ATC 24

GUIDELINES FOR CYCLIC SEISMIC TESTING OF COMPONENTS OF STEEL STRUCTURES

ATC

APPLIED TECHNOLOGY COUNCIL

Funded by
American Iron and Steel Institute
American Institute of Steel Construction
National Center for Earthquake Engineering Research
National Science Foundation

ATC-24

Guidelines for Cyclic Seismic Testing of Components of Steel Structures

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Funded by
AMERICAN IRON AND STEEL INSTITUTE
AMERICAN INSTITUTE OF STEEL CONSTRUCTION
NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH
(Project 88-6604)
NATIONAL SCIENCE FOUNDATION
(Grant No. BCS-8912602)

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Preface

In 1988 Applied Technology Council (ATC) commenced the ATC-24 project to develop standardized procedures for seismic testing of components of steel structures. The need for the project arose from the recognition that results from numerous previous laboratory experiments nationwide have been difficult to interpret and assess. Contributing to this difficulty has been the variation in selected loading histories and the variation in presentation of test results.

In recognition of these difficulties, the American Iron and Steel Institute (AISI), the National Center for Earthquake Engineering Research (NCEER), the American Institute for Steel Construction (AISC), and the National Science Foundation (NSF) jointly awarded ATC funding, beginning in 1988, to develop guidelines that would assist in preparation, execution, and documentation of experiments that are performed to evaluate load-deformation characteristics and to assess the seismic performance of structural steel components.

The recommendations and companion commentary presented in this report pertain to loading histories, presentation of test results, and other aspects of experimentation, which can be employed in most cyclic experiments on components of steel structures for the purpose of consistency in experimental procedures and test evaluation. These recommendations are written specifically for experiments with slow cyclic load application. Issues associated with other experimental methods are not addressed.

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Applied Technology Council gratefully acknowledges the valuable assistance, support and cooperation provided by Hank Martin, AISI Project Officer, James Marsh, AISC Project Officer, and Shi-Chi Liu, NSF Program Officer.

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Notation

+, -	signs used as superscripts to denote positive or negative excursion
A_i+	hysteretic area enclosed by Q-δ diagram of excursion i^+
C, c	structural performance parameters
D	cumulative damage
i	index for cycle consisting of excursions i^+ and i^-
i^+	index for positive excursion of cycle i
i^-	index for negative excursion of cycle i
K_e	elastic stiffness of Q-δ diagram
K_i+	slope of Q-δ diagram at the start of unloading in excursion i^+ (see Figure 1)
$K_{o,i}+$	slope of Q-δ diagram at the start of loading in excursion i^+ (see Figure 1)
m	total number of inelastic load steps in a test
n_j	number of cycles in load step j
N	total number of inelastic excursions in a test
N_f	number of inelastic excursions to failure
Q	"force" quantity measured in experiment or deduced from measurements
Q_i+	"force" at peak deformation in excursion i^+ (see Figure 1)
$Q_{max,i}+$	maximum "force" in excursion i^+ (see Figure 1)
Q_{min}	required strength before failure
Q_y	yield "force" deduced from measurements or predicted analytically (see Figure 2)
δ	"deformation" quantity measured in experiment or deduced from measurements
δ_i+	peak "deformation" in excursion i^+ (see Figure 1)
$\delta_{o,i}+$	"deformation" at beginning of excursion i^+ (see Figure 1)
δ_y	yield "deformation" deduced from measurements or predicted analytically (see Figure 2)
Δ	increment in peak deformation per load step
$\Delta\delta_i+$	deformation range of excursion i^+ (see Figure 1)
$(\Delta\delta_{pm})_i+$	measured plastic deformation range of excursion i^+ (see Figure 1)
$(\Delta\delta_t)_i+$	total deformation range for excursion i^+ (see Figure 1)
μ	ductility ratio δ / δ_y (δ measured w.r.t undeformed configuration)
$\mu_{e,i}+$	excursion ductility ratio for excursion i^+ ($\mu_{e,i}+ = \Delta\delta_i+ / \delta_y$)

Table of Contents

List of Figures

List of Tables

Part I: Recommendations

1. Introduction

Adequate protection of structures from the effects of earthquakes requires detailed knowledge of strength and deformation characteristics of the elements and element assemblies making up the structural system that provides resistance to seismic effects. Available analytical methods based on principles of mechanics are often inadequate to provide reliable information on these characteristics, primarily because of the random nature of the cyclic deformation demands imposed on elements and the dependence of the response characteristics on the deformation history to which an element is subjected. For this reason experiments with physical specimens, which reproduce the field conditions as realistically as feasible, are needed to provide fundamental information that can be used to develop, augment, or confirm analytical models that will form the basis for seismic protection procedures.

1.1 Experimentation in Earthquake Engineering

Experimentation in earthquake engineering may have a variety of objectives and may utilize different testing techniques, ranging from field to laboratory experimentation, dynamic to pseudo-dynamic to slow cyclic experimentation, two- to three-dimensional experimentation, and experimentation on components, subassemblies or complete structural configurations. Each of these techniques has distinct advantages, and the type to be utilized most effectively depends on the specific objectives. These guidelines are concerned only with slow cyclic experimentation and are not intended to address experimental needs and relative merits of different testing techniques.

"Slow cyclic" implies that load or deformation cycles are imposed on a test specimen in a slow, controlled and predetermined manner, and dynamic effects as well as rate of deformation effects are not considered. Cyclic tests are useful to provide basic information on element or subassembly behavior, including data on strength and stiffness characteristics, deformation capacities, cyclic hardening or softening effects, and deterioration behavior at large deformations. In general, the objective of an experiment is to acquire as much of this information as feasible since it is unlikely that all future uses of the experimental data can be foreseen at the time of testing. For this reason the intent of these guidelines is to maximize the information that can be acquired from a single experiment or an experimental program. The need to exercise judgment in the interpretation and implementation of the guidelines is stressed.

1.2 Purpose and Scope of Document

Much experimental work on steel components and subassemblies directed towards achieving a better understanding of the response of steel structures to seismic excitations has been done in recent years in laboratories of universities, government, and industry. Most commonly, these experiments are performed with slow cyclic load application. In these experiments the selection of loading histories and presentation of test results have always been central issues, since no guidelines existed in the past and decisions were usually made in a subjective manner. This has raised many questions in interpretation of experimental results and has made a consistent assessment of seismic performance of components of steel structures a difficult task.

This document gives guidelines and associated commentary (starting on page 19) on loading histories, presentation of test results, and other aspects of experimentation, that can be employed in most cyclic experiments on components of steel structures for the purpose of consistency in experimental procedures and test evaluation. The objective is to facilitate interpretation of experiments rather than to impose undue constraints on the ingenuity and inventiveness of the experimentalist. The guidelines are kept as simple as possible and, for this reason, cannot be all-inclusive. There are situations, particularly in research, in which loading histories other than those recommended here may be advantageous. It is left to the judgement of the experimentalist to modify these recommendations to suit the specific objectives of a testing program. It is also understood that special devices, such as base isolation and energy dissipation devices, may require approaches that differ significantly from those presented in these guidelines.

The guidelines were developed to assist in preparation, execution, and documentation of experiments that are performed to evaluate load-deformation characteristics and to assess the seismic performance of structural steel components. In particular, the following questions were considered in the development:

- How many cycles, what deformation amplitudes, and what sequence of cycles should be employed to evaluate seismic performance?
- How can the results of one experiment under a predetermined loading history be generalized so that conclusions can be drawn on the response of the same component under different loading histories?
- How can the results of different test series be compared and interpreted so that full advantage can be taken of the combined experimental information generated by different laboratories?

These recommendations are written specifically for experiments with slow cyclic load application. Issues associated with other experimental methods are not addressed.

2. Definitions

Cycle: A load or deformation history unit consisting of two sequential excursions, one in the positive and one in the negative loading direction. A cycle is not necessarily a closed unit, since the total deformation ranges of the two excursions may not be equal.

Deformation: A generic quantity, δ, including strains, angles of shear distortion, rotations, axial deformations, and displacements.

Deformation range of excursion: The deformation range between the beginning and the peak deformation of an excursion.

Ductility ratio: The ratio of peak deformation over yield deformation.

Excursion: A load or deformation history unit that starts and finishes at zero load, and contains a loading and unloading branch.

Excursion ductility ratio: The ratio of deformation range of an excursion over yield deformation, i.e., $\mu_{e,i}+ = \Delta\delta_i+ / \delta_y$ (see Figure 1).

Force: A generic quantity, Q, including internal forces (force or moment), and externally applied loads.

Force at peak deformation: The force at a load reversal point.

Hysteretic area: The area enclosed by a force-deformation diagram.

Load or deformation step: A load history unit consisting of a series of cycles with constant peak load or deformation.

Maximum force: The maximum force measured in an excursion.

Peak deformation: The deformation at a load reversal point.

Plastic deformation range: The permanent deformation between the beginning and end of an excursion.

Total deformation range: The total deformation between the peak of an excursion and the peak of the preceding opposite excursion.

Yield force or deformation: The predicted or measured force or deformation at which significant yielding occurs.

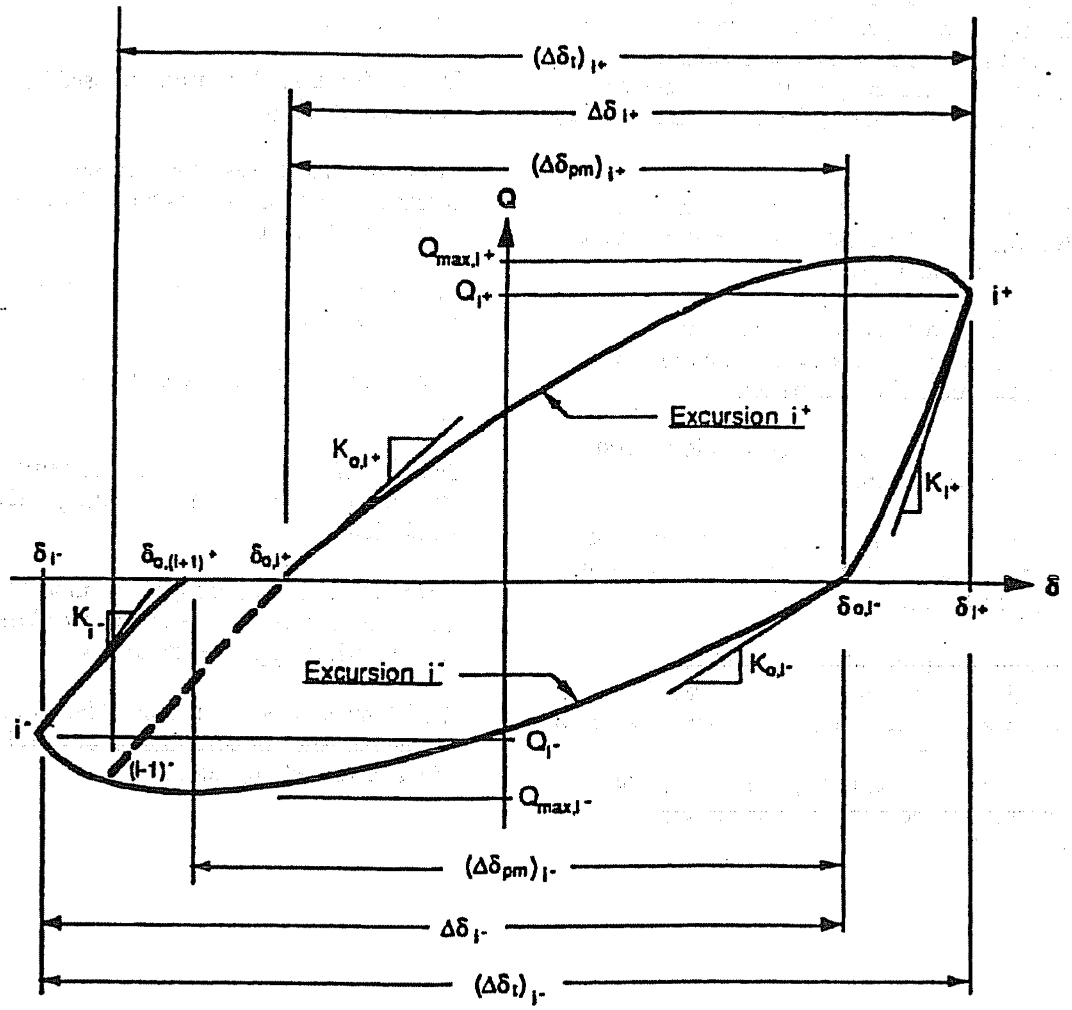


Figure 1 Parameters of cycle *i*

3. General Considerations

Laboratory simulation of component behavior necessitates consideration of all important field conditions, including initial and boundary conditions, field fabrication conditions, and loading conditions. Appropriate efforts need to be devoted to the acquisition of material properties through material testing, analytical prediction of the anticipated response, and careful planning of the loading and instrumentation program.

