"Reasonable Safety" of Existing Structures, Part 1

What does safe mean?

by Keith E. Kesner, David G. Tepke, Liying Jiang, and Stephen S. Szoke

Several authorities having jurisdiction (AHJ) have initiated milestone safety assessment requirements for existing buildings over the past 20 years. This includes Broward County, FL, USA, which implemented an assessment and certification program in 2005 for buildings aged 40 years with recertification requirements every 10 years thereafter.[1] In 2022, New York City, NY, USA, added new Article 323 to Local Law 126 requiring periodic condition assessment of parking structures.[2] In 2022, Jersey City, NJ, USA, implemented a façade and structural assessment requirement.[3] In response to recent events, requirements for assessing existing buildings are being considered in additional areas. Table 1 provides a summary of the ordinance requirements from varying geographic regions in the United States.

Conceptually, ordinances represent a critical strategy to protect the public by mandating surveys of existing structures to identify conditions that may be of structural concern or potentially unsafe. As ordinances are being developed and promulgated for assessment of existing buildings with regard to continued occupancy and use, care must be taken by governing bodies in developing meaningful provisions and clarifying interpretations to make the ordinances both useful to the public and implementable by both professionals and the AHJ. The following sections discuss the ordinances, perceptions related to the requirements of the ordinances, and some of the limitations associated with condition assessment surveys.

The heightened awareness of the need for condition surveys of existing structures to identify unsafe conditions has driven authorities, owners, the public, legislators, and other interested parties to look for verification by licensed design professionals (LDPs) that existing structures or designated portions of structures are safe for continued use. Legislation, rules, and other requirements are being proposed and, in some instances, already promulgated, that use terms such as: safe, secure, structurally sound, or maintained free from deterioration.[4,5] These are vague terms, and their meanings will vary with the audience. To the public, such phrases may be typically understood to mean there *will not be* any catastrophic failure, total or partial collapse, or unsafe conditions that could cause harm to occupants or users. LDPs, however, will recognize that categorizing an existing structure as "safe," "free of deterioration," or "free of defects" is either not possible, or severely limited by the knowledge the LDP has about the structure, the ability of the LDP to examine the structure, and uncertainty in past, current, and future loads. Thus, the distinction between the perceptions of absolute safety versus reality based on good engineering practices and judgment is of crucial importance.

This four-part series is written to discuss the complexities and challenges of condition surveys for qualifying structural safety that are being required by AHJ to determine if there are readily discoverable indications of deficiencies in existing structural systems. This article provides background related to expectations of structural performance and suggests practical expectations for routine condition surveys of structures.

Safety, Health, and General Welfare

A recent edition of the International Code Council's International Building Code (IBC) serves as the basis for most building codes adopted and enforced in the United States. The purpose of the 2021 IBC is stated in Section 101.3:

"…to establish the minimum requirements to provide a reasonable level of safety, health, and general welfare through structural strength, means of egress, stability, sanitation, light and ventilation, energy conservation, and for providing a reasonable level of life safety and property protection from the hazards of fire, explosion, or dangerous conditions, and to provide a reasonable level of safety to fire fighters and emergency responders during emergency operations."[6]

A "reasonable level" of safety is prescribed for multiple reasons. For the performance of existing structures, there are three significant aspects related to the provisions in the code.

First, the design events are established in the codes based on the probability of occurrence. Actual events may exceed

Table 1:
Summary of selected ordinance requirements

Location and ordinance	Ordinance description							
	Façade	Structural	Occupancy/ Type	Age	Criteria	Frequency	Subject	Terminology
San Francisco, CA, Ord. 67-16	F		Type I, II, III, IV construction	Any	> 5 stories	Based on age for first survey, then every 5 years	100% walls, 100% balconies, 100% parapets	Risk of death or injury
State of Florida, Statute 553.71		S	Condominium cooperative	30 years, 25 years if within 3 miles of coast	—	10 years	Structural elements	Safe for continued use, substantial structural deterioration, structurally sound
Broward County, FL, Broward County Building Safety Inspection Program		S	Except 1- and 2-family and government or tribal buildings	40 years	≥ 3500 ft^2	10 years	Structural elements	Structural failures
Dade County, FL, §8-11		S	Except 1- and 2-family and government or tribal buildings	40 years	≥ 2,000 ft^2	10 years	Structural elements	Safe condition
Chicago, IL, Rules for the Maintenance of High-Rise Exterior Walls and Enclosures	F		All	Any	> 80 ft	2 years critical exam, every 4 years	50% walls, 100% cornices, 100% terracotta	Unsafe, imminently hazardous, safe with repair, safe condition
Boston, MA, Ord. 9.9-12	F		All	Any	> 70 ft	5 years	100% walls	Life-safety protection
Detroit, MI, Ord 15-88, § 9-1-35	F		All	Any	≥ 5 stories	5 years	100% cornices, 100% projections	—
St. Louis, MO, Ord. 68791	F		Any	Any	> 6 stories	5 years	100% walls	—
Jersey City, NJ, Ord. 21-054		S	All	Any	> 6 stories	10 years	Foundations, balconies, structural elements	Safe, unsafe
Jersey City, NJ, Ord. 21-054	F		All	Any	> 6 stories, masonry façades > 4 stories	5 years	Foundations, balconies, structural elements	Safe, unsafe
New York, NY, Law 11 of 1998	F		All	Any	≥ 6 stories	5 years	100% walls, 100% appurtenances	Safe condition
New York, NY, Title 28, Art. 323		S	Parking, except for 1- and 2-family homes	Any	Any	3 years	Structural elements	Unsafe condition, safe with repair, faulty construction, partial or complete collapse possible
Cincinnati, OH, Ch. 1127	F		All	≥ 15 years	> 5 stories, > 65 ft	8 and 12 years based on category	100% walls by Category IV – reinforced with corrodible metal	Safe
Cincinnati, OH, §1101.43		S	Commercial	Per director	N/A	Per director		Dangerous, unsanitary, unsafe
Cleveland, OH, Ord. 3143.02	F		All	≥ 30 years	> 75 ft	5 years	100% walls	Safe, habitable

Columbus, OH, Ord 1296-85, §4109.073	F		All	≥ 20 years	Any*	5 years	100% walls	Protection
Philadelphia, PA, §PM-304.0	F		All	Any	≥ 6 stories	5 years	100% walls	Safe, safe with repair, unsafe
Pittsburgh, PA, §304	F		Except R3, including single family residences	Any	Any	5 years	100% walls, 100% extensions, 100% decorative features, 100% chimneys	Structural soundness
Milwaukee, WI, Ch 275, §32-13	F		All	15 years	> 5 stories	5, 8, or 12 years (based on age)	100% walls	Safe condition

*Critical observation requirements also apply if building is within 10 ft of a public right of way

Note: 1 ft = 0.3 m; 1 ft^2 = 0.1 m

the design event. Often, when design events are exceeded and result in partial or disproportionate collapse, disaster reconnaissance provides information that permits a better understanding of structural performance, the need to further research and development, and implementation of new minimum code requirements. For example, the magnitude 6.9 earthquake that occurred in Loma Prieta, CA, USA, in 1989, led to significant changes in the building code regarding the use of soft stories and attachment of façades. Almost every major disaster leads to a better understanding of structural performance and improvement in minimum code requirements.[7]

Second, the performance expectations for structural design and construction are also based on the probability of member failure when exposed to design events. Design loads are established based on an acceptable probability of exceedance over a given period. For example, design live loads for multifamily residential construction as indicated in ASCE/SEI 7-22[8] are higher than those expected at any individual point in time and are established based on a probability of exceedance from variability in normal loads over a 50-year period, as well as transient loads from renovations or other higher loading events.

To provide affordable structures, a reasonable level of risk of failure is incorporated into the design and construction criteria. The level of risk varies with the type of event, the occupancy, and the expected use. The code adjusts the structural design criteria to establish different magnitudes of loads based on the nature of occupancy and exposure to natural hazards. Table 1604.5 in the 2021 IBC provides four risk categories:

- I—low hazard to human life in the event of failure;
- II—all buildings not assigned to the other risk categories;
- III—substantial risk to human life in the event of failure; and
- IV—essential facilities.

Most buildings are assigned to risk category II. Consequently, when built to the minimum requirements of the building code, a barn may not perform as well as an apartment building, and the apartment building may not perform as well as a hospital or fire station. Thus, for a given member, the probability of failure under design loading conditions is a function of the use of the structure, loading conditions, and the expected failure mode.

The third limitation is the inherent nature of existing structures. Once complete, existing structures are typically "grandfathered" and not subjected to upgrades to satisfy the current building code requirements. The International Existing Building Code (IEBC) and International Property Maintenance Code (IPMC), where adopted, delineate the expected performance and maintenance requirements for existing structures. As discussed in Parts 2 and 3 of this series, existing structures will deteriorate over time because of normal weathering processes; overall durability, serviceability, and life of materials; and/or possible faulty construction. These factors can result in substantially lower strength or performance than anticipated or a need for repairs to ensure a continued reasonable level of safety for the structure.

For these and other reasons, the building code does not establish that new or existing structures must be or can be classified as "safe and secure." The proper terminology, consistent with the building code, should be: "reasonably safe and reasonably secure" or "built in general conformance with building code requirements in place at the time of original construction." Given that new construction is initially designed and constructed to achieve a reasonable level of safety and security, no more should be expected when the LDP evaluates an existing structure, especially when considering the complications related to evaluation of the structural elements in existing buildings.

Verification of "Safe"

Due to recent events and in recognition of the abundance of aging structures in locations with severe environments, AHJs, owners, occupants, politicians, and other interested parties are now looking to LDPs to verify that buildings are safe for continued occupancy. However, a statement that a building is "safe for occupancy" is difficult to provide without knowing the details and properties of the as-built building, such as conditions at connections, structural components behind finishes, and foundations that are typically inaccessible. In most cases, these surveys are completed based on a representative visual survey of exposed and accessible structural elements with limited probing to confirm conditions. The following paragraphs describe the limited nature of the information that can be obtained during a visual survey with limited probing. Most buildings continue to be suitable for continued occupancy and thus, in-depth observations involving probes and/or deconstruction of interior and exterior finishes to access structural elements is not warranted.

In-place loads

If sufficient information is known from the design basis or original construction requirements, a survey will potentially verify that the in-place live loads do not exceed the loads used for the original design of the structure; however, potential transient loads and alternative uses also require consideration. Where nominal loads are exceeded, an analysis may be required to show that structural elements can support the in-place loads and load effects, or remedial action should be taken. Loads may be altered because of adding, replacing, and relocating furnishing and equipment, renovations to suit new occupants, or from changes in occupancy and use.

Dimensions

Dimensions from construction drawings can be verified in accessible representative areas; however, intrusive probes at representative areas will likely be required to confirm as-built conditions to a reasonable degree of certainty (Fig. 1).

Either visually verified dimensions or dimensions from construction documents may be used with construction drawing details and material properties from construction documents for a preliminary assessment of the capacity of the structure. Still, it must be recognized that obtaining complete information is impractical given the constraints associated with construction, materials, and investigative techniques.

Defects

Visible defects or potentially unsafe conditions can be documented. While identification of tripping hazards from spalling concrete or overhead falling hazards from loose

Fig. 1: Probes requiring deconstruction are not typical of visual surveys

materials may be more easily ascertained, other defects may present an uncertain condition. Visible conditions, such as cracking, deformation, or offset, may or may not be indicative of a potentially unsafe condition (Fig. 2 to 4). Conclusive determination of as-built conditions with absolute certainty, including those that may be unsafe, can be challenging due to structural redundancies, variable and uncertain levels of deterioration, variability in construction, variations in material properties, undocumented changes during construction, and other conditions.

Codes and standards

When the LDP is conducting a visual assessment, consideration should be given to the codes and referenced standards in place at the time of original construction and subsequent renovations, if any. For example, specific limits on chloride contents in new concrete were not required until the AHJ adopted a code that referenced ACI 318-83.[9] Additives containing chlorides were commonly used for cold weather concreting. Similarly, structural integrity provisions for post punching shear first appeared in ACI 318-89[10] and thus, were not required until that edition was adopted by the AHJ.

Classification

The typical outcome from a survey of an existing structure is a classification of the structure into one of five categories as described in Table 2, along with recommendations for future surveys, repairs, or both. Where an LDP has been engaged to investigate buildings, most existing structures fall into categories B, C, or D, with A and E being the exceptions. Further, some level of structural analysis may be required to confirm that an observed defect is unsafe. The most important thing to note is the limited nature of most condition surveys and the need for regular surveys to document changes in conditions over time.

Summary

Condition surveys are being proposed as a method to ensure the safety of existing structures, with the surveys required to establish that the existing structures or components are safe, secure, and free of defects. However, condition surveys, especially visual surveys, are limited in nature and the results are unlikely to establish the safety of the structure with a high degree of certainty. The requirement that an LDP determines if an existing structure is "safe" is also contrary to the building code requirements that are based upon new construction to provide a "reasonable level of safety." The conflict arises due to the limitations in our knowledge of existing construction and the limited amount of visible structure in typical construction.

The limitations of condition surveys will be examined in Parts 2 and 3 of this series. Part 4 will discuss the application of new technologies to enhance the ability of LDPs to survey existing structures and the benefits of routine surveys and assessments.

Fig. 2: Spalling that warrants remedial action

Fig. 3: Concrete cracks, and not all cracks in concrete warrant remedial action

Fig. 4: A crack that warrants remedial action

Table 2:
Classification of existing structures and possible further action

Category	Description	Occupancy restrictions	Further condition survey	Repairs required
A	No unsafe conditions or obvious structural defects are observed; the structure appears to be used consistent with the design intent. No limitation on use appears necessary.	None	Routine	Not at this time
B	No unsafe conditions are observed. Minor or isolated defects are present in the structure. Additional investigation or monitoring to confirm the type, extent, and severity of damage is recommended. The structure may stay in use while the additional evaluation is completed.	None	Yes	Possible
C	No unsafe conditions are observed. Defects are present in the structure that require additional investigation or monitoring to confirm the type, extent, and severity of damage. The structure may stay in use while the additional evaluation is completed.	None	Yes	Possible
D	Isolated unsafe conditions are observed. Defects are present in the structure that require additional investigation or monitoring to confirm the type, extent, and severity of damage. Immediate remediation or use limitations are required to keep the structure in service.	Possible	Yes	Yes
E	Obvious unsafe conditions are present. Use of the structure or portions thereof is not recommended until these conditions are addressed.	Yes	Yes	Yes

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Selected for reader interest by the editors.

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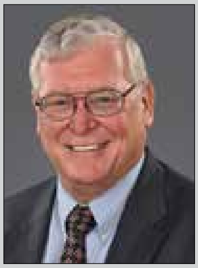

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ARTÍCULO

3 TRES

"Seguridad razonable" de las estructuras existentes, Parte 1

¿Qué significa seguridad?

por Keith E. Kesner, David G. Tepke, Liying Jiang, y Stephen S. Szoke

Varias autoridades con jurisdicción (AHJ, por sus siglas en inglés) en los últimos 20 años han iniciado requisitos de evaluación de la seguridad de edificios existentes. Por ejemplo, el condado de Broward (Florida, EE.UU.) puso en marcha en 2005 un programa de evaluación y certificación para edificios de 40 años de antigüedad, con requisitos de recertificación cada 10 años a partir de entonces[1]. En 2022, la ciudad de Nueva York (EE.UU.) añadió un nuevo artículo 323 a la Ley Local 126, que exige la evaluación periódica del estado de las estructuras de estacionamiento[2]. En 2022, la ciudad de Jersey (Nueva Jersey, EE.UU.) implantó un requisito de evaluación estructural y de fachadas[3]. En respuesta a acontecimientos recientes, se están estudiando requisitos para evaluar los edificios existentes en otras zonas. La Tabla 1 ofrece un resumen de los requerimientos de las ordenanzas de distintas regiones geográficas de Estados Unidos.

Desde el punto de vista conceptual, las ordenanzas representan una estrategia fundamental para proteger al público, ya que obligan a realizar estudios de las estructuras existentes para identificar las condiciones que puedan ser preocupantes desde el punto de vista estructural o potencialmente inseguras. A medida que se desarrollan y promulgan reglamentos para la evaluación de los edificios existentes con respecto a su ocupación y uso continuos, los órganos de gobierno deben tener cuidado a la hora de desarrollar disposiciones significativas y aclarar las interpretaciones para que las ordenanzas sean útiles para el público y aplicables tanto por los profesionales como por las AHJ. En las secciones siguientes se analizan las ordenanzas, las percepciones relacionadas con sus requisitos y algunas de las limitaciones asociadas a los sondeos de evaluación del estado de las estructuras.

La mayor conciencia sobre la necesidad de realizar estudios del estado de las estructuras existentes para identificar condiciones inseguras ha llevado a las autoridades, los propietarios, el público, los legisladores y otras partes interesadas a buscar la verificación por parte de profesionales del diseño con licencia (LDPs por sus siglas en inglés) de si las estructuras existentes o partes designadas de las estructuras son seguras para su uso continuo. Se están proponiendo e incluso promulgando leyes, normas y otros requisitos, que utilizan términos como: seguro, estable, estructuralmente estable o sin deterioro[4,5]. Se trata de términos vagos, y su significado variará en función del público. Para el público, estas frases pueden entenderse normalmente como que no habrá ninguna falla catastrófica, colapso total o parcial, o condiciones inseguras que puedan causar daños a los ocupantes o usuarios. Los LDPs, sin embargo, reconocerán que clasificar una estructura existente como "segura", "libre de deterioro" o "libre de defectos" no es posible o está severamente limitado por el conocimiento que el LDP tiene sobre la estructura, su capacidad de examinar la estructura y la incertidumbre en las cargas iniciales, actuales y futuras. Así pues, la distinción entre las percepciones de seguridad absoluta y la realidad basada en las buenas prácticas de ingeniería y el juicio es de crucial importancia.

Esta serie de cuatro partes está escrita para discutir las complejidades y desafíos de las inspecciones para calificar el estado y la seguridad estructural, que están siendo requeridas por las AHJ, para determinar si hay indicaciones fácilmente detectables de deficiencias en los sistemas estructurales existentes. Este artículo proporciona antecedentes relacionados con las perspectivas de rendimiento estructural y sugiere expectativas prácticas para las inspecciones rutinarias del estado de las estructuras.

Tabla 1: Resumen de los requisitos de las ordenanzas seleccionadas.

