The strength of existing concrete buildings may be evaluated analytically or by load tests. These recommendations indicate when such an evaluation may be needed, establish criteria for selecting the evaluation method, and indicate the data and background information necessary for an evaluation. Methods of determining material properties used in the analytical investigation are described in detail. Analytical investigations should follow the principles of strength design outlined in ACI 318. Procedures for conducting static load tests are recommended and criteria indicated for deflection under load and recovery.

Keywords: Buildings; cracking (fracturing); deflection; deformation; evaluation; instruments; leads; load tests (structural); nondestructive tests; reinforced concrete; reinforcing steel; serviceability static tests; strength; structural design; structures; tests.

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Chapter 1 --INTRODUCTION

1.1 -- Scope
This report provides recommendations to be followed in an investigation to establish the loadings that can safely be sustained by the structural elements of an existing concrete building. The procedures may be applied generally to other concrete structures provided that appropriate evaluation criteria are agreed to prior to the start of the investigation. This report covers conventionally reinforced cast-in-place concrete, precast-prestressed concrete, and post-tensioned, cast-in-place concrete.

1.2 -- Applications
The procedures recommended in this report apply where the strength evaluation of an existing concrete building is required in one or more of the following circumstances:

-- Distressed structures which show damage from excess or improper loading, vibrations, fire, etc.

-- Deteriorated structures where there is evidence of structural weakness, such as excessive cracking or spalling of the concrete, reinforcing bar corrosion, member deflection or rotation, etc.

-- Defective structures suspected to be substandard in design, detail, material, or construction

-- Structures where there is doubt as to structural adequacy with regard to future loading when the original design criteria are not known

-- Structures undergoing a change in use or occupancy where there is doubt concerning structural adequacy when the prospective loading exceeds the service load capacity calculated for the original design criteria

-- Structures which require performance testing following remedial measures (repair or strengthening)

1.3 -- Exceptions
This report does not address the following conditions:

-- Performance testing of structures with unusual design concepts

-- Product development testing where load tests are carried out for quality control or approval of mass produced elements

-- Evaluation of foundations and/or soil conditions

-- Structural engineering research

1.4 -- Categories of evaluation
There are a number of different characteristics or levels of performance of an existing concrete structure that can be evaluated. These include:

-- Stability of the entire structure

-- Stability of individual components of the structure

-- Strength and safety of individual structural elements

-- Stiffness of the entire structure

-- Stiffness of individual structural elements

-- Susceptibility of individual structural elements to excess long-term deformation

-- Dynamic response of individual structural elements

-- Durability of the structure

-- Fire resistance of the structure

-- Serviceability of the structure

1.5 -- Procedure for a structural evaluation
Most structural evaluations have a number of basic steps in common. However, each evaluation should be treated as unique and emphasis placed on the different steps as dictated by the project. Generally, the evaluation will consist of:
Defining the existing condition of the building, including:

1. Reviewing available information on the building
2. Conducting a condition survey of the building
3. Determining the cause and rate of progression of existing distress
4. Determining the degree of repair to precede the evaluation

Selecting the structural elements which require detailed evaluation
Assessing past, present, and future loading conditions to which the structure has and will be exposed under the anticipated use
Conducting the evaluation
Evaluating the results

1.6 -- Commentary

Engineering judgment is a critical element in the strength evaluation of reinforced concrete buildings. Judgment of trained structural engineers may take precedence over compliance with rigid code provisions or formulas for analyses. It should be recognized that there is no such thing as an absolute measurement of structural safety in an existing concrete building, particularly in buildings that are deteriorated due to prolonged exposure to the environment, or that have been damaged in a physical event such as a fire. Similarly, there are no generally recognized criteria for evaluating serviceability of an existing concrete building. Engineering judgment and close consultation with the owner regarding the intended use of the building is required in this type of evaluation.

The following conclusions are possible regarding the integrity of a structure as a result of a strength evaluation:

- The structure is adequate for normal use over its expected life if maintained properly
- The structure, although adequate for present loading and existing conditions, may not remain so in the future
- The structure is inadequate for its current or intended use, but may be adequate for alternative use
- The structure is inadequate or unsafe, and needs remedial work
- The structure is unsafe and beyond repair
- The information or data are not sufficient to reach a definitive conclusion

1.7 -- Organization of the report

The remainder of this report is structured into the following four chapters:

Chapter 2 -- The preliminary investigation, discusses the information that must be gathered to perform a strength evaluation and how that information can be gathered. Two primary topics are covered. The first is a review of existing records on the building. The second is the condition survey of the building, including guidelines on the proper recognition of abnormalities in a concrete structure, and survey methods available for evaluation of structural concrete.

Chapter 3 -- Methods for material evaluation, outlines procedures that should be undertaken to assess the quality and mechanical properties of the concrete and reinforcing steel materials in the structure, in their present condition. Discussion is included on sampling techniques, petrographic and chemical analysis of concrete, and test methods available to assess the mechanical properties of concrete and steel.

Chapter 4 -- Assessment of loading and selection of evaluation method, provides information regarding procedures necessary to properly assess the past, present, and future loading conditions of the structure, or structural component in question. The second part of the chapter is devoted to a discussion of how to select the proper method for evaluating the strength of an existing structure.

Chapter 5 -- The evaluation, provides commentary on the conduct of a strength evaluation for an existing concrete structure. Analytical techniques are discussed, and the use of load tests to supplement the analytical evaluation is considered.

CHAPTER 2 -- THE PRELIMINARY INVESTIGATION

This chapter describes the initial, preliminary, work that should be performed during a strength evaluation of an existing concrete building. Sources of information that should be reviewed are discussed and detailed information is presented about procedures for conducting a condition survey.

2.1 -- Review of existing information

All sources of existing information concerning the design, construction, and service life of the building should be researched to learn as much as possible about the structure. Attempts should be made to clearly recon-
struct the original design assumptions and theories. The objective is to minimize the number of assumptions necessary to perform an analytical evaluation. The following is a comprehensive listing of available information sources. It is intended as a guide only. It should be recognized that each source need not be consulted in a strength evaluation.

2.1.1 The original design -- The following sources of information should be researched to define the parameters used in the original design:

- Architectural, structural, mechanical, electrical, and plumbing contract drawings
- Structural design calculations
- Change orders to the original contract drawings and specifications
- Records of the local building department

2.1.2 Construction materials -- Project documents should be checked to develop an understanding of the type of materials that were originally specified and actually used for the building. These include:

- Reports on the proportions and properties of the concrete mixtures
- Reinforcing steel mill test reports
- Material shop drawings, including all placing drawings prepared by suppliers that were used to place their products (bars, welded wire fabric, and prestressing steel) in the original construction of the building; formwork drawings; and mechanical, electrical, and plumbing equipment drawings

2.1.3 Construction records -- In many cases, documentation dating from original construction will be available to the investigator. These often include:

- Correspondence records of the design team, the owner, the general contractor, the specialty subcontractors, and the material suppliers and fabricators
- Field inspection reports
- Contractor and subcontractor diaries
- Job progress photographs
- Concrete cylinder compressive strength test reports

2.1.4 Design and construction personnel -- Other excellent sources of information concerning the design and construction of the building under investigation are the individuals involved in those processes. Interviews with these personnel often will yield valuable information for a strength evaluation. This information can be of particular value if the members of the design and construction teams reveal any problems that may have occurred during the design and construction of the building.

2.1.5 Service history of the building -- This includes all documents that define the history of the building from the original construction to the present, such as:

- Records of current and former owners, their legal representatives, and their insurers
- Maintenance records
- Documents and records concerning previous repair and remodeling
- Records maintained by owners of adjacent structures
- Weather records
- Logs of seismic activity

2.2 -- Condition survey of the building

All forms and areas of deterioration and distress existing in the structural elements of the building should be located, inspected and recorded as to type, location, and degree of severity. Procedures for performing this condition survey are described in this section. The reader should also refer to ACI 201.1R. A considerable degree of engineering judgment must be exercised in performing a condition survey. All of the steps outlined below may not be required in a particular strength evaluation. The investigator performing the evaluation must decide what
information will be needed to determine the existing condition of structural elements of the particular building that is being evaluated.

2.2.1 Recognition of abnormalities -- A fundamental knowledge of the basic characteristics of structural concrete and the types of distress and defects that may be observed in a concrete building is essential for successful performance of a strength evaluation. Additional information on the causes and evaluation of concrete distress is found in ACI 201.1R, ACI 207.3R, ACI 222R, ACI 224R, ACI 224.1R, ACI 309.2R, and ACI 362R.