3.1 Purpose of Experiments

These guidelines are written for experiments that are performed to draw conclusions on the seismic performance of a component or subassembly. This implies that the factors of primary interest are strength and stiffness characteristics and their history dependent variation (e.g., cyclic hardening, softening, deterioration, failure).

3.2 Test Specimens

A test specimen may be an individual component or a set of components connected together to form a structural subassembly.

3.2.1 Types of Test Specimens

Generic test specimen. A specimen is so designated if it serves the purpose to study a general behavior mode that may occur within different configurations in structures (e.g., local flange buckling, joint shear distortion, brace buckling). For such specimens, boundary and initial conditions may not be well defined, and deformation demands need to be established such that they are representative for a wide range of configurations and structures.

Specific test specimen. A specimen is so designated if it represents a well defined configuration within a structure of known characteristics and if it is located in a known seismic environment.

3.2.2 Boundary and Initial Conditions

Testing of specimens should be performed in a test setup that permits adequate simulation of all important boundary and initial conditions that are imposed on the component or structural subassembly by the construction and behavior of the structure. In particular, appropriate out-of-plane bracing needs to be provided in two-dimensional specimens. It is desirable to establish boundary conditions such that the "force" control parameter (see Section 3.5) and other relevant force quantities can be determined directly from measurements of the applied loads.

Gravity loads should be simulated whenever their effect on specimen performance is judged to be important. These loads should be simulated in a manner in which they have the most detrimental effect on seismic performance.

3.2.3 Specimen Fabrication

Test specimens should be fabricated in a manner that simulates field conditions, following the procedures of workmanship and quality control as required by the applicable standards. This applies particularly to welding and bolting. Welds that may contribute to strength deterioration or failure should be tested with nondestructive techniques before the experiment to assess initial imperfections. Similarly, the pretensioning of critical bolts should be verified.

Test specimens should be as close as possible to full size in order to minimize size effects. Failure modes in and around weldments should be investigated only in full-size specimens in which welding is performed with the same number and size of passes and in the same sequence and position as in the field.

3.3 Material Testing

The basic monotonic stress-strain properties of the test specimen's material(s) should be determined before the test. As a minimum, these properties include the yield and tensile strengths, but they should also preferably include a complete trace of the tension stress-strain diagram to fracture. Material tension tests following the procedures presented in ASTM Standard E8 should be performed.

If the test specimen is made of a material for which the cyclic strain hardening (or softening) characteristics are not known, it is recommended to perform, in addition to the tension tests, at least one cyclic material test to establish these characteristics. The specimen used for this purpose should conform to the geometric requirements set forth in ASTM Standard E606. A universal testing machine with a self-aligning grip should be used since alignment of the test specimen in the testing apparatus poses a major problem. The test specimen should be subjected to step-wise increasing symmetric strain amplitude cycles with three to five cycles performed at each amplitude (Multiple Step Test). The increase in strain amplitude per step should be between two and four times the yield strain. A curve placed through the peak points of the last cycle of each step will resemble the cyclic stress-strain curve with adequate accuracy for seismic considerations.

Additional material tests should be performed if material low-cycle fatigue and fracture may affect the performance of the component. The basic material test for low-cycle fatigue data is the constant strain amplitude test described in ASTM Standard E606. Other methods for fatigue and fracture testing are presented in the ASTM Standards E1150, E466, E647, E813, E23, E399, and E561.

3.4 Planning and Execution of Experiment

Analytical Predictions. A prerequisite for testing is an effort to predict the response of the test specimen as accurately as possible by analytical means. In particular, the yield and maximum strengths and deformations of the test specimen should be predicted analytically to develop a suitable loading history, evaluate the needs for instrumentation, establish the range of load and deformation measurements to be taken, and reduce the risk of unexpected behavior during the experiment.

Testing Program and Loading History. These issues are discussed in Chapter 4.

Load Application. Loads may be applied by means of hydraulic or mechanical actuators or other feasible mechanisms. The rate of loading may be controlled manually or automatically. In the latter case a manual override should be available to safeguard against unexpected behavior. The results of slow cyclic load tests may be affected by strain rate effects since in such tests the rate of loading is usually much lower than that experienced in a real structure subjected to earthquakes. In order to reduce these effects it is preferable that the loading and unloading branches of an excursion are executed continuously without intermittent stops and pauses.

Instrumentation. As a minimum, instrumentation should be provided to obtain an accurate record of the "force" and "deformation" control parameters (see Section 3.5) during the entire experiment. Preferably, sufficient instrumentation should be provided to measure all important response parameters needed to evaluate the performance of the component or subassembly under study. The objective should be to relate important deformation quantities to the force quantities that are the primary cause of the deformations. In statically indeterminate test specimens it is recommended to provide instrumentation within elements whose internal forces are important for test interpretation but cannot be deduced with confidence from the measured applied loads.

Data Acquisition. Measured force and deformation quantities should be recorded either continuously on analog recorders or digitally at sufficiently close intervals to permit a trace of the force-deformation response that contains all important characteristics. Whenever possible, the relationship between the "force" and "deformation" control parameters should be traced continuously and should be displayed during the test for observation.

3.5 Test Control and Control Parameters

The recommendations in this document are for cyclic load tests in which the loading history is predetermined and carefully planned. Cyclic implies that the "force" quantity used to monitor the test reverses sign in subsequent excursions. In the elastic range a test may be performed under either force or deformation control. In the inelastic range a test should be performed under deformation control. This implies that absolute or normalized values of a "force" or "deformation" control parameter are being used to determine the loading history. If normalized values are being used, normalization should be done with respect to experimentally determined or analytically predicted yield values of "force" and "deformation" control parameters.

"Deformation" control parameter. The most relevant deformation quantity measured in an experiment should be selected as the control parameter for the loading history. This should be a deformation quantity that can be related to the most relevant structure deformation parameter, which is usually the interstory drift.

"Force" control parameter. The "force" quantity that can be related best to the "deformation" control parameter should be selected to control the loading applied to the test specimen. Whenever feasible, this parameter should be selected such that the product of "force" and "deformation" control parameters results in an energy term (force times length).

Yield values of "force" and "deformation" control parameters. These values are needed for test control and may be either determined experimentally (from a monotonic load test) or predicted analytically. In either case, judgment is needed to determine these values, and it is understood that these parameters are for test control only and that different values may be more useful for test interpretation. The yield values to be used for test control should be associated with *significant* yielding in the critical region of the test specimen, which should be reflected by a clear nonlinearity in the control force-deformation relationship.

It is recommended to estimate the yield force Q_y and use the procedure illustrated in Figure 2 to deduce the yield defomation δ_y and the elastic stiffness K_e. This procedure requires force control loading to a level of 0.75 Q_y, measurement of the corresponding control deformation δ^*, and prediction of δ_y and K_e as shown in the figure.

The estimate of Q_y may be based on the results of a monotonic test or may be accomplished by employing established design equations but using the measured material yield strengths.

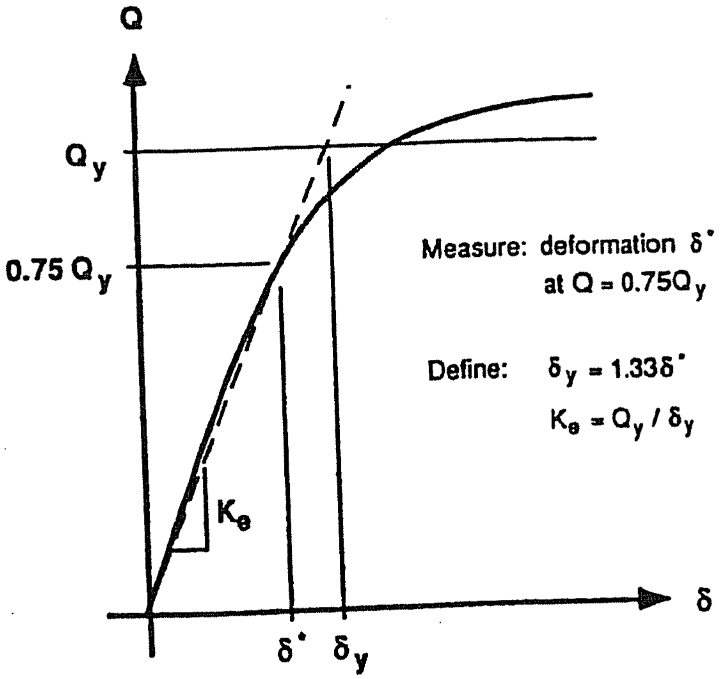


Figure 2 Determination of yield values Q_y and δ_y and elastic stiffness K_e

4. Testing Programs and Loading Histories

The choice of a testing program and associated loading history depends on the purpose of the experiment, type of test specimen, and type of anticipated failure mode (e.g., rapid strength deterioration, slow strength deterioration, member buckling). The Commentary provides a discussion of these issues.

4.1 Single Specimen Testing Program

This is the basic testing program that may be performed if only one specimen is available, the monotonic load-deformation response (or at least the yield strength) can be predicted with good confidence, the rate of strength deterioration is slow (or the level at which rapid strength deterioration occurs is well defined, e.g., member buckling), and analytical cumulative damage modeling is not part of the investigation. This testing program should not be used if the rate of strength deterioration is rapid and the level at which deterioration occurs may exhibit considerable scatter.

The recommended loading (deformation) history to be applied in this testing program consists of stepwise increasing deformation cycles (Multiple Step Test) as illustrated in Figure 3.

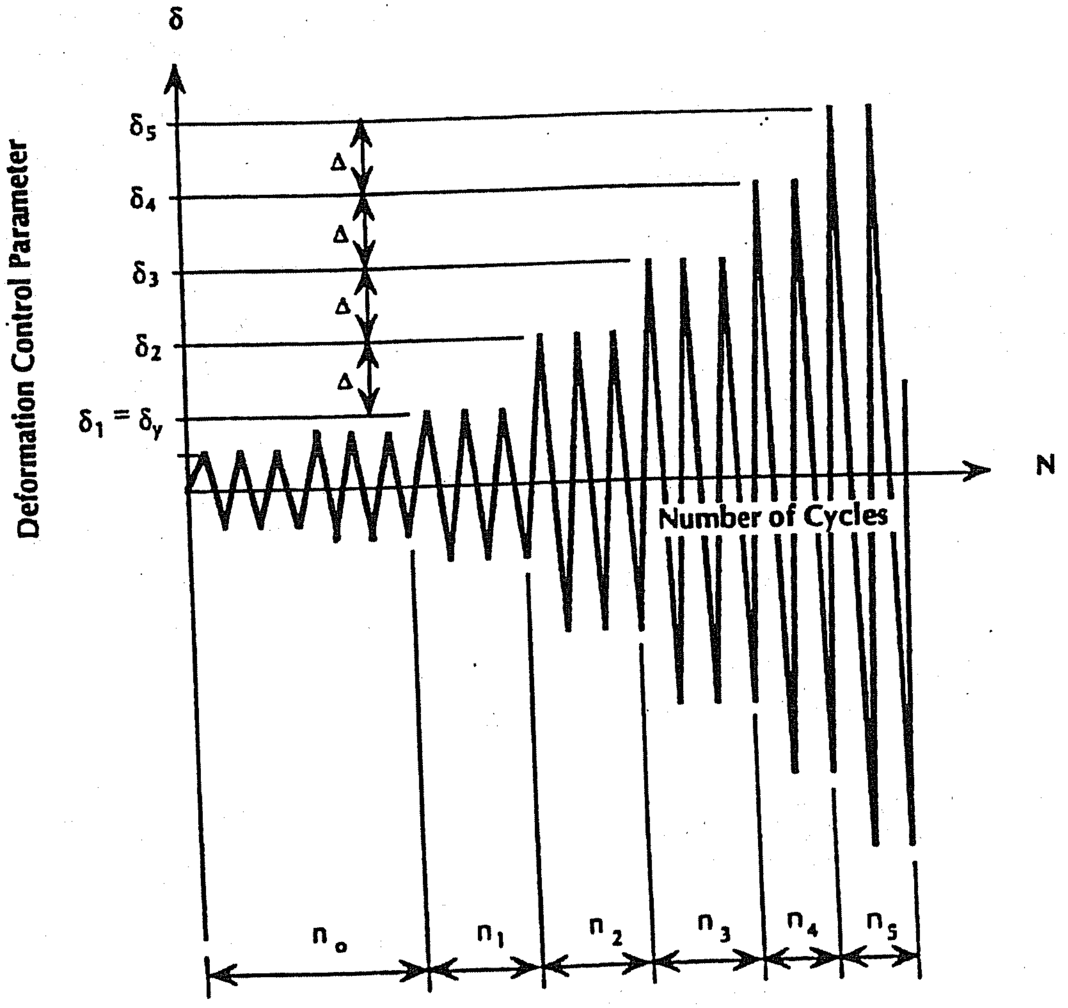


Figure 3 Deformation history for multiple step test

In this history the cycles should be symmetric in peak deformations unless good reasons exist to do otherwise. The history is divided into steps and the peak deformation of each step j is given as δ_j, a predetermined value of the "deformation" control parameter. Thus, the loading history is defined by the following parameters:

δ_j the peak deformation in load step j (or the corresponding force Q_j if force control is used in the elastic range)

n_j the number of cycles to be performed in load step j

m the total number of load steps to be performed with peak deformations equal to or exceeding the yield deformation

Δ the increment in peak deformation between two consecutive steps.

