

Load Tests of Concrete Structures: Methods, Magnitude, Protocols, and Acceptance Criteria

Reported by ACI Committee 437



American Concrete Institute®

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Reported by ACI Committee 437

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This report provides the recommendations of Committee 437 regarding selection of test load magnitudes, protocol, and acceptance criteria to be used when performing load testing as a means of evaluating safety and serviceability of concrete structural members and systems. The history of load factors and acceptance criteria as found in the ACI 318 building code is provided along with a review of other load test practice. Recommended revisions to load factors to be used at this time, additions to load testing protocol, and revisions to acceptance criteria used to evaluate the findings of load testing are provided.

Keywords: acceptance criteria; cyclic load test; deflection; deterioration; load test factors; load test protocol; monotonic load test; reinforced concrete; strength evaluation.

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CHAPTER 1—INTRODUCTION**1.1—Background**

Significant revisions were made in Chapter 9 of ACI 318-02 to the load factors to be used for determining required strength. The load factor for dead load was reduced from 1.4 to 1.2, and the load factor for live load was reduced from 1.7 to 1.6; other changes were also made as given in equations for required strength in Chapter 9. The strength-reduction factors (ϕ -factors) were also modified. The ϕ -factor for shear and torsion was reduced from 0.85 to 0.75, while the ϕ -factor for compression-controlled members was reduced from 0.70 to 0.65 unless spiral reinforcement is provided. The ϕ -factor for tension-controlled members (most flexural members) was not reduced, and remains 0.9.

The load factors and load combinations of ACI 318-05 match those of ASCE 7-02 (American Society of Civil Engineers 2002). The changes were made to unify the load factors used to design concrete structures with those generally used to design structures constructed of other materials, such as structural steel. The changes also facilitated the design of

concrete structures that included members of materials other than concrete.

Chapter 20 (Strength Evaluation of Existing Structures) of 318-02 and 318-05 was not changed from the previous code with regard to load test procedures. Section 20.3.2 (Load Intensity) of ACI 318-02 was not changed from the 1999 edition; that is, the total test load (including dead load already in place) was still defined to be not less than $0.85(1.4D + 1.7L)$, with live load permitted to be reduced in accordance with the applicable building code.

The reduction in load factors used for computing required strength without a corresponding reduction in the test load intensity resulted in two effects. First, the test load was no longer a fixed percentage of the required strength. Second, the test load was now in the range of 93 to 98% of the required strength for tension-controlled sections rather than 85% of the required strength as was the case in ACI 318-71 through 318-99.

ACI Committee 318 requested that Committee 437 review and report on the load intensity requirements of Chapter 20. In the process, Committee 437 has undertaken a thorough review of the historical background of load testing and developed not only recommendations for revisions to the test load magnitude (TLM), but also to the protocol for load testing and the acceptance criteria used to evaluate the results.

1.2—Introduction

The provisions of Chapter 20 of ACI 318 have remained essentially unchanged for an unprecedented period of time since the publication of ACI 318-71, when the code was changed from working stress design to ultimate strength design. Before the 1971 code, the test load requirements or acceptance criteria were revised with almost every new edition of the code dating back to 1920. **Chapter 3** and **Appendix B** of this report provide a detailed review of the history of the load test requirements and acceptance criteria in ACI 318. They also provide a discussion of other international standards and of significant research and reporting of other organizations on the subject of load testing.

The changes made in the load factors and load combinations of ACI 318-05 require a re-examination of the load test requirements of Chapter 20 of ACI 318-05. This report presents the recommendations of Committee 437 for revisions to the requirements of Chapter 20. Three key areas are addressed: load factors to be used in defining the TLM; the load test protocol; and acceptance criteria.

As will be discussed further in **Chapter 4**, the purposes of the recommended revisions to the TLM definition are twofold. The first purpose is to define a test load that will demonstrate a consistent safe margin of capacity over code-required service live load levels. Secondly, the definition of the test load primarily in terms of service live load rather than required (ultimate) strength is meant to emphasize the fact that load testing is (typically) a proof loading. In the experience of the committee members, most structures being load tested pass with small deflections. Load testing does not typically provide an indication of the ultimate strength of the structure, and this indication usually is not the goal of load testing.

Since 1920, the acceptance criteria used with load testing have incorporated a limit on measured maximum deflections after a 24-hour holding period of the total test load. The current criteria have not changed since ACI 318-63. Currently, the deflection limit is described by the formula $\Delta_{max} \leq l_t^2/20,000h$. The theoretical basis for this formula had its origins in the first decades of the 20th century. The committee has researched the origins of the formula and re-evaluated its appropriateness. The committee recommends adopting other more meaningful deflection acceptance criteria.

Chapters 5 and 6 of the report discuss selection of a load test protocol and recommended changes to the acceptance criteria used in strength evaluation and load testing. Committee 437 in its report 437R-03, "Strength Evaluation of Existing Concrete Buildings," has discussed a cyclic load test method that offers advantages in terms of reliability and understanding of structural response to load when compared with the conventional static load test. Chapter 6 presents recommended acceptance criteria for both the 24-hour static test and for the cyclic test. Acceptance criteria for serviceability are also given.

1.3—Limitations

Procedures and recommendations provided in this report are intended for structures and buildings using concretes of normal strengths. The methods are not intended for bridges, structures with unusual design concepts, or other special structures. The methods are not intended to be used for product development testing where load testing is used for quality control or approval of mass-produced members. Testing for resistance to wind and seismic loads is not discussed. AASHTO provisions for load testing of bridge structures are outside the scope of this report. Load testing to determine ultimate strength is also outside the scope of this report.

