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Guide for Evaluation of Concrete Structures Prior to Rehabilitation

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This report presents the guidelines and general procedures that may be used for evaluation of concrete structures prior to rehabilitation. Among the subjects covered are: preliminary investigation; detailed investigations documentation; field inspection and condition survey; sampling and material testing evaluation; and final report. Seismic evaluation is considered beyond the scope of this report.

Keywords: buildings: concrete; condition survey: evaluation; field observation; historic structures: **nondestructive evaluation;** rehabilitation: sampling; service history: testing.

CONTENTS

ACI Committee Reports, Guides, Standard Practices, and Commentaries are intended for guidance in designing, planning. executing, or inspecting construction and in preparing specifications. References to these documents shall not be made in the Project Documents. If items found in these documents are desired to be a part of the Project Documents, they should be phrased in mandatory language and incorporated into the Project Documents.

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CHAPTER l-INTRODUCTION

l.l-General

This report outlines procedures that may be used for evaluation of concrete structures prior to rehabilitation. The procedures should be used as a guide and are not intended to replace judgment by the engineer responsible for the evaluation. The evaluation work is generally performed for one or several of the following purposes:

a) To determine the feasibility of changing the use of a structure or retrofitting the structure to accommodate a different use from the present one. The feasibility of enlarging the structure or changing the appearance of the structure may also be determined.

b) To determine the structural adequacy and integrity of a structure or selected elements.

c) To evaluate the structural problems or distress which result from unusual loading or exposure conditions, inadequate design, or poor construction practices. Distress may be caused by overloads, fire, flood, foundation settlement, deterioration resulting from abrasion, fatigue effects, chemical attack, weathering, or inadequate maintenance.

d) To determine the feasibility of modifying the existing structure to conform to current codes and standards.

Many failures have taken place in rehabilitation projects due to erroneous procedure and improper judgment. It should be recognized that 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. Similarly, there are no generally recognized criteria for evaluating serviceability of an existing structure. Engineering judgment and close consultation with the owner regarding the intended use of the structure are required in the evaluation of structures prior to rehabilitation.

It is important to clearly define the objective of the rehabilitation effort. 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 proceed with little, if any, interference with normal operations, it is obviously more costly to carry out rehabilitation work under such conditions. The owner should be consulted and provided with relative costs for various levels of interference, so that an informed decision as to how to proceed with the rehabilitation work can be made.

Due to the many unknowns inherent in rehabilitation work, it is essential to retain the services of consultants experienced in this type of work. It is also equally important to retain services of a well-experienced specialty contractor on a negotiated basis so that a better control in terms of total cost, level of disturbance to the users, and the quality of work can be achieved. 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 here 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 reestablishing the materials, form, and appearance of a structure to those of a particular era of the structure

Strengthening-The process of increasing the load-resistance capacity of a structure or portion thereof.

1.3-Purpose and scope

The purpose of this report is to provide a source of information on the evaluation of concrete structures (except those subjected to seismic effects) prior to rehabilitation. This is of particular importance since there is a substantial difference between the complexity of rehabilitation design, as compared with the design of a new structure. Evaluation of specialty structure types such as bridges, dams, and tunnels are considered beyond the scope of this report.

The report is presented as a series of recommended guidelines, based on experience drawn from existing sources and past investigations. Case histories are not given so as not to deviate from a guideline approach.

(For case histories, see ACI SP-85, ACI SCM 21, and *Concrete International*, March 1993.) The guidelines given in this report are general in character, but specific enough for use as a format to model an evaluation procedure for a structure.

The report is presented in the order in which an investigation would normally be conducted. The first and the most important single effort in evaluation prior to rehabilitation is the "preliminary investigation," as described in Chapter 2. After having the results of the preliminary investigation, the detailed investigation can proceed, if deemed desirable. Chapter 3 outlines the efforts required for the detailed investigation which generally consist of five major tasks: reviewing pertinent documents, performing a field inspection and condition survey, sampling and material testing, evaluating and analyzing the information and data, and preparing a final report. Chapter 4 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 assess the structural condition are described in Chapter 5. Chapter 6 provides information on practices and procedures for sampling and material testing, including visual examination, nondestructive evaluation, and field and laboratory investigations. Chapter 7 contains discussions on review of all the accumulated information and data, material and structural evaluation, identification and evaluation of rehabilitation alternatives, and costs. Guidelines for preparing the final report are presented in Chapter 8.

CHAPTER 2-PRELIMINARY INVESTIGATION

2.1—Introduction

The goals of the preliminary investigation are to provide initial information regarding the condition of the structure, the type and seriousness of the problems affecting it, the feasibility of performing the intended rehabilitation, and information on the need for a detailed investigation.

The preliminary investigation, once authorized by the owner, is based on an established objective or reason for performing the rehabilitation. It is necessary to meet with the owner to fully evaluate the owner's needs and perceptions and to determine the objectives of the investigation. A written agreement, stating the objectives and the scope of these studies, is recommended. It is important to recognize that preliminary investigations are typically introductory in nature and are not comprehensive. Preliminary investigations commonly identify the need for a more detailed and extensive study and for an additional scope of services. However, in some cases, the preliminary investigation may determine that it is not desirable to proceed with a further detailed investigation, as in the case of excessive damage where the structural integrity cannot be economically restored or the owner's objectives cannot be satisfactorily met.

2.2-Scope and methodology

The scope and methodology of a preliminary investigation can involve one or more of the following steps, depending on the size and complexity of the project.

a) Review of plans, specifications, and construction records

b) Site observations of conditions

c) Measurement of geometry, deflections, displacements, cracks, and other damage

d) Nondestructive testing

e) Exploratory removal

f) Sampling, testing, and analysis

It should be noted that only a limited amount of investigation within each step is generally required to establish the feasibility of the rehabilitation project. Detailed studies are generally deferred until the detailed investigation phase, if such investigation is deemed desirable.

2.2.1 *Plans, specifications, and construction records*- The first task is to review available plans, specifications, and construction records. It may be necessary to search many sources to obtain these documents. For older structures, the process can be tedious and difficult and can consume far more time than the actual review. The owner's files, city archives, original designers, and original contractors are generally the best sources to search for documents and records. Testing agencies, building management firms, or large subcontracting companies are also possible avenues for obtaining construction documents. Universities, libraries, historic societies, and state preservation offices may have design documents and construction records for historic structures.

When original documents are not available, the study must begin without precise knowledge of the structure. Special steps should be taken to compensate for the missing information. Nondestructive testing and physical measurements can be used to supplement visual observations. Nondestructive testing to locate reinforcement can be a practical alternative to exploratory removals. The use of nondestructive techniques can yield valuable information on which to base decisions regarding further testing and evaluation. Nondestructive tests must be correlated with the testing of a sufficient number of samples to confirm their reliability (ACI 437R).

Once the plans and specifications are obtained and field checks have been performed to confirm that the structure is in reasonable conformance with the construction drawings, then a study of the plans, specifications, and other construction records can proceed. Checks of the critical design details, arrangement of critical members, and installation of any special features can then be accomplished. If variations from the drawings are noted or if scope changes occurred during construction, proper documentation should be made so that site observations can confirm or clarify features of the actual structure. It is important to check what code requirements were applicable at the time of design. These should be compared to presently applicable codes and

standards. Critical data such as loading requirements and allowable stresses should be reviewed. It may also be necessary to determine the physical properties of the construction materials if such information is not available from the existing documentation. If soils or foundation information is available, it should be retained for future use.

As the review progresses, parallel steps may be taken to develop field observation record sheets for recording information obtained during the field investigation. Such record sheets should provide essential information on structural features such as perimeter boundaries, column, beam, and wall locations and dimensions. If the structure being examined is a multifloor structure, one record sheet may be developed for each floor. A list of items or questions obtained during the records review concerning as-built status, alterations, or possible changes in structure use since its original construction should be developed and checked in the field. Alterations to existing structures in service are common and must be carefully noted and evaluated, because they represent potentially sensitive areas in the structural system.