2.2.2 Survey methods for evaluation of structural concrete

2.2.2.1 Visual examination -- All obvious distress, deterioration, and damage existing in the structure should be located by means of a thorough visual inspection of all structural components of the building. Liberal use of photographs, notes, and sketches to document this walk-through inspection is recommended. All abnormalities found to exist should be recorded as to type, magnitude, location, and severity.

When the investigator conducting the visual examination finds defects that are considered to be of such a nature as to render a portion or all of the building unsafe, the condition should be reported to the owner immediately. Appropriate temporary measures should be undertaken immediately to secure the structure before it is placed back in use and the survey continued.

To employ the analytical method of strength evaluation it is necessary to collect from verified records, as described in Section 2.1, sufficient information on the member properties, physical size, and positioning of the structural components in the building. If this information is incomplete, missing, or of questionable accuracy, the missing and unreliable information must be determined through a field survey.

2.2.2.2 In-place tests for assessing the strength of concrete -- A number of test methods are available for estimating the in-place concrete strength or for locating areas of low strength concrete. These have been traditionally referred to as “nondestructive tests” to contrast them with the drilling and testing of core samples. A more descriptive term for these tests is “in-place tests” because they are performed on concrete as it exists in a structure. Additional information on these methods may be found in ACI 228.1R and Malhotra (1976).

The common feature of these methods is that they do not directly measure the compressive strength of the concrete. Rather they measure some other quality which has been found to have an empirical correlation with compressive strength. These methods can be used to estimate compressive strength or to compare the relative compressive strength at different locations in the structure. Depending on which application is desired, different procedures are needed.

If these methods are used for estimating the in-place compressive strength, it is necessary to develop a relationship between compressive strength and the quantity measured by the in-place test. Such a relationship should be developed by performing the in-place test on the structure and testing core samples that have been drilled from areas adjacent to the test locations. An attempt should be made to obtain paired data from different parts of the structure so as to obtain as wide a spread as possible in the range of compressive strength. Regression analysis of the correlation data can be used to develop a prediction equation along with the confidence limits for the predicted strength. These correlation relationships have been found to be influenced by the specific materials used in the concrete. The use of general correlation curves supplied with test equipment or developed from concrete other than that in the structure being evaluated is not recommended. The use of in-place test procedures can reduce the number of cores taken, but cannot eliminate the need for drilling cores from the building.

When using these methods to compare relative concrete strength it is not necessary to develop correlation relationships. However, the user must be aware of the factors that may influence the in-place test results, otherwise it is possible to draw wrong conclusions concerning the relative in-place strength.

Sections 2.2.2.2.1 - 2.2.2.2.4 summarize the operating principles of a number of currently available in-place tests, and highlight factors that significantly influence test results.

2.2.2.2.1 Rebound number -- Procedures for conducting this test are given in ASTM C 805. The test instrument consists of a metal housing, a spring-loaded mass (the hammer) and a steel rod (the plunger). To perform a test, the plunger is placed perpendicular to the concrete surface and the housing is pushed toward the concrete. This action causes the extension of a spring connected to the hammer. When the instrument is pushed to its limit, the hammer is propelled toward the concrete and it impacts a shoulder on the plunger. The hammer rebounds, and the rebound distance is measured on a scale numbered from 10 to 100. The rebound distance is recorded as the “rebound number” indicated on the scale.

The rebound distance depends on how much of the initial hammer energy is absorbed in the interaction of the plunger with the concrete. The greater the amount of absorbed energy, the lower the rebound number. The energy absorbed by the concrete depends on its stress-strain relationship. For this reason, there is not a simple direct relationship between rebound number and compressive strength. However, it has been shown empirically that for a given concrete mixture there may be good correlation between compressive strength and rebound number.

The concrete in the immediate vicinity of the plunger has the greatest effect on the measured rebound number. Hence, test results are sensitive to the local conditions at the test point. For example, a test per-
formed directly above a hard particle of coarse aggregate results in a higher rebound number than a test over mortar. To account for the variations in local conditions, ASTM C 805 requires the averaging of ten rebound readings for a test. Procedures for discarding abnormally high or low values are also given.

The measured rebound number is affected by the properties of the concrete near the surface and may not be representative of the rebound value of the interior concrete. A surface layer of carbonated or deteriorated concrete results in a rebound number which is significantly different from that for the interior concrete. The rebound number increases as the moisture content of the concrete decreases, and tests on a dry surface can give the wrong estimation for interior concrete that is moist. Since rebound distance is affected by the direction of the instrument (sideward, upward, downward), this must be considered when comparing readings and using correlation relationships. The manufacturer provides correction factors to account for varying hammer positions.

The rebound number is a simple method for quickly obtaining information about the surface properties of a structural member. However, there are many factors other than strength that influence the measured rebound number. These factors are identified in ASTM C 805 and must be considered when evaluating test results.

2.2.2.3 Probe penetration -- The procedures for performing this method are given in ASTM C 803. The test involves the use of a special powder-actuated gun to drive a hardened steel rod (probe) into the surface of a concrete member. The penetration of the probe into the concrete is taken as an indicator of concrete strength.

The probe penetration technique is similar to the rebound number except that the probe impacts the concrete with a much higher energy level. A theoretical analysis of this test is complex. Qualitatively it involves the initial kinetic energy of the probe and the energy absorption by friction and by failure of the concrete. As the probe penetrates the concrete there is crushing of mortar and aggregate along the penetration path and there is extensive fracturing within a conic region around the probe. Hence, the strength properties of the aggregates and the mortar will influence the penetration depth. This contrasts with the behavior of ordinary strength concrete in a compression test, in which aggregate strength plays a secondary role compared with mortar strength. Thus, an important characteristic of the probe penetration test is that the type of coarse aggregate strongly affects the correlation relationship between compressive strength and probe penetration.

Because the probe penetrates into the concrete, test results are not highly sensitive to local surface conditions such as texture and moisture content. In practice, the exposed lengths of the probes are measured, and according to ASTM C 803, a test result is the average of three probes located within 7 in. (180 mm) of each other.

The probe penetration system enables the use of a lower power level or a larger probe for testing relatively weak [less than 3000 psi, (20 MPa)] or lightweight concrete. The correlation relationships are only valid for a specific power level and probe type.

The method is useful for comparing relative compressive strength locations in a structure. However, as is the case with other methods, the strengths of cores taken from the structure are required to estimate compressive strength. The probe penetration test is unreliable in the evaluation of high-strength concrete.

2.2.2.3 Pulse velocity -- The procedures for this method are given in ASTM C 597. The test equipment includes a transmitter, a receiver, and electronic instrumentation. The test consists of measuring the time it takes for a pulse of vibrational energy to travel through a concrete member. The vibrational energy is introduced into the concrete by the transmitting transducer, which is coupled to the surface with an acoustic couplant such as grease. The pulse travels through the member and is detected by the receiving transducer, which is coupled to the opposite surface. Instrumentation measures and displays the pulse transit time. The distance between the transducers is divided by the transit time to obtain the pulse velocity through the concrete under test.

The pulse velocity is proportional to the square root of the elastic modulus and inversely proportional to the mass density of the concrete. The elastic modulus of concrete has been found to vary in proportion to the square root of compressive strength. Hence, large changes in compressive strength produce only minor changes in pulse velocity. There are factors other than strength that affect pulse velocity, and changes in velocity due to these factors can easily overshadow changes due to strength. One of the most critical of these is moisture content. An increase in moisture content increases the pulse velocity and this could be incorrectly interpreted as an increase in compressive strength. The presence of reinforcing steel aligned with the pulse travel path can also significantly increase pulse velocity.

Under laboratory conditions, excellent correlations have been reported between velocity and compressive strength. However, these findings should not be interpreted to mean that highly reliable in-place strength predictions can be routinely made. Reasonable strength predictions are possible only if correlation relationships include those characteristics of the in-place concrete that have a bearing on pulse velocity. It is for this reason that the pulse velocity method is not generally recommended for estimating in-place strength. However, it is an excellent technique for locating regions in a structure where the concrete is of a different quality, or where there may be internal defects such as cracking and honeycombing.
However, it is not possible to determine the nature of the defect based solely on the measured pulse velocity (see Section 2.2.2.3).

