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Guide for Evaluation of Concrete Structures before Rehabilitation

Reported by ACI Committee 364

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Guide for Evaluation of Concrete Structures before Rehabilitation

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This guide presents general procedures for evaluation of concrete structures before rehabilitation. Among the subjects covered are: preliminary investigation, detailed investigation, documentation, field observation and condition survey, sampling and material testing, evaluation, and final report. Evaluation to identify seismic deficiencies is beyond the scope of this report.

Keywords: concrete; condition survey, deterioration; distress; evaluation, investigation, rehabilitation; sampling; testing.

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CHAPTER 1—INTRODUCTION

1.1—General

This report outlines procedures for the evaluation of concrete structures before rehabilitation; however, it may also be useful for evaluation of structures even if rehabilitation is not contemplated. These procedures are intended to be used as a guide to assist the architect/engineer responsible for the evaluation. The evaluation work is generally performed for one or more of the following purposes:

(a) To assess deterioration due to exposure conditions;
(b) To evaluate structural damage or distress resulting from unusual loadings, improper design, poor construction, overloads, fire, flood, foundation settlement, abrasion, fatigue effects, chemical attack, weathering, or inadequate maintenance;
(c) To determine the feasibility of changing the use of a structure;
(d) To assess the capacity of a structure to accommodate larger loads;
(e) To enlarge a structure or change the appearance of the structure;
(f) To determine the feasibility of modifying an existing structure to conform to current codes and standards; and
(g) To verify the structural adequacy and integrity of a structure or selected elements within a structure.

The objective and extent of the rehabilitation effort should be clearly defined, thereby providing focus for the evaluation. The owner should be consulted and provided with relative costs for various levels of interference during the evaluation process so that an informed decision can be made as to how to proceed with the rehabilitation work. The cost associated with items, such as interference with normal operations or a complete shutdown of a structure, can easily exceed those of the actual rehabilitation work. Although rehabilitation can often be planned and executed with minimal interference with normal operations, it is usually more cost effective to cease normal operations during rehabilitation work.

There is no absolute measurement of structural safety in an existing structure, particularly in structures that have deteriorated due to prolonged exposure to the environment, or that have been damaged by a physical event. Guidance for the strength evaluation, however, is provided in ACI 318, Chapter 20, Strength Evaluation of Existing Structures. Engineering judgment and close consultation with the owner regarding the intended use of the structure are required in the evaluation of structures. Many repair failures have been observed in rehabilitation projects due to erroneous rehabilitation procedure and or improper judgment.

Due to the many unknowns inherent in evaluating existing structures, it is essential to retain the services of consultants, such as design professionals, experienced in this type of work and possessing necessary registration with the applicable state licensing board. The agencies performing tests of the materials should be experienced in the testing and testing procedures and accredited, if applicable. The technicians should be certified in their field, as applicable to the tests. It is equally important to retain services of an experienced specialty contractor to provide better cost estimates, evaluate the level of disturbance to the users, and the difficulty of work. If competitive bidding is used, consideration should be given to limiting bidding to prequalified contractors with an established record in completing similar rehabilitation projects.

1.2—Definitions

The following definitions are defined herein as in ACI 116R:

preservation—the process of maintaining a structure in its present condition and arresting further deterioration.

rehabilitation—the process of repairing or modifying a structure to a desired useful condition.

repair—to replace or correct deteriorated, damaged, or faulty materials, components, or elements of a structure.

restoration—the process of re-establishing the materials, form, and appearance of a structure to those of a particular era of the structure.

strength—the ability of a material to resist strain or rupture induced by external forces.

The following terms are defined herein for the purpose of clarification and used throughout the balance of this report:

assembly—components of a structure that act together to resist gravity, lateral, and other forces, including gravity frames, moment-resisting frames, braced frames, shearwalls, and diaphragms.

component—the basic structural members that constitute a structure, including beams, columns, slabs, ties, walls, and piers.

condition assessment—conclusions based on engineering judgment about the condition of a structure.

condition survey—quantitatively defining the physical condition of a structure, principally by visual inspection and supplemented by nondestructive tests.

element—a separate, identifiable part of a structure.

evaluation—using the results from investigations and structural engineering principles to derive conclusions regarding a structure's behavior, condition, integrity, and the need for preservation, rehabilitation, restoration, or strengthening.

inspection—the process of using aided and unaided visual techniques to ascertain the physical condition of a structure and extent of deterioration, damage, or distress present.

investigation—collecting and assembling data and detailed information regarding a structure's behavior, condition, and strength, acquired from analyses of documents, surveys, observations and tests, and other means, such as conducting interviews with persons knowledgeable of the structure.

sampling—identifying and removing materials or components from the structure for the purpose of conducting laboratory tests to determine material or structural properties or to further quantify physical condition.

strengthening—increasing the load-resistance capacity of a structure or portion thereof.

structure—the building, components of a building, or other structural system; considered to be concrete in this guide unless otherwise noted.

testing—quantifying material or physical properties of the structure through the use of testing procedures and calibrated equipment, either in the field or laboratory. Testing may be nondestructive or destructive; destructive testing often requires follow-up repair.

1.3—Purpose and scope

The purpose of this guide is to provide general procedures for the evaluation of concrete building structures before rehabilitation. This is of particular importance because there is a substantial difference between the complexity of design to rehabilitate an existing structure, compared with the design of a new structure. Evaluation of specialty structure types, such as bridges, dams, nuclear power plants, and tunnels, are beyond the scope of this report, though the concepts are similar.

This guide presents recommendations based on experience drawn from publications, past investigations, and evaluations. The guidelines provided are general in character, but specific enough for use as a model evaluation procedure for a structure.

This report is presented in the order in which an evaluation would normally be conducted. The first and the most important single effort in evaluation before rehabilitation is the preliminary investigation, as described in Chapter 2. After completion of the preliminary investigation, the detailed investigation can proceed if deemed desirable or necessary. Investigations generally involve three major tasks: locating and reviewing pertinent documents, performing field observations and condition surveys, and sampling and material testing. From the investigation results, evaluation and analysis can be completed and a final report prepared. The flowchart in Fig. 1.1 identifies methodology and major tasks that are commonly undertaken in an investigation, before rehabilitation. In some cases, the pertinent documentation is not available; in those cases, the success of the evaluation is dependent on the experience and judgment of the design professional.

Chapter 2 of this report defines the attributes and uses of both preliminary and detailed investigations in the evaluation process and provides an overview of the report. Chapter 3 identifies those documents and sources of information that would normally be reviewed during the evaluation. The efforts required in performing field observations to verify and survey the structural condition are described in Chapter 4. Chapter 5 provides information on practices and procedures for sampling and material testing, including visual inspection, nondestructive tests, and field and laboratory destructive tests. Chapter 6 discusses the evaluation, including review of the accumulated information and data, interpretation of data obtained from investigations, acceptance criteria for material and structural evaluations, identification and evaluation of rehabilitation alternatives, and costs. Guidelines for preparing the final report are presented in Chapter 7, and references are included in Chapter 8.

CHAPTER 2—PRELIMINARY AND DETAILED INVESTIGATION

2.1—Introduction

The goal of an investigation is to provide information regarding the existing condition of a structure. It should identify the type and seriousness of any apparent conditions affecting the structure's behavior, performance, or intended function. The investigation should also allow the owner to evaluate the feasibility of performing the intended rehabilitation.

Before beginning the investigation, the owner's needs and expectations should be evaluated to determine whether a preliminary or detailed investigation is appropriate. Due to the nature of any investigation, hidden or unexpected conditions may be discovered. As a result, the preliminary investigation may not provide enough information to properly evaluate the concrete structure, and a more detailed investigation may be needed. A written agreement between the owner and design professional contracted to perform the evaluation is recommended, stating the objectives and the scope of work.

The findings of the preliminary and detailed investigations will directly influence the final outcome of the evaluation process, the choices of various rehabilitation methods to be considered, the estimated cost associated with each rehabilitation alternative, and ultimately, the selection of the appropriate rehabilitation method.