Recommendations for numerical values of these parameters and details of the loading history are provided here. There may be good reasons to modify these recommendations for specific testing programs since the number and relative magnitudes of cycles a component may have to resist depend on the structure of which the component is part and on the severity of the ground motion the structure is expected to experience. The Commentary provides an extensive discussion on this issue.

1. Recommendations on the numbers of cycles and peak deformations in each load step:
   - The number of cycles n_0 with a peak deformation less than δ_y should be at least six.
   - The number of cycles n_1 with peak deformation δ_1 equal to δ_y should be at least three.
   - The number of cycles n_2 with peak deformation $\delta_2 = \delta_y + \Delta$ should be at least three unless a lower number can be justified.
   - The number of cycles n_3 with peak deformation $\delta_3 = \delta_y + 2\Delta$ should be at least three unless a lower number can be justified.
   - The number of cycles n_4 to n_m with peak deformation $\delta_4 = \delta_y + 3\Delta$ to $\delta_m = \delta_y + (m-1)\Delta$ should be at least two unless a lower number can be justified.
2. More cycles per step than those specified in (1) should be applied if (a) it is anticipated that in a severe earthquake the component as part of a structure would experience a cumulative plastic deformation range (sum of plastic deformation ranges) that is larger than that simulated in the test at the maximum deformation level predicted for this earthquake, or (b) deterioration occurs during a load step and it is deemed appropriate to evaluate the rate of deterioration through additional cycles of the same load step amplitude.
3. It is often advisable to interrupt the recommended loading history with small cycles in order to evaluate intermittent stiffness degradation. It is suggested to perform these cycles with force control, using a peak value of approximately 0.75 Q_y.
4. Elastic cycles should be performed with force control. At least three of the elastic cycles should be carried out using a force amplitude of 0.75 Q_y. The cycles with $\delta = \delta_y$ and all cycles with larger peak deformations should be performed with deformation control.
5. In all load steps with a peak deformation greater than δ_y the increment in peak deformation, Δ, should be a constant. This increment should be equal to δ_y if the deformation control parameter and the story drift are linearly related. Otherwise, the increment should be determined as discussed in the Commentary.
6. It is recommended that the loading history be continued in the established pattern until severe strength deterioration is evident, even if a deformation level is attained that is unlikely to be exceeded by the component in a maximum credible earthquake. If the force or displacement limit of the test setup is approached before deterioration occurs, the test specimen should be cycled at maximum

4.2 Multi-Specimen Testing Programs

The need for testing of more than one identical specimen may exist if (a) the monotonic behavior cannot be predicted with reasonable confidence, either analytically or from the results of a single Multiple Step Test, (b) the strength deterioration is rapid and the level at which deterioration occurs may exhibit considerable scatter, or (c) a cumulative damage model needs to be developed. For case (a) it is recommended to perform one or two monotonic tests (in the positive and negative direction, as needed) until severe strength deterioration occurs. For case (b) one of the two options discussed in Sections 4.2.1 and 4.2.2 should be executed. For case (c) a Cumulative Damage Testing Program, discussed in Section 4.2.2, is appropriate.

4.2.1 Multi-Specimen Multiple Step Tests

Additional Multiple Step Tests should be performed if the results of a single Multiple Step Test disclose that rapid strength deterioration occurs within the deformation range of interest due to a failure mode whose characteristics may exhibit considerable scatter (e.g., crack propagation and fracture at weldments, which is affected by workmanship). The loading history for the additional tests should be the same as for the first one. A minimum of three specimens should be tested and the performance evaluation should be based on the test with the smallest cumulative measured plastic deformation range unless a sufficient number of specimens are tested to permit a statistical evaluation of the results.

4.2.2 Cumulative Damage Testing Program

A special testing program is needed if a cumulative damage model is to be developed for the purpose of assessing seismic performance of the component under arbitrary loading histories. A cumulative damage model may be utilized to evaluate the cumulative effect of inelastic cycles (or excursions) on a limit state of acceptable behavior. This limit state may be associated with excessive strength deterioration or other measures of damage tolerance. A cumulative damage model is based on a damage hypothesis and may include several structural performance parameters. The validity of the hypothesis and the values of the performance parameters have to be determined experimentally. This requires a multi-specimen testing program whose details depend on the type of damage model and failure mode to be investigated. Suggestions on a Cumulative Damage Testing Program are presented in the Commentary.

5. Documentation of Experimental Results

For each experiment the following information should be documented.

1. Geometric data and important details of the test specimen, including important fabrication details, boundary conditions, constraints, and applied loads.
2. Locations of instruments for the measurement of primary response parameters (parameters needed to evaluate the performance of the test specimen).
3. All material test data needed for performance evaluation, including results of nondestructive tests of welds and verification of bolt pretensioning.
4. The following data for the "force" and "deformation" control parameters:
    - A schematics of the "deformation" control history with sequential cycle numbers indicated at the positive peaks
    - A trace of the force-deformation history that shows all important aspects of the response, including the point at which first yielding of the material or first deviation from a linear relationship was detected
    - The yield values that have been used for load (deformation) history control
    - Numerical values (either absolute or normalized with respect to the given yield values) of the following measurements for the positive and negative excursions of individual cycles, with appropriate sign. Only those data points that show an appreciable change compared to previously registered values need to be documented.

        Peak "deformation," δ_i^+, δ_i^-,

        "Deformation" at start of excursion, $\delta_{o,i}^+$, $\delta_{o,i}^-$

        Measured plastic deformation range, $(\Delta\delta_{pm})_i^+$, $(\Delta\delta_{pm})_i^-$

        "Force" at peak deformation, Q_i^+, Q_i^-

        Maximum "force" in excursion, $Q_{max,i}^+$, $Q_{max,i}^-$

        Slope of Q-δ diagram at start of loading, $K_{o,i}^+$, $K_{o,i}^-$

        Slope of Q-δ diagram at start of unloading K_i^+, K_i^-

        Area enclosed by Q-δ diagram of excursion, A_i^+, A_i^-

5. Observations made during the test and identification of any problems that may affect the interpretation of the data.
6. Data similar to those listed under Item 4 should be documented for other primary response parameters to the extent needed for a performance evaluation.

An example of a force-deformation history trace and of a table containing the measurements enumerated in Item 4 is presented in the Commentary.

6. Evaluation of Performance

Experiments that follow these guidelines may be used to evaluate seismic performance of components as parts of structures. Adequate performance implies that a component fulfills a set of specified performance requirements. These requirements may be based on strength and stiffness characteristics, deformation capacity, energy dissipation capacity, or any combination thereof. For a component this implies that its role within a structure needs to be identified and its *capacities* (strength, deformation, and energy dissipation capacities) as well as the *demands* imposed by earthquakes need to be quantified. Thus, seismic input as well as structural response have to be quantified with due consideration given to uncertainties in demands and capacities.

These recommendations are concerned with criteria for assessing the *capacities*. Parameters that may prove to be useful for capacity evaluation are enumerated in the Commentary. The *demands* on a component depend strongly on the type of structure of which the component is part, on the seismicity at the site, as well as on design criteria, which are code dependent and therefore dependent on age of design, geographic region, and local practices. The Commentary provides a discussion of important issues and of a general approach to the evaluation of demand and capacity in the context of performance assessment.

Part II: Commentary

C.1 Introduction (Commentary)

The main objective of this document is to provide a set of recommendations for laboratory experimentation on components and subassemblies of steel structures that may be subjected to severe earthquake ground motions. These recommendations are for experimental work intended to produce reliable information that can serve as a basis for analytical modeling or the developing of rational design criteria, or that will demonstrate the integrity and safety of specific structural configurations under various levels of ground motions.

The recommendations are intended to assist in the decision process for experimental studies that can be followed by all affected user communities such as researchers, the engineering profession, and industry. In particular, the problems of selecting representative cyclic loading histories and documenting and interpreting test results are addressed in detail. It is assumed that a test should provide comprehensive information for various levels of seismic demands and that the purpose of experimentation is to assess the performance of components and subassemblies, where performance refers to strength and stiffness characteristics as well as to assess deterioration and failure under cyclic inelastic loading. Emphasis is placed on guidelines for documentation intended to communicate this information in a format useful for others not involved in the experiment.

These recommendations are written specifically for experiments with slow cyclic load application. This experimental method is widely used and has its distinct advantages. It is cost effective and permits explicit control of force and deformation histories and visual observation of damage. However, this method has also evident limitations, as it distorts time and does not permit simulation of dynamic effects such as modal effects and damping. These guidelines are not intended to advocate usage of slow cyclic testing for all cases; there are instances in which other test methods, such as pseudo-dynamic or shaking table testing, have clear advantages.

C.2 Definitions (Commentary)

Sign Convention. Throughout this document it is presumed that all force and deformation quantities are documented with their appropriate sign. This includes yield forces and yield deformations, which may have different values in the positive and negative direction. Deformation ranges, which are differences in deformations, are always considered to be positive.

Excursions, Cycles, and Load Steps. These quantities are the basic history units of a cyclic experiment. Each load step consists of one or more cycles with predetermined positive and negative peak deformations (or loads), and each cycle consists of a positive and a negative excursion. The basic unit for documentation is an excursion and not a cycle, since the two excursions of a cycle may exhibit very different characteristics and a cycle is not necessarily a closed unit (see Figure 1). In reporting it is recommended to number cycles in sequence of their occurrence and to identify the excursions with the cycle number and a superscripted sign.

Deformation Ranges. This term identifies differences in deformations within excursions or between peaks of excursions. The total deformation range includes elastic as well as inelastic deformations between two successive peaks of the loading history. Plastic deformation ranges pertain to an individual excursion and are always measured along the zero load axis.

Ductility Ratios. In general, a ductility ratio is the ratio of a deformation quantity over yield deformation. The deformation may be measured from the undeformed configuration or from the beginning of an excursion (excursion ductility ratio). The yield deformation used to compute a ductility ratio has no unique definition except for an idealized bilinear force-deformation relationship. For this reason the term ductility ratio is avoided in these guidelines unless it is needed to illustrate a basic concept. The yield deformation used for test control and defined in Section 3.5 may not be the most useful value to compute a ductility ratio in test interpretation.

C.3 General Considerations (Commentary)

In planning and executing slow cyclic component experiments and in interpreting test results, consideration should be given to the following limitations:

- Isolated components may behave differently than components as parts of structures unless all important initial and boundary conditions are simulated adequately.
- Slow cyclic loading implies that time is distorted and ***strain-rate effects*** may alter the load-deformation response of a specimen compared to dynamic loading. Reported evidence points to the conclusion that slow cyclic testing, compared to dynamic testing, results in a small decrease in strength and increase in the rate of deterioration (Krawinkler, 1988). Thus, the results from these tests can be considered as conservative for the purpose of performance assessment.
- Whenever feasible, component experiments should be performed on full-size specimens. When the size of test specimens is reduced, ***size effects*** will distort the behavior of the specimens. Size effects may be due to fabrication (particularly at welds), but are also inherent in material response due to the change in material volume. Size effects may affect the specimen response considerably and must be considered in the interpretation of experimental results. A discussion of scale effects, including size and strain-rate effects, is given in Krawinkler (1988).