CHAPTER 2—NOTATION AND TERMINOLOGY

2.1—Notation

The notations reported in this section refer to the symbols used in the numbered chapters.

h	= overall thickness of member, in. (mm)
l_t	= span of member under load test; units depend on structural member considered (ACI 318)
s	= average spacing between cracks, in. (mm)
D	= total dead load: $D_w + D_s$; units depend on structural member considered
D_s	= superimposed dead load; units depend on structural member considered
D_w	= dead load due to self-weight; units depend on structural member considered
F	= loads due to weight and pressure of fluids with well-defined densities and controllable maximum heights; units depend on structural member considered
I_{DL}	= deviation from linearity index, dimensionless
I_P	= permanency index, dimensionless
I_R	= repeatability index, dimensionless
L	= live loads produced by use and occupancy of the building not including construction, environ-

	mental loads, and superimposed dead loads; units depend on structural member considered
L_r	= roof live loads produced during maintenance by workers, equipment, and materials or during life of structure by moveable objects such as planters and people; units depend on structural member considered
P	= applied load during load test (Fig. 6.1 and 6.2)
P_i	= load of point i in load-deflection envelope for computation of I_{DL} acceptance criterion (Fig. 6.2)
P_{min}	= minimum load to be maintained during load test (typically 10% of total test load)
P_{ref}	= reference load for computation of I_{DL} acceptance criterion (Fig. 6.2)
R	= rain load, or related internal moments and forces; units depend on structural member considered
S	= snow load; units depend on structural member considered
TL	= test load per ACI 318 before 1971; units depend on structural member considered
TL_{05}	= TL_{99} = test load per ACI 318-71 through ACI 318-05 = $0.85(1.4D + 1.7L) = 1.19D + 1.44L$; units depend on structural member considered
TLM	= test load magnitude (including dead load already in place); units depend on structural member considered
U	= required strength to resist factored loads
U_{99}	= required strength per ACI 318-99 = $1.4D + 1.7L$
U_{05}	= required strength per ACI 318-05 = $1.2D + 1.6L$
α_i	= slope of secant line of point i in load-deflection envelope, degrees
α_{ref}	= slope of reference secant line in load-deflection envelope, degrees
$\Delta \epsilon_s$	= strain difference in longitudinal reinforcement
Δ_i	= deflection of point i in load-deflection envelope for computation of I_{DL} acceptance criterion (Fig. 6.2)
Δ_{max}	= measured maximum deflection, in. (mm)
Δ_{ref}	= reference deflection for computation of I_{DL} acceptance criterion (Fig. 6.2)
$\Delta_{r,max}$	= measured residual maximum deflection, in. (mm)
Δ_{max}^A	= maximum deflection in Cycle A under maximum test load, in. (mm)
Δ_r^A	= residual deflection after Cycle A under minimum test load, in. (mm)
Δ_{max}^B	= maximum deflection in Cycle B under maximum load, in. (mm)
Δ_r^B	= residual deflection after Cycle B under minimum test load, in. (mm)
ϕ	= strength-reduction factor as per ACI 318

2.2—Terminology

The following definitions are important to the understanding of this report.

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

dead load (D), total—in this report, a distinction is made between dead load due to self-weight and superimposed

dead loads. Total dead load D will include both dead load due to self-weight and superimposed dead loads; that is, $D = D_w + D_s$. This definition creates a distinction not used in ACI 318 or the International Building Code (IBC).

dead load (D_w), self-weight—dead load due to self-weight D_w is to include the weight of the concrete structural system only.

dead load (D_s), superimposed—this report uses superimposed dead load to designate all other weight of materials of construction incorporated into a building other than self-weight of the concrete structural system. Such loads include, but are not limited to, partitions, floor finishes, nonstructural topping slabs and overlays, roofing materials, ceiling finishes, cladding, stairways, fixed service equipment, and landscaping, including fixed planters, soils, and plantings.

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.

proof load and proof load ratio—proof load is used to describe a load applied to a structure with intent to prove a safe margin of satisfactory performance beyond code-required service live and dead loads. For this reason, proof load is defined in terms of service loads and not in terms of required or ultimate strength. A proof load is generally not intended to provide an indication of the ultimate strength of the structure. Arithmetically, the proof load ratio is defined as the TLM minus the total dead load divided by the service live load; that is, proof load ratio = $(TLM - D)/L$.

strip or patch test load—a test load distributed over a limited portion of the tributary area of the structure or member to be tested and typically applied by means of hydraulic jacks.

test load magnitude (TLM)—TLM is defined as all existing dead load due to self-weight and existing superimposed dead load plus additional test loads used to simulate effects of factored service live loads and factored superimposed dead loads. The factors to be applied to live loads and superimposed dead loads to establish the TLM are provided in Chapter 4. The factor for superimposed dead loads is to be applied to both existing superimposed dead loads and those not already in place.

CHAPTER 3—HISTORY OF LOAD TEST, LOAD FACTORS, AND ACCEPTANCE CRITERIA

3.1—Scope of historical review

An extensive review of the existing literature has been done to develop a history of load testing of reinforced concrete structures. The results of this work are reported in detail in Appendix B. The focus of this literature search has been in the following areas that are under consideration for revision in ACI 318:

- The purpose or goal of load testing, and the types of load tests that should be used;
- Development of appropriate superimposed loads to be used in a load test; and
- Establishment of appropriate acceptance criteria for structural response to those test loads.

Appendix B begins with a history of the development of load testing within the United States and development of ACI building code requirements for load testing. This section of the appendix is followed by a section presenting general discussion of work done by various organizations in the United States and around the world in the area of load testing of concrete structures. The purpose of Appendix B is to provide a historical perspective of changes to ACI 318 recommended by Committee 437. It serves to show the origins of the present state of practice and why changes are considered appropriate. It provides a discussion of research on and practices for load testing outside the United States.

3.2—Summary and conclusions

The key points drawn from the literature survey and derived conclusions are provided herein.

3.2.1 Purpose of load testing

1. Load testing originated in the late 1800s as proof (or acceptance) testing to show that a structure could resist specified service loads with a reasonable margin of safety against failure. It was generally not employed to determine the ultimate strength of a concrete member;

2. Provisions for load testing in ACI 318 and prevailing industry interpretations of those provisions have, over time, blurred to imply that the purpose of load testing is: 1) to ensure that the structure being tested meets the requirements of ACI 318; and 2) to assess the ultimate strength of that concrete structure; and

3. Consideration of historical information and data suggests that the purpose of load testing should be divided into three distinct categories:

- a. Proof testing to show that a structure can safely resist intended design loads with an adequate factor of safety against failure;
- b. Proof testing to show that a structure can resist the working design loads in a serviceable fashion where deflections and cracking are within limits considered acceptable by ACI 318; and
- c. Testing to failure to show the ultimate capacity of a structural member either in the field or as a model in a laboratory setting.