Ubicación y ordenanza	Descripción de la Ordenanza							
	Fachada	Estructural	Ocupación/Tipo	Edad	Criterio	Frecuencia	Asunto	Terminología
San Francisco, CA, Ord. 67-16	F		Construcción de tipo I, II, III y IV	Cualquiera	> 5 pisos	Basada en la antigüedad de la primera encuesta, luego cada 5 años	100% paredes, 100% balcones, 100% parapetos	Riesgo de muerte o lesiones
Estado de Florida, Estatuto 553.71		E	Cooperativa de propietarios	30 años, 25 años si está a 3 millas de la costa	—	10 años	Elementos estructurales	Seguro para uso continuo, deterioro estructural sustancial, estructuralmente sólido
Broward County, FL, Programa de inspección de seguridad de edificios del condado de Broward		E	Excepto edificios de 1 y 2 familias y edificios gubernamentales o tribales	40 años	≥ 3500 ft^2	10 años	Elementos estructurales	Fallos estructurales
Dade County, FL, §8-11		E	Excepto edificios de 1 y 2 familias y edificios gubernamentales o tribales	40 años	≥ 2,000 ft^2	10 años	Elementos estructurales	Condición de seguridad
Chicago, IL, Reglas para el mantenimiento de muros y cubiertas exteriores de edificios de gran altura	F		Todos	Cualquiera	> 80 ft	2 años examen crítico, cada 4 años	50% paredes, 100% cornisas, 100% terracota	Inseguro, inminentemente peligroso, seguro con reparación, condición segura
Boston, MA, Ord. 9.9-12	F		Todos	Cualquiera	> 70 ft	5 años	100% paredes	Protección de la vida
Detroit, MI, Ord 15-88, § 9-1-35	F		Todos	Cualquiera	≥ 5 pisos	5 años	100% cornisas, 100% proyecciones	—
St. Louis, MO, Ord. 68791	F		Cualquiera	Cualquiera	> 6 pisos	5 años	100% paredes	—
Jersey City, NJ, Ord. 21-054		E	Todos	Cualquiera	> 6 pisos	10 años	Cimientos, balcones, elementos estructurales	Seguro, inseguro
Jersey City, NJ, Ord. 21-054	F		Todos	Cualquiera	> 6 pisos, fachadas de obra > 4 pisos	5 años	Cimientos, balcones, elementos estructurales	Seguro, inseguro
New York, NY, Ley 11 of 1998	F		Todos	Cualquiera	≥ 6 pisos	5 años	100% muros, 100% accesorios	Condición de seguridad
New York, NY, Título 28, Art. 323		E	Estacionamiento, excepto para viviendas unifamiliares y bifamiliares	Cualquiera	Cualquiera	3 años	Elementos estructurales	Estado inseguro, seguro con reparación, construcción defectuosa, posible derrumbe parcial o total
Cincinnati, OH, Ch. 1127	F		Todos	≥ 15 años	> 5 pisos, > 65 ft	8 y 12 años según la categoría	100% muros de categoría IV - reforzados con metal corrosible	Seguro

Cincinnati, OH, §1101.43		E	Comercial	Por director	N/A	Por director		Peligroso, insalubre, inseguro
Cleveland, OH, Ord. 3143.02	F		Todos	≥ 30 years	> 75 ft	5 años	100% paredes	Seguro, habitable
Columbus, OH, Ord 1296-85, §4109.073	F		Todos	≥ 20 años	Cualquiera*	5 años	100% paredes	Protección
Philadelphia, PA, §PM-304.0	F		Todos	Cualquiera	≥ 6 pisos	5 años	100% paredes	Seguro, seguro con reparación, inseguro
Pittsburgh, PA, §304	F		Excepto R3, incluidas las residencias unifamiliares	Cualquiera	Cualquiera	5 años	100% muros, 100% ampliaciones, 100% elementos decorativos, 100% chimeneas	Solidez estructural
Milwaukee, WI, Ch 275, §32-13	F		Todos	15 años	> 5 pisos	5, 8 o 12 años (basados en la antigüedad)	100% paredes	Condición de seguridad

*Los requisitos de observación crítica también se aplican si el edificio se encuentra a menos de 10 pies de una vía pública.

Nota: 1 pie = 0,3 m; 1 pie2 = 0,1 m

Seguridad, salud y bienestar general

Una edición reciente del Código Internacional de la Edificación (IBC por sus siglas en inglés) del Consejo Internacional de Códigos sirve de base para la mayoría de los códigos de edificación adoptados y aplicados en Estados Unidos. El propósito del IBC de 2021 se establece en la Sección 101.3:

"...establecer los requisitos mínimos para proporcionar un nivel razonable de seguridad, salud y bienestar general a través de la resistencia estructural, medios de egreso, la estabilidad, el saneamiento, la luz y la ventilación, la conservación de la energía, y para proporcionar un nivel razonable de seguridad de la vida y la protección de la propiedad contra los riesgos de incendio, explosión o condiciones peligrosas, y para proporcionar un nivel razonable de seguridad a los bomberos y personal de respuesta durante las operaciones de emergencia[6]."

Esta serie de cuatro partes está escrita para discutir las complejidades y desafíos de las inspecciones para calificar el estado y la seguridad estructural, que están siendo requeridas por las AHJ, para determinar si hay indicaciones fácilmente detectables de deficiencias en los sistemas estructurales existentes. Este artículo proporciona antecedentes relacionados con las perspectivas de rendimiento estructural y sugiere expectativas prácticas para las inspecciones rutinarias del estado de las estructuras.

Se prescribe un "nivel razonable" de seguridad por múltiples razones. Para el comportamiento de las estructuras existentes, hay tres aspectos significativos relacionados con las disposiciones del código.

En primer lugar, los eventos de diseño se establecen en los códigos en función de la probabilidad de que se produzcan. Los sucesos reales pueden superar el evento de diseño. A menudo, cuando se superan los eventos de diseño y se produce un colapso parcial o desproporcionado, el reconocimiento de la catástrofe proporciona información que permite comprender mejor el comportamiento estructural, la necesidad de seguir investigando y desarrollando, y la aplicación de nuevos requisitos mínimos del código. Por ejemplo, el terremoto de magnitud 6,9 que se produjo en Loma Prieta, California (EE. UU.), en 1989, dio lugar a importantes cambios en el código de edificación en relación con el uso de pisos blandos y la fijación de las fachadas. Casi todas las grandes catástrofes conducen a una mejor comprensión del comportamiento estructural y a la mejora de los requisitos mínimos de los códigos[7].

En segundo lugar, las perspectivas de rendimiento para el diseño estructural y la construcción también se basan en la probabilidad de falla de los elementos cuando se exponen a los eventos de diseño. Las cargas de diseño se establecen en función de una probabilidad aceptable de excedencia durante un período determinado. Por ejemplo, las cargas vivas de diseño para la construcción de viviendas multifamiliares, tal y como se indica en ASCE/SEI 7-22[8], son superiores a las esperadas en cualquier punto individual en el tiempo y se establecen en base a una probabilidad de excedencia de la variabilidad de las cargas normales durante un período de 50 años, así como las cargas transitorias de las reformas u otros eventos de carga superiores.

Para proporcionar estructuras asequibles, se incorpora un nivel razonable de riesgo de falla a los criterios de diseño y construcción. El nivel de riesgo varía en función del tipo de evento, la ocupación y el uso previsto. El código ajusta los criterios de diseño estructural para establecer diferentes magnitudes de cargas basadas en la naturaleza de la ocupación y la exposición a peligros naturales. La tabla 1604.5 del IBC 2021 establece cuatro categorías de riesgo:

- I - bajo riesgo para la vida humana en caso de avería;
- II - todos los edificios no asignados a las demás categorías de riesgo;
- III - riesgo sustancial para la vida humana en caso de falla; y
- IV – instalaciones esenciales.

A la mayoría de los edificios se les asigna la categoría de riesgo II.

En consecuencia, cuando se construye según los requisitos mínimos del código de construcción, un granero puede no funcionar tan bien como un edificio de apartamentos, y el edificio de apartamentos puede no funcionar tan bien como un hospital o una estación de bomberos. Así pues, para un elemento determinado, la probabilidad de falla en las condiciones de carga de diseño depende del uso de la estructura, de las condiciones de carga y del modo de falla previsto.

La tercera limitación es la naturaleza inherente de las estructuras existentes. Una vez terminadas, las estructuras existentes suelen estar "protegidas" y no están sujetas a actualizaciones para satisfacer los requisitos actuales del código de construcción. El Código Internacional de Edificación Existente (IEBC) y el Código Internacional de Mantenimiento de la Propiedad (IPMC), cuando se adoptan, definen los requisitos de rendimiento y mantenimiento previstos para las estructuras existentes. Como se discute en las Partes 2 y 3 de esta serie, las estructuras existentes se deteriorarán con el tiempo debido a los procesos normales de intemperismo; durabilidad en general, capacidad de servicio y vida útil de los materiales; y/o posible construcción defectuosa. Estos factores pueden dar lugar a una resistencia o un rendimiento sustancialmente inferiores a los previstos o a la necesidad de efectuar reparaciones para garantizar un nivel de seguridad razonable y continuado de la estructura.

Por estas y otras razones, el código de edificación no establece que las estructuras nuevas o existentes deban o puedan clasificarse como "seguras y protegidas." La terminología adecuada, coherente con el código de edificación, debería ser: "razonablemente seguro y razonablemente estable" o "construido de conformidad general con los requisitos del código de construcción vigentes en el momento de la construcción original". Dado que las nuevas construcciones se diseñan y construyen inicialmente para alcanzar un nivel razonable de seguridad, no debería esperarse más cuando el LDP evalúa una estructura existente, especialmente si se tienen en cuenta las complicaciones relacionadas con la evaluación de los elementos estructurales de los edificios existentes.

Verificación de "seguridad”

Debido a los recientes acontecimientos y en reconocimiento de la abundancia de estructuras envejecidas en lugares con entornos severos, AHJs, propietarios, ocupantes, políticos y otras partes interesadas están buscando ahora a los LDP para verificar que los edificios sean seguros para la ocupación continua. Sin embargo, es difícil afirmar que un edificio es "seguro para su ocupación" sin conocer los detalles y las propiedades del edificio tal y como se construyó, como las condiciones de las conexiones, los componentes estructurales detrás de los acabados y los cimientos, que suelen ser inaccesibles. En la mayoría de los casos, estas inspecciones se basan en una inspección visual representativa de los elementos estructurales expuestos y accesibles, con sondeos limitados para confirmar condiciones. Los párrafos siguientes describen la naturaleza limitada de la información que puede obtenerse durante una inspección visual con sondeos limitados. La mayoría de los edificios siguen siendo aptos para seguir siendo ocupados y, por lo tanto, no se justifican observaciones en profundidad que impliquen sondeos y/o la deconstrucción de los acabados interiores y exteriores para acceder a los elementos estructurales.

Cargas in situ

Si se conoce suficiente información de la base de diseño o de los requisitos de construcción originales, un estudio verificará potencialmente que las cargas vivas in situ no superan las cargas utilizadas para el diseño original de la estructura; sin embargo, las posibles cargas transitorias y los usos alternativos también requieren consideración. Si se superan las cargas nominales, puede ser necesario realizar un análisis para demostrar que los elementos estructurales pueden soportar las cargas in situ y los efectos de las cargas, o bien deben tomarse medidas correctivas. Las cargas pueden alterarse debido a la adición, sustitución y reubicación de mobiliario y equipos, renovaciones para adaptarse a nuevos ocupantes, o por cambios en la ocupación y el uso.

Dimensiones

Las dimensiones de los planos de construcción pueden verificarse en zonas representativas accesibles; sin embargo, es probable que se necesiten sondeos intrusivos en zonas representativas para confirmar las condiciones de construcción con un grado razonable de certeza (Fig. 1).

Las dimensiones verificadas visualmente o las dimensiones de los documentos de construcción pueden utilizarse con los detalles de los planos de construcción y las propiedades de los materiales de los documentos de construcción para una evaluación preliminar de la capacidad de la estructura. No obstante, hay que reconocer que la obtención de información completa es poco práctica dadas las limitaciones asociadas a la construcción, los materiales y las técnicas de investigación.

Defectos

Los defectos visibles o las condiciones potencialmente inseguras pueden documentarse. Mientras que la identificación de los peligros de tropiezo por desprendimientos de concreto o los peligros de caídas desde arriba por materiales sueltos pueden determinarse más fácilmente, otros defectos pueden presentar una condición incierta. Las condiciones visibles, como grietas, deformaciones o desplazamientos, pueden ser o no indicativas de una condición potencialmente insegura (Fig. 2 a 4). La determinación concluyente de las condiciones de construcción con absoluta certeza, incluyendo aquellas que pueden ser inseguras, puede ser un reto debido a redundancias estructurales, niveles variables e inciertos de deterioro, variabilidad en la construcción, variaciones en las propiedades de los materiales, cambios no documentados durante la construcción y otras condiciones.

Códigos y estándares

Cuando el LDP lleve a cabo una evaluación visual, deberá tener en cuenta los códigos y normas de referencia vigentes en el momento de la construcción original y de las renovaciones posteriores, si las hubiera. Por ejemplo, no se exigieron límites específicos sobre el contenido de cloruro en el concreto nuevo hasta que el AHJ adoptó un código que hacía referencia a ACI 318-83[9]. Los aditivos que contenían cloruros se utilizaban habitualmente para el vertido de concreto en climas fríos. Del mismo modo, las disposiciones de integridad estructural para el esfuerzo cortante posterior al punzonamiento aparecieron por primera vez en ACI 318-89[10] y, por lo tanto, no se exigieron hasta que esa edición fue adoptada por el AHJ.

Clasificación

El resultado típico de un estudio de una estructura existente es una clasificación de la estructura en una de las cinco categorías descritas en la Tabla 2, junto con recomendaciones para futuros estudios, reparaciones o ambas cosas. Cuando se ha contratado a un LDP para investigar edificios, la mayoría de las estructuras existentes se clasifican en las categorías B, C o D, siendo A y E las excepciones.

Categoría	Descripción	Restricciones de ocupación	Estudio del estado	Reparaciones requeridas
A	No se observan condiciones inseguras ni defectos estructurales evidentes; la estructura parece utilizarse de acuerdo con la intención del diseño. No parece necesaria ninguna limitación de uso.	Ninguna	Rutina	No en este momento
B	No se observan condiciones inseguras. La estructura presenta defectos menores o aislados. Se recomienda una investigación o supervisión adicional para confirmar el tipo, el alcance y la gravedad de los daños. La estructura puede seguir en uso mientras se completa la evaluación adicional.	Ninguna	Sí	Posible
C	No se observan condiciones inseguras. Existen defectos en la estructura que requieren una investigación o supervisión adicional para confirmar el tipo, el alcance y la gravedad de los daños.	Ninguna	Sí	Posible
D	Se observan condiciones inseguras aisladas. Existen defectos en la estructura que requieren una investigación o supervisión adicionales para confirmar el tipo, el alcance y la gravedad de los daños. Se aplican medidas correctoras inmediatas o limitaciones de uso.	Posible	Sí	Sí
E	Existen condiciones de inseguridad evidentes. No se recomienda el uso de la estructura o de partes de ella hasta que se solucionen estas condiciones.	Sí	Sí	Sí

Tabla 2: Clasificación de las estructuras existentes y posibles nuevas medidas.

Además, es posible que se requiera algún nivel de análisis estructural para confirmar que un defecto observado es inseguro. Lo más importante a tener en cuenta es el carácter limitado de la mayoría de los estudios de estado y la necesidad de realizar estudios periódicos para documentar los cambios en las condiciones a lo largo del tiempo.

Resumen

Las inspecciones de estado se proponen como método para garantizar la seguridad de las estructuras existentes, ya que se requiere que las inspecciones establezcan que las estructuras o componentes existentes son seguros y no presentan defectos. Sin embargo, los estudios de estado, especialmente los visuales, son de naturaleza limitada y es poco probable que los resultados establezcan la seguridad de la estructura con un alto grado de certeza. El requisito de que un LDP determine si una estructura existente es "segura" también es contrario a los requisitos del código de construcción que se basan en que las nuevas construcciones proporcionen un "nivel razonable de seguridad." El conflicto surge debido a las limitaciones en nuestro conocimiento de las construcciones existentes y la cantidad limitada de estructuras visibles en una construcción típica.

Las limitaciones de los estudios de estado se examinarán en las partes 2 y 3 de esta serie. En la parte 4 se analizará la aplicación de nuevas tecnologías para mejorar la capacidad de los LDP para inspeccionar las estructuras existentes y las ventajas de las inspecciones y evaluaciones rutinarias.

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"Reasonable Safety" of Existing Structures, Part 2

Limitations: Buildings and their evaluation

by David G. Tepke, Liying Jiang, Keith E. Kesner, and Stephen S. Szoke

Part 1 of this series examined some key aspects and considerations when evaluating the safety of existing reinforced concrete structures. Parts 2 and 3 of the series will discuss limitations in evaluating structures and some of the complications presented by the structures themselves. In Part 1, the safety of an existing structure was described as a qualitative concept that only becomes quantitative when viewed probabilistically against predetermined norms or expectations established by a governing body. Effective communication to owners and the public about what licensed design professionals (LDPs) *do* and *do not* know, or more correctly, what they *can* and *cannot* know, is important. Given the complexity of existing structures and our evolving understanding of material performance, material variability, and variability in construction, stating that a structure is safe or unsafe without additional context oversimplifies the issue. Still, it is important to communicate to the public accurate information that is useful and understandable. The following sections describe some of the key concepts and limitations impacting our understanding and ability to make statements regarding safety, with an emphasis on how limited documentation of existing structures and changes in building codes influence our ability to assess existing structures.

Discoverable Documentation

A critical step in evaluating an existing structure is the examination of available information from initial construction and from renovations, maintenance, and repair programs. For public structures and structures with institutional or professional management, documentation may be extensive. For many older structures, especially structures that have changed ownership or management, documentation may be limited due to loss or ineffective record keeping. This can lead to a significant gap of knowledge that is difficult or costly to overcome, and one that may present significant uncertainties in the structural evaluation.

The quality of original construction documents can also vary widely, influenced by governing codes and local practices at the time of construction. In some cases, the construction documents can contain meticulous descriptions of as-built construction, including project specifications, responses to requests for information (RFIs), shop drawings, and construction materials testing records. In other cases, only schematic descriptions of existing construction may be available. When shop drawings, project specifications, and material test reports are not available, it is difficult to ascertain how much change was implemented during construction. Even when as-built or record drawings are available, there can be questions regarding the completeness and accuracy of these documents.

Information associated with repairs or maintenance sometimes can also be difficult to obtain, as these actions may not be well documented. This includes property condition assessments and structural condition assessment reports that may or may not be preserved, as well as maintenance scopes and repair design documents. Depending on the authority having jurisdiction (AHJ), repair programs may not require permits, which may limit the extent of repair documentation.

When available, documentation and anecdotal information can provide important information for use as a basis, but a level of confirmation commensurate with acceptable risk is necessary when evaluating structures for safety. This is clearly indicated in documents prepared by ACI (that is, ACI Committees 364, Rehabilitation; and 562, Evaluation, Repair, and Rehabilitation of Concrete Structures) and ASCE/SEI (for example, ASCE/SEI 41-17[1], Seismic Evaluation and Retrofit of Existing Buildings). The process of verification may result in the identification of conditions that impact safety, including misplaced reinforcing steel, improper design, materials-related distress, or other issues.