2.2.2.4 Pullout test -- The pullout test consists of measuring the load required to pull an embedded metal insert from a concrete member. The force is applied by a jack which bears against the concrete surface through a reaction ring concentric with the insert. As the insert is extracted, a conical fragment of the concrete is also removed. The test produces a well-defined failure in the concrete and measures a static strength property. However, there is currently no consensus on which strength property is measured and so a correlation relationship must be developed between compressive strength and pullout strength (Stone and Carino, 1983). The relationship is valid only for the particular test configuration and concrete materials used in the correlation testing.

ASTM C 900 describes procedures for performing pullout tests. However, the standard method deals with inserts cast in the concrete during construction. Recent developments have been made in adapting the pullout test to existing structures by using various types of anchors that can be placed in a hole drilled in the structure (Mailhot et al. 1979). Some of these methods produce a failure pattern similar to the standard test (Peterson 1984) and others produce an entirely different pattern (Chabowski and Bryden-Smith 1979). Presently, there are no standard procedures for performing “drilled in” pullout tests on existing structures.

2.2.2.3 Nondestructive tests for identifying internal abnormalities -- A strength evaluation may also include determining if internal abnormalities exist which may adversely affect structural capacity. For example, it may be necessary to determine if there are internal voids, cracks, or regions of inferior concrete quality. This section describes some of the available methods for these applications. Compared with methods of strength determination, some of the techniques for locating internal defects require more complex instrumentation and specialized expertise to perform the tests and interpret the results. However, the investigator should be aware that such procedures are available.

2.2.2.3.1 Sounding -- Hollow areas or planes of delamination below the concrete surface can be detected by striking the surface with a hammer or a steel bar. A “hollow” or “drum-like” sound results when the surface over a defective area is struck, compared with a “ringing” noise over sound concrete. For slabs, a heavy steel chain can be dragged over the concrete surface. Sounding is a simple and effective method for locating regions with subsurface fracture planes. However, the sensitivity and reliability of the method decreases as the depth of the defect increases. Procedures for using sounding in pavements and slabs may be found in ASTM D 4580.

2.2.2.3.2 Pulse velocity -- The principle of the method is discussed in Section 2.2.2.2. Pulse travel time between the transmitting and receiving transducers is affected by the concrete properties along the travel path and the actual travel path distance. If there is a region of low quality concrete between the transducers, the travel time increases and a lower velocity value is computed. If there is a void between the transducers, the pulse travels through the concrete around the void. This increases the actual path length, increases the travel time, and a lower pulse velocity is computed. While the pulse velocity method can be used to locate abnormal regions, it cannot by itself identify the nature of the abnormality. Therefore, cores are recommended to determine the nature of the indicated abnormality.

2.2.2.3.3 Pulse (impact)-echo -- This technique also involves measuring the transit time of a pulse of vibrational energy. Unlike the pulse velocity method, in this case the pulse is generated and received on the same surface. The measured transit time represents the elapsed time for the pulse to travel through the concrete and travel back after reflection from an interface. A reflecting interface is a boundary between materials having different acoustic impedances (product of mass density and pulse velocity). For a sound member, reflection occurs from the member boundary opposite from where the pulse is generated. If there is an internal interface, such as that created by a crack or a void, the pulse is reflected from this interface and the echo is received sooner. By knowing the pulse velocity through the concrete and the measured transit time, the depth of the interface can be computed.

While the principle of this method is rather simple, a pulse-echo test system that is reliable and simple to use is not commercially available. However, this is an area of active research and tools may be available in the near future. A technique under development uses a short-duration, mechanical impact to create a transient resonance between the impact point and reflecting interface. It has been demonstrated that this method, which is called “impact echo,” is capable of detecting a variety of defects within concrete (Sanalone and Carino 1986, 1989).

2.2.2.3.4 Ground probing radar -- This method is in principle, similar to the pulse-echo technique except that electromagnetic radiation is introduced into the material. An antenna placed on the concrete surface sends out an extremely short-duration radar pulse. A portion of the pulse is reflected back to the antenna, which also acts as receiver, and a portion penetrates into the concrete. If the concrete member contains boundaries between materials with different electrical properties, some of the pulse is reflected back to the antenna. Knowing the velocity of the radar pulse in the concrete, the depth of the interface can be determined. Recording systems are available which display a profile view of the reflecting interfaces within the member as the antenna is moved over the surface. Interpretation of the recorded profiles is the most difficult aspect in using commercially available radar systems. This
method has been used successfully to locate embedded metal, such as reinforcing steel, and to locate regions of deterioration in pavements. The penetrating ability of the radar pulse depends on the electrical conductivity of the material and the frequency of the radiation. As electrical conductivity increases radar penetration decreases. In testing concrete, a higher moisture content reduces the depth of penetration.

2.2.2.3.5 **Infrared thermography** --
A surface having a temperature above absolute zero emits electromagnetic energy. At room temperature, the wave length of this radiation is in the infrared region of the electromagnetic spectrum. The rate of energy emission from the surface depends on its temperature, so by using infrared detectors it is possible to “see” differences in surface temperature. If a concrete member contains an internal defect, such as a large crack or void, and there is heat flow though the member, the presence of the defect may influence the temperature of the surface above the defect. A “picture” of the surface temperature can be created by using an infrared detector to locate “hot” or “cold” spots on the surface. The locations of these hot and cold spots serve as indications of the locations of internal defects in the concrete. The technique has been successfully used to locate regions of delamination in concrete pavements and bridge decks.

There must be heat flow through the member to use infrared thermography. This can be achieved by the natural heating from sunlight or by applying a heat source to one side of the member. In addition, this surface of the member must be of one material and have a uniform value of a property known as emissivity, which is a measure of the efficiency of energy radiation by the surface. Changes in emissivity cause changes in the rate of energy radiation which can be incorrectly interpreted as changes in surface temperature. The presence of any material on the surface, such as paint or grease, will affect the results of infrared thermography by changing the temperature of the surface. It is often useful to take a photographic or video record of the same areas of the concrete surface so that it may be compared to the infrared photographic record. In this manner surface defects can be eliminated from consideration as internal defects in the concrete.

2.2.2.3.6 **Radiography** --
Radiography can determine the internal condition of a structural member or locate embedded steel by using penetrating radiation, such as x rays or gamma rays. As the radiation passes through the member its intensity is reduced according to the thickness, density and absorption characteristics of the materials within the member. The quantity of radiation passing through the member is recorded on x ray film similar to that used in medical applications. Reinforcing bars absorb more energy than the surrounding concrete and show up as light areas on the exposed film. Cracks and voids, on the other hand, absorb less radiation and show up as dark zones on the film. Crack planes parallel to the radiation direction are detected more readily than cracks perpendicular to the radiation direction.

Produced by an electrical device, the penetrating ability of x rays can be varied. However, the penetrating ability of portable x ray units is limited [the technique works best on members less than 12 in. (300 mm) thick] and gamma radiation is used more commonly in field application. Gamma rays result from the radioactive decay of unstable isotopes. As a result, a gamma ray source cannot be turned off and extensive shielding is needed to contain the rays when not used for inspection. The shield requirements make gamma rays sources heavy and bulky, especially when high penetrating ability is required. The penetrating ability of gamma rays depends on the type and age of the isotope source. Gamma ray sources are available that can penetrate up to 18 in. (450 mm) of concrete. For thicker structural elements, a hole may be drilled and the source placed inside the member.

Radiographic inspection poses health hazards if proper operating procedures are not followed and must be performed by licensed and trained personnel. One drawback to radiography is that it can interrupt tenant or construction activities because the exposure areas must be evacuated.

**CHAPTER 3 -- METHODS FOR MATERIAL EVALUATION**

This chapter describes procedures that should be undertaken to assess the quality and mechanical properties of the concrete and reinforcing steel in a structure. Sampling techniques, petrographic and chemical analysis of concrete, and test methods available to assess the mechanical properties of concrete and steel are discussed.

3.1 **Concrete**

3.1.1 **Techniques for proper sampling of concrete**--
Samples of concrete in an existing structure may be retrieved to determine strength as well as physical and chemical properties. It is essential that the samples be obtained, handled, identified (labeled), and stored in proper fashion to prevent damage or contamination. Sampling techniques are discussed in this section.

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 entire structure, or to characterize some 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 depends on the necessary laboratory tests and the degree of confidence desired in the average values obtained from the tests.

