ADMINISTRATIVE BULLETIN

NO. AB-099 :

DATE : July 2, 2012 (Updated 01/01/14 for code references)

SUBJECT : Permit Review and Operations

TITLE : **Post-Earthquake Repair and Retrofit Requirements for Concrete Buildings**

PURPOSE : The purpose of this Bulletin is to establish policy for interpreting the San Francisco Building Code regarding post-earthquake damage retrofit triggers for concrete buildings constructed before May 21, 1973 and to detail the scope and criteria for such triggered retrofits and other repairs.

REFERENCES : 2013 San Francisco Building Code

- Section 3401.10, Lateral force design requirements for existing buildings
- Section 3402, Definition of Disproportionate Damage [*pending code revision*]
- Section 3402, Definition of Substantial Structural Damage
- Section 3405, Repairs

2013 California Historical Building C ode, CCR Title Part 8

ASCE/SEI Standard 31, Seismic Evaluation of Existing Buildings

ASCE/SEI Standard 41, Seismic Rehabilitation of Existing Buildings, with Supplement 1

California Health and Safety Code, Section 17920.3

CAPSS Report, *Here Today – Here Tomorrow: The Road to Earthquake Resilience in San Francisco*, Post-Earthquake Repair and Retrofit Requirements (ATC-52-4 Report), http://www.sfcapss.org/PDFs/PostQuakeRepair.pdf

1997 NHERP Guidelines for the Seismic Rehabilitation of Buildings (FEMA 273)

FEMA 306: Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings: Basic Procedures Manual (FEMA, 1999)

FEMA 308: The Repair of Earthquake Damaged Concrete and Masonry Wall Buildings (FEMA, 1999)

FEMA 356: Prestandard and Commentary for the Seismic Rehabilitation of Buildings (FEMA, 2000)

DISCUSSION : San Francisco Building Code, Section 3405.2 triggers seismic evaluation, and possibly retrofit, of buildings when earthquake-related damage reaches the level of "substantial structural damage to vertical elements of the lateral-force-resisting system." Substantial structural damage is defined in Section 3402 as, in essence, a loss of lateral capacity of 20 percent or more in any horizontal direction. The code gives no specific rules for identifying a 20-percent loss or guidance as to how to calculate capacity loss, so implementation of these code provisions relies on interpretation by the Department of Building Inspection. This Bulletin presents the Department's interpretation of a 20-percent lateral capacity loss for concrete buildings constructed before May 21, 1973.

In addition to substantial structural damage, San Francisco Building Code, Section 3405.4 triggers seismic evaluation, and possibly retrofit, when earthquake-related damage reaches the level of disproportionate damage, defined in Section 3402 [*provisional, pending San Francisco Building Code adoption of provisions for Disproportionate Damage*] as, in essence, a lateral capacity loss of 10 percent or more in an earthquake of limited intensity. This Bulletin presents the Department's interpretation of a 10-percent capacity loss for concrete buildings constructed before May 21, 1973.

For concrete shear wall and infill buildings, the evaluation procedures developed in FEMA 306 and the simplified version of the methodology in FEMA 308 are used determine whether a building with substantial structural damage or disproportionate damage needs to be restored to its pre-earthquake capacity or retrofitted. Substantial structural damage or disproportionate damage may also be deemed to exist when damage to specific building components or conditions reaches the severity of "earthquake triggering damage" based on visual observation and classification .

For concrete moment-frame buildings, repair and retrofit requirements are based only on visual observation and classification of specific components damage.

Residential buildings that incur substantial structural damage or disproportionate damage as detailed in this Bulletin are considered to be "substandard" per California Health and Safety Code Section 17920.3(b) Structural hazards and (o) Inadequate structural resistance to horizontal forces.

APPLICABILITY:

A building is eligible to apply the interpretations and provisions of this Bulletin if all of the following criteria are met:

A. The building has cast-in-place concrete bearing walls or cast-in-place concrete frames, and

B. The building has at least one floor diaphragm constructed with cast-in-place concrete.

Buildings of other construction types may also apply the provisions of this Bulletin on a case-by-case basis when approved by the Department of Building Inspection. Other methods of determining capacity loss based on analysis, testing, or other objective data may also be allowed at the discretion of the Department.

Qualified buildings may be permitted to be evaluated or retrofitted using the provisions in the California Historical Building Code, provided that such standards do not result in seismic performance less than the evaluation and retrofit engineering criteria detailed in this Bulletin.

DEFINITIONS:

For the purpose of this bulletin, the following definitions shall apply:

- **CONCRETE SHEAR WALL**: A concrete wall which resists lateral forces applied parallel to the plane of the wall.
- **CONCRETE MOMENT FRAME**: A building frame system in which seismic shear forces are resisted by shear and flexure in members and joints of the frame, including slab-column moment frames.
- **CONCRETE INFILL FRAME**: A concrete moment frame having panel(s) of masonry that participate in resisting lateral forces that are placed within the frame members.
- **NONSTRUCTURAL REPAIR**: Repairs that improve the visual appearance of damage to a component. These repairs may also restore the nonstructural properties of a component, such as weather protection. Any structural benefit is negligible. This is defined as "Cosmetic Repair" in FEMA 308.

EVALUATION PROCEDURE AND RETROFIT SCOPE

Concrete Shear Wall and Infill Frame Buildings

General

Substantial structural damage to elements of the lateral force-resisting system shall be deemed to exist when the results of a FEMA 306 evaluation shows that capacity loss exceeds 20% for a concrete shear wall or infill frame building, or when any of the “triggering damage” criteria for substantial structural damage described in Table 1 is observed in an eligible building.

Additionally, disproportionate damage shall be deemed to exist when a FEMA 306 evaluation shows a capacity loss exceeding 10%, or when any of the “triggering damage” for disproportionate damage described in Table 1 is observed in an eligible building.