2.2.2 *Field observations*--A walk-through of the structure may be adequate to establish the project scope and to serve the project needs. However, in instances of extensive rehabilitation, more detailed checks of various items followed by preliminary tests may be required.

The principal focus of the preliminary investigation generally involves recording the nature and extent of observed problems and identifying the affected members. Frequency and severity of problems throughout the structure must also be recorded. In the event that serious distress or deficiencies are discovered, which may result in unsafe or potentially hazardous conditions, the owner should be notified for immediate action. Temporary evacuation, temporary shoring measures, or any other emergency safety measures, if required, should be recommended to the owner. Monitoring of movements, cracks, and progressive distress should follow immediately.

Assessment of the conditions observed, and specifically the need for follow-up and appropriate remedial actions, should be recorded. Initial impressions can be very valuable; they often accurately characterize the nature of a problem. If structural problems are suspected, special attention should be given to connections, support regions, areas of abrupt geometric change, and areas in the structure where load concentrations occur. Where cracks of structural significance are found, consideration should be given to monitoring the movements of the cracks. This information will be of value for future investigations.

Photographic records or videotapes are valuable aids in classifying and communicating information on the conditions and problems observed in the field (Buchanan 1983). Where unusually severe deterioration or distress is observed, a photographic record of this information is essential.

2.2.3 *Measurements*-The field condition survey generally requires measurements of member dimensions, span lengths, and deflection magnitudes. Any displacement, cracks, separations, or distortion of the structural frame, curtain walls, or other load-bearing or enclosure systems should be noted and characterized. Existing floor or roof slopes should also be noted.

Additional measurements may be necessary where alterations to a structure have been made without proper documentation. It is common to encounter alterations in a structural system that have been made without an awareness of the significance that such alterations may have on the structural system. If there is reason to believe that alterations may be affecting a structural system's response or capacity, recommendations for remedial action may be appropriate. The owner should be notified immediately if the nature and extent of problems discovered require urgent action.

2.2.4 *Nondestructive testing*-Limited nondestructive testing can supplement observations and measurements. Some of the most common techniques used during preliminary investigation are listed in the following:

a) Acoustic impact (sounding and chain dragging)
b) Magnetic detection instrument (cover meters)
c) Rebound hammer
d) Penetration resistance
e) Forced vibration tests

It is unlikely that all of these methods will be used during a preliminary investigation. Preliminary nondestructive testing can often help to identify locations within a structure where more comprehensive nondestructive and destructive testing may be required. A detailed description of nondestructive test methods and procedures is included in Chapter 6 of this report.

2.2.5 *Exploratory removal*-Exploratory removal is used when there is substantial evidence of serious deterioration or distress, when hidden defects are suspected, or when there is insufficient information. Exploratory removals help to determine existing features and to gain reliable information about the nature and extent of existing problems. During preliminary investigation, selected exploratory removals are considered the exception and not the rule. It is more common to defer removals until the detailed investigation phase.

2.2.6 *Sampling testing, and analysis*-sampling and testing are not usually performed during the preliminary investigation. When performed, sampling generally consists of extracting cores or small specimens, or collecting other readily obtainable samples for compressive strength testing and petrographic examination (ACI 437R). Powder samples may be extracted during the preliminary investigation for chemical analysis and determinations of chloride ion content. Reinforcing steel samples may be analyzed to determine strength, hardness, and carbon content.

2.3-Results

The results of the preliminary investigation should be summarized in a report that will generally include structural capacity check, project feasibility, identification of

structural problems, strengthening requirements, and needs for further investigation.

2.3.1 *Structural capacity check*-The structural capacity check generally produces one of three results: (1) The structure or individual members are adequate for the intended use; (2) The structure or individual members are adequate for the existing loads but may not be adequate for intended use; (3) The analysis may be inconclusive. Depending on the results, the adequacy of the structure must be established. It may also be necessary to propose immediate action to deal with a condition affecting the safety or stability of the structure.

2.3.2 *Project feasibility*-An assessment based on technical and cost considerations should indicate whether a proposed rehabilitation is feasible. Points that should be considered in reaching a conclusion regarding project feasibility include the expected effectiveness of the rehabilitation and its estimated life-cycle cost. The effects of the rehabilitation on the structural system and the anticipated impact on the operation of the structure should also be considered.

2.3.3 *Structural problems*-when structural problems are identified, they should be described in terms of their seriousness and extent. Steps should be taken to verify the significance of the structural problems discovered and to determine whether or not corrective action is required to remedy the existing conditions or to protect the existing structural system. It is not unusual to encounter problems that require immediate action to mitigate deficiencies discovered. In such cases, the owner should be notified for immediate action. Preliminary investigation, especially for older structures, frequently identifies conditions which may be in marginal compliance with or in violation of current codes.

2.3.4 *Strengthening requirements*-Alternate strengthening methods should be considered to satisfy the intended loading requirements and applicable code requirements. Actions taken to strengthen existing structures must take into consideration the operation of the structure both in terms of current and possible future use. The investigation should also consider the cost effectiveness of repairing, replacing, or strengthening the existing structural members.

2.3.5 *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 must be addressed in planning the next phase of the work include the objectives of the detailed investigation and the additional data or information required to satisfy these objectives. Other important issues are the time required for investigation, the cost of investigation, and the intended use of detailed investigation.

CHAPTER 3-DETAILED INVESTIGATION

3.1-Introduction

The detailed field investigation should only be performed after the preliminary investigation is completed, the owner's goals identified and tentatively determined to be feasible, and the objectives of the detailed investigation properly defined. It is important before proceeding with the detailed investigation that the project budgets and costs of the detailed investigation be approved by the owner.

The detailed investigation may be divided into five major tasks:

a) Documentation
b) Field observations and condition survey
c) Sampling and material testing
d) Evaluation
e) Final report

The findings of the detailed investigation 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. Therefore, extreme care is required in planning and executing the detailed investigation.

3.2-Documentation

Intensive effort should be made to locate, obtain, and review the pertinent documents relating to the structure. Thorough review of the available documentation will save both time and cost for any rehabilitation project. Chapter 4 provides a guide describing the type of documentation needed for various types of structures and where it may be obtained.

3.3-Field observations and condition survey

Even with complete documentation and construction information, investigation is required to verify reliability and accuracy in the field. 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 5.

3.4-Sampling and material testing

Material testing is often required to determine the existing material properties and conditions. The testing may be destructive or nondestructive and may be performed both in the field and in the laboratory. Chapter 6 describes the types of testing and the methods of sampling that may be performed during the detailed investigation.

3.5-Evaluation

Chapter 7 identifies the major types of evaluations that should be performed to reach a conclusion to proceed with the rehabilitation project or to choose an alternative plan.

3.6-Final report

The final report should include the results of all phases of the investigation field observations, testing, and evaluation, and should also include conclusions and recommendations to the owner on how to proceed with the rehabilitation project. It should include an action plan, cost estimates, and tentative design and construction schedules. Guidelines for preparing the final report are included in Chapter 8.

CHAPTER 4-DOCUMENTATION

4.1-Introduction

This chapter identifies documents and sources of information that should be reviewed during the evaluation of structures prior to their rehabilitation. This review process is necessary to minimize the assumptions necessary to evaluate 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.

4.2-Design information

4.2.1 *Structures*-Documentation that may contain useful structural information includes:

a) Design drawings, specifications, and calculations

b) Shop drawings of assemblies and steel framing

c) Placing drawings of concrete reinforcement

d) Alteration plans, addenda, and change orders

e) As-built drawings, photographs, job field records, and correspondence

f) Building codes

g) Manufacturer's technical information, descriptions of construction materials, patents, and test data

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 political subdivision in which the structure is located, the general contractor, the subcontractors, and the fabricators. Local building departments' records may be valuable in locating alteration plans and possible violations.

The assembly of all this information can be time-consuming, but it is extremely important for a successful rehabilitation project.

