walls provide attractive enclosures for the MEP/FP chases, serve as bearing walls to support the floor and roof decks, and contribute to the structure's lateral force-resisting system. Openings in the CLT walls and decks were designed and detailed to allow MEP/FP systems to pass through the structure as needed. Electrical conduit buried within the composite CLT decks required additional coordination to maneuver the runs around the composite CLT-concrete shear connectors but allowed for a cleaner-looking ceiling in the end.

A striking example

As one of the larger modern mass timber buildings in the United States, and a first of its kind in Massachusetts, the Design Building uses wood products in new and creative ways to serve as a positive example for future work and provides a collaborative learning space for UMass's design programs. The Design Building offers a striking, first-of-its-kind example of many uses for mass construction methods and successfully provides an inspiring space for students, faculty, and visitors.

Watch videos about design and construction of the UMass John W. Olver Design Building at http://bct.eco.umass.edu/about-us/the-design-building-at-umass-amherst/design-building-videos.

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EVALUATION AND REPAIR OF 100-YEAR-OLD CONCRETE STRUCTURES

CAREFULLY CONSIDER MATERIALS, DETAILING, AND HISTORIC CONSTRUCTION TECHNIQUES TO DESIGN APPROPRIATE REPAIRS.

By David Schnerch, Ph.D., P.E.

THE CURRENT TREND toward revitalization of many cities' downtown districts has resulted in change in use of reinforced-concrete industrial buildings to condominiums or office buildings. Many cities also have bridges and other civil engineering structures that are approaching 100 years in age. Evaluation of these structures is necessary due to this change of use, particularly when additions or alterations result in increased stresses or different load paths. Additionally, repair may be necessitated by the deterioration of reinforcement or concrete over time, variation in the original quality of the materials, or deleterious degradation mechanisms caused using unsuitable materials.

History of reinforced concrete structures

Although concrete technology was developed and used since Roman times, reinforced concrete structures were uncommon in the United States before 1905, but the use of reinforced concrete for large structures quickly became an economic means of construction (Gaudette and Slaton, 2007). Additionally, more and more factories, warehouses, and agricultural facilities began to use this "new" material in the 1910s and 1920s to avoid flammability issues ascribed to timber structures.

Development of standards and material specifications occurred in parallel with increased use of reinforced concrete. The Joint Committee on Reinforced Concrete was established in 1904 before the founding of the National Association of Cement Users (later to become the American Concrete Institute (ACI)) (Kerekes and Reid, 1954) to organize the various entities researching concrete properties, develop uniform methods for analysis and testing, and support research.

The first attempt to develop a code for reinforced concrete occurred in 1907. By the 1920s, codes established by the ACI were being routinely discussed and revised based on the assemblage of applied research and developing industry practice. Additionally, local building codes, such as those available for Boston, New York, and Chicago, provided allowable concrete stresses together with minimum design loads that would have been utilized in the respective jurisdictions.

Concrete reinforcement became readily available beyond 1900 and specifications for these bars were developed by the Association of American Steel Manufacturers in 1910 and were later adopted by the American Society for Testing and Materials in 1911 (CRSI, 2001). Steel reinforcing was available in round and square bars with deformed round bars available from 1/4- to 1-inch diameter and square bars available in 1/2-, 1-, 1-1/8-, and 1-1/4-inch sizes (Figure 1). Wire fabric of cold-drawn steel and other proprietary systems were also commonly available for the reinforcement of concrete floors.

Evaluation of existing concrete structures

The ACI developed ACI 562 (ACI, 2016) to provide minimum requirements for evaluating existing concrete structures and subsequently developing repairs. This document has not yet been adopted as part of the building code but in the interim can be used by design professionals to provide guidance on evaluation of existing and historic reinforced concrete structures. The exact evaluation process undertaken will depend on the planned use for the building, the extent of deteriorated conditions, and the impact of changes to the load path.

Evaluation of a structure generally includes a review of the available

Figure 1: Deformed square cross-section reinforcing bar

documents, if available. Construction documents may provide useful information about the size and spacing of reinforcement, basic geometry, and detailing at connections. Review of historical building codes and standards applicable at the time of construction can also provide information useful to evaluation of the structure.

It is important to consider that changes may have been made during or subsequent to the original construction such that the available construction drawings are no longer accurate. Information about the original construction may have also been lost over time, such that verification of the original structure is required. This may require one or more evaluation methods, including visual inspection, measurement, and ferromagnetic or ground penetrating radar surveys of the reinforcement. Any non-destructive technique to assess conditions that cannot be directly observed at the surface should also be verified by a more limited number of destructive investigation openings that can be repaired as part of a subsequent phase.

The evaluation onsite should determine the extent of problems and the corresponding extent of required repairs. Close-up visual inspection is the most frequently used evaluation technique and provides a great deal of information about the condition of the structure but is limited to exposed and accessible surfaces. Visual observation techniques can be supplemented with mechanical sounding to identify locations of underlying shallow concrete distress, such as delamination occurring due to corrosion of the underlying reinforcement.

Concrete cores may be obtained and tested in compression to assess the concrete strength (Figure 2). Minimum values of concrete compressive strengths are provided in ACI 562. Similar information is available to determine the minimum tensile yield and ultimate strength of reinforcing bars. Tensile testing may be warranted if an accurate assessment of the structural capacity is required.