The type of sampling plan which is required on a particular project depends on whether the concrete is
generally believed to be uniform, or if there are likely to be two or more regions which are different in composition, condition, or quality. The preliminary investigation and 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:

- The maximum allowable difference (or error) that one is willing to accept between the sample average and the true average
- The variability of the test results, and
- The risk one is willing to accept that the allowable difference is exceeded

Fig. 3.1 illustrates how ASTM E 122 may be used to determine the sample size. The vertical axis indicates the number of samples as a function of the maximum difference (as a percentage of the true average) and as a function of the coefficient of variation of the test results. In Fig. 3.1 the risk that the allowable error will be exceeded is 5 percent, but other levels may be used depending on the particular situation. Since the variability of test results is usually not known in advance, an estimate should be made and adjusted as test results become available. Economy should also be considered in the selection of sample sizes. In some cases increasing the sample size may only result in a minimal decrease in the risk that the error is exceeded. The cost of additional sampling and testing would not be justified in these situations.

The investigator must recognize that concrete is not isotropic 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. Typically the strength of concrete decreases as its elevation within a placement increases.

3.1.1.1 Core sampling -- The procedures for properly removing concrete samples by core drilling are given in ASTM C 42. The following guidelines are of particular importance in core sampling:

- Equipment: Cores should be taken using diamond-studded core bits when the cores will be tested for strength. A shot drill may be acceptable for other applications when the core is drilled vertically. However, diamond-studded core bits are recommended for other drill orientations
- 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
- Core diameter: Cores to be tested for a strength property should have a minimum diameter of three times the maximum nominal size of the coarse aggregate, or 2 in. (50 mm), whichever is greater
- Core length: Where possible, cores to be tested for a strength property should have a length of at least twice their diameter
- Reinforcing steel should not be included in a core to be tested for strength
- Caution should be exercised to avoid cutting electrical conduits or prestressing steel
- Where possible, core drilling should completely penetrate the concrete section to avoid having to break off the core to facilitate removal. If through-drilling is not feasible, an extra 2 in. (50 mm) should be drilled to allow for possible damage at the base of the core
- Where cores are taken to determine strength, at least three cores should be removed at each location in the structure. The strength value should be taken as the average of the cores. A single core should not be used to evaluate or diagnose a particular problem

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

3.1.2 Petrographic and chemical analysis -- A qualified petrographic and chemical laboratory can be helpful in determining characteristics and properties of
Fig. 3.1—Sample size based on ASTM E 122, risk equals 5 percent

Concrete from an existing structure which may be important in a strength evaluation. A qualified petrographer who is familiar with problems commonly encountered with concrete should be consulted prior to the removal of samples from an existing structure. The petrographer should be provided with information regarding the pre-construction, construction, and post-construction history and performance of the structure.

3.1.2.1 Aggregates -- The following properties of aggregates can be determined by petrographic evaluation of concrete samples (ASTM C 856):

-- Particle shape, size distribution, and composition

-- The extent to which the particles are coated, and the nature of the coating substance

-- The potential for deleterious reactions between the aggregate and cement alkalies, sulfates, and sulfides

-- Presence of unsound aggregates (fractured, porous, and degree of weathering)

Mielenz (1978) describes petrographic examination of concrete aggregates in more detail.

3.1.2.2 Concrete -- The following characteristics of the concrete can be determined by petrographic analysis in accordance with ASTM C 856:

-- Density of the cement paste, and color of the cement

-- Homogeneity of the concrete

-- Occurrence of settlement and bleeding in fresh concrete

-- Presence of deterioration caused by exposure to freezing and thawing

-- Occurrence and distribution of fractures

-- Characteristics and distribution of voids

-- Presence of contaminating substances

-- Proportion of unhydrated cement

-- Presence of mineral admixtures

-- Volumetric proportions of aggregates, cement paste, and air voids

-- Air content and various dimensional characteristics of the air void system (including entrained and entrapped air)

-- Weathering patterns from surface-to-bottom

-- Presence of deterioration due to abrasion or fire exposure

Mather (1978) provides additional information
on petrographic examination of hardened concrete.

3.1.3.2 Nondestructive testing -- The investigator performing a strength evaluation is cautioned that currently there are no nondestructive tests which yield direct compressive strengths of concrete in an existing structure. Nondestructive tests are commonly used in conjunction with tests of drilled cores to reduce the amount of coring required to establish compressive strengths throughout the structure. Considerable care is required to established valid estimates of compressive strength based on nondestructive testing. See Section 2.2.2.2 for further information.

3.2 -- Reinforcing steel

3.2.1 Locational survey methods -- The size, number, and location of steel reinforcing bars can be determined by the following methods, or combination thereof:

3.2.1.1 Magnetic tests -- Magnetic instruments for locating reinforcing steel embedded in concrete are based on the fact that the presence of steel affects the alternating magnetic field produced by a hand-held search unit. As the search unit is moved along the concrete surface, a meter indicates when the unit is located directly above a reinforcing bar. With proper calibration, these meters can be used to estimate the depth of a bar if its size is known, or estimate the bar size if the depth of cover is known. Dixon (1986) and Snell, Wallace, and Rutledge (1987) report additional details.

Magnetic tests are limited to detecting reinforcement located within 7 in. (175 mm) of the exposed concrete surface. This method may not be effective in heavily reinforced sections, particularly sections with two or more adjacent bars or nearly adjacent layers of reinforcement. Battery powered equipment will give erroneous readings at ambient temperatures less than 32 F (0 C). It is possible to operate the equipment at lower ambient temperatures if it is kept warm with external heat pads.

The accuracy of these devices depends on bar spacing and thickness of concrete cover. Inaccurate results may occur when the depth of concrete cover is equal to or close to the spacing of the reinforcing bars. Care should be taken to insure that the search unit is not used close to other ferrous materials, as inaccurate results may be obtained.

Results from tests should be calibrated or correlated by drilling or chipping to confirm concrete cover and bar size, see Section 3.2.1.4.

3.2.1.2 Radiographic evaluation -- As discussed in Section 2.2.2.3, radiography may be used to determine the size, position, and configuration of embedded reinforcing steel. Inspection by x ray is especially useful in locating post-tensioning strands in concrete slabs. Gamma ray inspection may be used in concrete up to 18 in. (450 mm) thick and is generally acceptable as a field test method because of its portability.
Results from radiographic tests should be calibrated or correlated by drilling or chipping to confirm actual concrete cover and bar size.

3.2.1.3 Radar -- Pulsed radar systems may also be used to locate embedded reinforcement. It offers advantages over magnetic methods when searching for bars in heavily reinforced concrete or when searching for nonferrous metals. Interpretation of the results of a radar survey requires an experienced operator.

3.2.1.4 Removal of concrete cover -- This method can take the form of actual removal of concrete cover to locate and determine the size of embedded reinforcing steel, or power drilling to determine the depth of cover for embedded reinforcing steel. These methods are used primarily for verification and calibration of the results of the nondestructive methods outlined above.

Removal of concrete cover is the only reliable technique available to determine the condition of embedded reinforcing steel in deteriorated structures.

3.2.2 Determination of yield strength -- The yield strength of the reinforcing steel used in the building can be established by two methods. Information from tests data furnished by the manufacturer of the reinforcing steel may be used if it is agreed to by the investigator and the building official. However, tensile strengths from mill test reports tend to be greater than those obtained from tests of field samples. Where this is not possible or desirable, sampling and destructive testing of specimens taken from the structure will be required. Guidelines for this method are given in Section 3.2.3. Concrete Reinforcing Steel Institute (1981) provides additional information on reinforcing systems in older structures.

3.2.3 Sampling techniques -- When the yield strength of embedded reinforcing steel is to be determined by destructive testing of specimens taken from the building, the recommendations listed below should be followed:

- Test specimen characteristics, specimen selection, and specimen preparation are recommended in ASTM A 370. Whole bars can also be tested.

- Specimens should be removed at locations of minimum stress in the reinforcement.

- No two specimens should be removed from the same cross section of a structural member.

- 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.

- For single structural elements having a span of less than 25 ft (7.5 m) or a loaded area of less than 625 ft² (60 m²), at least one specimen should be taken from the main longitudinal reinforcement (not stirrups or ties).

- For longer spans or larger loaded 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.

- Samples should be at least 16 in. (400 mm) long. However, smaller samples can be obtained and then machined according to the requirements of ASTM A 370 for testing and determination of mechanical properties.

CHAPTER 4 -- ASSESSMENT OF LOADING CONDITIONS AND SELECTION OF EVALUATION METHOD

4.1 -- Assessment of loading and environmental conditions

The most fundamental aspect of any strength evaluation, regardless of the method of evaluation employed, is the assessment of the loads and environmental conditions to which the structure has been exposed and to which the structure will be exposed in its remaining life. It is imperative that these factors be accurately defined so that the results of the strength evaluation process will be accurate and realistic.