2.2—Investigation: overview

Preliminary and detailed investigations often contain varying levels of some or all of the following items:

1. Document review;
2. Field investigation;
3. Sampling and material testing;
4. Evaluation; and
5. Reporting.

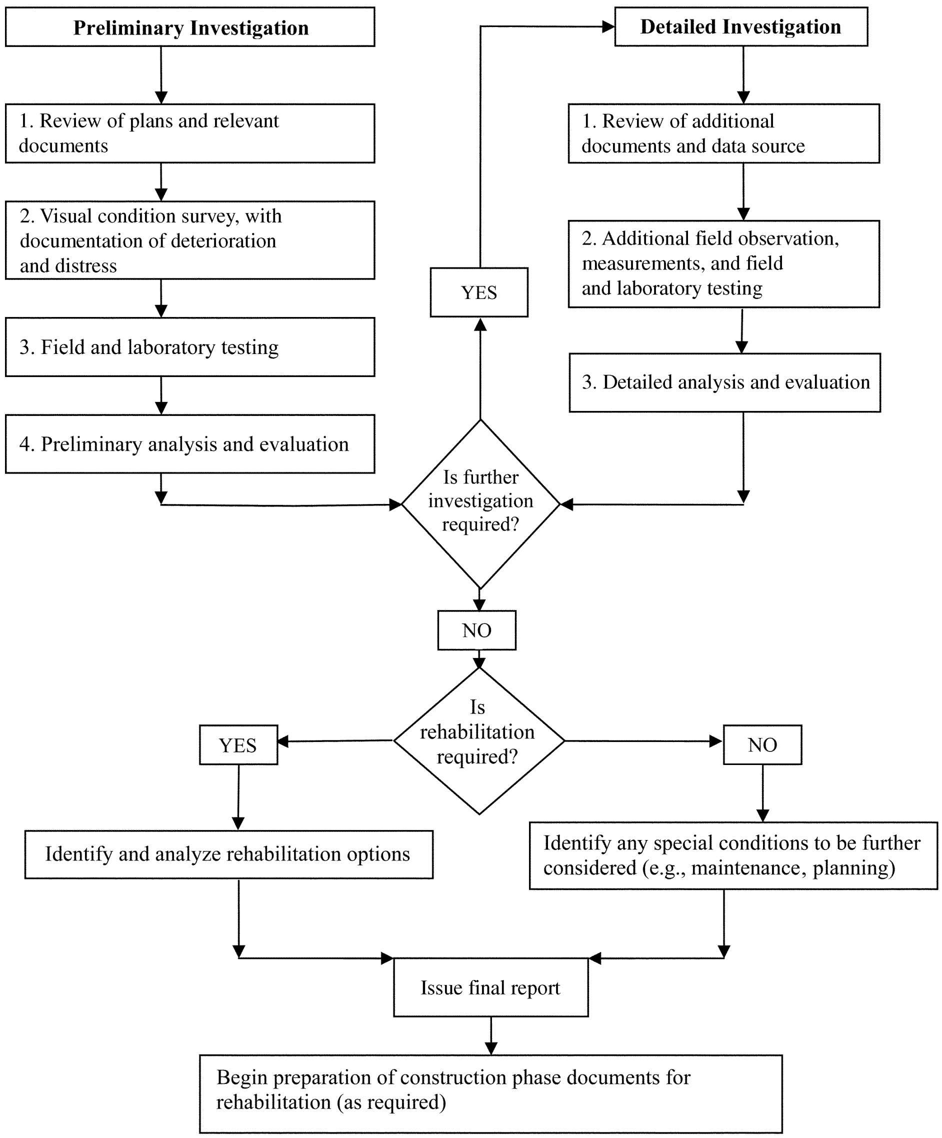

Fig. 1.1—Evaluation methodology.

2.3—Preliminary investigation

The preliminary investigation develops an initial assessment of the concrete structure's behavior, condition, and existing performance based on an established objective or reason for performing the rehabilitation. A preliminary investigation may be sufficient when the proposed usage changes involve the same or similar loadings, where extensive documentation on the construction and maintenance of the structure exist, or where minimal distress or unusual conditions exist. The preliminary investigation may determine that it is undesirable to proceed with a further detailed investigation, as in the case of severe damage where the structural integrity cannot be economically restored or where it becomes obvious that the owner's objectives cannot be satisfactorily met.

A preliminary investigation is not intended to be a comprehensive study. Preliminary investigations are general in nature, and may not be comprehensive enough to achieve the established objective. Preliminary investigations commonly recommend the need for a detailed investigation to more thoroughly evaluate the concrete structure.

A preliminary investigation should, as a minimum, include acquisition of available documents from the owner and known sources, field observation, and measurements of the structure to survey for condition and conformance to documents, and local sampling or testing if found needed (Chapters 3 through 5). In the event that the observations indicate severe distress, the owner should be immediately contacted to provide, at a minimum, temporary shoring or stabilization of the observed component experiencing distress.

2.4—Detailed investigation

A detailed investigation is performed when the initial site visit or preliminary investigation has identified a need for a more in-depth assessment of the concrete structure's behavior or condition to meet the owner's goals for the work and rehabilitation objectives. The detailed investigation may include additional assessment of concrete structure, modification of the investigation strategy, and supplemental technical and economic analyses. If a preliminary investigation was conducted that led to the need for a detailed investigation, it is important to re-evaluate the owner's needs, expectations, and objectives before beginning the detailed investigation. A supplemental written agreement stating the objectives and the scope of the detailed investigation is recommended.

2.5—Document review

It is important to locate, obtain, and review the pertinent documents relating to the structure. A thorough review of the available documentation will save both time and cost for any evaluation and follow-up rehabilitation project. Chapter 3 provides further guidance on the type of documentation needed for various types of structures and where such documentation may be obtained. When original documents are unavailable, the study should begin with special steps to compensate for the missing information. Steps may include nondestructive testing, material sampling and testing, and making detailed documentation of the existing structural system and its condition.

Sometimes it is necessary to search many sources to obtain plans, specifications, shop drawings, construction records, previous investigation reports, or other related information. Especially when older structures are involved, obtaining documents can consume far more time than the actual review. The owner's files, city or library archives, original designers, and original contractors are generally the best sources to search for documents and records. Testing agencies, building management firms, precast concrete manufacturers, or large subcontracting companies are other possible resources for obtaining construction documents. Universities, libraries, historic societies, and state preservation offices may have design documents, construction records, and photographs of historic structures.

A review of the plans, specifications, and other construction records includes checking of critical design details, and understanding the arrangement of critical components, elements, load paths, and the presence of any unusual features. Applicable code requirements at the time of the design should be checked. These can be compared with current applicable codes and standards to determine margins. Critical data, such as loading requirements, capacity, and serviceability, should be reviewed. It is often necessary to determine the in-place physical properties of the existing construction materials. If such information is not available from the available documentation, physical properties can be determined from sampling and testing.

As the document review progresses, field survey drawings should be developed for recording information obtained during the field investigation. Field survey record drawings provide essential information on structural features such as perimeter boundaries, columns, beams, and wall locations and dimensions. If the structure being examined is a multifloor structure, one record document sheet may be developed for each floor. A list of items or questions concerning as-built status, alterations, or possible changes in structure use since its original construction should be developed during the record review process then cross-checked in the field. Alterations to in-service structures are commonly made, and should be carefully noted and evaluated for potential implications to changing load paths or the behavior of the entire structural system.

2.6—Field investigation

An investigation generally documents the nature and extent of observed conditions and identifies any problems and the related components or elements. A walk-through of the structure may be adequate to establish the project scope and to define the project needs. For rehabilitation projects, however, more detailed checks of various items and close examination of representative or typical areas are warranted. Frequency, extent, and severity of problems (for example, deterioration, distress, or nonconformity to documentation) throughout the structure should be recorded.

Assessment of the observed conditions and identifying the need for follow-up and appropriate remedial actions should be documented in a report. Initial impressions often accurately characterize the nature of a problem. If structural problems, such as distress, are suspected, the design professional should use experienced structural engineers for further investigation and evaluation. In general, attention should be given to connections, support regions, areas of abrupt geometric change, and areas in the structure where load concentrations occur. Field notes, photographic records, and videos are valuable aids in classifying and communicating information on the conditions and problems observed in the field (ACI 201.1R; ACI 207.3R; Buchanan 1983). Where unusually severe deterioration or distress is observed, a photographic record of this condition is essential.

When serious distress or deficiencies are discovered that may result in unsafe or potentially hazardous conditions, the owner should be notified immediately. In such a case, temporary evacuation, temporary shoring measures, or other emergency safety measures should be recommended to the owner. Subsequent monitoring of movements, cracks, and progressive distress may be needed.

Even with complete documentation and construction information, field observation is required to verify reliability and accuracy of these documents. Field observations should not only address the as-built geometry and materials of construction, but also the present condition of the structure, its environment, and the loads to which it is subjected. The guidelines for field observation and condition survey are given in Chapter 4.

2.7—Sampling and material testing

In addition to field observation, it may be necessary to employ nondestructive tests on components of the structure or in-place materials to investigate their condition and strength or to take samples for laboratory tests.

2.7.1 *Nondestructive testing*—Nondestructive testing supplements visual observations, and can yield valuable information for decisions regarding further testing and evaluation (ACI 228.2R). For example, nondestructive tests can be used to locate reinforcement as an alternative to exploratory openings. Nondestructive tests, however, should be correlated with testing of samples or exploratory openings to confirm their reliability (ACI 437R). Some of the most common techniques used during preliminary investigation are:

1. Sound testing (hammer testing or chain-drag) to locate shallow delaminations;
2. Cover meters to locate reinforcing steel;
3. Rebound hammer to estimate compressive strength; and
4. Measuring of half-cell potentials to determine corrosion status of reinforcing steel.

It is unlikely that all of these methods will be used during a single preliminary investigation. During a preliminary investigation, usually only select areas of a structure are tested. The results of this testing often help identify locations within a structure where more comprehensive nondestructive and destructive testing are required as part of detailed investigations. Detailed investigations may use more extensive test methods such as pulse velocity, impact-echo, impulse-response, radiography, and structural load testing (in-place). A description of available nondestructive test methods and procedures is included in Chapter 5 of this report and in ACI 228.2R.