Variation in dimensions beyond tolerances permitted in codes and standards may be encountered. This includes improper placement of reinforcing steel resulting in either too little cover, making the structure potentially more susceptible to deterioration, reduced fire rating, or in extreme cases, compromised composite behavior, or too much cover, reducing structural capacity (Fig. 1). Documentation from previous construction litigations, such as complaints and rulings, if available, can provide information regarding defects, particularly cracking (Fig. 2), which is a common topic of dispute. Other conditions that may be encountered include undocumented or unsubstantiated previous removal, addition or alteration of structural elements that could require analysis, or investigation to determine implications. These conditions impact how one may evaluate safety and may be difficult to ascertain from a visual review.

Evolution of Building Codes and the State of Practice

Building codes and standards evolve over time to incorporate knowledge gained through research and practice to provide safer, more durable, and more sustainable structures. Structures constructed to earlier codes inherently lack features identified by newer codes as being important for the intended use. However, it is recognized that there is not an expectation of equivalency to new construction. When limited amounts of damage or defects are present, building codes applicable to existing buildings, such as International Existing Building Code (IEBC), International Property Maintenance Code (IPMC), and ACI CODE-562, allow continued use of existing structures. In special cases where an industry-wide issue has been identified that significantly impacts safety, retrofit of existing structures may be required by an AHJ.

ACI CODE-562-21[2] provides options for using data from original construction drawings, data obtained through sampling and testing, and historical default values provided in the standard as a basis for evaluating concrete and reinforcing steel strength. Default values in ACI CODE-562-21 are based on conservative estimates of materials typically in use contemporary to their historical periods. This provides an initial check for properties if drawings or test reports are not available. However, sampling and testing may be necessary or justified to estimate actual in-place properties if adequate capacity cannot be confirmed through use of the conservative default values.

Tepke[3] provides a discussion on the evolution of industry standards and building codes with respect to strength and durability considerations that may impact the performance of existing structures. Knowledge and control of corrosion, alkali-silica reactivity, sulfate attack (internal and external), chemical attack, freezing and thawing, and other deterioration mechanisms have evolved considerably (Fig. 3).

Initiatives such as the durability code being developed by ACI Committee 321, Concrete Durability Code, and the incorporation of global warming potential (GWP) provisions into specifications will modify the way structures are viewed and designed in the future. Structures that predate identification or comprehensive control of a deterioration mechanism may be susceptible to associated damage or deterioration. This must be considered during the assessment stage and factored into consideration for potential safety implications.

Understanding how code provisions have evolved is important in understanding the safety of an existing structure. The LDP examining existing structures needs to consider both the mechanisms contributing to damage and the susceptibility of the structure as a function of its time of construction.

The LDP must also consider that industry knowledge predates incorporation into industry-standard codes (such as ACI CODE-318[4]). For example, requirements for the use of air-entraining admixtures to provide resistance to cyclic freezing-and-thawing distress were not implemented until ACI 318-63,[5] and comprehensive provisions for air content were not included until ACI 318-71,[6] although the need for air entrainment for mitigating freezing-and-thawing damage became understood in the late 1930s. The Bureau of Reclamation required

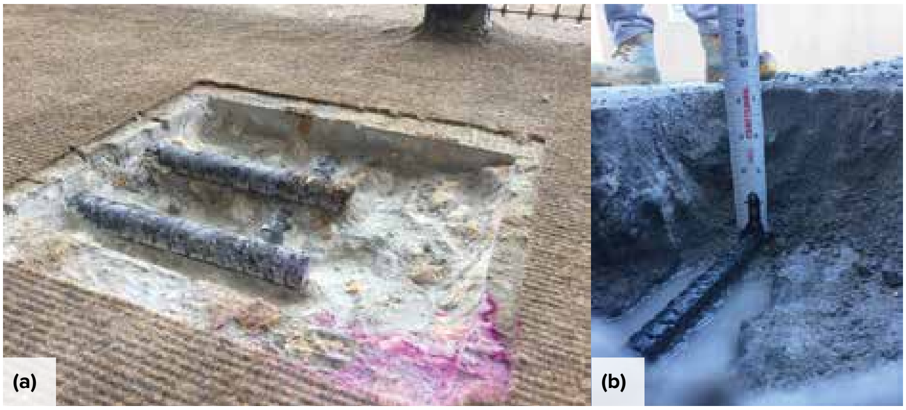

Fig. 1: Examples of improper placement of reinforcing bars: (a) inadequate cover; and (b) excessive cover

Fig. 2: Evidence of changes in the extent of cracking can impact conclusions developed during an investigation

entrained air in concrete as early as the 1940s,[7] indicating possible implementation of it in other structures in those early periods. Significant research on corrosion of embedded steel in concrete has been conducted since the 1950s; however, chloride limits for new construction limiting susceptibility to corrosion were not included in the ACI Code until ACI 318-83.[8] While delayed ettringite formation (DEF) resulting from excessive curing temperatures was first widely understood in the 1990s,[9] DEF was not addressed in ACI 301 specifications until 2010.[10] Other examples of these types of provisions are included in Reference 3.

Other code topics related to safety include the incorporation of structural integrity provisions for collapse resistance that appeared in ACI 318-89[11] and the changes to corrosion protection of prestressing steel that evolved over the last half of the twentieth century.

Further, the LDP should be aware that there is a time lag for incorporation of industry standards into codes adopted by the AHJ, particularly for new codes that require precedence or familiarity prior to inclusion. For example, ACI 562, first published in 2013,[12] will be referenced as the revised 2021 version in the 2024 edition of the IEBC, an 11-year lag. There are other situations where there have been lags of 20 years or more of ACI 318 Code requirements being enforced by state or local AHJs. While codes relevant to many older buildings were probably updated less frequently than codes affecting more recent structures, it is important to attempt to track the lineage of codes on existing drawings if available.

Structural systems and their influence on the approach to evaluation

The design of structural systems has evolved over time, with changes made to improve performance and resilience. The evolution of design means some structural systems are inherently more redundant or are less vulnerable to damage from inadvertent loads, deterioration, design errors, or construction deficiencies. Some considerations for different systems and failure modes are presented in the following sections. However, it is beyond the scope of this article for comprehensive treatment of the systems. ACI PRC-377-21[13] provides discussion on collapse prevention of concrete floor systems. Nowak and Szerszen[14] and Szerszen and Nowak[15] provide discussion on reliability indices for a variety of structural systems, failure modes, and loads for new structures. The application of reliability for determining potentially unsafe conditions in existing structures is discussed by Stevens et al.[16] The following paragraphs discuss some potential vulnerabilities of common structural systems and how industry guides and codes evolved to address them.

Flat plate concrete slabs

Owing to structural efficiency, flat-plate slabs are of relatively thin construction. These systems may include drop panels and capitals at columns to limit deflections and provide additional negative moment capacity and two-way shear capacity. Due to their thin nature, the placement of reinforcing steel becomes a critical parameter that significantly affects both flexural and two-way (punching) shear capacity. Punching shear capacity is critical due to its brittle failure mechanism, and thus, conditions that suggest it may be a possible mechanism should be investigated (Fig. 4). The depth of the top reinforcing steel is of critical importance as small variations in steel location can induce large reductions in calculated capacity (for deeper steel) or higher susceptibility to deterioration in corrosive environments (for shallower steel). This is particularly important for structures constructed prior to implementation of provisions for structural integrity.

Load capacity in the vicinity of the column is critical due to possible failures that may initiate sudden collapse. As indicated in ACI PRC-377-21, collapse may be initiated in flat-plate slabs from two-way shear failure of the slab around a column, failure of a column, or flexural failure of the slab. Settlement or failure of a column effectively sheds loads to

Fig. 3: Freezing-and-thawing/scaling damage in structural slabs from a stadium constructed circa mid 1920s, prior to the use of air-entrainment in concrete

Fig. 4: Cracking at column perimeter that is cause for further investigation *(photo courtesy of Structural Technologies)*

the slab connection and to other column/slab connections. As explained in ACI PRC-377-21, progressive or disproportionate collapse can occur from subsequent punching shear failures at surrounding columns, from detachment of slabs that create impact loads on floors below that result in pancaking, and from column failures resulting in additional floor loads. To enhance the resilience of two-way construction, significant changes have been made in design code requirements to provide continuous reinforcement across two-way construction in ACI 318-89.

Unbonded post-tensioned concrete

Unbonded post-tensioned concrete members include tendons that typically extend multiple spans and, therefore, a local failure of a tendon can affect large area in a structure. The strands are concealed, so it can be difficult to determine the extent of deterioration from corrosion by visual inspection. Grease stains in slab soffits or deteriorated end anchorage pockets can be indicators of distress, but these conditions may not be prevalent. Additionally, failure of strands can result in violent concrete rupture at floors or soffits in occupied space or at slab edges that may create potentially dangerous conditions. Design or construction deficiencies promoting overstress can lead to cracking that impacts overall durability or structural performance (Fig. 5).

Fig. 5: Cracking and efflorescence in post-tensioned concrete

Fig. 6: A view of a damaged slab soffit at a flange-to-flange connection of precast double tees

Post-tensioned concrete construction requirements and design practices have improved dramatically over the past 70 years, with numerous changes being incrementally added to codes to improve corrosion protection. Post-tensioning used in structures today is required to be sheathed in plastic with corrosion protection and have protected anchorages. Older post-tensioned systems included button head systems, and tendons sheathed in kraft paper. Those systems lacked corrosion protection in the areas behind anchorages and were sensitive to damage. Changes in post-tensioned construction include the development of fully encapsulated strands and more durable sheathing, as described in ACI 423.4-14.[17]

Prestressed precast concrete

Prestressed concrete components are generally reliant on external connections for connectivity; some that are bearing allow for a moderate amount of movement and others provide restraint. The performance of bearing connections was identified as an issue during the 1994 Northridge earthquake. Significant changes in design practice were subsequently made to improve diaphragm performance and connections between members.[18] The connection between precast double-tee members has also been identified as being susceptible to fatigue and corrosion damage[19] (Fig. 6). Improved connection designs are expected to address these issues.

Accessibility, Site Survey Selection, and Subjectivity During Assessment

Evaluation of an existing structure implies some level of examination of the structure to locate possible defects. Some structure types, such as parking structures or Brutalist buildings, provide an open expanse of concrete to examine. More typical are structures with only limited extents of visible structure due to façades and interior finishes. Removal of finishes, whether interior or exterior, inherently increases the cost and difficulty of a survey. Limitations on accessibility will result in the need for extrapolation of results from the survey locations to the full structure.

In the preceding sections, locations where damage is expected to have a greater effect on the performance of an existing structure are described. Accordingly, when planning an evaluation, these locations are critical spots for probes or other focused investigations. However, these locations may represent only a small fraction of the structure, which introduces sampling subjectivity into the evaluation process. Consideration of structure globally and particularly sensitive areas locally are important and will be addressed in Part 3 of this series.

Evaluation and analysis of existing structures relies on engineering principles and mechanics. However, conditions encountered in practice often invoke a level of subjectivity. In cases where components of an existing structure are sound and intact, similar methods as those used for new structures can be used to calculate capacity. For example, objective analysis is possible where characteristic strength is different from design, reinforcing steel is improperly located (Fig. 7), or support conditions vary. Conditions of materials-related distress of concrete (Fig. 8) or corrosion of embedded steel (Fig. 9) can result in more uncertainly in the analysis. Bond of reinforcing steel to concrete for supporting conditions of composite action; incremental damage from inherent deterioration from alkali-silica reactivity, DEF, or other mechanisms; impact of corrosion and delamination on bond and development length; and other conditions may not be easily quantifiable due to evaluation or analysis constraints. The experience of the LDP plays a crucial role in making judgments regarding safety. In some situations, shoring and then implementation of load tests may be prudent; however, where future progressive deterioration is possible from materials-related distress (for example, corrosion), consideration of future or imminent conditions is necessary in interpretation of load testing result and associated future reduction of capacity from deterioration. Mitigation of the deterioration mechanism through preservation methods and structural health monitoring might be necessary if the structure or component remains in service.

Fig. 7: Ground penetrating radar survey showing locations of stirrups for evaluation of shear capacity

Fig. 8: Horizontal cracking in a beam found to be a manifestation of internal sulfate attack

Fig. 9: Corrosion of embedded reinforcing steel resulting in compromised composite action and development length

Closing

Part 2 describes some conditions that may impact the evaluation of "safety." Assessment of existing structures requires an understanding of the expected performance of the structure and how the performance is affected by the requirements of the building codes in place at the time of construction. The assessment will also be affected by the availability and quality of documentation from original design and building performance over time. The structural system and assessment constraints add additional complexity to the process. Consideration of these parameters in combination with existing conditions may make it difficult to ascertain the overall performance of the structure.

Part 3 of this article series will continue to examine limitations in the evaluation process including historical exposure and use, visual assessment of deterioration and distress, quantification and significance of observed deterioration, and consideration of the remaining service life.

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Selected for reader interest by the editors.

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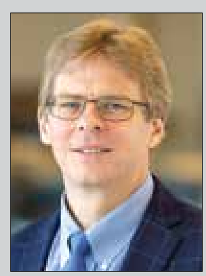

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ARTÍCULO

4 CUATRO

"Seguridad Razonable" para las Estructuras Existentes, Parte 2

Limitaciones: los edificios y su evaluación

por David G. Tepke, Liying Jiang, Keith E. Kesner, y Stephen S. Szoke

En la Parte 1 de esta serie se examinaron algunos aspectos y consideraciones clave a la hora de evaluar la seguridad de las estructuras existentes de concreto armado. Las partes 2 y 3 de la serie tratarán sobre las limitaciones en la evaluación de estructuras y algunas de las complicaciones que presentan las propias estructuras. En la Parte 1, se describió la seguridad de una estructura existente, como un concepto cualitativo que sólo se convierte en cuantitativo cuando se compara probabilísticamente con normas predeterminadas o expectativas establecidas por un organismo rector. Es importante la comunicación efectiva hacia los propietarios y al público, sobre lo que saben y lo que no saben los profesionales del diseño autorizados (LDPs por sus siglas en inglés), o más correctamente, lo que pueden y no pueden saber. Dada la complejidad de las estructuras existentes y nuestra creciente comprensión sobre el desempeño de los materiales, la diversidad de materiales y la variabilidad en la construcción, afirmar que una estructura es segura o insegura sin un contexto adicional, simplifica en exceso la cuestión. Aun así, es importante comunicar al público información precisa que sea útil y comprensible. Las siguientes secciones describen algunos de los conceptos clave y las limitaciones que afectan a nuestra comprensión y a nuestra capacidad para hacer afirmaciones sobre la seguridad, haciendo hincapié sobre lo limitada que es la documentación de las estructuras existentes y en que los cambios en los códigos de construcción influyen en nuestra capacidad para evaluar las estructuras existentes.

Documentación identificable

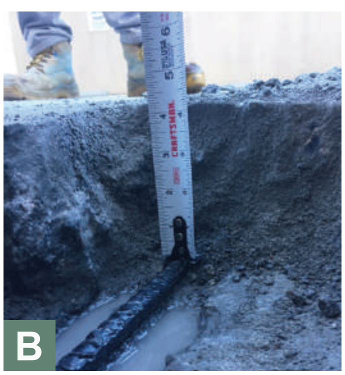
Un paso fundamental en la evaluación de una estructura existente es el examen de la información disponible sobre la construcción inicial y los programas de renovación, mantenimiento y reparación. En el caso de estructuras públicas y estructuras con gestión institucional o profesional, la documentación puede ser extensa. En el caso de muchas estructuras antiguas, especialmente las que han cambiado de propietario o de gestión, la documentación puede ser limitada debido a pérdidas o a un mantenimiento ineficaz de los registros. Esto puede dar lugar a una importante laguna de conocimiento que resultara difícil o costosa de superar, y que puede presentar importantes incertidumbres en la evaluación estructural.

Al momento de la construcción, la calidad de los documentos de construcción originales también puede variar mucho en función de los códigos vigentes y las prácticas locales. En algunos casos, los documentos de construcción pueden contener descripciones meticulosas de la construcción tal y como se realizó, incluidas las especificaciones del proyecto, las respuestas a las solicitudes de información (RFIs por sus siglas en inglés), los planos de taller y los registros de pruebas de materiales de construcción. En otros casos, sólo se dispone de descripciones esquemáticas de la construcción existente. Cuando no se dispone de los planos de taller, las especificaciones del proyecto y los informes de pruebas de materiales, es difícil determinar qué cambios se introdujeron durante la construcción. Incluso cuando se dispone de planos de construcción o de registro, pueden surgir dudas sobre la integridad y la exactitud de estos documentos.

A veces también puede ser difícil obtener la información asociada a las reparaciones o al mantenimiento, ya que estas acciones pueden no estar bien documentadas. Esto incluye las evaluaciones del estado de la propiedad y los informes de evaluación del estado estructural que pueden o no conservarse, así como los alcances del mantenimiento y los documentos de diseño de las reparaciones. Dependiendo de la autoridad que tenga jurisdicción (AHJ por sus siglas en inglés), los programas de reparación pueden no requerir permisos, lo que puede limitar el alcance de la documentación de las reparaciones.

Cuando está disponible, la documentación y la información anecdótica pueden proporcionar información importante para utilizarla como base, pero cuando se evalúan las estructuras en cuanto a su seguridad es necesario un nivel de confirmación acorde con un riesgo aceptable. Esto se indica claramente en los documentos elaborados por el ACI (es decir, los Comités ACI 364, Rehabilitación; y 562, Evaluación, reparación y rehabilitación de estructuras de concreto) y ASCE/SEI (por ejemplo, ASCE/SEI 41-17[1], Evaluación sísmica y rehabilitación de edificios existentes). El proceso de verificación puede dar lugar a la identificación de condiciones que afecten a la seguridad, como acero de refuerzo mal colocado, diseño inadecuado, problemas relacionados con los materiales u otras cuestiones.


A



B

Fig. 1: Ejemplos de barras de refuerzo colocadas de manera incorrecta: (a) recubrimiento inadecuado; y (b) recubrimiento excesivo.

Pueden encontrarse variaciones en las dimensiones más allá de las tolerancias permitidas en los códigos y normas. Esto incluye la colocación incorrecta del acero de refuerzo, lo que puede dar lugar a un recubrimiento insuficiente que haga que la estructura sea potencialmente más susceptible al deterioro, reducir la resistencia al fuego o, en casos extremos, comprometa el desempeño del material compuesto, o que un recubrimiento excesivo reduzca la capacidad estructural (Fig. 1). La documentación de litigios de construcción anteriores, como denuncias y sentencias, si está disponible, puede proporcionar información sobre los defectos, en particular sobre el agrietamiento (Fig. 2), el cual es un tema habitual de disputa. Otras condiciones que pueden encontrarse incluyen la eliminación previa no documentada o no demostrada, la adición o alteración de elementos estructurales que podrían requerir un análisis o una investigación para determinar las implicaciones. Estas condiciones influyen en la forma de evaluar la seguridad y pueden ser difíciles de determinar a partir de una inspección visual.