4.2.2 *Historic structures-Buildings*-Buildings designated as historic structures are required to be preserved, and their rehabilitation may fall under federal, state, or city preservation statutes or acts (HUD 1982). Often, rigid rules must be observed, and these should be carefully studied.

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 often were 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. Many of these systems 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.

The Historic American Building Survey (HABS), National Park Service, U.S. Department of the Interior, Washington, D. C., 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 ACI Bibliography on the History of Concrete (ACI B-14), and in Concrete Reinforcing Steel Institute Publication CDA-24.

4.2.3 *Historic structures-Bridges*-The discussion in Paragraph 4.2.2 on historic structures is also applicable to reinforced concrete bridges. Bridges almost always have been public structures built under the aegis of county and local governments, or state highway departments. Thus, public records, including drawings of a particular bridge, may be found in the archives. Often, if details of a particular bridge are lacking, documents may be available for a bridge designed and built by the same engineering group or agency at the same time and to the same specifications.

Drawings of existing historic bridges may be obtained from the Historic American Engineering Record (HAER), National Park Service, U.S. Department of the Interior, Washington, D.C.

Beginning about 1905, hundreds of bridges were built according to catalog designs. A careful review of such designs may prove beneficial in documenting the design of a particular bridge. In addition, a number of railroad bridges were built by railroad companies. These railroad companies generally keep good records. Possibilities of obtaining original design plans and inspection and maintenance records from the railroad companies should be investigated.

4.3-Materials information

The following information on the materials used in a particular structure may be available, especially for more recently constructed structures, and should be sought:

a) Concrete mixture components, proportions, and test results

b) Mill test reports on cement and reinforcing and prestressing steel

c) Material specifications and drawings, including those prepared by material suppliers and used to place

their products in the original construction

4.4-Construction information

Various construction documents from the original construction may have been retained and may be helpful in documenting the construction methods, materials, and problems encountered. If available, this information will prove to be valuable in the rehabilitation process.

The following records should 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

k) Information concerning the foundation and soil-bearing capacity, including soil-bearing reports prepared prior to construction; allowable soil-bearing pressures used in the design; and soil and foundation work, including backfill and compaction conducted 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. Also, local geotechnical engineers may be aware of soil 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. Local newspaper and trade publications may have provided coverage of the original construction.

4.5-Service history

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

a) Records of current and former owners, or users of the structure, their legal representatives, and their insurers

b) Maintenance, repair, and remodeling records

c) Reports maintained by owners of adjacent structures

d) Weather records

e) Interviews with operation and maintenance personnel

f) Logs of seismic activity, geologic activity, etc.

g) Insurance reports and records of damage to the structure by fire, wind, snow, overloads, earthquake, fatigue, etc.

h) Information on operation, occupancy, instances of overloading, and load limits

i) Records from government or local building departments or departments of licenses and inspection. Inspection reports and reports of violations are often useful

j) Photographs

k) Local newspapers and trade publications

4.6-Communication

All documentation obtained should be kept in separately organized files. These files should identify the origin of the documents and data obtained.

Copies of all documents should be made available to the owner for his information. These documents may also be made available to the contractor selected for the rehabilitation project.

CHAPTER 5-FIELD OBSERVATIONS AND CONDITION SURVEY

5.1-Introduction

Once the available design, construction, and materials information, and service history of the structure have been collected and reviewed, the next step is to perform field observations to verify the previously obtained information, and to survey and assess the condition of the as-built construction.

The field observations can be divided into the following four major efforts:

a) Preparation and planning

b) Verification of as-built construction

c) Condition assessment of the structure

d) Summary report

Each of these efforts may be modified depending on the type, size, complexity, age, intended future use, and the overall nature of a particular project.

5.2-Preparation and planning

The scope of the field observation effort is, in part, dictated by the availability of funds and time, but it must be sufficient to include relevant information consistent with project goals. Before a detailed field observation is undertaken, the conclusions of the preliminary investigation should be reviewed thoroughly. Additionally, the available documentation should be reviewed to determine the type and extent of information that is to be obtained or verified during field inspection. Recording procedures and appropriate forms should be developed to document properly information obtained in the field.

When original documents are not available, special steps should be taken to compensate for the missing information. Nondestructive testing (ACI 228.1R) and physical measurements should be used to supplement visual observations.

A reconnaissance should be made to establish general site conditions and to decide if special access equipment

or permits are required, if any finishes have to be removed, if services of subcontractors are required to provide the appropriate means of access, or if specialized inspection services such as rigging, underwater inspection, etc., are required. In addition, photographs or a video-recording of critical areas should be taken during the field observations to assist in planning of equipment, access, and inspection methodology.

5.3-Field verification of as-built construction

5.3.1 *Geometry and structural materials*--Spans and cross sections of the structural members should be measured, particularly at critical locations, because as-built conditions may vary considerably from those shown on available drawings. Variations may be due to later design modifications or field changes. In particular, unrecorded alterations may be critical because they may be the cause of reduced strength of the structure. It is essential that location and size of openings in structures and holes through members be measured and recorded.

Nondestructive testing methods such as a magnetic detection instrument, radiography, ultrasonic pulse velocity, or other methods may be used to estimate either number, size, length, or spacing of reinforcing steel in concrete. If the reinforcing details are available, the nondestructive testing methods can be used to verily the information at a few random locations (ACI 228.lR, Carino and Malhotra 1991). If they are not available, nondestructive testing methods may have to be used extensively to establish reinforcing steel sixes and locations at critical sections. An adequate number of tests at other locations should also be made to establish a reliable estimate (ASTM E 122). The results of nondestructive testing methods should always be verified by removal of concrete cover at some locations.

Nondestructive testing can be used to identify areas of reinforcing corrosion, delamination, or cracking. Nondestructive testing can also be used to estimate the concrete strength and overall concrete quality. Results of nondestructive tests are most useful when supplemented by a limited number of destructive test procedures.

Exploratory removal of portions of a structure may be required when it is not possible to fully evaluate visible evidence of a seriously deteriorated or distressed condition. Removal may also be required when there is a lack of information about a portion of a structure. Since removal and replacement of portions of a structure may require services of a subcontractor, this work should be planned well in advance with the owner's approval. Furthermore, since most rehabilitation projects require extensive removal during construction, it may be more efficient and more convenient to plan inspection of hidden areas or conditions during early phases of the construction.

5.3.2 *Loadings and environment*-The existing loads, loading combinations, soil pressures, and environmental conditions acting on a structure may be different from those assumed and provided for at the time of design. The inspection should note any changes that can affect the total load-carrying capacity of the structure.

5.3.2.1 *Dead loads*--Differences between design and actual dead loads may arise from variations in the dimensions, and the density and moisture content of the construction materials. Change in architectural finishes, addition of partition walls, changes in facade construction, or addition of nonstructural elements can also affect the actual dead loads.

5.3.2.2 *Imposed Loads*-Since the imposed loads depend on the use of the structure, a full description of current and proposed usage should be obtained from the owner. The imposed loads should be verified during the field observations. Code requirements for wind and seismic loads may now be more stringent than when the structure was originally constructed. Roth static and dynamic effects of the imposed loads should be considered.

5.3.2.3 *Warehouse loading and storage*-In a warehouse, attention should be given to the current and proposed methods and patterns of storage. Mechanical stacking may induce dynamic effects and thus increase loading. It is necessary to confirm whether the materials stored are of similar characteristics to those assumed in the original design. Overloading is a common problem in warehouses.

5.3.3.4 *Loads from equipment and machinery*-Static and dynamic loadings induced by mechanical equipment to the structure should be field-verified. Attention should be given to the loads applied during the installation, relocation, or replacement of equipment. The size, location, and direction of application of point loads from lifting equipment may be of significance. Dynamic effects of mobile equipment, e.g., forklift trucks, should be investigated. Observations should be made of impact responses from presses, hammers, compressors, and similar equipment, producing cyclic loads that may induce dynamic effects. The fatigue properties of the supporting members should be investigated. Loads from pipes, valves, and other services should be examined to confirm that the loads used in the design are adequate.