3.2.2 Test load magnitude

1. The test load magnitude used in U.S. load testing practice generally originated as two times the live load. This criterion has been found in the oldest references reviewed, including those dating into the late 1890s. The exact origin of this test load has not been found. It is believed to be a rule of thumb that was adopted in that era;

2. This test load was used for structures designed using allowable stress design techniques that are generally no longer used in the United States;

3. The criterion for using a superimposed test load of two times the live load was abandoned by ACI in 1963, although it continued to persist in various local and state building codes well beyond that time;

4. Load test practice in ACI did not change to any appreciable degree when ultimate strength design was introduced in the ACI 318 code in 1963 and 1971. Ultimate strength design

methods generally resulted in a lower factor of safety against failure than allowable stress design methods, and the resulting designs were often more flexible than those of the earlier methods. The TLM was scaled back approximately 10%; however, the deflection criteria remained unchanged;

5. Over time, the TLM has been modified in ACI 318 from a high of $TL = 1.5D + 2.0L$ to the current low of $TL = 0.85(1.4D + 1.7L)$, which equates to $TL = 1.19D + 1.44L$. As shown in Table B.4, no agreement exists regarding load factors for defining the test load magnitude in similar documents throughout the world. Ideally, a minimum factor of safety should be explicitly agreed upon in terms of TLM;

6. It is suggested that a load level consisting of the service load equal to $1.0D + 1.0L$ should be included in the load test procedure to provide for assessment of the serviceability of the structure. Deflections and crack widths should be compared with maximum allowable, code-defined, or desirable values; and

7. More specific criteria should be developed to define what constitutes visible evidence of failure.

3.2.3 Protocol for application of the load test

1. Modern practice for load testing seems to be turning in the direction of applying the test load in increments that include multiple cycles of incremental loading and unloading until the full desired test load is attained. This appears to have benefits relative to ensuring that the structure is adequately and properly responding to the desired test load in terms of deflection and deflection recovery;

2. Load test practice should include application of one or more preliminary load tests at values well below the full desired superimposed test load to assess the conditions of end restraint and fixity acting in the portion of the structure being tested and to identify the degree of load sharing that is occurring from the member being loaded to the surrounding monolithic or structurally attached members; and

3. Duration of the application of the full desired test load has historically been set at 24 hours. Because a sufficient correlation of shorter-term tests with 24-hour tests has not been found, the 24-hour holding period at full TLM should be retained in the code to take creep of concrete into consideration (even if to a limited extent) and to allow the structure to properly respond and adjust to the maximum test load.

3.2.4 Acceptance criteria for load testing

3.2.4.1 Use of maximum deflection

1. The current acceptance criterion for maximum allowable deflection (that is, $\Delta_{max} = l_t^2/20,000h$) in a load test was developed for simple span members and does not adequately reflect any variations in end fixity of structural members from that condition. Further, that equation was developed during the era of allowable stress design methods. The equation is based on concepts of uncracked sections and maximum allowable stress in concrete. The allowable stress and elastic modulus built into the equation were derived for lower-strength concrete than is often employed in design today. The equation does not take into account the actual strength and stiffness of the concrete in the member being tested;

2. No correlation exists between structural response to a test load of $TL = 0.85(1.4D + 1.7L)$ and the deflection criteria that are currently being used in ACI load test practice;

3. The maximum deflection of a structure following application of a test load should be compared, where possible, against calculated values using the best available calculation methods that are based on thorough and comprehensive field investigation of the physical and mechanical properties of the concrete in the area of the structure under investigation; and

4. It is the current provision of IBC 2003 to limit deflections during load tests to values established as simple percentages of the span (for example, $l_t/360$) relating to serviceability criteria.

3.2.4.2 Use of deflection recovery

1. With the single exception of work done and reported in Israel in 1950 (Arnan et al. 1950), historical load test practice suggests that deflection recovery can be properly used as an acceptance criterion for load testing of concrete structures. The concerns expressed in the 1950 Israeli report regarding deflection recovery can be addressed through implementation of a load test practice that includes preliminary load testing or application of the test load in several cycles of loading and unloading of the structure in increasing increments until the full test load is in place;

2. Historical practice suggests that the deflection recovery after 24 hours in a static load test, without incremental loading and unloading of the structure as suggested previously, should be at least 75%. The Israeli research and more current work with cyclic load testing suggest that the deflection recovery requirement should be significantly higher, on the order of 90%, when using the cyclic load test method or when retesting a structure using the static load test method; and

3. Alternative methods of analyzing deflection recovery data to establish new criteria for acceptance have been introduced recently to accompany the cyclic load test method. If cyclic load testing is to be incorporated into ACI 318, then the appropriate accompanying deflection recovery acceptance criteria need to be defined.

CHAPTER 4—LOAD FACTORS

4.1—Introduction

A revised definition of TLM should be developed to address the change of load factors and load combinations used in ACI 318-05 for defining required strength compared with load factors used in ACI 318-71 through 318-99. The new definition should address concerns regarding whether structures designed by earlier codes should have different TLMs than structures designed in accordance with ACI 318-05. The new definition should also address whether the load test will be performed on all suspect portions of a structure or only on selected limited areas.

This chapter presents recommendations for revisions to the definition of test load magnitude (TLM). The TLM is intended for proof testing; that is, load testing to show that a structure can safely support code-required service loads. Load testing to determine ultimate strength is outside the scope of this report.