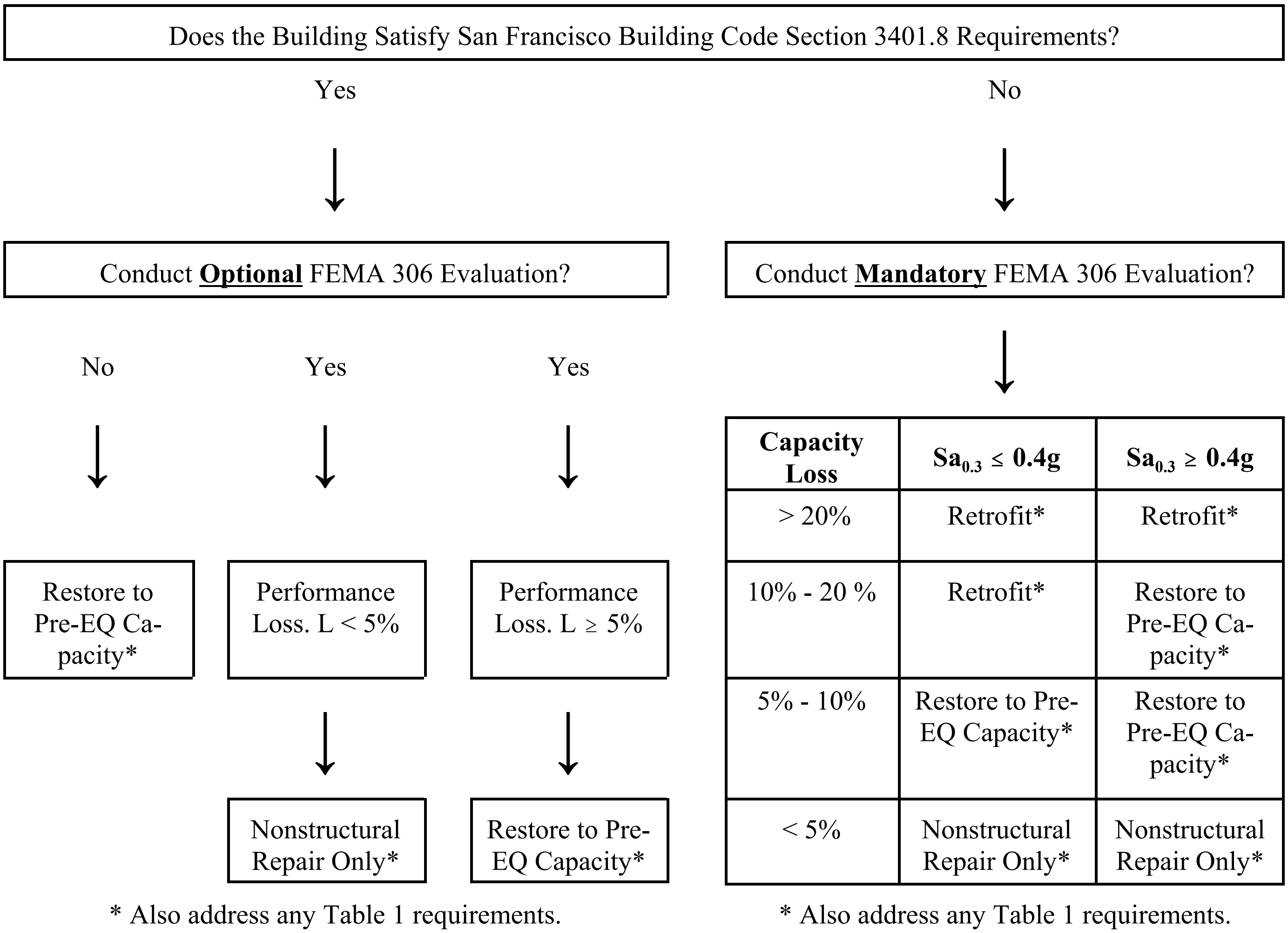
Overview

The flowchart in Figure 1 shall be followed to determine the post-earthquake damage repair or retrofit requirements related to substantial structural damage to concrete shear wall and infill frame buildings.

The process begins with a determination of whether the damaged building has sufficient pre-earthquake capacity to satisfy San Francisco Building Code, Section 3401.10, which references the May 21, 1973 milestone requirements of San Francisco Building Code, Section 1604.11.1. If the building in its pre-damaged state satisfies this code provision, then the building need not be retrofitted regardless of the level of damage, and restoration to pre-earthquake capacity is sufficient. Alternatively, if a full FEMA 306 evaluation (labeled as “Optional FEMA 306 Evaluation” in Figure 1) shows a capacity loss of less than 5 percent, nonstructural repair to the building instead of restoration to pre-earthquake capacity shall be permitted, except that individual component damage or condition repair per Table 1 is also required.

If the building does not meet the San Francisco Building Code, Section 1604.11.1 requirements per San Francisco Building Code Section 3401.10, then a full FEMA 306 evaluation (labeled as “Mandatory FEMA 306 Evaluation” in Figure 1) is required, and nonstructural repair, restoration to pre-earthquake capacity, or retrofit requirements may be triggered as shown in Figure 1. In addition, individual component damage or condition repair per Table 1 is required.

Figure 1: Flowchart for Post-Earthquake Repair and Retrofit of Concrete Shear Wall and Infill Frame Buildings



Capacity Loss	**$Sa_{0.3} \leq 0.4g$**	**$Sa_{0.3} \geq 0.4g$**
> 20%	Retrofit*	Retrofit*
10% - 20 %	Retrofit*	Restore to Pre-EQ Capacity*
5% - 10%	Restore to Pre-EQ Capacity*	Restore to Pre-EQ Capacity*
< 5%	Nonstructural Repair Only*	Nonstructural Repair Only*

* Also address any Table 1 requirements.

FEMA 306 Evaluation Process

A FEMA 306 evaluation process for the pre-event structure and the damaged structure shall be performed using the guidelines below:

1. The evaluation shall use the nonlinear static procedures defined in FEMA 306 to determine the capacity for pre-event and damaged conditions [Attachment A]. FEMA 306 was developed at the time FEMA 273 was also in development, prior to the publication of FEMA 356. Since then, additional research and development effort was incorporated into FEMA 356 and later into ASCE 41. Therefore, the comparable, more current equations in ASCE 41 shall be used in performing a FEMA 306 evaluation rather than the FEMA 273 equivalents.
2. The global displacement demand shall be determined in accordance with ASCE 41.
3. The performance objective shall meet the requirements of ASCE 41 for Life Safety Structural Performance Level (S-3) at 75% of the spectral demand associated with the current code value at the building site.

Simplified FEMA 308 Evaluation Process

The following simplified version of the FEMA 308 approach, based on loss in performance, L, may be used for the purpose of determining threshold triggers for restoration to pre-earthquake capacity and retrofit. The process is similar to that outlined in Figure 1. The FEMA 308 parameters shall be determined using the guidelines as follows. For further definition of the FEMA 308 parameters needed for the evaluation, see Attachment B.

1. To use this method, first determine the following performance capacity and loss indices:
2. • **Pre-event (Undamaged) Performance Index**:

$$P = d_c / d_d,$$

where d_c is the global displacement capacity for the selected performance objective and d_d is the maximum global displacement demand for the selected ground motion. This performance index is calculated using component properties for the pre-event conditions in accordance with the methodology outlined in FEMA 306.

• **Damaged Performance Index**:

$$P' = d'_c / d'_d,$$

where the prime symbol (') denotes that the global displacement capacity and demand, d'_c and d'_d, respectively, are determined for the components in their damaged state using FEMA 306.

• **Loss**:

$$L = 1 - (P' / P),$$

where L is the performance loss of a building due to earthquake damage, and is given by the ratio of the damaged performance index, P', to the undamaged performance index, P, for a specific performance objective. L ranges between 0 and 1.

3. To determine whether earthquake damage is acceptable and neither restoration to pre-earthquake capacity nor retrofit is triggered, the performance loss, L, is compared against the FEMA 308 Table 3-1 [Attachment B] threshold parameters defined below:

- $L_{r(min)}$: The Loss threshold below which neither restoration to pre-earthquake capacity nor retrofit is triggered, shall be defined as follows:
  - $L_{r(min)}$ = 0.05 for earthquake event with $Sa_{0.3} \leq 0.4g$
  - $L_{r(min)}$ = 0.05 for earthquake event with $Sa_{0.3} > 0.4g$
- $L_{r(max)}$: The Loss threshold above which either restoration to pre-earthquake capacity or retrofit is triggered. For this simplified procedure, $L_{r(max)}$ may be taken to be the same as $L_{r(min)}$ since Lr does not vary:
  - $L_{r(max)}$ = 0.05 for earthquake event with $Sa_{0.3} \leq 0.4g$
  - $L_{r(max)}$ = 0.05 for earthquake event with $Sa_{0.3} > 0.4g$

Alternatively, the Damaged Performance Index, P' may be used to determine whether earthquake damage is acceptable and neither restoration to pre-earthquake capacity nor retrofit is triggered by comparing P' against the FEMA 308 Table 3-1 [Attachment B] limit parameters defined below:

- P'_{min}: The Damage Performance Index limit below which restoration to pre-earthquake capacity or retrofit is triggered, is not used since L_r does not vary for the simplified method.
- P'_{max}: The Damage Performance Index limit above which neither restoration to pre-earthquake capacity nor retrofit is triggered regardless of the value of Loss, L, shall be defined as 1.0.

