

2. General Requirements

2.1 Scope

This chapter sets forth general requirements for data collection, analysis procedures, methods, and strategies for the design of seismic rehabilitation projects.

Section 2.2 specifies data collection procedures for obtaining required as-built information on buildings. Section 2.3 outlines the Simplified and Systematic Methods for seismic rehabilitation of buildings. Section 2.4 specifies limitations on selecting analysis procedures, and defines component behavior types and corresponding acceptance criteria. Section 2.5 identifies acceptable rehabilitation strategies. Section 2.6 contains general design requirements for rehabilitation designs. Section 2.7 specifies construction quality assurance requirements. Section 2.8 specifies procedures for developing alternative modeling parameters and acceptance criteria.

2.2 As-Built Information

The as-built information on building configuration, building components, site and foundation, and adjacent structures shall be obtained in accordance with Sections 2.2.1, 2.2.2, 2.2.3, 2.2.4 respectively. This data shall be obtained from available drawings, specifications, and other documents for the existing construction. The data collected shall be in sufficient detail to permit classification of components as primary or secondary as specified in Section 2.2.5 and shall comply with the data collection requirements of Section 2.2.6. Data collected from available documents shall be supplemented and verified by on-site investigations including nondestructive examination and testing of building materials and components as required in Section 2.2.6.

At least one site visit shall be made to observe exposed conditions of building configuration, building components, site and foundation, and adjacent structures, made accessible by the owner, to verify that as-built information obtained from other sources is representative of the existing conditions.

C2.2 As-Built Information

Existing building characteristics pertinent to seismic performance should be obtained from the following sources, as appropriate:

1. Field observation of exposed conditions and configuration made accessible by the owner.
2. Construction documents, engineering analyses, reports, soil borings and test logs, maintenance histories, and manufacturers' literature and test data, which may be available from the owner or the code official.
3. Reference standards and codes from the period of construction as cited in Chapters 5 through 8.

4. Destructive and nondestructive examination and testing of selected building materials and components as specified in Section 2.2.6.
5. Interviews with building owners, tenants, managers, the original architect and engineer, contractor(s), and the local building official.

The information required for an existing building may also be available from a previously conducted seismic evaluation of the building. Where seismic rehabilitation has been mandated according to building construction classification, familiarity with the building type and typical seismic deficiencies is recommended. Such information is available from several sources, including ASCE 31. Such information may be sufficient for Simplified Rehabilitation. Additional as-built information may be needed for Systematic Rehabilitation.

Where a destructive and nondestructive testing program is necessary to obtain as-built information, it is prudent to perform preliminary calculations to select key locations or parameters prior to establishing a detailed testing program. These obtain knowledge at a reasonable cost and with as little disruption as possible of construction features and materials properties at concealed locations.

If the building is a historic structure, it is also important to identify the locations of historically significant features and fabric, which should be thoroughly investigated. Care should be taken in the design and investigation process to minimize the impact of work on these features. Refer to the Secretary of the Interior's *Standards for the Treatment of Historic Properties with Guidelines for Preserving, Rehabilitating, Restoring, and Reconstructing Historic Buildings* (1995) as discussed in Appendix A. The services of a historic preservation expert may be necessary.

2.2.1 Building Configuration

The as-built building configuration information shall include data on the type and arrangement of existing structural components of the vertical- and lateral-force-resisting systems, and the nonstructural components of the building that either affect the stiffness or strength of the structural components, or affect the continuity of the structural load path. The as-built building configuration shall be examined to identify the vertical and lateral load paths.

C2.2.1 Building Configuration

The as-built information on building configuration should identify the load-resisting components. Load-resisting components may include structural and nonstructural components that participate in resisting lateral loads, whether or not they were intended to do so by the original designers. This information should identify potential seismic deficiencies in load-resisting components, which may include discontinuities in the load path, weak links, irregularities, and inadequate strength and deformation capacities.

ASCE 31 is one example of a seismic evaluation tool that offers guidance on building configuration.

2.2.2 Component Properties

Sufficient as-built information shall be collected on components of the building, including their geometric and material properties and their interconnection with other components, to permit computation of their strengths and deformation capacities. To account for any uncertainty associated with component as-built information, a knowledge factor κ shall be used in the capacity evaluation as specified in Section 2.2.6.4.

C2.2.2 Component Properties

Meaningful structural analysis of a building's probable seismic behavior and reliable design of rehabilitation measures require good understanding of the existing components (such as beams, columns, and diaphragms), their interconnection, and their material properties (mainly the mechanical properties – such as strength, deformability, and toughness). The strength and deformation capacity of existing components should be computed, as specified in Chapters 4 through 9 and 11, based on derived material properties and detailed component knowledge. Existing component action strengths must be determined for two basic purposes: to allow calculation of their ability to deliver load to other components, and to allow determination of their capacity to resist forces and deformations.

2.2.3 Site and Foundation Information

Data on foundation configuration and soil surface and subsurface conditions at the site shall be obtained from existing documentation, visual site reconnaissance, or a program of site-specific subsurface investigation in accordance with Chapter 4. A site-specific subsurface investigation shall be performed where Enhanced Rehabilitation Objectives are selected, or where insufficient data are available to quantify foundation capacities or determine the presence of geologic site hazards identified in Section 4.2.2. Where historic information indicates geologic site hazards have occurred in the vicinity of the site, a site-specific subsurface investigation shall be performed to investigate the potential for geologic site hazards at the site. Use of applicable existing foundation capacity or geologic site hazard information available for the site shall be permitted.

A site reconnaissance shall be performed to observe variations from existing building drawings, foundation modifications not shown on existing documentation, presence of adjacent development or grading activities, and evidence of poor foundation performance.

C2.2.3 Site and Foundation Information

Sources of applicable existing site and foundation information include original design information, foundation capacity information included on the drawings, and previous geotechnical reports for the site or for other sites in the immediate vicinity.

Adjacent building development or grading activities that impose loads on or reduce the lateral support of the structure can affect building performance in a future earthquake. Evidence of poor foundation performance can include settlement of building floor slabs and foundations, or

differential movement visible at adjacent exterior sidewalks or other miscellaneous site construction.

2.2.4 Adjacent Buildings

Sufficient data shall be collected on the configuration of adjacent structures to permit investigation of the interaction issues identified in Section 2.2.4.1 through 2.2.4.3. If the necessary information on adjacent structures is not available, the authority having jurisdiction shall be informed of the potential consequences of the interactions that are not being evaluated.

2.2.4.1 Building Pounding

Data shall be collected to permit investigation of the effects of building pounding in accordance with Section 2.6.10, wherever a portion of an adjacent structure is located within 4% of the height above grade at the location of potential impact.

C2.2.4.1 Building Pounding

Building pounding can alter the basic response of the building to ground motion and impart additional inertial loads and energy to the building from the adjacent structure. Of particular concern is the potential for extreme local damage to structural elements at the zones of impact.

2.2.4.2 Shared Element Condition

Data shall be collected on adjacent structures that share common vertical- or lateral-force-resisting elements with the building to permit investigation in accordance with Section 2.6.9.

C2.2.4.2 Shared Element Condition

Buildings sharing common elements, such as party walls, have several potential problems. If the buildings attempt to move independently, one building may pull the shared element away from the other, resulting in a partial collapse. If the buildings behave as an integral unit, the additional mass and inertial loads of one structure may result in extreme demands on the lateral-force-resisting system of the other. All instances of shared elements should be reported to the building owner and the owner should be encouraged to inform adjacent building owners of hazards if identified.

2.2.4.3 Hazards from Adjacent Buildings

Data on hazards from adjacent buildings shall be collected to permit consideration of their potential to damage the subject building as a result of an earthquake. If there is a potential for such hazards from an adjacent building, the authority having jurisdiction over the subject building shall be informed of the effect of such hazards on achieving the selected Rehabilitation Objective.

C2.2.4.3 Hazards from Adjacent Buildings

Hazards from adjacent buildings such as falling debris, aggressive chemical leakage, fire, or explosion that may impact building performance or the operation of the building after an earthquake should be considered and discussed with the building owner. Consideration should be given to hardening those portions of the building that may be impacted by debris or other hazards from adjacent structures. Where Immediate Occupancy of the building is desired and ingress to the building may be impaired by such hazards, consideration should be given to providing suitably resistant access to the building. Sufficient information should be collected on adjacent structures to allow preliminary evaluation of the likelihood and nature of hazards such as potential falling debris, fire, and blast pressures. Evaluations similar to those in FEMA 154 may be adequate for this purpose.

Data	Level of Knowledge							
	Minimum		Usual				Comprehensive	
Rehabilitation Objective	BSO or Lower		BSO or Lower		Enhanced		Enhanced	
Analysis Procedures	LSP, LDP		All		All		All	
Testing	No Tests		Usual Testing		Usual Testing		Comprehensive Testing	
Drawings	Design Drawings	Or Equivalent	Design Drawings	Or Equivalent	Design Drawings	Or Equivalent	Construction Documents	Or Equivalent
Condition Assessment	Visual	Comprehensive	Visual	Comprehensive	Visual	Comprehensive	Visual	Comprehensive
Material Properties	From Drawings or Default Values	From Default Values	From Drawings and Tests	From Usual Tests	From Drawings and Tests	From Usual Tests	From Documents and Tests	From Comprehensive Tests
Knowledge Factor (κ)	0.75	0.75	1.00	1.00	0.75	0.75	1.00	1.00

Table 2-1 Data Collection Requirements

2.2.5 Primary and Secondary Components

Data shall be collected to classify components as primary or secondary in accordance with Section 2.4.4.2. Data on primary and secondary components shall be collected in sufficient detail to permit modeling and analysis of such components in accordance with the requirements of this standard.

2.2.6 Data Collection Requirements

Data on the as-built condition of the structure, components, site, and adjacent buildings shall be collected in sufficient detail to perform the selected analysis procedure. The extent of data collected shall be consistent with minimum, usual, or comprehensive levels of knowledge as specified in Sections 2.2.6.1, 2.2.6.2, or 2.2.6.3. The required level of knowledge shall be determined considering the selected Rehabilitation Objective and analysis procedure in accordance with Table 2-1.

2.2.6.1 Minimum Data Collection Requirements

As a minimum, collection of as-built information shall consist of the following:

1. Information shall be obtained from design drawings with sufficient information to analyze component demands and calculate component capacities. For minimum data collection, the design drawings shall show, as a minimum, the configuration of the vertical-and lateral-force-resisting system and typical connections with sufficient detail to carry out linear analysis procedures. Where design drawings are available, information shall be verified by a visual condition assessment in accordance with Chapters 5 through 8.
2. In the absence of sufficient information from design drawings, incomplete or non-existent information shall be supplemented by a comprehensive condition assessment including destructive and nondestructive investigation in accordance with Chapters 5 through 8.
3. In the absence of material test records and quality assurance reports, use of default material properties in accordance with Chapters 5 through 8 shall be permitted.
4. Information needed on adjacent buildings, referenced in Section 2.2.4, shall be gained through field surveys and research of as-built information made available by the owner of the subject building.
5. Site and foundation information shall be collected in accordance with Section 2.2.3.