Table 4.1—Design strength and test load comparison: full load test*

Type of facility	D_w , lb/ft ² † (kN/m ²) (1)	D_s , lb/ft ² (kN/m ²) (2)	L , lb/ft ² (kN/m ²) (3)	$\frac{L}{D}$ (4)	U_{99} , lb/ft ² (kN/m ²) (5)	U_{05} , lb/ft ² (kN/m ²) (6)	U_{05} U_{99} (7)	TL_{05} , lb/ft ² (kN/m ²) (8)	TL_{05} U_{05} (9)	TL_{05} $D + L$ (10)	$TL_{05} - D$ L (11)	$\frac{TLM}{U_{05}}$, lb/ft ² (kN/m ²) (12)	$\frac{TLM}{U_{05}}$ U_{05} (13)	$\frac{TLM}{U_{99}}$ U_{99} (14)	$\frac{TLM - D}{L}$ (15)	$\frac{TLM - D}{L}$ (16)
Parking slab, unreduced live load	65 (3.11)	—	50 (2.39)	0.77	176 (8.43)	158 (7.57)	0.90	150 (7.18)	0.95	1.30	1.69	135 (6.46)	0.90	0.85	0.77	1.40
Parking beam, reduced live load	100 (4.79)	—	30 (1.44)	0.30	191 (9.15)	168 (8.04)	0.88	162 (7.76)	0.97	1.25	2.08	142 (6.80)	0.87	0.85	0.74	1.40
Office slab, unreduced live load	65 (3.11)	20 (0.96)	50 (2.39)	0.59	204 (9.77)	182 (8.71)	0.89	173 (8.28)	0.95	1.28	1.77	157 (7.52)	0.91	0.86	0.77	1.44
Storage, light	110 (5.27)	—	125 (5.99)	1.14	367 (17.57)	332 (15.90)	0.91	312 (14.94)	0.94	1.33	1.61	285 (13.65)	0.91	0.86	0.78	1.40
Storage, light with heavier structure	150 (7.18)	—	125 (5.99)	0.83	423 (20.25)	380 (18.19)	0.90	359 (17.19)	0.95	1.31	1.67	325 (15.56)	0.90	0.86	0.77	1.40
Storage, heavy	150 (7.18)	—	250 (11.97)	1.67	635 (30.40)	580 (27.77)	0.91	540 (25.86)	0.93	1.35	1.56	500 (23.94)	0.93	0.86	0.79	1.40
Manufacturing, very heavy	175 (8.38)	—	400 (19.15)	2.29	925 (44.29)	850 (40.70)	0.92	786 (37.63)	0.93	1.37	1.53	735 (35.19)	0.93	0.86	0.79	1.40
Landscaped pedestrian plaza	200 (9.58)	300‡ (14.36)	100 (4.79)	0.20	870 (41.66)	760 (36.39)	0.87	740 (35.43)	0.97	1.23	2.40	670 (32.08)	0.91	0.88	0.77	1.70
Plaza, truck dock	200 (9.58)	—	250 (11.97)	1.25	705 (33.76)	640 (30.64)	0.91	599 (28.68)	0.94	1.33	1.60	550 (26.33)	0.92	0.86	0.78	1.40
Average	—	—	—	—	—	—	0.90	—	0.95	1.31	—	—	0.91	0.86	0.77	1.44

*TLM definition for testing all suspect portions of structure.

†1 lb/ft² = 47.88 N/m².

‡Landscaped pedestrian plaza value of 300 lb/ft² (14.36 kN/m²) is not defined by ASCE-7, but is selected herein for illustrative purposes to represent 2.5 ft (0.76 m) of uniformly distributed saturated soil weighing 120 lb/ft³ (1922 kg/m³) such as might be encountered in a large fixed planter containing trees.

Definitions:

D_w = dead load to self-weight; D_s = superimposed dead load; $D = D_w + D_s$ = total dead load; and L = live load.

U_{99} = required strength per 318-99 = $1.4D + 1.7L$.

U_{05} = required strength per 318-05 = $1.2D + 1.6L$.

$TL_{05} = TL_{99}$ = test load per 318-71 through 318-05 = $0.85(1.4D + 1.7L) = 1.19D + 1.44L$.

$TL_{99}/U_{99} = 0.85$ for any value of D and L .

TLM = proposed test load magnitude = $1.0D_w + 1.1D_s + 1.4L$ (simplified by assuming F , L_r , S , and R equal to 0).

4.2—Load factors for various components of service load

4.2.1 Reasons for change—The required strength U (and design strength) of tension-controlled members of structures designed in accordance with ACI 318-02 and 318-05 has been reduced compared with the required strength per previous editions of ACI 318. As a result, the test load as defined in Chapter 20 of ACI 318-02 and 318-05 is not a fixed percentage of the required strength.

Table 4.1 provides a comparison of required strengths as defined in ACI 318-99 and 318-05 for a variety of structures. The table assumes that the members being considered (slabs and beams) are not over-reinforced and therefore qualify as tension-controlled members, which is usually the case in most concrete structures. Representative values for dead and live loads as shown in Columns 1, 2, and 3 are taken from typical buildings. Column 4 shows that the live load to total dead load ratio varies from 0.20 to 2.29. Columns 5 and 6 show the total factored demands (or minimum required strengths) according to ACI 318-99 and 318-05, while Column 7 shows their ratios. Column 8 shows the test load computed according to ACI 318-05. Note that while the ratio of test load to required strength in ACI 318-99 was 0.85, the

ratio of test load (TL_{05}) to required strength (U_{05}) defined by ACI 318-05 varies from 0.93 to 0.97 for the selected examples as shown in Column 9.

In Table 4.1, Columns 9 and 10 provide a comparison of the test loads as defined in ACI 318-05 with required strength and total service loads. Note that the ratio of test load to total service loads varies from 1.23 to 1.37 for the examples provided, which is a reasonably close range. The table also provides in Column 11 a comparison of the test load minus the total dead load divided by the live load (the proof load ratio). Note that this ratio varies from 1.53 to 2.40, which is a considerably wider spread.

A consequence of defining the test load as a constant percentage of the required design strength is that the relationship between the proof load applied to the structure and the service live load is not apparent and is not a reasonably constant ratio. The variation in this ratio is among the reasons the TLM should be redefined, the goal being more consistent proof testing of structures.

It is recommended that the TLM be redefined in terms of proof loading rather than as a percentage of required strength. As discussed in Chapter 3, proof loading has historically been the purpose of load testing. The proof load ratio

readily reveals the factor of safety of test load over service loads, and therefore adds clarity to the intent of load testing.