4. If a building is required to be restored to its pre-earthquake capacity or retrofitted per step 2, the Performance Loss, *L*, is compared against the FEMA 308 Table 3-2 [Attachment B] threshold parameters defined below to determine if retrofit is triggered:

   - $L_{u(min)}$: The Loss threshold below which earthquake damage does not trigger retrofit but requires restoration to pre-earthquake capacity, shall be defined as below:
     - $L_{u(min)}$ = 0.10 for earthquake event with $Sa_{0.3} \leq 0.4g$
     - $L_{u(min)}$ = 0.20 for earthquake event with $Sa_{0.3} > 0.4g$
   - $L_{u(max)}$: The Loss threshold above which earthquake damage triggers retrofit, shall be taken to be the same as $L_{u(min)}$ since L_u does not vary for the simplified method:
     - $L_{u(max)}$ = 0.10 for earthquake with $Sa_{0.3} \leq 0.4g$
     - $L_{u(max)}$ = 0.20 for earthquake with $Sa_{0.3} > 0.4g$

   Alternatively, the Undamaged Performance Index, *P* may be used to determine whether restoration to pre-earthquake capacity or retrofit is triggered by comparing *P* against the FEMA 308 Table 3-2 limit parameters defined below:

   - P_{min}: The Pre-event Performance Index limit below which existing earthquake damage triggers retrofit, is not used since L_u does not vary for the purpose of the simplified method.
   - P_{max}: The Pre-event Performance Index limit above which existing earthquake damage does not trigger retrofit and restoration to pre-earthquake capacity is sufficient regardless of the value of Loss, *L*, shall be taken as 1.0.

Retrofit Triggers due to Specific Component Damage or Conditions

In addition to the retrofit triggers per the FEMA 306 and 308 methodologies described above, damage to any of the specific components or other conditions noted in Table 1 below shall trigger retrofit shown in the “Action Required” column of the table if damage is observed to reach the severity of “triggering damage.” The conditions noted in Table 1 are primarily related to gravity-load-carrying component damage, load path failures, or significant damage in individual components. For damage less than the “triggering damage,” repairs shall be made to return the building to original strength or condition by methods acceptable to the Department of Building Inspection.

Table 1: Triggers for Specific Components or Conditions in Concrete Buildings			
Components or Conditions	***Triggering Damage***		***Action Required***
	Substantial Structure Damage	***Disproportionate Damage***	
Shear cracks in gravity load-carrying columns or bearing walls supporting less than 30% of the area of a roof or an individual floor.	Preemptive diagonal tension crack meeting the "Moderate" or worse criteria of the RC2H component in Section 5.5 of FEMA 306 or any component with "Extreme" damage per Section 5.5 of FEMA 306 [See Attachment A].	Preemptive diagonal tension crack meeting "Moderate" criteria of the RC2H component in Section 5.5 of FEMA 306, except that inclined crack widths are to be taken as between 1/16″ and 1/8″. [See Attachment A].	Replace component.
Shear cracks in gravity-load-carrying columns or bearing walls supporting 30% or more of the area of a roof or an individual floor.	Preemptive diagonal tension crack meeting the "Moderate" or worse criteria of the RC2H component in Section 5.5 of FEMA 306 or any component with "Extreme" damage per Section 5.5 of FEMA 306 [Attachment A].	Preemptive diagonal tension crack meeting "Moderate" criteria of the RC2H component in Section 5.5 of FEMA 306, except that inclined crack widths are to be taken as between 1/16″ and 1/8″ [Attachment A].	Replace component and retrofit lateral system to SFBC Section 3405.3.
Leaning story (excessive drift) in a concrete moment-frame building.	Permanent lateral displacement of 1% of the story height or more resulting from earthquake damage.	Permanent lateral displacement of 0.5% of the story height or more resulting from earthquake damage.	Retrofit lateral system to SFBC Section 3405.3.
Beam-column joint shear at joints with at least one exterior face in columns supporting less than 30% of the area of a roof or individual floor.	Cracking representative of joint shear at the beam-column joint with cracks at least 1/8″ wide or offset along the crack at least 1/16″		Replace component.
Beam-column joint shear at joints with at least one exterior face in columns supporting more than 30% of the area of a roof or individual floor.	Cracking representative of joint shear at the beam-column joint with cracks at least 1/8″ wide or offset along the crack at least 1/16″.		Replace component and retrofit lateral system to SFBC Section 3405.3.

<table>
<tr><th colspan="4">Table 1: Triggers for Specific Components or Conditions in Concrete Buildings</th></tr>
<tr><th rowspan="2">Components or Conditions</th><th colspan="2">Triggering Damage</th><th rowspan="2">Action Required</th></tr>
<tr><th>Substantial Structure Damage</th><th>Disproportionate Damage</th></tr>
<tr><td>Punching shear damage at slab around columns without intersecting beams in columns supporting less than 30% of the area of a roof or individual floor.</td><td colspan="2">Evidence representative of potential punching shear such as fresh circular cracking in the slab around a column with or without vertical offset at the crack.</td><td>Replace component.</td></tr>
<tr><td>Punching shear damage at slab around columns without intersecting beams in columns supporting more than 30% of the area of a roof or individual floor.</td><td colspan="2">Evidence representative of potential punching shear such as fresh circular cracking in the slab around a column with or without vertical offset at the crack.</td><td>Replace component and retrofit lateral system to SFBC Section 3405.3.</td></tr>
<tr><td>Separation of floor-to-wall connections.</td><td colspan="2">• Permanent separation or sliding at joint of 1″ or more, or
• Permanent movement that results in inadequate bearing of supported member.</td><td>Retrofit connection using forces from SFBC Section 3405.3.</td></tr>
<tr><td>Delamination of more than 30% of cast-in-place topping from precast floor or roof framing where topping serves as the diaphragm.</td><td colspan="2">Permanent separation of topping from precast members.</td><td>Replace damaged topping slab and tie new slab to underlying precast members using SFBC Section 3405.3 forces and current detailing.</td></tr>
<tr><td>Fractured bars at diaphragm chords or collectors.</td><td colspan="2">• Permanent separation or sliding at joint of 1″ or more, or
• Permanent movement that results in inadequate bearing of supported member.</td><td>Replace damaged bars and tie or splice new components to surrounding structural elements using SFBC Section 3405.3 forces and current detailing.</td></tr>
</table>

Concrete Moment-Frame Buildings

The process for determining whether repair or retrofit is triggered for a concrete moment-frame building begins with a determination of whether the damaged building has adequate pre-earthquake capacity to comply with San Francisco Building Code, Section 3401.10, which references the May 21, 1973 milestone requirements of the San Francisco Building Code, Section 1604.11.1. If this is satisfied, then the building need not be retrofitted regardless of the level of damage, and restoration of the building to its pre-earthquake capacity shall be undertaken. Unlike concrete shear-wall and infill buildings, nonstructural repairs shall not be permitted even if a full FEMA 306 evaluation has determined that the capacity loss is below 5 percent. For non-complying buildings, if any of the component damage or conditions given in Table 1 is present, the building shall be retrofitted as required by Table 1.

For concrete frame buildings with any interacting walls, in addition to the Table 1 checks, the evaluation procedure and retrofit scope given above for concrete shear wall and infill frame buildings shall be applied. When a FEMA 306 analysis is used to determine loss of capacity outlined in this bulletin for concrete shear wall and infill frame buildings, the moment-frame capacity may not be included in development of the force-displacement pushover curve.

EVALUATION AND RETROFIT ENGINEERING CRITERIA

When retrofit is triggered by earthquake damage at any level, the engineering criteria for retrofit shall be permitted to use earthquake loads that are 75 percent of those prescribed by the San Francisco Building Code for new construction, in accordance with SFBC Section 3405.2.

