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Guide for Testing Reinforced Concrete Structural Elements under Slowly Applied Simulated Seismic Loads

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This is a guide for testing reinforced concrete structural elements under slowly applied simulated seismic loading. The tests are primarily intended for assessing strength, stiffness, and deformability of elements under earthquake effects. Integrated are guidelines on primary stages of structural testing, including design and preparation of test specimens, materials testing, instrumentation, test procedure and loading regime, test observations and data collection, and reporting of test observations and test data. Emphasis is on the correlation of test data and predetermined structural performance levels to enable performance-based design practices. Drift ratio is adopted as the primary performance indicator. Increments of drift ratio are used in describing the loading history. More refined deformation components are used to describe element performance levels and assist in establishing whether a given test specimen meets the requirements of a specific performance level.

This guide summarizes ASCE 41-06 performance levels as operational, immediate occupancy, life safety, and collapse prevention. It outlines different types of structural elements and subassemblies that may be tested, and identifies specific requirements for boundary conditions, instrumentation, and test setups. Unidirectional and bidirectional loading histories are described in terms of incrementally increasing lateral drift ratio cycles. Methods of recording and reporting essential components of deformation and force quantities are identified to correlate test data and target performance levels. This guide is intended to maximize the usefulness of information that can be acquired from experimental research. It is intended to complement guidelines for structural testing with specific focus. This guide is not intended for seismic qualification by testing agencies, though they can be used as resource materials for the development of such qualification protocols.

Keywords: cyclic loading; earthquake effects; instrumentation; performance-based design; performance levels; seismic design; seismic loads; structural concrete; structural testing; structural testing guidelines.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Seismic design practice worldwide is moving toward performance-based design of buildings. This approach aims at producing buildings capable of developing predictable performance levels to achieve predefined performance objectives when subjected to earthquake ground motions. The performance objectives are met by ensuring the structure and its components achieve target performance levels associated with different states of damage for specified seismic hazards. Usually, the seismic hazard is expressed in terms of the intensity of ground motion for a specified return period. Performance levels (capacity) that can be developed by structural components and ground motion intensity (demand) for which the building is designed form the fundamental framework of performance-based seismic design of buildings.

The design of structural components for target performance levels requires an assessment of strength, stiffness, and deformation characteristics typically into the nonlinear range of elements and subassemblies that make up the seismic-force-resisting system. Despite advances in computational techniques and increased computing power, available analytical approaches and computational models based on the principles of mechanics may not be sufficiently accurate for design. This is especially true for performance-based design of concrete buildings for which the knowledge of seismic performance of structures during loading, unloading, and reloading beyond post-cracking and post-yielding stages of deformations, including strength and stiffness degradation under reversed cyclic loading, becomes vitally important. For this reason, tests of large-scale specimens representing actual conditions in the field are needed to generate fundamental knowledge on inelastic behavior of reinforced concrete structural components and subassemblies.

Many experiments have been conducted by university research laboratories, government agencies, and private institutions. Laboratory testing continues to enhance knowledge on earthquake-resistant behavior and design of concrete structures. During testing, the selection of loading histories, measurement of data, and the presentation of test observations and results are sometimes decided by the researchers without consistency. This reduces the effectiveness of the research effort. Though consensus has been reached on certain aspects of seismic structural testing, and guidelines have been developed for specific applications, the lack of uniform guidelines continues to create challenges for experimentalists, occasionally necessitating additional tests. This guide responds to this need and provides a testing protocol for reinforced concrete structural components to maximize the usefulness of information acquired from experimental research. This guide intends to complement those with specific focus, including ATC-24 for steel structures, Seible and Hose (2000) for bridges, SEAOSC (1997) for framed wall buildings, ACI 374.1 for concrete frames, Richards and Uang (2006) for short links in steel frames, ASTM E2127 for shear resistance of walls, and FEMA 461 for structural and nonstructural elements.

1.1.1 *Experimental research in earthquake engineering*—Experimental research in earthquake engineering has a broad scope, covering laboratory and field investigations. Experimental research can be broadly classified under three categories: 1) tests under slowly applied and incrementally increasing or decreasing loads (quasi-static loads); 2) pseudo-dynamic tests; and 3) dynamic tests. The test protocol in this guide is limited to tests of structural components under quasi-static loading. Slowly applied load indicates that the load is applied either in a load-controlled or deformation-controlled mode, following a predetermined loading regime slow enough so that the dynamic inertia effects and strain rate effects on materials do not develop. (For further discussion of strain rate effects in reinforced concrete, refer to Li and Li [2012], Mander et al. [1988], Pandey et al. [2006], and Paulay and Priestley [1992]). Tests under slowly applied loads can be grouped into: 1) tests under cyclic or reversed cyclic loading; and 2) tests under monotonically increasing load/deflection increments. The former category forms the primary scope of this document. The latter is included because some of the fundamental knowledge on generic material and element performance is obtained by performing tests under monotonically increasing loads.