As noted in [Chapter 3](#), ACI 318 has wavered on whether some additional percentage of the design dead load should be included in the test load. Defining the test load as a combination of factored design dead and live loads is not unique to ACI. Introducing a factor other than 1.0 for dead loads in defining the TLM makes the relationship between the TLM and the service live loads variable (that is, a function of the relative magnitude of the dead loads and live loads). As shown in [Table 4.1](#), when the ratio of live load to dead plus superimposed dead loads is small (Column 4), the test load as defined in ACI 318-05 approaches the required strength (Column 9). This relationship tends to penalize structures that are heavy compared with the live loads they support even though calculation of a substantially accurate dead load is achievable on existing structures. This aspect of the current test load definition is another reason modifications to the definition of the TLM are recommended.

4.2.2 Recommended changes to test load magnitude—As defined in [Section 2.2](#), a proof load is a load applied to a structure to prove a safe margin of satisfactory performance beyond code-required service live and dead loads. It is proposed that the proof load be defined in terms of those parts of the total load a structure will likely be subjected to that are variable. Therefore, when defining proof load, unlike when defining required strength, there is a need to separate the components of dead load that do not vary from those that do. For this reason, dead load is separated into two categories: dead load due to self-weight (D_w) and dead load due to weight of construction and other building materials (D_s). This latter category is defined as superimposed dead loads and, as noted in [Section 1.3](#), includes weights of finishes, cladding, partitions, and fixed landscaping elements.

Dead load due to self-weight should be based on the as-constructed dimensions of those portions of the structure to be tested or dimensions of the structural members that are considered to be representative of the as-built structure, if different. Because this is a known and existing load, there is no need to apply a factor greater than unity to this self-weight when defining the test load as a proof load.

Superimposed dead loads may be defined by the local building code or may be defined in the design documents for the structure. Because these loads represent a variable that may change over time depending on the owner's use of the facility and construction and maintenance means and methods, a factor greater than 1.0 is suggested for superimposed dead loads. The actual factor used will depend on the degree of variability anticipated by the engineer defining the load test or by the building official. A load factor of 1.1 is recommended for superimposed dead loads except as discussed herein.

For partial load testing (when only portions of the suspect areas of a structure are to be tested), a higher test load is recommended to improve the level of confidence that significant flaws or weaknesses in the design, construction, or current condition of the structure are made evident by the load test. This recommendation reinstitutes the format of

ACI 437R-67, in which two different test load definitions were provided. The exception in these current recommendations is when the members to be tested are determinate (for example, cantilevers or simple span members) and the possibility exists of producing an inelastic response in the members if the test load approaches the design strength too closely. While the new strength-reduction factors of ACI 318-05 provide for a higher nominal strength with respect to design or required strength than did the factors of ACI 318-99, the new factors are still based not only on desired reliability, but also on probable inaccuracies in design or construction; for an existing structure, these latter concerns mean that it is not possible to know how great the buffer between design strength and nominal strength is. Therefore, for determinate members, the lower TLM is recommended.

Where the suspected shortcoming or weakness among structural members is highly variable throughout the structure (for example, corrosion and debonding of embedded reinforcing steel), it is critical that the engineer select areas for testing that represent conditions believed to be severe with respect to the safety and performance of the structure. It is important to note that it is not only the severity of damage to the structural member, but rather the combination of severity with the location of minimum strength reserve that is of most interest. The percentage increase in TLM recommended as follows for partial tests will not significantly improve probability that the tested structure can safely support code loads if the tested areas are not well chosen.

It is recommended that the load intensity as provided in Section 20.3.2 of ACI 318-05 be defined as follows. The equations are proposed to be consistent with the load combinations of Chapter 9.

Load intensity—When all suspect portions of a structure are to be load tested or when the members to be tested are determinate and the suspect flaw or weakness is controlled by flexural tension, the test load magnitude, *TLM*, (including dead load already in place) shall not be less than

$$TLM = 1.2(D_w + D_s) \quad (20-1)$$

or

$$TLM = 1.0D_w + 1.1D_s + 1.4L + 0.4(L_r \text{ or } S \text{ or } R) \quad (20-2)$$

or

$$TLM = 1.0D_w + 1.1D_s + 1.4(L_r \text{ or } S \text{ or } R) + 0.9L \quad (20-3)$$

where

- D_s = superimposed dead load;
- D_w = dead load due to self-weight;
- L = live loads, or related internal moments and forces;
- L_r = roof live load, or related internal moments and forces;
- R = rain load, or related internal moments and forces; and
- S = snow load, or related internal moments and forces.

Table 4.2—Design strength and test load comparison: partial load test*

Type of facility	$TLM, \text{ lb/ft}^2$ (kN/m ²) (12)	$\frac{TLM}{TL_{05}}$ (13)	$\frac{TLM}{U_{05}}$ (14)	$\frac{TLM}{U_{99}}$ (15)	$\frac{TLM - D}{L}$ (16)
Parking slab, unreduced live load	145 (6.94)	0.97	0.92	0.82	1.60
Parking beam, reduced live load	148 (7.09)	0.91	0.88	0.77	1.60
Office slab, unreduced live load	167 (7.99)	0.96	0.92	0.82	1.64
Storage, light	310 (14.84)	1.00	0.93	0.85	1.60
Storage, light with heavier structure	350 (16.76)	0.97	0.92	0.83	1.60
Storage, heavy	550 (26.33)	1.02	0.95	0.87	1.60
Manufacturing, very heavy	815 (39.02)	1.04	0.96	0.88	1.60
Landscape pedestrian plaza	690 (33.04)	0.93	0.91	0.79	1.90
Plaza, truck dock	600 (28.73)	1.00	0.94	0.85	1.60
Average	—	0.98	0.92	0.83	1.64

*TLM definition for testing only part of suspect portions of structure.

Definitions:

TLM = proposed test load magnitude = $1.0D_w + 1.1D_s + 1.6L$ (simplified by assuming $F, L_r, S,$ and R equal to 0).