5.3.2.5 *Snow and ice loadings*-Consideration should be given to the buildup of snow and ice, particularly in roof valleys and snow drift accumulation against vertical surfaces.

5.4-Condition assessment

ACI 201.1R should be followed in assessing the condition of the concrete. The condition of a structure should be considered without prejudging the cause and type of defects. There is a danger that defects outside of previous experience of the investigator will be missed, and that significant effort may go into trying to find a type of defect that is not present. Therefore, it is necessary to describe the conditions adequately so they can be evaluated objectively. Photographs and videotapes can be valuable in this regard.

A visual inspection should be carried out to document

the extent and severity of any distress or deterioration which could affect the load-carrying capacity or service life of the structure. Previously repaired or modified portions of the structure should also be included in the inspection. The inspection records should be supplemented with sketches, photographs, and videotapes, as appropriate. Cracks, spalls, corrosion of reinforcing steel, etc., should be identified as follows (ACI 201.1R and Concrete Society 1982):

a) Cracks should be measured and recorded for width, depth, length, location, and type (i.e., structural or nonstructural). Structural cracks should be further identified, as flexure, shear, or direct tension, if known. Crack patterns should be plotted. Results of crack monitoring or recommendations for such monitoring should be considered

b) Spalling, scaling, honeycombing, efflorescence, and other surface defects should be measured and recorded

c) Corrosion of reinforcing bars, including the extent and amount of lost cross section, should be measured and recorded

d) Loose, corroded, or otherwise defective connectors for precast concrete elements, or ties to architectural elements or cladding should be noted

e) Deformations, whether permanent or transient under loads, out-of-plumb columns, and other misalignments, should also be measured and recorded. Continuous monitoring should be considered, as appropriate

f) Signs of foundation settlement or heave, and related distress, should be noted

g) Water leakage, ponding areas, areas of poor drainage, or other indications of water problems should be noted

h) Evidence of aggressive chemical deterioration such as sulfate attack and acid attack should be noted

In general, the visual inspection should include the measurement and assessment of three basic conditions: visible damage, visible deviations and deformations, and foundation settlement.

5.4.1 *Visible damage*-It is generally difficult to quantify the visible damage since it depends on subjective criteria and the experience of the inspectors. Moreover, damage which is acceptable in one region or one type of structure may not be acceptable in another circumstance. Therefore, before commencing the field observations, some guidelines should be established in assessing the observations so that a consistent representation and understanding of the significance of the damage is possible. A six-point assessment classification is recommended as follows:

a) Unsafe
b) Potentially hazardous
c) Severe
d) Moderate
e) Minor
f) Good condition

Any of the components of the structure can then be evaluated using this rating system.

The condition assessment using the preceding classifications should be supplemented by sketches, photographs, videotapes, measurements, and brief descriptions. It is important to note the extent and severity of deteriorated areas with respect to the entire structure being assessed. For example, if extensive spalling of a concrete beam is observed, it is important to note what percentage of the beam is spalled and what is the condition of the beam that is not spalled.

5.4.2 *Visible deviations and deformations*-Unintended visible deviations of members from the vertical or horizontal should be measured and recorded. Appraisal of relative movement is often guided by comparisons with neighboring or adjacent structures or members. Deviations from the vertical or horizontal in excess of about $L/250$ are likely to be noticed where L represents the span length. For horizontal members, a slope exceeding $L/50$ (¼ in./ft) would be visible, as would a deflection-to-length ratio of more than about $L/240$.

5.4.3 *Foundation settlement*-The field investigation should include an assessment 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 in the vicinity. If signs of differential settlement are present, it may be necessary to carry out a more detailed gee-technical investigation to assess fully the impact of the observed conditions.

5.5-Unsafe or potentially hazardous conditions

When unsafe or potentially hazardous conditions are discovered, the owner must be immediately notified of the potential consequences of these conditions. Temporary evacuation, temporary shoring measures, or any other emergency safety measures, if required, should be recommended to the owner. If public safety is involved, a follow-up of the conditions discovered should continue with the owner until satisfactory safety measures are implemented.

CHAPTER 6-SAMPLING AND MATERIAL TESTING

6.1-Introduction

This chapter contains information on practices and procedures for assessing the condition and properties of structural materials in an existing structure. These practices and methods include visual examination, nondestructive evaluation (NDE) tests, and destructive tests which include field and laboratory procedures.

6.2-Determination of testing requirements

The requirements for testing will depend on the findings during the preliminary investigation, the study of available documents, and the requirements of the proposed rehabilitation.

There is no need for testing where the available information is sufficient to complete the evaluation with confidence. A structure may clearly be in sound condition and without defects, and the dimensions measured during the investigation may allow analysis to confirm suitability for its intended future use.

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

Where testing is required, it is necessary to make an assessment of what specific information is needed. The purpose of each test and the information that it can provide must be understood so that the appropriate tests are carried out. Test methods range widely in cost, reliability, and complexity. Some tests require little or no disturbance, while others are destructive and require that a portion of the structure be removed from service while they are conducted. In some circumstances, the cost of testing may be so high that remedial action may be the more economic solution. Appropriate experience is necessary so that the required tests are performed properly and interpreted correctly.

The selection of the proper test methods (ACI 228.1R), and the number of tests and their locations will depend on:

a) Variation in material properties within the structure

b) Critical locations

c) Probable error in a test result

d) Extent of the structure over which a property is measured, e.g., ultrasonic-pulse-velocity measurements indicate the average quality through the entire depth of a member, whereas a core test measures only the condition of the material in the core

6.3-Testing and evaluation

Evaluation of existing concrete should include determinations of strength and quality (NRMCA 1979, ACI 228.1R, and Shroff 1986 and 1988). Proper assessment and subsequent evaluation should provide some understanding of the structural ability to sustain the loads and environmental conditions to which the structure is being or will be subjected (Mather 1985).

6.3.1 *Evaluation procedures for concrete*-The function of concrete material in a structure is twofold. First, the concrete functions as one component of the composite structural material that constitutes the load-carrying element. Second, the concrete provides an overall protection against fire and environmental forces. Specifically, the concrete cover provides protection against corrosion of the embedded steel reinforcement, insulates it against the effects of fire, and thereby provides durability.

For concrete to function as a load-carrying structural element, the following three coincidental characteristics are required: adequate strength, adequate cross-sectional area of both concrete and reinforcing steel, and adequate bond of concrete to steel. If the combination of these three characteristics is not adequate, the concrete is unacceptable.

For concrete to function as an effective cover for reinforcing or prestressing steel and to provide durability, it must a) be relatively dense, b) be nonporous, c) have low capillarity, d) have low permeability, and e) contain aggregates and cement that are nonreactive with each other and with the environment. Although some of these properties are related to compressive strength, the desired properties are usually achieved by controlling the amount and type of cement, degree of air entrainment, slump, water-cementitious materials ratio, type of aggregate and types of admixtures, and by controlled procedures for mixing, placing, and curing.

The preceding concepts indicate that concrete properties and physical conditions tabulated in Tables 6.1(a) and 6.1(b) may be considered in evaluating the acceptability of existing concrete and its future performance (ASCE 11). These tables should be used as a guide by the engineer performing the investigation based on past experience and judgment.

6.3.2 *Evaluation procedures for steel reinforcement*--**The** function of the embedded steel reinforcement in a concrete structure is to carry tensile and compressive forces. Not only must the properties and physical conditions of the steel be determined to evaluate this load-carrying ability, but the means of transmitting and distributing the stresses to the concrete structure must also be determined. These requirements indicate that the properties or physical conditions tabulated in Table 6.2 (ASCE 11) may be considered in evaluating the acceptability of the embedded steel reinforcement.

6.4-Nondestructive evaluation methods

The available nondestructive evaluation methods that may be used in the field or in the laboratory to assess the properties and physical conditions of structural materials are summarized in Table 6.3(a) through (e) (ASCE ll), in which each test is briefly explained along with its requirements, advantages, and limitations (Carino and Sansalone 1990, Clifton et al. 1982, Clifton 1985, Malhotra 1976, and Carino and Malhotra 1991).