Evolución de los códigos de construcción y el estado de la práctica

Los códigos y normas de construcción evolucionan con el tiempo para incorporar los conocimientos adquiridos a través de la investigación y la práctica, con el fin de proporcionar estructuras más seguras, duraderas y sostenibles. Las estructuras construidas conforme a códigos anteriores carecen inherentemente de las características identificadas por los códigos más recientes, lo cual es importante para el uso previsto. Sin embargo, se reconoce que no existe una expectativa de equivalencia con las nuevas construcciones. Cuando los daños o defectos son limitados, los códigos de construcción aplicables a los edificios existentes, como el Código Internacional de Edificios Existentes (IEBC por sus siglas en inglés), el Código Internacional de Mantenimiento de Propiedades (IPMC por sus siglas en inglés) y el ACI CODE-562, permiten seguir utilizando las estructuras existentes. En casos especiales, en los que se haya identificado un problema en un amplio sector de la industria,


Fig. 2: La evidencia de cambios en la extensión de las grietas puede influir en las conclusiones que surjan durante una investigación.

que afecte significativamente a la seguridad, el AHJ puede exigir el reacondicionamiento de las estructuras existentes.

El código ACI-562-21[2] proporciona opciones para utilizar información de los planos de construcción originales, información obtenida mediante muestreo y ensayos, y valores predeterminados históricos proporcionados en la norma como base para evaluar la resistencia del concreto y del acero de refuerzo. Los valores predeterminados en el código ACI-562-21 se basan en estimaciones conservadoras para materiales típicamente en uso contemporáneo, con relación a sus períodos históricos. Esto sirve como comprobación inicial de las propiedades, en caso de que no se disponga de planos o informes de ensayos. Sin embargo, si no puede confirmarse una capacidad adecuada mediante el uso de los valores conservadores predeterminados, puede ser necesario o justificar el realizar muestreos y ensayos para estimar las propiedades reales en el lugar.

En lo que respecta a las consideraciones de resistencia y durabilidad que pueden afectar al desempeño de las estructuras existentes, Tepke[3] proporciona un análisis de la evolución de las normas industriales y los códigos de construcción. El conocimiento y el control de la corrosión, la reactividad álcali-sílice, el ataque por sulfatos (interno y externo), el ataque químico, el congelamiento-descongelamiento y otros mecanismos de deterioro han evolucionado considerablemente (Fig. 3).

Iniciativas como el código de durabilidad que está desarrollando el Comité 321 del ACI, Código de Durabilidad del Concreto, y la incorporación de disposiciones sobre el potencial de calentamiento global (GWP por sus siglas en inglés) en las especificaciones, modificarán la forma de ver y diseñar las estructuras en el futuro. Las estructuras anteriores a la identificación o el control exhaustivo de un mecanismo de deterioro, pueden ser susceptibles de sufrir daños o deterioros asociados. Esto debe tenerse en cuenta en la fase de evaluación y al considerar las posibles implicaciones para la seguridad.

Comprender cómo han evolucionado las disposiciones del código es importante para entender la seguridad de una estructura existente. El LDP que examina las estructuras existentes, debe tener en cuenta tanto los mecanismos que contribuyen a los daños, como la susceptibilidad de la estructura en función de la época en la que se construyó.

Fig. 3: Descascaramiento por congelamiento-descongelamiento en losas estructurales de un estadio construido a mediados de la década de 1920, antes de la utilización de los inclusores de aire en el concreto.

El LDP también debe tener en cuenta que los conocimientos de la industria son anteriores a la incorporación en los códigos estándar de la industria (como el código ACI-318[4]). Por ejemplo, los requisitos para el uso de aditivos inclusores de aire para proporcionar resistencia a los ciclos de congelamiento-descongelamiento no se implementaron hasta que el ACI 318-63[5], y las disposiciones integrales para el contenido de aire no se incluyeron hasta que se publicó el ACI 318-71[6], a pesar de que la necesidad de incluir aire para mitigar los daños por congelamiento-descongelamiento se comprendió hasta finales de 1930. En la década de 1940[7], el Departamento de Recuperación (Bureau of Reclamation) especificó la inclusión de aire en el concreto, indicando también su posible aplicación en otras estructuras en esos primeros periodos. Desde la década de 1950 se han llevado a cabo importantes investigaciones sobre la corrosión del acero embebido en el concreto; sin embargo, los límites de cloruro para las nuevas construcciones que limitan la susceptibilidad a la corrosión no se incluyeron en el Código ACI hasta el ACI 318-83[8]. Aunque la formación retardada de etringita (DEF por sus siglas en inglés) resultante de temperaturas de curado excesivas se comprendió ampliamente por primera vez en la década de 1990[9], la DEF no se abordó en las especificaciones del ACI 301 hasta 2010[10]. En la Referencia 3 se incluyen otros ejemplos de este tipo de disposiciones.

Otros temas del código relacionados con la seguridad, incluyen la incorporación de disposiciones de integridad estructural para la resistencia al colapso, que aparecieron en ACI 318-89[11] y los cambios en la protección contra la corrosión del acero pretensado que evolucionaron a lo largo de la última mitad del siglo XX.

Además, el LDP debe ser consciente de que existe un desfase temporal para la incorporación de las normas industriales en los códigos adoptados por el AHJ, en particular para los nuevos códigos que requieren precedencia o familiaridad antes de su inclusión. Por ejemplo, la norma ACI 562, publicada por primera vez en 2013[12], será referenciada como la versión revisada de 2021 en la edición de 2024 del IEBC, lo que supone un desfase de 11 años. Hay otras situaciones en las que se han producido retrasos de 20 años o más en la aplicación de los requisitos del Código ACI 318 por parte de los AHJ locales o estatales. Aunque los códigos relevantes para muchos edificios antiguos probablemente se actualizaron con menos frecuencia que los códigos que afectan a estructuras más recientes, es importante intentar rastrear el linaje de los códigos en los planos existentes si se dispone de ellos.

Los sistemas estructurales y su influencia en el enfoque de la evaluación

El diseño de los sistemas estructurales ha evolucionado con el tiempo, con cambios introducidos para mejorar el rendimiento y la resistencia. La evolución del diseño significa que algunos sistemas estructurales son intrínsecamente más redundantes o menos vulnerables a los daños provocados por cargas inadvertidas, deterioro, errores de diseño o deficiencias de construcción. En las siguientes secciones se presentan algunas consideraciones para diferentes sistemas y modos de fallo. Sin embargo, queda fuera del alcance de este artículo el tratamiento exhaustivo de los sistemas. El ACI PRC-377-21[13] proporciona una discusión sobre la prevención del colapso de los sistemas de pisos de concreto. Nowak y Szerszen[14] y Szerszen y Nowak[15] proporcionan información sobre los índices de confianza para una variedad de sistemas estructurales, modos de fallo y cargas para estructuras nuevas. La aplicación de la confiabilidad para determinar condiciones potencialmente inseguras en estructuras existentes es analizada por Stevens et al[16]. Los siguientes párrafos analizan algunas vulnerabilidades potenciales de sistemas estructurales comunes y cómo las guías y códigos de la industria evolucionaron para abordarlas.

Losas planas de concreto

Debido a la eficiencia estructural, las losas planas son de construcción relativamente delgada. Estos sistemas pueden incluir paneles ábacos y capiteles sobre las columnas para limitar las deformaciones y proporcionar capacidad adicional de momento negativo y de cortante bidireccional. Por ser de poco espesor, la colocación del acero de refuerzo resulta un parámetro crítico que

Fig. 4: Fisuración en el perímetro de la columna que requiere una investigación más detallada (foto cortesía de Structural Technologies).

afecta significativamente tanto a la capacidad de flexión, como a la capacidad de corte bidireccional (punzonamiento/penetración). La capacidad de corte por punzonamiento es crítica debido a que su mecanismo de falla es frágil, si las condiciones sugieren que este mecanismo de falla es posible, esto debe ser investigado (Fig. 4). La profundidad del acero de refuerzo superior es de importancia crítica ya que pequeñas variaciones en la ubicación del acero pueden inducir grandes reducciones en la capacidad calculada (para acero más profundo) o una mayor susceptibilidad al deterioro en ambientes corrosivos (para acero menos profundo). Esto es especialmente importante para las estructuras construidas antes de la aplicación de las disposiciones relativas a la integridad estructural.

La capacidad de carga en las proximidades de una columna es crítica debido a las posibles fallas que pueden iniciar un colapso repentino. Tal y como se indica en el ACI PRC-377-21, el colapso puede iniciarse en losas planas por el fallo por cortante bidireccional de la losa alrededor de una columna, el fallo de una columna o el fallo por flexión de la losa. El asentamiento o el fallo de una columna transfiere cargas a la conexión de la losa y a otras conexiones columna/losa. Como se explica en ACI PRC-377-21, puede producirse un colapso progresivo o desproporcionado debido a fallos de punzonamiento subsiguientes en las columnas circundantes, al desprendimiento de losas que crean cargas de impacto en los pisos inferiores que dan lugar a pancakes, y a fallos en columnas que dan lugar a cargas adicionales en los pisos. Para mejorar la resistencia de la construcción bidireccional, se han introducido cambios significativos en los requisitos del código de diseño ACI 318-89, para proporcionar un refuerzo continuo a través de la construcción bidireccional.

Concreto postensado con torones no adheridos

Los elementos de concreto postensado no adheridos incluyen tendones que normalmente se extienden por varios claros y, por lo tanto, un fallo local de un tendón puede afectar a una gran área de una estructura. Los tendones están ocultos, por lo que puede ser difícil determinar mediante una inspección visual el alcance del deterioro por corrosión. Las manchas de grasa en los fondos de las losas o el deterioro de las cavidades de anclaje de los extremos pueden ser indicadores de deterioro, pero estas condiciones pueden no ser frecuentes. Además, el fallo de los torones puede provocar la rotura violenta del concreto en pisos o plafones en espacios ocupados o en los bordes de las losas, lo que puede crear condiciones potencialmente peligrosas. Las deficiencias de diseño o construcción que promueven el sobreesfuerzo pueden provocar fisuras que afecten a la durabilidad general o al desempeño estructural (Fig. 5).

Los requisitos de construcción y las prácticas de diseño del concreto postensado han mejorado drásticamente en los últimos 70 años, con numerosos cambios añadidos progresivamente a los códigos para mejorar la protección contra la corrosión. Hoy en día, el postensado que se utiliza en las estructuras debe estar revestido de plástico con protección anticorrosiva y tener anclajes protegidos. Los sistemas de postensado más antiguos incluían sistemas de cabeza de botón y tendones revestidos con papel kraft. Estos sistemas carecían de protección contra la corrosión en las zonas situadas detrás de los anclajes y eran sensibles a los daños. Los cambios en la construcción postensada incluyen el desarrollo de torones totalmente encapsulados y revestimientos más duraderos, tal y como se describe en el ACI 423.4-14[17].

Fig. 5: Fisuración y eflorescencia en concreto postensado.

Fig. 6: Vista de un plafón dañado en una conexión entre dos doble T prefabricadas.

Prefabricados de concreto pretensado

Los componentes del concreto pretensado generalmente dependen de conexiones externas para su conectividad; algunas que son portantes permiten una cantidad moderada de movimiento y otras proporcionan restricción. El comportamiento de las conexiones portantes se identificó como un problema durante el terremoto de Northridge de 1994. Posteriormente se introdujeron cambios significativos en las prácticas de diseño para mejorar el comportamiento de los diafragmas y las conexiones entre los elementos[18]. La conexión entre los elementos prefabricados de doble T también se ha identificado como susceptible de sufrir daños por fatiga y corrosión[19] (Fig. 6). Se espera una mejora en el diseño de las conexiones para solucionar estos problemas.

Accesibilidad, selección de encuestas sobre el terreno y Subjetividad durante la evaluación

La evaluación de una estructura existente implica cierto nivel de estudio de la estructura para localizar posibles defectos. Algunos tipos de estructuras, como los estacionamientos o los edificios de concreto expuesto, ofrecen una extensión abierta de concreto por examinar. Son más típicas las estructuras con una extensión limitada de estructura visible, debido a las fachadas y a los acabados interiores. La eliminación de los acabados, ya sean interiores o exteriores, aumenta intrínsecamente el costo y la dificultad del estudio. Las limitaciones de accesibilidad obligan a extrapolar los resultados de los lugares inspeccionados a toda la estructura.

En los apartados anteriores se han descrito los lugares en los que se espera que los daños afecten más el desempeño de una estructura existente. En consecuencia, al planificar una evaluación, estos lugares son puntos críticos para realizar sondeos u otras investigaciones específicas. Sin embargo, estos lugares pueden representar sólo una pequeña fracción de la estructura, lo que introduce subjetividad de muestreo en el proceso de evaluación. La consideración de la estructura en su conjunto y de las zonas especialmente sensibles a nivel local es importante y se abordará en la Parte 3 de esta serie.

La evaluación y el análisis de las estructuras existentes se basan en principios de ingeniería y mecánica. Sin embargo, las condiciones que se dan en la práctica suelen conllevar un cierto grado de subjetividad. En los casos en que los componentes de una estructura existente son sólidos y están intactos, para calcular la capacidad se pueden utilizar métodos similares a los empleados para las

Fig. 7: Estudio con radar de penetración mostrando la ubicación de los estribos para la evaluación de la capacidad de corte.

Fig. 8: Agrietamiento horizontal en una viga como una manifestación de un ataque interno de sulfato.

Fig. 9: Corrosión del acero de refuerzo embebido que compromete el servicio del material compuesto y la longitud de desarrollo del acero.

estructuras nuevas. Por ejemplo, es posible realizar un análisis objetivo cuando la resistencia característica difiere de la de diseño, el acero de refuerzo está mal situado (Fig. 7) o varían las condiciones de apoyo. Las condiciones de deterioro del concreto relacionadas con los materiales (Fig. 8) o la corrosión del acero embebido (Fig. 9), pueden dar lugar a una mayor incertidumbre en el análisis. La adherencia del acero de refuerzo al concreto para soportar condiciones de acción compuesta; daño incremental por deterioro inherente por reactividad álcali-sílice, DEF, u otros mecanismos; impacto de la corrosión y delaminación en la adherencia y longitud de desarrollo; y otras condiciones pueden no ser fácilmente cuantificables debido a restricciones de evaluación o análisis. La experiencia del LDP juega un papel crucial a la hora de emitir juicios sobre la seguridad. En algunas situaciones, el apuntalamiento y la posterior realización de pruebas de carga puede ser razonable; sin embargo, cuando es posible un futuro deterioro progresivo debido a un deterioro relacionado con los materiales (por ejemplo, corrosión), es necesario tener en cuenta las condiciones futuras o inminentes a la hora de interpretar el resultado de las pruebas de carga y la futura reducción de la capacidad asociada al deterioro. Si la estructura o el componente permanecen en servicio, puede ser necesario mitigar el mecanismo de deterioro mediante métodos de conservación y vigilancia de la salud estructural.

Cierre

En la Parte 2 se describen algunas condiciones que pueden influir en la evaluación de la "seguridad". La evaluación de las estructuras existentes requiere una comprensión del comportamiento esperado para la estructura y de cómo este comportamiento se ve afectado por los requisitos de los códigos de construcción vigentes en el momento de la construcción. La evaluación también se verá afectada por la disponibilidad y la calidad de la documentación del diseño original y el comportamiento del edificio a lo largo del tiempo. El sistema estructural y las limitaciones de la evaluación añaden complejidad al proceso. La consideración de estos parámetros en combinación con las condiciones existentes pueden dificultar la determinación del comportamiento global de la estructura.

La parte 3 de esta serie de artículos seguirá examinando las limitaciones del proceso de evaluación, incluyendo la historia de su exposición y su uso, la evaluación visual del deterioro, la cuantificación e importancia del deterioro observado y la consideración de la vida útil restante.

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“Reasonable Safety” of Existing Structures, Part 3

Reading the structure

by David G. Tepke, Liying Jiang, Keith E. Kesner, and Stephen S. Szoke

Part 2 of this series focused on challenges associated with the availability of documentation, the evolution of the building codes and construction practices, and how these changes impact the assessment of structural safety.[1] The process of “reading” the structure typically starts with a visual survey to identify indicators of potential distress such as cracks, deterioration, excessive deformations, or signs of leakage (Fig. 1).

As described in Part 1 of this series, some milestone safety assessment ordinances have been adopted in the United States.[2] These ordinances all require an assessment of the structure, with only a limited number requiring anything beyond a visual survey. However, assessment from a visual survey alone is a difficult task, especially given the challenges posed by limited access to structural elements, the potential for hidden deterioration, and the aging of structures.

The goal of Part 3 is to discuss some of the intricacies associated with “reading the structure,” which is the process of examining the structure, determining the need for focused testing or further evaluation, and then deciding on a path forward. Part 4 will discuss how technological advancements may provide new hope for existing structures.

Visual Surveys

Visual surveys are the most common starting point in the evaluation of existing structures. ACI CODE-562-21,[3] ACI 364.1R-19,[4] and SEI/ASCE 11-99[5] provide requirements and guidance for performing an initial assessment of a structure. Visual surveys are limited both in terms of the extent of the structure that can be examined and the types of defects that can be identified. Visual surveys also require discernment of the significance of cracking and other visible “defects” in an existing structure. Though not generally requisite, a visual survey may be supplemented with crack width measurements, limited deflection measurements, sounding for delaminations, or other nondestructive testing for the purposes of preliminarily supporting observations.

Fig. 1: Leakage with corrosion staining at an existing parking garage framing structure

Identifying potential hazards and vulnerabilities requires an understanding of the expected structural system encountered, and what constitutes unexpected behavior. Part 2 of this series described special considerations associated with the vulnerabilities of different structural systems. The licensed design professional (LDP) completing the visual survey needs to recognize that damage has different implications depending on the structural system and the age of the structure. Existing structures, through normal construction processes, routine service, and exposure conditions, generally have some level of “defects.” Defects may be in the form of cracks, surface blemishes, material degradation, variations in member geometry or location of embedments, unexpected structural response, or other conditions. In most cases, these “defects” will not significantly impact the intended use or overall stability of a structure. However, design or construction errors outside standard tolerances, misuse or unintended use of the structure, exposure to loads or conditions not accounted for in design, or deterioration from longer-than-anticipated service in a given environment can lead to defects or damage that may be of concern. As described in ACI CODE-562-21, condition(s) observed during the visual survey perceived to be "potentially dangerous" or that give cause for the LDP to question the capacity of the structure or structural element—for example, the observed condition that is inconsistent with expectations of the design—must be further evaluated. This concept is illustrated in Fig. 2 and 3. Figure 2 shows a "typical" or "expected" crack on a concrete beam. This type of crack is common in concrete structures under "typical" service conditions. In contrast, Fig. 3 shows an example of atypical concrete cracking.

While visual surveys can provide indicators of unsafe conditions, structural elements are typically concealed by the presence of floor and wall coverings, ceilings, interior partitions, exterior envelope and veneer, ceiling-mounted mechanical equipment, and other obstructions. "Excessive" vertical deflections of structural members are commonly used as an indication of damage or unexpected performance, but these can only be observed when longer sections of the span are visible. It follows that a structure generally cannot be fully surveyed visually, and it is not reasonable to assume that all conditions that impact safety can be located. Structural capacity and serviceability of concrete structures are inherently dependent on the location, quantity, and type of embedded reinforcement; material properties are also heavily dependent on concrete production and construction practices. Therefore, visual surveys may be used to identify unsafe conditions, but they may not always be a viable strategy for confirming "reasonable safety" to assess safety. Visual survey results are also a common trigger for additional investigation and other forms of analysis.