When only part of suspect portions of a structure is to be load tested and members to be tested are indeterminate, the **TLM** (including dead load already in place) shall not be less than

$$TLM = 1.3(D_w + D_s) \tag{20-4}$$

or

$$TLM = 1.0D_w + 1.1D_s + 1.6L + 0.5(L_r \text{ or } S \text{ or } R) \tag{20-5}$$

or

$$TLM = 1.0D_w + 1.1D_s + 1.6(L_r \text{ or } S \text{ or } R) + 1.0L \tag{20-6}$$

- D_s = superimposed dead load;
- D_w = dead load due to self-weight;
- L = live loads, or related internal moments and forces;
- L_r = roof live load, or related internal moments and forces;
- R = rain load, or related internal moments and forces; and
- S = snow load, or related internal moments and forces.

In Eq. (20-2), the coefficient of the live load shall be permitted to be reduced in accordance with the requirements of the applicable Model Code or General Building Code. If impact factors have been used for the live load in design of the structure, then the same impact factor should be included in the above equations.

The total dead load shall include all superimposed dead loads, D_s , considered in design or considered by the engineer or building official to be relevant to the proposed load test. Where superimposed dead loads represent a significant portion of the total service loads, are not already in place on

the structure, and/or may not be of controllable intensity, a factor greater than 1.1 shall be considered for the superimposed dead load in the above equations for calculating the test load magnitude.

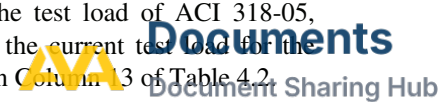
The commentary to this section in the building code could provide further explanatory discussion on this paragraph; for example, the possible variability of soil loading intensity and construction equipment loads on a landscaped structure. For this example, if soil loads are not already in place on the structure to be tested, then it will likely be appropriate to increase the test load magnitude by using a factor such as 1.4 or 1.6 to account for the variability of the loads the structure will be subjected to during installation of the soils and other landscaping features.

Commentary language should be provided in the building code to caution users when testing structures designed according to Chapter 9 of ACI 318-02 or 318-05 that, for some structures, the test load may induce bilinear elastic (cracked) or inelastic behavior. Discussion is provided in Chapter 5 regarding linearity of response as part of acceptance criteria recommended for adoption in ACI 318.

When testing members not meeting the minimum shear reinforcement requirements of ACI 318-05, Section 11.5.6.1 but meeting strength requirements on the basis of Section 11.5.6.2, an assessment of the test load at which significant cracking or damage in the web-shear region will occur is recommended. Significant cracking that does not close after removal of the test load may result if nonprestressed reinforcement yields during the load test or if the web shear region has no nonprestressed reinforcement. An appropriate adjustment of the proof load may be required to prevent permanent damage (that is, permanent open cracking) to such members. Equations (20-1) through (20-3) are recommended for determining TLM for such cases.

Tables 4.1 and 4.2, Column 12, provide the value of the proposed TLM for the example structures selected for full and partial load tests, respectively. Comparisons of the TLM with the total test load and required strength defined by ACI 318-05 are given in Columns 13 and 14, respectively. As shown in Table 4.1, the proposed TLM definition for full load tests has the effect of reducing the test load by approximately 10% compared with the test load of ACI 318-05 (Column 8), and so also reduces the TLM relative to required strength. In fact, the TLM is typically about 86% of the required strength per ACI 318-05 (Column 14) and about 77% of required strength per ACI 318-99 (Column 15). No examples have been provided of structures supporting fluid loads; however, the 1.2 factor recommended is 86% of the load factor for fluid loads F provided in Chapter 9 of ACI 318-05 for defining required strength U , and thus would produce a TLM versus required strength ratio consistent with the ratio for structures with live loads $L, L_r, R,$ and S .

The proposed TLM definition for partial load tests where only parts of the suspect areas are to be tested results in a test load close in magnitude to the test load of ACI 318-05, varying from 91 to 104% of the current test load for the example structures as shown in Column 13 of Table 4.2.



Proposing a ratio of the TLM to the required strength of approximately 85% for full load testing is, of course, not accidental. The ratio of test load to required strength was explicitly set at 85% in 1971. Calculations made by members of Committee 437 also indicate that the ratio of the TLM to ultimate strength appears generally to have been on the order of 80 to 85% in previous allowable stress design versions of the code. That is to say, one can design a slab or beam using the allowable stress design methods and typical materials strengths of the 1940s and 1950s, and then calculate the resulting nominal strength using current principles. If one then calculates the TLM defined in earlier editions of ACI 318 (for example, ACI 318-51 and 318-56) and compares that with the nominal strength of the designs that resulted from those code provisions, it turns out that the ratio is often approximately 80 to 85%. Thus, having an upper limit to the TLM of about 85% of required strength has considerable sustained history in ACI. This limit is furthermore considered prudent to avoid possibly causing excessive inelastic deformations in a structure as a result of load testing.

A concern, but unavoidable consequence, of maintaining the ratio of TLM to required strength at 85% is that with the reduced load factors of ACI 318-05, the proven factor of safety resulting from load testing would now be lower than at any time in the history of ACI. The proof load ratio that resulted from the TLM defined in ACI 318-71 through 318-05 has typically been on the order of 1.7 (Column 11). The proof load ratio resulting from the new TLM would typically be 1.4 when all suspect portions of a structure are to be tested, or 1.6 when only part of the suspect portions are to be tested. With respect to international standards, however, this remains about average. In addition, as a practical matter, because most load tests involve testing only part of the suspect portions of a structure, the proposed Eq. (20-4) through (20-6) will generally control and provide a TLM that is roughly 90 to 95% of the required strength and, for most of the examples presented, is close to the TLM of ACI 318-05.

The recommended new TLM provides a rational balance between providing an adequate factor of safety, but not causing damage to the structure in the process. Refer also to Section 4.3 of this report regarding modifications to load factors.

4.2.3 Applicability of TLM to structures designed per earlier codes—The new TLM should be considered applicable for existing structures regardless of the code under which they were designed. The nominal strength of tension-controlled members designed in accordance with the provisions of ACI 318-71 through 318-99 was approximately 10% greater than those designed per 318-05, but generally at least 10% less than members designed according to the allowable stress method of earlier codes. Members designed according to the earlier allowable stress methods would have been subjected to higher TLMs using the test loads of ACI 318-51 and 318-56. As discussed previously, the ratio of these TLMs to the members' nominal strength would have been on the order of 80 to 85%. Therefore, applying test loads defined by 318-71 through 318-05 to structures designed according to earlier codes tests them to a lower percentage of their nominal strength. This method has become accepted practice.