2.2.6.2 Usual Data Collection Requirements

Usual collection of as-built information shall consist of the following:

1. Information shall be obtained from design drawings with sufficient information to analyze component demands and calculate component capacities. For usual data collection, , the design drawings shall show, as a minimum, the configuration of the vertical-and lateral-force-resisting system and typical connections with sufficient detail to carry out the selected analysis procedure. Where design drawings are available, information shall be verified by a visual condition assessment in accordance with Chapters 5 through 8.
2. In the absence of sufficient information from design drawings, incomplete or non-existent information shall be supplemented by a comprehensive condition assessment including destructive and nondestructive investigation in accordance with Chapters 5 through 8.
3. In the absence of material test records and quality assurance reports, material properties shall be determined by usual materials testing in accordance with Chapters 5 through 8.
4. Information needed on adjacent buildings, referenced in Section 2.2.4, shall be gained through field surveys and research of as-built information made available by the owner of the subject building.

5. Site and foundation information shall be collected in accordance with Section 2.2.3.

2.2.6.3 Comprehensive Data Collection Requirements

Comprehensive collection of as-built information shall consist of the following:

1. Information shall be obtained from construction documents including design drawings, specifications, material test records, and quality assurance reports covering original construction and subsequent modifications to the structure. Where construction documents are available, information shall be verified by a visual condition assessment in accordance with Chapters 5 through 8.
2. If construction documents are incomplete, missing information shall be supplemented by a comprehensive condition assessment including destructive and nondestructive investigation in accordance with Chapters 5 through 8.
3. In the absence of material test records and quality assurance reports, material properties shall be determined by comprehensive materials testing in accordance with Chapters 5 through 8. The coefficient of variation in material test results shall be less than 20%.
4. Information needed on adjacent buildings, referenced in Section 2.2.4, shall be gained through field surveys and research of as-built information made available by the owner of the subject building.
5. Site and foundation information shall be collected in accordance with Section 2.2.3.

C2.2.6.3 Comprehensive Data Collection Requirements

Where materials testing results have a coefficient of variation greater than 20%, additional materials testing can be performed until the coefficient of variation is less than 20% or a knowledge factor consistent with a lesser data collection requirement can be used.

2.2.6.4 Knowledge Factor

2.2.6.4.1 General

To account for uncertainty in the collection of as-built data, a knowledge factor, κ , shall be selected from Table 2-1 considering the selected Rehabilitation Objective, analysis procedure, and data collection process. Knowledge factors shall be selected from Table 2-1 on an individual component basis as determined by the level of knowledge obtained for that component during data collection. Knowledge factors shall be applied to determine component capacities as specified in Section 2.4.4.6.

C2.2.6.4.1 General

The κ factor is used to express the confidence with which the properties of the building components are known, where calculating component capacities. The value of the factor is established from the knowledge obtained based on access to original construction documents, or condition assessments including destructive or nondestructive testing of representative components. The values of the factor have been established, indicating whether the level of knowledge is "minimum," "usual," or "comprehensive."

2.2.6.4.2 Linear Procedures

Where linear procedures are used, data collection consistent with the minimum level of knowledge shall be permitted.

2.2.6.4.3 Nonlinear Procedures

Where nonlinear procedures are used, data collection consistent with either the usual or comprehensive levels of knowledge shall be performed.

2.2.6.4.4 Assumed Values of Knowledge Factor

It shall be permitted to perform an analysis in advance of the data collection process using an assumed value of κ , provided the value of κ is substantiated by data collection in accordance with the requirements of Section 2.2.6 prior to implementation of the rehabilitation strategies.

If the assumed value of κ is not supported by subsequent data collection, the analysis shall be revised to include a revised κ consistent with the data collected in accordance with the requirements of Section 2.2.6.

If an analysis using an assumed value of κ results in no required rehabilitation of the structure, the value of κ shall be substantiated by data collection in accordance with the requirements of Section 2.2.6 before the analysis is finalized.

2.3 Rehabilitation Methods

Seismic rehabilitation of the building shall be performed to achieve the selected Rehabilitation Objective in accordance with the requirements of the Simplified Rehabilitation Method of Section 2.3.1 or the Systematic Rehabilitation Method of Section 2.3.2.

2.3.1 Simplified Rehabilitation Method

The Simplified Rehabilitation Method shall be permitted for buildings that conform to one of the Model Building Types contained in Table 10-1, and all limitations in that table with regard to building size and level of seismicity.

Use of the Simplified Rehabilitation Method shall be restricted to Limited Rehabilitation Objectives consisting of the Life Safety Building Performance Level (3-C) at the BSE-1 Earthquake Hazard Level, or Partial Rehabilitation as defined in Section 1.4.3.2.

The Simplified Rehabilitation Method shall be performed in accordance with the requirements of Chapters 2, 10, and 11.

C2.3.1 Simplified Rehabilitation Method

Simplified Rehabilitation may be applied to certain buildings of regular configuration that do not require advanced analytical procedures. The primary intent of Simplified Rehabilitation is to reduce seismic risk efficiently, where possible and appropriate, by seeking Limited Objectives. Partial Rehabilitation measures, which target high-risk building deficiencies such as parapets and other exterior falling hazards, are included as Simplified Rehabilitation techniques, but their use should not be limited to buildings that conform to the limitations of Table 10-1.

The Simplified Rehabilitation Method is less complicated than the complete analytical rehabilitation design procedures found under Systematic Rehabilitation. In many cases, Simplified Rehabilitation represents a cost-effective improvement in seismic performance, and it often requires less detailed evaluation or partial analysis to qualify for a specific performance level.

2.3.2 Systematic Rehabilitation Method

The Systematic Rehabilitation Method shall be permitted for all rehabilitation designs and shall be required for rehabilitations that do not satisfy the criteria of Section 2.3.1. The Systematic Rehabilitation Method includes the following steps:

1. An analysis procedure shall be selected in accordance with the requirements and limitations of Section 2.4.
2. A preliminary rehabilitation scheme shall be developed using one or more of the rehabilitation strategies defined in Section 2.5.
3. An analysis of the building, including rehabilitation measures, shall be performed, and the results of the analysis shall be evaluated in accordance with the requirements of Chapters 2 through 9 and 11 to verify that the rehabilitation design meets the selected Rehabilitation Objective.

C2.3.2 Systematic Rehabilitation Method

Systematic Rehabilitation may be applied to any building and involves thorough checking of each existing structural component, the design of new ones, and verification of acceptable overall performance represented by expected displacements and internal forces. The Systematic Rehabilitation Method focuses on the nonlinear behavior of structural response and employs procedures not previously emphasized in seismic codes.

The Systematic Rehabilitation Method is intended to be complete and contains all requirements to reach any specified performance level. Systematic Rehabilitation is an iterative process,

similar to the design of new buildings, in which modifications of the existing structure are assumed for the purposes of a preliminary design and analysis, and the results of the analysis are verified as acceptable on a component basis. If either new or existing components still prove to be inadequate, the modifications are adjusted and, if necessary, a new analysis and verification cycle is performed. A preliminary design is needed to define the extent and configuration of corrective measures in sufficient detail to estimate the interaction of the stiffness, strength, and post-yield behavior of all new, modified, or existing components to be used for lateral force resistance. The designer is encouraged to include all components with significant lateral stiffness in a mathematical model to assure deformation capability under realistic seismic drifts. However, just as in the design of new buildings, it may be determined that certain components will not be considered part of the lateral-force-resisting system, as long as deformation compatibility checks are made on these components to assure their adequacy.

A mathematical model, developed for the preliminary design, must be constructed in connection with one of the analysis procedures defined in Chapter 3. These are the linear procedures (Linear Static and Linear Dynamic) and the nonlinear procedures (Nonlinear Static and Nonlinear Dynamic). With the exception of the Nonlinear Dynamic Procedure, this standard defines the analysis and rehabilitation design procedures sufficiently that compliance can be checked by an authority having jurisdiction in a manner similar to design reviews for new buildings. Modeling assumptions to be used in various situations are given in Chapters 4 through 9, and in Chapter 11 for nonstructural components. Requirements for seismic demand are given in Chapter 1. Requirements are specified for use of the Nonlinear Dynamic Procedure; however, considerable judgment is required in its application. Criteria for applying ground motion for various analysis procedures is given, but definitive rules for developing ground motion input are not included in this standard.

This standard specifies acceptance criteria for stiffness, strength, and ductility characteristics of structural components for three discrete structural performance levels in Chapters 4 through 8 for use in the Systematic Rehabilitation Method, and acceptance criteria for the performance of nonstructural components in Chapter 11 for use in Systematic and Simplified Rehabilitation Methods.

Inherent in the concept of performance levels and ranges is the assumption that performance can be measured using analytical results such as story drift ratios or strength and ductility demands on individual components. To enable structural verification at the selected performance level, stiffness, strength, and ductility characteristics of many common components have been derived from laboratory tests and analytical studies and are presented in a standard format in Chapters 4 through 8 of this standard.

This standard specifies two new technologies in Chapter 9: seismic isolation and energy dissipation, for use in seismic rehabilitation of buildings using the Systematic Rehabilitation Method.

It is expected that testing of existing materials and components will continue and that additional corrective measures and products will be developed. It is also expected that systems and products intended to modify structural response beneficially will be advanced. The format of the analysis

techniques and acceptance criteria of this standard allows rapid incorporation of such technology. Section 2.8 gives specific requirements in this regard. It is expected that this standard will have a significant impact on testing and documentation of existing materials and systems as well as on new products.

2.4 Analysis Procedures

An analysis of the building, including rehabilitation measures, shall be conducted to determine the forces and deformations induced in components of the building by ground motion corresponding to the selected Earthquake Hazard Level, or by other seismic geologic site hazards specified in Section 4.2.2.

The analysis procedure shall comply with one of the following:

1. Linear analysis subject to limitations specified in Section 2.4.1, and complying with the Linear Static Procedure (LSP) in accordance with Section 3.3.1, or the Linear Dynamic Procedure (LDP) in accordance with Section 3.3.2.
2. Nonlinear analysis subject to limitations specified in Section 2.4.2, and complying with the Nonlinear Static Procedure (NSP) in accordance with Section 3.3.3, or the Nonlinear Dynamic Procedure (NDP) in accordance with Section 3.3.4.
3. Alternative rational analysis in accordance with Section 2.4.3.

The analysis results shall comply with the applicable acceptance criteria selected in accordance with Section 2.4.4.

C2.4 Analysis Procedures

The linear procedures maintain the traditional use of a linear stress-strain relationship, but incorporate adjustments to overall building deformations and material acceptance criteria to permit better consideration of the probable nonlinear characteristics of seismic response. The Nonlinear Static Procedure, often called "pushover analysis," uses simplified nonlinear techniques to estimate seismic structural deformations. The Nonlinear Dynamic Procedure, commonly known as nonlinear time history analysis, requires considerable judgment and experience to perform, as described in Commentary Section C2.4.2.2 of this standard.

2.4.1 Linear Procedures

Linear procedures shall be permitted for buildings, which do not have an irregularity defined in Section 2.4.1.1. For buildings that have one or more of the irregularities defined in Section 2.4.1.1, linear procedures shall not be used unless the earthquake demands on the building comply with the demand capacity ratio (DCR) requirements in Section 2.4.1.1. For buildings incorporating base isolation systems or supplemental energy dissipation systems, the additional limitations of Section 9.2.4 or Section 9.3.4 shall apply.

C2.4.1 Linear Procedures

The results of the linear procedures can be very inaccurate where applied to buildings with highly irregular structural systems, unless the building is capable of responding to the design earthquake(s) in a nearly elastic manner. The procedures of Section 2.4.1.1 are intended to evaluate whether the building is capable of nearly elastic response.