In addition, any of the following alternative codes, standards, or guidelines may be used as alternative evaluation or retrofit criteria for qualifying buildings:

A. Meets the requirements of ASCE 31-03 for the Life Safety Performance Level, or

B. Meets the requirements of ASCE 41-06 for the Life Safety Performance Level (S-3) in the BSE-1 earthquake hazard level, or

C. Meets the requirements of 2010 San Francisco Building Code 3401.10.

Signed:

Tom C. Hui, S.E. 7/2/2012
Acting Director
Department of Building Inspection

Approved by the Building Inspection Commission on 6/20/2012

Attachment A: Excerpt from FEMA 306: Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings: Basic Procedures Manual, Chapters 4-5

Attachment B: Excerpt from FEMA 308: The Repair of Earthquake Damaged Concrete and Masonry Wall Buildings, Chapter 3

ATTACHMENT A

FEMA 306 BASIC PROCEDURES MANUAL

Chapter 4: Evaluation of Earthquake Damage and Chapter 5: Reinforced Concrete

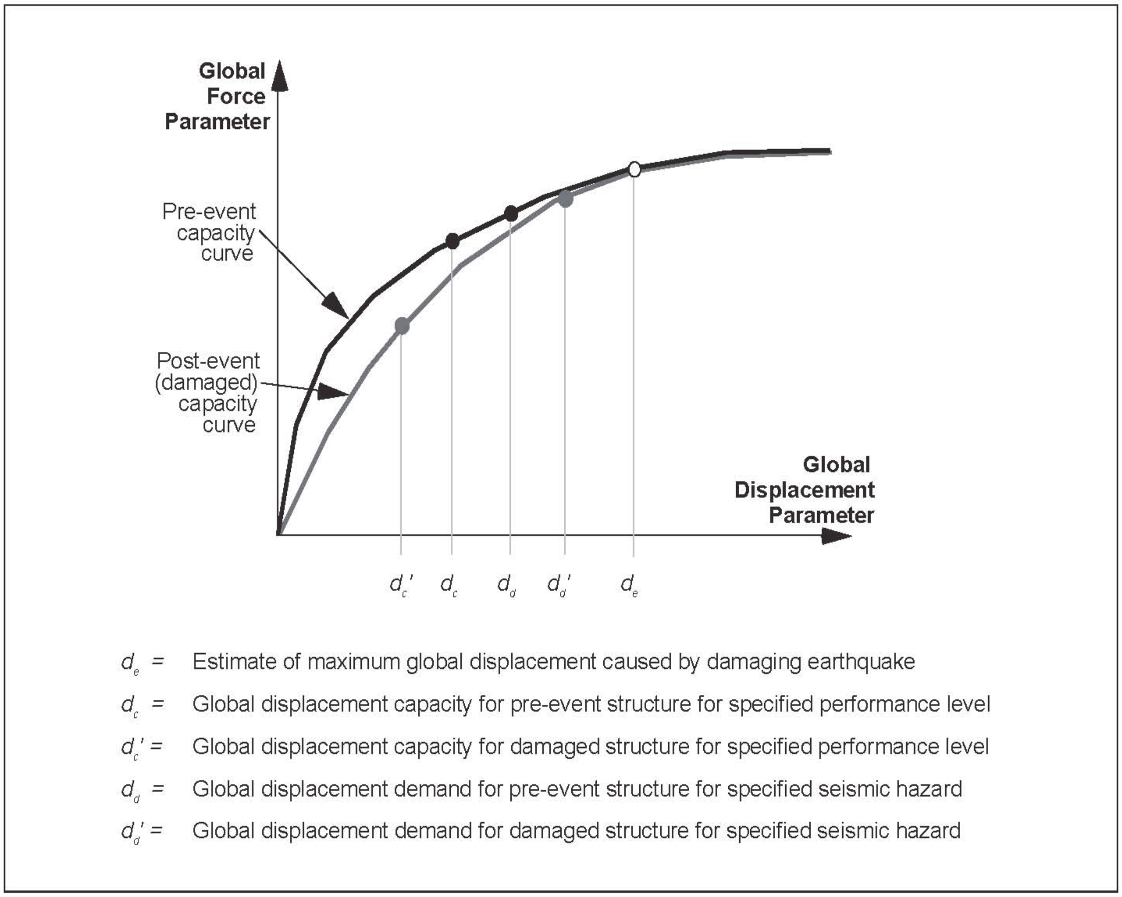


Figure 4-1 Displacement Parameters for Damage Evaluation

however, is relatively less restrictive for concrete and masonry wall buildings because of their tendency to repond in the fundamental mode. Future development of the procedures may also allow improved treatment for higher modes (Paret et al., 1996). Nonlinear static procedures must be carefully applied to buildings with flexible diaphragms.

The basic steps for using the procedure to measure the effect of damage caused by the damaging ground motion on future performance during the performance ground motion is outlined as follows:

1. Using the properties (strength, stiffness, energy dissipation) of all of the lateral-force-resisting components and elements of the pre-event structure, formulate a capacity curve relating global lateral force to global displacement.

2. Determine the global displacement limit, d_c, at which the pre-event structure would just reach the performance level specified for the performance objective under consideration.

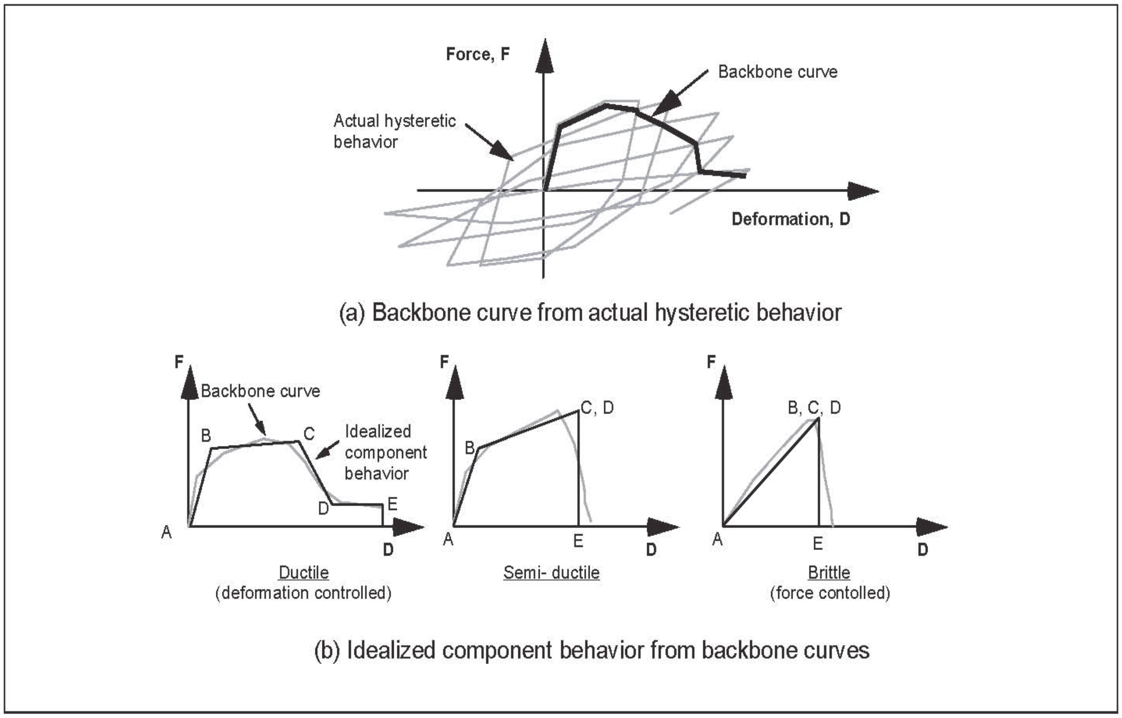


Figure 4-2 Idealized Component Force-Deformation Relationship

3. For the specified performance ground motion, determine the hypothetical maximum displacement for the pre-event structure, d_d. The ratio of d_c to d_d indicates the degree to which the pre-event structure satisfies the specified performance objective.

4. Using the results of the investigation of the effects of the damaging ground motion, modify the component force-deformation relationships using the Component Damage Classification Guides in Chapters 5 through 8. Using the revised component properties, reformulate the capacity curve for the damaged building and repeat steps 2 and 3 to determine d'_c and d'_d. The ratio of d'_c to d'_d indicates the degree to which the damaged structure satisfies the specified performance objective.