6.5-Sampling techniques

6.5.1 *Concrete*-Samples of concrete in an existing structure may be used to determine strength as well as physical and chemical properties, as discussed earlier. It is essential that the samples be obtained, handled, identified (labeled), and stored in a proper fashion 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 statistical information about the properties of concrete in the structure or to characterize some

Table 6.1(a)-Evaluation of properties of concrete

EVALUATION PROCEDURE / CHEMICAL AND PHYSICAL PROPERTIES	ACOUSTIC IMPACT (Table 6.3)	AIR CONTENT TEST (ASTM C457)	CEMENT CONTENT TEST (ASTM C1084)	CHEMICAL TESTS	CORE TESTING (ASTM C42)	ELECTRICAL POTENTIAL MEASUREMENTS (Table 6.3)	ELECTRICAL RESISTANCE MEASUREMENTS (Table 6.3)	FLEXURAL TESTS (ASTM C42)	FREEZE-THAW TEST (ASTM C666)	GAMMA RADIOGRAPHY (Table 6.3)	NUCLEAR MOISTURE METER (Table 6.3)	PERMEABILITY TEST (CRD C48)	PETROGRAPHIC ANALYSIS (ASTM C856)	PULLOUT TESTING (ASTM C900)	REBOUND HAMMER (ASTM C805)	ULTRASONIC PULSE (ASTM C597)	WINDSOR PROBE (ASTM C803)
ACIDITY				●									●				
AIR CONTENT		●											●				
ALKALI-CARBONATE REACTION													●				
ALKALI-SILICA REACTION													●				
CEMENT CONTENT			●	●									●				
CHEMICAL COMPOSITION				●									●				
CHLORIDE CONTENT				●	●								●				
COMPRESSIVE STRENGTH					I									I	I	I	I
CONTAMINATED AGGREGATE				●									I				
CONTAMINATED MIXING WATER				I									●				
CORROSION ENVIRONMENT				I		●											
CREEP					●												
DENSITY					I					●							
ELONGATION					I												
FROZEN COMPONENTS													I				
MODULUS OF ELASTICITY					●											●	
MODULUS OF RUPTURE					I			●									
MOISTURE CONTENT					●		I				I						
PERMEABILITY												●	●				
PULL OUT STRENGTH														I			
QUALITY OF AGGREGATE													I				
RESISTANCE TO FREEZING AND THAWING					I				●				I				
SOUNDNESS					I					I			I				
SPLITTING TENSILE STRENGTH					I												
SULFATE RESISTANCE				I									●				
TENSILE STRENGTH					●			●									
UNIFORMITY	I												●		●		●
WATER-CEMENT RATIO													I				

Table 6.1(b)-Evaluation of physical conditions of concrete

PHYSICAL CONDITION \ EVALUATION PROCEDURE	ACOUSTIC EMISSIONS (Table 6.3)	ACOUSTIC IMPACT (Table 6.3)	CHEMICAL TESTS	CORE TESTING (ASTM C42)	FIBER OPTICS (Table 6.3)	GAMMA RADIOGRAPHY (Table 6.3)	INFRARED THERMOGRAPHY (Table 6.3)	LOAD TESTING (ACI 437R)	PETROGRAPHIC ANYLYSIS (ASTM C856)	PHYSICAL MEASUREMENT	RADAR (Table 6.3)	REBOUND HAMMER (ASTM C805)	ULTRASONIC PULSE (ASTM C597)	ULTRASONIC PULSE-ECHO (Table 6.3)	VISUAL EXAMINATION (ACI 201.1R, ASTM C823)	WINDSOR PROBE (ASTM C803)
BLEEDING CHANNELS									I						●	
CHEMICAL DETERIORATION			I						●						●	
CORROSION OF STEEL			●	●					●						●	
CRACKING	●	●		●	●		●		●	●	●		●	●	●	
CROSS SECT PROPERTIES AND THICKNESS				●		●				●			●			
DELAMINATION		●		●	●	●	●		●		●		●	●	●	
DISCOLORATION			●						●						●	
DISINTEGRATION				●		●	●		●				●		●	
DISTORTION															●	
EFFLORESCENCE			I						●						●	
EROSION									●						I	
FREEZE-THAW DAMAGE									●						●	
HONEYCOMB				●	●	●	●		●				●		●	
POPOUTS															●	
SCALING															●	
SPALLING				●		●	●								●	
STRATIFICATION		I			●									●	●	
STRUCTURAL PERFORMACE	I							●							I	
UNIFORMITY OF CONCRETE						●			●			I	●	I	●	

Table 6.2-Evaluation of properties of reinforcing steel

EVALUATION PROCEDURE / PROPERTIES AND CONDITIONS	ACOUSTIC IMPACT (Table 6.3)	CHEMICAL ANALYSIS (ASTM A751)	COATING TESTS (ASTM A775, G12, 14, 20)	COVER METERS PACHOMETER (Table 6.3)	ELECTRICAL POTENTIAL MEASUREMENTS (Table 6.3)	GAMMA RADIOGRAPHY (Table 6.3)	PHYSICAL MEASUREMENTS	RADAR (Table 6.3)	TENSION TESTS (Table 6.3)	ULTRASONIC PULSE-ECHO (Table 6.3)	VISUAL INSPECTION
ADHESION OF EPOXY COATING			●								
ANCHORAGE							●				
BEND TEST							●				
BREAKING STRENGTH									●		
CARBON CONTENT		●									
CHEMICAL COMPOSITION		●	●								
COATING PROPERTIES		●									
CONCRETE COVER				●		●	●	●			
CONTINUITY OF EPOXY COATING			●								
CORROSION					●		●				●
CROSS-SECTIONAL PROPERTIES & THICKNESS							●				
DEFORMATIONS							●				●
ELONGATION									●		
EXPOSURE											●
REBAR LOCATION	●			●		●	●	●			
REDUCTION OF AREA									●		
SHAPE							●				
STRENGTH OF CONNECTIONS							●				
TENSILE STRENGTH									●		
THICKNESS OF EPOXY COATING			●								
WELD SHEAR STRENGTH							●				
YIELD STRENGTH									●		

Table 63-Description of nondestructive (event as noted) evaluation methods for concrete