2.4.1.1 Method to Determine Limitations on Use of Linear Procedures

The methodology presented in this section shall be used to determine the applicability of linear analysis procedures based on four configurations of irregularity defined in Section 2.4.1.1.1 through Section 2.4.1.1.4. The determination of irregularity shall be based on the configuration of the rehabilitated structure. A linear analysis to determine irregularity shall be performed by either an LSP in accordance with Section 3.3.1 or an LDP in accordance with Section 3.3.2. The results of this analysis shall be used to identify the magnitude and uniformity of distribution of inelastic demands on the primary elements and components of the lateral-force-resisting system.

The magnitude and distribution of inelastic demands for existing and added primary elements and components shall be defined by demand-capacity ratios (DCRs) and computed in accordance with Equation (2-1):

$$DCR = \frac{Q_{UD}}{Q_{CE}} \quad (2-1)$$

where:

Q_{UD} = Force due to the gravity and earthquake loads calculated in accordance with Section 3.4.2.

Q_{CE} = Expected strength of the component or element, calculated as specified in Chapters 5 through 8.

DCRs shall be calculated for each action (such as axial force, moment, or shear) of each primary component. The critical action for the component shall be the one with the largest DCR. The DCR for this action shall be termed the critical component DCR. The largest DCR for any element at a particular story is termed the critical element DCR at that story. If an element at a particular story comprises multiple components, then the component with the largest computed DCR shall define the critical component for the element at that story.

If one or more component DCRs exceed 2.0 and any irregularity described in Section 2.4.1.1.3 or Section 2.4.1.1.4 is present, then linear procedures are not applicable, and shall not be used.

C2.4.1.1 Method to Determine Limitations on Use of Linear Procedures

The magnitude and distribution of inelastic demands are indicated by demand-capacity ratios (DCRs). Note that these DCRs are not used to determine the acceptability of component

behavior. The adequacy of structural components must be evaluated using the procedures contained in Chapter 3 along with the acceptance criteria provided in Chapters 4 through 8. DCRs are used only to determine a structure's regularity. It should be noted that for complex structures, such as buildings with perforated shear walls, it may be easier to use one of the nonlinear procedures than to ensure that the building has sufficient regularity to permit use of linear procedures.

If all of the computed controlling DCRs for a component are less than or equal to 1.0, then the component is expected to respond elastically to the earthquake ground shaking being evaluated. If one or more of the computed DCRs for a component are greater than 1.0, then the component is expected to respond inelastically to the earthquake ground shaking.

2.4.1.1.1 In-Plane Discontinuity Irregularity

An in-plane discontinuity irregularity shall be considered to exist in any primary element of the lateral-force-resisting system wherever a lateral-force-resisting element is present in one story, but does not continue, or is offset within the plane of the element, in the story immediately below. Figure 2-1 depicts such a condition.

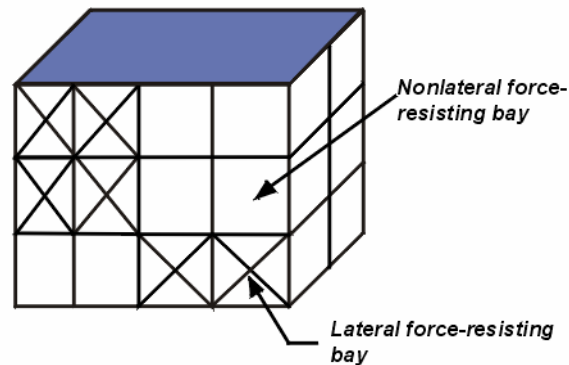


Figure 2-1 In-Plane Discontinuity in Lateral System

2.4.1.1.2 Out-of-Plane Discontinuity Irregularity

An out-of-plane discontinuity irregularity shall be considered to exist in any primary element of the lateral-force-resisting system where an element in one story is offset out-of-plane relative to that element in an adjacent story, as depicted in Figure 2-2.

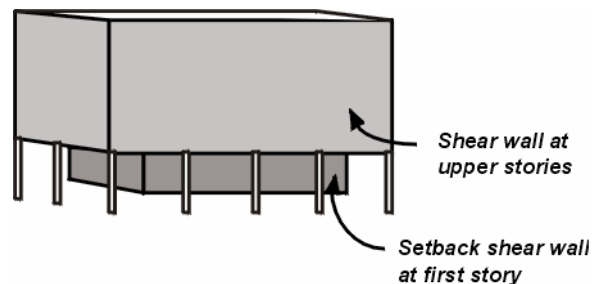


Figure 2-2 Typical Building with Out-of-Plane Offset Irregularity**2.4.1.1.3 Weak Story Irregularity**

A weak story irregularity shall be considered to exist in any direction of the building if the ratio of the average shear DCR of any story to that of an adjacent story in the same direction exceeds 125%. The average DCR of a story shall be calculated by Equation (2-2):

$$\overline{DCR} = \frac{\sum_1^n DCR_i V_i}{\sum_1^n V_i} \quad (2-2)$$

where:

\overline{DCR} = Average DCR for the story

DCR_i = Critical action DCR for element i of the story

V_i = Total calculated lateral shear force in an element i due to earthquake response, assuming that the structure remains elastic

n = Total number of elements in the story

For buildings with flexible diaphragms, each line of framing shall be independently evaluated.

2.4.1.1.4 Torsional Strength Irregularity

A torsional strength irregularity shall be considered to exist in any story if the diaphragm above the story under consideration is not flexible and, for a given direction, the ratio of the critical element DCRs for primary elements on one side of the center of resistance of a story, to those on the other side of the center of resistance of the story, exceeds 1.5.

2.4.1.2 Limitations on Use of the Linear Static Procedure

Where Section 2.4.1.1 permits the use of linear procedures, the Linear Static Procedure shall not be used for a building with one or more of the following characteristics:

1. The fundamental period of the building, T , is greater than or equal to 3.5 times T_s .
2. The ratio of the horizontal dimension at any story to the corresponding dimension at an adjacent story exceeds 1.4 (excluding penthouses).

3. The building has a torsional stiffness irregularity in any story. A torsional stiffness irregularity exists in a story if the diaphragm above the story under consideration is not flexible and the results of the analysis indicate that the drift along any side of the structure is more than 150% of the average story drift.
4. The building has a vertical stiffness irregularity. A vertical stiffness irregularity exists where the average drift in any story (except penthouses) is more than 150% of that of the story above or below.
5. The building has a non-orthogonal lateral-force-resisting system.

C2.4.1.2 Limitations on Use of the Linear Static Procedure

For buildings that have irregular distributions of mass or stiffness, irregular geometries, or non-orthogonal lateral-force-resisting systems, the distribution of demands predicted by an LDP analysis will be more accurate than those predicted by the LSP. Either the response spectrum method or time history method may be used for evaluation of such structures.

2.4.2 Nonlinear Procedures

Nonlinear procedures shall be permitted for any of the rehabilitation strategies contained in Section 2.5. Nonlinear procedures shall be used for analysis of buildings where linear procedures are not permitted. Data collection for use with nonlinear procedures shall be in accordance with Section 2.2.6.

2.4.2.1 Nonlinear Static Procedure

The NSP shall be permitted for structures with all of the following characteristics:

1. The strength ratio R , calculated in accordance with Equation 3-15 is less than R_{max} calculated in accordance with Equation 3-16.
2. Higher mode effects are not significant, as defined in this section.

To determine if higher modes are significant, a modal response spectrum analysis shall be performed for the structure using sufficient modes to produce 90% mass participation. A second response spectrum analysis shall also be performed, considering only the first mode participation. Higher mode effects shall be considered significant if the shear in any story resulting from the modal analysis considering modes required to obtain 90% mass participation exceeds 130% of the corresponding story shear considering only the first mode response.

If higher mode effects are significant, the NSP shall be permitted if an LDP analysis is also performed to supplement the NSP. Buildings with significant higher mode effects must meet the acceptance criteria of this standard for both analysis procedures, except that an increase by a factor of 1.33 shall be permitted in the LDP acceptance criteria for deformation-controlled actions (m -factors) provided in Chapters 5 through 9. A building analyzed using the NSP, with or

without a supplementary LDP evaluation, shall meet the acceptance criteria for nonlinear procedures specified in Section 3.4.3.

If R exceeds R_{max} , an NDP analysis shall be performed.

C2.4.2.1 Nonlinear Static Procedure

The NSP is generally a more reliable approach to characterizing the performance of a structure than are linear procedures. However, it is not exact, and cannot accurately account for changes in dynamic response as the structure degrades in stiffness, nor can it account for higher mode effects in MDOF systems. Where the NSP is utilized on a structure that has significant higher mode response, the LDP is also employed to verify the adequacy of the design. Where this approach is taken, less restrictive criteria are permitted for the LDP, recognizing the significantly improved knowledge that is obtained by performing both analysis procedures.

The strength ratio, R is a measure of the extent of nonlinearity, and R_{max} is a measure of the system degradation. Structures that experience nonlinear demands exceeding R_{max} have significant degradation and an NDP is required to confirm the dynamic stability of the building.

2.4.2.2 Nonlinear Dynamic Procedure

The NDP shall be permitted for all structures. Where the NDP procedure is used, the authority having jurisdiction shall consider the requirement of review and approval by an independent third-party engineer with experience in seismic design and nonlinear procedures.

C2.4.2.2 Nonlinear Dynamic Procedure

The NDP consists of nonlinear Time-History Analysis, a sophisticated approach to examining the inelastic demands produced on a structure by a specific suite of ground motion time histories. As with the NSP, the results of the NDP can be directly compared with test data on the behavior of representative structural components in order to identify the structure's probable performance when subjected to a specific ground motion. Potentially, the NDP can be more accurate than the NSP in that it avoids some of the approximations made in the more simplified analysis. Time-History Analysis automatically accounts for higher mode effects and shifts in inertial load patterns as structural softening occurs. In addition, for a given earthquake record, this approach directly solves for the maximum global displacement demand produced by the earthquake on the structure, eliminating the need to estimate this demand based on general relationships.

Despite these advantages, the NDP requires considerable judgment and experience to perform. These analyses tend to be highly sensitive to small changes in assumptions with regard to either the character of the ground motion record used in the analysis, or the nonlinear stiffness behavior of the elements. As an example, two ground motion records enveloped by the same response spectrum can produce radically different results with regard to the distribution and amount of inelasticity predicted in the structure. In order to apply this approach reliably to rehabilitation design, it is necessary to perform a number of such analyses, using varied assumptions. The sensitivity of the analysis results to the assumptions incorporated is the principal reason why this

method should be used only on projects where the engineer is thoroughly familiar with nonlinear dynamic analysis techniques and limitations.

2.4.3 Alternative Rational Analysis

Use of an approved alternative analysis procedure that is rational and based on fundamental principles of engineering mechanics and dynamics shall be permitted. Such alternative analyses shall not adopt the acceptance criteria contained in this standard without first determining their applicability. All projects using alternative rational analysis procedures shall be reviewed and approved by an independent third-party engineer with experience in seismic design.