2.7.2 *Exploratory removal and openings*—Exploratory removal of material and creating openings are useful to determine as-built conditions and to expose hidden conditions in a structure. Exploratory openings help to determine existing as-built features and to gain reliable information about the nature and extent of existing problems. Selective inspection openings are also used to verify the results of nondestructive tests. During the preliminary investigation, the use of inspection openings are often deferred to the detailed investigation phase.

2.7.3 *Sampling, testing, and analysis*—Physical properties of the construction materials can be obtained through sampling and laboratory testing, if not identified in the construction documents or by observations. Even when construction documents are available, verification of physical properties is recommended. When needed soil or foundation information is missing, excavation and testing of soil properties may also be necessary.

Extensive sampling and laboratory testing is usually not performed during the preliminary investigation. When performed, sampling generally consists of extracting a representative number of concrete cores (ASTM C 42/C 42M), small sawed specimens, or other readily obtainable samples for compressive strength testing (ASTM C 42/C 42M), petrographic examination (ASTM C 856), and others. Powder samples may also be extracted for chemical analysis and determination of chloride-ion content as a function of sample depth from surface. Reinforcing steel samples may be taken and tested to determine properties such as yield strength, hardness, and carbon content, and prestressing steel (pretensioned strands or bars or unbonded post-tensioning tendons) may be carefully removed to assess mechanical properties.

Material testing is often required to determine the existing mechanical properties (for example, strength) and physical condition (for example, alkali-aggregate reaction). The testing may be destructive or nondestructive, and may be performed either in the field with portable equipment or in the laboratory. Chapter 5 describes the types of testing and the methods of sampling that may be performed during the investigation.

2.8—Evaluation

The results of an investigation (document review, field observations and condition survey, material sampling and testing) are considered in the evaluation of the structure. The evaluation should address the need for rehabilitation and feasibility of options, identification of structural distress, structural capacity check, material deterioration, strengthening requirements, and needs for further investigation. Chapter 6 identifies elements that should be evaluated to reach a conclusion to leave the structure as-is, to proceed with the rehabilitation project, to conduct a more detailed investigation, or to choose an alternative plan.

2.8.1 *Structural capacity check*—A structural capacity check is based on the construction documents obtained, results of the investigation, accepted engineering principles, and engineering assumptions (such as those illustrated in ACI 437R). The structural capacity check generally produces one of four conclusions:

1. The structure or its individual components are adequate for the intended use;
2. The structure or individual components are adequate for the existing service loads, but are not adequate for intended use;
3. The structure is not adequate for resisting expected loads or serving the intended use; or
4. The check is inconclusive. Based on the results, a determination should be made regarding the adequacy of the structure and actions to be taken.

2.8.2 *Feasibility of rehabilitation*—An assessment based on technical and cost considerations should determine whether a proposed rehabilitation option is feasible. Points that should be considered in reaching a conclusion regarding feasibility include the expected effectiveness of the rehabilitation, estimated service life, life-cycle cost, and maintenance requirements. The effects of the rehabilitation on the structural system and the anticipated functional and economic impact on the operation of the facility should also be considered.

2.8.3 *Structural distress or material deterioration*—Preliminary investigation, especially for older structures, frequently identifies conditions that may be in marginal compliance with or in violation of current building codes. When structural or material problems are identified, they should be described in terms of their seriousness and extent, along with the steps required to remedy the distress or deterioration. Steps should be taken to verify the significance of the identified structural problems and to determine whether immediate action is required to ensure the safety or protection of the structural system. It is not unusual to encounter problems that require immediate action. In such cases, the owner, or possibly the local authorities, should be notified of the immediate actions needed. In many cases, a detailed investigation is subsequently required to identify the extent of the structural problem and the corrective actions required. It may be necessary to propose immediate action to deal with a condition affecting occupant safety or stability of the structure.

2.8.4 *Strengthening requirements*—Usually, strengthening requirements are not fully addressed in a preliminary investigation. If required, however, various strengthening methods should be considered to satisfy the intended loading requirements and applicable code requirements. The nature of the strengthening, whether temporary or long-term, should be clearly stated. Actions taken to strengthen existing structures should consider the current and possible future operation of the facility. The investigation should also consider the cost effectiveness of repairing, replacing, or strengthening the existing structural components or elements. Both capital cost and future maintenance costs for each strengthening method considered should be compared.

2.8.5 *Further investigation*—The need for a further (detailed) investigation should be identified. Frequently, the end product of a preliminary investigation is the determination that a detailed investigation is required. Issues that can be addressed in planning the next phase of the work include the objectives, cost and time anticipated for the detailed investigation, and the additional data or information required to satisfy these objectives.

2.9—Report

The final report should include the results of all phases of the preliminary or detailed investigation, including the listing of available existing documentation for the structure, field observations, field and test data, and evaluation methodology. The final report should include the design professional's conclusions and any recommendations to the owner on how to proceed with rehabilitation, if required. The report may also include an action plan, rehabilitation options, cost estimates, and tentative design and construction schedules. Guidelines for preparing the final report are included in Chapter 7.

CHAPTER 3—DOCUMENT REVIEW

3.1—Introduction

Before performing an evaluation of a concrete structure, research of all pertinent information should be performed. The purpose of this chapter is to identify the documents and sources of information that should be reviewed during the evaluation of concrete structures before rehabilitation. This review process allows the design professional to become familiar with the structure before performing the evaluation and minimizes the assumptions required to properly evaluate the structure. The conditions observed during the document review should be verified during the evaluation of the structure. Details of the rehabilitation project and the type of structure being rehabilitated will dictate the nature and quantity of information that should be reviewed. In some cases, no documentation is found and a detailed investigation will be necessary.

3.2—Design information

For the purposes of this guide, the structures are categorized as nonhistoric structures and historic structures. An historic structure is a structure that is at least 50 years old and is associated to a significant historic event or significant individual.

3.2.1 *Nonhistoric structures*—Documents that may contain useful information include:

(a) Design drawings, specifications, addenda, and calculations;
(b) Shop drawings;
(c) Placing drawings of concrete reinforcement;
(d) Alteration plans, addenda, submittals, and change orders;
(e) As-built drawings, photographs, job field records, test data, and correspondence;
(f) Applicable building code(s) at the time of original design;
(g) Manufacturer's technical information, descriptions of construction materials, patents, and test data;
(h) Textbooks written at the time of design;
(i) Previous maintenance, inspection, and repair reports; and
(j) Design and applicable age-appropriate building codes.

Information regarding original construction or alteration plans may be obtained from the owner, the architect or engineer, local building departments or regulatory agencies for the governmental entity in which the structure is located, the general contractor, the subcontractors, the fabricators, and the suppliers. Local building departments' records may be valuable in locating alteration plans and other related records (such as inspection reports or violation notices). The assembly of all this information can be time-consuming, but it is extremely important for completion of the evaluation and subsequent success of the rehabilitation project.

3.2.2 *Historic structures*—Buildings may be designated as historic structures on multiple levels—federal, state, or local—with each entity establishing their own restrictions on the extent of required preservation and rehabilitation. Often, rigid rules need to be carefully studied and followed.

When working on historic structures, it is important to relate the structural system used in the project to the design practices existing at the time of construction. Fortunately, on many older structural designs, there is a substantial amount of available information. Reinforced concrete designs were often developed in a competitive commercial atmosphere. As a result, there were many reinforcement systems, including many reinforcing bar deformation patterns that were protected by patents and were illustrated in catalogs. Not only were design calculations often presented in tabular form, but often the strength of the system was validated by load tests, and the results of tests included in the catalogs. Early textbooks and handbooks also included much of this information, and are especially helpful. Newspaper clippings and old photographs may be helpful during the process of planning for the preservation of historic structures.

Documents that may contain useful information for historical structures are similar to those noted previously for nonhistoric structures, along with the following additional documents:

1. Historic American Building Survey (HABS) (U.S. Department of Interior 2007) documents;
2. State and local historical society records;
3. Historic photographs; and
4. Archives for the architect and structural engineer.

HABS (U.S. Department of Interior 2007) has drawings and reports on many historic buildings (McKee 1970). HABS publishes an index of all drawings that are stored in the Library of Congress. The state historic preservation office may also have drawings and reports.

Much of the general information on early concrete systems can be found in the *History of Concrete* (ACI Committee 120 1982) and in CRSI EDR48.

3.3—Materials information

Information on materials may be available, especially for more recently constructed structures, from the following:

1. Submittals delineating concrete mixture components, proportions, and test results;
2. Mill test reports on cement, reinforcing and prestressing steel;
3. Ready-mix supplier historical data on specific mixtures used; and
4. Material specifications and drawings, including those prepared by design professionals and material suppliers for use in placing their products in the original construction.

