifications, manufacturer's review of selected products and systems, mock-ups, and an experienced contractor, the authors recommend that field quality control testing be performed to verify adhesion and compatibility of applied sealants and coatings periodically during a repair project. Coating pull-off adhesion strength testing can be performed in accordance with ASTM D4541, *Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers*,[18] and sealant adhesion testing can be performed in accordance with ASTM C1521-13, *Standard Practice for Evaluating Adhesion of Installed Weatherproofing Sealant Joints*.[19] In addition to tests required by the manufacturer for warranty purposes, specifications should also require third-party field quality control testing. The extent of testing should be clearly defined to include information regarding next steps in the case of failed tests. Determining issues early during the project via testing will benefit all parties rather than allowing issues to manifest after demobilization.

Product 1

CAUTIONS

For exterior use only.

Protect from freezing.

Non-photochemically reactive.

Not for use on horizontal surfaces (floors, roofs, decks, etc.) where water will collect.

Not for use on overhead horizontal surfaces (undersides of balconies, soffits, etc.)

Not for use below grade. Will not withstand hydrostatic pressure.

Before using, carefully read CAUTIONS on label.

Product 2

Special Information

- Intermix different batches or multiple cans of custom colors. Always test apply a small area to verify color.
- Do not apply if air or surface temperature is below 20°F or if condensation is present.
- Do not apply late in the day or when rain or dew is expected within 12 hours.
- To assure color uniformity, always paint to a natural "break" in the surface.
- Not recommended for below grade masonry.
- Do not apply to horizontal surfaces.
- Not recommended on exterior insulation finish systems (EIFS) surfaces.
- Sealants should not be applied over coatings.
- Read label directions, warnings and cautions before using.

Figure 12. *Exterior wall acrylic coating product data (excerpts).*

CONCLUSION

Maintaining and repairing the inventory of existing concrete-frame buildings is more sustainable than demolishing existing buildings and starting anew. Each concrete repair project is unique, and there is no one-size-fits-all approach to repair design and implementation. The investigation, repair design, and eventual repair of structures with exposed concrete elements require design and construction teams with expertise associated with concrete materials,

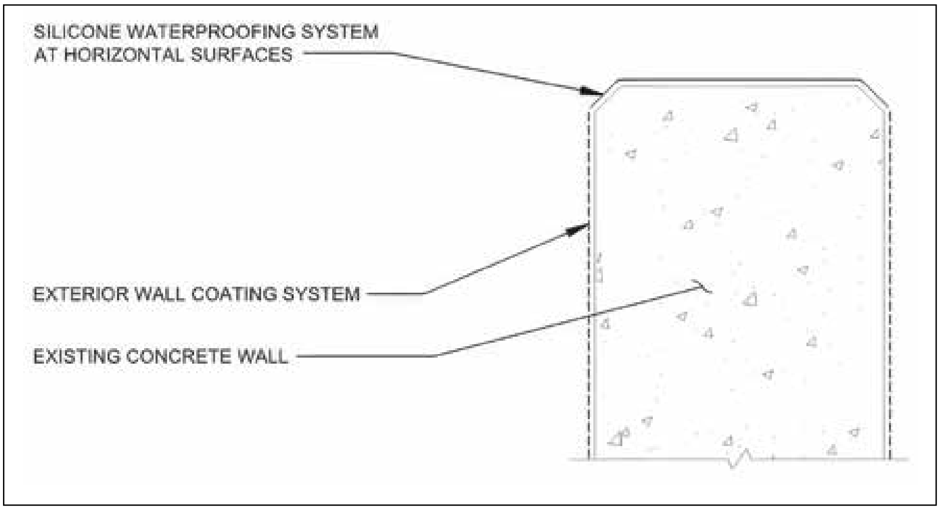

Figure 13. *Conceptual repair detail with different coatings for vertical and horizontal surfaces.*

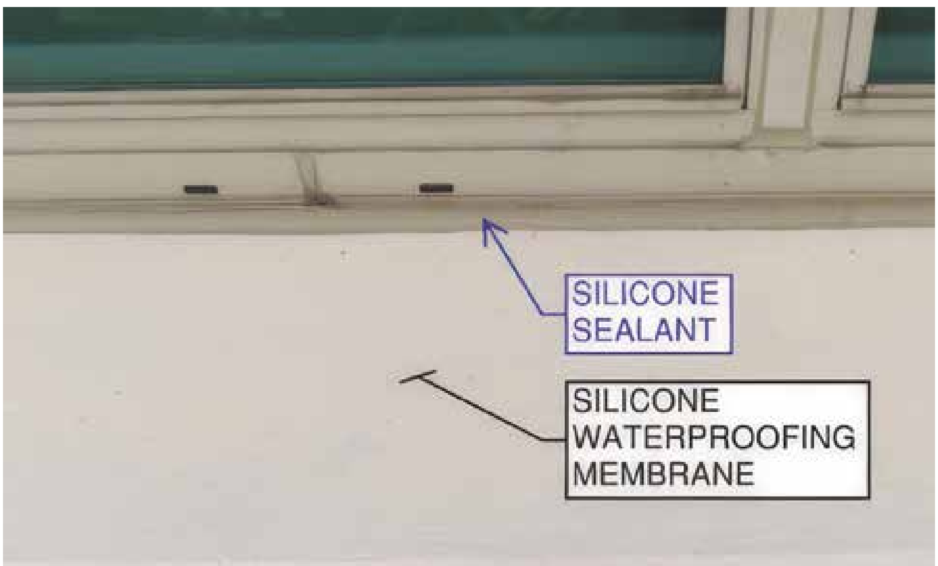

Figure 14. *Windowsill interface condition at horizontal projection.*

structural engineering, building science, and waterproofing principles. Reviving the concrete giants will require a concerted team effort now and for many years into the future.

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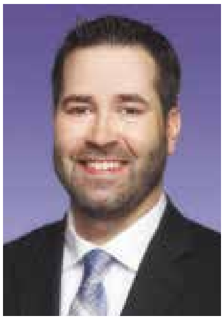

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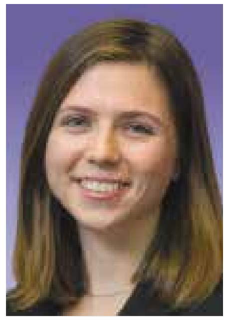

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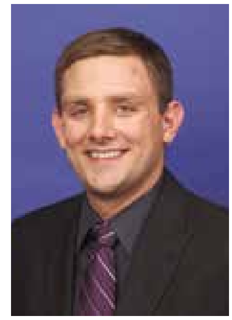

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