2.4.4 Acceptance Criteria

2.4.4.1 General

The acceptability of force and deformation actions shall be evaluated for each component in accordance with the requirements of Section 3.4. Prior to selecting component acceptance criteria for use in Section 3.4, each component shall be classified as primary or secondary in accordance with Section 2.4.4.2, and each action shall be classified as deformation-controlled (ductile) or force-controlled (nonductile) in accordance with Section 2.4.4.3. Component strengths, material properties, and component capacities shall be determined in accordance with Sections 2.4.4.4, 2.4.4.5, and 2.4.4.6, respectively. Component acceptance criteria not specified in this standard shall be determined by qualification testing in accordance with Section 2.8.

The rehabilitated building shall be provided with at least one continuous load path to transfer seismic loads, induced by ground motion in any direction, from the point of application of the seismic load to the final point of resistance. All primary and secondary components shall be capable of resisting force and deformation actions within the applicable acceptance criteria of the selected performance level.

2.4.4.2 Primary and Secondary Components

Components that affect the lateral stiffness or distribution of forces in a structure, or are loaded as a result of lateral deformation of the structure, shall be classified as primary or secondary, even if they are not intended to be part of the lateral-force-resisting system.

A structural component that is required to resist seismic forces in order for the structure to achieve the selected performance level shall be classified as primary.

A structural component that is not required to resist seismic forces in order for the structure to achieve the selected performance level shall be permitted to be classified as secondary.

C2.4.4.2 Primary and Secondary Components

The designation of primary and secondary components has been introduced to allow some

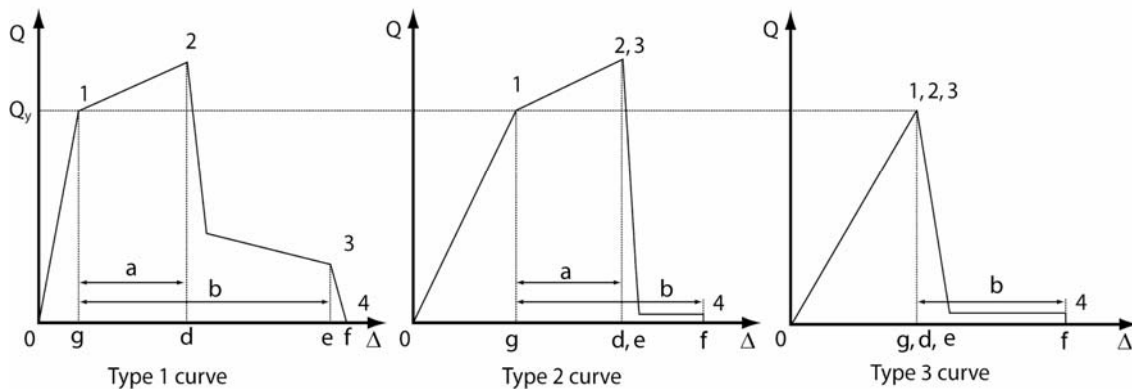
flexibility in the rehabilitation analysis and design process. Primary components are those that the engineer relies on to resist the specified earthquake effects. Secondary components are those that the engineer does not rely on to resist the specified earthquake effects. Typically, the secondary designation will be used where a component does not add considerably or reliably to the earthquake resistance. In all cases, the engineer must verify that gravity loads are sustained by the structural system, regardless of the designation of primary and secondary components.

The secondary designation typically will be used where one or more of the following cases apply.

1. The secondary designation may be used where a nonstructural component does not contribute significantly or reliably to resist earthquake effects in any direction. A gypsum partition is a nonstructural component that might be designated secondary in a building because it does not provide significant stiffness or strength in any direction.
2. The secondary designation may be used where a structural component does not contribute significantly to resist earthquake effects. A slab-column interior frame is an element whose structural components might be designated as secondary in a building braced by much stiffer and stronger perimeter frames or shear walls. If the stronger perimeter frames or shear walls exist only in one direction, the components of the slab-column interior frame may be designated as secondary for that direction only.

The connection at the base of a column that is nominally pinned where it connects to the foundation is a component that might be designated as secondary because the moment resistance is low, relative to the entire system resistance.

3. The secondary designation may be used where a component, intended in the original design of the building to be primary, is deformed beyond the point where it can be relied on to resist earthquake effects. For example, it is conceivable that coupling beams connecting wall piers will exhaust their deformation capacity before the entire structural system capacity is reached. In such cases, the engineer may designate these as secondary, allowing them to be deformed beyond their useful limits, provided that damage to these secondary components does not result in loss of gravity load capacity.



Notes:

1. Only secondary component actions permitted between points 2 and 4;
2. The force, Q , after point 3 diminishes to approximately zero.

Figure 2-3 Component Force Versus Deformation Curves**2.4.4.3 Deformation-Controlled and Force-Controlled Actions**

All actions shall be classified as either deformation-controlled or force-controlled using the component force versus deformation curves shown in Figure 2-3.

Deformation-controlled actions are defined in Chapters 4 through 8 of this standard by the designation of linear and nonlinear acceptance criteria. Where linear and nonlinear acceptance criteria are not specified in the standard and component testing in accordance with Section 2.8 is not performed, actions shall be taken as force-controlled.

The Type 1 curve depicted in Figure 2-3 is representative of ductile behavior where there is an elastic range (points 0 to 1 on the curve) and a plastic range (points 1 to 3), followed by loss of lateral-force-resisting capacity at point 3 and loss of vertical-force-resisting capacity at point 4. The plastic range can have either a positive or negative post-elastic slope (points 1 to 2) and a strength-degraded region with non-negligible residual strength to resist lateral and gravity loads (points 2 to 3). Primary component actions exhibiting this behavior shall be classified as deformation-controlled if the plastic range is such that $d \geq 2g$; otherwise, they shall be classified as force-controlled. Secondary component actions exhibiting this behavior shall be classified as deformation-controlled for any d/g ratio.

The Type 2 curve depicted in Figure 2-3 is representative of ductile behavior where there is an elastic range (points 0 to 1 on the curve) and a plastic range (points 1 to 3). The plastic range can have either a positive or negative post-elastic slope (points 1 to 3) followed by substantial loss of lateral-force-resisting capacity at point 3. Loss of vertical-force-resisting capacity takes place at the deformation associated with point 4. Primary component actions exhibiting this behavior shall be classified as deformation-controlled if the plastic range is such that $e \geq 2g$; otherwise, they shall be classified as force-controlled. Secondary component actions exhibiting this behavior shall be classified as deformation-controlled if $f \geq 2g$; otherwise, they shall be classified as force-controlled.

The Type 3 curve depicted in Figure 2-3 is representative of a brittle or nonductile behavior where there is an elastic range (points 0 to 1 on the curve) followed by loss of lateral-force-resisting capacity at point 3 and loss of vertical-force-resisting capacity at the deformation associated with point 4. Primary component actions exhibiting this behavior shall be classified as force-controlled. Secondary component actions exhibiting this behavior shall be classified as deformation-controlled if $f \geq 2g$; otherwise, they shall be classified as force-controlled.

C2.4.4.3 Deformation-Controlled and Force-Controlled Actions

Deformation-controlled actions may not be designated as such based on the discretion of the engineer. Deformation-controlled actions are defined in this standard by the designation of linear or nonlinear deformation capacities in Chapters 4 through 8, or alternatively, must be validated through testing in accordance with Section 2.8.

Acceptance criteria for primary components that exhibit Type 1 or Type 2 behavior typically are within the elastic or plastic ranges between points 0 and 2, depending on the performance level. Acceptance criteria for secondary components that exhibit Type 1 or Type 2 behavior can be within any of the performance ranges.

Acceptance criteria for primary components exhibiting Type 3 behavior will always be within the elastic range. Acceptance criteria for secondary components exhibiting Type 3 behavior can be within any of the performance ranges.

Table C2-1 provides some examples of possible deformation- and force-controlled actions in common framing systems. Classification of deformation- or force-controlled actions are specified for foundation and framing components in Chapters 4 through 8.

A given component may have a combination of both deformation- and force-controlled actions.

Component	Deformation-Controlled Action	Force- Controlled Action
Moment Frames • Beams • Columns • Joints	Moment (M) M -- --	Shear (V) Axial load (P), V V ¹
Shear Walls	M, V	P
Braced Frames • Braces • Beams • Columns • Shear Link	P -- -- V	-- P P P, M
Connections	P, V, M ³	P, V, M
Diaphragms	M, V ²	P, V, M

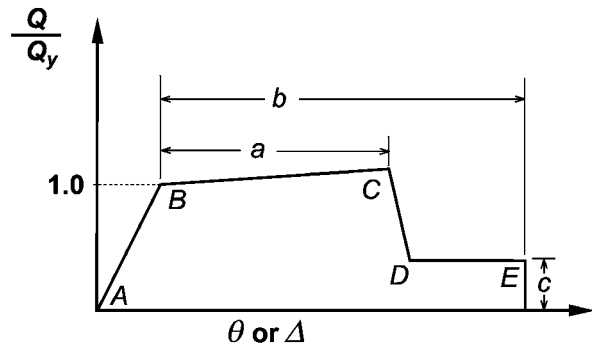
1. Shear may be a deformation-controlled action in steel moment frame construction.
2. If the diaphragm carries lateral loads from vertical seismic resisting elements above the diaphragm level, then M and V shall be considered force-controlled actions.
3. Axial, shear, and moment may be deformation-controlled actions for certain steel and wood connections.

Table C2-1 Examples of Possible Deformation-Controlled and Force-Controlled Actions

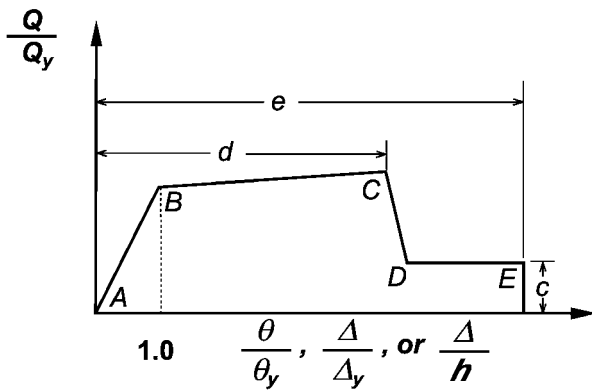
Figure C2-1 shows the generalized force versus deformation curves used throughout this standard to specify component modeling and acceptance criteria for deformation-controlled actions in any of the four basic material types. Linear response is depicted between point *A* (unloaded component) and an effective yield point *B*. The slope from point *B* to point *C* is typically a small percentage (0-10%) of the elastic slope, and is included to represent phenomena such as strain hardening. Point *C* has an ordinate that represents the strength of the component, and an abscissa value equal to the deformation at which significant lateral strength degradation begins (line *CD*). Beyond point *D*, the component responds with substantially reduced lateral strength to point *E*. At deformations greater than point *E*, the component lateral strength is essentially zero. The vertical-force-resisting capacity is maintained until point *F*. Deformations beyond point *F* should not be permitted unless there is an alternate load path for the gravity actions supported by that component.

The sharp transition as shown on idealized curves in Figure C2-1 between points *C* and *D* can result in computational difficulty and an inability to converge where used as modeling input in nonlinear computerized analysis software. In order to avoid this computational instability, a small slope (10 vertical to 1 horizontal) may be provided to the segment of these curves between points *C* and *D*.