5. If the ratio of d'_c to d'_d is the same, or nearly the same, as the ratio of d_c to d_d , the damage caused by the damaging ground motion has not significantly degraded future performance for the performance objective under consideration.

6. If the ratio of d'_c to d'_d is less than the ratio of d_c to d_d, the effects of the damage caused by the damaging ground motion has diminished the future performance characteristics of the structure. Develop hypothetical actions in accordance with Section 4.5, to restore or augment element and component properties so that the ratio of d^*_c to d^*_d (where the * designates the restored condition) is the same, or nearly the same, as the ratio of d_c to d_d.

4.4.2 Global Displacement Performance Limits

The global displacement performance limits (d_c, d'_c, d^*_c) are a function of the acceptability of the deformation of the individual components of the structure as it is subjected to appropriate vertical loads and to a monotonically increasing static lateral load distributed to each floor and roof level in an assumed pattern. The deformation of the components depends on both their geometric configuration in the model and their individual force-deformation characteristics (see Section 2.4) compared to those of other components. The plot of the total lateral load parameter

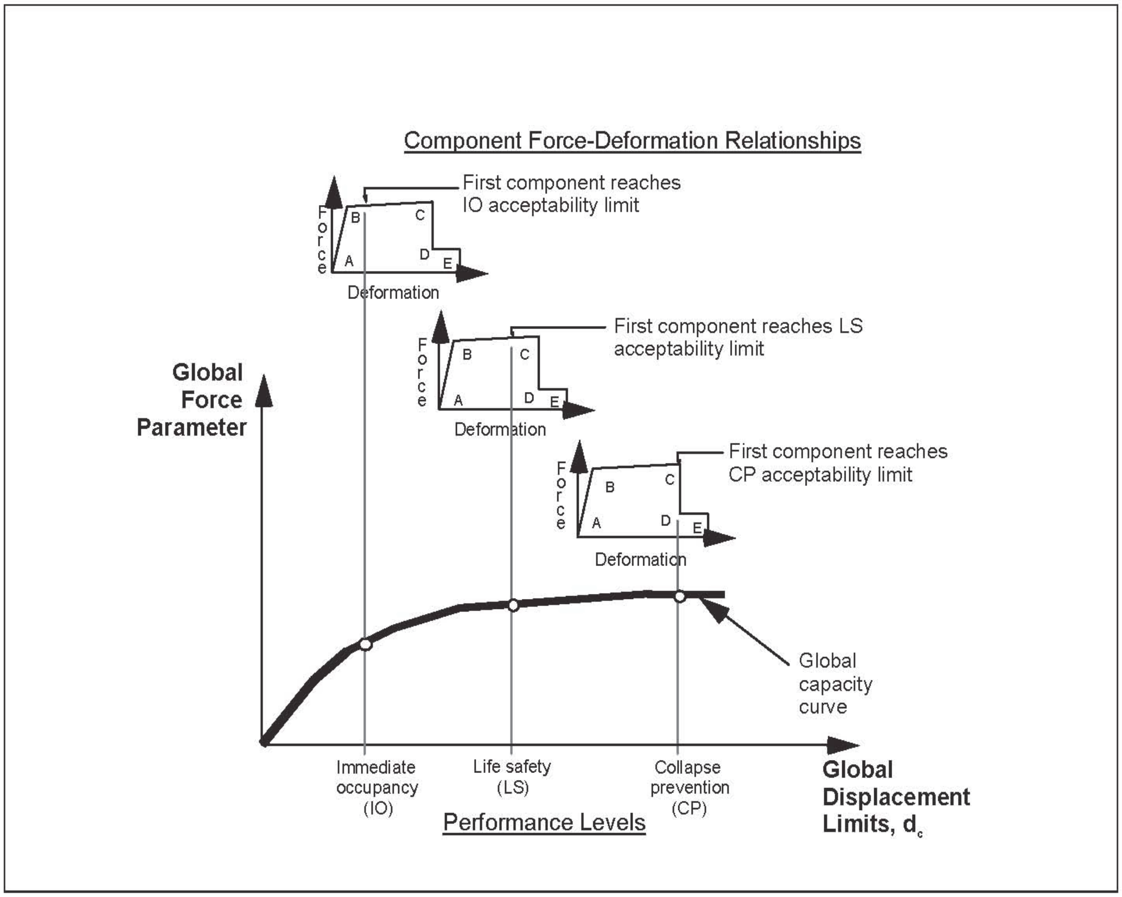


Figure 4-3 Global Displacement Limits and Component Acceptability used in FEMA 273/274

versus global displacement parameter represents the capacity curve for the building for the assumed load pattern. Thus, the capacity curve is characteristic of the global assembly of individual components and the assumed load pattern.

The current provisions of FEMA 273 limit global displacements for the performance level under consideration (e.g., Immediate Occupancy, Life Safety, Collapse Prevention) to that at which any single component reaches its acceptability limit (see Figure 4-3). The provisions of FEMA 273/274 allow for the re-designation of such components as "secondary." Secondary components have higher deformation acceptability limits but the remaining primary lateral load resisting system components must be capable of meeting acceptability criteria without them. The same allowance may be made for relative performance analysis of earthquake damaged buildings as long as it is applied appropriately to both the pre-event and damaged models.

The acceptability limits were developed for FEMA 273 to identify and mitigate specific seismic deficiencies in buildings to improve anticipated performance. As such, they are intended to be conservative. In a relative performance analysis, the degree of conservatism should be same for both the pre-event and damaged models to give reliable results to estimate the scope of restoration repairs. In an actual earthquake, some "unacceptable" component behavior may not result necessarily in unacceptable global performance. In the future, it is possible that alternative procedures for better estimating global displacement limits will emerge. These also may be suitable for relative performance analyses provided that they are applied consistently and appropriately to both the pre-event and the damaged models.

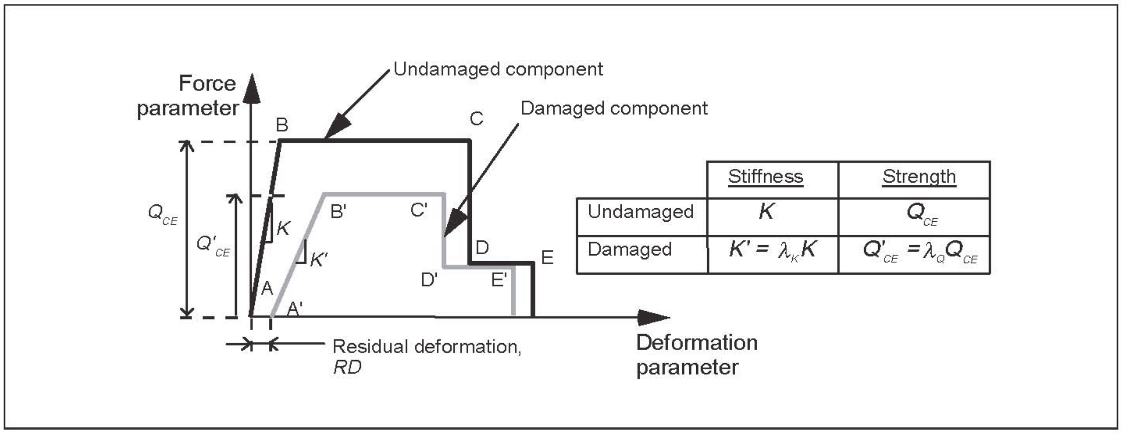


Figure 4-4 Component Modeling Criteria

4.4.3 Component Modeling and Acceptability Criteria

4.4.3.1 Pre-Event Building

In determining the capacity curve for the pre-event building, component properties are generated using the procedures of FEMA 273/274 or ATC-40, modified, if necessary, to reflect the results of the damage investigation. Modifications may be warranted for two reasons:

1. The procedures assume a normal, relatively minor, degree of deterioration of the building due to service conditions. If the investigation reveals preexisting conditions (see Section 3.4) that affect component properties beyond these normal conditions, then the "pre-event" component properties must be modified to reflect the condition of the structure just before the earthquake.

