Code Requirements for Load Testing of Concrete Structures (ACI 437.2) and Commentary

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This code provides requirements for test load magnitudes, test protocols, and acceptance criteria for conducting a load test as a means of evaluating the safety and serviceability of concrete structural members and systems of structures. A load test may be conducted as part of a structural evaluation to determine whether a structure requires repair and rehabilitation, or to verify the adequacy of repair and rehabilitation measures.

Keywords: acceptance criteria; cyclic load test; load test; monotonic load test; test load magnitude; test protocol

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CHAPTER 1—GENERAL

1.1—Scope

1.1.1 The scope, purpose, applicability, limitations, interpretation principles, and units of measure are defined in this chapter.

1.2—General

1.2.1 The requirements of this Code shall govern for the evaluation of safety and serviceability of members in concrete structures by load testing.

1.2.2 The requirements of this Code shall apply to reinforced concrete structures, or portions of reinforced structures, with prestressed reinforcement, nonprestressed reinforcement, or both.

1.2.3 Procedures and requirements provided in this Code are not applicable to structures having concretes with compressive strengths above 8000 psi unless permitted by the licensed design professional.

1.2.4 Load testing of structures or portions of structures shall be performed after 56 days of casting, unless the owner, contractor, licensed design professional and other interested parties agree to perform the load test at an earlier age.

1.3—Purpose

1.3.1 The purpose of this Code is to establish the minimum requirements for the test load magnitudes, load test procedures, and acceptance criteria applied to concrete structures as part of an evaluation of safety, serviceability, or both to determine whether a structure requires repair and rehabilitation, to verify the adequacy of repair and rehabilitation measures applied to a structure, or to provide for public health and safety through structural safety and serviceability.

1.3.2 Load tests shall be conducted according to the load test procedures described in Chapter 5.

1.3.3 All references in this Code to the licensed design professional shall be understood to mean a person licensed to practice structural design in the jurisdiction where this Code is being used. The licensed design professional for a project is responsible for and in charge of the evaluation of safety and serviceability of the structure.

1.4—Applicability

1.4.1 This Code does not apply to slabs-on-ground, or structures whose responses are dominated by in-plane actions.

1.4.2 This Code shall not be used for product development testing where load testing is used for quality control or approval of mass-produced members.

1.4.3 This Code does not apply to testing for resistance to load effects of fatigue, wind, and earthquakes.

1.4.4 This Code does not apply to determining design strength or load-carrying limit at failure.

1.4.5 This Code does not cover load testing for the approval of new design or construction methods.

1.5—Interpretation

1.5.1 The official version of this Code is the English language version using inch-pound units published by the American Concrete Institute.

1.5.2 In case of conflict between the official version of this Code and other versions of this Code, the official version governs.

1.6—Units of measurement

Values in this Code are stated in inch-pound units. A companion Code in SI units is also available.

COMMENTARY

R1.1.1 A load test is required if the effect of a strength deficiency is not well understood or it is not practicable to measure the dimensions and determine the material properties of the members required for analysis.

R1.2.1 The determination of situations where a load test is required is outside the scope of this Code. Furthermore, this Code does not address procedures for analytical strength evaluations, condition evaluation of structures, or assessment of structural deterioration and its consequences. The licensed design professional should advise the owner and parties participating in the load testing of a structure of the potential for damage or even failure of the portions of the structure to be load tested in accordance with the procedures of this Code.

This Code may be used to evaluate whether a structure or a portion of a structure satisfies safety requirements. A strength evaluation may be required if the materials are considered to be deficient in quality, if there is evidence of faulty construction, if a structure will be used for a new function, or if, for any reason, a structure or a portion of it does not appear to satisfy safety requirements. In such cases, this Code provides minimum requirements for performing a strength evaluation of the structure by load testing.

If a load test is prescribed as part of the strength evaluation process, all parties should agree on the region to be loaded, the magnitude of the load, the load test protocol, and the applicable acceptance criteria before conducting the load test. If the safety concerns are related to an assemblage of members or an entire structure, it may not be feasible to load test every member and section. In such cases, an investigation plan should be developed to address the specific safety concerns.

R1.2.2 If there is doubt or concern about the shear strength of a member or members, or the development of reinforcement, a load test may be the most efficient solution to confirm the safety of the member or structure.

A load test may also be appropriate if it is not feasible to determine the material properties and structural dimensions required for analysis, even if the cause of the concern relates to flexure or axial load.

R1.2.3 Experience is lacking in the application of the procedures and requirements in this Code to structures having high-strength concrete, that is, compressive strengths over 8000 psi as defined in ACI 363. Structures or members constructed of high-strength concrete may exhibit a response that is nearly linear as the structure approaches its load-carrying limit and therefore may provide little warning of an impending failure. Structures or members constructed of high strength may also experience a more brittle failure in comparison to structures with concrete strengths less than 8000 psi.

R1.2.4 Loading concrete structures at early ages may affect both immediate and long-term response. Concrete creep depends on age of loading (ACI 209R). Other involved parties may include building officials, concrete subcontractors, and persons with a future interest in the structure.

R1.4.1 The procedures and requirements in this Code have been developed and applied to structural members subjected to gravity loads and where the structural response is dominated by flexure, such as typical members of the gravity load-resisting system in a building. This Code is not applicable to structures where the response involves significant in-plane or membrane action, where soil-structure interaction may govern behavior. Structures that should generally not be evaluated on the basis of the requirements of this Code include shells, arches, bins and silos, and chimneys. The response of to blast loading should also not be evaluated by the requirements of this code.

R1.4.4 The procedures and requirements of this Code are not intended to provide any indication of the design strength or load-carrying limit of a member or structure at failure. The term “design strength” refers to the strength of a member or cross section as used in the context of the basic requirement for strength design, expressed as “design strength ≥ required strength” (based on factored load combinations of the general building code). The design strength is calculated in accordance with the provisions and assumptions of the strength design method of the general building code and includes the appropriate strength reduction factor ϕ.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

D = total dead load: $D_w + D_s$, or related internal moments or forces

D_s = superimposed dead load, or related internal moments or forces

D_w = load due to self-weight of the concrete structural system, and other permanent structural framing members of which the effects are in-place.

F = load due to weight and pressure of fluids with well-defined densities and controllable maximum heights, or related internal moments or forces

I_{DL} = deviation from linearity index

I_{Pi} = permanency index for the i-th cycle at specified load level of a cyclic load test

$I_{P(i+1)}$ = permanency index for the $(i + 1)^{th}$ cycle at specified load level of a cyclic load test

I_{pr} = permanency ratio index

L = live load due to use and occupancy of the building not including snow or rain load and superimposed dead load, or related internal moments or forces

L_r = roof live load produced during maintenance by workers, equipment, and materials or during life of structure by moveable objects such as planters and people, or related internal moments or forces

l_t = span of member under load test and taken as the smaller of: (a) distance between centers of supports and (b) clear distance between supports plus thickness *h* of member; span for a cantilever shall be taken as twice the distance from face of support to cantilever end, in.