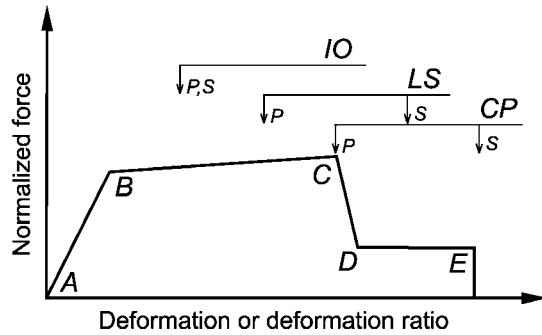
For some components it is convenient to prescribe acceptance criteria in terms of deformation (such as θ or Δ), while for others it is more convenient to give criteria in terms of deformation ratios. To accommodate this, two types of idealized force vs. deformation curves are used in Figures C2-1 (a) and (b). Figure C2-1(a) shows normalized force (Q/Q_y) versus deformation (θ or Δ) and the parameters a , b , and c . Figure C2-1(b) shows normalized force (Q/Q_y) versus deformation ratio (θ/θ_y , Δ/Δ_y , or Δ/h) and the parameters d , e , and c . Elastic stiffnesses and values for the parameters a , b , c , d , and e that can be used for modeling components are given in Chapters 5 through 8. Acceptance criteria for deformation or deformation ratios for primary components (P) and secondary components (S) corresponding to the target Building Performance Levels of Collapse Prevention (CP), Life Safety (LS), and Immediate Occupancy (IO) as shown in Figure 2-1(c) are given in Chapters 5 through 8.



(a) Deformation



(b) Deformation ratio



(c) Component or element deformation acceptance criteria

Figure C2-1 Generalized Component Force-Deformation Relations for Depicting Modeling and Acceptance Criteria

2.4.4.4 Expected and Lower-Bound Strength

In Figure 2-3, Q_y represents the yield strength of the component. Where evaluating the behavior of deformation-controlled actions, the expected strength, Q_{CE} , shall be used. Q_{CE} is defined as the mean value of resistance of a component at the deformation level anticipated for a population of similar components, including consideration of the variability in material strength as well as strain hardening and plastic section development. Where evaluating the behavior of force-controlled actions, a lower-bound estimate of the component strength, Q_{CL} , shall be used. Q_{CL} is defined as the mean minus one standard deviation of the yield strengths, Q_y , for a population of similar components.

C2.4.4.4 Expected and Lower-Bound Strength

In Figure 2-3, the strength of a component is affected by inherent variability of the strength of the materials comprising the individual components as well as differences in workmanship and physical condition. See Chapters 5 through 8 for specific direction regarding the calculation of expected and lower-bound strengths of components.

2.4.4.5 Material Properties

Expected material properties shall be based on mean values of tested material properties. Lower-bound material properties shall be based on mean values of tested material properties minus one standard deviation (σ).

Nominal material properties, or properties specified in construction documents, shall be taken as lower-bound material properties unless otherwise specified in Chapters 5 through 8. Corresponding expected material properties shall be calculated by multiplying lower-bound values by appropriate factors specified in Chapters 5 through 8 to translate from lower-bound to expected values.

C2.4.4.5 Material Properties

Where calculations are used to determine expected or lower-bound strengths of components, expected or lower-bound material properties, respectively, shall be used.

2.4.4.6 Component Capacities

2.4.4.6.1 General

Detailed criteria for calculation of individual component force and deformation capacities shall comply with the requirements in individual materials chapters as follows:

1. Foundations-Chapter 4.
2. Components composed of steel or cast iron-Chapter 5.
3. Components composed of reinforced concrete-Chapter 6.

4. Components composed of reinforced or unreinforced masonry-Chapter 7.
5. Components composed of timber, light metal studs, gypsum, or plaster products-Chapter 8.
6. Seismic isolation systems and energy dissipation systems-Chapter 9.
7. Nonstructural (architectural, mechanical, and electrical) components-Chapter 11.

Elements and components composed of combinations of materials are covered in the chapters associated with each material.

2.4.4.6.2 Linear Procedures

If linear procedures are used, capacities for deformation-controlled actions shall be defined as the product of m -factors and expected strengths, Q_{CE} . Capacities for force-controlled actions shall be defined as lower-bound strengths, Q_{CL} , as summarized in Table 2-2.

Parameter	Deformation- Controlled	Force-Controlled
Existing Material Strength	Expected mean value with allowance for strain hardening	Lower-bound value (approximately mean value -1σ level)
Existing Action Capacity	$\kappa \cdot Q_{CE}$	$\kappa \cdot Q_{CL}$
New Material Strength	Expected material strength	Specified material strength
New Action Capacity	Q_{CE}	Q_{CL}

Table 2-2 Calculation of Component Action Capacity-Linear Procedures

Parameter	Deformation- Controlled	Force-Controlled
Deformation Capacity- Existing Component	$\kappa \cdot$ deformation limit	N/A
Deformation Capacity- New Component	deformation limit	N/A
Strength Capacity- Existing Component	N/A	$\kappa \cdot Q_{CL}$
Strength Capacity- New Component	N/A	Q_{CL}

Table 2-3 Calculation of Component Action Capacity-Nonlinear Procedures

2.4.4.6.3 Nonlinear Procedures

If nonlinear procedures are used, component capacities for deformation-controlled actions shall be taken as permissible inelastic deformation limits, and component capacities for force-controlled actions shall be taken as lower-bound strengths, Q_{CL} , as summarized in Table 2-3.

2.5 Rehabilitation Strategies

A Rehabilitation Objective shall be achieved by implementing rehabilitation measures based on a strategy of addressing deficiencies identified by a prior seismic evaluation. Each rehabilitation measure shall be evaluated in conjunction with other rehabilitation measures, and the existing structure as a whole, to assure that the complete rehabilitation scheme achieves the target Building Performance Level for the selected Earthquake Hazard Level. The effects of rehabilitation on stiffness, strength, and deformability shall be taken into account in an analytical model of the rehabilitated structure. The compatibility of new and existing components shall be checked at displacements consistent with the demands produced by the selected Earthquake Hazard Level and geologic site hazards present at the site.

One or more of the following strategies shall be permitted as rehabilitation measures.

- Local modification of components
- Removal or reduction of existing irregularities
- Global structural stiffening
- Global structural strengthening
- Mass reduction
- Seismic isolation, in accordance with Chapter 9
- Supplemental energy dissipation, in accordance with Chapter 9

- Other rehabilitation strategies approved by the authority having jurisdiction

C2.5 Rehabilitation Strategies

Although not specifically required by any of the strategies, it is very beneficial for the rehabilitated lateral-force-resisting system to have an appropriate level of redundancy, so that any localized failure of a few components of the system will not result in local collapse or an instability. This should be considered when developing rehabilitation designs.

Local Modification of Components

Some existing buildings have substantial strength and stiffness, but some of their components may not have adequate strength, toughness, or deformation capacity to satisfy the Rehabilitation Objectives. An appropriate strategy for such structures may be to perform local modifications of components that are inadequate while retaining the basic configuration of the building's lateral-force-resisting system. Local modifications that can be considered include improvement of component connectivity, component strength, and/or component deformation capacity. This strategy tends to be the most economical rehabilitation approach where only a few of the building's components are inadequate.

Local strengthening allows one or more under-strength components or connections to resist the strength demands predicted by the analysis without affecting the overall response of the structure. This could include measures such as cover plating steel beams or columns, or adding wood structural panel sheathing to an existing timber diaphragm. Such measures increase the strength of the component and allow it to resist more earthquake-induced force before the onset of damage.

Local corrective measures that improve the deformation capacity or ductility of a component allow it to resist large deformation levels with reduced amounts of damage, without necessarily increasing the strength. One such measure is placement of a confinement jacket around a reinforced concrete column to improve its ability to deform without spalling or degrading reinforcement splices. Another measure is reduction of the cross-section of selected structural components to increase their flexibility and response displacement capacity.

Removal or Reduction of Existing Irregularities

Removal or reduction of existing irregularities may be an effective rehabilitation strategy if a seismic evaluation shows that the irregularities result in the inability of the building to meet the selected Structural Performance Level.

The results of analysis should be reviewed to detect existing irregularities. Stiffness, mass, and strength irregularities may be detected by reviewing the results of a linear analysis, by examining the distribution of structural displacements and DCRs, or by reviewing the results of a nonlinear analysis by examining the distribution of structural displacements and inelastic deformation demands. If the distribution of values of structural displacements, DCRs, or inelastic deformation demands predicted by the analysis is nonuniform with disproportionately high values within one

story relative to the adjacent story, or at one side of a building relative to the other, then an irregularity exists.

Such irregularities are often, but not always, caused by the presence of a discontinuity in the structure, such as termination of a perimeter shear wall above the first story. Simple removal of the irregularity may be sufficient to reduce demands predicted by the analysis to acceptable levels. However, removal of discontinuities may be inappropriate in the case of historic buildings, and the effect of such alterations on important historic features should be considered carefully.

Effective corrective measures for removal or reduction of irregularities, such as soft or weak stories, include the addition of braced frames or shear walls within the soft or weak story. Torsional irregularities can be corrected by the addition of moment frames, braced frames, or shear walls to balance the distribution of stiffness and mass within a story. Discontinuous components such as columns or walls can be extended through the zone of discontinuity.

Partial demolition can also be an effective corrective measure for irregularities, although this obviously has significant impact on the appearance and utility of the building, and this may not be an appropriate alternative for historic structures. Portions of the structure that create the irregularity, such as setback towers or side wings, can be removed. Expansion joints can be created to transform a single irregular building into multiple regular structures; however, care must be taken to avoid the potential problems associated with pounding.

Global Structural Stiffening

Global stiffening of the structure may be an effective rehabilitation strategy if the results of a seismic evaluation show deficiencies attributable to excessive lateral deflection of the building, and critical components do not have adequate ductility to resist the resulting deformations.

Construction of new braced frames or shear walls within an existing structure are effective measures for adding stiffness.

Global Structural Strengthening

Global strengthening of the structure may be an effective rehabilitation strategy if the results of a seismic evaluation show unacceptable performance attributable to a global deficiency in structural strength. This can be identified where the onset of global inelastic behavior occurs at levels of ground shaking that are substantially less than the selected level of ground shaking or large DCRs (or inelastic deformation demands) are present throughout the structure. By providing supplemental strength to such a lateral-force-resisting system, it is possible to raise the threshold of ground motion at which the onset of damage occurs. Shear walls and braced frames are effective elements for this purpose, but they may be significantly stiffer than the structure to which they are added, requiring them to provide nearly all of the structure's lateral resistance. Moment-resisting frames, being more flexible, may be more compatible with existing elements in some structures; however, such flexible elements may not become effective in the building's response until existing brittle elements have already been damaged.

Mass Reduction

Mass reduction may be an effective rehabilitation strategy if the results of a seismic evaluation show deficiencies attributable to excessive building mass, global structural flexibility, or global structural weakness. Mass and stiffness control the amount of force and deformation induced in a structure by ground motion. Reductions in mass can result in direct reductions in both the amount of force and the deformation demand produced by earthquakes and, therefore, can be used in lieu of structural strengthening and stiffening. Mass can be reduced through demolition of upper stories, replacement of heavy cladding and interior partitions, or removal of heavy storage and equipment loads.