Method	Applications	Principle of operation	User expertise	Advantages	Limitations
Acoustic emission (Clifton et al., 1982;	Continuous monitoring of structure during service life to detect impen, ding failure; monitoring performance of structure during proof testing.	During crack growth or plastic deformation, the rapid release of strain energy produces acoustic (sound) waves that can be detected by sensors in contact with or attached to the surface of a test object.	Extensive knowledge required to plan test and to interpret results.	Monitors structural response to applied load; capable of locating source of possible failure; equipment is portable and easy to operate, good for load tests.	Expensive test to run; can be used only when structure is loaded and when flaws are growing; interpretation of results required an expert; currently largely confined to laboratory; limited track record, further work required.
Acoustic impact (Clifton et al., 1982)	Used to detect debonds, delaminations. voids, and hairline cracks.	Surface of object is struck with an implement. The frequency and damping characteristics of resulting sound, giving an indication of the presence of defects; equipment may vary from simple hammer or drag chain to sophisticated trailer-mounted electronic equipment.	Low level of expertise required to use auditory system but the electronic system requires training.	Portable equipment; easy to perform with auditory system; electronic device requires more equipment.	Geometry and mass of test object influence results; poor discrimination for auditory system; reference standards required for electronic testing.
Core testing (ASTM C 42)	Direct determination of concrete strength; concrete evaluation of condition type and quality of aggregate, cement, and other components.	Drilled cylindrical core is removed from structure; tests may be performed on core to determine compressive and tensile strength, torsional properties, static modulus of elasticity, etc.	Special care not to damage cores must be taken in obtaining drilled cores; moderate level of expertise required to test and evaluate results.	Most widely accepted method to determine reliably the strength and quality of in-place concrete. Good for examinations of cracks, embedded reinforcing bars, and for sample for chemical tests.	Coring damages structures and repairs may be required. Destructive test.
Cover meters/Pachometers (Malhotra 1976)	Measure cover, size, and location of reinforcement and metal embedments in concrete or masonry.	Presence of steel in concrete or masonry affects the magnetic field of a probe. The closer the probe is to steel, the greater the effect.	Moderate; easy to operate; training needed to interpret results.	Portable equipment, good results if concrete is lightly reinforced. Good for locating reinforcing or prestressing tendons and wires to avoid damage in coring.	Difficult to interpret results if concrete is heavily reinforced or if wire mesh is prerent. Not reliable for cover of 4 in.; and form ties often mistaken for anchors.
Electrical potential measurements (Mathey and Clifton 1988)	Indicating condition of steel reinforcing bars in concrete masonry. Indicating the corrosion activity in concrete pavements.	Electrical potential of concrete indicates probability of corrosion.	Moderate level of experience required, user must be able to recognize problems.	Portable equipment, field measurements readily made; appears to give reliable information	Information on rate of corrosion is not provided; access to reinforcing bars required.
Electrical resistance measurements (Mathey and Clifton 1988)	Determination of moisture content of concrete.	Determination of moisture content of concrete is based on the principle that the conductivity of concrete changes with changes in moisture conlent.	High level of expertise required to interpret results; equipment is easy to use.	Equipment is automated and easy to use.	Equipment is expensive and requires high-frequency specialized applications; dielectric properties also depend on salt content and temperature of specimen, which poses problems in interpretation of results. Not too reliable.

Table 6.3 cont.-Description of nondestructive evaluation methods for concrete

Method	Applications	Principle of operation	User expertise	Advantages	Limitations
Fiber optics (Mathey and Clifton 1988)	To view portions of a structure that are inaccessible to the eye.	Fiber optic probe consisting of flexible optical fibers. lens, and illuminating system is inserted into a crack or drilled hole in concrete; eyepiece is used to view interior to look for flaws such as cracks, voids, or aggregate debonds, commonly used to look into areas where cores have been removed or bore boles have been drilled. Examination of cavity walls and other masonry boles.	Equipment is easy to handle and operate.	Gives clear high-resolution images of remote objects. Camera attachment for photos is available. Flexible hose enables multidirectional viewing.	Equipment expensive; many bore boles are required to give adequate access. Mortar in masonry walls binders view.
Infrared thermography (Mathey and Clifton 1988)	Detection of internal flaws, crack growth, delamination, and internal voids.	Flaws detected by using selective infrared frequencies to detect various passive heat patterns which can be identified as belonging to certain defeds. Through cracks in concrete and masonry ma: be detected on cold days.	High level of expertise required to interpret results.	Has potential for becoming a relatively inexpensive and accurate method for detecting concrete defects; can over large areas quickly	Requires special skill and equipment. Effective where temperature differential between surfaces is high.
Load testing (ACI 4371)	Determine performance of a structure under a simulation of actual loading conditions, using overload factors.	Test load is applied to structure in a manner that will simulate the load pattern under design conditions.	High level of expertise required to formulate and conduct the test program and to evaluate the results. Protecion shoring is required 'or safety.	Provides highly reliable prediction of structure's ability to perform satisfactorily under expected loading conditions.	Expensive and time-consuming; testing may cause limited or even permanent damage to the structure or some of its elements.
Nuclear moisture meter (ASTM D 3017)	Estimation of moisture content of hardened concrete.	Moisture content in concrete determined based on the principle that materials (such as water) decease the speed of fast neutrons in accordance with the amount of hydrogen produced in test specimen.	Must be operated by rained and licensed personnel.	Portable moisture estimates can be made of in-place concrete.	Equipment sophisticated and expensive; NRC License required to operate; moisture gradients in specimen may give erroneous results. Measures all nitrogen in concrete as well as nitrogen in water.
Petrographic analysis (ASTM C 856)	Used to determine a variety of properties of concrete or mortar sample removed from structure; some of these include 1) denseness of cement. 2) homogeneity of concrete 3) location of cracks, 4) air content, 5) proportions of aggregate, cc-ment, and air voids, and 6) curing.	Used in conjunction with other tests. chemical and Physical analysis of concrete samples is performed by qualified petrographer.	High level of skill and raining required to perform and analyze test results.	Provides detailed and reliable information of concrete ingredients. paste, aggregates, curing, possible damage, and freezing	Qualified experienced petrographer required; relatively expensive and time-consuming.
Pullout testing (ASTM C 900)	Estimation of compressive and tensile strengths of existing concrete.	Measure the force required to pull out the steel rod with enlarged head cast in concrete; pullout forces produce tensile and shear stresses in concrete.	Low level of expertise required, can be used by field personnel.	Directly measures in-place strength of concrete; appears to give good prediction of concrete strength.	Pullout devices must be inserted during construction; cone of concrete may be pulled out, necessitating minor repairs.

Table 6.3 cont.-Description of nondestructive evaluation methods for concrete

Method	Applications	Principle of operation	User expertise	Advantages	Limitations
Pull-off testing (Long and Murray 1984)	Estimation of the compressive strength of existing concrete.	Circular steel probe is bonded to concrete. Tensile force is applied using portable mechanical system until concrete fails. Compressive strength can be estimated using calibration charts.	Highly skilled operator is not required.	Simple sad inexpensive.	Standard test procedure not yet available. Limited track record. Concrete must be repaired at test locations.
Radar (Mathey and Clifton 1988)	Detection of substratum voids, delaminations. and embedments. Measuremeat of thickness of concrete pavements.	Uses transmitted electromagnetic impulse signals for void detection.	High level of expertise required to operate equipment sad interpret results.	Expedient methods can locate reinforcing bars and voids regardless of depths. May be used when only one surface is available.	Equipment is expensive; reliability of void detention greatly reduced if reinforcement present; procedure still under development.
Gamma radiography (Malhotra 1976)	Estimation location, size, sad condition of reinforcing bars; voice in concrete; density.	Based on principle that the rate of absorption of gamma rays is affected by density sad thickness of test specimen; gamma ray are emitted from source. penetrate the specimen, exit on opposite side, end are recorded on file.	Use of gamma-pro ducing isotopes is closely controlled by NRC, equipment must be operated by licensed inspectors.	Internal defects can be detected; applicable to variety of materials; permanent record on film, gamma-ray equipment easily portable.	Equipment is expensive; gamma-ray source is health and safety hazard; requires access to both sides of specimen.
Rebound hammer (ASTM C 805)	Compares quality of concrete from different areas of specimen; estimates of concrete strength based on calibration curves with limited accuracy.	Springdriven mass strikes surface of concrete sad rebound distance is given in R-values; surface hardness is measured and strength estimated from calibration curves provided by hammer manulecturer.	Simple to operate; can be readily operated by field personnel.	Equipment is lightweight simple to operate, and inexpensive, large amount of data can be quickly obtained, good for determining uniformity of concrete and stress potentially low strength.	Results effected by condition of concrete surface; does not give precise prediction of strength; estimates of strength should be used with great care; frequent calibration of equipment required.
Ultrasonic pulse (ASTM C 597)	Gives estimates of uniformity, quality. compressive strength. (when previously correlated) of concrete; internal discontinuities can be located sad their size estimated; most widely used stress wave method for field use.	Operates on principle that stress wave propagation velocity is affected by quality of concrete; pulse waves are induced in materials sad the time of arrival measured at the receiving surface with a receiver.	Varying level of expertise required to Interpret results. Operator requires a fair degree of training.	Equipment relatively inexpensive and easy to operate; accurate measurement of uniformity sad quality. By correlating compressive strength of cores and wave velocity, in-situ strength can be estimated.	Good coupling between transducer and concrete is critical; interpretation of results can be difficult density, amount of aggregate, moisture variations. and presence of metal reinforcemeat may affect results; calibration standards required.
Visual examination (ACI 2O1.1R and ASTM C 823)	(a) Evaluation of the surface condition of concrete (finish, roughness, scratches cracks, color). (b) Determining deficiencies in joints. (c) Determining deformations and differential movements of structure.	Visual examination with or without optical aids, measurement tools, photographic records, or other low-cost tools, differential movement determined over long periods with surveying methods and other instrumentation	Experience required to letermine what to look for, what measurement to take, interpretation of conditions, and what follow-up testing to specify.	Generally low costs; rapid evaluation of concrete conditions.	Trained evaluation required, primary evaluation confined to surface of structure.