P_i = applied load corresponding to point *i* in load-deflection envelope in a cyclic load test, used for calculation of α_i in I_{DL} acceptance criterion, lb

P_{max} = applied load corresponding to 100 percent of test load magnitude, lb

P_{min} = minimum load to be maintained during a cyclic load test, lb

P_{ref} = reference load corresponding to the peak load of the first cycle (reference point) in a cyclic load test, used for computation of α_{ref} in I_{DL} acceptance criterion, lb

R = rain load, or related internal moments and forces

S = snow load, or related internal moments or forces

tan (α_i) = slope of secant line of point *i* in load-deflection envelope, where secant line passes through origin and point of interest, *i*, in a cyclic load test

tan (α_{ref}) = slope of reference secant line in load-deflection envelope, where reference secant line passes through origin and peak load of the first cycle (reference point) in a cyclic load test

Δ_i = measured deflection corresponding to point *i* in load-deflection envelope in a cyclic load test, used for computation of tan (α_i) in I_{DL} acceptance criterion, in.

Δ_l = maximum measured deflection (cyclic or monotonic load test) relative to the position of the structure at the beginning of the test, in.

Δ_{l2} = maximum deflection measured during a retest relative to the position of the structure at the beginning of the retest, in.

Δ_r = residual deflection measured within 24 hours after complete removal of the load at the completion of the load test in.

Δ_{ref} = measured reference deflection corresponding to the peak load of the first cycle (reference point) in a cyclic load test, used for computation of tan (α_{ref}) in I_{DL} acceptance criterion, in.

Δ_{rrt} = residual deflection measured within 24 hours after complete removal of the load at the completion of the repeat load test; residual deflection during the repeat test is relative to the position of the structure at the beginning of the repeat test, in.

Δ^{i}_{max} = measured maximum deflection at the end of the *i*-th cycle at a given load level of a cyclic load test, in.

Δ^{i}_{r} = measured residual deflection after unloading to the minimum load, P_{min}, at the completion of the *i*-th cycle at a given load level of a cyclic load test, in.

$\Delta^{(i+1)}_{max}$ = measured maximum deflection at the end of the $(i + 1)^{th}$ cycle at a given load level of a cyclic load test, in.

$\Delta^{(i+1)}_{r}$ = measured residual deflection after unloading to the minimum load, P_{min}, at the completion of the $(i + 1)^{th}$ cycle at a given load level of a cyclic load test, in.

2.2—Definitions

acceptance criteria—set of explicit and quantitative rules to establish whether or not a structure (or a portion of it) passes a load test.

applied test load (ATL)—load applied to the structure, in addition to dead load already in place, to produce test load magnitude (TLM- D_w).

cyclic load test—a load test with application of test load magnitude using a defined set of repeated load cycles of increasing load level.

failure—when referred to the performance of a structure (or a portion of it) under load test, it indicates that one or more acceptance criteria are not met.

load cycle—a series of load steps of increasing magnitude from the minimum load up to the peak load for that cycle and followed by decreasing load steps of equal and opposite magnitude down to the minimum load required during a cyclic load test.

load-deflection envelope—curve enclosing the points on a plot of applied load versus measured deflection from a cyclic load test; only loads greater than or equal to loads in any previous load cycle are included.

load level—maximum load attained during a loading cycle in a cyclic load test or an intermediate load before the full test load magnitude is applied in a monotonic load test.

load step—load increment applied during a monotonic load test; load increment applied during the loading portion or load decrement removed during the unloading portion of the load cycle in a cyclic load test

load test—application of a prescribed load to a structure or member and measurement response for the purposes of evaluation of safety, serviceability, or both.

monotonic load test—a load test involving the application of test load in at least four approximately equal load steps and then maintaining the test load magnitude for at least 24 hours.

reference point—point on a plot of applied cyclic load versus measured deflection corresponding to the peak load of the first load cycle.

reference secant line—line passing through the origin and the reference point in the plot of applied cyclic load versus measured deflection

response measurement—a quantitative measure of structural behavior under the action of the applied test load (ATL) and used to determine if acceptance criteria are satisfied.

service load—all loads, static or transitory, imposed on a structure or element thereof, during the operation of a facility, without load factors.

superimposed dead load, D_s—This includes, but is not limited to, walls, roofs, ceilings, stairways, built-in partitions, finishes, cladding, and other similarly incorporated architectural and structural items; the weight of fixed service equipment such as cranes, plumbing stacks and risers, electrical, heating, ventilating and air-conditioning systems, and fire sprinkler systems.

total dead load D—This Code makes a distinction between dead load due to self-weight and superimposed dead loads in this Code. The total dead load D includes both dead load due to self-weight and superimposed dead loads; that is, $D = D_w + D_s$.

tension-controlled section—a cross section in which the net tensile strain in the extreme tension steel at nominal strength is at least $\varepsilon_{ty} + 0.003$, where ε_{ty} equals the yield strain for deformed reinforcement or a strain of 0.002 for prestressed reinforcement.**test load magnitude (TLM)**—total load to be used in conjunction with acceptance criteria in this Code to determine whether or not a structure, or a portion of it, passes a load test.

COMMENTARY

R2.2—Definitions

acceptance criteria— In addition to the quantitative rules set to establish if a structure passes a load test, the licensed design professional should carefully consider structural response to determine if the structure responds adequately to the applied load, refer to Chapter 6.

load step—Refer to Fig. 4.7.1 for clarification of the meaning of "load step" in a monotonic load test, and refer to Fig. 4.8.1 for clarification of the meaning in a cyclic load test

response measurement—Deflection is the most common response measurement and is used in this Code for judging acceptable performance. In addition to deflection, response measurements may include rotation, strain, and crack widths.

test load magnitude (TLM)—this includes factored dead, live, snow, and rain loads, and is established using the load factors and combinations defined in Chapter 3 of this Code. It includes dead load that is already in place in the structure, including self-weight and super-imposed dead load, plus additional applied test loads to reach the desired TLM.

CHAPTER 3—TEST LOAD

3.1—Service loads

3.1.1 Service loads shall be determined by the licensed design professional.

3.1.2 The dead load portion of the service loads shall be separated into components D_w and D_s.

3.1.3 Unless documentation or tests are available to define the density of concrete used in the structure, the density of normal weight reinforced concrete shall be taken as 150 lb/ft^3 for calculation of D_w.