4.1.1 Dead loads -- Dead loads can be estimated using unit material weights as recommended in ANSI A58.1, and using the field measured dimensions of the various components of the structure. Design dimensions should be used with caution because significant differences can exist between dimensions shown on original construction drawings and actual, as-built dimensions. Similarly, significant differences are often found in material densities due to variations in moisture content. If such differences are suspected, field samples should be obtained and analyzed to quantify the unit weights.

4.1.2 Live loads -- The magnitude, location, and orientation of live loads on a structural component is dependent on the use of the particular area of the building. It is imperative that past, present, and future usage conditions be established accurately, so that appropriate assumptions can be made for the selection of live loads to use in the strength evaluation. When evaluating a structure for safety, code-defined live loads, based on usage, can be used. In the absence of an applicable local building code the live loads specified in ANSI A58.1 can be used.

When evaluating a structure for serviceability, an
attempt must also be made to evaluate the probable live loads that will be present during normal conditions of occupancy of the building.

4.1.3 Wind loads -- ANSI A58.1 can provide guidance in developing wind loads for use in the strength evaluation. The investigator should also research the local wind conditions at the specific building site. Such information can be obtained from the nearest local office of the United States Weather Bureau, or directly from the National Oceanic and Atmospheric Administration (NOM).

4.1.4 Snow and ice loads -- Care should be exercised in selecting appropriate superimposed loads for simulation of anticipated snow and ice conditions. Consideration should be given to the possibility of build-up of snow and ice at changes in the building roof profile, or due to the presence of adjacent, higher structures.

Consideration should also be given to local, as well as regional, geographical locations, when estimating ground snow loads. In the absence of specific code requirements, reference should be made to ANSI A58.1 and information available from NOAA.

4.1.5 Seismic loads -- Loading conditions due to seismic events are usually well defined in local building codes. In the absence of such guidance ANSI A58.1 or the Uniform Building Code (UBC) can be used.

4.1.6 Thermal effects -- When restraint exists, expansion and contraction of a concrete building due to daily and seasonal variations in ambient temperature can cause significant forces in the structural elements. The investigator should consult local weather records or NOM to determine the range of temperatures which the structure may experience. Approximate data regarding seasonal temperature variations is available in the PCI Design Handbook (Prestressed/Precast Concrete Institute 1985).

Large concrete sections do not respond quickly to sudden changes in ambient temperature. Therefore, effects of rate of heat gain and loss in individual concrete elements may also be important.

Variations in the temperature within a building should also be considered. Consideration should be given to conditions such as areas of the building where heating or cooling is turned off at night, inadequately or over-insulated areas, existence of cold rooms, etc.

4.1.7 Creep and shrinkage -- The effects of long-term creep and shrinkage are important concerns for concrete elements (see ACI 209R). Cracks or other distress may be caused by restrained shrinkage, see ACI 224R. Internal stresses may exist in a concrete structure due to restrained shrinkage and long-term creep of concrete elements. These stresses can be significant when combined with other loads on the structure. Examples of this are a reinforced concrete column under sustained loading, where stresses in the embedded reinforcing steel can increase over time due to creep of the concrete, or post-tensioned structures, where creep and shrinkage induced problems have been frequently found in the past.

4.1.8 Soil pressure -- Significant lateral loads can be imposed on a building from soil pressure. These must be fully and accurately defined. Unit weights of soil can vary significantly, as can the lateral pressure exerted by the soil. It is often prudent to sample and establish actual soil weights and properties such as the internal angle of friction. Variations in moisture content can also result in large variations in the lateral pressure exerted on the side of a structure from soil surcharges. Overall stability can be critical in structures that are built on a slope, due to unbalanced soil pressure that may be present.

Consideration should also be given to loads or damage caused by frost heaving of soil, soil shrinkage or swelling, differential soil settlement, and improper drainage.

4.1.9 Fire -- If the building being evaluated has been exposed to fire, consideration must be given to the effects of localized damage that may have been caused by the heat of the fire or by the fire-fighting efforts. Careful attention must be paid to the overall thermal effects on the structure from the heat of the fire. Volume changes of concrete elements during a fire can cause significant damage. Potential damage to reinforcing steel or prestressing tendons, must also be evaluated carefully. This damage must be considered in the evaluation process. Additional information on damage due to fire may be found in ACI 216R.

4.1.10 Loading combinations -- For purposes of strength evaluation load factors and load combinations should conform to the requirements of ACI 318 (see also ACI 318R) and the local building code. If factors other than those of ACI 318 are used, the resulting evaluation will imply a different level of structural safety. Where serviceability is also to be evaluated, consider using load factors equal to 1.0 for all load cases. Load combination factors may also be used, such as when wind load effects are checked. In some situations a serviceability check may use a live load different than the full live load required by the local building code.

4.2 -- Selecting the proper method of evaluation

The following recommendations are provided to assist in selecting the most appropriate method of strength evaluation. The choice of the evaluation method is dependent on such factors as the nature of the structure and how much information is known about its existing condition. The typical choices are evaluation by analysis, evaluation by analysis and full scale load testing, and evaluation by analysis and structural modeling.

4.2.1 Evaluation by analysis

4.2.1.1 Applications -- Evaluation solely by analysis is recommended where:

-- Sufficient information is available, or readily obtainable by field investigation, about the physical characteristics, material properties, and structural behavior and loadings to which the structure will
be subjected

-- Load testing is impractical or unsafe because of the magnitude, complexity of the loads and testing arrangements required, or both

-- Load testing members which are suspected of being susceptible to sudden failure, would endanger the safety of the structure and those persons conducting such tests. This would include columns or arches likely to fail in compression and cases susceptible to shear or anchorage failure

4.2.1.2 Conditions for using this method-- Analytical evaluation is considered appropriate if all of the following conditions are satisfied:

-- There exists a verified theory for the analysis of the type of structural systems under consideration. Information on analysis methods for reinforced concrete buildings may be found in ACI 442R

-- Characteristics of the structural elements under consideration can be determined and modeled within acceptable limits of error

-- There is no distress of such a nature or magnitude that uncertainties are introduced which render the application of the theory excessively difficult or impossible

4.2.2 Evaluation by analysis and physical load testing -- Since the previous edition of this report, considerable experience has been assembled and reported on the subject of full-scale load tests of existing structures. Refer to Bares and FitzSimons (1975), FitzSimons and Longinow (1975), Ivani (1976), Guedelhoefer and Janney (1980), Raths and Guedelhoefer (1980) and Elstner et al. (1987) for further information.

4.2.2.1 Applications -- Evaluation by analysis and physical load testing is recommended in the following cases:

-- The complexity of the design concept and lack of experience with such types of structural elements make evaluation solely by analytical methods impractical or uncertain in outcome

-- The loading and material characteristics of the structural element(s) under consideration cannot be readily determined

-- The nature of existing distress introduces significant uncertainties into the parameters necessary to perform an analytical evaluation

-- For structural elements suspected to be substandard in design, materials, or construction where the degree of such defects cannot be readily determined

-- Where there is doubt concerning adequacy of the structural element(s) when the likely future loading exceeds the service load capacity calculated using the original design criteria

4.2.2.2 Preliminary analytical evaluation -- Preliminary approximate analytical evaluation should precede evaluation by load test methods. These analyses should be used to determine the location and magnitude of the test loading, to determine the effects of existing load effects in the structure (i.e. volume change forces, differential settlement, etc.), to plan the test, and to predict the results of the load test.

4.2.2.3 Vertical loads -- Generally, load testing is recommended only for evaluating the strength of a structure with respect to vertically-applied gravity-type loads. With some exceptions, in-situ load testing is not recommended for evaluating the strength of a structure to resist lateral loads such as wind and seismic events. Analytical and/or structural modeling evaluation methods are recommended in those cases.

4.2.2.4 Sudden failure -- If the structure or element under consideration is known to contain defects that may cause brittle behavior, load testing is specifically not recommended. This condition may most frequently be encountered when evaluating structural elements for shear capacity. Refer to Section 5.2.8 for additional guidance.

4.2.3 Evaluation by analysis and structural modeling -- In some cases the construction and testing of structural models may be a feasible alternative to conducting a full-scale load test (Harris 1980). Sabnis et al. (1983) provide a detailed treatment of structural modeling and experimental techniques. ACI 444R discusses the specifics of models for concrete structures.