C.3.1 Purpose of Experiments

Seismic performance assessment requires information on the strength, deformation, and failure characteristics of structures and their components. In the design or evaluation of structures, analytical predictions of these characteristics are the sole recourse in most cases. Only under exceptional circumstances can experimental seismic verification of a design be afforded. Even then, the uncertainty in the seismic input limits the value of an experiment, and experimental verification has to be supplemented with analytical modeling. Thus, rarely does an experiment provide a final answer, rather it usually serves to develop and/or verify analytical predictions. The process of knowledge acquisition consists usually of preliminary analytical predictions, experimental exploration and verification, and improved analytical modeling. Understanding the physical phenomena and providing information for analytical predictions are, therefore, the main purposes of experiments.

The information deduced from an experiment on a component would be misleading unless it is provided in the context of the assumptions made in simulating all the important conditions that may affect the response of the component as part of a complete structure. Much of Chapters 3 and 4 of these recommendations is concerned with simulation of these conditions.

C.3.2 Test Specimens

Test specimens may be individual components or structural subassemblies, subjected to single-point or multi-point loading, each point being subjected to one, two, or three dimensional load application. The simpler the specimen and load application, the easier will be the test and its interpretation.

C.3.2.1 Types of Test Specimens

The testing program and loading history to be executed depend, among other factors, on the extent of knowledge that exists on the configuration of the component within a structure, on the characteristics of the structure itself, and on the expected response of the structure. These recommendations are written primarily for ***generic test specimens***, which are tested to study a general mode of behavior that may occur in different configurations and different structures. The loading histories applied to such specimens must be designed so that they simulate the most critical excitation to which the component may be subjected and permit a general performance assessment for all feasible structural configurations.

If a test is performed to assess the performance of a component in a specific configuration (*specific test specimen*) within a structure of known global characteristics and predicted types of excitations, then the loading history may be tailored towards the predicted response. However, it must also be considered that the seismic input is random and the simulation of one specific seismic response history may not serve the purpose of a general performance assessment.

C.3.2.2 Boundary and Initial Conditions

Boundary Conditions. It is desirable that test specimens be statically determinate so that internal force quantities can be determined from equilibrium without reliance on internal force measurements. However, this should not become an overriding consideration in cases in which redundancy contributes significantly to the behavior of a component. Examples are bracing elements that are rigidly connected to framing members, and beam-column joints whose shear yielding may lead to significant redistribution of internal forces in statically indeterminate structures. Much attention needs to be paid also to three-dimensional effects, as for instance in experimental studies on composite beams in which the width of the floor slab becomes an important consideration.

Initial Conditions. For generic specimens, initial deformations and forces caused by gravity or other effects are usually not well established. These initial conditions should be simulated in the most damaging manner if they have a detrimental effect on seismic performance. They should be ignored if they improve the seismic performance, unless they follow a well established pattern that applies to all possible configurations

C.3.2.3 Specimen Fabrication

A test specimen should be a replica of a component that is part of a structure that has been fabricated and erected in accordance with standard practice. Thus, the usual field procedures for workmanship and quality control should be applied in specimen fabrication. Particular attention must be paid to simulation of all important field (or shop) conditions for weldments and bolt arrangements that may affect the performance of the test specimen.

Only full-size specimens should be used if crack propagation and fracture in or around weldments are expected to be the primary sources of deterioration and failure. In reduced scale specimens it is impossible to simulate accurately the size of heat affected zones, the distribution of residual and restraining stresses, and the shape, distribution and size of initial imperfections. Moreover, notch toughness and crack propagation rates in steel are sensitive to size and strain-rate effects (Krawinkler, 1988).

C.3.3 Material Testing

Standard material tests are described in the ASTM Standards listed in the References. Monotonic tension tests should be performed as needed, with the number of test specimens dependent on the magnitude of residual stresses in the element(s) and their importance in test evaluation. Since there may be significant variations in material properties through the thickness of a plate, the average stress-strain characteristics should be determined from machined test specimens whose thickness is as close as possible to that of the plate element from which the specimens are taken.

For the determination of cyclic material properties the Multiple Step Test is appropriate. In this test it is customary to perform in each step as many constant strain amplitude cycles as needed to achieve stabilization of the stress amplitude. For the purpose of establishing properties of interest in seismic response, three to five cycles per amplitude should be adequate even if full stabilization is not reached.

Low-Cycle Fatigue and Fracture Testing. Deterioration and failure of components are often caused by localized crack initiation and propagation, which may occur (a) in the base material in the rolling direction, (b) in the base material in the through-thickness direction (orthogonal to rolling direction), (c) in the heat affected zone near weldments, and (d) in weld material. The fatigue and fracture properties in these four material zones are very different and may necessitate separate testing programs.

Basic low-cycle fatigue data for all four material zones can be obtained from standard constant-amplitude low-cycle fatigue tests with machined specimens. Properties in the through-thickness direction of the base material and properties of weld materials depend strongly on imperfections and the thickness of plates and size of welds, and a sufficient number of tests should be performed to permit an assessment of the scatter of properties (Krawinkler et al., 1983). When crack propagation is the predominant problem, the determination of crack growth rates, which relate the crack growth per cycle (da/dN) to a relevant crack propagation parameter (e.g., ΔK, $\Delta\varepsilon$, or ΔJ), will become important. The standard LCF specimen (ASTM Standard E606) is appropriate for this purpose if gross yielding around the crack needs to be represented. If crack growth rates at smaller (almost elastic) strain amplitudes are of interest, compact or bend specimens may be suitable (ASTM Standard E399).

C.3.4 Planning and Execution of Experiment

Analytical Predictions. In order to predict the important force and deformation quantities as accurately as possible, it is highly desirable to perform a thorough analytical study prior to the planning and execution of an experiment. Loading histories, instrumentation plans, data acquisition, and test execution should be based on the results of this analytical study. If no monotonic load test results are available for the test specimen, yield values of the "force" and "deformation" control parameters must be predicted analytically to determine the cyclic loading history to be applied in the experiment.

Instrumentation. The recommendations allude to a minimum instrumentation requirement that is concerned only with the measurement of the "force" and "deformation" control parameters. This minimum may indeed fulfill the needs in a test that has no research objective and is performed only to verify adequate performance of a component or subassembly. Even then, the lack of additional instrumentation may become a major problem if failure modes are predicted wrongly and the selected control parameters are found to be inappropriate. Thus, it serves to safeguard against surprises, in addition to providing much needed data, if additional instrumentation is provided. The extent of instrumentation depends on the purpose of the test, the configuration of the test specimen, the complexity of the failure mode(s), and the planned synthesis of test results. As stated in the recommendations, the basic guideline is that sufficient instrumentation should be provided to be able to relate all important deformation quantities to all the force quantities that are the primary cause of the deformations.

C.3.5 Test Control and Control Parameters

Cyclic loading necessitates pre-planned control over the most relevant "force" and "deformation" parameters of the test specimen. In the early (elastic) stage of testing it is advisable to use force rather than deformation control because the initial stiffness may be very high and deformations may not be predictable or controllable with sufficient accuracy. Once the force approaches the yield strength, or when considerable inelastic deformations are observed, deformation control should be employed unless the specimen is so stiff that deformation control becomes unreliable. For instance, for unloading of very stiff specimens, force control may be the preferred control mode.

Control Parameters. The choice of proper "force" and "deformation" control parameters is critical for test execution, test interpretation, and performance evaluation. These parameters should be quantities that (1) represent the primary cause and effect of damage and failure in the component or subassembly under study, (2) can be related with confidence to global structural response parameters (story shear and story drift), and (3) represent, whenever possible, a measure of energy dissipation capacity of the test specimen, i.e., their product should have the dimensions of force times length.

Examples of suitable "force" control parameters are story shear force for story subassembly tests, moments for beam and beam-to-column connection tests, sum of beam moments at column faces for joint shear tests, and axial force for brace tests. Examples of suitable "deformation" control parameters are story deflection for story subassembly tests, rotation at a plastic hinge location for beam tests, average joint distortion for joint shear tests, relative rotation between beam and column for beam-to-column connection tests, and axial shortening/extension for brace tests.

Yield Values. It is conventional, although not necessary, practice to use yield values of force and deformation parameters to control the loading history. Thus, a consistent method is needed to establish these yield values even though "yielding" is usually not a well defined point in the load-deformation response of a component.

None of the different methods for obtaining "yield points" for component behavior proposed in the literature give satisfactory results for all cases since judgment is involved in all definitions. The method recommended in Section 3.5 is described in Cheung et al. (1991). It presumes that a reasonable estimate is available for the yield force (from a monotonic test or analytical predictions), and that the yield deformation can be obtained from experimental data as illustrated in Figure 2. A disadvantage of using this yield deformation to control the experiment is that the information is obtained from the elastic portion of the test and final decisions on deformation control values cannot be made in advance of testing.

A distinction needs to be made between yield values used for test control and those used for test interpretation. For the purpose of test interpretation, i.e., performance assessment and analytical modeling, yielding is a reference value that identifies distinct deviation from a linear elastic response and should permit the analytical modeling of the force-deformation response by means of bilinear or multilinear diagrams. For consistency, this definition should apply also to the yield values used for test control. Thus, it is most desirable that the yield values for test control and test interpretation be the same, but they may not be because of several reasons. If no monotonic load test is performed, at least one of the yield values for test control must be established analytically. There may be significant differences between the predicted values and those observed in a cyclic test. It becomes a matter of judgment whether it is useful to change the values of the control parameters based on observations made early in the experiment. If the differences between predicted and observed values are large, it is advisable to modify the control values provided this change can be made early in the inelastic portion of the loading history. The purpose of these predicted or modified values is to control the loading history according to guidelines presented in Chapter 4. These values should become part of the test documentation, and they should, but need not be, the yield values used for test interpretation. Test interpretation for analytical modeling and performance assessment should be based on the "best" yield value, which may be available only after completion of the test.

It is not always necessary to establish yield values for force and deformation parameters. It may be better in some cases to control the loading history with absolute rather than normalized values of deformations.

C.4 Testing Programs and Loading Histories (Commentary)

Chapter 4 of the recommendations presents simple testing programs whose main objective is to provide the information needed for seismic performance assessment. Emphasis is on performance in severe earthquakes in which deterioration and safety against failure become overriding considerations. Performance may be considered an issue of demand and capacity, with adequate performance implying that the capacity exceeds the demand with an adequate margin of safety.

Experimentation is explicitly concerned with the evaluation of the capacity of structures or their components. However, in seismic problems, capacity and demand cannot be separated since one may strongly depend on the other. Therefore, single capacity parameters, such as maximum deformation or maximum ductility ratio, will provide inadequate descriptions of capacity unless all other important demand and capacity parameters are considered in the loading history applied to the test specimens and in the test evaluation.

Because of the randomness of the seismic demand and the dependence of the capacity on the demand, a single test or even a series of tests may not provide all the information needed for seismic performance assessment. Thus, the choice of testing programs and loading histories should be guided by the objective to maximize information and minimize complexities that will complicate test evaluation. The following summary on important issues of capacity and demand is intended to provide the background that forms the basis for selecting the testing programs and loading histories given in these recommendations.

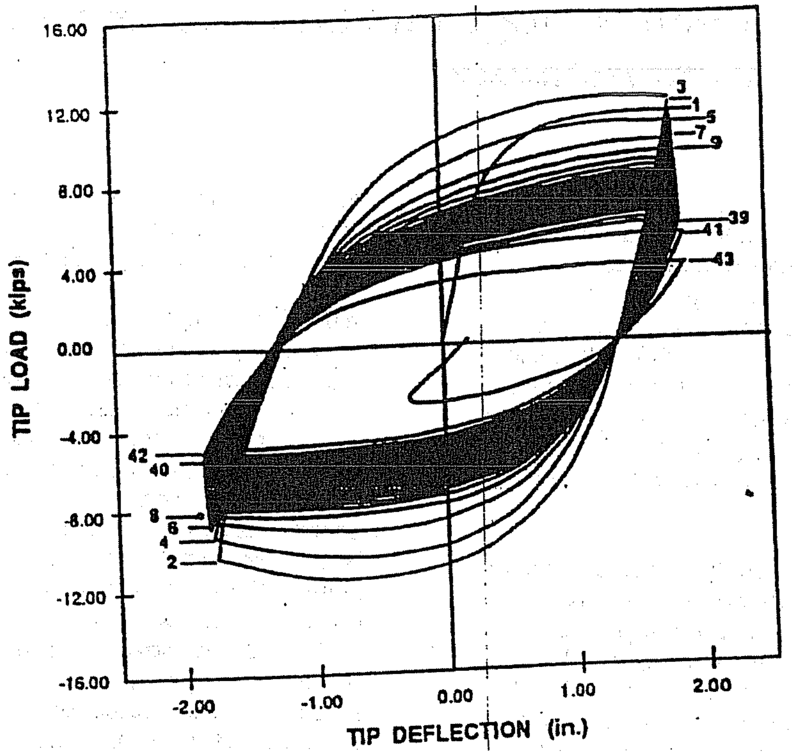
Seismic Capacity. Basic seismic capacity parameters for a component are strength, stiffness, inelastic defomation or ductility capacity, and cumulative capacity parameters such as energy dissipation capacity. All these parameters are expected to deteriorate as the number of damaging cycles and the amplitude of cycling increases. The type of deterioration depends on the failure mode of the component. Figure C.1 illustrates examples of deterioration for two distinctly different failure modes; *slow and gradual deterioration* (of strength and stiffness), Figure C.1(a), and *rapid deterioration* of strength, Figure C.1(b).