Seismic Isolation

Seismic isolation may be an effective rehabilitation strategy if the results of a seismic evaluation show deficiencies attributable to excessive seismic forces or deformation demands, or if it is desired to protect important contents and nonstructural components from damage. Where a structure is seismically isolated, compliant bearings are inserted between the superstructure and its foundations. This produces a system (structure and isolation bearings) with a nearly rigid body translation of the structure above the bearings. Most of the deformation induced in the isolated system by the ground motion occurs within the compliant bearings, which are specifically designed to resist these concentrated displacements. Most bearings also have excellent energy dissipation characteristics (damping). Together, this results in greatly reduced demands on the existing structural and nonstructural components of the building and its contents. For this reason, seismic isolation is often an appropriate strategy to achieve Enhanced Rehabilitation Objectives that include the protection of historic fabric, valuable contents, and equipment, or for buildings that contain important operations and functions. This technique is most effective for relatively stiff buildings with low profiles and large mass. It is less effective for light, flexible structures.

Supplemental Energy Dissipation

Installation of supplemental energy dissipation devices may be an effective rehabilitation strategy if the results of a seismic evaluation show deficiencies attributable to excessive deformations due to global structural flexibility in a building. Many available technologies allow the energy imparted to a structure by ground motion to be dissipated in a controlled manner through the action of special devices—fluid viscous dampers (hydraulic cylinders), yielding plates, or friction pads—resulting in an overall reduction in the displacements of the structure. The most commonly used devices dissipate energy through frictional, hysteretic, or viscoelastic processes. In order to dissipate substantial energy, dissipation devices typically must undergo significant deformation (or stroke), which requires that the structure experience substantial lateral displacements. Therefore, these systems are most effective in structures that are relatively flexible and have some inelastic deformation capacity. Energy dissipaters are most commonly installed in structures as components of braced frames. Depending on the characteristics of the device, either static or dynamic stiffness is added to the structure as well as energy dissipation

capacity (damping). In some cases, although the structural displacements are reduced, the forces delivered to the structure can actually be increased.

2.6 General Design Requirements

The requirements of this section shall apply to all buildings for which the systematic rehabilitation method is selected for any target Building Performance Level and any selected Earthquake Hazard Level unless specified otherwise.

2.6.1 Multidirectional Seismic Effects

Components shall be designed to resist seismic forces acting in any horizontal direction. Seismic forces in the vertical direction shall be considered where required by Section 2.6.11. Multidirectional seismic effects shall be considered in the analysis as specified in Section 3.2.7.

2.6.2 P- Δ Effects

Components of buildings shall be designed for P- Δ effects, defined as the combined effects of gravity loads acting in conjunction with lateral drifts due to seismic forces, as specified in Section 3.2.5.

2.6.3 Horizontal Torsion

Components of buildings shall be designed to resist the effects of horizontal torsion as specified in Section 3.2.2.2.

2.6.4 Overturning

Components of buildings shall be designed to resist the effects of overturning at each intermediate level as well as the base of the structure. Stability against overturning shall be evaluated as specified in Section 3.2.10. Effects of overturning on foundations shall be evaluated as specified in Section 4.4.

2.6.5 Continuity

All structural components shall be tied together to form a complete load path for the transfer of inertial forces generated by the dynamic response of portions of the structure to the rest of the structure. Actions resulting from the forces specified in this section shall be considered force-controlled.

1. Smaller portions of a structure, such as outstanding wings, shall be connected to the structure as a whole. Component connections shall be capable of resisting, in any direction, the horizontal force calculated using Equation (2-3). These connections are not required if the individual portions of the structure are self-supporting and are separated by a seismic joint permitting independent movement during dynamic response.

$$F_p = 0.133S_{XS} W \quad (2-3)$$

where:

F_p = Horizontal force in any direction for the design of connections between two portions of a structure

S_{XS} = Spectral response acceleration parameter at short periods for the selected Earthquake Hazard Level and damping, adjusted for site class

W = Weight of the smaller portion of the structure

2. A positive connection for resisting horizontal force acting parallel to the member shall be provided for each beam, girder or truss to its support. The connection shall have a minimum strength of 5 percent of the dead load and live load reaction.
3. Where a sliding support is provided at the end of a component, the bearing length shall be sufficient to accommodate the expected differential displacement between the component and the support.

C2.6.5 Continuity

A continuous structural system with adequately interconnected elements is one of the most important prerequisites for acceptable seismic performance. The requirements of this section are similar to parallel provisions contained in FEMA 450.

2.6.6 Diaphragms

Diaphragms shall be defined as horizontal elements that transfer earthquake-induced inertial forces to vertical elements of the lateral-force-resisting systems through the collective action of diaphragm components including chords, collectors, and ties.

Diaphragms shall be provided at each level of the structure as necessary to connect building masses to the primary vertical elements of the lateral-force-resisting system. The analytical model of the building shall account for the behavior of the diaphragms as specified in Section 3.2.4.

Diaphragms and their connections to vertical elements providing lateral support shall comply with the design requirements specified in Section 5.8 for metal diaphragms, Section 6.10 for concrete diaphragms, Section 6.11 for precast concrete diaphragms, and Section 8.5 for wood diaphragms.

2.6.6.1 Diaphragm Chords

Except for diaphragms evaluated as "unchorded" as specified in Chapter 8, a boundary component shall be provided at each diaphragm edge (either at the perimeter or at an opening) to

resist tension or compression resulting from the diaphragm moment. This boundary component shall be a continuous diaphragm chord, a continuous component of a wall or frame element, or a continuous combination of wall, frame, and chord components. The boundary components shall be designed to transfer accumulated lateral forces at the diaphragm boundaries. At re-entrant corners in diaphragms, and at the corners of openings in diaphragms, diaphragm chords shall be extended a distance sufficient to develop the accumulated diaphragm boundary forces into the diaphragm beyond the corner.

2.6.6.2 Diaphragm Collectors

At each vertical element a diaphragm collector shall be provided to transfer to the element accumulated diaphragm forces that are in excess of the forces transferred directly to the element in shear. The diaphragm collector shall be extended beyond the element and attached to the diaphragm to transfer the accumulated forces.

2.6.6.3 Diaphragm Ties

Diaphragms shall be provided with continuous tension ties between chords or boundaries. At a minimum, ties shall be designed for axial tension as a force-controlled action calculated using Equation (2-4).

$$F_p = 0.4S_{XS} W \quad (2-4)$$

where:

F_p = Axial tensile force for the design of ties between the diaphragm and chords or boundaries

S_{XS} = Spectral response acceleration parameter at short periods for the selected hazard level and damping, adjusted for site class

W = Weight tributary to that portion of the diaphragm extending half the distance to each adjacent tie or diaphragm boundary

Where diaphragms of timber, gypsum, or metal deck construction provide lateral support for walls of masonry or concrete construction, ties shall be designed for the wall anchorage forces specified in Section 2.6.7 for the area of wall tributary to the diaphragm tie.

C2.6.6 Diaphragms

The concept of a diaphragm chord, consisting of an edge member provided to resist diaphragm flexural stresses through direct axial tension or compression, is not familiar to many engineers. Buildings with solid structural walls on all sides often do not require diaphragm chords. However, buildings with highly perforated perimeter walls do require these components for proper diaphragm behavior. This section of this standard requires that these components be provided where appropriate.

A common problem in buildings that nominally have robust lateral-force-resisting systems is a lack of adequate attachment between the diaphragms and the vertical elements of the lateral-force-resisting to effect shear transfer. This is particularly a problem in buildings that have discrete shear walls or frames as their vertical lateral-force-resisting elements. This section provides a reminder that it is necessary to detail a formal system of force delivery from the diaphragm to the walls and frames.

Diaphragms that support heavy perimeter walls have occasionally failed due to tension induced by out-of-plane forces generated in the walls. This section is intended to ensure that sufficient tensile ties are provided across diaphragms to prevent such failures. The design force for these tensile ties, taken as $0.4S_{XS}$ times the weight, is an extension of provisions contained in the 1994 *Uniform Building Code* (ICBO, 1994). In that code, parts and portions of structures are designed for a force calculated as $C_p I Z$ times the weight of the component, with typical values of C_p being 0.75 and Z being the effective peak ground acceleration for which the building is designed. The 1994 UBC provisions use an allowable stress basis. This standard uses a strength basis. Therefore, a factor of 1.4 was applied to the C_p value, and a factor of $1/(2.5)$ was applied to adjust the Z value to an equivalent S_{XS} value, resulting in a coefficient of 0.4.

2.6.7 Walls

Walls shall be evaluated for out-of-plane inertial forces as required by this section and as further required for specific structural systems in Chapters 5 through 8. Actions that result from application of the forces specified in this section shall be considered force-controlled. Nonstructural walls shall be evaluated using the provisions of Chapter 11.

2.6.7.1 Out-of-Plane Anchorage to Diaphragms

Walls shall be positively anchored to all diaphragms that provide lateral support for the wall or are vertically supported by the wall. Walls shall be anchored to diaphragms at horizontal distances not exceeding eight feet, unless it can be demonstrated that the wall has adequate capacity to span horizontally between the supports for greater distances. Anchorage of walls to diaphragms shall be designed for forces calculated using Equation (2-5), which shall be developed in the diaphragm. If sub-diaphragms are used, each sub-diaphragm shall be capable of transmitting the shear forces due to wall anchorage to a continuous diaphragm tie. Sub-diaphragms shall have length-to-depth ratios not exceeding 3:1. Where wall panels are stiffened for out-of-plane behavior by pilasters or similar components, anchors shall be provided at each such component and the distribution of out-of-plane forces to wall anchors and diaphragm ties shall consider the stiffening effect and accumulation of forces at these components.

$$F_p = \chi S_{XS} W \quad (2-5)$$

where:

F_p = Design force for anchorage of walls to diaphragms

χ = Factor from Table 2-4 for the selected Structural Performance Level. Increased values of χ shall be used where anchoring to flexible diaphragms

S_{XS} = Spectral response acceleration parameter at short periods for the selected hazard level and damping, adjusted for site class

W = Weight of the wall tributary to the anchor

exceptions:

1. F_p shall not be less than the minimum of 400 lb/ft or 400 S_{XS} (lb/ft) for concrete or masonry walls.

Structural Performance Level	χ^1	
	Flexible Diaphragms	Other Diaphragms
Collapse Prevention	0.9	0.3
Life Safety	1.2	0.4
Immediate Occupancy	1.8	0.6

1. Value of χ for flexible diaphragms need not be applied to out-of-plane strength of walls in Section 2.6.7.2.

Table 2-4 Coefficient χ for Calculation of Out-of-Plane Wall Forces

2.6.7.2 Out-of-Plane Strength

Wall components shall have adequate strength to span between locations of out-of-plane support when subjected to out-of-plane forces calculated using Equation (2-6).

$$F_p = \chi S_{XS} W \quad (2-6)$$

where:

F_p = Out-of-plane force per unit area for design of a wall spanning between two out-of-plane supports

χ = Factor from Table 2-4 for the selected performance level. Values of χ for flexible diaphragms need not be applied to out-of-plane strength of wall components

S_{XS} = Spectral response acceleration at short periods for the selected hazard level and damping, adjusted for site class

W = Weight of the wall per unit area

C2.6.7.2 Out-of-Plane Strength

Application of these requirements for unreinforced masonry walls and infills is further defined in Chapter 7.

2.6.8 Nonstructural Components

Nonstructural components, including architectural, mechanical and electrical components, shall be anchored and braced to the structure in accordance with the provisions of Chapter 11.