3.1.4 Fluid loads *F*, due to weight and pressure of fluids with well-defined densities and controllable in-service maximum heights, are permitted to be included in the superimposed dead load, D_s, for defining the test load magnitude in 3.2. If fluid loads *F* are due to weight and pressure of fluids that do not have well-defined densities or controllable maximum heights *F* shall be included with live load *L* for defining the test load magnitude in 3.2.

3.2—Test load magnitude

3.2.1 Test load magnitude (TLM) shall be as defined in 3.2.2 and 3.2.3 except as modified by 3.2.4 and 3.2.5, or as permitted or required by the local building official. For load testing and evaluation, live loads are permitted to be reduced in accordance with the general building code and as permitted by 3.2.5. If the general building code requires application of impact factors to the live loads, the same impact factors shall be included in the live load used in 3.2.2 through 3.2.4.

3.2.2 If load testing will evaluate only some portions of a structure that are suspected of containing deficiencies or that have been repaired or rehabilitated and whose adequacy is to be verified, and members to be tested are statically indeterminate, the TLM shall not be less than the largest value from Eq. (3.2.2a) through (3.2.2c).

$$\text{TLM} = 1.3(D_W + D_S) \qquad (3.2.2a)$$

$$\text{TLM} = 1.0D_W + 1.1D_S + 1.6L + 0.5(L_r \text{ or } S \text{ or } R) \qquad (3.2.2b)$$

$$\text{TLM} = 1.0D_W + 1.1D_S + 1.6(L_r \text{ or } S \text{ or } R) + 1.0L \qquad (3.2.2c)$$

3.2.3 If all suspect portions of a structure are to be load tested, or if members to be tested are statically determinate and the suspect flawed or weakened members are tension controlled at the critical section, the TLM shall not be less than the largest value from Eq. (3.2.3a) through (3.2.3c). If the suspect statically determinate members are not tension controlled at the critical section, the largest value from Eq. (3.2.2a) through (3.2.2c) shall be used for the TLM.

$$\text{TLM} = 1.2(D_W + D_S) \qquad (3.2.3a)$$

$$\text{TLM} = 1.0D_W + 1.1D_S + 1.4L + 0.4(L_r \text{ or } S \text{ or } R) \qquad (3.2.3b)$$

$$\text{TLM} = 1.0D_W + 1.1D_S + 1.4(L_r \text{ or } S \text{ or } R) + 0.9L \qquad (3.2.3c)$$

3.2.4 If serviceability is a criterion in the evaluation of the structure, a test load level equal to $1.0D + 1.0L + 1.0(L_r$ or S or $R)$ shall be included as a load level so that the behavior of the structure at service load can be evaluated.

3.2.5 If the ratio of service live loads to service dead loads exceeds 2.0, that is, if $(L + (L_r \text{ or } S \text{ or } R))/(D_W + D_S) > 2.0$ and if the suspect deficient member is tension-controlled at the critical section, it shall be permitted to reduce the load factor applied to the live load L in Eq. (3.2.2b) to 1.4 and in Eq. (3.2.3b) to 1.3, and to reduce the load factor applied to roof live loads, snow loads, or rain loads **(**L_r or S or R) in Eq. (3.2.2c) to 1.4 and in Eq. (3.2.3c) to 1.3.

COMMENTARY

R3.1—Service loads

R3.1.2 ACI 437R provides guidance on estimating self-weight before conducting the load test.

R3.2—Test load magnitude

The required test load magnitude (TLM) follows the recommendations of ACI 437.1R. The value of the TLM is intended to be consistent with the factored load combinations of ASCE/SEI 7-16. The TLM is appropriate for evaluating concrete structures designed in accordance with the current or previous editions of ACI 318.

If testing structures designed using the load factors and ϕ-factors in the 2002 and later editions of ACI 318, wherein load factors and ϕ-factors are changed from earlier editions, the test load may induce bilinear elastic (cracked) or inelastic behavior for some structures. Chapter 5 provides discussion regarding linearity of response as part of the acceptance criteria.

If members being tested do not meet the minimum shear reinforcement requirements of the applicable code but meet strength requirements, an assessment of the test load at which cracking in the web-shear region will occur is recommended. The applicable code can be used to determine the shear force that will cause web-shear cracking in prestressed concrete members. Cracking that does not close after removal of the test load may occur if nonprestressed reinforcement yields during the load test. Precast stressed members with thin webs, such as double tees, can be a concern in this regard because they may be prone to developing permanent damage from full test loads.

R3.2.3 Smaller load factors are permitted for statically determinate tension-controlled members to reduce the potential for inelastic deformations as a result of the load test and because of the extra ductility and associated warning expected to develop before failure or collapse. Tension-controlled members are also usually less sensitive to variations in concrete strength.

R3.2.5 For buildings with large live loads compared with the structure's self-weight and weight of superimposed dead loads, there may be a concern that an otherwise adequate structure could be loaded into the inelastic range during the load test, inducing permanent deformations. This could occur, for example, when testing a structure prestressed for a lower, more typical, service load condition but reinforced with bonded reinforcement to provide adequate design strength for full factored code-required live load. Section 3.2.5 provides some flexibility for moderating the TLM in such cases. This provision in effect permits reducing the TLM if the ratio of service live loads to service dead loads exceeds 2.0. These reductions are permitted if the limiting strength being tested is tension-controlled, implying a ductile failure mode with large accompanying deflections.

CHAPTER 4—LOAD TEST PROTOCOL

4.1—Selection of Test Protocol

4.1.1 Test protocol shall be selected by the licensed design professional as either the monotonic test protocol in accordance with 4.7 or the cyclic test protocol in accordance with 4.8

4.2—Safety

4.2.1 Load tests shall be conducted in a manner to provide safety to people and the structure during the test. Shoring shall be designed by a licensed design professional and installed before the start of the load test.

4.2.2 Safety measures shall be implemented in such a way as not to interfere with load test procedures or affect results.

4.3—Load arrangement

4.3.1 Application of test load shall be selected to maximize the response characteristics due to applied test load (ATL) specified in Section 4.6.1. More than one test load arrangement shall be used if a single arrangement will not simultaneously result in maximum values of the effects necessary to demonstrate the adequacy of the structure.

4.3.2 Either distributed or concentrated loads are permitted. In the case of distributed loading, arching of the applied load shall be avoided. The effects of concentrated load shall be investigated before conducting a load test. If concentrated loads are used to simulate distributed loading, they shall be of such magnitude and so located as to produce maximum internal moments and forces at critical cross sections as would be produced by distributed loads.