Table 6.3 cont.-Description of nondestructive evaluation methods for concrete

Method	Applications	Principle of operation	User expertise	Advantages	Limitations
Penetration resistance (ASTM C 803)	Estimates of compressive strength. uniformity. and quality of concrete may he used for estimating strength prior to form removal.	Probes are gun-driven into concrete; depth of penetration converted to estimates of concrete strength by using calibration curves.	Simple to operate, can be readily operated in the field with little training. Safety require operator certificate.	Equipment is simple, durable. and requires little maintenance, useful in assessing the quality and relative strength of concrete; does relatively little damage to specimen.	May not yield accurate estimates of concrete strengths; interpretation of results depends on correlation curves. Difficulty in removing the probes, which are often broken and damaging to cover concrete.
Ultrasonic pulse-echo (Thornton and Alexander 1987)	Gives estimates of compressive strength, uniformity, and quality of cooncrete. Can locate reinforcing bar. defects, voids delamination, sad determine thickness.	Operates on principle that original direction, amplitude, sad frequency conteat of stress waves intro duced into concrete are modified by the presence of interfaces such as cracks, objects, sad sections which have different acoustic impedance.	High level of expertise required to interpret results. Operator should have considerable training to use equipment and knowledge of electronics, and should have considerable training in the area of condition survey of concrete struclures.	Can operate where only oat surface is accessible. Can operate in dry (in theory - never saw publicized material). Allows one to "see" inside concrete.	Is still in develop mental stage. Needs development of measurement criteria. Not presently a standard test method. Digital signal pro cessing can improve interpretation but data must be returned to laboratory for processing at present.
Resonant frequency testing (Carino and Sansalone 1990)	Is used in the laboratory to determine various fundamental modes of vibration for calculating moduli; used in field to detect voids, delaminations.	A resonant frequency condition is set up between two reflecting interfaces. Energy can be introduced by hammer impact oscillator-amplifier-electromagnetic driver system.	High level of expertise required to interpret results. Operator can be easily trained for laboratory measuremeats as specimens have simple geometry.	Allows one to "see inside" concrete structures, can penetrate to depths of a number of feet; a newly developed transducer receiver can improve results over an accelerometer.	Operates in sonic range and does not have resolution of ultrasonics. Still in developing stage.

unusual or extreme conditions in specific portions of the structure. In the first case, sample locations should be randomly distributed throughout the structure. The number and size of samples depend on the laboratory tests and the degree of confidence desired in the average values obtained from the tests.

The sampling plan depends on whether the concrete is generally believed to be uniform, or if there are likely to be two or more regions different in composition, condition, or quality. The results of the preliminary investigation and the review of other sources of information 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 strength, elastic modulus, or air content, the number of samples should be determined in accordance with ASTM E 122. The required number of samples generally depends on:

a) Maximum difference (or error) that one is willing to accept between the sample average and the true average

b) Variability of the test results

c) Risk that one is willing to accept that the allowable difference is exceeded

Since the variability of test results is usually not known in advance, an estimate should be made and adjusted as test results become available. Cost should also be considered in the selection of sample sizes. In some cases, increasing the sample size may result 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.

It should be recognized that 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 members, such as columns, walls, and deep beams, because concrete properties will vary with elevation due to differences in placing and compaction procedures, segregation, or bleeding.

6.5.1.1 *Core sampling*-The procedures for properly removing concrete samples by core drilling are given in ASTM C 42. The number, size, and location of core samples should be carefully selected to permit all necessary laboratory tests. If possible, use virgin samples for all tests so that there will be no influence from prior 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 problem.

For determining compressive strength or static or dynamic modulus of elasticity, the diameter of the core should not be less than three times the nominal maximum size of aggregate.

6.5.1.2 *Sampling of concrete with sawed beams*-Where appropriate, sampling by sawing beams in accordance with ASTM C 42 may be used as an alternative to drilled core sampling. However, research has shown that significant reductions in strength may be encountered when using sawed beam samples. This should be taken into consideration in the final analysis of the results.

6.5.1.3 *Random sampling of broken concrete*-Sampling of broken concrete generally should not be used where a strength property of concrete is in question. This method is most frequently used when evaluating chemical or physical properties of deteriorated concrete members.

6.5.2 Steel reinforcement-Samples of steel reinforcement from existing members may be retrieved to determine the strength, physical or chemical properties, or both. The removed reinforcing bars should be replaced if required by design. The characteristics, selection, and preparation of samples are discussed in ASTM A 370. Some of the important considerations are:

a) 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 member

b) Locations of specimens in continuous concrete construction should be separated by at least the development length of the reinforcement to avoid excessive weakening of the member

c) 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)

d) For longer spans or larger areas, more specimens should be taken from locations well distributed through the portion being investigated, to determine whether the same strength of steel was used throughout the structure

e) Information from Grade Marks and Mill Marks should be collected when possible and used as appropriate in guiding sample collection

CHAPTER 7-EVALUATION

7.1—Introduction

Evaluation is a process of determining the adequacy of a structure or component for its intended use by analyzing systematically the information and data assembled from reviews of existing documentation, field inspection, condition survey, and material testing. This investigative process of evaluation cannot be generally standardized into a series of well-defined steps because the number and type of steps 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. Only general guidelines are presented in this chapter.

Structural evaluations should be performed to determine the load-carrying capacity of all critical elements of the structure, and the structure as a whole. The ability of the structure to support all present and anticipated loads according to current code requirements or standards should be considered. Where these code requirements are not met with the structure in its current condition, appropriate strengthening methods and techniques should be determined.

Ihe need to meet architectural requirements should also be evaluated. Both changes in architectural layout and modifications to the facades of the structure should be evaluated. Final schemes should be selected by the owner from various design alternatives. The cost of various alternatives should be estimated and the implications evaluated.

7.2-Dimensions and geometry

The actual dimensions of the structure and architectural layout should be evaluated for use, access, and needed space. The field-measured cross sections of the critical structural components should be reviewed. Discrepancies between the field-measured dimensions and those indicated on available drawings should be evaluated.

7.3-Materials evaluation

Field and laboratory test results should be studied so that components of the structure that require repair can be identified. The structural components which require total replacement should be identified and new materials selected. All existing materials should be evaluated for strength, quality, and satisfactory performance in terms of life expectancy, future loads, and intended usage.

Where rehabilitation is required, the appropriate materials should be studied and recommendations made. The materials should be selected based on the environment, type of use, life expectations, and compatibility with existing materials. After evaluation of the existing conditions, it may be determined that protection from further deterioration is required. Methods such as coating, shielding, or specialized systems (e.g., cathodic protection) should be considered.

7.4-Structural evaluation

Using the information obtained from the field survey, dimension and geometry evaluation, and material evaluations, the load-carrying capacity of the structure or portion of the structure undergoing evaluation should be determined. The choice of the evaluation method is dependent on such factors as the nature of the structure and the amount of information known about its existing condition. The typical choices are 1) evaluation by analysis, 2) evaluation by analysis and full-scale load testing, or 3) evaluation by analysis and structural modeling (ACI 437R).

Evaluation by analysis, the most common method, is recommended when sufficient information is available about the physical characteristics, material properties, structural configuration, and loadings to which the structure has been and will be subjected.