2.6.9 Structures Sharing Common Elements

Buildings sharing common vertical- or lateral-force-resisting elements shall be rehabilitated considering interconnection of the two structures, or they shall be separated as specified in this section.

2.6.9.1 Interconnection

Buildings sharing common elements, other than foundation elements, shall be thoroughly tied together so as to behave as an integral unit. Ties between the structures at each level shall be designed for the forces specified in Section 2.6.5. Analyses of the combined response of the buildings shall account for the interconnection of the structures and shall evaluate the structures as one integral unit.

If the shared common elements are foundation elements, and the superstructures meet the separation requirements of Section 2.6.10, the structures need not be tied together. Shared foundation elements shall be designed considering an analysis of the combined response of the two buildings.

2.6.9.2 Separation

Buildings sharing common elements shall be completely separated by introducing seismic joints between the structures meeting the requirements of Section 2.6.10. Independent lateral-force-resisting systems shall be provided for each structure. Independent vertical support shall be provided on each side of the seismic joint, unless slide bearings are used and adequate bearing length is provided to accommodate the expected independent lateral movement of each structure. It shall be assumed for such purposes that the structures move out of phase with each other in opposite directions simultaneously. The original shared element shall be either completely removed, or anchored to one of the structures in accordance with the applicable requirements of Section 2.6.5.

2.6.10 Building Separation

2.6.10.1 Minimum Separation

Buildings shall be separated from adjacent structures to prevent pounding by a minimum distance s_i at any level i given by Equation (2-7) unless exempted as specified in Section 2.6.10.2.

$$s_i = \sqrt{\Delta_{i1}^2 + \Delta_{i2}^2} \quad (2-7)$$

where:

Δ_{i1} = Lateral deflection of the building under consideration, at level i , relative to the ground, calculated in accordance with the provisions of this standard for the selected hazard level

Δ_{i2} = Lateral deflection of an adjacent building, at level i , relative to the ground, estimated using the provisions of this standard or other approved approximate procedure. Alternatively, it shall be permitted to assume $\Delta_{i2} = (0.03)(h_i)$ for any structure in lieu of a more detailed analysis, where h_i is the height of level i above grade

The value of s_i need not exceed 0.04 times the height of the level under consideration above grade at the location of potential impact.

2.6.10.2 Exceptions

For Structural Performance Levels of life safety or lower, buildings adjacent to structures that have diaphragms located at the same elevation, and differ in height by less than 50% of the height of the shorter building, need not meet the minimum separation distance specified in Section 2.6.10.1.

Where an approved analysis procedure that accounts for the change in dynamic response of the structures due to impact is used, the rehabilitated buildings need not meet the minimum separation distance specified in Section 2.6.10.1. Such an analysis shall demonstrate that:

1. The structures are capable of transferring forces resulting from impact, for diaphragms located at the same elevation; or
2. The structures are capable of resisting all required vertical and lateral forces considering the loss of any elements or components damaged by impact of the structures.

C2.6.10.2 Exceptions

This standard permits rehabilitated buildings to experience pounding as long as the effects are adequately considered by analysis methods that account for the transfer of momentum and energy between the structures as they impact.

Approximate methods of accounting for these effects can be obtained by performing nonlinear time history analyses of both structures (Johnson, 1992). Approximate elastic methods for evaluating these effects have also been developed and are presented in the literature (Kasai, 1990).

Buildings that are likely to experience significant pounding should not be considered capable of meeting Enhanced Rehabilitation Objectives. This is because significant local crushing of components is likely to occur at points of impact. Further, the very nature of the impact is such that high frequency shocks can be transmitted through the structures and potentially be very damaging to architectural components, and mechanical and electrical systems. Such damage is not consistent with the performance expected of buildings designed to Enhanced Rehabilitation Objectives.

2.6.11 Vertical Seismic Effects

The effects of the vertical response of a structure to earthquake ground motion shall be considered for the following cases:

1. Cantilever components of structures.
2. Pre-stressed components of structures.
3. Structural components in which demands due to gravity loads specified in Section 3.2.8 exceed 80% of the nominal capacity of the component.

2.7 Construction Quality Assurance

Construction of seismic rehabilitation work shall be checked for quality of construction and general compliance with the intent of the plans and specifications of the rehabilitation design. Construction quality assurance shall conform to the requirements of this section and the additional testing and inspection requirements of the building code and reference standards of Chapters 5 through 11.

C2.7 Construction Quality Assurance

The design professional responsible for the seismic rehabilitation of a specific building may find it appropriate to specify more stringent or more detailed requirements. Such additional requirements may be particularly appropriate for those buildings having Enhanced Rehabilitation Objectives.

2.7.1 Construction Quality Assurance Plan

A Quality Assurance Plan (QAP) shall be prepared by the design professional and approved by the authority having jurisdiction. The QAP shall identify components of the work that are subject to quality assurance procedures and identify special inspection, testing, and observation requirements to confirm construction quality. The QAP shall also include a process for

modifying the rehabilitation design to reflect unforeseen conditions discovered during construction.

C2.7.1 Construction Quality Assurance Plan

The QAP should, as a minimum, include the following:

1. Required contractor quality control procedures.
2. Required design professional construction quality assurance services, including but not limited to the following:
 - 2.1. Review of required contractor submittals.
 - 2.2. Monitoring of required inspection reports and test results.
 - 2.3. Construction consultation as required by the contractor on the intent of the construction documents.
 - 2.4. Construction observation in accordance with Section 2.7.2.1.

2.7.2 Construction Quality Assurance Requirements

2.7.2.1 Requirements for the Design Professional

The design professional shall be responsible for preparing the QAP applicable to the portion of the work for which they are in responsible charge, overseeing the implementation of the plan, and reviewing special inspection and testing reports.

The design professional shall be responsible for performing periodic structural observation of the rehabilitation work. Structural observation shall be performed at significant stages of construction, and shall include visual observation of the work for substantial conformance with the construction documents and confirmation of conditions assumed during design. Structural observation shall be performed in addition to any special inspection and testing that is otherwise required for the work.

The design professional shall be responsible for modifying the rehabilitation design to reflect conditions discovered during construction.

C2.7.2.1 Requirements for the Design Professional

Following structural observations, the design professional should report any observed deficiencies in writing to the owner's representative, the special inspector, the contractor, and the code official. Upon completion of the work, the design professional should submit to the authority having jurisdiction a written statement attesting that the site visits have been made, and

identifying any reported deficiencies that, to the best of the structural construction observer's knowledge, have not been resolved or rectified.

2.7.2.2 Special Inspection

The owner shall engage the services of a special inspector to observe construction of the following rehabilitation work:

1. Items designated in Section A.9.3.3 of Appendix A of ASCE 7,
2. Other work designated for such special inspection by the design professional or the authority having jurisdiction.

2.7.2.3 Testing

The special inspector shall be responsible for verifying that special test requirements, as described in the QAP, are performed by an approved testing agency for the following rehabilitation work:

1. Work described in Section A.9.3.4 of Appendix A of ASCE 7,
2. Other work designated for such testing by the design professional or the authority having jurisdiction.

2.7.2.4 Reporting and Compliance Procedures

The special inspector shall furnish copies of progress reports to the owner's representative and the design professional, noting any uncorrected deficiencies and corrections of previously reported deficiencies. All observed deficiencies shall be brought to the immediate attention of the contractor for correction.

Upon completion of construction, the special inspector shall submit a final report to the owner's representative and the design professional, indicating the extent to which inspected work was completed in accordance with approved construction documents. Non-compliant work shall have been corrected prior to completion of construction.

C2.7.2 Construction Quality Assurance Requirements

The special inspector should be a qualified person who should demonstrate competence, to the satisfaction of the authority having jurisdiction, for inspection of the particular type of construction or operation requiring special inspection.

2.7.3 Responsibilities of the Authority Having Jurisdiction

The authority having jurisdiction shall be responsible for reviewing and approving the QAP and specifying minimum special inspection, testing, and reporting requirements.

C2.7.3 Responsibilities of the Authority Having Jurisdiction

The authority having jurisdiction should act to enhance and encourage the protection of the public that is represented by such rehabilitation. These actions should include those described in the following subsections.

1. Construction Document Submittals- Permitting

As part of the permitting process, the authority having jurisdiction should require that construction documents be submitted for a permit to construct the proposed seismic rehabilitation measures. The documents should include a statement of the design basis for the rehabilitation, drawings (or adequately detailed sketches), structural/seismic calculations, and a QAP as recommended by Section 2.7.1. Appropriate structural construction specifications are also recommended, if structural requirements are not adequately defined by notes on drawings.

The authority having jurisdiction should require that it be demonstrated (in the design calculations, by third-party review, or by other means) that the design of the seismic rehabilitation measures has been performed in conformance with local building regulations, the stated design basis, the intent of this standard, and/or accepted engineering principles. The authority having jurisdiction should be aware that compliance with the building code provisions for new structures is often not possible and is not required by this standard. It is not intended that the authority having jurisdiction assure compliance of the submittals with the structural requirements for new construction.

The authority having jurisdiction should maintain a permanent public file of the construction documents submitted as part of the permitting process for construction of the seismic rehabilitation measures.

2. Construction Phase Role

The authority having jurisdiction should monitor the implementation of the QAP. In particular, the following actions should be taken.

- 2.1 Files of inspection reports should be maintained for a defined length of time following completion of construction and issuance of a certificate of occupancy. These files should include both reports submitted by special inspectors employed by the owner, as in Section 2.7.2.2, and those submitted by inspectors employed by the authority having jurisdiction.
- 2.2 Prior to issuance of certificates of occupancy, the authority having jurisdiction should ascertain that either all reported noncompliant aspects of construction have been rectified, or such noncompliant aspects have been accepted by the design

professional in responsible charge as acceptable substitutes that are consistent with the general intent of the construction documents.

- 2.3 Files of test reports prepared in accordance with Section 2.7.2.4 should be maintained for a defined length of time following completion of construction and issuance of a certificate of occupancy.

2.8 Alternative Modeling Parameters and Acceptance Criteria

It shall be permitted to derive required parameters and acceptance criteria using the experimentally obtained cyclic response characteristics of a subassembly, determined in accordance with this section. Where relevant data on the inelastic force-deformation behavior for a structural subassembly are not available, such data shall be obtained from experiments consisting of physical tests of representative subassemblies as specified in this section. Approved independent review of this process shall be conducted.

C2.8 Alternative Materials and Methods of Construction

This section provides guidance for developing appropriate data to evaluate construction materials and detailing systems not specifically covered by this standard. This standard specifies stiffnesses, m -factors, strengths, and deformation capacities for a wide range of components. To the extent practical, this standard has been formatted to provide broad coverage of the various common construction types present in the national inventory of buildings. However, it is fully anticipated that in the course of evaluating and rehabilitating existing buildings, construction systems and component detailing practices that are not specifically covered by this standard will be encountered. Further, it is anticipated that new methods and materials, not currently in use, will be developed that may have direct application to building rehabilitation. This section provides a method for obtaining the needed design parameters and acceptance criteria for elements, components, and construction details not specifically included in this standard.

The approach taken in this section is similar to that used to derive the basic design parameters and acceptance criteria contained in this standard for various components, except that no original experimentation was performed. The required story-force deformation curves were derived by this standard developers, either directly from research testing available in the literature, or based on the judgment of engineers knowledgeable in the behavior of the particular materials and systems.