3.4—Construction information

Various original construction documents may have been retained and are helpful in documenting the construction methods, materials, and any problems encountered during construction. This information is valuable in the rehabilitation investigation process. The following records may be sought:

(a) Correspondence between members of the construction team, design team, and owner or developer;
(b) Results of tests on fresh and hardened concrete;
(c) Quality control data and field inspection reports;
(d) Diaries or journals kept by the construction team;
(e) Job progress photographs;
(f) As-built drawings;
(g) Survey notes and records;
(h) Reports filed by building inspectors;
(i) Drawings and specifications kept on the job, including modifications and change orders;
(j) Material test reports for all structural materials used; and
k) Information concerning the foundation and soil-bearing capacity, including:
  - Geotechnical reports prepared before construction;
  - Allowable pressures and foundation type used in the design;
  - Soil and foundation work, including backfill and compaction conducted during construction; and
  - Location of the water table during construction.

Pile-driving records and pile cap modification drawings may be helpful. The soils and foundation records may be useful when foundation loadings are to be increased during the rehabilitation or whenever foundation settlements have been noted. Local geotechnical engineers may be aware of geotechnical and groundwater information for recently built and adjacent structures.

Other possible sources of information regarding recently constructed structures may be the construction superintendent and the owner's representative. More information can often be obtained through a personal interview with involved personnel (for example, the concrete superintendent). Local newspaper and trade publications may also have provided coverage of the original construction.

3.5—Service history

Documents that relate to the structure's service history should be reviewed to learn as much as possible about the maintenance of the building and any distress, damage, deterioration, and subsequent repairs that have occurred. The types of information that may be available include:

(a) Records of current and former owners, or users of the structure;
(b) Maintenance, repair, and remodeling records;
(c) Reports from past consultant inspections;
(d) Reports maintained by owners of adjacent structures;
(e) Weather records;
(f) Interviews with operation and maintenance personnel;
(g) Logs of seismic activity or geologic activity;
(h) Insurance reports and records of damage to the structure by fire, wind, snow, overloads, earthquake, or fatigue;
(i) Information on operation, occupancy, instances of overloading, and load limits;
(j) Records from government or local building departments or departments of licenses and inspection, including inspection reports and reports of violations;
(k) Photographs; and
(l) Local newspapers and trade publications.

3.6—Project documents

All documents obtained should be organized into a set of files. The files should identify the origin of the documents, the data obtained, and the range of dates for the documents included; this information should be listed in the final report bibliography. Copies of all documents should be made available to the owner for their information. All pertinent information that may be beneficial to the rehabilitation project should be made available to the contractor selected for the rehabilitation project.

When original documents are not available, the survey should compensate for the missing information, such as by recording of accurate dimensions for structural components and presence of reinforcing steel through use of pachometers or by direct inspection after cover removal.

CHAPTER 4—FIELD INVESTIGATION

4.1—Introduction

Once the available design, construction records, materials information, and service history of the structure have been collected and reviewed, the next step is to perform a field investigation. The investigation includes observations to verify the accuracy of previously obtained information along with a condition survey to assess the physical condition of the as-built construction.

The field investigation can be divided into the following three major tasks:

1. Preparation and planning;
2. Verification of as-built construction; and
3. Condition survey of the structure.

The extent of each of these tasks should be based on the type, size, complexity, age, and intended future use of the structure, and the scope of the rehabilitation project.

4.2—Preparation and planning

Planning for the preliminary investigation usually begins with a meeting with owner's representatives to discuss building history, known conditions, maintenance concerns, schedule and scope of the survey, access to the facility, impact of the observation and survey on the structure as well as the users of the facility, and the expectations of the owner. Vehicular traffic may have to be rerouted and/or parking spaces may have to be cordoned off temporarily in garage structures to accommodate survey and testing operations.

Preliminary planning should also include a review of the site to establish general site conditions and determine if special access equipment or permits are required, if any finishes have to be removed for access, if services of subcontractors are required to provide the appropriate means of access, or if specialized inspection services, such as rigging or underwater inspection, are required. In addition, photography or video-recording of critical areas should be made during the field observations to assist in planning of equipment access and inspection methodology, and for documentation reasons.

The scope of the field observation task is, in part, dictated by the availability of funds and time, but should be sufficient to include relevant information consistent with project goals. Before a detailed field observation and survey is undertaken, the conclusions of any preliminary investigation should be reviewed thoroughly. Additionally, the available documentation should be reviewed to determine the type and extent of information that needs to be obtained or verified during field observation (see 3.6). In planning these tasks, procedures and appropriate forms should be developed to document information obtained in the field. Various methods of nondestructive testing (ACI 228.2R) and measurement equipment should be used to supplement visual observations.

4.3—Field verification of as-built construction

4.3.1 *Geometry and structural materials*—Spans and cross sections of the structural components and elements should be measured, particularly at critical locations, because as-built conditions can vary considerably from those shown on available drawings. Variations encountered may be due to subsequent design modifications or field changes. In particular, unrecorded alterations may be the cause of reduced strength of the structure. It is essential that location and size of openings in structures and holes through components be measured and recorded. Recommendations for further investigation and subsequent repair may be required to fully understand any changes to the original design of the structure.

To supplement field observations, the following nondestructive testing methods can be used:

1. Sounding or chain drag (ASTM D 4580);
2. Reinforcing steel cover meter (pachometer);
3. Ground-penetrating radar (extrapolation of ASTM D 6432);
4. Impact echo (ASTM C 1383);
5. Ultrasonic pulse velocity (ASTM C 597);
6. Penetration resistance (ASTM C 803/C 803M and C 805); and
7. Corrosion potential (ASTM C 876).

If the original construction reinforcing details or original shop drawings are available, the nondestructive testing methods can be used to verify original construction or repair information at several random locations (ACI 228.2R; Carino and Malhotra 2004). When original shop drawing details are unavailable, nondestructive testing methods may have to be used extensively to establish existing conditions, such as reinforcing steel size and spacing at critical sections. An adequate number of tests at selected locations establishes a reliable estimate (ASTM E 122). To confirm the testing, the results should be verified with field measurements by removal of concrete cover at selected locations.

Nondestructive testing can identify existing conditions, such as the potential for embedded reinforcing steel corrosion, the presence of delamination, or cracking. Nondestructive testing can also estimate the concrete strength and overall concrete quality. Results of nondestructive tests are valid when supplemented by a limited number of destructive test procedures to verify their accuracy.

Exploratory removal of portions of a structure may be required when nondestructive tests indicate an internal void or region of honeycombing that may not be visibly evident on the surface. Removal and replacement of portions of a structure may necessitate the installation of temporary shoring, both requiring the services of a subcontractor.

4.3.2 *Loadings and environment*—The loads, soil pressures, and environmental conditions acting on a structure may be different from those assumed during the original design. During the course of the field survey, it may be necessary to determine the structure's load history, relying upon any available documents such as those for previous renovations. A comparison can be made between loadings present during the survey and those stated on record documents. The survey should note any changes that can affect the load-carrying capacity of the structure.

4.3.2.1 *Dead loads*—Differences between design and actual dead loads may arise from variations in the dimensions of the structure, use and modification of the structure, from load transfer resulting from physical changes in structural components (for example, change in density and moisture content of the construction materials can affect stiffness), or deformation. Alteration of architectural aspects, such as the addition of partition walls, recladding or changes in façade construction, or addition of nonstructural elements or penetrations, can also affect the dead loads.

4.3.2.2 *Imposed loads*—Because the imposed loads depend on occupancy use, a full description of current and proposed uses should be obtained from the owner. The imposed loads acting at the time of the field observation should be documented. Code requirements for wind, snow, and seismic loads may have increased since the structure was designed. Both static and dynamic effects of the imposed loads should be considered in the evaluation, so the field observation should also note conditions that can affect dynamic response. A partial list of imposed loads is offered for consideration; this list is not comprehensive, but rather, intended as an example of additional loadings to be considered:

1. Warehouse and storage loads;
2. Equipment and machinery operating loads;
3. Snow and ice loads, including effects of drifting;
4. Thermal loads and differential thermal effect;
5. Seismic loads;
6. Impulse/impact loads (for example, effects of traveling cranes); and
7. Time-related change to prestressing steel tension.

4.4—Condition survey and visual inspection

ACI 201.1R should be followed in surveying the condition of the concrete. The condition of a structure should be surveyed without prejudging the cause and type of any deterioration identified. The experience of the design professional in assessing a broad range of concrete distress/deterioration minimizes the potential for missing or misdiagnosing conditions, as well as avoiding unnecessary effort to locate deterioration that may not be present. Therefore, the survey should describe the conditions adequately so they can be evaluated objectively. Photographs and videos can be valuable in this regard.