4.3.3 If the load test is conducted to evaluate shear strength near continuous supports, the ratio of moment-to-shear at the critical sections shall be consistent with the ratio of moment-to-shear computed for load combinations in Chapter 3.

4.3.4 The load shall be applied at locations so that its effects on the structural members for which safety or serviceability is in doubt are maximized and the possibility of unloaded members sharing the applied load is minimized. Analysis to determine the effect of adjacent members shall be completed before conducting the load test. The contribution of adjoining members shall be taken into account and applied test load magnitude shall be selected accordingly. It is permitted to separate or isolate the member or members to be tested from adjacent members through cutting or other means.

4.4—Response measurements

4.4.1 Response measurements shall include deflection in all load tests. The resolution of deflection measurement devices shall not exceed 1/100 of the expected deflection response at the applied test load (ATL).

4.4.2 Response measurements shall be taken 10 minutes before the application of the first load step and continued throughout loading and unloading phases.

4.4.3 Measurements shall be made at locations where maximum responses are expected as established by the licensed design professional.

4.4.4 Response measurements shall be evaluated at each load level or after each load step for the presence of excessive deformations or rotations.

4.5—Visual inspection

4.5.1 The structure shall be inspected following application of each load level for the formation, widening, or lengthening of cracks and other forms of distress.

4.5.2 The licensed design professional shall assess the significance of any distress and determine whether it is safe to continue with the test.

4.6—Load application

4.6.1 The magnitude of load or load effect applied to the structure or element to perform a load test shall be ATL. This magnitude combined with the magnitude of self-weight dead load in-place shall equal the TLM determined by Chapter 3.

4.6.2 Load shall be applied in accordance with either 4.7 or 4.8, as determined by the licensed design professional.

4.6.3 Load shall be applied without impact and without causing vibration of the structure.

4.6.4 The difference between the two load levels for the twin cycles in the cyclic load test shall not exceed 10 percent of the target load.

4.7—Monotonic load test protocol

4.7.1 Applied test load (ATL) shall be applied in a predetermined pattern in at least four approximately equal increments. The tolerance for the applied sustained load shall be ±5 percent of the full ATL. In the event that this tolerance is exceeded, the effect shall be evaluated by the licensed design professional.

4.7.2 Load levels and load steps for a monotonic load test are shown in Fig. 4.7.1. After each load level is attained, response measurements shall be made at equal time intervals until the measurements stabilize. Measurements shall be considered stabilized when the difference between successive readings taken no less than 2 minutes apart does not exceed 10 percent of either reading. The next load step shall be applied after response measurements have stabilized. The full ATL shall be maintained for at least 24 hours.

4.7.3 A set of response measurements shall be made at the beginning and the end of the 24-hour sustained load period.

4.7.4 After response measurements are made at the end of the 24-hour sustained load period, the test load shall be removed as quickly as practicable.

4.7.5 A final set of response measurements shall be made not more than 24 hours after removal of the load. If the structure has met the acceptance criteria at the conclusion of the unloading phase, it is not necessary to wait the full 24-hour period to make the final set of response measurements.

4.8—Cyclic load test protocol

4.8.1 Applied test load (ATL) shall be applied in repeated cycles of increasing magnitude. At least six cycles of loading and unloading shall be used with the following magnitudes of load level:

a) Cycles A and B—Service load level if serviceability is a criterion, otherwise 50 percent of ATL

b) Cycles C and D—Halfway between Cycle A and 100 percent of ATL

c) Cycles E and F—100 percent of ATL

The tolerance for the applied load shall be ±5 percent of ATL for each load cycle. Load steps within respective portions of loading and unloading phases shall be equal in magnitude.

4.8.2 Load level and load steps for each cycle of loading and unloading are shown in Fig. 4.8.1 and are described in 4.8.4 through 4.8.6. After each load step is applied, response measurements shall be made at equal time intervals until the responses stabilize. Response shall be considered stabilized when the difference between successive response readings taken no less than 2 minutes apart does not exceed 10 percent of either reading. The next load step shall be applied after response measurements have stabilized.

4.8.3 At the end of each unloading phase of the cycle a load P_{min} of at least 10 percent of ATL shall be maintained to keep the test devices engaged. P_{min} shall not exceed 15 percent of ATL.

4.8.4 *Load Cycles A and B*—For Load Cycle A, the load steps shall be initiated at P_{min}. The first load cycle consists of five approximately equal load steps beyond P_{min}. Load Cycle B is a repeat of Load Cycle A.

4.8.5 *Load Cycles C and D*—For Cycles C and D, the load at the first of five steps shall be at the same level as the third step of Cycle A, and the load at the second step shall be at the level of maximum load attained in Cycle A. The remaining three steps are of approximately equal magnitude.

4.8.6 *Load Cycles E and F*—For Cycles E and F, the load at the first of five steps shall be at the same level as the third step of Cycle C, and the load at the second step shall be at the level of maximum load attained in Cycle C. The remaining three steps shall be of approximately equal magnitude.

COMMENTARY

R4.1 – Selection of Test Protocol

R.4.1.1 If the strength of the structure being evaluated is limited by the strength of plain concrete, the expected failure of the structure is controlled by shear, or development of the reinforcing steel, the monotonic load test protocol prescribed in 4.7 is recommended because the sustained load applied during the monotonic protocol allows time for widening of cracks, compressive creep, and slip of reinforcing steel.

R4.2—Safety

R4.2.1 Shoring should be provided during a load test, whether the entire structure or only a portion is involved, to support the structure in case of failure during the test. Shoring should be designed to support dead loads, the ATL, and all additional superimposed loads, including test equipment, on the portion of the building for which collapse is possible. If test load is applied by hydraulics, such load is not likely to be present if collapse occurs. 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 and design of shoring members. This may be accomplished by designing the shoring to support at least twice the applied test load plus the existing dead load.

For multistory structures, shoring more than one level to prevent progressive collapse in the event of failure may be required. If all floors below the test floor cannot support the weight of the test member, the loads it supports, and the applied test loads, the shoring should be extended to a suitable bearing surface.

R4.2.2 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. Similar arrangements should be made for other types of members. Shoring should not influence or interfere with the free movement of the structure during the load test.

R4.3—Load arrangement

R4.3.2 Arching can be caused by the stacking of masses and refers to the tendency for the load to be transmitted nonuniformly to the flexural member being tested. For example, if a slab is loaded by a uniform arrangement of bricks with the bricks contacting each other, arching can result in reduction of the load on the slab near the midspan of the slab.

The internal moments and forces resulting from the application of concentrated loads will not reproduce exactly the effects of distributed loads. The ability of the structure to withstand concentrated loads without localized damage needs to be investigated, and bearing plates may be required at locations of concentrated loads.