1.2—Scope

This guide provides a testing protocol for structural testing of reinforced concrete elements and assemblies under slowly applied simulated seismic loading. Tests of nonstructural elements are not included. An emphasis is placed on the characterization of force-deformation relationships of test specimens to quantify performance indicators for use in subsequent evaluation of seismic structural performance. These guidelines are primarily intended for new tests, but they may also be used for interpreting existing test data. This guide has a broad scope and may not cover all the details of experimental research programs. Users should exercise appropriate judgment during the course of research and make adjustments to the protocol contained herein. It is, however, encouraged to use as many of the guidelines outlined in this document as possible. This guide is not intended for the purposes of seismic qualification by testing agencies, though it can be used as a resource for developing such qualification protocols.

In the course of developing this document, consideration was given to creating a standardized format for reporting experimental data. However, it was recognized that variations in reporting formats necessarily arise from differences in instrumentation, test equipment, and test objectives, and that a standardized reporting format would be impractical. Therefore, this guide focuses on defining the essential information that should be recorded.

This guide does not anticipate the varying challenges that could arise from the varied testing types. Each experimental program is unique in itself, making it impossible for the authors to anticipate every problem arising in planning and conducting a specific test. Instead, solutions to the more common concerns that might arise during testing are addressed.

Regulatory agencies or building officials may wish to consult this guide as a resource for approving new forms of design or construction that are outside the scope of current building codes. Such approval might be contingent on performance of component testing following the procedures suggested in this guide. This guide has refrained, however, from presenting specific seismic performance criteria that could be applied to qualify a specific structural component or assembly for use in a particular seismic design application. This guide does not anticipate the full range or combinations of possible applications, components, and performance goals. Any attempt to define such specific numerical goals would certainly not address all situations, and might inappropriately constrain or liberalize approval of a particular structural component or system. This guide presents examples of possible acceptance criteria, leaving the establishment of program-specific criteria to the regulatory agency.

The document is organized to provide information on:

a) ASCE/SEI 41 performance levels

b) Requirements for preparation of test specimens, support and boundary conditions, and test setups

c) Instrumentation needs, data acquisition, and test observations

d) Description of loading regime, including amplitude and sequence of load, deformations, or both, including the number of cycles required for each load level, deformation level, or both

e) Documentation, including reporting of test data, test observations, and correlations with performance levels

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A_g = gross area of concrete section, in.^{2} (mm^2)
A_s = area of nonprestressed longitudinal tension reinforcement, in.^{2} (mm^2)
A_s' = area of compression reinforcement, in.^{2} (mm^2)
b_w = web width, in. (mm)
d = distance from extreme compression fiber to centroid of longitudinal tension reinforcement, in. (mm)
E_c = concrete elastic modulus, psi (MPa)
F = lateral force, lb (N)
f_c' = specified compressive strength of concrete, psi (MPa)
f_y = specified yield strength of reinforcement, psi (MPa)
h = overall height of member, in. (mm)
I_e = effective moment of inertia of section, including the effects of cracking before yielding, in.^{4} (mm^4)
K_e = effective elastic stiffness, lb/in. (N/mm)
ℓ, L = member length, in. (mm)
ℓ_p = plastic hinge length, in. (mm)
ℓ_u = unsupported length of compression member, in. (mm)
ℓ_w = wall length, in. (mm)
M = bending moment, in.-lb (N-mm)
M_y = yield moment of a member or a test specimen, in.-lb (N-mm)
P = axial force, lb (N)
P_o = nominal axial strength at zero eccentricity, lb (N)
t_w = wall thickness, in. (mm)
Q = generalized force in a component, lb (N)
Q_y = yield strength of a component, lb (N)
V = shear force, lb (N)
V_n = nominal shear strength, lb (N)
V_s = nominal shear strength provided by shear reinforcement, lb (N)
α = fraction of Q_y that is used to define idealized effective elastic stiffness
Δ_y = displacement at member yield load, in. (mm)
δ, Δ = displacement, in. (mm)
δ_e = elastic displacement under a load of αQ_y, in. (mm)
δ_y = yield displacement under a load of Q_y, in. (mm)
ϕ = drift ratio (Δ/L)
ϕ_1 = drift ratio at half drift ratio at member yield load
ϕ_2 = drift ratio at member yield load
ϕ_3 = drift ratio at two times drift ratio at member yield load
ϕ_4 = drift ratio at three times drift ratio at member yield load