The condition survey should document the approximate extent and severity of any distress or deterioration, especially that which could adversely affect the strength, durability, or service life of the structure. Previously repaired or modified portions of the structure should also be included in the survey. The survey records should be supplemented with appropriate sketches, photographs, and videos. Conditions listed as follows should be identified, measured, and recorded using the guidelines in ACI 201.1R and the Concrete Society technical standards No. 22, 32, and 54 (Concrete Society 1992, 1989, 2001):

(a) Measure and record crack width, depth, length, location, and type (that is, whether structural or nonstructural). Structural cracks should be further identified as flexure, shear, or direct tension, if known. Crack patterns should be plotted and a determination of whether the crack is actively moving or dormant should be made. Refer to ACI 224R, 224.1R, and 224.2R for further information;
(b) Surface defects such as spalling or delamination due to distress or corrosion of embedded reinforcing steel, scaling, honeycombing, and efflorescence;
(c) Corrosion of reinforcement, including the extent and amount of reduced cross section;
(d) Loose, corroded, or otherwise defective connectors for precast concrete elements, or ties to architectural elements or cladding;
(e) Permanent or transient deformations, out-of-plumb columns, and other misalignments. Continuous monitoring may be appropriate;
(f) Signs of foundation settlement or heave and related distress;
(g) Water problems, such as leakage and areas of poor drainage or ponding;
(h) Evidence of physical or chemical deterioration due to chemical or environmental attack;
(i) Erosion of concrete matrix (washing out of cement and fine aggregate); and
(j) Other concrete material problems, such as, alkali-aggregate reaction or scaling.

4.4.1 *Visible deterioration*—It is generally difficult to quantify the visible deterioration because it depends on subjective criteria and experience. Moreover, deterioration that is acceptable in one circumstance may not be acceptable in another. Therefore, guideline descriptions should be established before surveying begins for a consistent representation and understanding of the significance of the damage. Survey descriptions such as the following may be used:

1. Unsafe or potentially hazardous;
2. Severe distress or deterioration;
3. Moderate distress or deterioration;
4. Minor distress or deterioration; or
5. Acceptable or good condition.

Sketches, photographs, videos, measurements, and brief descriptions should supplement the condition survey using the preceding descriptions. The extent and severity of deteriorated areas with respect to the entire structure being surveyed should be noted. For example, if spalling of a concrete beam is recorded, it is important to note the location and extent of the spall and the condition of the beam in unspalled regions.

4.4.2 *Visible deviations and deformations*—Visible deviations of components or elements from the intended location and size should be measured and recorded. Appraisals of deviations are often guided by comparisons with neighboring or adjacent structures or components or elements thereof. For example, deviations from the vertical or horizontal in excess of approximately $L/240$ are likely to be noticed where L represents the span length. For horizontal components, a slope exceeding $L/50$ (1/4 in./ft) would be noticeable, as would a deflection-length ratio of more than approximately $L/240$.

4.4.3 *Foundation settlement*—The field investigation should include a survey of any foundation settlements. The movements, tilts, and separations of structural elements and cracks that result from differential settlements should be measured and recorded. Before commencing the field investigation of foundation settlement, the existing foundation design drawings should be reviewed for type of foundations, types of soils, design water table, surrounding terrain, site drainage, and adjacent structures.

The field investigation should note any changes in the water table, any signs of erosion and scour, and the addition of structures or other construction, such as underground storm sewers, in the vicinity. If signs of differential settlement are present, it may be necessary to carry out a more detailed geotechnical investigation to fully consider the impact of the observed conditions.

4.5—Unsafe or potentially hazardous conditions

When conditions that appear to be unsafe or potentially hazardous are discovered at any point during the field investigation, the owner should be immediately notified of the potential consequences of these conditions. Temporary evacuation, temporary shoring measures, or other emergency safety measures may be recommended until an investigation can be completed.

CHAPTER 5—SAMPLING AND MATERIAL TESTING

5.1—Introduction

This chapter contains information on practices and procedures to investigate the condition and properties of structural materials that characterize the behavior of the structure (for example, load testing). These practices and methods include visual inspection, nondestructive tests, and destructive tests, which include field and laboratory procedures.

5.2—Determination of testing requirements

The requirements for testing will depend on the findings of the preliminary investigation, the study of available documents, and the proposed rehabilitation. There may be no need for testing where the available documentation is sufficient to complete the evaluation with confidence. A structure that is observed to be in sound condition and without defects, and one where the dimensions measured in the field are consistent with record documents, may allow analysis to confirm suitability for its use without a sampling and material testing program.

Requirements for testing arise where there is inadequate information about the materials in a structure or where deterioration or deleterious materials are suspected.

Tests can both evaluate the strength of existing concrete and locate flaws/defects in concrete structures (ACI 228.1R; ACI 228.2R). The selection of appropriate test methods requires an assessment of the size and number of tests needed to produce a statistically valid sample size (see Table 5.1). Strength testing of core samples will be needed to correlate with strength test results from nondestructive testing methods. Appropriate experience is necessary so that the required tests are performed properly and interpreted correctly. In some circumstances, the cost of testing can be so high as to obviate rehabilitation as an economical solution.

The selection of the suitable test methods (ACI 228.1R; ACI 228.2R; ASCE 11) and the number of tests and their locations will depend on:

1. Variation in material properties within the structure;

2. Variations in exposure, loading, and use;

3. Critical locations, such as connections and lateral load-transfer points;

4. Probable error in a test result;

5. Extent of the structure over which a property is measured; for example, ultrasonic-pulse-velocity measurements indicate the average wave speed through the entire depth of a component, whereas testing on a core sample measures only the condition of the material in the core.

ACI 437R provides insight on the selection of test methods and locations where investigation into the strength and deformation properties of a structure, its elements, or components are needed.

5.3—Testing and evaluation

Evaluation of existing concrete should be based on strength, deformation, and quality properties of the structure as derived from field tests or laboratory tests on samples removed (ACI 228.1R; ACI 214.3R; ACI 437R; NRMCA 1999; Concrete Society 1989). Proper assessment and subsequent evaluation should provide an understanding of the structure's ability to sustain the loads and environmental conditions to which it is subjected (Mather 1985; Hookham 1994).

5.3.1 *Evaluation procedures for concrete*—Table 5.1 (adopted from ACI 228.2R) shows a summary of test methods used to evaluate concrete properties. This table should be used as a guide by the investigator. Before using a test, the investigator should be familiar with the test method and the accuracy and limitations of the test method.

5.3.2 *Evaluation procedures for steel reinforcement*—The properties and physical conditions of steel reinforcement, as tabulated in Table 5.2, should be considered in evaluating the acceptability of the embedded steel reinforcement.

5.4—Test methods

In Tables 5.1 and 5.2, properties of interest are presented with test methods (primary and secondary) presented along with an explanation of their requirements, advantages, and limitations (Thornton and Alexander 1987; Mathey and Clifton 1988; Carino and Malhotra 2004; ACI 228.2R; ASCE 11).

5.5—Sampling techniques

5.5.1 *Concrete*—Concrete samples can be tested to determine strength as well as physical and chemical properties, as discussed previously. It is essential that the samples be obtained, handled, identified (labeled), and stored properly to prevent damage or contamination (Stowe and Thornton 1984).

Guidance on developing an appropriate sampling program is provided by ASTM C 823. Samples are usually taken to obtain overall statistical information about the properties of concrete in the structure or to characterize some unusual or extreme conditions in specific portions. In the first case, sample locations should be randomly distributed throughout the structure. The number and size of samples depend on the number of laboratory tests to be run and the degree of confidence desired.

The results of the preliminary investigation should be considered before a detailed sampling plan is prepared. Where a property is believed to be uniform, sampling locations should be distributed randomly throughout the area of interest, and all data treated as one group. Otherwise, the study area should be subdivided into regions believed to be relatively uniform, with each region sampled and analyzed separately.

For tests intended to measure the average value of a concrete property, such as compressive strength, elastic modulus, or air content, the number of samples should be determined in accordance with ASTM E 122 and C 42/42M and ACI 214.4R. For example, a large structure with little or no distress or deterioration may warrant few, if any, core samples, especially where design documents are available and no change of usage is planned. Alternatively, a structure exhibiting a wide range of distress or deterioration over

Table 5.1—Test methods to evaluate hardened concrete in existing structures (adopted from ACI 228.2R and ASCE 11)