R4.3.3 If the load test is being conducted to evaluate shear strength, the moment in the section will influence the shear strength of the section.

R4.3.4 The load arrangement should cause the maximum demands at the critical sections. Analysis should be completed to consider the effects of adjacent members. If it is shown that adjoining unloaded members will help support some of the test load, the load test magnitude should be adjusted with consideration of the expected load sharing, as to represent the desired internal member forces required for the evaluation. In some cases, the licensed design professional may elect to isolate the member to be tested from the adjacent members. For example, if testing simply supported members, such as double tee beams in parking garages, it is possible to separate the member being tested from adjacent members by cutting the connections between adjacent members and overlay (if present).

R4.4—Response measurements

If an electronic data acquisition system is used, measurements can generally be taken at a rate of once each second. The data acquisition rate can be reduced to once each minute during the 24-hour sustained load period of the monotonic load test protocol. Mechanical instrumentation, such as analog dial gauges, may be used. When analog instrumentation is used, multiple measurements should be made after each load step or point of interest and care should be taken to ensure that readings are stable prior to moving to the next load step. A minimum of three measurements taken 30 second apart are generally required to establish a reading as stable.

If temperature changes are expected to have significant effects on the deflection response (e.g., roof members), ambient temperatures, surface temperatures and member deflections should be measured over a 24-hour period before performing the load test, to determine the correlation between temperature and measured deflections. Temperatures should be recorded during the load test, and their effects on the measured deflections should be considered when evaluating acceptance criteria prescribed in Chapter 5.

R4.6—Load application

R4.6.1 In Chapter 3 the demand required of a load test is defined as test load magnitude (TLM). In performance of a load test the magnitude of self-weight, Dw, is in-place and therefore does not need to be applied to the structure. As such, applied test load (ATL) is used.

R4.6.2 The cyclic load test protocol allows performing a real-time assessment of member characteristics such as linearity and permanency of deformations at different load levels. Hydraulic loading devices are generally required to complete the cyclic load test protocol within a reasonable period of time. In some instances, the use of hydraulic loading devices may not be practicable.

R4.6.3 Vibrations of the structure due to load application may affect the results of the load test. Vibrations may also be caused by other portions of the structure left in service while the load testis being performed. The licensed design professional should verify that measurements are not affected by ambient vibrations or vibrations induced by the applied load.

R4.7—Monotonic load test protocol

R4.7.1 If the sustained load is applied using hydraulic loading systems, as the structure deforms over time, the applied load may fall outside the 5 percent tolerance. Efforts to sustain the ATL should be considered in design of the test and loading system. If ATL falls outside of the tolerance it should be evaluated by the licensed design professional.

R4.7.4 Intermediate response measurements should be made at selected intervals to determine whether significant short-term creep is occurring during the hold period.

R4.8—Cyclic load test protocol

R4.8.1 In the cyclic load test procedure, the loads are applied in loading-unloading cycles of increasing magnitude. Typically, this is achieved by using hydraulic loading systems. Using a sequence of loading-unloading cycles up to the predetermined maximum load level provides the opportunity to evaluate the structural response at different load levels. The load sequence is intended to identify, in an explicit manner, any undesirable response. Because the structure is initially loaded and unloaded at low levels, the licensed design professional has the ability to better understand end fixity and load transfer characteristics of the tested member by comparing measured responses with calculated values. For statically indeterminate structures in particular, this ability allows checking the accuracy of the assumptions on fixity and load sharing made in the structural analysis. As a result, the licensed design professional has the ability to determine more precisely the induced member forces and moments, and is better able to interpret structural behavior or response.

R4.8.3 The structure is not completely unloaded between cycles as this may disengage the measuring devices and may result in incorrect maximum and residual responses. Once the test has begun, applied load should not fall below a minimum load, P_{min}. This allows all devices to remain engaged during the load test. Depending on test parameters and measurement devices P_{min} should be set within the range of 10 to 15 percent of the ATL.

CHAPTER 5—ACCEPTANCE CRITERIA

5.1—Distress caused by load test

5.1.1 The portion of the structure tested using the cyclic load test protocol or monotonic load test protocol shall show no evidence of failure.

5.1.2 At each load level, deflections or other measured responses due to the test loads, or other measured responses, that exceed precalculated magnitudes shall be evaluated by the licensed design professional. Based on this evaluation, a decision on whether to continue the load test shall be made by the licensed design professional.

5.1.3 Cracking shall be evaluated by the licensed design professional who shall decide on whether to continue the load test.

5.1.4 If at any time during the load test a member develops cracks indicating imminent shear failure, the member shall be considered as having failed the load test. Retesting of the failed member is not permitted.

5.1.5 In regions of anchorage and lap splices, the appearance of a series of short cracks inclined to the axis of the reinforcement or cracks parallel to the axis of the reinforcement shall be evaluated by the licensed design professional who shall decide on whether to continue the load test.

5.2—Performance assessment at service load level

5.2.1 If serviceability is a criterion in the evaluation of the structure, deflections, crack spacing, and crack widths under a test load equivalent to the service condition shall be recorded and checked against limit values that are established by the licensed design professional before conducting the load test. If serviceability is evaluated in a load test conducted to evaluate safety, and the limit values are exceeded at the service load level, the licensed design professional shall determine whether to terminate the load test.

5.3—Acceptance criteria for monotonic load test protocol

5.3.1 *Deflection limits*

5.3.1.1 The member or structure shall be considered to have passed the load test if the residual deflection, Δ_r, satisfies Eq. (5.3.1.1) at any time within the 24-hour recovery period after removal of load.

$$\Delta_r \leq \frac{\Delta_l}{4} \qquad (5.3.1.1)$$

5.3.1.2 If the maximum deflection measured during the test, Δ_l, is less than 0.05 in. or the deflection as a fraction of the span length, l_t, is less than $l_t/2000$, the residual deflection requirements given by Eq. (5.3.1.1) shall be permitted to be waived.

5.3.2 *Retesting*

5.3.2.1 If the measured residual deflection Δ_r does not satisfy Eq. (5.3.1.1), it shall be permitted to repeat the load test if the maximum deflection Δ_l satisfies Eq. (5.3.2.1).

$$\Delta_l \le \frac{l_t}{180} \qquad (5.3.2.1)$$

The licensed design professional shall be permitted to adopt a different value for the maximum deflection Δ_l in Equation (5.3.2.1) if justified by detailed analysis.

5.3.2.2 The repeat test shall be conducted not earlier than 72 hours after complete removal of the test load for the first test.