4.2.3.1 Applications -- This method of evaluation may be appropriate when:

-- Analytical evaluation, alone, results in indefinite conclusions regarding the adequacy of the structural element(s) under consideration

-- Load testing is physically impractical

-- Load testing of members which are prone to sudden failure may endanger
It is desired to evaluate the strength of a portion of the building, but testing of the component to failure is not practical.

The complexity of the design concept and lack of experience with such types of structural elements make other methods of evaluation impractical or impossible.

For structural elements where the magnitude of existing load effects due to restrained volume changes (shrinkage, creep, temperature, differential settlement, etc.) is significant, alone, or in combination with vertical loads.

**4.2.3.2 Conditions for using this method--**

Evaluation by using tests of structural models is considered appropriate only if:

- The material properties, nature and magnitude of loading, structural boundary conditions, and physical details and connections are capable of being realistically simulated so as to result in an accurate portrayal of the existing condition of the structural element(s) being evaluated.

- The investigator is knowledgeable in the principles of structural modeling.

- The influence of adjacent structural elements or whole structures can be accounted for in conducting the tests and evaluating the results.

**CHAPTER 5 -- THE EVALUATION**

**5.1 -- Analytical evaluation**

The information gathered from the preliminary investigation and material evaluations should be used to determine analytically the safe load-carrying capacity of the structure or portion of the structure being evaluated. This chapter provides guidelines for performance of the evaluation, and criteria for interpreting the results of the evaluation.

**5.1.1 Forms of analysis --** In the evaluation of concrete structures by analytical methods, “analysis” has two different meanings. One deals with finding the values of forces and moments which exist in the structure. The second uses the characteristics of the structure or member to predict how it will respond to the existing load effects.

A structure must be “analyzed” to determine the bending moments, shear forces, axial forces, etc., at the sections which are believed to be critical. This analysis invariably involves computations and calculations, perhaps using a computer. Most engineers will conduct this part of the analysis using methods which assume that individual members have linear and elastic material properties, even though this is not strictly true for reinforced concrete. The alternative, “plastic analysis” is not routinely feasible and requires special capabilities not found in most engineering offices. However, this is not a significant drawback, since an analysis done by elastic methods provides a reasonable estimate for the values of important load effects.

In the second form of analysis, an assumption is made about the behavior of structures. For an evaluation of structural performance at service loads, it may be reasonable to assume that concrete and reinforcing steel behave in a linearly, elastic manner. However, it is necessary to account for the fact that concrete has a relatively low tensile strength, and cracked section properties are often used. Where structural safety is the principal concern, the strength of the member or structure must be established. The principles of strength design, as applied in ACI 318 provide a basis for establishing a nominal capacity for structural members. The average core compressive strength may be divided by 0.85 to arrive at the concrete strength value to be used in strength calculations (Bloem 1968).

**5.1.2 Levels of analysis --** “Exact” or “approximate” analyses may be used in strength evaluation.

**5.1.2.1 Exact analysis --** Analysis based on experimentally verified theories of structural mechanics are useful under the following conditions:

- Loading conditions for the building are known with a high degree of certainty after examining existing data.

- Detailed structural engineering drawings and material specifications for the building are available, and the information given therein is believed to be reliable or has been confirmed or supplemented with data obtained by the condition survey. For example:

1) Dimensions of the structure and its members can be determined directly by field measurements, and these can be used to establish the dead loads of the structure.

2) The location, size, and depth of concrete cover of embedded reinforcing steel can be determined by field investigation.
3) Material characteristics basic to the analysis can be determined, or estimated reasonably, by the use of destructive or nondestructive tests

4) Estimates of the strength of the foundations can be obtained through consultations with foundation engineers and by conducting appropriate soil tests

-- Sufficient data can be collected to make an adequate assessment of the existing physical condition of the structure including estimation of the effects of distress, deterioration, and damage

5.1.2.2 Approximate analysis -- Use of approximate methods of analysis requires considerable experience with the type of structural system under evaluation and its behavior. Most importantly, approximate methods require the exercise of sound engineering judgment. Approximations must be applicable to the specific circumstances. Two basic guidelines should be followed:

-- All assumptions necessary for completion of the structural analyses should be clearly documented. Particular care should be taken to describe those assumptions made to reduce strength in accounting for existing distress, deterioration, or damage

-- All assumptions necessary to conduct the theoretical structural analysis should be made to provide a conservative lower bound for the safe load-carrying capacity of the structure

5.1.3 General considerations -- The assumed behavior of the structure and the results of the theoretical analyses must be compatible with the observed behavior of the structure. The analyses should consider fully, and model appropriately, characteristics of the structure such as:

-- The effects of nonprismatic members on the relative stiffness of components in the structure

-- Torsional characteristics of structural members

-- Two-way load response in slab systems

-- Column support and structural fixities in terms of moment-rotation characteristics

-- Column base characteristics as influenced by soil conditions

Modifications may be made to the results of the theoretical structural analyses to account for the anticipated future condition of the structure. These modifications should include full consideration for any anticipated repairs and continuing maintenance of the structure, as well as any future anticipated deterioration of the structure.

5.1.4 Acceptance criteria -- The structure or structural component being evaluated may be deemed to have sufficient strength if the analytical evaluation clearly demonstrates that the predicted design capacity of the elements under consideration satisfies the requirements and the intent of ACI 318.

Where field work has established the actual material strengths of steel and concrete; indicated the size, location, and configuration of reinforcement; and identified member and structural dimensions, uncertainty about the structure is clearly reduced. Some investigators believe that this supporting work can serve as justification for using a different capacity reduction factor \( \phi \) for evaluation, as opposed to design. There is a great potential for developing this concept, but at present there is no consensus or appropriate methodology. Experience and engineering judgment of the investigator are extremely important in this case.

In case the analytical evaluation shows the structure does not satisfy the intent of ACI 318, the building official may approve a lower load rating for the structure based on the results of the evaluation.

5.1.5 Findings of the analytical evaluation -- Three scenarios may describe the findings of an analytical strength evaluation:

1. Analyses show that the building or structural element has an adequate margin of safety according to the provisions of the applicable building code. In this case the design capacity (nominal capacity multiplied by capacity reduction factor \( \phi \)) exceeds that required for factored loads.

2. Analyses show that the design capacity is less than that required for factored loads, but greater than required for service loads (load factors equal to or greater than 1.0 for all load cases). This situation may be particularly difficult to resolve where there is no evidence of structural distress in the building or element.

In this case the building or structural element is not adequate. Consideration may be given to load testing the struc-
Analyses show that the design capacity of the structure is less than required for service loads under the applicable building code. In such cases, the owner should be notified and consideration given to the installation of shoring, severe restriction of use, or evacuation of the structure until remedial work can be done.

5.2 -- Supplementing the analytical evaluation with load tests

5.2.1 Conditions for use -- In-situ load testing is recommended only if all of the following conditions are met:

-- The test results will permit rational interpretation of the structural capacity of the element to be tested

-- The influence of adjacent structural members, components, or whole structures can be accounted for in conducting the tests and in evaluating the results of the tests. This influence includes full accounting of alternate load paths which are available in the building

-- The structure can be monitored adequately and safely by appropriate instrumentation so as to provide the necessary data to make an evaluation of the structural capacity

-- The safety of all participants in the test and all passersby can be assured during setup and performance of the test

An analytical evaluation of some type should always be done before conducting a load test. This evaluation may employ approximate methods. The analysis should be performed to allow for a reasonable prediction of the performance of the structure during the load test. One should recognize that theoretical calculations for predicting deflections of concrete structural elements are in many cases unreliable. Considerable care and engineering judgment are required when comparing calculated deflections with those that actually occur during a load test. Reports are available to assist the investigator in calculating deflections of reinforced concrete structures (ACI 435.1R, ACI 435.2R, ACI 435.4R, ACI 435.5R, ACI 435.6R, ACI 435.7R, ACI 435.8R).