Property	Possible test methods — Primary	Possible test methods — Secondary	Comment
Compressive strength	Cores for compression testing (ASTM C 42/C 42M and C 39/C 39M; ACI 214.3R)	Penetration resistance (ASTM C 803/ C 803M); pullout testing (drilled in)	Strength of in-place concrete; comparison of strength in different locations; drilled in pullout test not standardized by ASTM
Relative compressive strength	Rebound number (ASTM C 805); ultrasonic pulse velocity (UPV) (ASTM C 597)	—	Rebound number influenced by near-surface properties; UPV gives average result through the thickness
Tensile strength	Splitting tensile strength of cores (ASTM C 496/C 496M)	—	Determine approximate tensile strength of concrete
Flexural strength	Break-off test (Carino and Malhotra 2004)	Sampling and testing of sawed beams (ASTM C 42/C 42M)	Limitations posed by aggregate size and nonhomogeneity
Density	Specific gravity of samples (ASTM C 642)	—	Special technique requiring calibration curve
Moisture content	Moisture meters (ASTM D 3017)	—	—
Static modulus of elasticity	Compression test of cores (ASTM C 469)	—	—
Dynamic modulus of elasticity	Resonant frequency testing of sawed specimens (ASTM C 215)	Ultrasonic pulse velocity (ASTM C 597); impact-echo; spectral analysis of surface waves (SASW)	Requires knowledge of density and Poisson's ratio (except ASTM C 215); dynamic modulus is typically greater than static elastic modulus
Shrinkage/ expansion	Length change of drilled or sawed specimens (ASTM C 341/C 341M)	—	Measure of incremental potential length change
Resistance to chloride penetration	90-day ponding test (AASHTO T 259)	Electrical indication of concrete's ability to resist chloride-ion penetration (ASTM C 1202)	Establish relative susceptibility of concrete to chloride-ion intrusion; determine effectiveness of chemical sealers, membranes, and overlays
Air content; cement content; and aggregate properties (alkali-silica reactivity; freezing-and-thawing susceptibility)	Petrographic examination of concrete samples removed from structure (ASTM C 856 and C 457); cement content (ASTM C 1084)	—	Assist in determination of cause(s) of distress; degree of damage; quality of concrete when originally cast and current
Alkali-silica reactivity (ASR)	Petrographic examination of concrete samples removed from structure (ASTM C 856 and C 457)	Cornell/SHRP rapid test (SHRP C-315)	Establish in field if observed deterioration is due to ASR
Carbonation, pH	Phenolphthalein (qualitative indication); pH meter	Petrographic examination, pH indicators (for example, litmus paper)	Assess corrosion protection value of concrete with depth and susceptibility of steel reinforcement to corrosion; depth of carbonation
Fire damage	Petrographic examination of cores (ASTM C 856), compressive strength tests (ASTM C 39/C 39M), split tensile strength tests (ASTM C 496/C 496M)	SASW; UPV; impact-echo; impulse-response	Rebound number permits demarcation of damaged surface
Freezing-and-thawing damage	Petrographic examination of cores (ASTM C 856), compressive strength tests (ASTM C 39/C 39M), split tensile strength tests (ASTM C 496/C 496M)	SASW; UPV; impact echo; impulse-response	Freezing and thawing can cause internal cracking in concrete; split tensile strength is useful in determining the tensile strength capacity of concrete
Chloride-ion content	Acid-soluble (ASTM C 1152/C 1152M) and water-soluble (ASTM C 1218/C 1218M)	Specific ion probe (SHRP S-328)	Chloride ingress increases susceptibility of steel reinforcement to corrosion
Air permeability	SHRP surface airflow method (SHRP S-329), Figg Technique		Measures in-place permeability index of the near-surface concrete 0.60 in. (15 mm); results vary depending on the moisture content of concrete
Electrical resistance of concrete	AC resistance using four-probe resistance meter	SHRP surface resistance test (SHRP S-327)	AC resistance useful for evaluating effectiveness of admixtures and cementitious additions; SHRP method useful for evaluating effectiveness of sealers
Internal voids, delaminations	Acoustic impact (ASTM D 4580), impulse response impact-echo, infrared thermography, UPV, radar	Gamma radiography	Success dependant on test procedure, equipment, and personnel, as well as void geometry

different parts of the structure may warrant numerous samples to adequately diagnose the conditions. Cost should also be considered in the selection of sample sizes. In some cases, increasing the sample size results in only a minimal decrease in the risk that the error is exceeded. The cost of additional sampling and testing would not be justified under these situations. Similarly, reduction or elimination of the sampling and testing can occur through use of lower-bound default material properties (FEMA 356-357).

Concrete is not an isotropic material and properties will vary depending on the direction that samples are taken. Particular attention should be given to vertical concrete components or elements, such as columns, walls, and deep beams because concrete properties will vary with elevation due to differences in placing and compaction procedures, segregation, and bleeding.

5.5.1.1 *Core sampling*—The procedures for properly removing concrete samples by core drilling are given in ASTM C 42/C 42M. The number, size, and location of core

Table 5.2—Test methods to determine structural properties and determine condition of reinforcing steel (partially adopted from ACI 228.2R and ASCE 11)

Property/condition	Possible test method: Primary	Possible test method: Secondary	Comment
Reinforcement location	Expose reinforcement for measurement, pachometer; ground-penetrating radar (GPR) (ASTM D 4748)	X-ray and γ-ray radiography	Steel location and distribution; concrete cover
Reinforcement cross-sectional area reduction	Expose reinforcement and measure diameter; ultrasonic thickness gauge (requires direct contact with steel)	Intrusive probing; radiography	Observe and measure rust and reduction in steel; observe corrosion of embedded post-tensioning components; verify location and extent of deterioration; provide more certainty in structural capacity calculations
Corrosion potentials	Half-cell potential (ASTM C 876)	—	Identification of active reinforcement corrosion
Corrosion rate	Linear polarization (SHRP S-324 and S-330)	Electrochemical impedance	Corrosion rate of embedded steel; rate influenced by environmental conditions
Tensile testing	Tension testing of metallic materials (ASTM A 370 and E 8)	—	Tension testing of removed samples
Chemical analysis	Lab test on sample (ASTM A 751)	—	Needed for determining weldability or to confirm bar grade
Protective coating thickness	Remaining coating thickness on exposed surfaces (ASTM E 376, G 12, G 14, G 20)	—	Requires calibrated test equipment

Note: Other mechanical property testing of metal components, such as hardness and impact, are described in ASTM A 370 and E 8 and their references.

samples should be carefully selected to permit all necessary laboratory tests. Even though more than one test, such as nondestructive pulse velocity testing followed by compressive strength test, is feasible on one core, it is recommended that separate core samples be used for different tests so that there will be no influence from previous tests. Where cores are taken to determine a strength property, at least three cores should be removed at each location in the structure. The strength value should be taken as the average of the three cores. A single core should not be used to evaluate or diagnose a particular strength problem (ACI 318). Refer to ACI 214.4R for variations in core test strengths.

For determining compressive strength or static or dynamic modulus of elasticity, the diameter of the core should be in accordance with the applicable ASTM standard.

5.5.1.2 *Sampling of concrete with sawed beams*—Where appropriate, sampling by sawing beams in accordance with ASTM C 42/C 42M may be used as an alternative to drilled core sampling. Research (including ACI 214.4R and ASCE 11), however, has shown that significant variations between in-place strength and that recorded by tests on retrieved samples may be encountered when using cores and sawed beam samples.

5.5.1.3 *Random sampling of broken concrete*—Sampling of broken concrete generally should not be used where a strength property of concrete is in question, but is frequently used when evaluating chemical or physical deterioration by petrographic or other laboratory analyses.

5.5.2 *Steel reinforcement*—Samples of steel reinforcement can be tested to determine its physical or chemical properties. The characteristics, selection, and preparation of samples are discussed in ASTM A 370. Some general considerations related to nonprestressed reinforcement are:

1. Specimens should be removed at locations of minimum stress in the reinforcement. Not more than one specimen should be removed from the same cross section of a structural component or element;

2. Specimen locations should be separated by at least the development length of the reinforcement to avoid excessive weakening of the component;

3. For structural elements having a span of less than 25 ft (7.5 m) or a loaded area of less than 625 ft^2 (60 m^2), at least one specimen should be taken from the main longitudinal reinforcement (not stirrups or ties) (ACI 437R);

4. For longer spans or larger areas, more specimens should be taken from locations well distributed through the portion being investigated to determine whether or not the same strength of steel was used throughout the structure;

5. Information from grade marks and mill marks from reinforcing bars should be collected when possible and used as appropriate in guiding sample collection;

6. Newer nonprestressed reinforcing steel typically exhibits low variability in material properties across a structure. As a result, less sampling may be needed to gain reasonable confidence in in-place mechanical properties. For older structures, where smooth, square, or iron-based reinforcement was used, additional sampling may be needed; and

7. The minimum gauge length for testing mechanical properties should be in accordance with ASTM A 370. Shorter samples may still be useful. Coupons for testing may be obtained from samples even 4 in. (100 mm) in length, which will provide some information on physical properties.

Sampling of prestressed reinforcement for laboratory testing should be undertaken with extreme care, using proven safety procedures. When the anchorages of unbonded tendons are accessible, the visual examination and lift-off tests can be conducted to measure the prestress force. Sampling of bonded tendons and wires is generally not recommended unless the presence of corrosion, cracking, or loss of prestress is identified. Bonded prestressed reinforcement generally locks up in bond. Sampling and testing of prestressed reinforcement should be done by experienced personnel. For example, slippage of the center wire in a seven-wire strand can influence measured properties. Also, special end chucks may be required to prevent slippage in the jaws. The strand should not be allowed to rotate during testing.

Testing of samples for mechanical properties is addressed in ASTM A 370; minimum gauge length for the sample is 24 in. (610 mm), so at least 35 in. (889 mm) sample lengths should be recovered.

CHAPTER 6—EVALUATION

6.1—Introduction

Evaluation is a process to determine the adequacy of a structure or component for its intended use by systematically analyzing the information and data assembled from reviews of existing documentation, field inspection, condition survey, and material testing. This investigative process of evaluation cannot be standardized into a series of well-defined steps because the number and type of steps will vary depending on the specific purpose of the investigation, the type and physical condition of the structure, the completeness of the available design and construction documents, and the strength and quality of the existing construction materials.