Evaluation by analysis and full-scale load testing or structural modeling or both is recommended when the complexity of the design concept and lack of experience with the structural system make evaluation solely by analytical methods unreliable, or when the nature of existing distress introduces significant uncertainties into the magnitude of the parameters necessary to perform an analytical evaluation, or when the geometry and the material characteristics of the structural elements being evaluated cannot be readily determined.

Critical structural components including members and connections should be identified for evaluation based on the document review, dimension and geometry check, and material evaluation.

The capacities of the critical structural components should be determined preferably by the strength design method. Sophisticated methods such as finite element analyses may be used. All existing and expected dead loads and live loads, equipment and piping loads, and code-mandated wind and earthquake requirements must be considered.

Where applicable, the nonstructural components should also be evaluated to insure that they are capable of resisting the prescribed loads and deformations. Ihe effect of nonstructural components on the overall performance of the structure should also be considered.

7.5 Evaluation of rehabilitation alternatives

Even if the existing structure appears to meet all the strength requirements, cosmetic or other types of repairs may stiIl be required to restore the structure to an appropriate condition. Alternate repair methods, as well as the possibility of using the "do nothing approach," should be evaluated based on comparative cost estimates, schedules, and relative levels of interference with the operations.

When the existing structure (or components) does not meet the strength requirements, alternate methods of strengthening should be evaluated, comparative cost estimates should be prepared for the various alternates, and a recommendation for the selected method or methods should be made for the owner's approval.

Where the structure to be restored is occupied, the effect of repair or strengthening procedures on the normal operations of the structure must be considered. This includes effects such as noise, dust, and physical interruption of operations. The possibility of work during off-hours, (nights and weekends) should be evaluated because it often proves to be desirable and cost effective.

7.6-Cost evaluation

A cost evaluation should be conducted for all feasible repair or rehabilitation alternatives. The cost of rehabilitation is subject to many factors; however, the cost for certain types of structural repair or strengthening work can often be reasonably estimated based on previous experience. Such an estimate can form the basis for an initial decision regarding the appropriate alternative to be selected and the overall economic feasibility of the project.

A more detailed cost of rehabilitation should be documented, taking into account the location of the project and the existing and available labor and skilled contractors. These costs should be computed for the approximate time of the actual construction schedule. It must be recognized that unanticipated conditions requiring extra cost are common in many rehabilitation projects and adequate contingencies should be provided.

In the event the estimated costs exceed the available budget, another cycle of possible reductions should be studied. The final rehabilitation program then can be modified and approved by the owner, who should be advised that actual costs can be determined only after preparation of detailed contract documents (drawings and specifications) and after obtaining firm bids from contractors.

If the cost of upgrading is determined to be prohibitive, possible alternate uses of the structure should be studied, or a recommendation made for continuing its present use or for phasing out its use.

CHAPTER 8 FINAL REPORT

8.l-Introduction

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

a) Purpose and scope of investigation
b) Existing construction and documentation
c) Field observations and condition survey
d) Sampling and material testing
e) Evaluation
f) Findings and recommendations

8.2-Purpose and scope of investigation

This section of the report should describe the purpose and scope of the investigation as agreed with the owner, including any modifications made during the course of the evaluation.

8.3-Existing construction and documentation

A brief summary of information on the existing structure including location, size, history, architectural and structural details, etc., 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 collected and their sources should be included.

8.4-Field observations and condition survey

The results of the inspection and condition survey for all portions of the structure, including its envelope and foundations, should be included. The report should briefly describe methods and equipment used, results of as-built verification efforts, including all deviations, major deficiencies that require remedial work, and all portions of the structure that are to be altered for change of use or appearance. The report should also include photographs, sketches, drawings, and other pertinent information prepared during the inspection and field survey operations.

8.5-Sampling and material testing

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 in terms of physical condition, strength, and future performance of all structural and architectural materials tested.

8.6-Evaluation

The report should summarize the results of the strength evaluation of the structure. All assumptions made and methods used in the evaluation process should be clearly documented. A brief description of each repair alternate (Corps of Engineers 1986) or strengthening method studied, along with sketches showing typical details, cost estimates, and the impact of the repair method, should be included.

8.7-Findings and recommendations

The findings from each preceding task discussed should be summarized in this section of the report. The findings should include a discussion of the condition of the structure and the feasibility of the rehabilitation. The recommendations must address the following topics: action plan, cost estimates, scheduling, and determining constraints and feasibility.

8.7.1 *Action plan*-The recommendation should clearly point out an appropriate course of action, such as 1) accept the structure as-is, 2) strengthen the structure to correct deficiencies identified, 3) change the use of the structure, or 4) phase the structure out of service. 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 are severe, it may be necessary to assign priorities to repairs and to stage the program accordingly over several years. Feasible alternatives to the recommended plan of action should be identified including estimated costs and payback periods.

8.7.2 *Cost estimates*--Project costs often influence every aspect of a recommended rehabilitation plan and, while not necessarily controlling the final recommendations, can have a major influence on them. 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 repair schemes, and the life expectancy of the entire structure, should be considered. The total cost estimate should also include cost of the required engineering services, testing services, and contingencies.

8.7.3 *Scheduling*--Project schedule may be 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 must consider the lead time for engineering and for preparation of construction documents. 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.

8.7.4 *Constraints and feasibility determination*-Rehabilitation often involves the constraints associated with working around existing operations. 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. Special project planning meetings are often helpful in determining the most appropriate way of handling these constraints. It is of critical importance to insure that any constraints mandated by the owner be considered and incorporated into the rehabilitation plan.

CHAPTER 9-RECOMMENDED REFERENCES

9.1-Recommended references

The documents of the various standards-producing organizations referred to in this document are listed with their serial designations.

American Concrete Institute

116R Cement and Concrete Technology

201.1R Guide for Making a Condition Survey of Concrete in Service

228.1R In-Place Methods for Determination of Strength of Concrete

437R Strength Evaluation of Existing Concrete Buildings
B-14 History of Concrete
SP-85 Rehabilitation, Renovation, and Preservation of Concrete and Masonry Structures

ASTM
A 370 Test Methods and Definitions for Mechanical Testing of Steel Products
A751 Methods, Practices, and Definitions for Chemical Analysis of Steel Products
A 775 Specification for Epoxy-Coated Reinforcing Steel Bars
C 42 Methods of Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
C 457 Practice for Microscopical Determination of Air-Void Content and Parameters of the Air-Void System in Hardened Concrete
C 597 Test Method for Pulse Velocity Through Concrete
C 666 Test Method for Resistance of Concrete to Rapid Freezing and Thawing
C 803 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 900 Test Method for Pullout Strength of Hardened Concrete
C 1084 Test Method for Portland-Cement Content of Hardened Hydraulic-Cement Concrete
D 3017 Test Method for Moisture Content of Soil and Soil Aggregate in Place by Nuclear Methods (Shallow Depths)
E 122 Practice for Choice of Sample Size to Estimate the Average Quality of a Lot or Process
G 12 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

Other standards
ASCE 11-90 Guideline for Structural Condition Assessment of Existing Buildings
CRD C 48 Method of Test for Water Permeability of Concrete, U.S. Army Corps of Engineers Standard

The preceding references are available from:

American Concrete Institute
P.O. Box 19150
Detroit, MI 48219.0150

ASTM 1916 Race St.
Philadelphia, PA 19103

American Society of Civil Engineers
345 East 47th St.
New York, NY 10017

U.S. Army Engineer Waterway Experiment Station
Vicksburg, MS 391809.

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Shroff, 1986, "Old Concrete Arches," *Concrete International Design & Construction*, V. 8, No.5, May, pp. 52-57.

Shroff, 1988, "Evaluating a 50 Year Old Concrete Bridge," *Concrete International: Design & Construction*, V. 10, No. 5, May, pp. 56-62.

Stowe, R.L., and Thornton, H.T., 1984, "Engineering Condition Survey of Concrete in Service," *Technical Report* REMR-CS-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

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 Engineer Waterways Experiment Station, Vicksburg, MS.

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