In the first example a beam with slender flanges was tested (Krawinkler et al., 1983). Local flange buckling occurred early and a decrease in strength is evident after the first load reversal. During subsequent cycles the flange buckles increased in size, leading to gradual deterioration in strength and stiffness in each cycle. In the second example a beam was tested in which crack propagation at a beam-to-column flange weld was the cause of failure. The crack, which initiated at an imperfection at the weld toe, was visible after several cycles and grew slowly for several more cycles without leading to noticeable deterioration in the load-displacement response. When the crack depth exceeded half the flange thickness, the crack became unstable and fracture occurred instantaneously. This led to a complete loss of strength at the beam-to-column connection as seen in the figure.

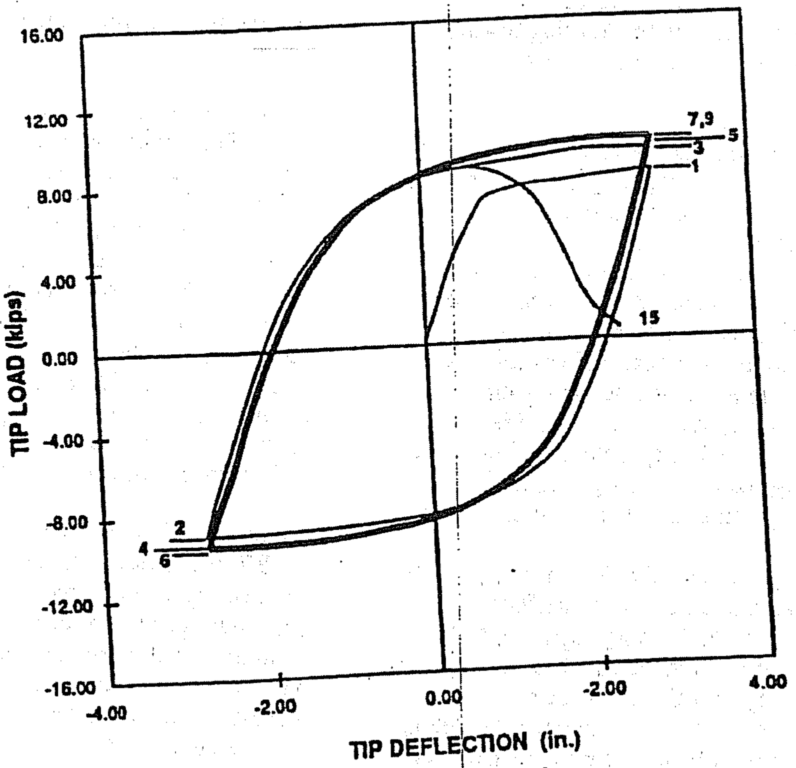
Each mode of deterioration and failure has its own characteristics that may affect the choice of testing program and loading history. For instance, a failure mode exhibiting the rapid strength deterioration illustrated in Figure C.1(b) is usually caused by local imperfections that lead to material fracture. The characteristics of these imperfections may have considerable scatter and, therefore, the level at which deterioration occurs is uncertain. Thus, little confidence can be placed in the results of a single test, particularly since a clear margin of safety must be established for a failure mode with rapid strength deterioration.

Generic loading histories, which are to be applied to different specimens with different failure modes, represent a compromise that is based on important performance characteristics that are common to all specimens tested. The recommended loading histories are based on a general cumulative damage concept of the following characteristics:

1. Every excursion in the inelastic range causes damage in a component. Damage implies that



(a) Slow Deterioration



(b) Rapid Deterioration

Figure C.1 Different modes of deterioration and failure

C.4.1 Single Specimen Testing Program

Multiple Step Test. This test is recommended as the basic performance test in a single specimen testing program. It is simple to execute through deformation control (except in the elastic range) and results in essentially symmetric cycles for which the important response parameters can be evaluated consistently.

In the loading history for such a test the primary parameters are the number of inelastic excursions. N, the magnitude of the plastic deformation range of each inelastic excursion, $\Delta\delta_{pi}$, the sum of the plastic deformation ranges, $\Sigma\Delta\delta_{pi}$, and the maximum ductility ratio that will be experienced in the earthquake for which performance is to be evaluated. In order to render a test useful for generic specimens, the last parameter must remain a variable to be addressed in performance evaluation, and the other three parameters should be determined so that the loading history represents the seismic demand for the full range of practical maximum ductility ratios.

Based on these requirements and the preceding discussion, the following arguments are used to establish the recommended loading history:

1. It is assumed that the seismic demand for the interstory drift in complex structures can be represented by the response of bilinear SDOF systems.

2. The loading history should represent a "reasonable and generally conservative" demand on N, $\Delta\delta_{pi}$, and $\Sigma\Delta\delta_{pi}$ for the full range of practical story drift ductility ratios. Since both N and $\Sigma\Delta\delta_{pi}$ depend strongly on the period of the structure of which the component is part, the demands should be established for short period structures for which the demands are high. SDOF systems with periods of 0.2 and 0.5 seconds were selected to benchmark these demands.

3. "Reasonable and generally conservative" implies that the total number of inelastic excursions, N, should be represented as an average, and that the cumulative plastic deformation range, $\Sigma\Delta\delta_{pi}$, should be represented conservatively. Consideration should also be given to the fact that small inelastic excursions are much more frequent than large ones.

The loading history recommended in Section 4.1 comes close to fulfilling these requirements as is illustrated in Table C.1. This table shows, for three selected periods T and different ductility ratios μ, representative values of predicted SDOF seismic demands (mean values and mean plus standard deviation σ of N and $\Sigma\Delta\delta_{pi}/\delta_y$ deduced from the data given in Nassar and Krawinkler (1991)) and the corresponding values obtained from the recommended loading history with the increment in peak deformation, Δ, being equal to the story yield displacement δ_y. The third part of the table illustrates how conservative the loading history is for components in long period structures.

This table shows that for all periods and all ductility ratios the experimentally executed $\Sigma\Delta\delta_{pi}/\delta_y$ is greater than the predicted mean + σ, whereas the experimentally executed number of inelastic excursions in the period range from 0.2 to 0.5 seconds is smaller than the predicted mean. The reason for this disparity is that in earthquakes short period structures experience a large number of small inelastic excursions and a small number of large inelastic excursions, whereas in the recommended loading history the magnitudes of inelastic excursions are distributed more uniformly. The argument for replacing the many small excursions of an earthquake by a few larger excursions in an experiment is that the total number of cycles that have to be performed in an experiment is reduced, but the cumulative damage effect, represented by $\Sigma\Delta\delta_{pi}/\delta_y$, is still simulated conservatively. It is left to the judgment of the experimentalist to modify the loading history and simulate the expected number of inelastic excursions more accurately. It should be considered that the predicted values are from West Coast earthquakes with magnitudes between 5.7 and 7.7 and for stiff site soil conditions. For larger earthquakes with longer strong motion duration and soft soil sites the number of inelastic excursions as well as the cumulative plastic deformation ranges may be considerably larger. On the other hand, for smaller magnitude earthquakes in regions of lower seismicity the opposite may be true. Thus, modifications to the recommended loading history may be in order if much larger or smaller seismic demands are anticipated.

Increment in Peak Deformation, Δ. The increment in peak deformation between load steps may be expressed in absolute or normalized terms. The basis for determining Δ is that the loading

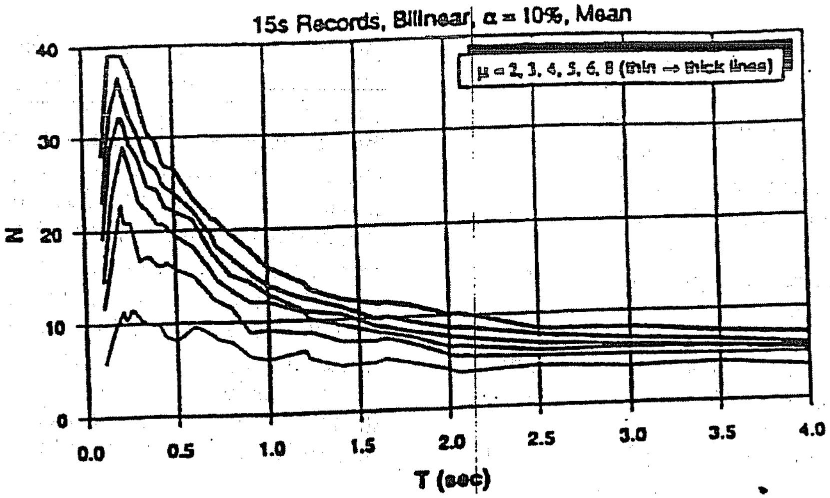


Figure C.2 Dependence of mean number of inelastic excursions on natural period and ductility ratio (Nassar and Krawinkler, 1991)

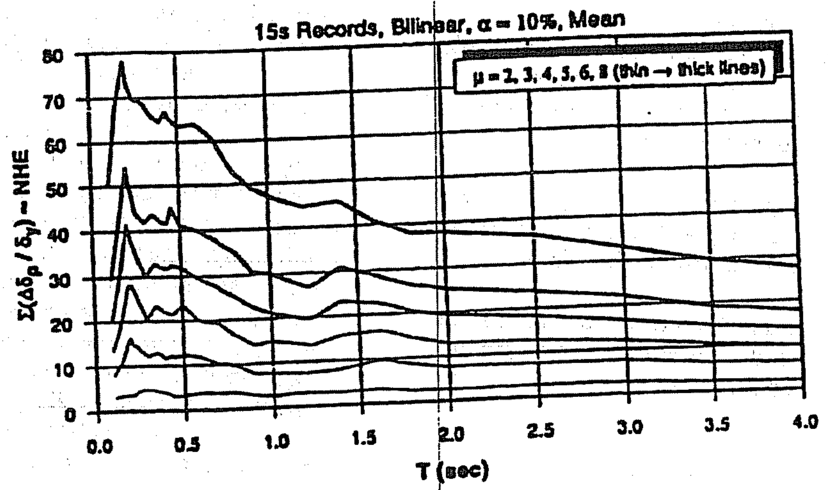


Figure C.3 Dependence of the mean of the sum of normalized plastic deformation ranges ($\Sigma\Delta\delta_{pi}/\delta_y$) on natural period and ductility ratio (Nassar and Krawinkler, 1991)

Sum of Normalized Plastic Deformation Ranges, $\Sigma\Delta\delta_{pi}/\delta_y$. This parameter is used here as the basic cumulative damage parameter. For bilinear systems it is equal to the dissipated hysteretic energy normalized by $F_y\delta_y$. Similar to N, this parameter depends strongly on the period T and the ductility ratio μ. The dependence of the mean value of this parameter on T and μ is illustrated in Figure C.3.

This brief summary shows the great dependence of the demand parameters on the natural period of the structure of which the component is part. For generic test specimens the need exists to base these parameters on short period structures, with the understanding that their values may be very conservative for long period structures. It is to be recognized that cyclic demands for structures depend on a great number of variables and a unique loading history will always be a compromise, but one that should be conservative for most practical cases. It also needs to be considered that the values shown in Figures C.2 and C.3 may be low for earthquakes of large magnitudes (because of long strong motion durations) and high for earthquakes in regions of lower seismicity.

macro- or microstructural changes occur, which causes visible or invisible deterioration of strength and stiffness properties and brings the component closer to failure.

2. The component has a memory, i.e., the damage from inelastic excursions is cumulative.

3. Large excursions cause much larger damage than small excursions.

4. The relative amount of damage caused by an excursion depends on the plastic deformation range of the excursion, $\Delta\delta_p$, the mean deformation of the excursion (a measure of symmetry with respect to the undeformed configuration), and the sequence in which large and small excursions are applied to the component (sequence effects).