Model building codes such as IBC provide that the strength of structures designed per earlier codes is to be calculated according to the current code. Committee 437, in its reports ACI 437R-67 through 437R-03, has stated that strength evaluation of existing structures by analytical means is to be based on principles of strength design as applied in ACI 318 (using current principles).

Similarly, the proposed modified definition of the TLM should be considered appropriate for strength evaluation of structures designed per earlier editions of ACI 318. If the proof load recommended herein provides an acceptable margin of safety over maximum anticipated service loads for a structure designed in accordance with 318-05, then the same factor of safety should be considered adequate for structures designed in accordance with earlier codes. The proposed TLM will be less than the test loads defined in earlier editions of ACI 318. Therefore, no inherent danger exists of overloading such structures when using the proposed TLM.

4.3—Load factors for extreme ratios of live load to total dead load

Service conditions where the ratios of live load to total dead load are considered outside the normal range are defined as follows

$$\begin{cases} \frac{L}{D_w + D_s} < 0.50, \text{ where } 0.50 \text{ is lower limit of normal range} \\ \frac{L}{D_w + D_s} > 2.0, \text{ where } 2.0 \text{ is upper limit of normal range} \end{cases} \quad (4-1)$$

For structures where $L/(D_w + D_s) < 0.50$, the load factors applied to the dead load due to self-weight and superimposed dead load in the recommended new TLM definition achieve two ends. First, they remove the potential penalty against structures with large self-weight compared with the live loads they carry by eliminating the extra dead load component of the test load. They also reduce the TLM as a percentage of the required strength per ACI 318-05 compared with the test load defined in ACI 318-05 versus required strength. As can be seen in Table 4.1, Column 14, the ratio of the proposed new TLM to required strength remains nearly constant, regardless of the L/D , whereas Column 9 shows the penalty assigned to structures with low L/D by the current test load definition. For partial load testing, the ratio is not as constant, and Column 14 of Table 4.2 shows that structures with higher L/D ratios also have larger TLMs relative to their required strength, but the TLMs are not significantly different than the current test load.

It is recommended that the load factor for the live load component of the service loads for such structures with L/D less than 0.50 be the same as for structures falling in the normal range of L/D . The minimum TLM given by Eq. (20-1) and (20-4), however, provides an additional lower bound to the test load that will apply in those cases where the live-dead load ratio is very small (L/D less than 0.15), where the factored live load does not provide a sufficiently large portion with respect to the self-weight and superimposed dead loads.

For structures with large live loads compared with the structure's self-weight and weight of other superimposed dead loads, that is, $L/(D_w + D_s) > 2.0$, the committee sees conflicting concerns. As noted in [Chapter 3](#), the RILEM document TBS-2 recommends increasing the test load if the live load exceeds twice the dead load, although that document does not provide further explanation of why an increased factor of safety is considered appropriate nor what the magnitude of that increased factor of safety should be. On the other hand, this approach could result in situations where otherwise adequate structures are 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 ultimate strength for full code-required live load.

If the engineer and building official are of the opinion that the service live loads for a structure to be evaluated by load testing are known, controllable, and free from dynamic magnification effects, it is recommended that the load factor to be used on the live load portion of the service loads be reduced to 1.2 and 1.3, respectively, for full and partial load tests when $L/(D_w + D_s) > 2.0$.

The following text is proposed for inclusion in the commentary for R20.3.2 of ACI 318:

For structures where the ratio of live load to total dead load (L/D) is larger than 2.0, the multiplier of the live load, L , can be reduced from 1.4 to 1.2 in [Eq. \(20-2\)](#), and from 1.6 to 1.3 in [Eq. \(20-5\)](#) when the engineer determines that the magnitude of the live load is known and controllable and free from dynamic magnification effects.

CHAPTER 5—LOAD TEST PROTOCOL

5.1—Introduction

To apply test loads to a structure or portion of a structure in a systematic fashion for purposes of evaluating safety and serviceability, a number of items should be considered. They include, but are not limited to: test load configuration, the means by which the test load is applied, the procedure for application of the test load, and the duration of application of the test load. These items are discussed in this chapter. In addition, two common test methods are defined and discussed in general terms.

5.2—Test load configuration

According to Chapter 20 of ACI 318-05, the test load must be arranged to maximize the deflection and stresses in the critical regions of the structural members under investigation. There are no other requirements for the configuration of the test load. Several possible options could be used to satisfy the Chapter 20 requirements. The test load could be applied so as to replicate the uniformly distributed load used for design, or the test load could be applied with a series of concentrated loads to simulate the effects of a uniformly distributed load.

5.2.1 Uniformly distributed load pattern—Perhaps the most obvious way to determine if a structure is capable of

carrying the loads for which it is designed is to apply those loads in the same load pattern that is assumed in the design. To simulate a uniformly distributed load condition, test loads are commonly applied by means of dead weights, which is discussed in another section of this chapter. When test loads are applied in a uniform pattern over the full structure or over a large enough area to fully load the critical member being investigated as well as surrounding structural members that could contribute to supporting the load, then concerns such as load sharing and end fixity need not be as thoroughly investigated as when a small number of concentrated loads are applied.