2. If the verification process (see Section 3.6) indicates component types or behavior modes inconsistent with the FEMA 273/274 or ATC-40 predicted properties, then the pre-event component properties are modified to reflect the observed conditions.

4.4.3.2 Damaged Building

The effects of damage on component behavior are modeled as shown generically in Figure 4-4. Acceptability criteria for components are illustrated in Figure 4-5. The factors used to modify component properties are defined as follows:

λ_K = modification factor for idealized component force-deformation curve accounting for change in effective initial stiffness resulting from earthquake damage.

λ_Q = modification factor for idealized component force-deformation curve accounting for change in expected strength resulting from earthquake damage.

λ_D = modification factor applied to component deformation acceptability limits accounting for earthquake damage.

RD = absolute value of the residual deformation in a structural component, resulting from earthquake damage.

The values of the modification factors depend on the behavior mode and the severity of damage to the individual component. They are tabulated in the Component Guides in Chapters 5 through 8. The notation λ^* is used to denote modifications to pre-event properties for restored components. These also vary by behavior mode, damage severity, and type of restoration measure, in accordance with the recommendations of Chapters 5 through 8. Figure 4-6 illustrates the general relationship between damage severity and the modification factors. Component stiffness is most sensitive to damage, so this parameter must be modified even when damage is slight. Reduction in strength implies more significant damage. After relatively severe damage, the magnitudes of acceptable displacements are reduced.

4.4.3.3 Establishing λ Factors by Structural Testing

The component modification factors (λ factors) for an earthquake damaged building can be established by*

* ***Editor's note:***

As set forth in AB-099. Original text ended at page break.

Pseudo-dynamic test sequences may need to be carefully selected to produce enough cycles in each direction.

4.4.4 Global Displacement Demand

Prior earthquake damage may alter the future seismic response of a building by affecting the displacement demand and the displacement capacity. Effects of prior damage on the future displacement demands may be evaluated according to methods described in this section. Effects of prior damage on displacement capacity are described in Section 4.4.3.

FEMA 307 describes analytical and experimental studies of effects of prior damage on future earthquake response demands. A primary conclusion is that prior earthquake damage often does not cause a statistically significant change in maximum displacement demand for the overall structural system in future earthquakes under the following circumstances:

a. there is not rapid degradation of resistance with repeated cycles.

b. the performance ground motion associated with the future event produces a maximum displacement, d_d, larger than that produced by the damaging ground motion, d_e.

c. the residual drift of the damaged or repaired structure is small relative to d_e.

If the performance ground motion produces a maximum displacement, d'_d less than that produced by the damaging ground motion, d_e, the response of the damaged structure is more likely to differ from that of the pre-event structure, d_d (see Figure 4-8).

There are several alternatives for estimating the displacement demand for a given earthquake motion. FEMA 273 relies primarily on the displacement coefficient method. This approach uses a series of coefficients to modify the hypothetical linear-elastic response of a building to estimate its nonlinear-inelastic displacement demand. The capacity spectrum method (ATC 40) characterizes seismic demand initially using a 5% damped linear-elastic response spectrum and reduces the spectrum to reflect the effects of energy dissipation in an iterative process to estimate the inelastic displacement demand. The secant stiffness method (Kariotis et al., 1994), although formatted differently, is fundamentally similar to the capacity spectrum method. Both these latter two methods can be related to the substitute structure method (Shibata and Sozen, 1976). The use of each of these approaches to generate estimates of global displacement demand (d_d, d_d', and d_d^*) is summarized in the following sections. Generally, any of the methods may be used for the evaluation of the effects of damage; however, the same method should be used to calculate each of the global displacement demands (d_d, d_d', and d_d^*) when making relative comparisons using these parameters.

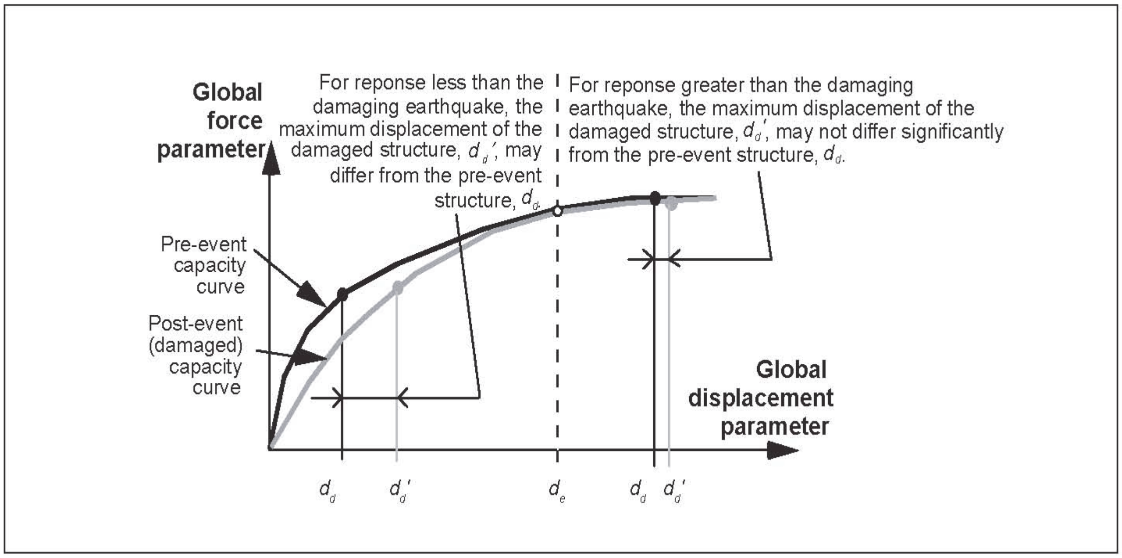


Figure 4-8 ***Maximum Displacement Dependency on Damaging Earthquake***

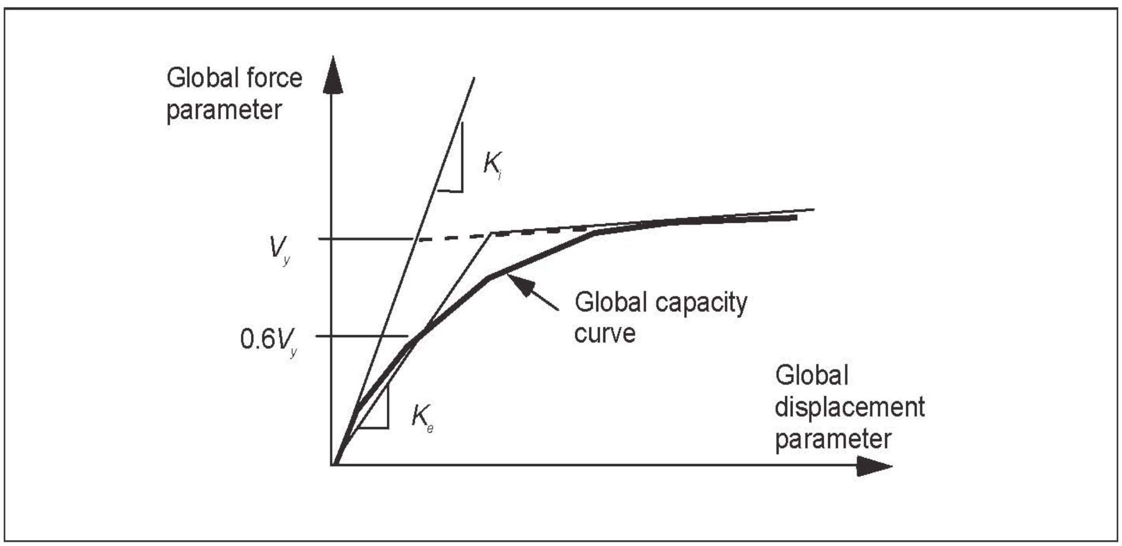


Figure 4-9 ***Global Capacity Dependency on Initial and Effective Stiffness***

4.4.4.1 Displacement Coefficient Method

The displacement coefficient method refers to the nonlinear static procedure described in Chapter 3 of ASCE-41. ~~FEMA 273.~~ The method also is described in Section 8.2.2.2 of ATC 40. The reader is referred to those documents for details in application of the procedure. A general overview and a description of the application of the method to damaged buildings are presented below.