(a)


(b)

Fig. 2: A beam within a parking garage structure: (a) a general view; and (b) a close-up view of a crack on the beam face and soffit

Cracks, Visual Defects, and Deterioration

Cracks and other visual defects are frequently observed on exposed concrete elements. While they may provide an indication of significant distress, such indications may also result from reasonable movement associated with volume change or minor construction blemishes. ACI 201.1R-08[6] provides a pictorial description of different types of cracking and other types of defects in concrete structures. ACI 224.1R-07,[7] ACI 224R-01,[8] and ACI 224.4R-13[9] provide information about causes, control, and detailing for mitigation of cracking, and ACI PRC-201.2-23[10] provides information on materials-related distress mechanisms that may lead to cracking or distress. When cracks and other defects are observed in a visual survey, some critical questions that should be asked include:

- Are the shape, size, frequency, and orientation of cracks consistent with the expected structural behavior of the structure?
- Are the crack patterns, defect characteristics, effluent deposits, or associated staining consistent with possible deterioration or materials-related distress mechanisms?
- Does cracking or delamination represent a potentially dangerous condition associated with falling concrete, a tripping hazard, or loss of required fire protection?
- What are the possible future implications of cracking or observed defects on durability or prolonged continued use?
- Do similar members in the structure exhibit similar crack patterns and characteristics?
- Has cracking or distress worsened over time?

Concerns shall be raised if the cracks and visual damage are consistent with structural behavior issues or represent a reduction in capacity from excessive deterioration. These include but are not limited to the following conditions:

Fig. 3: Vertical cracks and concrete delamination in a column

- Differential settlement, excessive deflections, or other deformations. In some cases, settlement cracks in walls, usually wider at one end than the other, may have stabilized and only warrant monitoring to determine if additional settlement occurs. If settlement creates cracks at connections, further investigation and assessment may be required;
- Cracks due to flexure or shear of structural elements may warrant further investigation, particularly wider cracks, cracks indicative of development failure, and cracks in members with limited redundancy. An example of a member with limited redundancy is a cantilever beam. Shear cracks, regardless of redundancy, require additional investigation due to the potential nature of the failure (Fig. 4);
- Cracks in elevated floor slabs that radiate outward from columns combined with cracks encircling the column are likely to be an indication of a condition that could result in punching shear failure. As discussed in Part 2, crack patterns that indicate the possibility of punching shear failure should be regarded as an eminent risk of catastrophic failure;
- Cracks in lateral force-resisting members may suggest deficiencies or previous overloading conditions that require investigation; and
- Widespread cracking with effluent material, cracking with corrosion stains, or cracking consistent with materials-related distress that could compromise the general integrity, quality of concrete, or embedded reinforcement should be investigated. Spalling and other losses of the section of concrete elements and corrosion and section loss of steel reinforcement can significantly impair the ability of concrete elements to resist nominal loads (Fig. 5). In addition to corrosion and losses of sections, the presence of moisture, water stains, corrosion stains on or near structural concrete, or finishes concealing concrete may warrant further investigation.

The conditions described previously are commonly triggers for additional investigation to determine how the capacity of the structure is affected.

Exterior conditions, particularly in corrosive environments, can result in deterioration and distress that may lead to safety issues. Impending detachment of concrete sections, sometimes referred to as incipient spalls, can present localized hazards, particularly when they may be tripping hazards or overhead falling hazards. As described in Tepke and Isgor[11] and ACI 222R-19,[12] corrosive conditions also can occur inside structures; for example, where exterior contaminants may penetrate to the interior, heightened moisture may be present, or chemicals or contaminants may exist. Therefore, consideration of corrosion where these conditions may exist should not be neglected during visual surveys.

Historical Exposure, Uses, and Changes

Repairs, alterations, and additions can significantly impact both structural performance and evaluation. Documents related to maintenance, repair, alteration, or addition are often not available or are in partial form. Thus, it can be difficult to ascertain through document review what work has been done after initial construction, when it was done, and the possible implications with respect to building performance.

As discussed in Part 2, the state of practice and governing building codes at the time of construction should be considered when evaluating structures. One should also consider common practices with regard to maintenance and building use, as they may correlate with materials-related distress. For example, changes in processes in industrial or manufacturing facilities (such as textile mills and plating and food-processing facilities), or chemicals used in environmental structures or pools, can impact the expected rate of deterioration.

Quantification of Defects, Damage, and Deterioration

Quantification of defects, damage, or deterioration can be challenging. In addition to the aforementioned obstructions that limit ready access for visual surveys or testing, the variable nature of concrete, construction, and exposures can

Fig. 4: This wide diagonal crack near a support indicates the need for shoring and additional investigation

Fig. 5: Corroded reinforcing bars within a balcony (under repair)

lead to an array of conditions. ACI 228.2R-13,[13] ACI 228.1R-19,[14] ACI 437R-19,[15] ACI 214R-11,[16] and ACI 364.1R-19[4] can be used to help develop a detailed investigation and evaluation plan. Plans may include a more detailed visual survey, testing analysis, or a combination of these at a subset or all the critical areas, depending on the suspected defects and potential deterioration mechanism, the likelihood for repetitive presence at the structure, the level of uncertainty based on the initial review, the ability to analytically assess the condition, the practical constraints (access), the exposure and loading, and the potential impact of a localized failure at the area. Investigation plans may include excavations, probes, or viewports to evaluate conditions identified through testing.

Evaluation of materials-related distress is one typical example. While concrete distress can often be evaluated using techniques described in ACI 228.2R-13,[13] comprehensive evaluation of damage, including the bond between reinforcement and surrounding concrete, layered variation in damage, and specific section loss of hidden steel (in the case of corrosion) can be challenging. Deterioration rates, even if estimated with some accuracy, can be heavily dependent on environmental conditions and thus can vary. Damage from corrosion, alkali-silica reaction, delayed ettringite formation, or other issues generally requires specialized testing for evaluation.

In cases where the capacity of the structure or structural elements are in question, load testing in accordance with ACI 437.1R-07[17] and ACI CODE-437.2-22[18] can be used. The possibility of continued deterioration should be considered in further evaluations after the load testing.

Localized versus Global Evaluation

When attempting to understand overall structural safety, it is important to consider the safety of the building holistically as well as potential impacts from localized damage or defects. Random sampling may be adequate for evaluating the general nature of a structure, but it is important to consider localized defects or damage that may be significant in nature, particularly if associated with elements of critical concern, as described earlier in this article and series. An adequate sampling and investigative plan must be established if there is concern that localized conditions may impact safety.

Evaluation of localized exposure requires considerations of potential atypical exposure conditions from previous spills, uses, or operations in chemical, manufacturing, or water treatment facilities, as well as those derived from wind patterns, orientation with respect to coastal exposures, shielding, and height of obstructions from corrosive exposures. Figure 6 shows the variability in required repairs and service-life extension measures for structures in coastal environments after approximately 20 to 25 years of service. Additional information on two of these repair projects is provided in Tepke et al.[19,20]

Service Life and End of Service

Buildings do not last forever. Proper maintenance and implementation of proactive service-life extension measures can significantly extend their useful life. At the end of service, buildings are either strengthened sufficiently to extend service life, decommissioned, or reach an unplanned failure condition. Fortunately, condition assessments can significantly minimize the probability of the latter. It should be recognized, however, that at some point all structures if left in service and not evaluated, will develop potentially unsafe conditions as the end of service condition is approached. This is an important concept that transcends materials (wood, steel, masonry, or concrete). It places the concept of building service life and safety in perspective and reframes the question from "if" to "when." Further, the concept emphasizes the importance of continued diligence. The more important question that must be answered by an LDP evaluating an existing building is, "How far along is this building in its service life?" While this may be answered in the confines of a specific deterioration mechanism, based on averages of information obtained, it is difficult to explicitly determine for a given structure.

There is an increased concern about coastal buildings and parking structures exposed to chlorides, where corrosion of the embedded reinforcement and associated concrete deterioration is often the primary mechanism of deterioration. Many coastal condominiums and high-rises were built in the 1970s, 1980s, and 1990s, making many of these structures 30, 40, and 50 years old at present. Without proper evaluation and maintenance, questions of safety associated with these structures will increase as cracking,

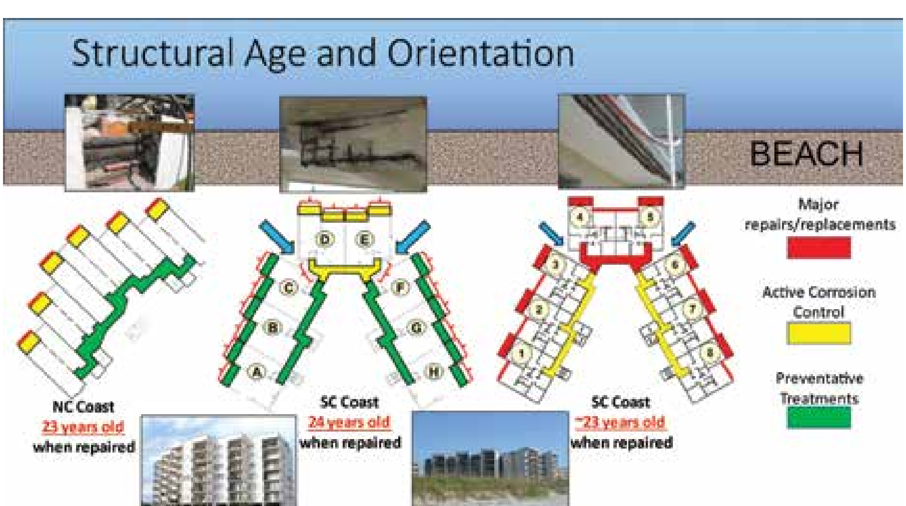

Fig. 6: Required major repairs/replacement and active corrosion control for structures in coastal environments after approximately 20 to 25 years of service

delamination, and spalling occurs. Figure 7 shows a graphical representation of the deterioration of a structure over time. Evaluation, maintenance, and repair of these structures in a timely manner is critical for extending service life and maintaining safe conditions.

Summary

The preceding sections describe some of the challenges and limitations associated with reading the conditions of a structure based upon visual surveys, and when survey results can act as a trigger for a more detailed evaluation. All structures will deteriorate over time and will eventually exhibit signs of aging. Determination of when and how these changes will affect the safety of a structure requires a detailed understanding of how the structure was built, the exposure conditions, and the measures already taken to prolong the service life.

Parts 1 through 3 of this series have described some of the challenges associated with existing structures, trying to examine what is reasonable when evaluating safety. However, the definition of "reasonable" was not provided, as "reasonable" is always conditional on what is known about the structure, the service environment, assumptions of analysis, and the time frame being considered. It is important for LDPs to understand and be able to accurately convey what can and cannot be said about the safety of the structure. It is unrealistic for an LDP to make absolute statements about safety. When one asks if a building or a specific component is safe, considerations must include the probability of failure, the implications of the failure, the duration being considered, and the implications of various assumptions that might be made in analyzing situations inconsistent with standard assumptions for new or undamaged components. Considerations must also include the possibility of hidden conditions that differ from what is known, or construction, service, or exposure conditions that are contrary to what is expected, reported, or determined from sampling.

"Is the structure safe?" or "Is the structure 'reasonably' safe in accordance with industry standards based on the 'reasonable' evaluation possible at this time?" When considering safety, one must consider the probability of an extraordinary event over a period of time and the potential localized conditions as discussed herein. "Is it likely to be unsafe in the next 30 minutes?" is a different question than "Is it likely to be unsafe in the next 6 months?" or "Is it likely to be unsafe in the next 50 years?"

When one asks about safety, one should ask:

- in comparison to…?
- with respect to…?
- in terms of…?
- under the conditions of…?
- with a probability of failure of…?
- in accordance with…?
- for a period of…?

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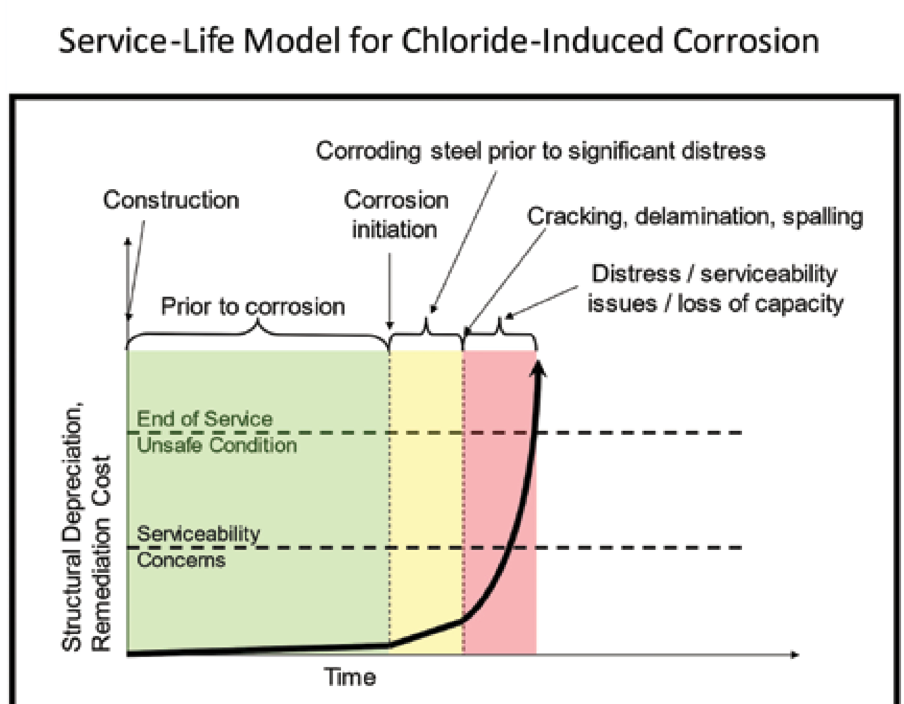

Fig. 7: Graphical representation of the deterioration of a structure over time

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ARTÍCULO

4 CUATRO

"Seguridad razonable" de las estructuras existentes, Parte 3

Lectura de la estructura

por David G. Tepke, Liying Jiang, Keith E. Kesner, y Stephen S. Szoke

La Parte 2 de esta serie se centra en los retos asociados a la disponibilidad de documentación, la evolución de los códigos de construcción y las prácticas de construcción, y cómo afectan estos cambios a la evaluación de la seguridad estructural[1]. El proceso de "lectura" de la estructura suele comenzar con una inspección visual para identificar indicadores de posibles problemas, como grietas, deterioro, deformaciones excesivas o signos de filtraciones (Fig. 1).

Como se describe en la Parte 1 de esta serie, algunos hitos normativos de evaluación de la seguridad se han adoptado en Estados Unidos[2]. Todas estas ordenanzas exigen una evaluación de la estructura, y sólo un número limitado exige algo más que una inspección visual. Sin embargo, la evaluación a partir de un mero reconocimiento visual es una tarea difícil, sobre todo teniendo en cuenta las dificultades que plantean el acceso limitado a los elementos estructurales, el potencial de deterioro no visible y el envejecimiento de las estructuras.

Fig. 1: Filtraciones con manchas de corrosión en una estructura de pórticos de un estacionamiento existente.

El objetivo de la tercera parte es debatir algunos de las complejidades asociadas a la "lectura de la estructura", es decir, el proceso de examinar la estructura, determinar la necesidad de realizar pruebas específicas o evaluaciones adicionales y, a continuación, decidir el camino a seguir. La cuarta parte tratará de cómo los avances tecnológicos pueden aportar nuevas expectativas a las estructuras existentes.

Inspecciones visuales

Las inspecciones visuales son el punto de partida más común en la evaluación de estructuras existentes. ACI CODE-562-21[3], ACI 364.1R-19[4], y SEI/ASCE 11-99[5] proporcionan requisitos y lineamientos para realizar una evaluación inicial de una estructura. Las inspecciones visuales están limitadas tanto en términos de la extensión de la estructura que se puede examinar, como de los tipos de defectos que se pueden identificar. Las inspecciones visuales también requieren discernir la importancia de las grietas y otros "defectos" visibles en una estructura existente. Aunque generalmente no es un requisito, un estudio visual puede complementarse con mediciones de ancho de grietas, mediciones de deflexión, sondeos para detectar delaminaciones u otras pruebas no destructivas con el fin de respaldar preliminarmente las observaciones.

La identificación de peligros y vulnerabilidades potenciales requiere una comprensión del sistema estructural encontrado y de lo que constituye un comportamiento inesperado. En la Parte 2 de esta serie se describen las consideraciones especiales asociadas a las vulnerabilidades de los diferentes sistemas estructurales. El profesional de diseño con licencia (LDP) que completa la inspección visual

Fig. 2: Una viga dentro de la estructura de un estacionamiento: (a) una vista general; y (b) una vista en primer plano de una grieta en la cara de la viga y la losa.

necesita reconocer que el daño tiene diferentes implicaciones dependiendo del sistema estructural y la antigüedad de la estructura. Las estructuras existentes, a través de procesos normales de construcción, servicio rutinario y condiciones de exposición, generalmente tienen algún nivel de "defectos". Los defectos pueden adoptar la forma de grietas, imperfecciones superficiales, degradación del material, variaciones en la geometría de los elementos o en la ubicación de las conducciones, respuesta estructural inesperada u otras condiciones. En la mayoría de los casos, estos "defectos" no afectarán significativamente al uso previsto o a la estabilidad general de una estructura.

Sin embargo, los errores de diseño o construcción fuera de las tolerancias estándar, el uso indebido o no previsto de la estructura, la exposición a cargas o condiciones no tenidas en cuenta en el diseño, o el deterioro debido a un servicio más prolongado de lo previsto en un entorno determinado pueden dar lugar a defectos o daños que pueden ser motivo de preocupación. Tal y como se describe en ACI CODE-562-21, la(s) condición(es) observada(s) durante la inspección visual percibida(s) como "potencialmente peligrosa(s)" o que dé(n) lugar a que el LDP cuestione la capacidad de la estructura o elemento estructural - por ejemplo, la condición observada que es inconsistente con las expectativas del diseño - debe(n) ser evaluada(s) más a fondo. Este concepto se ilustra en las figuras 2 y 3. La figura 2 muestra una grieta "típica" o "esperada" en una viga de concreto. Este tipo de grieta es común en estructuras de concreto bajo condiciones de servicio "típicas". Por el contrario, la Fig. 3 muestra un ejemplo de fisuración atípica del concreto.

Fig. 3: Grietas verticales y delaminación del concreto en una columna.