5.2.2 Identifying the form of test to be conducted--

Evaluation of structural adequacy may be performed using analytical methods aided by one or both of the following forms of in-situ load testing:

-- Static tests

-- Dynamic tests, using special test procedures developed specifically for the characteristics of the structure to be tested. Such procedures are beyond the scope of this report

5.2.3 General requirements -- The following general requirements are applicable to the process of conducting a load test:

-- A qualified investigator, acceptable to the building official, should design and directly supervise and control the tests

-- A load test should not be made until that portion of the structure to be tested is at least 56 days old. Earlier testing may be permitted if mutually acceptable to all parties involved. In such cases it is important to consider carefully the age of the concrete in the structure as it relates to the strength of that concrete

-- The structure or portion of the structure to be load tested should be loaded in such a manner as to adequately test the suspected source of weakness

-- Load tests that are conducted on environmentally exposed structures should be conducted at a time when the effects of sunlight on the structure and the monitoring devices are minimized (i.e., early morning, late evening, or at night)

-- Load tests on exposed concrete structures should preferably be conducted at temperatures above 32 F (0 C)

-- The environmental conditions, especially the ambient temperatures should be recorded accurately at frequent intervals during the performance of a load test on environmentally exposed structures

5.2.4 Test loads-- The following guidelines may
be useful for selecting the type of test load or loading device in conducting a load test of a concrete structure:

- When the test load is applied by using separate pieces, such as iron bars, bricks, concrete block, etc., the pieces must be separated throughout the duration of the test to prevent arching action. The separate pieces or stacks of pieces should have a largest base dimension less than one-sixth of the span of the structural element being tested. These pieces or stacks should be separated by a clear lateral distance of at least 4 in. (100 mm)

- If test loads are applied by using separate pieces, the pieces should be of uniform shape and weight. The weight of each piece should not differ by more than 5 percent from the average weight. The average weight should be determined by weighing at least 20 pieces taken at random. If nonuniform load elements are used, each separate piece should be measured (i.e., determine surface contact area), weighed, and marked appropriately

- The weight of the loading elements should be easily measurable

- The load devices should be easy to apply and readily removable

- Hygroscopic materials should not be used as test load devices

- Test load devices applied to sloping surfaces must be securely anchored to prevent shifting. Load components, which may be applied to the structure, must be accounted for in all directions

- It is usually preferable to apply test loads with hydraulic or pneumatic devices because of the ease of application and speed of removal (unloading)

- When using hydraulic or pneumatic load-application systems, it is necessary to provide properly and safely for the reactions of those devices, except where these reactions are part of the loading scheme. It is also necessary to insure that these loading devices will continue to function in a uniform fashion, even with significant deformation of the structure during application of the test load.

- If water, loosely sprinkled sand, or other similar materials are used for the test load, they should be contained within small compartments to prevent “ponding” effects or shifting of the test load during significant deformation of the structure that may occur while the test load is acting

- The total accumulated test load should be within 5 percent of the intended value

- Arrangement of the test load should consider the following:

  1. The test load should be arranged as close as possible to the arrangement of the load for which the structure was designed

  2. If the test load cannot be arranged as described above, it should be designed and arranged in such a fashion as to produce load effects in the structure similar to those that would be produced by the design load

  3. If uniform design loads are approximated with converging (concentrated) load systems, such systems must be designed so that significant stress concentrations do not occur at the points of load application

  4. Consideration should be given in designing the application of the test load to produce maximum load effect in the area of the structure being tested. This includes use of checkerboard or similar type pattern loads

5.2.5 Instrumentation-- The following guidelines are applicable to installation of instrumentation systems for monitoring the performance of a structure or structural element during a load test. Russell (1980) provides additional background on field instrumentation.

- Instrumentation should be provided for monitoring deflections, lateral deformations, support rotations, support settlement or shifting, etc., during application of the test load

- Strain measurements should be made on flexural members at critical locations
Deflection and strain measurement devices should be duplicated in critical areas.

The acceptable error in instruments used for measuring displacements should not exceed 5 percent of the calculated theoretical deformation, or 0.005 in. (0.13 mm).

Measurement devices should be provided and mounted so that it is possible to determine relative changes in the shape of the structure or structural element during the test.

Instrumentation should be protected during the load test from environmental influences such as direct sunlight, significant temperature variations, and wind.

All instrumentation should be installed in advance of the start of the load test to allow for determination of the effects of daily thermal changes on the deformations of the structure and on the instruments themselves. If necessary, compensation factors can be developed for application to the data obtained from the load test.

Deflection of structural members can be measured with electronic or mechanical devices, or with conventional surveying equipment.

Displacement transducers and resistance strain gage are available and may allow rapid electronic collection of data from a large number of points. However, their installation can be time consuming and costly, particularly on sites exposed to the weather.

Mechanical devices, such as dial gages, are typically more reliable, but collection of data can be slow, and requires that someone enter into the structure during performance of the test, which can be dangerous. These devices are valuable for measuring small deflections in stiff structures.

Large deflections can be easily measured by suspending graduated scales from critical points and reading them remotely with a surveyor’s level.

Deflection measurement devices should be placed at the point(s) of maximum expected deflection. Devices should also be placed at the supports to detect column shortening, if deemed appropriate by the investigator.

Crack width can be measured by using graduated magnifying glasses, or “crack comparators.” Their use during a load test is, of course, restricted for safety reasons. If they are used, marks should be placed at each point on the cracks where readings are to be taken so that subsequent readings are taken at the same positions.

Crack movement (opening or closing) can be measured with dial gages, displacement transducers, or mechanical strain gages. Crack movement can also be measured accurately by using gage points and a mechanical extensometer.

Thermometers or thermocouples should be used to measure the ambient temperature during a load test. Temperature readings should be taken in all areas of a structure that are affected by the load test. For structural slabs, thermometers should be placed above and below the slab surface. Accurate records of variations of sunlight should be maintained for roof slabs and other areas of the structure which are exposed to direct sunlight during performance of a load test.

5.2.6 Shoring -- Shoring should be provided prior to a load test, whether the whole structure or only a portion is involved, to support the structure in case of failure during the test. The shoring should be strong enough to carry the existing dead load and all additional superimposed test loads on the portion of the building for which collapse is possible. The effects of impact loading on the shoring, which is likely if a structure or member fails during the test, should be considered in the selection of shoring elements. For horizontal members, shoring should clear the underside of the structure by not more than the maximum expected deflection plus an allowance not to exceed 2 in. (50 mm). Similar arrangements should be made for other types of members. In any case, shoring should not influence or interfere with the free movements of the structure under the test load, and should be designed and constructed to protect all people working on, below, or beside the structure to be tested, in case of excessive deformation or collapse.
5.2.7 Static load tests of flexural members

5.2.7.1 Guidelines -- The following guidelines are presented for conducting static load tests of flexural members:

--- Install shoring and instruments before any test load is applied

Take a series of base elevation readings immediately prior to the application of the test load, to serve as a datum for making deflection readings on the various elements of the structure during the load test

--- A load which simulates the effect of any portion of the service dead load \( D \) which is not already present should be applied and should remain in place until after the load test has been declared completed. This application of additional dead load is most often done when load testing is performed during rehabilitation or before a structure has been completed, and various partitions, ceilings, ductwork, etc., have not yet been installed. Deflection readings should be made immediately after this additional dead load is applied. This additional dead load should be in place for at least 48 hr before additional increments of the test load are applied

--- No portion of the test load which represents live loads should be applied before the deflections due to the simulated dead load have effectively reached constant values

--- After dead load deflections have stabilized, existing cracks and other defects should be observed, marked, and recorded

--- Immediately before applying any increment of the test load, the readings of all measuring devices should be recorded

--- The portion of the structure selected for loading should be subjected to a total test load \( TL \), including all dead loads already acting, equivalent to the following:

\[
TL = 0.85(1.4D + 1.7L)
\]

where

\( D = \) dead loads

\( L = \) live loads

--- In continuous structures the test load \( TL \) should be defined as the load which produces a load effect (bending moment, shear force, or axial force, as appropriate) equal to \( 0.85(1.4D + 1.7L) \) at the section being studied. Elstner et al. (1987) discuss the determination of test loads in reinforced concrete construction

The determination of the test load should include live load reductions as permitted by the applicable general building code

--- The test load should be applied in the predetermined pattern in at least four approximately equal increments. If serviceability is a criterion in the evaluation of the structure, an intermediate load increment equivalent to \( 1.0D + 1.0L \) should be included, so that the service behavior of the structure can be evaluated

The test loads should be applied without impact and without causing vibration of the structure

After applying each increment of the test load, deflection measurements should be made at equal time intervals until the deflections attain effectively constant values. For this purpose, if the change between successive deflection readings taken at least 2 hr apart does not exceed 10 percent of the initial total deflection recorded for the current load increment, it may be considered that the deflections have effectively stabilized. If the measured deflections reach or exceed pre-calculated values, the test should be stopped and only be continued with the recorded permission of the supervising engineer

--- The investigator should inspect closely the structure following application of each load increment for the formation or worsening of cracking and distress, as well as for the presence of excessive deformations, rotations, etc. The investigator should analyze the significance of any distress and determine whether it is safe to proceed with the test

Load-deflection curves should be developed during the load test for all critical points of deflection measurements. Var-
ious types of electronic data-gathering and plotting equipment are available to automatically plot such curves. These curves should be closely monitored during the load test. They are a valuable tool in determining the load-deflection response of the structure, and for determining if the structure is approaching its ultimate capacity.