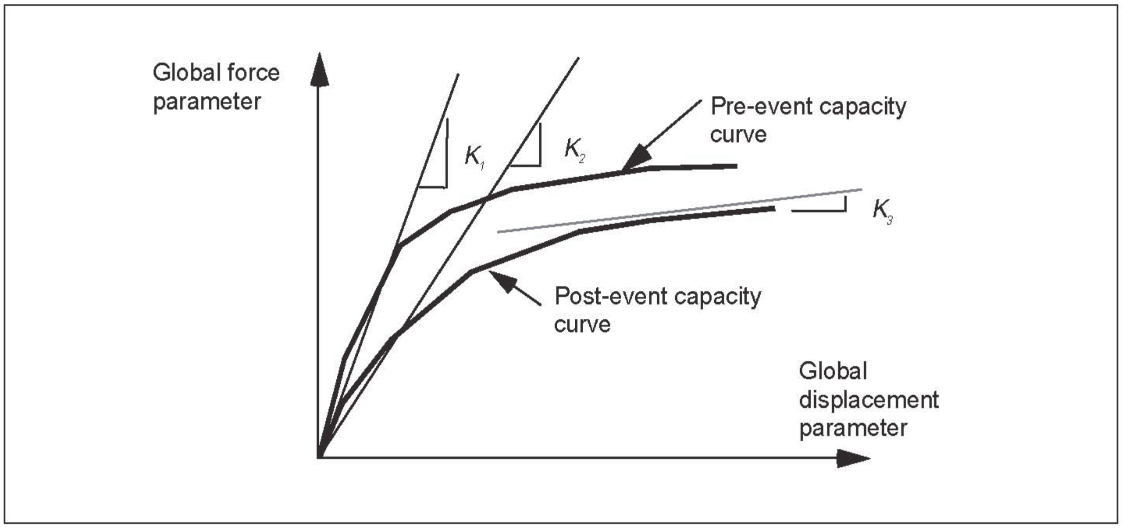


Figure 4-10 Pre- and Post-Event Capacity Curves with Associated Stiffnesses

The displacement coefficient method estimates the earthquake displacement demand for the building using a linear-elastic response spectrum. The response spectrum is plotted for a fixed value of equivalent damping, and the spectral response acceleration, S_a, is read from the spectrum for a period equal to the effective period, T_e. The effective period is defined by the following:

$$T_e = Ti \sqrt{\frac{K_i}{K_e}} \quad (4\text{-}1)$$

where T_i is the elastic fundamental period (in seconds) in the direction under consideration calculated by elastic dynamic analysis, K_i is the elastic lateral stiffness of the building in the direction under consideration (refer to Figure 4-9), and K_e is the effective lateral stiffness of the building in the direction under consideration (refer to Figure 4-9). As described in ASCE-41, ~~FEMA 273,~~ the effective lateral stiffness is taken as a secant to the capacity curve at base shear equal to $0.6V_y$. For a concrete or masonry wall building that has not been damaged previously by an earthquake, the effective damping is taken equal to 5% of critical damping.

The target displacement, δ_v, is calculated as:

$$\delta_1 = C_0 \quad C_1 \quad C_2 \quad C_3 \quad C_a \frac{T_e^2}{4\pi^2} \quad (4\text{-}2)$$

where C_0, C_1, C_2, C_3 are modification factors defined in ASCE-41, ~~FEMA 273,~~ and all other terms are as defined previously.

The maximum displacement, d_d, of the building in its pre-event condition for a performance ground motion is estimated by applying the displacement coefficient method using component properties representative of the pre-event conditions. To use the displacement coefficient method to estimate the maximum displacement demand, d'_d, during a performance ground motion for a building damaged by a previous earthquake use the following steps: (See Figure 4-10.)

1. Construct the relation between lateral seismic force (base shear) and global structural displacement (roof displacement) for the pre-event structure. Refer to this curve as the pre-event capacity curve. Pre-event force-displacement relations should reflect response characteristics observed in the damaging earthquake, as discussed in Section 3.6.

2. Construct a similar relationship between lateral seismic force and global structural displacement for the structure based on the damaged condition of the structure, using component modeling parameters defined in Section 4.4.3. Refer to this curve as the post-event capacity curve.

3. Define effective stiffnesses K_1, K_2, and K_3 as shown in Figure 4-10. K_1 is K_e (see Figure 4-9) calculated from the pre-event capacity curve. K_2 is K_e (see Figure 4-9) calculated from the post-event capacity curve. K_3 is the effective post-yield stiffness from the post-event capacity curve.

4. Apply the displacement coefficient method as defined in FEMA 273 with the effective stiffness taken as $K_e = K_1$, effective damping equal to 5% of critical damping, post-yield stiffness defined by stiffness K_3 , and effective yield strength defined by the intersection of the lines having slopes K_1 and K_3 to calculate δ_1 using Equation 4-2. Assign the displacement parameter d'_{d1} the value calculated for δ_1.

5. Apply the displacement coefficient method as defined in FEMA 273 with the effective stiffness taken as $K_e = K_2$, effective damping as defined by Equation 4-3, post-yield stiffness defined by stiffness K_3, and effective yield strength defined by the intersection of the lines having slopes K_2 and K_3 to calculate the displacement parameter d'_{d2}.

6. Using the displacement parameters d'_{d1} and d'_{d2}, estimate the displacement demand, d'_d, for the structure in its damaged condition as follows:

   a. If d'_{d1} is greater than d_e, then $d'_d = d'_{d1}$

   b. If d'_{d1} is less than d_e, then $d'_d = d'_{d2}$

The effective damping as defined by Equation 4-3 is consistent with experimental results obtained by Gulkan and Sozen (1974),

$$\beta = 0.05 + 0.2\left[1 - \left(\frac{K_2}{K_1}\right)^{0.5}\right] \quad (4\text{-}3)$$

For a restored or upgraded structure, the displacement demand, d^*_d, for a performance ground motion may be calculated using the displacement coefficient method with 5% damping using a capacity curve generated using applicable properties for existing components, whether repaired or not, and any supplemental components added to restore or upgrade the structure.

4.4.4.2 Capacity Spectrum Method

The capacity spectrum method is described in Section 8.2.2.1 of ATC 40. The reader is referred to that document for details in application of the procedure. A general overview and a description of the application of the method to damaged buildings are presented below.

The capacity spectrum method estimates the earthquake displacement demand for the building using a linear-elastic response spectrum. The response spectrum is plotted for a value of equivalent damping based on the degree of nonlinear response, and the spectral displacement response is read from the intersection of the capacity curve and the demand curve. In some instances of relatively large ground motion, the curves may not intersect, indicating potential collapse. In these cases the displacement coefficient method could be used as an alternate method for damage evaluation.

The maximum displacement of the building in its pre-event condition, d_d, for a performance ground motion is estimated by applying the capacity spectrum method using component properties representative of the pre-event conditions. To use the capacity spectrum method to estimate the maximum displacement demand, d'_d, during a performance ground motion for a building damaged by a previous earthquake, use the following steps:

1. Construct the relation between lateral seismic force (spectral acceleration) and global structural displacement (spectral displacement) for the structure assuming the damaging ground motion and its resultant damage had not occurred. Pre-event component force-deformation relationships should reflect response characteristics observed in the damaging earthquake as discussed in Section 3.6. Refer to this curve as the pre-event capacity curve.

2. Construct a similar relation between lateral seismic force and global structural displacement for the structure based on the damaged condition of the structure, using component modeling parameters defined in Section 4.4.3. Refer to this curve as the post-event capacity curve.