Structural evaluations should be performed to determine the strength of all critical elements of the structure and the structure as a whole. The ability of the structure to meet current code loading requirements should be considered. Many building codes contain change-in-use and rehabilitation scope thresholds beyond which the structure needs to be upgraded. Where code requirements are not met, appropriate strengthening methods and techniques should be determined.

Architectural and historic requirements, such as changes in architectural layout or modifications to the façades of the structure, should be evaluated (Brown 1992). Various design rehabilitation alternatives should be identified along with their advantages and disadvantages. The initial and long-term costs of alternatives should be estimated.

6.2—Dimensions and geometry

The actual dimensions of the structural components should be determined for use in evaluation. The reasons for, and implications of, discrepancies between the field-measured dimensions of the critical structural components and those indicated on available drawings should be understood and properly considered in the evaluation. The architectural layout should be evaluated for use, access, and needed space.

6.3—Materials evaluation

Candidate materials and techniques for strengthening repair or replacement should be identified and evaluated. Rehabilitation of historic structures often requires repair concrete mixtures to match the color and texture of the existing concrete. The final selection of materials and techniques should be based on the exposure conditions for both installation and service, installation constraints, structural performance requirements, service-life requirements, architectural requirements, and compatibility with existing materials (ACI 546R). In addition to the repair or replacement, protection measures to reduce further deterioration and need for future repair may be desirable in certain situations. Common concrete protection measures include sealers, coatings, and cathodic protection (impressed current and sacrificial anodes).

6.4—Structural evaluation

Using the information obtained from the field survey of condition, dimension and geometry measurements, and material evaluations, the strength of the structure or portion of the structure being evaluated should be determined. Critical elements, components, and connections should be identified for evaluation. Dead and live loads, equipment and piping loads, and wind requirements should be considered. Where applicable, nonstructural components should also be evaluated to determine if they are capable of resisting the prescribed loads and deformations. The effect of nonstructural components on the overall performance of the structure should also be considered. The choice of the evaluation method (ACI 437R) is dependent on the nature of the structure and the amount of information known about its existing condition. The typical choices are evaluation by analysis, evaluation by analysis and physical load testing, or evaluation by analysis and structural modeling.

Evaluation by analysis, the most common method, is recommended when sufficient information is available about the physical characteristics, material properties, structural configuration, and loads to which the structure has been and will be subjected. The capacities of the critical structural components should be determined by an appropriate method (ACI 437R). The tolerance of structural components and elements to deterioration and distress is highly variable and situation-specific (Hookham 1994). Analysis of components and elements should be based on proven principles and standards (for example, ACI 318) with attention given to the fact that the calculation is for an existing structure. Variability in materials, accounted for in strength-reduction factors, should be considered.

Evaluation by full-scale load testing is recommended when an insufficient amount of information is available to analyze the structural behavior of the components. It may also be necessary to conduct a full-scale load test when the complexity of the design concept and lack of experience with the structural system make evaluation solely by analytical methods unreliable, when the nature of existing distress and deterioration introduces significant uncertainties about the parameters required to perform a meaningful analysis using generally accepted engineering principles, or when the geometry and the material characteristics of the structural elements being evaluated cannot be readily determined. Another reason for a load test is uncertainty of behavior due to deterioration or complexity of the system. Evaluation using full-scale load-testing procedures, however, might not be valid if the behavior of the structure beyond the elastic limit cannot be reliably predicted, such as in the case of a severely deteriorated structure.

Sometimes it may be impractical to conduct a full-scale load test of the component under consideration. In such situations, testing of full- or reduced-scale models can be used to determine the strength and ductility of critical portions of the structure. It is generally necessary to model all of the structural features that significantly contribute to the behavior of the structure to get reliable results.

6.5—Cost evaluation

A cost evaluation of each repair, strengthening, or replacement alternative should be prepared. It should include the costs of engineering and other technical services, construction materials, labor and equipment, construction administration, construction management if appropriate, and other costs such as falsework/rigging, legal costs, traffic control, or loss of income.

For projects with rehabilitation alternatives that have differing and significant future costs, such as the rehabilitation of a deteriorating structure, rehabilitation alternatives should be evaluated using economic evaluation methods. The life-cycle cost (LCC) method is a commonly used procedure. LCC is the sum of all costs, present and future, that occur during the selected evaluation period. Costs will include those listed in the preceding paragraph as well as estimated future maintenance and repair costs, and the salvage value at the end of the evaluation period. LCC is expressed in equivalent terms (often present value) by adjusting future costs with an estimated inflation rate and a selected discount rate that reflects the time value of money.

The costs for future maintenance and repair can often be predicted from the maintenance and repair records of the owner and from contractors who specialize in concrete repair and protection. Clients should provide input on the desired repaired life of the structure (which may be different than service life) along with valid escalation and discount rates. Analyses can be performed for a range of rates to evaluate upper- and lower-bound LCC values.

The prediction of the structure's service life, the various repair and protection alternatives, and the extent and frequency of future repair and protection work is crucial to a meaningful LLC analysis. Available service-life prediction models are in their infancy. Consequently, meaningful service-life prediction requires engineering judgment, experience, case histories and data from similar projects, materials science and chemistry expertise, and input from the client on maintenance and repair history. For more detail on economic evaluation and service life models, refer to ACI 365.1R.

6.6—Evaluation of rehabilitation alternatives

With any rehabilitation project, there are usually several alternatives for accomplishing the necessary repair, strengthening, and protection, or replacement. Alternatives can range from doing nothing (as long as the structure is safe and, in the case of a deteriorating structure, is monitored to ensure ongoing safety) to complete demolition and replacement. Between these extremes are usually several rehabilitation alternatives.

The design professional should propose technically acceptable rehabilitation alternatives, evaluate their costs (both initial and long-term), and identify their advantages and disadvantages. Advantages and disadvantages may include, but are not necessarily limited to, the following:

1. Magnitude of costs, both initial and long-term;
2. Degree to which the rehabilitation objectives are achieved;
3. Degree of disruption to ongoing operations;
4. Risks, uncertainties, and unknowns regarding future performance and future maintenance and repair needs; and
5. Salvage value.

The design professional's final recommendations will likely be influenced by first-hand knowledge of the client's intent regarding funds available and the long-term plans for the facility. In any event, the rehabilitation alternatives evaluation provides a rational basis upon which a selection can be made, with the guidance of the design professional.

CHAPTER 7—FINAL REPORT

7.1—Introduction

The results of the entire investigation and evaluation should be summarized in a final report. This report generally includes a brief description of the following basic areas addressed during the evaluation process:

1. Purpose and scope of investigation;
2. Documentation recovered to support evaluation;
3. Field observations and condition survey results;
4. Sampling and material testing results;
5. Evaluation process and results; and
6. Findings and recommendations.

7.2—Purpose and scope of investigation

This section of the report should describe the purpose and scope of the investigation as agreed upon with the owner, including any modifications made during the course of the evaluation, significant assumptions, and applicable building codes and standards. The level of investigation undertaken, as preliminary or detailed, should be clearly stated.

7.3—Documentation recovered to support evaluation

A summary of information on the existing structure including location, size, history, and architectural and structural details should be included in this section. The results of the documentation review should be summarized and supplemented by photographs, copies of drawings, and any other pertinent information as applicable. A list of all the documents reviewed or referenced and their sources should be included.

7.4—Field observations and condition survey

The results of the inspection and condition survey for the structure, including its façade, foundations, soils, and influences of adjoining structures should be included. The report should briefly describe methods and equipment used; results of as-built verification efforts including all deviations, major deficiencies, and deterioration or distress that require remedial work; and all portions of the structure that are to be rehabilitated or altered for change of use or appearance. When drawing documentation (such as design or as-built) is not available, the report should describe methods used to size and quantify structural components; this should include such assumptions on dimensions and configuration (for example, reinforcing steel layout) made throughout the structure. The report should also include photographs, sketches, drawings, and other pertinent information prepared during the inspection and field survey operations.

7.5—Sampling and material testing results

The locations, methods, and results of the nondestructive and destructive testing performed during the detailed investigation should be summarized. The results may be supplemented with photographs and copies of laboratory test reports as appropriate. The results should indicate adequacy of the structure in terms of physical condition, strength, and future performance of all structural and architectural materials and components tested.

7.6—Evaluation

The report should summarize the results of the strength and deformation evaluation of the structure and components and elements thereof. All assumptions made and methods used in the evaluation process should be clearly documented, including the structural model created and any computer-based analyses that were prepared and executed, and their results. If required, a brief description of each rehabilitation alternate or strengthening method studied, along with sketches or drawings showing typical details, cost estimates, and the impact of the rehabilitation method on the structure and its users, should be included. The report should also clearly indicate the extent to which strengthening or rehabilitation is necessitated by code-mandated provisions along with any special conditions (for example, rehabilitation procedures for historic buildings). The evaluation results should also identify any follow-up recommendations for the structure, such as:

1. Additional testing or analysis that could be used to confirm report conclusions;
2. Any immediate remedial actions needed from a safety or serviceability perspective;
3. Long-range maintenance suggestions to reduce the possibility for deterioration; and
4. Recommendations to improve building performance for seismic events.