Aunque los estudios visuales pueden proporcionar indicadores de condiciones inseguras, los elementos estructurales suelen quedar ocultos por la presencia de revestimientos de suelos y paredes, techos, tabiques interiores, revestimientos y recubrimientos exteriores, equipos mecánicos montados en el techo y otros obstáculos. Las deflexiones verticales "excesivas" de los elementos estructurales suelen utilizarse como indicación de daños o de un comportamiento inesperado, pero sólo pueden observarse cuando secciones más largas del vano son visibles. De ello se deduce que, por lo general, una estructura no puede inspeccionarse visualmente en su totalidad, y no es razonable suponer que todas las condiciones que afectan a la seguridad puedan localizarse. La capacidad estructural y la capacidad de servicio de las estructuras de concreto dependen intrínsecamente de la ubicación, la cantidad y el tipo de refuerzo embebido; las propiedades del material también dependen en gran medida de la producción del concreto y de las prácticas de construcción. Por lo tanto, las inspecciones visuales pueden utilizarse para identificar condiciones inseguras, pero no siempre son una estrategia viable para confirmar una "seguridad razonable" para evaluar la seguridad. Los resultados de las inspecciones visuales también suelen desencadenar investigaciones adicionales y otras formas de análisis.

Grietas, defectos visuales y deterioro

Las grietas y otros defectos visuales se observan con frecuencia en elementos de concreto expuestos. Aunque pueden ser una indicación de un deterioro significativo, tales indicaciones también pueden ser el resultado de un movimiento razonable asociado a un cambio de volumen o a pequeños defectos de construcción. ACI 201.1R-086 proporciona una descripción pictórica de los diferentes tipos de fisuración y otros tipos de defectos en estructuras de concreto. ACI 224.1R-07[7], ACI 224R-01[8], y ACI 224.4R-13[9] proporcionan información sobre las causas, control y detallado para la mitigación del agrietamiento, y ACI PRC-201.2-23[10] proporciona información sobre los mecanismos de deterioro relacionados con los materiales que pueden conducir al agrietamiento o deterioro. Cuando se observan grietas y otros defectos en una inspección visual, algunas preguntas críticas que deben hacerse incluyen:

- ¿Son la forma, el tamaño, la frecuencia y la orientación de las grietas coherentes con el comportamiento estructural esperado de la estructura?
- ¿Son los patrones de las grietas, las características de los defectos, los depósitos de efluentes o las manchas asociadas coherentes con un posible deterioro o con mecanismos de daño relacionados con los materiales?
- ¿Representa el agrietamiento o la delaminación una condición potencialmente peligrosa asociada a la caída del concreto, un riesgo de tropiezo o la pérdida de la protección contra incendios requerida?
- ¿Cuáles son las posibles implicaciones futuras del agrietamiento o de los defectos observados sobre la durabilidad o el uso continuado prolongado?
- ¿Miembros similares de la estructura presentan patrones y características de fisuración similares?
- ¿Se han agrietado o han empeorado con el tiempo?

Fig. 4: Esta amplia grieta diagonal cerca de un soporte indica la necesidad de apuntalamiento e investigación adicional.

Fig. 5: Barras de refuerzo corroídas en un balcón (en reparación).

Se deberán plantear inquietudes si las grietas y los daños visuales son coherentes con problemas de comportamiento estructural o representan una reducción de la capacidad debido a un deterioro excesivo. Esto incluye, pero no se limita a, las siguientes condiciones:

- Asentamientos diferenciales, deflexiones excesivas u otras deformaciones. En algunos casos, las grietas de asentamiento en los muros, normalmente más anchas en un extremo que en el otro, pueden haberse estabilizado y sólo es necesario vigilarlas para determinar si se producen asentamientos adicionales. Si el asentamiento crea grietas en las conexiones, puede ser necesaria una mayor investigación y evaluación;
- Las grietas debidas a la flexión o al cortante de los elementos estructurales pueden justificar una investigación más profunda, en particular las grietas más anchas, las grietas indicativas de falla en desarrollo y las grietas en miembros con redundancia

limitada. Un ejemplo de elemento con redundancia limitada es una viga en voladizo. Las grietas de corte, independientemente de la redundancia, requieren una investigación adicional debido a la naturaleza potencial de la falla (Fig. 4);

- Las grietas en losas de piso elevadas que se irradian hacia afuera desde las columnas, combinadas con grietas que rodean la columna, son probablemente una indicación de una condición que podría resultar en una falla por cortante de punzonamiento. Como se ha comentado en la Parte 2, los patrones de grietas que indican la posibilidad de fallo por cortante de punzonamiento deben considerarse como un riesgo notable de fallo catastrófico;
- Las grietas en los elementos de resistencia a fuerzas laterales pueden sugerir deficiencias o condiciones de sobrecarga previas que requieren investigación; y
- Deben investigarse las grietas generalizadas con material efluente, las grietas con manchas de corrosión o las grietas consistentes con problemas relacionados con los materiales que puedan comprometer la integridad general, la calidad del concreto o el refuerzo embebido. El desprendimiento y otras pérdidas de sección de los elementos de concreto y la corrosión y pérdida de sección de la armadura de acero pueden perjudicar significativamente la capacidad de los elementos de concreto para resistir las cargas nominales (Fig. 5). Además de la corrosión y las pérdidas de sección, la presencia de humedad, manchas de agua, manchas de corrosión en el concreto estructural o cerca de él, o acabados que oculten el concreto, pueden justificar una investigación adicional.

Las condiciones descritas anteriormente suelen ser desencadenantes de investigaciones adicionales para determinar cómo se ve afectada la capacidad de la estructura.

Las condiciones exteriores, sobre todo en entornos corrosivos, pueden provocar un deterioro y un peligro que pueden dar lugar a problemas de seguridad. El desprendimiento inminente de secciones de concreto, a veces conocido como desprendimientos incipientes, puede presentar peligros localizados, particularmente cuando pueden ser peligros de tropiezo o de caída por encima de la cabeza. Como se describe en Tepke e Isgor[11] y ACI 222R-19[12], también pueden darse condiciones corrosivas en el interior de las estructuras; por ejemplo, cuando los contaminantes exteriores pueden penetrar en el interior, puede haber una mayor humedad, o pueden existir productos químicos o contaminantes. Por lo tanto, la consideración de la corrosión donde puedan existir estas condiciones no debe descuidarse durante las inspecciones visuales.

Exposición histórica, usos y cambios

Las reparaciones, reformas y ampliaciones pueden afectar significativamente tanto en el rendimiento estructural como en la evaluación. Los documentos relacionados con el mantenimiento, la reparación, la reforma o la ampliación no suelen estar disponibles o lo están de forma parcial. Por lo tanto, puede resultar difícil determinar a través de la revisión de documentos qué trabajos se han realizado después de la construcción inicial, cuándo se hicieron y las posibles implicaciones con respecto al rendimiento del edificio.

Como se ha expuesto en la Parte 2, al evaluar las estructuras deben tenerse en cuenta el estado de la práctica y los códigos de construcción vigentes en el momento de la construcción. También deben tenerse en cuenta las prácticas habituales en relación con el mantenimiento y el uso de los edificios, ya que pueden estar relacionadas con el deterioro de los materiales. Por ejemplo, los cambios en los procesos de las instalaciones industriales o de fabricación (como fábricas textiles e instalaciones de revestimiento y procesamiento de alimentos), o los productos químicos utilizados en estructuras medioambientales o piscinas, pueden influir en la tasa de deterioro prevista.

Cuantificación de defectos, daños y deterioro

La cuantificación de los defectos, daños o deterioros puede resultar difícil. Además de los obstáculos antes mencionados que limitan el acceso para inspecciones visuales o pruebas, la naturaleza variable del concreto, la construcción y las exposiciones pueden conducir a una variedad de condiciones. ACI 228.2R-13[13], ACI 228.1R-19[14], ACI 437R-19[15], ACI 214R-11[16], y ACI 364.1R-194 pueden utilizarse para ayudar a desarrollar un plan detallado de investigación y evaluación. Los planes pueden incluir un estudio visual más detallado, análisis de ensayos o una combinación de estos en un subconjunto o en todas las áreas críticas, dependiendo de los presuntos defectos y el mecanismo de deterioro potencial, la probabilidad de presencia repetitiva en la estructura, el nivel de incertidumbre basado en la revisión inicial, la capacidad de evaluar analíticamente el estado, las limitaciones prácticas (acceso), la exposición y la carga, y el impacto potencial de un fallo localizado en la zona. Los planes de investigación pueden incluir excavaciones, sondeos o visores para evaluar las condiciones identificadas mediante pruebas.

La evaluación de los daños relacionados con los materiales es un ejemplo típico. Aunque el deterioro del concreto puede evaluarse a menudo utilizando las técnicas descritas en la norma ACI 228.2R-13[13], la evaluación exhaustiva de los daños, incluyendo la unión entre la armadura y el concreto circundante, la variación de los daños por capas y la pérdida de secciones específicas de acero oculto (en el caso de la corrosión) puede ser un reto. Los índices de deterioro, incluso si se estiman con cierta precisión, pueden depender en gran medida de las condiciones ambientales y, por tanto, pueden variar. Los daños causados por la corrosión, la reacción álcali-sílice, la formación retardada de etringita u otros problemas suelen requerir pruebas especializadas para su evaluación.

En los casos en que se cuestione la capacidad de la estructura o de los elementos estructurales, puede recurrirse a pruebas de carga de acuerdo con ACI 437.1R-07[17] y ACI CODE-437.2-22[18]. La posibilidad de que continúe el deterioro debe tenerse en cuenta en las evaluaciones posteriores a la prueba de carga.

Evaluación localizada frente a evaluación global

Cuando se intenta comprender la seguridad estructural general, es importante considerar la seguridad del edificio de forma holística, así como los impactos potenciales de daños o defectos localizados. El muestreo aleatorio puede ser adecuado para evaluar la naturaleza general de una estructura, pero es importante tener en cuenta los defectos o daños localizados que pueden ser de naturaleza significativa, especialmente si están asociados a elementos de preocupación crítica, como se ha descrito anteriormente en este artículo y en la serie. Debe establecerse un plan de muestreo e investigación adecuado si existe la preocupación de que las condiciones localizadas puedan afectar a la seguridad.

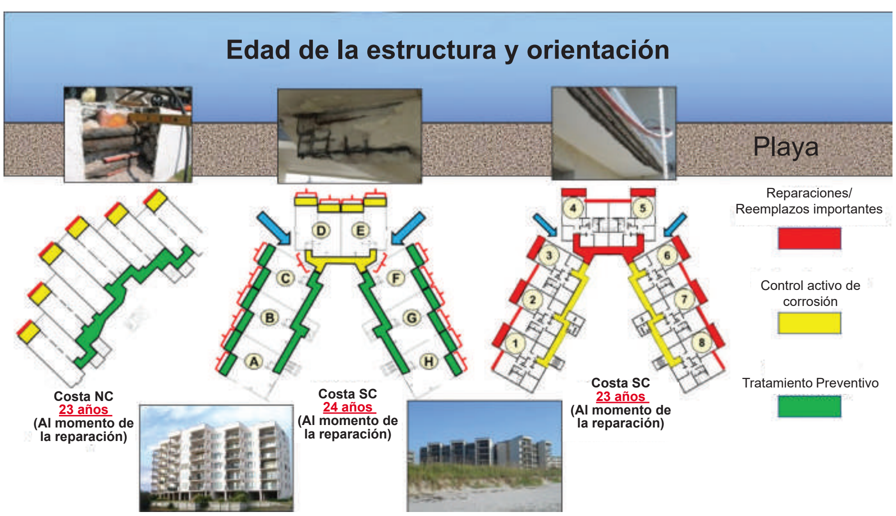

Fig. 6: Reparaciones/reemplazos importantes necesarias y control activo de la corrosión para estructuras en ambientes costeros después de aproximadamente 20 a 25 años de servicio.

La evaluación de la exposición localizada requiere tener en cuenta las posibles condiciones de exposición atípicas derivadas de vertidos, usos u operaciones anteriores en instalaciones químicas, de fabricación o de tratamiento de aguas, así como las derivadas de los patrones de viento, la orientación con respecto a las exposiciones costeras, el blindaje y la altura de los obstáculos de las exposiciones corrosivas. La Figura 6 muestra la variabilidad de las reparaciones necesarias y las medidas de prolongación de la vida útil de las estructuras en entornos costeros después de aproximadamente 20 a 25 años de servicio. En Tepke et al.[19,20] se ofrece información adicional sobre dos de estos proyectos de reparación.

Vida útil y fin de servicio

Los edificios no son eternos. Un mantenimiento adecuado y la aplicación de medidas proactivas de prolongación de la vida útil pueden extender significativamente su vida de servicio. Al final de su vida útil, los edificios se refuerzan lo suficiente como para prolongarla, se desmantelan o llegan a una situación de fallo imprevisto. Afortunadamente, las evaluaciones del estado pueden minimizar significativamente la probabilidad de que se produzca este último caso. Sin embargo, debe reconocerse que, en algún momento, todas las estructuras, si se dejan en servicio y no se evalúan, desarrollarán condiciones potencialmente inseguras a medida que se acerque la condición de fin de servicio. Se trata de un concepto importante que trasciende los materiales (madera, acero, mampostería u concreto). Sitúa el concepto de vida útil y seguridad del edificio en perspectiva y replantea la pregunta de "si" a "cuándo". Además, el concepto subraya la importancia de la diligencia continua. La pregunta más importante que debe responder un LDP que evalúa un edificio existente es: "¿En qué fase de su vida útil se encuentra este edificio?". Si bien esto puede responderse en los confines de un mecanismo de deterioro específico, basado en promedios de información obtenida, es difícil de determinar explícitamente para una estructura dada.

Existe una creciente preocupación por los edificios y estacionamientos costeros expuestos a los cloruros, en los que la corrosión de la armadura embebida y el deterioro del concreto asociado suelen ser el principal mecanismo de deterioro. Muchos condominios y rascacielos costeros se construyeron en las décadas de 1970, 1980 y 1990, por lo que muchas de estas estructuras tienen 30, 40 y 50 años en la actualidad. Sin una evaluación y un mantenimiento adecuados, las cuestiones de seguridad asociadas a estas estructuras aumentarán a medida que se produzcan grietas, delaminación y desprendimientos. La figura 7 muestra una representación gráfica del deterioro de una estructura con el paso del tiempo. La evaluación, el mantenimiento y la reparación de estas estructuras en el momento oportuno son fundamentales para prolongar la vida útil y mantener unas condiciones seguras.

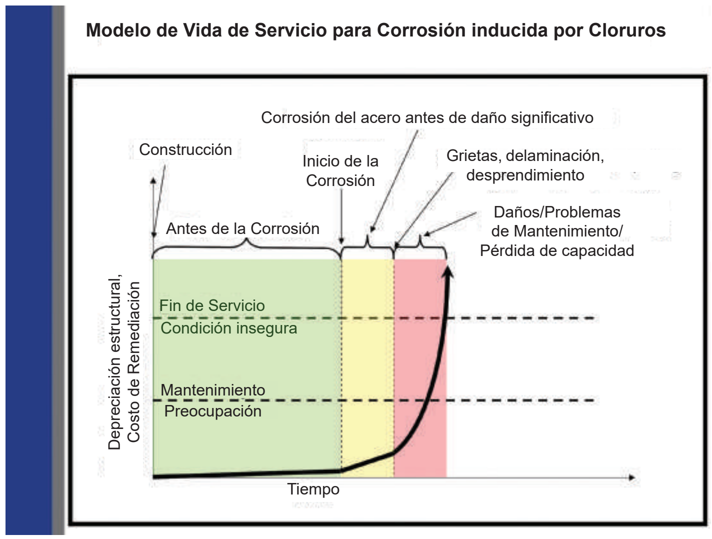

Fig. 7: Representación gráfica del deterioro de una estructura a lo largo del tiempo.

Resumen

Los apartados anteriores describen algunos de los retos y limitaciones asociados a la lectura de las condiciones de una estructura basándose en inspecciones visuales, y cuándo los resultados de la inspección pueden actuar como desencadenantes de una evaluación más detallada. Todas las estructuras se deterioran con el tiempo y acaban mostrando signos de envejecimiento. La determinación de cuándo y cómo afectarán estos cambios a la seguridad de una estructura requiere un conocimiento detallado de cómo se construyó la estructura, las condiciones de exposición y las medidas ya adoptadas para prolongar su vida útil.

En las partes 1 a 3 de esta serie se han descrito algunos de los retos asociados a las estructuras existentes, tratando de examinar lo que es razonable a la hora de evaluar la seguridad. Sin embargo, no se ha proporcionado la definición de "razonable", ya que "razonable" siempre está condicionado por lo que se conoce sobre la estructura, el entorno de servicio, los supuestos de análisis y el marco temporal que se está considerando. Es importante que los LDP comprendan y sean capaces de transmitir con precisión lo que puede y no puede decirse sobre la seguridad de la estructura. No es realista que un LDP haga afirmaciones absolutas sobre la seguridad. Cuando uno se pregunta si un edificio o un componente específico es seguro, las consideraciones deben incluir la probabilidad de fallo, las implicaciones del fallo, la duración que se está considerando y las implicaciones de varias suposiciones que podrían hacerse al analizar situaciones inconsistentes con las suposiciones estándar para componentes nuevos o no dañados. Las consideraciones también deben incluir la posibilidad de que existan condiciones ocultas que difieran de lo que se conoce, o condiciones de construcción, servicio o exposición que sean contrarias a lo que se espera, informa o determina a partir del muestreo.

"¿Es segura la estructura?" o "¿Es 'razonablemente' segura la estructura de acuerdo con las normas del sector basadas en la evaluación 'razonable' posible en este momento?". A la hora de considerar la seguridad, hay que tener en cuenta la probabilidad de que se produzca un suceso extraordinario durante un periodo de tiempo y las posibles condiciones localizadas, tal y como se ha comentado aquí. "¿Es probable que sea inseguro en los próximos 30 minutos?" es una pregunta diferente a "¿Es probable que sea inseguro en los próximos 6 meses?" o "¿Es probable que sea inseguro en los próximos 50 años?".

Cuando uno pregunta por la seguridad, debe preguntar:

- ¿en comparación con...?
- ¿respecto a...?
- ¿en términos de...?
- ¿en las condiciones de...?
- ¿con una probabilidad de fallo de...?
- ¿de acuerdo con...?
- ¿durante un periodo de...?

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“Reasonable Safety” of Existing Structures, Part 4: A New Hope

by David G. Tepke, Liying Jiang, Keith E. Kesner, and Stephen S. Szoke

The first three parts of this series examined the question of what constitutes “reasonable safety” of an existing structure and the limitations associated with the assessment of safety. This final part will provide some parting words on evaluating “reasonable safety” through condition assessments, discuss the impact of paradigm shifts in construction, and explore advancing trends and technologies that will carry the industry into the future, providing “a new (or continued) hope.” The rapid rate of advancement makes it an exciting time to be in the industry!