There are multiple field and laboratory tests that can be applied to historic concrete structures to identify potentially problematic conditions. This includes carbonation testing, chloride testing, and petrographic analysis. Carbonation testing can be used to assess the potential for accelerated corrosion of the reinforcement. Carbonation is a slowly occurring process whereby concrete (in the presence of moisture) reacts with carbon dioxide in the air, thereby reducing the pH of the concrete. Over a century, the carbonation depth may be on the order of several inches depending on the quality of the concrete. If reinforcing bars are present within the carbonated concrete, the protective oxide film normally present in concrete is absent, leaving the surface of the steel potentially active for corrosion.

Chloride testing may be performed using powder or core samples so that the chloride content can be determined at multiple depths. If the chloride content is relatively uniform at each depth, this may suggest that the chloride may have been included as an admixture or introduced through the materials. A decreasing chloride profile with depth would suggest that the chlorides are being introduced over time from the surface by sea spray or deicing salts. Guidelines are available to identify if the level of chloride at the depth of the reinforcement is sufficient to result in corrosion.

Figure 2: Concrete core sampling for corrosion testing

Petrographic analysis of lapped core samples may be used to identify many types of concrete material distress including alkali-aggregate reactions and sulfate attack, among others. It can also be used to qualitatively assess the presence of entrained air. Air entraining admixtures were not developed until the mid-1930s (Portland Cement Association). For older concrete structures or structures where air-entraining admixtures were not used, much of the void structure of the concrete is due to entrapped air rather than entrained, and the ability to resist freeze-thaw distress is diminished.

Common issues

Reinforcement — Corrosion of the existing reinforcement is the most commonly encountered condition in historic reinforced concrete structures. Corrosion of the reinforcement can result in delamination and spalling of the concrete, particularly where the reinforcement has minimal cover. A thorough understanding of the cause of the corrosion and whether the rate of corrosion is likely to increase is important to develop repairs that will reduce the rate of corrosion.

Concrete aggregates and admixtures — Early concrete structures often utilized aggregates found locally. The ability of the concrete to protect the reinforcement from corrosion was not fully understood when reinforced concrete structures began to be widely constructed and sodium chloride present in batching water or fine aggregate was not limited by initial building codes provided that the chlorides did not reduce the compressive strength of the concrete, as can occur at very high concentrations. Calcium chloride was also widely used because it drew moisture from the air to assist with curing and also accelerated the rate of strength increase of the concrete.

Aggregate gradation was not as closely controlled as in current practice. Very large aggregate, including baseball size or above, is sometimes observed in reinforced concrete structures from a century ago, though ACI limited the maximum size of aggregate (the size of which 95 percent by weight of the material can be passed) to not larger than one-fifth of the narrowest dimension between forms or three-fourths of the minimum clear spacing between reinforcing bars (ACI, 1925). Aggregate gradation can also affect the relative proportion of cement paste.

Placement — Placing concrete was performed without internal vibration. As such, consolidation of the concrete through spading or tamping was required periodically throughout the concrete placement. Together with variation in aggregate gradation, this placement method can result in significant regions of voids or honeycombing. Honeycombing can result in discontinuity of the load path if the size of the voided region is significant. Additionally, the voids result in less concrete cover over the reinforcing bars and can cause increased moisture retention.

Construction joints are frequently observed in historic concrete structures at locations where they may not be typically found today. Although available codes required that laitance and unsound material be removed before placing new concrete in contact with previously placed concrete, cracking, leaks, and efflorescence are frequently observed along these joints.

Repairs

There are multiple considerations with regard to repair design. These considerations reflect not only the technical constraints but also the cost and the appropriate level of durability of the repair that is desired by the owner. Too often, the compressive strength, and particularly achieving a high strength at an early age, is given too much importance. While restoring the overall capacity of the structure is important, it is generally not necessary to use very high-strength (and correspondingly high-stiffness) repair materials that are not compatible with the existing historic concrete. The selection process for a repair material must consider the transfer of stresses through the bonded interfaces at the perimeter of repairs, the potential for shrinkage of the repair mortar, and the ability of the new repair mortar to protect the reinforcement.

Reinforcement that is exposed during the repair process may be protected, supplemented, or replaced depending on its condition. There are many methods for protecting existing reinforcing bars from additional corrosion. Each method must be considered based on the properties of the concrete, the exposure of the building to the environment, the current level of chlorides, and the depth of carbonation. Establishing procedures for maintaining continuity of the existing reinforcement must also be considered during the design process, particularly since the use of smooth (or non-deformed) reinforcing bars were much more prevalent.

The aesthetics of the repairs may be of more concern in a historic structure than a modern structure. Irregular boards and light gauge metal forms were frequently used. Modern form materials, which are generally much smoother, may not be appropriate. Use of historically appropriate form materials will result in the repair locations being much less evident but will add to the overall repair cost. Concrete colors can also be adapted if carefully controlled.

Summary

Evaluation of historic concrete structures requires careful consideration of the material, detailing, and construction aspects as reinforced concrete technology was quickly emerging in the last century. A thorough evaluation is necessary to develop appropriate repairs. The longevity of these structures demonstrates the suitability of reinforced concrete as a building material. Appropriately designed repairs should ensure that these impressive structures can be maintained well into the future.

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