After the maximum test load has been in position for 24 hr, deflection readings should be taken. The load should then be removed in decrements not greater than twice the increments used to apply the test load. Deflection readings should be taken before and after each load decrement has been removed. Final deflection readings should be taken 24 hr after removal of the entire test load.

5.2.7.2 Criteria for evaluation of the flexural load test-- The procedures and criteria for interpreting the data should be established completely before a load test is conducted. If structural safety is the only criterion for the evaluation of the structure, and if the structure under the test load does not show visible evidence of failure, it may be considered to have passed the test if it meets the following criteria specified in ACI 318:

1) If the measured maximum deflection of a beam, floor, or roof is less than $L_t^2/20,000\ h$; where $L_t =$ span of the member (in.) under load test and $h =$ the total depth of the member (in.). The span of a member is the distance between centers of supports, or clear distance between the supports plus the depth of the member, whichever is smaller. In determining limiting deflection for a cantilever, $L_t$ should be taken as twice the distance from the support to the end, and the deflection should be adjusted for movement of the support.

2) If the measured maximum deflection of a beam, floor, or roof exceeds $L_t^2/20,000\ h$, the deflection recovery within 24 hr after removal of the test load should be at least 75 percent of the maximum deflection for nonprestressed concrete, or 80 percent for prestressed concrete.

Note: “Visible evidence of failure” includes cracking, spalling, crushing, deflections, or rotations of such a magnitude and extent that it is obviously excessive and not compatible with the safety requirements for the structure.

Nonprestressed concrete construction failing to show 75 percent recovery of deflections may be retested not earlier than 72 hr after removal of the first test load. The portion of the structure which is retested should be considered satisfactory if:

1) There is no visible evidence of failure in the retest, and

2) Deflection recovery after the retest is at least 80 percent of the maximum deflection in the second test.

If serviceability is a criterion, the deflections caused by the test load corresponding to $1.0D + 1.0L$ should not exceed that stipulated prior to the test. The significance of any cracks should be considered.

If the structure fails the load test on the basis of the deflection criteria, but shows no evidence of structural or material failure, either all necessary repairs or changes should be made to make the structure adequate for the rated capacity, or a lower rating should be established. No retesting of a structure, or any portion thereof which has previously failed a load test, should be permitted, unless, appropriate structural repairs and strengthening are employed to upgrade the structure.

5.2.8 Static load tests of elements in shear -- Load tests to evaluate the shear capacity (see ACI 426R) of structural elements are not recommended except in unusual circumstances. This recommendation is due to the uncertainty associated with the brittle and sudden characteristics of shear failures. A great deal of reliance is placed on the judgment of the supervising engineer conducting a load test for shear capacity. Each test is unique in terms of the characteristics of the structural elements being evaluated. Therefore, specific guidelines for conducting such tests cannot be simply listed as for load tests of flexural members. However, the following guidelines are presented for consideration by the investigator who determines that a load test for evaluation of shear capacity must be conducted:

1) The structure must be thoroughly examined prior to the test. It is important to establish the concrete strength and the shear reinforcement details, as variations in these items greatly impact on the shear capacity of a structural element.

2) The test load should in no case exceed $0.85(1.4D + 1.7L)$.

3) The load test should be preceded by a structural analysis to closely predict the...
performance of the structure under application of the test load

**--** Shoring of the structure is imperative. Provide shoring similar to that discussed for testing flexural members

**--** Instrumentation of the structure should concentrate on crack width monitoring in addition to deflections

**--** The critical components of the structure must be monitored continuously during the test

**--** Acceptance criteria for the load test must be developed based on a mutual understanding of the investigator and the building official. Such acceptance criteria will likely be based on crack formation and movements at and along existing crack planes

### 5.2.9 Interpretation of load test results

Considerable engineering judgment must be exercised in developing an appropriate interpretation of the results of a load test conducted on a concrete building, or elements within the building. Confusion often arises when a concrete structure, which is believed to be deficient, passes a load test. This confusion, or perhaps misunderstanding, may be the result of any of the following reasons:

**--** Many concrete structures have been designed conservatively. There are a number of reasons for a high degree of conservatism in reinforced concrete construction. These include the use of supplemental reinforcing steel placed arbitrarily in the structure to minimize cracking, providing larger areas of reinforcement than required by calculation when selecting bars, use of conservative design theories, overestimation of dead loads, and inaccurate modeling of boundary and support conditions

**--** Actual concrete compressive strengths are often greatly in excess of the specified design strengths

**--** The structural analyses do not accurately model the load-sharing characteristics of the structure

**--** The structure is repaired or strengthened prior to the load test

## CHAPTER 6 -- REFERENCES

### 6.1 -- Recommended references

**American Concrete Institute (ACI)**

- 201.1R Guide for Making a Condition Survey of Concrete in Service
- 201.2R Guide to Durable Concrete
- 207.3R Guide for Evaluation of Concrete in Existing Massive Structures for Service Conditions
- 209R Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures
- 216R Guide for Determining the Fire Endurance of Concrete Elements
- 222R Corrosion of Metals in Concrete
- 224R Control of Cracking in Concrete Structures
- 224.1R Causes, Evaluation, and Repair of Cracks in Concrete Structures
- 228.1R In-Place Methods for Determination of Strength of Concrete
- 309.2R Identification and Control of Consolidation-Related Surface Defects in Formed Concrete
- 318 Building Code Requirements for Reinforced Concrete
- 318R Commentary on Building Code Requirements for Reinforced Concrete
- 426R Shear Strength of Reinforced Concrete Members
- 435.1R Deflections of Prestressed Concrete Members
- 435.2R Deflections of Reinforced Concrete Members
- 435.4R Variability of Deflections of Simply Supported Reinforced Concrete Beams
- 435.5R Deflections of Continuous Concrete Beams
- 435.6R Deflection of Two-Way Reinforced Concrete Floor Systems: State-of-the-Art Report
- 435.7R State-of-the-Art Report on Temperature-Induced Deflections of Reinforced Concrete Members
- 435.8R Observed Deflections of Reinforced Concrete Slab Systems, and Causes of Large Deflections
- 442R Response of Buildings to Lateral Forces
- 444R Models of Concrete Structures -- State of the Art

**American National Standards Institute (ANSI)**

- A58.1 Building Code Requirements forMinimum Design Loads in Buildings and Other Structures

**ASTM**

- A 370 Standard Method and Definitions for Mechanical Testing of Steel Products
- C 39 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
- C 42 Standard Method of Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
- C 597 Standard Test Method for Pulse Velocity Through Concrete
- C 803 Standard Test Method for Penetration
Resistance of Hardened Concrete

C 805 Standard Test Method for Rebound Number of Hardened Concrete

C 823 Standard Practice for Examination and Sampling of Hardened Concrete in Constructions

C 856 Standard Practice for Petrographic Examination of Hardened Concrete

C900 Standard Test Method for Pullout Strength of Hardened Concrete

D 4580 Standard Practice for Measuring Delaminations in Concrete Bridges by Sounding

E 122 Recommended Practice for Choice of Sample Size to Estimate the Average Quality of a Lot or Process

Resistance of Hardened Concrete

Recommended references are available from:

ACI American Concrete Institute
PO Box 9094
Farmington Hills MI 48333-9094

ANSI American National Standards Institute, Inc.
1430 Broadway
New York NY 10018

ASTM ASTM
1916 Race Street
Philadelphia PA 19103

ICBO International Conference of Building Officials
5360 South Workman Mill Road
Whittier CA 90601

6.2 -- Cited references


Chabowski, A.J., and Bryden-Smith, D. (1979), “A Simple Pull-Out Test to Assess the In-Situ Strength of Concrete,” Concrete International: Design and Construction, V. 1, No. 12, American Concrete Institute, Dec., pp. 35-40.


Malhotra, V.M. (1976), Testing Hardened Concrete: Non-destructive Methods, ACI Monograph No. 9, American Concrete Institute, Detroit, 204 pp.


Peterson, C.G. (1984), “LOK-test and CAPO-test Developments and Their Applications,” Proceedings, Institution of Civil Engineers (London), Part 1, 76, May, pp. 539-


This report was submitted to letter ballot of the Committee and approved according to Institute procedure.