“Reasonable Safety” or “Likely Unsafe” through Condition Assessments

It should be apparent that the concepts of “reasonable safety” and “likely unsafe” are conditions that invoke uncertainty and subjectiveness in most situations. Consider the schematic cases in Fig. 1 in combination with the continuum of conditions described in Table 2 in Part 1[1] of this series: from increasing certainty of “reasonable safety” (toward the right in the figures) compared to decreasing certainty of “reasonable safety” (or alternatively increasing

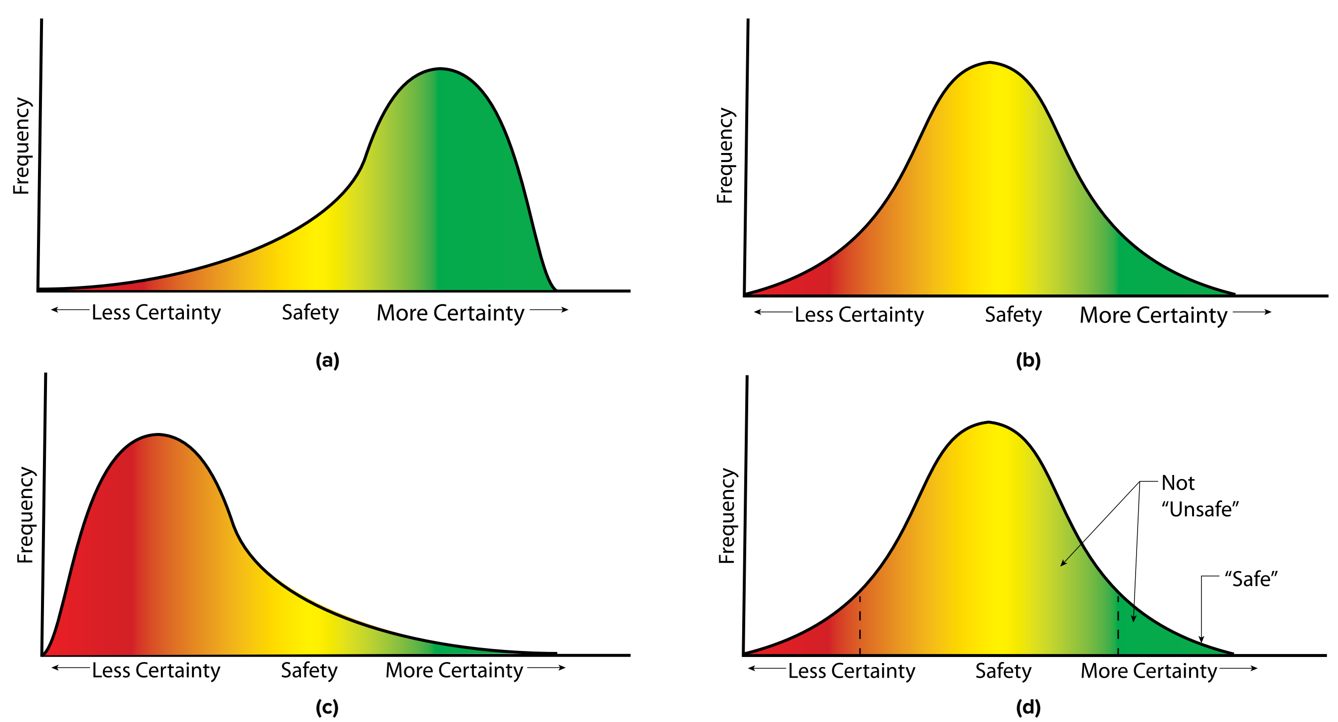

Fig. 1: Conceptual schematics showing certainty of safety based on visual surveys: (a) typical structures with no apparent damage or reason to believe there are deficiencies; (b) older structures with moderate damage; (c) structures with widespread or apparent critical damage; (d) difference in certainty required to conclude a structure or component is “safe” compared to that required to conclude that there is no visual evidence to suggest that a structure is “unsafe”

certainty of "unsafe" conditions) (toward the left in the figures). As shown in Fig. 1(a), new structures or typical structures relatively free of known defects provide a higher level of confidence of safety, represented by the "safe" skew. This is due to greater confidence that the structure was constructed in accordance with contemporary codes and special inspection procedures and has not been exposed to long-term service conditions that may have increased the likelihood of deterioration, the possibility of extreme events, or overload conditions.

For older structures or those with some moderate apparent damage (Fig. 1(b)), one may be less able to conclude safe conditions based on a visual survey until more information is gathered from a comprehensive assessment. Older structures with widespread or known critical damage (Fig. 1(c)) may lead to relatively high confidence that the structure is unsafe and relatively low confidence that one can conclude it is reasonably safe based on a visual survey. This is a shift to an "unsafe skew." In some cases, it may be possible to conclude with reasonable certainty that the structure or components are unsafe based on a visual inspection. This may be the case where there is concrete at significant risk of detachment in overhead areas accessible to the public, there is a partial collapse, structural elements are excessively damaged, or other similar conditions are present. However, there remains some small probability of "reasonable safety" due to possible redundancies or exceedances of expected strength that visual survey may not capture. Figure 1(d) schematically shows the difference between having sufficient evidence to conclude that a structure or component is "safe" compared to not having evidence that suggests the structure or component is "unsafe" based on a visual survey for a typical older building with some moderate damage or deterioration.

The burden of concluding relative certainty of safety is greater than that of concluding that there isn't evidence of "unsafe" conditions (as represented by the areas under the

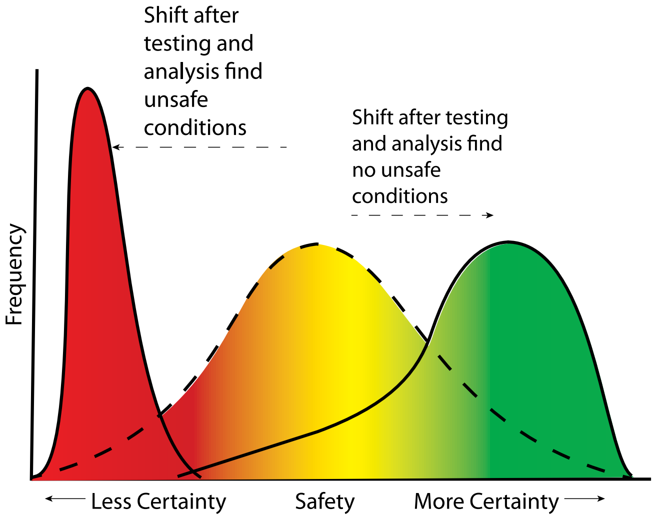

Fig. 2: Shift in certainty of safety after testing and analysis

curves in Fig. 1(d)). With additional testing and evaluation, relative certainty of the condition can be sharpened, thereby improving the confidence that a structure is "reasonably safe" or "likely unsafe." Figure 2 schematically shows the shifts comparing the certainty of visual surveys and the certainty once tests and more thorough evaluations are performed. Note that the shift to "likely unsafe" may be highly acute if a definitive condition is found representing a hazardous condition, whereas a shift to a "reasonable safety" skew through favorable testing and evaluation will still generally have some variability associated with the inability to conclusively evaluate all properties and conditions of the structure that may contain unfavorable hidden conditions.

Impact of Paradigm Shifts in Construction

Trends and technologies for designing new structures, investigating and maintaining existing structures, and repairing and extending the service life of damaged structures change over time. These changes lead to different expectations of norms associated with existing conditions and structural performance. For example, unless there is a construction deficiency, it is not common today for external sulfate attack to be a concern within a reasonable service life, provided that surrounding soil or water was adequately evaluated to establish the exposure condition and the concrete mixture was designed and produced for addressing the exposure. However, unless they are vigilant in studying historical and contemporary trends, practitioners may miss subtle nuances that are contrary to their experiences. A practitioner might conclude that certain types of structures are not prone to damage or certain types of distress because they haven't experienced such damage or distress in their practice.

Paradigm shifts in industry practices require vigilance and receptiveness to changing the way one thinks about or approaches the investigation and repair of existing structures. Table 1 gives examples of paradigm shifts in the industry, the potential assessment bias that can occur, and how each shift may impact the industry in the future.

Paradigms of new construction and the associated implications for subsequent service of existing structures change, and so too must the paradigms of assessing existing structures change to take advantage of technologies and developments. The remainder of Part 4 will discuss some of these expected paradigm changes for evaluating structures and safety.

Recent Trends

Codes, standards, and inspections

Since the 1960s, provisions have been added to building codes to help ensure that buildings are constructed in accordance with construction documents (refer to Special Inspection in Table 1). The need for continuous or periodic special inspection is listed as requirements in Chapter 17 of 2021 IBC.[4] For reinforced structural cast-in-place concrete, the 2021 IBC special inspection provisions include:

verification of the mixture design; fabrication of test specimens; determination of slump, air content, and temperature of concrete; curing techniques and temperatures; and inspection of formwork for shape, location, and dimensions. For reinforcement, placement must be verified. If welded, weldability must be verified and welding inspected. Anchors must also be inspected. There are additional requirements for precast and post-tensioned concrete and shotcrete.

The extent of inspection and special inspection required during the original construction should be considered when establishing a program to investigate the structural integrity of buildings, and where available, special inspection reports may aid assessment efforts. Buildings designed and constructed to recent building codes that include provisions such as those in Chapter 17 of the IBC are less likely to have deviations from construction documents, but structural deficiencies due to

Table 1:
Examples of paradigm shifts, implications, and associated assessment bias

Paradigm shift	Implications for existing structures	Possible assessment bias	Possible future implications
Use of air entrainment in concrete	Prior to the 1960s, ACI's standards and codes did not require air entrainment in new concrete exposed to freezing-and-thawing conditions. Air-entraining additives and testing protocols have advanced over time. Older structures may lack intentional resistance to freezing-and-thawing damage.	Limited: Most practitioners understand the issues and implications of air entrainment and freezing-and-thawing damage in concrete from historical evidence.	Limited
Special inspections	Since the 1960s, provisions have been added to building codes to help ensure that buildings are constructed in accordance with construction documents. In 1967, a few requirements for special inspection appeared in the Uniform Building Code, followed by the first appearance in the 1987 National Building Code.[2] The latter is largely attributed to a report submitted to the U.S. House of Representatives.[*]	Substantial: Inspection requirements for new construction are an integral part of current building codes. Code requirements without a means of enforcement through inspections would do little to satisfy the purpose of the building code, generally understood to include: "…establish the minimum requirements to provide a reasonable level of safety, health, and general welfare through structural strength…"[3]	Limited
Coastal construction	Many coastal condominiums in vacation destinations were built in the 1970s, 1980s, and 1990s. These structures are now 30, 40, or 50 years old and, unless well-maintained, may be at the end or nearing the end of the expected service life without extensive preservation measures.	While it is widely known that coastal structures are susceptible to corrosion and require maintenance and repair, practitioner experience with end of service considerations may be limited, and some practitioners may be less accustomed to considering end of service.	Coastal structures will require extensive preservation, or an increasing number will become structurally deficient or unsafe toward the end of service conditions.
Use of structural integrity steel	Prior to structures governed by ACI 318-89,[4] structural integrity steel was not required. Structures built more than 30 years ago may lack steel intentionally installed for enhanced collapse resistance.	It may be perceived by those who design new structures that older structures have inherent capabilities provided by integrity steel because many design professionals began careers in the 1980s or after.	Some types of older structures in corrosive or aggressive environments may increasingly become susceptible to critical conditions and safety concerns.
Corrosion protection of post-tensioned steel systems	Mid 1950s to 1960s, kraft paper and exposed tendons were used; prior to the late 1990s, less extensive corrosion resistance was required compared to requirements of today. Structures built more than 30 years ago may lack adequate corrosion protection by contemporary standards.	Earlier post-tensioned structures are approaching 50 years old or more, and those with protection less than that of today are approaching 30 years old or more. Perceptions for typical practitioners might be that they have performed well and would continue to do so. However, older structures may not be as durable as they might expect.	Post-tensioned structures in corrosive environments with deficient corrosion protection may become increasingly structurally unsafe unless well maintained during service, protected from deleterious conditions, or rehabilitated and preserved when conditions are identified.

[*]Committee on Science and Technology, "Structural Failures in Public Facilities (House Report 98-621)," U.S. Government Printing Office, Washington, D.C., Mar. 15, 1984, 156 pp. The report discusses the findings and recommendations from an investigation prompted by high-profile failures, including the 1973 Skyline Plaza collapse in Virginia, the 1979 Rosemont Horizon Arena roof collapse in Illinois, and the 1981 Hyatt Regency Hotel walkway collapse in Missouri

Table 2:
A decade of resource development

Year	Designation	Title	Status
2013	228.2R-13	Report on Nondestructive Test Methods for Evaluation of Concrete in Structures	Revision
	440.8-13	Specification for Carbon and Glass Fiber-Reinforced Polymer (FRP) Materials Made by Wet Layup for External Strengthening of Concrete and Masonry Structures	First edition
	562-13	Code Requirements for Evaluation, Repair, and Rehabilitation of Concrete Buildings and Commentary	First edition
2014	222.2R-14	Report on Corrosion of Prestressing Steels	Revision
	364.10T-14	Rehabilitation of Structure with Reinforcement Section Loss	First edition
	546.3R-14	Guide to Materials Selection for Concrete Repair	Revision
2015	364.11T-15	Managing Alkali-Aggregate Reaction Expansion in Mass Concrete	First edition
	364.12T-15	Repair of Leaking Cracks in Walls of Liquid Containment Structures	First edition
	364.13T-15	Repairs for Reinforcement with Shallow Cover	First edition
	440.1R-15	Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer (FRP) Bars	First edition
	440.9R-15	Guide to Accelerated Conditioning Protocols for Durability Assessment of Internal and External Fiber-Reinforced Polymer (FRP) Reinforcement	First edition
2016	562-16	Code Requirements for Assessment, Repair, and Rehabilitation of Existing Concrete Structures and Commentary	Revision
2017	364.14T-17	Section Loss Determination of Damaged or Corroded Reinforcing Steel Bars	First edition
2018	364.15T-18	Significance of the Shrinkage-Compensating and Nonshrink Labels on Packaged Repair Materials	First edition
	364.16T-18	Physical Properties and Characteristics Affecting the Sensitivity to Cracking of Cementitious Repair Materials	First edition
	364.17T-18	How to Measure pH of a Concrete Surface Prior to Installation of a Floor Covering	First edition
	563-18	Specifications for Repair of Concrete in Buildings	First edition
2019	222R-19	Guide to Protection of Reinforcing Steel in Concrete Against Corrosion	Revision
	228.1R-19	Report on Methods for Estimating In-Place Concrete Strength	Revision
	364.1R-19	Guide for Assessment of Concrete Structures before Rehabilitation	Revision
	562-19	Code Requirements for Assessment, Repair, and Rehabilitation of Existing Concrete Structures and Commentary	Revision
2020	546.2R-20	Guide to Underwater Repair of Concrete	Revision
	546.4R-20	Guide for Jobsite Quality Control and Quality Assurance of Cementitious Packaged Materials	First edition

damage, deterioration, inappropriate modifications during renovations, and other causes may still be present and need to be considered during the investigation for evaluating safety.

Paradigm shifts also include new concrete technologies and systems. These shifts create a need for new codes and standards. Table 2 provides an indication of the development of new codes and the revision of existing codes over the last decade to better ensure that design professionals and contractors have the appropriate resources, and owners have a better understanding for appropriately evaluating and repairing structures. Some specific examples of new code development include:

- Structural concrete internally reinforced with glass fiber-reinforced polymer (GFRP) reinforcement is gaining popularity, especially for elements in corrosive environments. ACI CODE-440.11-22[5] was recently published and is referenced in the 2024 International Building Code.[6] The new code is expected to facilitate construction with GFRP reinforcement. ACI Committee 440S, Fiber-Reinforced Polymer Repair and Rehabilitation Concrete Code, is developing a code for repair and rehabilitation using external FRP systems;
- Additive manufacturing using cementitious materials (three-dimensional [3-D] printed concrete) is also gaining popularity. ACI has formed Innovation Task Group ITG-12 on Code Requirements for Construction of Additively Constructed Walls to develop minimum design and construction requirements to aid in the acceptance and use of 3-D printed concrete;
- There is a trend to change the ingredients of concrete to lower its global warming potential and carbon footprint. ACI Committee 323, Low-Carbon Concrete Code, is

Table 2: Continued

2021	PRC-364.2-21	Increased Shear Capacity within Existing Reinforced Concrete Structures—TechNote	Revision
	PRC-364.4-21	Determining the Load Capacity of a Structure When Structural Drawings are Unavailable—TechNote	Revision
	PRC-364.5-21	Importance of Modulus of Elasticity in Surface Repair Materials—TechNote	First edition
	PRC-364.7-21	Evaluation and Minimization of Bruising in Concrete Repair—TechNote	First edition
	PRC-364.9-21	Cracks in a Concrete Repair—TechNote	First edition
	PRC-440.10-21	Fire Resistance of FRP-Strengthened Concrete Members—TechNote	First edition
	CODE-562-21	Assessment, Repair, and Rehabilitation of Existing Concrete Structures—Code and Commentary	Revision
2022	PRC-364.3-22	Cementitious Repair Material Data Sheet—Guide	Revision
	PRC-364.6-22	Concrete Removal in Repairs Involving Corroded Reinforcing Steel—TechNote	Revision
	PRC-364.8-22	Hydrodemolition for Concrete Removal in Unbonded Post-Tensioned Systems—TechNote	Revision
	CODE-440.11-22	Building Code Requirements for Structural Concrete Reinforced with Glass Fiber-Reinforced Polymer (GFRP) Bars—Code and Commentary	First edition
	SPEC-440.12-22	Strengthening of Concrete Structures with Externally Bonded Fiber-Reinforced Polymer (FRP) Materials Using the Wet Layup Method—Specification	First edition
	SPEC-440.5-22	Construction with Glass Fiber-Reinforced Polymer Reinforcing Bars—Specification	Revision
	SPEC-440.6-08(17)(22)	Specification for Carbon Fiber-Reinforced Polymer Bar Material for Concrete Reinforcement	Reapproved
	PRC-440.7-22	Externally Bonded Fiber-Reinforced Polymer Systems Design and Construction for Strengthening Masonry Structures—Guide	Revision
	SPEC-440.8-13(22)	Carbon and Glass Fiber-Reinforced Polymer (FRP) Materials Made by Wet Layup for External Strengthening of Concrete and Masonry Structures—Specification	Reapproved
2023	PRC-228.3-23	What an Owner Should Know about Nondestructive Testing—TechNote	First edition
	PRC-228.4-23	Visual Condition Survey of Concrete—Guide	Revision
	PRC-440.2-23	Design and Construction of Externally Bonded Fiber-Reinforced Polymer (FRP) Systems for Strengthening Concrete Structures—Guide	Revision
	PRC-546-23	Concrete Repair—Guide	Revision

Note: Additional information on documents listed in this table can be found at **www.concrete.org**

developing a standard that may impact mixture designs to achieve low-carbon concrete; and

- A need has been identified for formalizing durability and maintenance requirements to supplement code-required structural requirements for structures where extended service life is needed, the structure is in severe conditions, or both. It is anticipated that this need will be addressed in a durability code being developed by ACI Committee 321, Concrete Durability Code.

These are but a few examples of how codes and standards will facilitate further paradigm shifts as concrete and concrete technology are always advancing to meet ever-changing demands.