5.3.2.3 The portion of the structure tested in the repeat test shall be considered acceptable if the residual deflection Δ_{rrt}, satisfies Eq. (5.3.2.3) at any point within the 24-hour recovery period after removal of load.

$$\Delta_{rrt} \le \frac{\Delta_{l2}}{10} \qquad (5.3.2.3)$$

5.4—Acceptance criteria for cyclic load test protocol

5.4.1 *Deviation from linearity index*—The deviation from linearity index, I_{DL}, calculated in accordance with Eq. (5.4.1), shall be monitored during all cycles of the cyclic load test.

$$I_{DL} = 1 - \frac{\tan(\alpha_i)}{\tan(\alpha_{ref})} \qquad (5.4.1)$$

where $\tan(\alpha_i)$ is the secant stiffness of any point *i* on the increasing loading portion of the load-deflection envelope, and $\tan(\alpha_{ref})$ is the slope of the reference secant line for the load-deflection envelope, as shown in Fig. 5.4.1.

5.4.1.1 The deviation from linearity index shall be considered acceptable if it does not exceed 0.25 for any point on the loading portion of the load-deflection envelope.

5.4.1.2 If the deviation from linearity index criterion is not satisfied due to a transition from an uncracked to a cracked condition of the member or structure being tested, the load test shall be restarted and Cycles A to E performed with a new reference point being established.

5.4.2 ***Permanency ratio*—**The permanency ratio I_{pr}, calculated in accordance with Eq. (5.4.2a), shall be monitored during all cycles of the cyclic load test.

$$I_{pr} = \frac{I_{p(i+1)}}{I_{pi}} \qquad (5.4.2a)$$

where I_{pi} and $I_{p(i+1)}$ are the permanency indexes calculated for the *i*-th and $(i + 1)^{th}$ load cycles, respectively, at the same load level using Eq. (5.4.2b) and (5.4.2c) and deflections as defined in Fig. 5.4.2.

$$I_{pi} = \frac{\Delta_r^i}{\Delta_{max}^i} \qquad (5.4.2b)$$

$$I_{p(i+1)} = \frac{\Delta_r^{(i+1)}}{\Delta_{max}^{(i+1)}} \qquad (5.4.2c)$$

5.4.2.1 The permanency ratio shall be considered acceptable if it does not exceed 0.50 for all pairs of load cycles.

5.4.3 *Residual deflection*—The residual deflection Δ_r, measured not more than 24 hours after removal of the load at the completion of the load test, shall be considered acceptable if it satisfies Eq. (5.3.1.1).

5.4.4 *Retesting*

5.4.4.1 If any of the acceptance criteria in 5.4.1 to 5.4.3 is not satisfied, the member or structure shall be considered to have failed the load test except as provided in 5.4.4.2.

5.4.4.2 If the measured residual deflection Δ_r does not satisfy Eq. (5.3.1.1), it shall be permitted to repeat the load test if the maximum deflection Δ_l satisfies Eq. (5.3.2.1).

5.4.4.3 The repeat test shall be conducted not earlier than 24 hours after complete removal of the test load for the first test.

5.4.4.4 The portion of the structure that is retested shall be considered acceptable if the residual deflection Δ_{rrt}, measured not more than 24 hours after removal of the load, satisfies Eq. (5.3.2.3), where Δ_{l2} is the maximum deflection measured during the repeat test relative to the position of the structure at the beginning of the repeat test.

5.5—Provision for lower load rating

5.5.1 If the structure under investigation does not satisfy conditions of 5.1 and 5.2 and the criteria of 5.3 or 5.4, a lower load rating, based on the results of the load test or structural analysis, shall be allowed for continued use of the structure, if approved by the building official.

5.5.2 If the cyclic load test protocol is used the safe live load shall be established by subtracting the factored dead load from the load at which one of the acceptance criteria was not met, and dividing that difference by the live load factor. Load factors used for the determination of the safe live load shall be determined in accordance with the general building code. After unloading, the residual deflection shall satisfy Eq. (5.3.2.3).

5.5.3 If the structure or member has undergone significant damage, as determined by the licensed design professional, the distressed structure or members shall not be put into service, even at a lower load rating.

COMMENTARY

R5.1.1 A general acceptance criterion to assess the behavior of a structure during a load test is that no evidence of failure is observed. Evidence of failure includes cracking, crushing in compression zones, and deflections that are incompatible with the serviceability or safety requirements of the structure. No simple rules have been developed for application to all types of structures and conditions.

R5.1.2 Load tests are typically undertaken when it is not possible to evaluate by analytical means the performance of a structure with reasonable certainty due to the degree of deterioration or uncertainties in analysis. Therefore, calculated deflections under the test loads may not be sufficiently accurate to be used as mandatory acceptance criteria. The licensed design professional should, however, perform calculations to estimate deflections due to the test loads, considering as-built information for the structure as described in ACI 437R. If the measured deflections exceed the calculated deflections, careful consideration should be given before continuing the load test to higher load levels. The calculated deflections need to be used to assess the performance during the load test and to interpret the load test results. Recommendations for the calculation of deflections are available in ACI 435R.

R5.1.3 Even though it is recognized that calculations regarding crack widths may not be sufficiently accurate to justify using them as mandatory acceptance criteria, the licensed design professional is to include their assessment under service load and other load levels as an integral part of the structural performance evaluation process. The occurrence or excessive growth of cracks under service loads and other load levels needs to be evaluated because it may be an indication of structural deficiencies that may jeopardize safety if the load test is continued.

R5.1.4 Shear forces are transmitted across a shear crack plane and are resisted by a mechanism combining the effects of the transverse reinforcement crossing the crack, if present; aggregate interlock; and dowel action of the flexural reinforcement crossing the crack. As crack lengths increase to approach a horizontal projected length equal to the depth of the member and concurrently widen to the extent that aggregate interlock cannot occur, and as transverse stirrups, if present, begin to yield or display loss of anchorage, the member is assumed to be approaching imminent shear failure.

R5.1.5 Cracking along the axis of the reinforcement, at lap splices, and in anchorage zones may be related to high stresses associated with the transfer of forces between the reinforcement and the concrete. These cracks may be indicators of pending brittle failure of the member. The licensed design professional is required to evaluate the consequences of the observed cracking.

ACI 408R describes the cracking that may occur in concrete structures due to inadequate development.

R5.2.1 Serviceability performance may be evaluated as part of a load test conducted to evaluate safety, or serviceability may be evaluated independently if safety of the structure is not of concern.

Irrespective of the load test protocol (that is, monotonic or cyclic load) and type of load (that is, uniformly distributed load over the entire tributary area or concentrated loads), if the measured deflection or crack width exceed limits set by the licensed design professional before the load test, careful consideration should be given as to whether to continue the load test to higher load levels. The variable nature of cracking and the challenges in accurately measuring and predicting crack width make the corresponding limits difficult to implement. The intent of the provision is to caution the licensed design professional that the occurrence or growth of excessive cracks under service loads may be an indication of structural deficiencies. Influence of crack width is of particular significance for some members or structures, such as those exposed to aggressive environments.