5. For a given deformation amplitude the damage is largest for a symmetric excursion since this results in the largest possible plastic deformation range.

6. The importance of sequence effects has not yet been established through research, and the sequence of large vs. small excursions in a component of a structure subjected to a severe earthquake does not follow any consistent pattern. Thus, sequence effects are not being considered in the recommended loading histories.

7. As a consequence, the number of inelastic excursions and their plastic deformation ranges (or, for symmetric excursions, their deformation amplitudes), as well as the sum of the plastic deformation ranges, become the primary capacity parameters for loading histories.

Krawinkler et al. (1983) present an extensive discussion of the issues raised here and many others of interest in seismic testing and performance evaluation of structural steel components.

Seismic Demand. The demand imposed by a severe earthquake on a structural component depends on the configuration of the component within a structure, the strength and elastic and inelastic dynamic characteristics of the structure, and the seismic input to which the structure may be subjected. For generic components none of these variables is well defined or narrowly bracketed. The best mediator between component demand and seismic input appears to be the interstory drift in structures, since this parameter can usually be related to the component deformation and the demand on this parameter can be assessed from simplified dynamic models. Although there is no definite relationship between interstory drift in multistory structures and the deformation demand in single degree of freedom (SDOF) systems (Nassar and Krawinkler, 1991), the latter is often used to estimate the former.

In the context of developing loading histories with due consideration to seismic demands, general conclusions can be drawn from studies on SDOF systems. Statistical studies on bilinear and stiffness degrading SDOF systems subjected to a set of 15 Western U.S. earthquake ground motions are reported in Hadidi-Tamjed (1987) and Nassar and Krawinkler (1991). The shape of the average elastic response spectrum of these records closely resembles the shape of the ATC 3-06 ground motion spectrum for $A_a = A_v$ (ATC, 1978). Hadidi-Tamjed (1987) and Nassar and Krawinkler (1991) provide, amongst others, statistical information on demand parameters for inelastic systems with ductilities of 2 to 8. This information, which in part is summarized next, forms the basis for the recommendations on loading histories given in Chapter 4. In the interpretation of the quantitative information presented here, it must be considered that the 15 records used in this study (a) are from earthquakes whose magnitude varies from 5.7 to 7.7, (b) have strong motion durations that vary significantly, and (c) represent site response for stiff soil sites (soil type S_1).

Number of Inelastic Excursions, N. This number increases with a decrease in period T of the system, the rate of increase being very high for short period systems (exception: $T < 0.2$ seconds). The dependence of the mean value of N on T and the ductility ratio μ is illustrated in Figure C.2.

Individual Plastic Deformation Ranges, $\Delta\delta_{pi}$. The magnitudes of the plastic deformation ranges of the inelastic excursions can be represented by a lognormal distribution. Large plastic deformation ranges are rare events, and small ones are frequent. The median of the plastic deformation ranges in an earthquake is usually less than 15% of the maximum (Hadidi-Tamjed, 1987).

Table C.1 Predicted and Experimentally Executed Demands

Period	Ductility	N = number of inelastic excursions			$\Sigma\Delta\delta_{pi}/\delta_y$ = sum of plastic deformation ranges		
T	μ	mean	mean+σ	experiment	mean	mean+σ	experiment
0.2	2	12	19	6	4	7	11
	4	28	42	16	28	41	57
	6	36	55	24	54	76	127
	8	39	59	32	78	109	229
0.5	2	8	12	6	3	5	11
	4	19	30	16	23	36	57
	6	24	35	24	41	64	127
	8	26	38	32	64	97	229
2.0	2	4	7	6	3	4	11
	4	7	10	16	13	20	57
	6	9	12	24	25	36	127
	8	10	14	32	38	52	229

history is founded on the story drift concept and that Δ should correspond to a unit increase in story drift ductility, i.e., Δ should correspond to an increase in story drift equal to the yield displacement of the story.

If the deformation control parameter δ is a direct measure of story displacement, such as in a story subassembly test, the increment in peak deformation, Δ, should be equal to the yield value of the deformation control parameter, δ_y. If δ is not a direct measure of story displacement, then the increment Δ should be estimated from an appropriate geometric transformation that relates the deformation control parameter to the story drift. This is illustrated in the example shown in Figure C.4.

This example illustrates a beam-column subassembly in which the joint panel zone is the yielding element that causes all inelastic deformations. If the subassembly displacement δ_s is used as the deformation control parameter, then the increment in peak deformation, Δ, should be equal to the yield displacement $\delta_{s,y}$. However, if the average joint shear distortion γ is used as the deformation control parameter, then the increment in peak deformation should be equal to $3\gamma_y$ since the joint shear distortion contributes only 33% to the elastic story drift but accounts for all of the inelastic story drift.

The fact that in this example the story and joint ductility ratios differ by a factor of three should be accounted for in the selection of the deformation control parameter, in the increment in peak deformation, and in the performance evaluation. In such cases it is often equally feasible or better to estimate the increment in peak deformation in absolute terms (e.g., the angle of joint distortion

At yielding:

Subassembly: $\delta_s = \delta_{s,y}$

Joint panel zone: $\gamma = \gamma_y$

Assume: $\delta_{joint,y} = 0.33\delta_{s,y}$

At n times story yield displacement:

Subassembly: $\delta_s = n\delta_{s,y}$

$\Delta = \delta_{s,y}$

Joint panel zone: $\gamma = 3(n-0.67)\gamma_y$

$\Delta = 3\gamma_y$

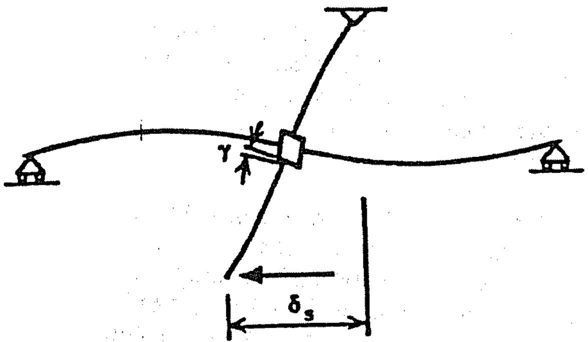


Figure C.4 Increment in peak deformation for different control parameters required to cause a story displacement increase of $\delta_{s,y}$) rather than normalized terms (e.g., $\Delta = 3\gamma_y$).

This section has provided background to the recommendations made in Section 4.1 on the Multiple Step Test. The focus on this test does not imply that the recommended stepwise increasing loading history is the only one that should be considered. The concepts of the Multiple Step Test are well established and have been employed for many years in material testing. The perception is that this test maximizes the information that can be obtained from a single test, since it permits the evaluation of cyclic hardening or softening, facilitates mathematical modeling, considers cumulative damage issues, identifies strength and stiffness deterioration characteristics, and permits a consistent comparison and evaluation of test results obtained from different studies. It has the drawback, like any other single specimen testing program, that the loading history is predetermined and sequence effects cannot be investigated. There are cases in which a reverse history, i.e., large cycles followed by small cycles, may lead to accelerated deterioration. The existence of this problem is recognized, but general recommendations of the type presented here cannot address this issue. For this and many other reasons it is emphasized that this document contains only recommendations. There may be good reasons to modify these recommendations in specific cases.

C.4.2 Multi-Specimen Testing Program

Monotonic tests are sometimes desirable to establish basic reference values such as yield strength, yield deformation, and strain hardening behavior. Such tests may not be necessary unless the monotonic response cannot be predicted with reasonable confidence and problems are foreseen in determining the control parameters for the cyclic test.

More than one cyclic test is needed if performance evaluation cannot be based with confidence on the results of a single test. This is the case for specimens that exhibit the behavior shown in Figure C.1(b). The illustrated response comes from a beam specimen in which failure was caused by crack propagation and fracture at a beam flange weld (Krawinkler et al., 1983). Although crack propagation occurred relatively early in the cyclic history, it did not lead to a noticeable deterioration until unstable crack growth occurred and the weld fractured suddenly, leading to a rapid deterioration in strength. Crack initiation and crack growth at weldments are phenomena that are greatly affected by workmanship, and their characteristics may exhibit considerable scatter. For instance, in the test series from which Figure C.1(b) was obtained, three identical specimens cycled at the same deflection amplitude failed after 8, 14, and 15 cycles, respectively, and two other identical specimens cycled at a smaller deflection amplitude failed after 46 and 92 cycles, respectively. If only a single test had been performed, the performance evaluation would have led to misleading results.

C.4.2.1 Multi-Specimen Multiple Step Tests

These tests are intended to give some consideration to the scatter in performance for the case identified above. The tests should be performed with identical loading histories. Ideally, a sufficient number of tests should be performed to permit a statistical evaluation of the results. Since this is economically unfeasible in most practical cases, the recommendation is to perform at least three tests and base the performance assessment on the test with the smallest cumulative measured plastic deformation range.

C.4.2.2 Cumulative Damage Testing Program

This testing program is primarily for research purposes. Its objective is to establish structural performance parameters that can be used together with a cumulative damage model to predict component performance under arbitrary loading histories. Its primary use is for the study of generic deterioration and failure modes, in which analytical means have to be combined with experimental results in order to predict performance for a wide range of applications.

The testing program depends on the postulated cumulative damage model. The simplest model of this type is one that is based on the two hypotheses of a Manson-Coffin relationship and Miner's rule (Krawinkler et al., 1983). The first hypothesis postulates that for constant amplitude cycling the number of excursions to failure, N_f, and the plastic deformation range, $\Delta\delta_p$, are related by the following equation:

$$N_f = C^{-1}(\Delta\delta_p)^{-c} \qquad \text{(C.1)}$$

In this equation C and c are structural performance parameters that have to be determined experimentally. The equation implies that on a log-log plot the relationship between N_f and $\Delta\delta_p$ is linear.

The second hypothesis is Miner's rule of linear damage accumulation, which postulates that the damage per excursion is $1/N_f$, and that the damage from excursions with different plastic deformation ranges, $\Delta\delta_{pi}$, can be combined linearly. Thus the total damage D is given by the equation

$$D = C\sum_{i=1}^{N}(\Delta\delta_{pi})^c \qquad \text{(C.2)}$$

If this hypothesis were accurate, a total damage of $D = 1.0$ would constitute failure. Because of the known shortcomings of Miner's rule (neglect of mean deformation and sequence effects) and the scatter in the structural performance parameters C and c, the limit value of damage that constitutes failure cannot be expected to be exactly 1.0. Krawinkler et al. (1983) provides an extensive discussion of many issues associated with this damage model.

A testing program utilizing this cumulative damage model requires at least three constant amplitude tests on identical test specimens in order to obtain values for C and c, and to verify that the relationship given by Eq. (C.1) represents reality with sufficient accuracy. For each test a new specimen must be used since each specimen is to be tested to failure. The deformation amplitudes for the three tests should be selected so that they cover the range of interest for performance assessment. For elements that are expected to behave ductilely, suggested values for the three deformation amplitudes are $3\delta_y$, $6\delta_y$, and $9\delta_y$.

Additional constant amplitude tests should be performed if strength deterioration is caused by a failure mode whose characteristics may exhibit considerable scatter. In order to evaluate the scatter, tests with previously used deformation amplitudes should be repeated.

Presuming that this damage model is reasonably accurate, it has the great advantage that it permits performance assessment for any arbitrary loading history the component may experience. In the study reported in Krawinkler et al. (1983) this testing and evaluation method was found to be rather accurate and most useful for an assessment of localized failure modes governed by flange buckling and weld fracture. There is good reason to believe that it will apply to other localized failure modes as well, and its use is encouraged for a detailed performance assessment of such failure modes. This method may not be applicable for an assessment of failures modes associated with large cyclic stiffness deterioration (e.g., column buckling) because constant amplitude tests and plastic deformation ranges are difficult to interpret for such cases.

Examples for which this testing program is recommended are:

- Width/thickness requirements for flanges and webs in beams and columns.
- Performance of welded beam flange to column flange (or web) connections.
- Continuity plate requirements at welded flange connections in beam-column joints.
- Weld requirements for beam web connections to columns.
- Welding requirements for brace connections.
- Shear design requirements for beam-column joints.
- Net section requirements in bolted beam and brace connections.
- Shear link behavior in eccentrically braced frames.
- Local buckling criteria in diagonal braces.

C.5 Documentation of Experimental Results (Commentary)

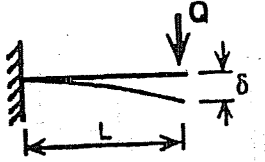
The recommendations in Section 5 are directed towards documentation that should permit individuals other than the experimentalist to assess the test, perform an independent performance evaluation, and take full advantage of the information generated in the experiment. For this purpose uniformity in notation and nomenclature is essential.