2.8.1 Experimental Setup

Each tested subassembly shall be an identifiable portion of the structural element or component, the stiffness of which is required to be modeled as part of the structural analysis process. The objective of the experiment shall be to estimate the lateral-force-displacement relationships (stiffness) for the subassemblies at different loading increments, together with the strength and deformation capacities for the desired Structural Performance Levels. These properties shall be used in developing an analytical model of the structure to calculate its response to earthquake

ground shaking and other hazards, and in developing acceptance criteria for strength and deformations. The limiting strength and deformation capacities shall be determined from the experimental program using the average values of a minimum of three tests performed for the same design configuration and test conditions.

The experimental setup shall replicate the construction details, support and boundary conditions, and loading conditions expected in the building. The loading shall consist of fully reversed cyclic loading at increasing displacement levels with the number of cycles and displacement levels based on expected response of the structure to the design earthquake. Increments shall be continued until the subassembly exhibits complete failure, characterized by the loss of lateral- and vertical-load resistance.

C2.8.1 Experimental Setup

This standard requires performing a minimum of three separate tests of each unique subassembly. This is because there can be considerable variation in the results of testing performed on "identical" specimens, just as there is inherent variability in the behavior of actual components in buildings. The use of multiple test data allows some of the uncertainty with regard to actual behavior to be defined.

A specific testing protocol has not been recommended, as selection of a suitable protocol is dependent on the anticipated failure mode of the subassembly as well as the character of excitation it is expected to experience in the real structure. In one widely used protocol (ATC, 1992), the specimen is subjected to a series of quasi-static, fully reversed cyclic displacements that are incremented from displacement levels corresponding to elastic behavior, to those at which failure of the specimen occurs. Other protocols that entail fewer or more cycles of displacement, and more rapid loading rates, have also been employed. In selecting an appropriate test protocol, it is important that sufficient increments of loading be selected to characterize adequately the force-deformation behavior of the subassembly throughout its expected range of performance. In addition, the total energy dissipated by the test specimen should be similar to that which the subassembly is anticipated to experience in the real structure. Tests should always proceed to a failure state, so that the margin against failure of the subassembly in service can be judged.

If the structure is likely to be subjected to strong impulsive ground motions, such as those that are commonly experienced within a few kilometers of the fault rupture, consideration should be given to using a protocol that includes one or more very large displacements at the initiation of the loading, to simulate the large initial response induced by impulsive motion. Alternatively, a single monotonic loading to failure may be useful as a performance measure for subassemblies representing components in structures subject to impulsive motion.

2.8.2 Data Reduction and Reporting

A report shall be prepared for each experiment. The report shall include the following:

1. Description of the subassembly being tested.
2. Description of the experimental setup, including:
 - 2.1. Details on fabrication of the subassembly,
 - 2.2. Location and date of testing,
 - 2.3. Description of instrumentation employed,
 - 2.4. Name of the person in responsible charge of the test, and
 - 2.5. Photographs of the specimen, taken prior to testing.
3. Description of the loading protocol employed, including:
 - 3.1. Increment of loading (or deformation) applied,
 - 3.2. Rate of loading application, and
 - 3.3. Duration of loading at each stage.
4. Description, including photographic documentation, and limiting deformation value for all important behavior states observed during the test, including the following, as applicable:
 - 4.1. Elastic range with effective stiffness reported,
 - 4.2. Plastic range,
 - 4.3. Onset of visible damage,
 - 4.4. Loss of lateral-force-resisting capacity,
 - 4.5. Loss of vertical-force-resisting capacity,
 - 4.6. Force-deformation plot for the subassembly (noting the various behavior states), and
 - 4.7. Description of limiting behavior states defined as the onset of specific damage mode, change in stiffness or behavior (such as initiation of cracking or yielding) and failure modes.

C2.8.2 Data Reduction and Reporting

It is important that data from experimental programs be reported in a uniform manner so that the performance of different subassemblies may be compared. The data reporting requirements

specified are the minimum thought to be adequate to allow development of the required design parameters and acceptance criteria for the various Systematic Rehabilitation Procedures. Some engineers and researchers may desire additional data from the experimentation program to allow calibration of their analytical models and to permit improved understanding of the probable behavior of the subassemblies in the real structure.

2.8.3 Design Parameters and Acceptance Criteria

The following procedure shall be followed to develop structural modeling parameters and acceptance criteria for subassemblies based on experimental data.

1. An idealized force-deformation pushover curve shall be developed from the experimental data for each experiment and for each direction of loading with unique behavior. The curve shall be plotted in a single quadrant (positive force versus positive deformation, or negative force versus negative deformation). In cases where deformation components (e.g., flexure, shear) are modeled separately, test instrumentation must be provided to enable force-deformation curves for each deformation component to be derived from the overall test force-deformation relations. The curves shall be constructed as follows:
 - 1.1. The appropriate quadrant of data shall be taken from the lateral-force-deformation plot from the experimental report.
 - 1.2. A smooth "backbone" curve shall be drawn through each point of peak displacement during the first cycle of each increment of loading (or deformation), as indicated in Figure 2-4.
 - 1.3. The backbone curve so derived shall be approximated by a series of linear segments, drawn to form a multi-segmented curve conforming to one of the types indicated in Figure 2-3.
2. The multilinear curves derived for all experiments involving the subassembly shall be compared and an average multilinear representation of the subassembly behavior shall be derived based on these curves. Each segment of the composite curve shall be assigned the average stiffness (either positive or negative) of the similar segments in the multilinear curves for the various experiments. Each segment on the composite curve shall terminate at the average of the deformation levels at which the similar segments of the multilinear curves for the various experiments terminate.
3. The stiffness of the subassembly for use in linear procedures shall be taken as the slope of the first segment of the composite curve. The composite multilinear force-deformation curve shall be used for modeling in nonlinear procedures.
4. For the purpose of determining acceptance criteria, subassembly actions shall be classified as being either force-controlled or deformation-controlled. Subassembly actions shall be classified as force-controlled unless any of the following apply.

- 4.1. The full backbone curve including strength degradation and residual strength is modeled; the composite multilinear force-deformation curve for the subassembly, determined in accordance with requirements in paragraph 2 above, conforms to either Type 1, Type 2, or Type 3 as indicated in Figure 2-3; and the component action is classified as deformation-controlled in accordance with Section 2.4.4.3.
- 4.2. Bilinear modeling is performed in accordance with the simplified NSP procedure of Section 3.3.3.2.2; the composite multilinear force-deformation curve for the subassembly, determined in accordance with requirements in paragraph 2 above, conforms to either Type 1 or Type 2, as indicated in Figure 2-3; and the deformation parameter d is at least twice the deformation parameter g .
5. The strength capacity, Q_{CL} , for force-controlled actions evaluated using either the linear or nonlinear procedures shall be taken as the mean minus one standard deviation strength Q_y determined from the series of representative subassembly tests.
6. The acceptance criteria for deformation-controlled actions used in nonlinear procedures shall be the deformations corresponding with the following points on the curves of Figure 2-3:
 - 6.1 Immediate Occupancy

The deformation at which permanent, visible damage occurred in the experiments but not greater than 0.67 times the deformation limit for Life Safety specified in 6.2.1.
 - 6.2 Primary Components
 - 6.2.1 Life Safety: 0.75 times the deformation at point 2 on the curves.
 - 6.2.2 Collapse Prevention: The deformation at point 2 on the curves but not greater than 0.75 times the deformation at point 3.
 - 6.3 Secondary Components
 - 6.3.1 Life Safety: 0.75 times the deformation at point 3.
 - 6.3.2 Collapse Prevention: 1.0 times the deformation at point 3 on the curve.
7. The m -factors used as acceptance criteria for deformation-controlled actions in linear procedures shall be determined as follows: (a) obtain the deformation acceptance criteria given in paragraph 6 above; (b) then obtain the ratio of this deformation to the deformation at yield, represented by the deformation parameter g in the curves shown in Figure 2-3; (c) then multiply this ratio by a factor 0.75 to obtain the acceptable m -factor.

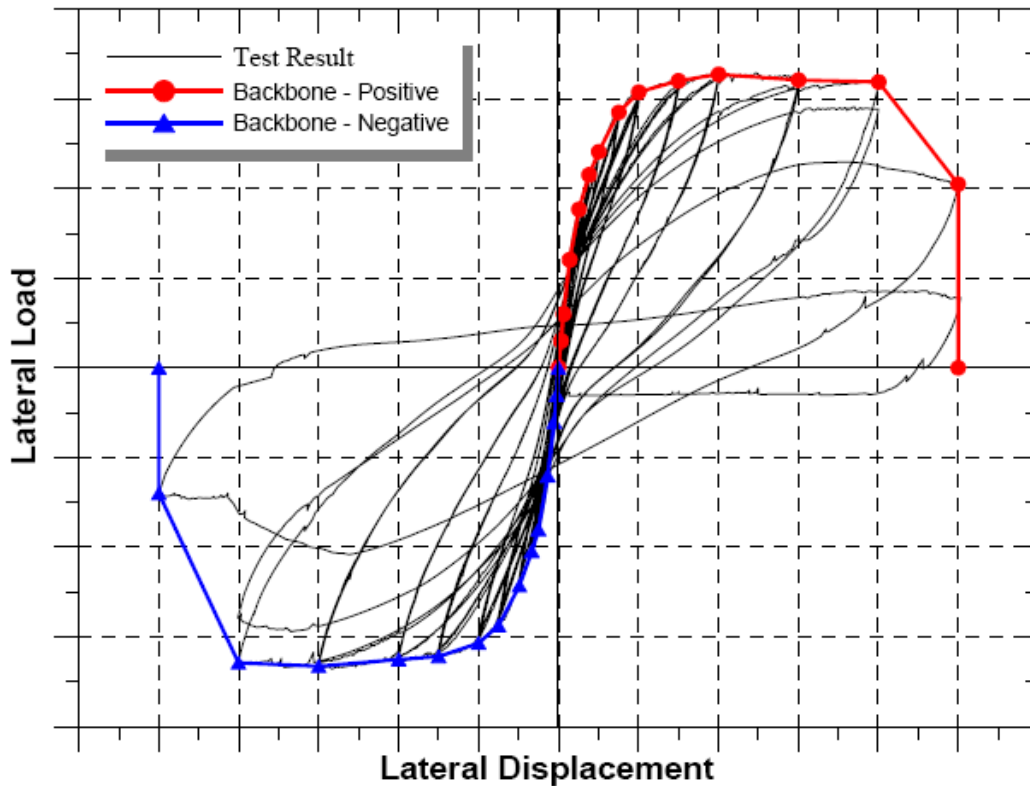


Figure 2-4 Backbone Curve for Experimental Data

C2.8.3 Design Parameters and Acceptance Criteria

A multistep procedure for developing design parameters and acceptance criteria for use with both the linear and nonlinear procedures is provided. The basic approach consists of the development of an approximate story lateral-force-deformation curve for the subassembly, based on the experimental data.

In developing the representative story lateral-force-deformation curve from the experimentation, use of the "backbone" curve is required. This takes into account, in an approximate manner, the strength and stiffness deterioration commonly experienced by structural components. Component testing normally involves multiple cycles at prescribed loading or deformation increments. The backbone curve is defined using the peak deformation obtained during the first cycle for each loading or deformation increment, as shown in Figure 2-4, and provides a good representation of

the overall component behavior. Further justification for the method used to create the backbone shown in Figure 2-4 can be found in Elwood et al. (2007).