Guidance for establishing possible limit values for deflection and crack width at service load is as follows:

1. Maximum measured deflection should not exceed the permissible values given in Table 24.2.2 of ACI 318-19 for the various types of members. This recommendation is only applicable if the load distribution pattern reflects the one used for design, which is typically not the case for test loads distributed over a limited portion of the tributary area. Furthermore, the first two values in Table 24.2.2 are intended for immediate live load deflections, while the third and fourth deflection limits are for the additional deflection occurring after attachment of nonstructural members due to long-term deflection caused by all sustained loads plus any immediate live load deflection. This makes these limits difficult to apply to a load test where only the immediate deflection due to applied loads are measured. Additional long-term deflection due to sustained loads can be calculated and then added to the load test deflection results for live loading to arrive at a value that can be compared with the latter two limits of Table 24.2.2.
2. The maximum width of new flexural cracks formed during the course of the load test or the change in width of existing flexural cracks should not exceed a limiting width determined by the licensed design professional before the load test. Consideration should be given to the intended use and exposure conditions for the structure or member. ACI 224R provides procedures for estimating crack widths under service load conditions and provides suggested tolerable crack width limits

R5.3.1 Deflection limits—The residual deflection limit for the monotonic load test follows past practice. If the structure shows no evidence of failure, recovery of deflection after removal of the test load is used to determine whether the performance of the structure is satisfactory. The maximum deflection limit in the 2013 version of this Code has been removed as part of the acceptance criteria, and is used only in 5.3.2 to establish whether a repeat test is permitted.

If the member or structure is sufficiently stiff, deflection recovery is not relevant. In fact, it may even be unfeasible to measure the deflection recovery due to limitations in the resolution or accuracy of the deflection measurement equipment. To avoid penalizing a satisfactory structure in such a case, recovery measurements are waived and no check on deflection recovery is required if the absolute deflection is lower than 0.05 in. or the deflection as a fraction of span length is less than l_t/2000 (ACI 437.1R). **R5.3.2**

Retesting—If the member or structure fails the residual deflection criterion (Eq. 5.3.1.1) but the maximum deflection measured in the load test satisfies Eq. (5.3.2.1), it is permitted to repeat the load test.

Some structural elements, such as long-span prestressed beams, have been reported to exceed deflection magnitudes on the order of Eq. (5.3.2.1) while still exhibiting adequate performance under test loads. In anticipation of such situations the maximum deflection criteria, Eq. (5.3.2.1), may be increased before conducting the load test if the licensed design professional can show, by detailed analysis, that the structure is expected to exceed the Eq. (5.3.2.1) limit under the applied test load (ATL). Such analysis should include measured structural properties such as member size, reinforcement location, concrete strength, and elastic modulus, and should include appropriate considerations of boundary conditions, concrete cracking and other factors affecting the calculated deflection, refer to ACI 437R and ACI 435R. The licensed design professional, owner and parties participating in the load testing should be in agreement on the modified deflection limit before conducting the load test.

R5.4.1 Deviation from linearity index—The deviation from linearity index is to be checked at the critical locations of the member being load tested. The deviation from linearity index is a measure of the nonlinear behavior of a member or structure being tested. As a member becomes increasingly more damaged, its load versus deflection behavior may become more nonlinear, and its deviation from linearity increases. To quantify deviation from linearity at any load level, the ratio of the slopes of two secant lines intersecting the load-deflection envelope, as shown in Fig. 5.4.1, is calculated. Equation R5.4.1 may be written as:

$$I_{DL} = 1 - \frac{\dfrac{P_i}{\Delta_i}}{\dfrac{P_{ref}}{\Delta_{ref}}} \qquad \text{(R5.4.1)}$$

If a member or structure is initially uncracked and becomes cracked during the load test, the change in flexural stiffness as a result of a drastic change in moment of inertia at the crack location(s) can produce a high deviation from linearity that is not necessarily related to degradation in strength (Nehil et al. 2007).

If the member or structure remains uncracked during the load test, the deviation from linearity should be computed under uncracked conditions.

R5.4.2 Permanency ratio—Permanency ratio is evaluated by considering the maximum deflection and the residual deflection for the two cycles at each load level. If the permanency ratio exceeds the specified limit, it may be an indication that load application has damaged the member or structure and that significant inelastic behavior is taking place. High permanency ratios at low load levels (generally below service loads) might not be indicative of inelastic behavior if the resolution of the measuring instruments is on the same order of magnitude as the measured deflections. The permanency ratio might not be of significance if the maximum deflections measured for the twin cycles are less than 0.05 in. or, as a fraction of span length, are less than l_t/2000.

R5.4.3 Residual deflection—If the structure shows no evidence of failure, recovery of deflection after removal of the test load is used to determine whether the performance of the structure is satisfactory. The residual deflection Δ_r is the difference between the initial and final deflections for the load test. The residual deflection limit for concrete structures with nonprestressed reinforcement follows past practice. Bares and FitzSimons (1975) suggest that a residual deflection of 25 percent of the maximum deflection is acceptable for reinforced concrete structures and 20 percent is acceptable for prestressed concrete structures.

R5.4.4 Retesting— The 24-hour wait period following complete removal of load before repeating a cyclic load test differs from the 72-hour wait period required before repeating a monotonic load test. The shorter wait period for the cyclic load test is because smaller maximum and residual deflections are induced compared with the monotonic load test protocol. However, the ratio of residual deflection to maximum deflection is generally higher for the cyclic load test protocol.

R5.5Provision for lower load rating—Except for load-tested structures that fail to support their load test magnitude or show extensive distress due to the load test, structures may be used at lower load ratings even if they fail the respective acceptance criteria of the test protocols presented in this chapter. The building official may issue a building permit the use of a structure or member at a load rating that is judged to be safe and appropriate on the basis of the test results. If the lower load rating is achieved through structural analysis, the structural model used to analyze the structure should represent the actual behavior and, therefore, it should be calibrated to replicate the load test performance.

R5.5.2 Additional load cycles may be used to establish a more accurate value of the maximum safe live load that the structure is able to sustain. Beginning from the last load level at which deviation from linearity and permanency ratios passed the acceptance criteria, additional twin load cycles at increasing intermediate load levels may be applied until either the deviation from linearity index or the permanency ratio fails.

R6—COMMENTARY REFERENCES

ACI Committee documents and documents published by other organizations that are cited in the commentary are listed first by document number, year of publication, and full title, followed by authored documents listed alphabetically.