Durability in design

When properly designed and maintained to resist deterioration from prevailing exposure conditions, concrete structures are very durable and resilient. U.S. building codes traditionally have not explicitly considered service life as part of the design. Durability provisions included in design requirements coupled with good construction practices have been used to achieve a reasonable design life and level of resistance against materials-related distress. As discussed in Tepke[7] and Part 2 of this series,[8] industry knowledge changes over time, and improved durability requirements are included to address newly discovered issues or better address known ones. Many reinforced concrete buildings built throughout the twentieth century that used older codes are still in service. Maintenance, routine assessments, and where warranted, more in-depth assessments and repairs with service-life extension measures can continue to extend the useful life of these existing concrete buildings, even when the codes and industry norms at the time of construction are not as advanced as more contemporary ones.

The current version of ACI CODE-318-19(22)[9] includes standard durability provisions. While some provisions are in general accordance with state of the practice for addressing particular durability concerns, some are not as enhanced or are less comprehensive for structures where there is a desire for longer-term service life or conditions are severe. For example, ACI CODE-318-19(22) has relatively comprehensive provisions for air entrainment to provide resistance to freezing-and-thawing damage and the use of sulfate-resistant cement to provide resistance to sulfate attack. However, provisions for addressing corrosion of embedded reinforcement in the Code are related to chloride contents in the concrete, water-cementitious materials ratio (*w/cm*), compressive strength, and a more generalized statement of increased protection (Section 20.5.1.4.1):

"In corrosive environments or other severe exposure conditions, the specified concrete cover shall be increased as deemed necessary. The applicable requirements for concrete based on exposure categories in 19.3 shall be satisfied, or other protection shall be provided."

These provisions generally provide "reasonable durability" for most structures and requirements that can generally be accommodated on most projects (including proportioning water, measuring strength as a surrogate for corrosion protection, and measuring admixed chloride levels), and thus are useful for many situations (as is evidenced by the long-term serviceability of many structures). However, some structures in more severe environments, or those requiring longer-than-normal service life may require additional direction, enhanced provisions, more flexibility for using alternative approaches, increased ability to use performance testing, specific consideration for service life, or more comprehensive treatment. It is expected that initiatives such as a more formal presentation of service-life prediction from ACI Committee 365, Service Life Prediction, and the formation of ACI Committee 321, Concrete Durability Code, will provide supplemental direction for increased durability or service life, when levels beyond those in ACI CODE-318 are required.

Durability is also a concept that can be applied to the continued use of structures that might otherwise have been removed from service due to deterioration or an extreme event. Using engineering assessments and proper repairs permits existing buildings to remain functional or even be salvaged after being subjected to extreme distress. ACI CODE-562-21[10] is an example of an industry standard that considers durability and service-life extension of repairs and represents the current formalization of industry information. Provisions for documenting conditions, considering service life, and providing maintenance plans after repairs are included to address durability. Durability is also intimately linked to sustainability, as discussed in the next section.

Sustainability

There has been considerable focus on reducing the global warming potential of new construction. The movement toward the use of more sustainable materials has resulted in alternatives to concrete mixtures with proven track records based on decades of development and use. The long-term durability and serviceability of these innovative concrete mixtures will need to be closely followed as the use of alternative materials in new construction may lead to differences in expected performance and required nuances in assessment or repair of existing structures. This increased scrutiny should provide valuable information to better understand the long-term performance of concrete produced with alternative materials.

While initiatives for reducing embodied carbon and global warming potential have been focused on new construction, there is also a realization that a similar focus is needed on maintaining and extending the life of existing structures.[11-13] The service life of buildings can be extended through appropriate building assessments and execution of repairs, service-life extension measures, and maintenance plans. This is often a more sustainable approach than demolition or deconstruction and replacement. Though the costs of assessments and repairs may at times be extensive and may involve partial or temporary relocation of occupants, they will generally be lower than permanent relocation, demolition or deconstruction, and replacement. Generally, assessment combined with repairs, if necessary, is more environmentally and economically sustainable.

The Winecoff Hotel in Atlanta, GA, USA, is an excellent example of a structure that has been repurposed for extended use through rational application of evaluation, repairs, and renovations. Originally built in 1913, the hotel was completely gutted by fire in 1946. With appropriate assessment and repairs, it reopened as the Peachtree Hotel in 1951, and in 1967, it became housing for the elderly. The Winecoff was left vacant for 20 years and then again, with appropriate assessments and repairs, it reopened as the luxurious Ellis Hotel in 2007.

Advancing Technologies

Recent developments in testing and evaluation

Several technologies and enhancements to existing technologies have been introduced to the industry in the late twentieth and early twenty-first century to aid in condition assessments of existing buildings. Many such advancements are influenced by enhanced processing speed, improved user interfaces, and graphical presentation of data. The multi-array dry point contact low frequency ultrasonic shear wave technique developed in the 1990s (ACI 228.3-2013[14]) has been made commercially available in the past 20 years by multiple manufacturers. The technology, also referred to as ultrasonic tomography, can produce two-dimensional (2-D) or 3-D images for detecting internal flaws (Fig. 3). User-friendly ground-penetrating radar (GPR) systems have also been developed with post-processing algorithms that convert traditional data into more intuitive visual representations for ready interpretation or reinforcing steel location (Fig. 4). Examples of some recent advancements in corrosion testing devices that show promise include contactless corrosion rate testing,[15] use of a flying robot for corrosion potential testing,[16] and electrochemical tomography

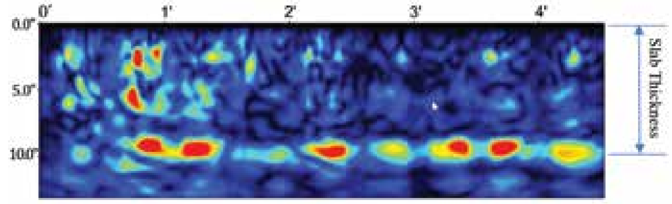

Fig. 3: Ultrasonic tomography of a concrete slab

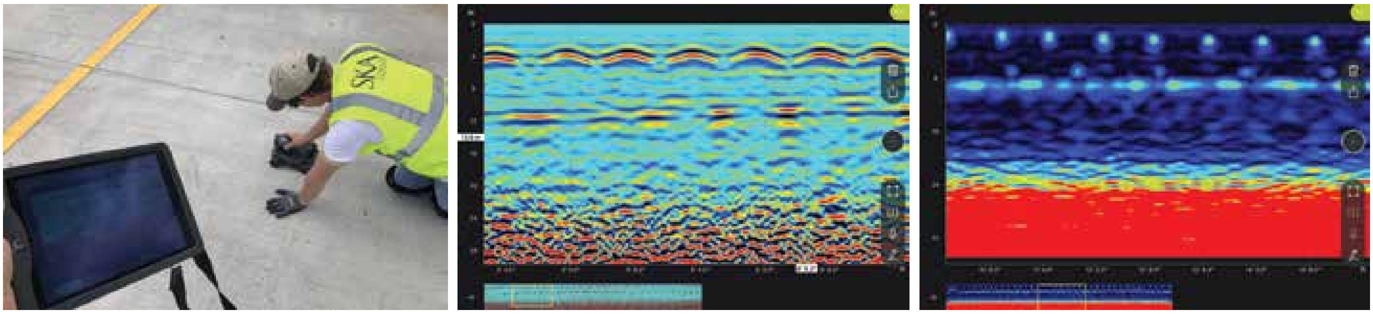

Fig. 4: Representation of reinforcing steel by ground penetrating radar: data collection (left), standard visual representation (center), and processed image showing reinforcing steel location (blue dots) and slab depth (blue line) (right)

for the detection of localized corrosion.[17] Newer advancements include the integration of machine learning and structural health monitoring, as discussed next. While not comprehensive, the listed advancements demonstrate continued progress and a promising outlook for the future.

Building information modeling

Building information modeling (BIM) has become the foundation of digital transformation in the architecture, engineering, and construction industry. BIM helps to optimize design, improve accuracy, and connect design to fabrication, thereby holistically improving the construction quality. BIM software is widely used to create 3-D models that extensively document structural components, connections, and materials for the entire building or structure.

On many projects, BIM is being employed for structural elements. The use of BIM continues to grow, especially for larger projects. Where BIM is used for new construction, the data (3-D model and outputs, including construction drawings) could be a great resource to assist in the assessment of the building when it ages and requires an assessment for structural safety (Fig. 5).

Lidar and photogrammetry

Lidar (light detection and ranging) scanning systems involve laser scanning to produce detailed 3-D images of complex environments and geometries in only a few minutes per scan. The resulting images comprise assemblies of millions of 3-D measurement points combined with photographs. The scan data is processed and registered with a computer to create a point cloud. The point cloud can be shared for viewing, planning, measuring, adding notes, or importing into computer-aided design (CAD) software. When imported into CAD software, a BIM model and drawings can be created from the point cloud of the as-built condition.

Line of sight to the object of interest is the most important factor in capturing scan data. Multiple scans must be taken to work around obstructions. Depending on what is being scanned, it may be necessary to raise or lower the tripod so that areas below and above objects are captured.

Lidar scanning is very useful for producing a 3-D model that reflects the existing condition/geometries from the interior of the building structure, including structural components, equipment, pipes, and any other obstructions. This is extremely helpful for old, existing complex buildings/structures where structural drawings are not available, the structural system is not apparently recognizable, or there is a significant number of obstructions that prevent access to specific hidden areas (Fig. 6). In addition, lidar scanning can also be effective in repair construction planning in terms of correlating the required repair locations, shoring and formwork locations, and obstruction identification/relocations.

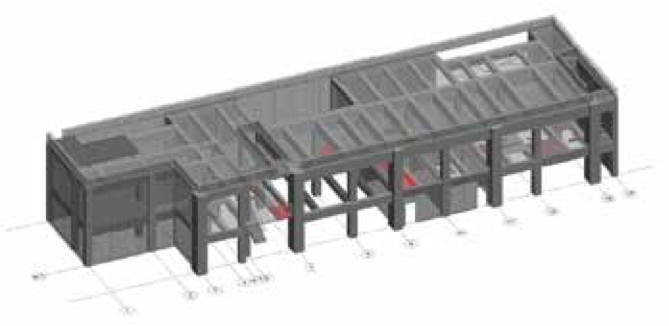

Fig. 5: Three-dimensional model of a building with indicated concrete delamination (shown in red highlighted areas)

With the integrated high-resolution camera, the collected photogrammetric data can also be overlayed on the 3-D model or BIM model, allowing a digital inspection of the existing condition of the structure. This also allows all inspection data to be collected at a sufficient rate so that the inspection could be more frequent while less expensive; alternatively, providing a more in-depth understanding of a structure's overall health, both immediately and over time.[18]

Structural health monitoring

A variety of technologies are available for monitoring structural response, environmental conditions, and deterioration initiation or propagation, with the goal of aiding owners and consultants in determining when actions should be taken to address safety concerns, maintenance issues, or deterioration. ACI PRC-444.2-21[19] lists several technologies currently available, including acoustic monitoring systems for post-tensioned structures, displacement strain and deflection

Fig. 6: Using lidar scanning to capture the condition of an inaccessible area: (a) mounting; and (b) an output

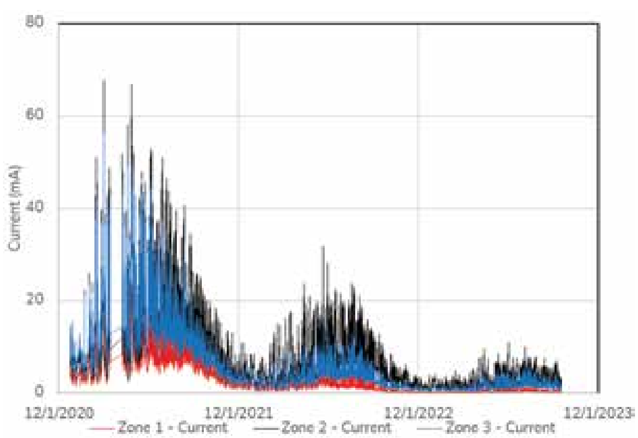

Fig. 7: Current recorded by SHM system in repaired stadium

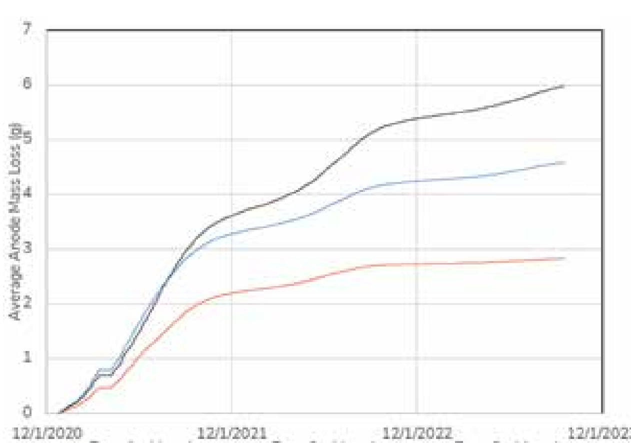

Fig. 8: Anode mass loss calculated from current generation

monitors for evaluating movement in key structural components, and corrosion monitoring for structures in susceptible environments, all components and conditions that can impact structural safety.

Results from structural health monitoring (SHM) can be used to monitor changes in performance or to predict the need for future repairs. Figures 7 and 8 show results from the monitoring of galvanic anodes installed in a stadium structure that was recently repaired. The current generated by the anodes in discrete was recorded by a data logger (Fig. 7). The current generated was then converted into the mass loss in the anodes using Faraday's Law. The anode mass loss over time (Fig. 8) will be used to predict the remaining anode service life. Additional embedded sensors are employed to monitor temperature and relative humidity in the grandstands to examine the expected service life of the applied coating.

Key considerations include selecting the number and locations of sensors to adequately describe the structure. While sensors can be installed in areas of perceived interest for evaluating the structure, there is an inherent risk to relying on sensors for complete information because whole structure monitoring can be difficult or cost-prohibitive. Thus, at present, there is a general need for site inspections. When site inspections indicate a potential issue and more traditional evaluation is done, SHM systems can be used to either augment the existing evaluations or initiate new ones. Significant advancements have been made in recent years with respect to user interfacing, data collection, data management and sharing, for example, in clouds, and minimizing tethering. It is expected that more advancements will follow in these aspects, but also in the applications of artificial intelligence and machine learning for selecting test sites and interpreting data.

Drones

Drones are unmanned aerial vehicles (UAV) that use propellers to fly to a desired position in the air while being controlled by a pilot on the ground. Drones are typically equipped with specialized high-resolution cameras to provide enhanced photographs of places and structures that are expensive, costly, and dangerous to inspect by human access, such as mid- to high-rise buildings or tall industrial structures, such as cooling towers and bridges. UAVs can be used to comprehensively scan exposed surfaces, and the resulting data can be processed to create precision high-resolution imagery and 3-D digital models.

The detailed imagery can be used to identify and measure visual defects, record the results for future use and comparison, determine the overall condition of the structure, and serve as a basis to select areas for detailed field investigation or assessment. It should be noted that an experienced inspector is required to do the digital surveys, as tasks include reviewing the 3-D model and images to identify and categorize defects. Although inspection results such as those shown in Fig. 9 cannot provide comprehensive data suitable for immediate

confirmation of reasonable safety of a structure, they can:
- Allow holistic collection of the defects immediately and over time at a relatively low cost (as compared to by human access);
- Provide comprehensive information on the overall health of a structure; and
- Allow further evaluation on whether an in-depth condition assessment is required to determine the reasonable safety of the structure.

Industrial rope access

Industrial rope access (IRA) refers to techniques by which access is gained to the exterior walls of buildings or other structures by means of ropes. The primary purpose of rope access is to enable access to difficult-to-reach locations of tall buildings or structures without scaffolding, swing stage, or drone that may be restricted to use per Federal Aviation Administration (FAA) regulations.

Rope access first came into use for industrial work in the 1980s. Since then, trade associations such as the Industrial Rope Access Trade Association (IRATA) and Society of Professional Rope Access Technicians (SPRAT) have codified it and made it into a tested, reliable method for getting people into hard-to-reach places to do work. Currently, rope access is typically a means for hands-on inspection on high-rise buildings or tall structures where scaffolding or swing stages are not practical or cost-prohibitive (Fig. 10). In addition to visual survey, additional nondestructive testing, such as acoustic impact survey, GPR survey, or corrosion survey, if considered as part of the evaluation to determine the structural safety, can be performed through rope access.

Machine learning

Machine learning (ML) is the study of computer algorithms that can learn and develop on their own with experience and historical data. ML is used in a broad range of applications, and there has been a recent exponential rise in the use of concrete technology based on a number of pertinent publications.[20] The earliest article identified in connection with concrete and ML was published in 1992.[21]

ML has been used in different fields of concrete technology, and the findings showed that ML techniques can predict the output based on historical data and are deemed to be acceptable to evaluate, model, and predict concrete properties from its fresh state to its hardening, and its hardened state to service life.

From the perspective of the safety of the structure, both durability and service life are necessary parameters that may be forecasted using ML technologies. For example, researchers used data recorded on carbonation for recycled aggregate concrete.[20] The model developed by ML captured the parameters that influenced the carbonation depth and opted to run a specific process that demonstrated exceptional performance in predicting the depth of carbonation, which is a great tool for predicting the durability of concrete that addresses carbonation-related corrosion issues.

ML is being developed for concrete cracking detection, which is one of the important and time-consuming tasks for condition assessment or periodical inspection that may be required for some existing structures. Current research indicates that algorithms can be used to detect cracks in concrete structures. For example, different ML algorithms are being adopted to monitor the concrete structural elements based on real-time sensor acquitted data and color image detection to detect usual cracks in the concrete surface, algorithms were being trained to recognize the patterns of the cracks and identify them accurately, and a deep-learning method is being used to develop an automatic detector of cracks in concrete. In addition, crack propagation in concrete structures can also be predicted using ML and is being studied currently.

The applications of ML in concrete technologies are still in their infancy and challenging; however, the research has been continuously developing. Similar to other advancing technologies, such as drone and lidar technologies, the advancements of ML provide a promising outlook for assisting in the assessment of the safety of the structures.

Fig. 9: Exterior damage can be highlighted on a 3-D model created using UAV photogrammetry

Fig. 10: Industrial rope access from the top of a tall structure

Summary

Design professionals are routinely being asked to evaluate the safety of existing structures, often based upon limited information and with limited access to the structure. This article series examined some of the challenges associated with condition assessments and the need for results to be presented within the context of the assessment limitations.

Since the first applications of structural concrete and subsequently the first design and construction standards, significant changes to concrete and concrete technology have occurred. In the last 50 years, there have been more substantial changes to better ensure new buildings are properly designed and constructed to satisfy the serviceability requirements and reasonable levels of safety, as well as assessment and evaluation of existing buildings and design and execution of repairs. This article discussed the continual advances in concrete and concrete technology for both new construction and extending the service life of existing structures as they pertain to the assessment and evaluation of existing structures.

A better understanding of concrete performance in existing structures, paradigm shifts, revision of existing codes and standards and development of new ones, and acceptance of new technologies all demonstrate that there is new hope to further ensure that structures designed and constructed using structural concrete will continue to reasonably provide for the health, safety, and general welfare of the public for their intended service life and beyond.

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