A complete set of data should be provided on the "force" and "deformation" control parameters. Complete implies that the performance parameters listed in Section C.6.1 can be deduced from the documented data. The extent to which similar data should be provided for other response parameters is left to the judgement of the experimentalist.

It is recommended that complete sets of data be provided for those parameters (or pair of parameters) that (a) have a significant effect on the inelastic response and (b) cannot be deduced from previously documented data.

The following table and figure provide examples of test documentation for the control parameters (tip load and tip deflection) of a cantilever beam test. The presented data are fictitious and have no relation to the real behavior of a W24x55 beam. A steel section designation is shown only to illustrate the type of information that needs to be documented. The data are presented in a normalized format, which facilitates interpretation of test results provided the yield values used to control the test are suitable for test interpretation.

Table C.2 Example Test Results: Tip Load and Deflection Data



Specimen C3:
Steel cantilever beam specimen, W24x55 section, A36 steel, span L = 144.0 in., fully welded connection
Measured material yield strengths: Flange: F_y = 42.4 ksi, Web: F_y = 44.3 ksi
Measured yield values of control parameters: Q_y = 38.1 k δ_y = 0.975 in.

Excursion	Peak Deflection	Deflection at Start of Excursion	Plastic Deflection Range	Load at Peak Deflection	Max. Load in Excursion	Initial Ldg. Stiffing	Initial Unldg. Stiffing	Hysteresis Area	Observations and Comments
i^+, i^-	δ/δ_y	δ_o/δ_y	$\Delta\delta_{pm}/\delta_y$	Q/Q_y	Q_{max}/Q	$K_o/(Q_y/\delta_y)$	$K/(Q_y/\delta_y)$	$A/(Q_y\delta_y)$	
1+	0.500	0.000	0.000	0.500	0.500	1.000	1.000	0.000	
1-	-0.500	0.000	0.000	-0.500	-0.500	1.000	1.000	0.000	
4+	0.750	0.000	0.000	0.750	0.750	1.000	1.000	0.000	
4-	-0.750	0.000	0.000	-0.750	-0.750	1.000	1.000	0.000	
7+	1.000	0.000	0.082	0.918	0.918	1.000	1.000	0.072	First yielding at Q = 20.7k
7-	-1.000	0.082	0.097	-0.918	-0.918	1.000	1.000	0.072	
8+	1.000	-0.015	0.060	0.953	0.953	1.000	1.000	0.081	
8-	-1.000	0.045	0.060	-0.953	-0.953	1.000	1.000	0.081	
9+	1.000	-0.015	0.030	0.984	0.984	1.000	1.000	0.101	
9-	-1.000	0.015	0.030	-0.984	-0.984	1.000	1.000	0.101	
10+	2.000	-0.015	0.858	1.156	1.156	1.000	1.000	0.965	
10-	2.000	0.843	1.603	-1.203	-1.203	1.000	1.000	1.792	
11+	2.000	-0.760	1.501	1.256	1.256	1.000	1.000	1.529	
11-	2.000	0.741	1.392	-1.302	-1.302	1.000	1.000	1.517	
12+	2.000	-0.651	1.348	1.313	1.313	1.000	1.000	1.459	First local buckle in bottom flange
12-	2.000	0.697	1.301	-1.343	-1.343	1.000	1.000	1.350	First local buckle in top flange
13+	3.000	-0.604	2.265	1.375	1.375	1.000	1.000	2.689	
13-	3.000	1.641	3.202	-1.441	-1.441	1.000	1.000	3.895	
14+	3.000	-1.561	3.286	1.316	1.344	1.000	0.998	4.002	
14-	3.000	1.725	3.352	-1.359	-1.359	0.998	0.997	4.052	
15+	3.000	-1.627	3.390	1.281	1.297	0.997	0.996	3.917	
15-	3.000	1.763	3.439	-1.281	-1.312	0.996	0.995	4.081	
16+	4.000	-1.676	4.543	1.093	1.234	0.995	0.995	5.129	Severe flange and web buckling
16-	4.000	2.867	5.569	-1.141	-1.190	0.995	0.990	6.096	
17+	4.000	-2.702	5.674	0.906	1.016	0.990	0.906	5.415	
17-	4.000	2.972	5.817	-0.906	-1.063	0.906	0.900	5.765	
18*	5.000	-2.845	6.967	0.0802	0.781	0.900	0.821	4.945	

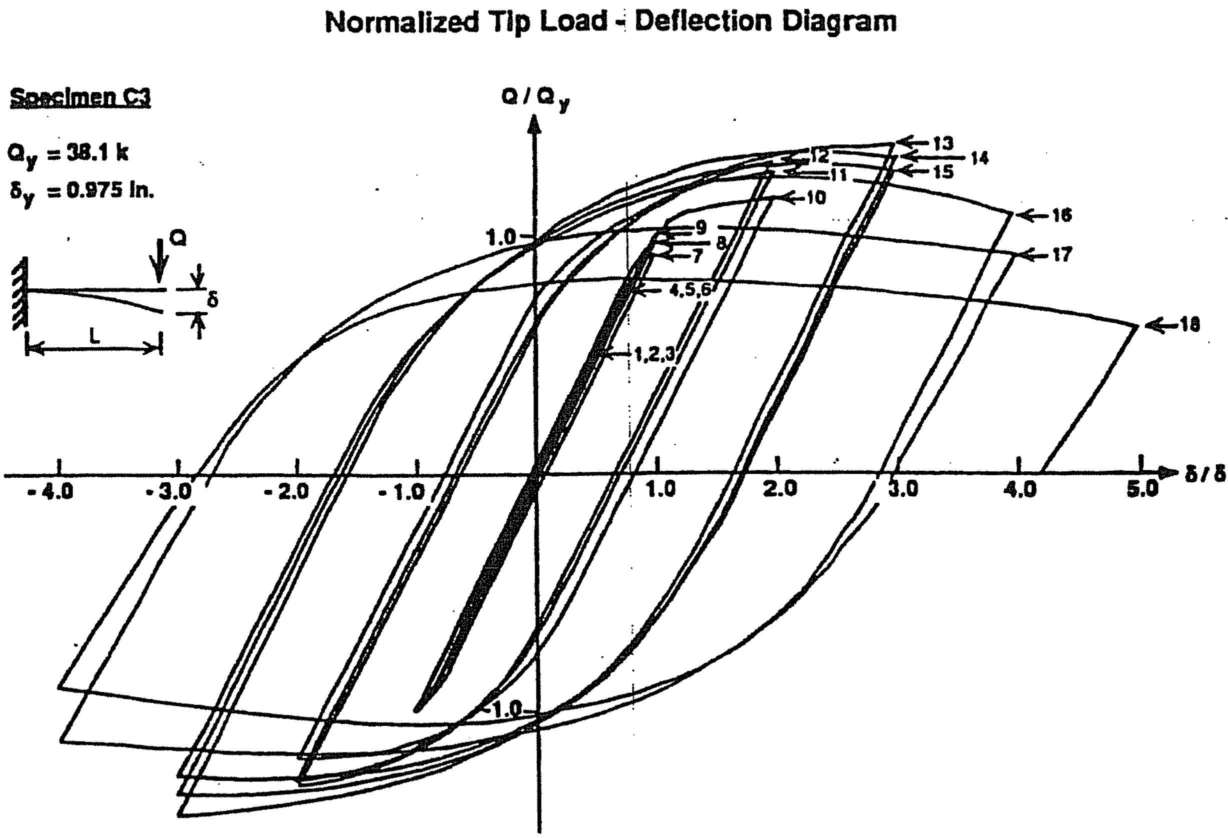
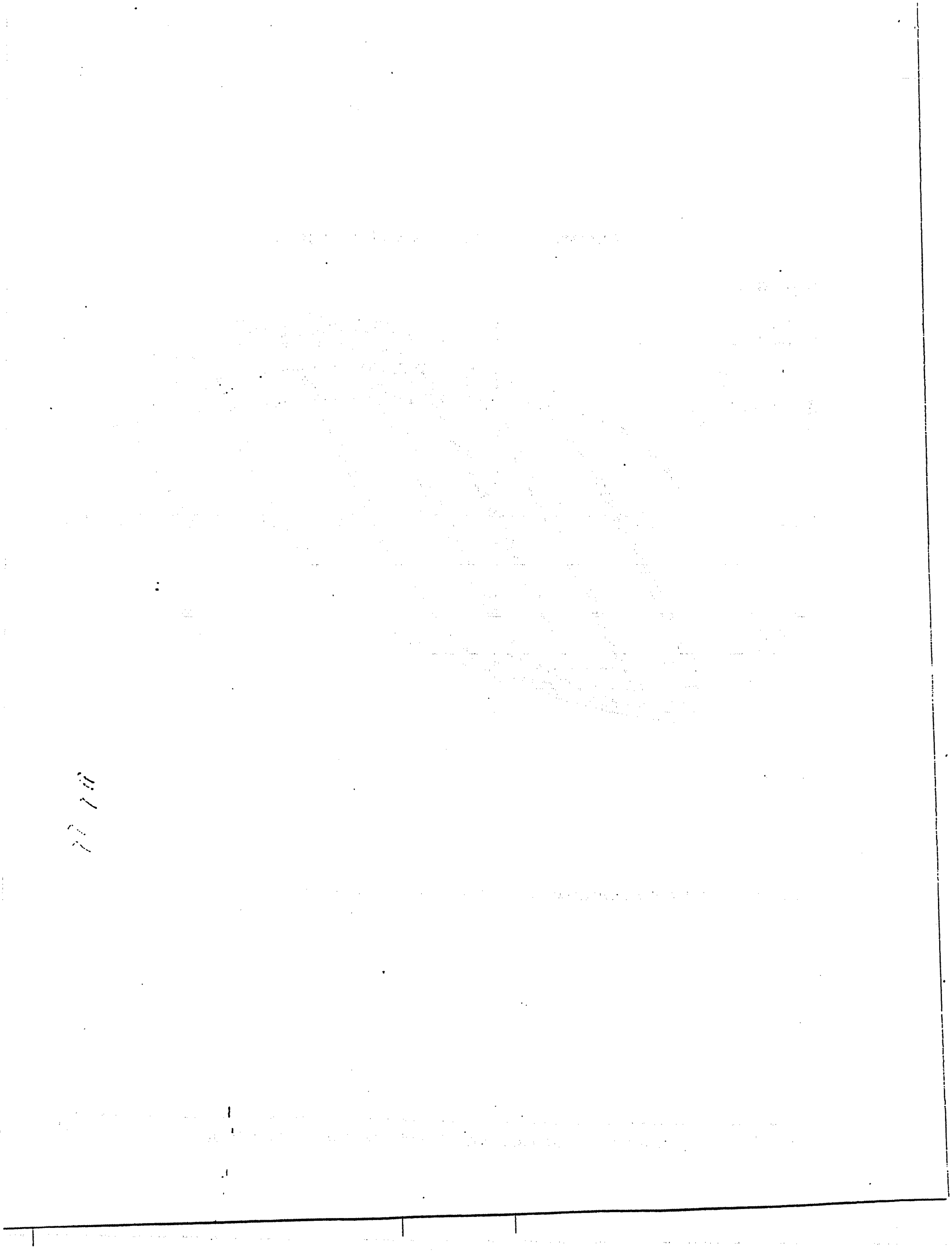


Figure C.5 Example test results: normalized tip load-deflection diagram



C.6 Evaluation of Performance (Commentary)

Following is a list of parameters and suggestions that may prove useful for performance evaluation. The utilization of these parameters is left to the user, as performance evaluation depends on the objective of the investigation and type of component being tested.

C.6.1 Parameters for Performance Evaluation

The parameters address, in sequence, the important issues of strength characteristics, stiffness characteristics, deformation capacity, and energy dissipation capacity.

Several of the parameters are shown in bold-faced type. Plots of these parameters against the ductility ratio are judged to be very useful for an assessment of cyclic performance.

The parameters listed may be evaluated separately for positive and negative excursions, or for both types of excursion together, if appropriate.

Several of the terms used here are illustrated in Figure C.6.