7.7—Findings and recommendations

The findings from each preceding task should be summarized in this section of the report. The findings should include a discussion of the current condition and expected future performance of the structure, and the feasibility of the rehabilitation under various scenarios and options. The recommendations should address the following topics: action plan, cost estimates, scheduling, and determining constraints and feasibility.

7.7.1 *Action plan*—The recommendation should clearly identify an appropriate course of action for the structure or components of the structure, such as:

1. Accept as is;
2. Correct deficiencies (deterioration, distress, or performance concerns) identified;
3. Change the use;
4. Phase out of service;
5. Close, or provide suitable protection against failure such as shoring; or
6. Conduct additional testing or evaluation.

The course of action that will best satisfy the owner's objectives should be considered, and an appropriate and cost-effective solution for the rehabilitation should be developed. Effective plans should address what action should be taken and how it should best be accomplished. Where budget constraints exist, it may be practical to assign priorities to rehabilitation and to stage the program accordingly over several years. Feasible alternatives to the recommended plan of action should be identified, including estimated costs.

7.7.2 *Cost estimates*—Project costs often influence every aspect of a recommended rehabilitation plan and, while not necessarily controlling the final recommendations, usually exert a major influence. Cost estimates should address the owner's requirements and consider the effects of interruptions of normal operations. Additionally, it is helpful to study possible phasing (or staging) of the project and to identify the influence that deferring of a particular phase would have on future rehabilitation costs. Inflation rates and interest rates should both be taken into account when evaluating the impact of a deferment on a rehabilitation program. Finally, the life expectancy of various systems and alternate rehabilitation schemes, and the life expectancy and life-cycle costs of the entire structure, should be presented (ACI 365.1R). The total cost estimate should also include cost of the engineering services, testing services, and contingencies.

7.7.3 *Scheduling*—The project schedule is usually determined by the urgency of the rehabilitation needs, the availability of funds, the effects on ongoing operations, and the optimal construction conditions. If rehabilitation work is required outdoors, work may be delayed until the weather is suitable or temporary protection measures may have to be considered. The schedule should consider the lead time for engineering, preparing construction documents, and permitting. Sufficient time should be allowed for contractor selection and mobilization. Where unknown conditions exist, sufficient time should be allowed for possible modifications and additional engineering services if newly discovered deficiencies are found during rehabilitation. Adequate delivery time for special materials, new or replacement equipment, or prefabricated components should be considered.

7.7.4 *Constraints and feasibility determination*—Rehabilitation often involves the constraints associated with working around existing operations and structure use. Special considerations are warranted for construction operations that produce dust, noise, odor, vibrations, or involve hazardous materials. Site access and materials-handling problems should also be considered. Project planning meetings are often helpful in determining the most appropriate way of handling these constraints. It is of critical importance to ensure that any constraints mandated by the owner be considered and incorporated into the rehabilitation plan.

CHAPTER 8—REFERENCES

8.1—Referenced standards and reports

The standards and reports listed below were the latest editions available at the time this document was prepared. Because these standards and references are revised frequently, the reader is advised to contact the proper sponsoring group or association if it is desired to refer to the latest version.

American Association of State Highway and Transportation Officials (AASHTO)

T 259 Method of Test for Resistance of Concrete to Chloride Ion Penetration

American Concrete Institute (ACI)

116R Cement and Concrete Technology
201.1R Guide for Making a Condition Survey of Concrete in Service
207.3R Practices for Evaluation of Concrete in Existing Massive Structures for Service Conditions
214.3R Simplified Version of the Recommended Practice for Evaluation of Strength Test Results of Concrete
214.4R Guide for Obtaining Cores and Interpreting Compressive Strength Results
224R Control of Cracking in Concrete Structures
224.1R Causes, Evaluation and Repair of Cracks in Concrete Structures
224.2R Cracking of Concrete Members in Direct Tension
228.1R In-Place Methods to Estimate Concrete Strength
228.2R Nondestructive Test Methods for Evaluation of Concrete in Structures
318 Building Code Requirements for Structural Concrete and Commentary
365.1R Service-Life Prediction
437R Strength Evaluation of Existing Concrete Buildings
546R Concrete Repair Guide

American Society of Civil Engineers (ASCE)

ASCE 11 Guideline for Structural Condition Assessment of Existing Buildings

ASTM International

A 370 Test Methods and Definitions for Mechanical Testing of Steel Products
A 751 Test Methods, Practices, and Terminology for Chemical Analysis of Steel Products
C39/C 39M Test Method for Compressive Strength of Cylindrical Concrete Specimens
C 42/C 42M Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
C 215 Test Method for Fundamental Transverse, Longitudinal, and Torsional Frequencies of Concrete Specimens
C 341/C 341M Practice for Length Change of Cast, Drilled, or Sawed Specimens of Hydraulic-Cement Mortar and Concrete
C 457 Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete
C 469 Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression
C 496/C 496M Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens
C 597 Test Method for Pulse Velocity through Concrete
C 642 Test Method for Density, Absorption, and Voids in Hardened Concrete
C 803/C 803M Test Method for Penetration Resistance of Hardened Concrete
C 805 Test Method for Rebound Number of Hardened Concrete
C 823 Practice for Examination and Sampling of Hardened Concrete in Constructions
C 856 Practice for Petrographic Examination of Hardened Concrete
C 876 Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete
C 1084 Test Method for Portland-Cement Content of Hardened Hydraulic-Cement Concrete
C1152/C 1152M Test Method for Acid-Soluble Chloride in Mortar and Concrete
C 1202 Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration
C 1218/C 1218M Test Method for Water-Soluble Chloride in Mortar and Concrete
C 1383 Test Method for Measuring the P-Wave Speed and the Thickness of Concrete Plates Using the Impact-Echo Method
D 3017 Test Method for Water Content of Soil and Rock in Place by Nuclear Methods (Shallow Depth)
D 4580 Practice for Measuring Delaminations in Concrete Bridge Decks by Sounding
D 4748 Test Method for Determining the Thickness of Bound Pavement Layers Using Short Pulse Radar
D 6432 Guide for Using the Surface Ground Penetrating Radar Method for Subsurface Investigation
E 8 Test Methods for Tension Testing of Metallic Materials
E 122 Practice for Calculating Sample Size to Estimate, with a Specified Tolerable Error, the Average for Characteristic of a Lot or Process
E 376 Practice for Measuring Coating Thickness by Magnetic-Field or Eddy-Current (Electromagnetic) Examination Methods
G 12-83(1998) Test Method for Nondestructive Measurement of Film Thickness of Pipeline Coatings on Steel
G 14 Test Method for Impact Resistance of Pipeline Coatings (Falling Weight Test)
G 20 Test Method for Chemical Resistance of Pipeline Coatings

Concrete Reinforcing Steel Institute (CRSI)

EDR48 Engineering Data Report, Evaluation of Reinforcing Bars in Old Structures

Federal Emergency Management Agency (FEMA)

356-357 Prestandard and Commentary for the Seismic Rehabilitation of Buildings

Strategic Highway Research Program (SHRP) (Transportation Research Board, National Academy of Sciences)

C-315 Handbook for the Identification of Alkali-Silica Reactivity in Highway Structures

S-324 Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion, Volume 2: Method for Measuring Corrosion Rate of Reinforcing Steel

S-327 Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion, Volume 52: Method for Evaluating Effectiveness of Penetrating Sealers

S-328 Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion, Volume 6: Method for Field Determination of Total Chloride Content

S-329 Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion, Volume 7: Method for Field Measurement of Concrete Permeability

S-330 A Guide to Determining Optimal Gradation of Concrete Aggregates

The preceding references are available from:

American Concrete Institute
PO Box 9094
Farmington Hills MI 48333-9094
www.concrete.org

ASTM International
100 Barr Harbor Dr
West Conshohocken PA 19428
www.astm.org

American Society of Civil Engineers
1801 Alexander Bell Dr
Reston VA 20191-4400
www.asce.org

Concrete Reinforcing Steel Institute
933 North Plum Grove Rd
Schaumberg IL 60173
www.crsi.org

Federal Emergency Management Agency
500 C Street SW
Washington DC 20472
www.fema.gov

Strategic Highway Research Program (SHRP)
National Academy of Sciences
2101 Constitution Ave NW
Washington DC 20418
www.tfhrc.gov/pubrds/marapr98/shrp.htm

U.S. Army Corps of Engineers
Waterways Experiment Station
Vicksburg MS 39180-6199
www.usace.army.mil/

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Thornton, H. T., Jr., and Alexander, A. M., 1987, "Development of Nondestructive Testing Systems for In Situ Evaluation of Concrete Structures," *Technical Report* REMR-CS-10, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Miss.

U.S. Department of Interior, 2007, National Park Service, "Historic American Building Survey (HABS)," Washington, D.C., http://www.cr.nps.gov/habshaer/habs/