5.2.2 Patch or strip equivalent loads—Chapter 20 of ACI 318-05 does not indicate the specific load distribution to be used; therefore, it is acceptable to apply equivalent concentrated (or patch) loads by means of hydraulic jacks or other methods. When using point loads applied by hydraulic jacks, it is difficult to determine the equivalent forces that will produce the same effects, including bending moments and shear forces, as the uniformly distributed load used in design. When planning a load test to determine the magnitude of the concentrated equivalent loads, the engineer may model the structural behavior of the members through the following methods:

- Numerical approaches (for example, finite element method) (Vatovec et al. 2002; Galati et al. 2004). Appropriate modeling is only possible given knowledge of material properties, internal reinforcement location, and overall geometry;
- Simplified models that analyze a portion of statically indeterminate structures. In this instance, it is necessary to have knowledge of the degree of fixity at the supports and the load sharing offered by adjacent members;
- Trial tests. For those situations where no information is available on the construction, and budget constraints disallow invasive and nondestructive testing before conducting a load test, a load-unload cycle could be used for calibration of actual member fixities and load transfer characteristics. Current practice in Europe (Lombardo and Mirabella 2004) shows that an equivalent force to substitute for uniformly distributed loads may be calibrated based on the knowledge of the deflection response of the member(s) and the surrounding structure. To this end, [Appendix A](#) presents a brief explanation of the methodologies to be used to establish service load and TLM in the case of a strip test load and patch test load(s).

5.3—Load application method

5.3.1 Dead weights—To simulate a uniformly distributed load condition, loads are commonly applied by means of dead weight such as masonry block, sand bags, and water, either ponded or in barrels. Test loads can typically be applied with rather unsophisticated technology, and do not require specialized equipment. Such procedures, however, lead to laborious and time-consuming activities for site preparation, affecting the overall cost of the test. In addition, when test loads are applied by means of dead

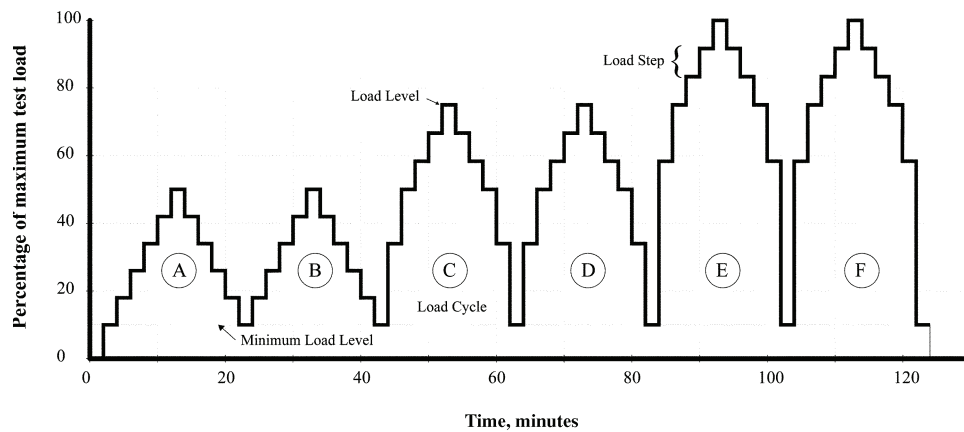


Fig. 5.1—Load tests and cycles for a cyclic load test.

weights, there is generally no feasible way to rapidly remove the load. In case of failure, adequately designed shoring becomes a critical safety measure.

5.3.2 Hydraulic jacks—The application of test loads using hydraulic jacks, rather than uniformly distributed dead loads, allows for faster and more controlled application of test loads. When a structure that is loaded by displacement-controlled hydraulic jacks experiences a softening postpeak behavior, the applied load decreases in a stable manner because the displacement rate remains constant. An added benefit of applying test loads with hydraulic jacks is that the test load can be removed almost instantaneously in case of impending failure. The use of hydraulics in the proper configuration may also create less of a disturbance to the occupants and finishes of the area being tested, thus resulting in a reduction of inconvenience to the users. While loading by means of hydraulic jacks may provide benefits during a load test, there is a need to create a reaction system for the hydraulic jacks that requires design and could be expensive and time consuming to implement. There are several ways to provide reactions to the hydraulic jacks that depend on the characteristics of the member to be tested and the overall site conditions. Several methods are defined in ACI 437R.

5.4—Loading procedures

Two procedures are currently in use for the application of test loads to buildings. The first has been used for many years, and involves applying loads in a monotonic fashion. The other, more recent, procedure applies test loads in a series of zero to maximum load cycles that increase incrementally (Fig. 5.1).

5.4.1 Monotonic loading—In current practice, monotonic loading is the standard loading procedure because of practical considerations and cost of placing and removing test loads that are commonly in the form of sand bags, water barrels, and other similar materials. Typically, loads are applied in not less than four approximately equal increments up to a predetermined maximum test load level. Data readings are usually taken at each loading stage. The time it takes to get to the maximum load depends on the test load configuration and the load application method as previously discussed. Monotonic loading is almost always used when the loads are

being applied with dead weights because of the time it takes to apply and remove the loads. Monotonic loading can also be used when applying test loads with hydraulic jacks.

5.4.2 Cyclic loading—In the cyclic loading procedure, the loads are applied in loading-unloading cycles of increasing magnitude using hydraulic jacks that are controlled by hand or electric pumps. Using a sequence of loading and unloading cycles up to the predetermined maximum load level provides the opportunity to work the structure and assess potential changes in response to repeated loading and to increasing load levels. The load sequence is intended to identify, in an explicit manner, any undesirable response. In recent work (Mettemeyer 1999; Casadei et al. 2005), the response has been characterized by monitoring parameters such as: linearity of structural deflection response, repeatability of load-deflection response, and permanency of deflections. Because the structure is initially loaded and unloaded at low levels, the engineer has the ability to better understand end fixity and load transfer characteristics of the tested member by comparing actual deflection responses with calculated deflection responses. For statically indeterminate structures in particular, this ability allows checking the accuracy of the assumptions made regarding fixity and load sharing used to plan the load test. The advantages of cyclic loading are not yet fully understood because the data base and experience obtained using this procedure are limited, so additional validation is desirable.

5.5—Loading duration

Once the maximum test load has been reached, it is held in place for a given amount of time. Depending on the test method that is used, this may be a short duration (approximately 2 minutes) or up to as long as 24 hours.

5.5.1 Twenty-four hours at maximum load—For more than 80 years, the maximum test load has been held for at least 24 hours according to ACI 318 requirements. The strength of concrete under sustained load is known to be lower than the strength under short-term load. The strength under sustained load is closely related to the stress at which cracks develop in the concrete paste. These are unstable cracks that grow under a sustained stress. Thus, the 24-hour sustained load