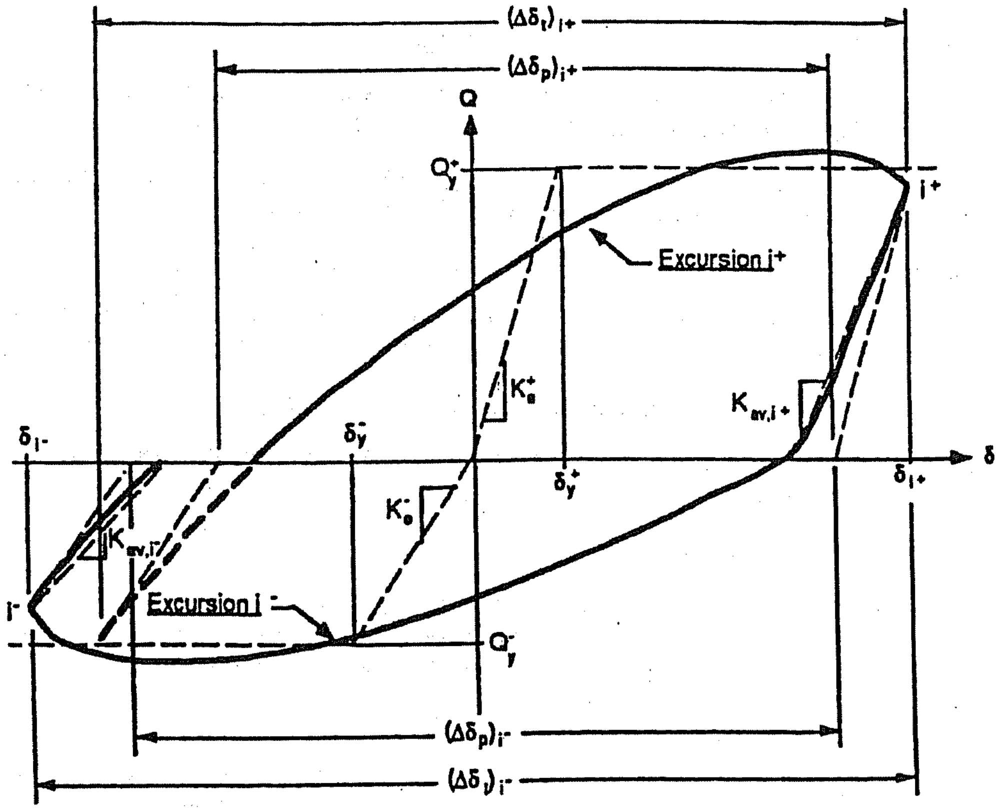


Figure C.6 Additional parameters of cycle *i*

Measures of Strength Characteristics:

Required strength before failure, Q_{min}. The minimum force at peak deformation that must be resisted according to a stipulated performance criterion. This force may be expressed as αQ_y. The parameter α is discussed later.

Maximum resistance, Q_u. The peak force that can be resisted by the specimen during the entire loading history.

Resistance Ratio, Q_i/Q_y (or $Q_{max,i}/Q_y$, if appropriate; e.g., compressive force in a buckling test)

Rate of hardening or strength deterioration, Q_{i+1}/Q_i.

Measures of Stiffness Characteristics:

Initial loading stiffness deterioration ratio, $K_{o,i}/K_e$.

Initial unloading stiffness deterioration ratio, K_i/K_e.

Average unloading stiffness deterioration ratio, $K_{av,i}/K_e$.

Measures of Deformation Capacity:

Maximum deformation, δ_{max}. The peak deformation of the excursion in which the peak force is larger than Q_{min} for the last time.

Maximum ductility ratio, $\mu_{max} = \delta_{max}/\delta_y$

Maximum excursion ductility ratio, $\mu_{e,max} = \Delta\delta_{max}/\delta_y$

Number of inelastic excursions to failure, N_f. The number of excursions with amplitudes larger than δ_y the specimen is able to resist before the force at peak defomation falls below Q_{min}.

Cumulative measured plastic deformation range, $(\Delta\delta_{pm})_{cum} = \Sigma(\Delta\delta_{pm})_i$. The sum of the measured plastic defomation ranges of all excursions for which $Q_i > Q_{min}$.

Normalized cumulative measured plastic deformation range, $(\Delta\delta_{pm})_{cum}/\delta_y$

Cumulative undeteriorated plastic deformation range, $(\Delta\delta_p)_{cum} = \Sigma(\Delta\delta_p)_i$. The sum of the undeteriorated plastic deformation ranges of all excursions for which $Q_i > Q_{min}$.

Normalized cumulative undeteriorated plastic deformation range, $(\Delta\delta_p)_{cum}/\delta_y$

Plastic deformation deterioration ratio, $(\Delta\delta_{pm})_i/(\Delta\delta_p)_i$. The ratio of measured over undeteriorated plastic deformation range of an excursion.

Measures of Energy Dissipation:

Cumulative hysteretic area, $A_{cum} = \Sigma A_i$. Cumulative hysteretic area enclosed by Q-δ diagram of all excursions for which $Q_i > Q_{min}$. This quantity represents the energy dissipation capacity if the product of Q times δ has the dimensions of force times length.

Normalized cumulative hysteretic area, $A_{cum}/(Q_y\delta_y)$.

Hysteretic area ratio, $A_i/A_{n,i}$. Ratio of measured hysteretic area of an excursion over computed hysteretic area based on an elastic - perfectly plastic model (see Figure C.6).

All but one of the listed parameters can be obtained directly from the experimental results and require no decision making. The only exception is the *required strength before failure*, Q_{min}, which must be assigned to the experiment. The importance of this parameter depends on the failure mode of the test specimen. If the failure mode is of the type shown in Figure C.1(a) (gradual strength deterioration), the value assigned to Q_{min} may greatly affect the maximum ductility ratio that can be assigned to the tested component. If the failure mode is of the type shown in Figure C.1(b) (rapid strength deterioration), the maximum ductility ratio will be insensitive to the value assigned to Q_{min}

It is convenient to express Q_{min} as αQ_y, where Q_y is either the measured or the predicted yield strength. The predicted yield strength is appropriate for this purpose if it is used in design and in the analytical studies on which the predicted seismic demand is based. The parameter α is a matter of judgment and should depend on the rate of strength and stiffness deterioration close to failure. If these rates are high, it is recommended to take α close to unity or maybe somewhat larger. If these rates are low, it should be acceptable to use α values less than unity.

The sensitivity of performance assessment to the value of α can be illustrated with Figure C.5. If a value of 0.9 is selected for α, the specimen passes the performance test for $\mu = 4$ since for all excursions the ratio Q_i/Q_y is larger than 0.9. However, if a value of 0.95 is selected, the specimen does not pass the performance test because in the second cycle the ratio Q_i/Q_y is less than 0.95. The fact that in the first cycle this ratio is greater than 0.95 is inadequate. The criterion $Q_i/Q_y > \alpha$ must be fulfilled for *all* excursions in order to pass the performance test for a specific ductility ratio. As was discussed in Section C.4.1, the reason to perform more than one cycle with larger amplitude is to compensate for the fact that the number of cycles with smaller amplitudes executed in the Multiple Step Test is smaller than predicted from seismic demand studies.

C.6.2 Adequate Performance

Performance in general may be concerned with several limit states, ranging from serviceability to safety against failure. Although test results will provide information on all limit states, these recommendations are written specifically for performance assessment for the limit state of failure. Failure is defined here as the inability of the component to resist an imposed seismic demand without excessive deterioration in strength. This necessitated the definition of the *required strength before failure*, Q_{min} in Section C.6.1.

Adequate performance depends on seismic demands and capacities. An experiment can only provide information on capacities, although due consideration can be given to certain demand characteristics as was discussed in Section C.4. In that section it was pointed out that the recommended loading history for the Multiple Step Test is intended to incorporate the most important cyclic demand characteristics of N and $\Sigma\Delta\delta_{pi}$, so that during performance assessment only one additional primary demand parameter remains to be considered. Conventionally, this additional demand parameter is the maximum ductility ratio.

The demand on the maximum ductility ratio for the component depends strongly on the seismicity at the site and the response characteristics of the structure of which the component is part. A comprehensive assessment of this ductility demand is a complex issue that cannot be addressed here. Section C.4 presents a simple but approximate way of relating component ductility demands to ductility demands imposed on bilinear SDOF systems for which statistical data can be generated and in part are available (Hadidi-Tamjed, 1987; Nassar and Krawinkler, 1991). In the statistical studies reported in these references it was also concluded that the ductility demands for stiffness degrading SDOF systems are not much different from those of bilinear systems. This does not hold true, however, for systems exhibiting strength deterioration.

Presuming that the component ductility demand can be evaluated with due consideration given to the uncertainty in seismic input, performance assessment can be based on the evaluation of *capacity/demand* ratios of ductility and other important performance parameters. The capacities to be used for this purpose are quantities associated with the deformation level that passes the Q_{min} test. The primary capacity/demand ratio is that for ductility, but other ratios, such as those for cumulative hysteretic area and cumulative undeteriorated as well as measured plastic deformation ranges, should also prove useful for performance evaluation.

Adequate performance implies that a margin of safety needs to be provided against failure. Thus, the required *capacity/demand* ratios should be larger than 1.0. How much larger depends on the degree to which input uncertainties are considered in the determination of ductility demands and on the mode of failure of the test specimen. If the mode of failure is associated with rapid strength deterioration, the required *capacity/demand* ratios should be larger than for modes of failure with gradual strength deterioration.

Recommendations on acceptable values of capacity/demand ratios are not within the scope of this document.

Applied Technology Council, 1978, *Tentative Provisions for the Development of Seismic Regulations for Buildings*, National Bureau of Standards, Special Publication 510, Applied Technology Council, Publication ATC 3-06, Redwood, California.

ASTM Standard E8, *"Test Methods of Tension Testing of Metallic Materials."*

ASTM Standard E23, *"Test Methods for Notched Bar Impact Testing of Metallic Materials."*

ASTM Standard E399, *"Test Method for Plane-Strain Fracture Toughness of Metallic Materials."*

ASTM Standard E466, *"Recommended Practice for Constant Amplitude Axial Fatigue Tests of Metallic Materials."*

ASTM Standard E561, *"Recommended Practice for R- Curve Determination."*

ASTM Standard E606, *"Recommended Practice for Constant-Amplitude Low-Cycle Fatigue Testing."*

ASTM Standard E647, *"Test Method for Measurements of Fatigue Crack Growth Rates."*

ASTM Standard E813, *"Test Method for J_{IC} a Measure of Fracture Toughness."*

ASTM Standard E1150, *"Definitions of Terms Relating to Fatigue."*

Cheung, P.C., 1991, Paulay, T., and Park, R., "New Zealand Tests on Full-Scale Reinforced Concrete Beam-Column-Slab Subassemblages Designed for Earthquake Resistance," *Design of Beam-Column Joints for Seismic Resistance, SP-123*, American Concrete Institute.

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Krawinkler, H., 1988, "Scale Effects in Static and Dynamic Model Testing of Structures," *Proceedings of the Ninth World Conference on Earthquake Engineering*, Tokyo-Kyoto, Japan, Vol. VIII, pp. 865-876.

Krawinkler, H., et al., 1983, *Recommendations for Experimental Studies on the Seismic Behavior of Steel Components and Materials*, John A. Blume Center Report No. 61, Department of Civil Engineering, Stanford University, Stanford, California.

Nassar, A.A., and Krawinkler, H., 1991, *Seismic Demands for SDOF and MDOF Systems*, John A. Blume Earthquake Engineering Center Report No. 95, Department of Civil Engineering, Stanford University, Stanford, California.

SMITH-EMERY COMPANY

NON UNION WEEKLY MILEAGE LOG

EMPLOYEE NAME: **Janeth Quintero**

EMPLOYEE # **246**

DEPT. 17

TODAYS DATE: **2/10/2003**

DATE	JOB NAME/EXPLANATION	JOB#	SATURDAY		SUNDAY		MONDAY		TUESDAY		WEDNESDAY		THURSDAY		FRIDAY		TOTAL MILES (Per Project)
			Beginning Odometer Reading	Ending Odometer Reading	Beginning Odometer Reading	Ending Odometer Reading	Beginning Odometer Reading	Ending Odometer Reading	Beginning Odometer Reading	Ending Odometer Reading	Beginning Odometer Reading	Ending Odometer Reading	Beginning Odometer Reading	Ending Odometer Reading	Beginning Odometer Reading	Ending Odometer Reading	
2/3/2003	Wilton Place (site recon)						73,952	73,982									30
2/3/2003	Wilton Place (phase II)														74,382	74,410	28
2/3/2003	Jim's house (pick up report)														74,410	74,442	32
																	0
																	0
																	0
																	0
																	0
																	0
																	0
																	0
																	0
																	0
																	0

EMPLOYEE SIGNATURE

DATE

TOTAL MILEAGE (WEEKLY) 90

MANAGER APPROVAL

DATE