American Concrete Institute

ACI 209R-92—Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures (Reapproved 2008)

ACI 224R-01—Control of Cracking in Concrete Structures (Reapproved 2008)

ACI 318-19—Building Code Requirements for Structural Concrete and Commentary

ACI 363R-10—Report on High-Strength Concrete

ACI 408R-03— Bond and Development of Straight Reinforcing Bars in Tension (Reapproved 2012)

ACI 435R-95—Control of Deflection in Concrete Structures (Reapproved 2000)

ACI 437R-19—Strength Evaluation of Existing Concrete Buildings

ACI 437.1R-07—Load Tests of Concrete Structures: Methods, Magnitude, Protocols, and Acceptance Criteria

American Society of Civil Engineers (ASCE)

ASCE/SEI 7-10—Minimum Design Loads for Buildings and Other Structures

Bares, R., and FitzSimons, N., 1975, "Load Tests of Building Structures," *Journal of the Structural Division*, V. 101, No. 5, May, pp. 1111-1123.

Nehil, T.; Nanni, A.; and Masetti, F., 2007, "Strength Evaluation by Load Testing," *Concrete International*, V. 29, No. 3, Mar., pp. 53-58.

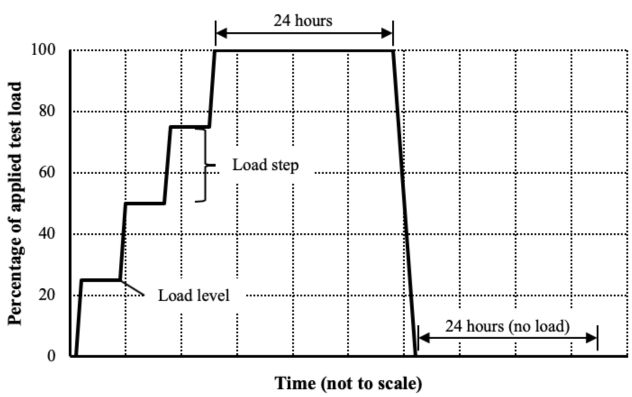

Fig. 4.7.1—Loading protocol for monotonic load test protocol.

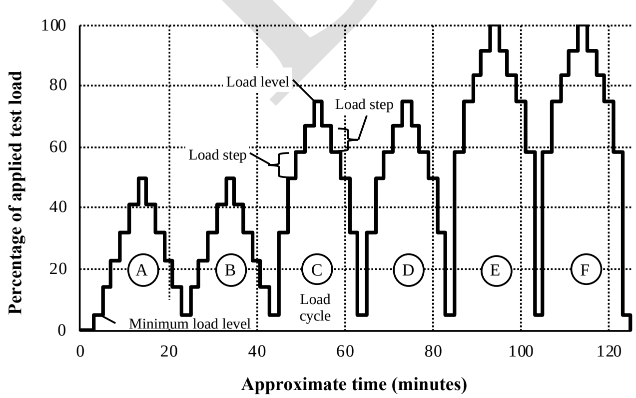

Fig. 4.8.1—Loading protocol for cyclic load test protocol.

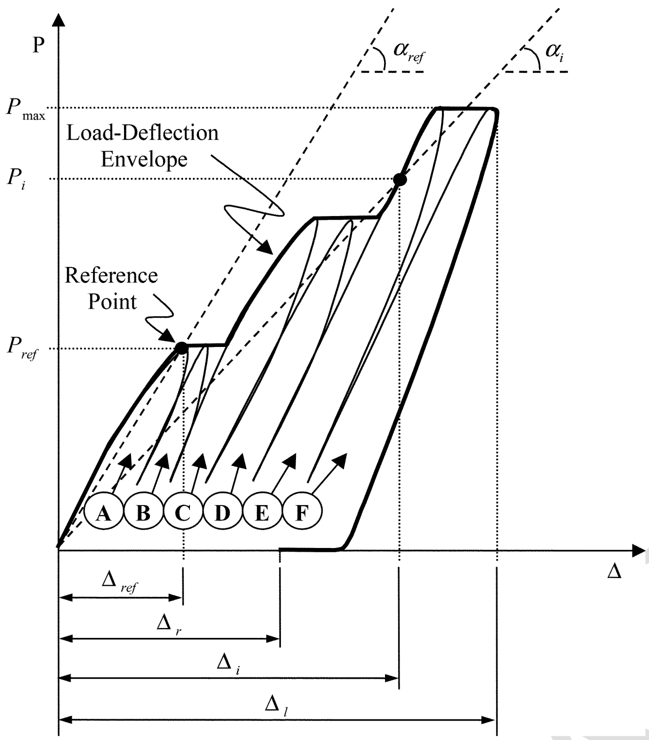

Fig. 5.4.1—Schematic load-versus-deflection curve for cyclic load test.

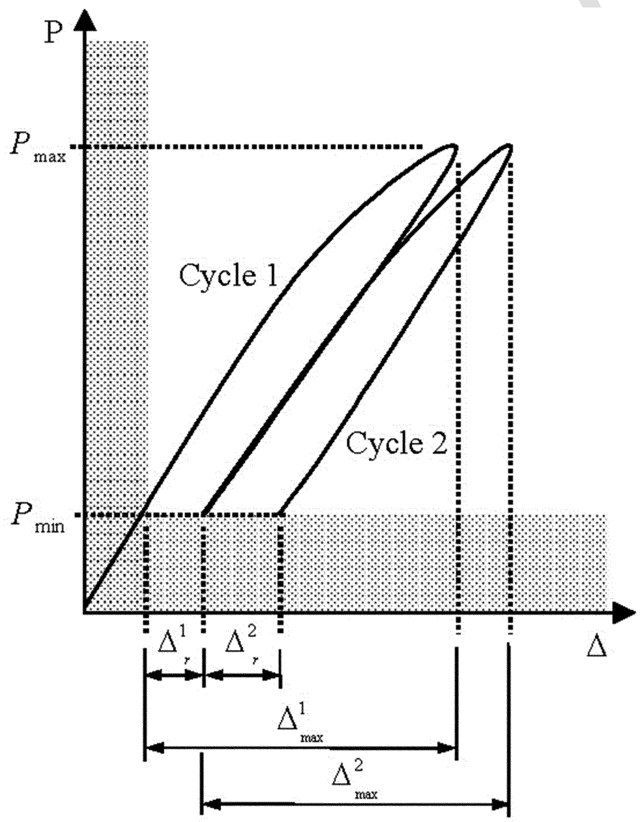

Fig. 5.4.2—Schematic of load-versus-deflection curve for two cycles at same load level