3. Apply the capacity spectrum method using the pre-event capacity curve to calculate the displacement parameter d'_{d1}.

4. Apply the capacity spectrum method using the post-event capacity curve to calculate the displacement parameter d'_{d2}. For determining the effective damping, the yield strength and displacement for the post-event capacity curve should be taken identically equal to the yield strength and displacement determined for the pre-event capacity curve. (See Equation 4-3.)

5. Using the displacement parameters d'_{d1} and d'_{d2}, estimate the displacement demand, d'_d, for the structure in its damaged condition as follows:

   a. If d'_{d1} is greater than d_e, then $d'_d = d'_{d1}$

   b. If d'_{d1} is less than d_e, then $d'_d = d'_{d2}$

For a restored or upgraded structure the displacement demand for a performance ground motion, d_{d*}, may be calculated using the capacity spectrum method based on a capacity curve using applicable properties for existing components, whether repaired or not, and any supplemental components added to restore or upgrade the structure.

4.4.4.3 Secant Stiffness Method

The secant stiffness method is described in Section 8.4.2.1 of ATC-40, *Seismic Evaluation and Retrofit of Concrete Buildings* (ATC, 1996). The reader is referred to that document for details in application of the procedure. To use the method for damaged buildings, the general procedure should be applied based on the properties of the damaged building.

4.4.4.4 Nonlinear Dynamic Procedure

As an alternative to the nonlinear static procedures described above, nonlinear dynamic response histories may be computed to estimate the displacement demand for the building. This dynamic analysis approach requires that suitable ground motion records be selected for both the damaging event and the performance ground motion. It also requires that representative structural models be prepared for the building in its pre-event (no superscript), damaged ('), and restored or upgraded (*) conditions. Detailed procedures have not been developed for the use of nonlinear dynamic response histories in relative performance analyses. The following sections offer general guidance on

Chapter 5: Reinforced Concrete

RC2H	COMPONENT DAMAGE CLASSIFICATION GUIDE	System: **Reinforced Concrete**
		Component Type: **Weaker Pier**
		Behavior Mode: **Preemptive Diagonal Tension**

How to distinguish behavior mode:

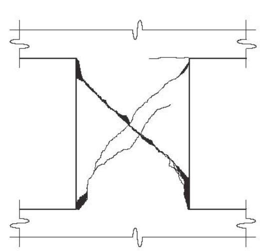
By observation:
For lower levels of damage, indications will be similar to those for other behavior modes, although flexural cracks may not be apparent. Damage quickly becomes heavy when diagonal cracks open up. Because flexural reinforcement never yields, flexural cracks should not have a width greater than 1/8 in.

Preemptive diagonal shear typically occurs in wall piers that have inadequate (or no) horizontal reinforcement, and that may have heavy vertical reinforcement. May be more prevalent in wall piers with low M/Vl_w ratio.

By analysis:
Strength in shear at low ductility is less than the capacity corresponding to moment strength, foundation rocking strength, or lap-splice strength (at low ductility).

Refer to Evaluation Procedures for:

- Identifying flexural versus shear cracks.
- Calculation of moment, shear, lap-splice, and foundation rocking strength.

Severity	Description of Damage		Performance Restoration Measures
Insignificant $\lambda_K = 0.9$ $\lambda_Q = 1.0$ $\lambda_D = 1.0$	*Criteria:* *Typical Appearance:*	• No shear cracking and • Flexural crack widths do not exceed 1/8 in. Similar to RC2A except no shear cracking and smaller crack widths.	See **RC1A**
Slight		Not Used	
Moderate $\lambda_K = 0.5$ $\lambda_Q = 0.8$ $\lambda_D = 0.9$	*Criteria:* *Typical Appearance:*	• No crack widths exceed 1/8 in. and • No vertical cracking or spalling Similar to insignificant damage except thin shear cracks may be present.	Inject cracks $\lambda_K^* = 0.8$ $\lambda_Q^* = 1.0$ $\lambda_D^* = 1.0$
Heavy $\lambda_K = 0.2$ $\lambda_Q = 0.3$ $\lambda_D = 0.7$ Note: λ_Q can be calculated based on shear strength at high ductility. See Section 5.3.6	*Criteria*: *Typical Appearance*:	Shear crack widths exceed 1/8 in. but do not exceed 3/8 in. Cracking becomes concentrated at one or more cracks. 	• Replacement or enhancement is required for full restoration of seismic performance. • For partial restoration of performance, Inject cracks. $\lambda_K^* = 0.5$ $\lambda_Q^* = 0.8$ $\lambda_D^* = 0.9$
Extreme	*Criteria:* *Typical Indications:*	• Reinforcement has fractured. • Wide shear cracking typically concentrated in a single crack.	Replacement or enhancement required.

ATTACHMENT B

FEMA 308 REPAIR OF EARTHQUAKE DAMAGED CONCRETE AND MASONRY WALL BUILDINGS
Chapter 3: Performance-Based Policy Framework

Table 3-1 Parameters governing whether damage is acceptable (see Figure 3-7a)

$L_{r(min)}$ =	Performance loss threshold below which restoration is not required regardless of the Damaged Performance Index, *P′*. (Avoids requiring restoration when the effects of damage on performance are small. This threshold would be comparatively lower for damaging earthquakes with small relative displacement demand (*S*) and higher for large ones.)
P'_{min} =	Damaged Performance Index limit below which restoration is required unless the Performance Loss is less than *Lr(min)*. (Limits how far the Damaged Performance Index (*P′*) can fall and still be acceptable without restoration. This limit would be comparatively lower for damaging earthquakes with large relative displacement demand (*S*) and higher for smaller ones.)
$L_{r(max)}$ =	Performance Loss threshold above which restoration is required unless the Damaged Performance Index exceeds P'_{max}. (Requires restoration for relatively large losses unless the Damaged Performance Index (*P′*) is high. The threshold would be comparatively lower for damaging earthquakes with small relative displacement demand (*S*) and higher for larger ones.)
P'_{max} =	Damaged Performance Index limit above which restoration is not required regardless of the Performance Loss. (Establishes when the Damaged Performance Index (*P′*) is acceptable without restoration. This limit would be comparatively lower for damaging earthquakes with large relative displacement demand (*S*) and higher for smaller ones.)

Table 3-2 Parameters governing whether restoration is acceptable (see Figure 3-7b)

$L_{u(min)}$ =	Performance Loss threshold below which upgrading is not required regardless of the Pre-event (Undamaged) Performance Index. (Avoids requiring upgrading when the effects of damage on performance are small. The threshold would be relatively lower for damaging earthquakes with small relative displacement demand (*S*) and higher for larger ones.)
P_{min} =	Pre-event Performance Index limit below which upgrading is required unless the Performance Loss is less than $L_{u(min)}$. (Establishes when the Pre-event Performance Index (*P*) is acceptable without upgrading. This limit would be relatively lower for damaging earthquakes with high relative displacement demand (*S*) and higher for smaller ones.)
$L_{u(max)}$ =	Performance Loss threshold above which upgrading is required unless the Pre-event Performance Index exceeds P_{max}. (Requires upgrading for relatively large losses unless the Pre-event Performance Index (*P*) is high. The threshold would be comparatively lower for damaging earthquakes with small relative displacement demand (*S*) and higher for larger ones.)
P_{max} =	Pre-event Performance Index limit above which upgrading is not required regardless of Performance Loss. (Establishes when the Pre-event Performance Index (*P*) is acceptable without upgrading. This limit would be comparatively lower for damaging earthquakes with large relative displacement demand (*S*) and higher for smaller ones.)

upgrading might not be required since the change in performance is negligible. This concept is represented by the horizontal line at $L_{r(min)}$. If the loss exceeds the minimum, then the decision on whether to accept the damage is controlled by how close the damaged performance index is to P'_{min} and P'_{max}. The lower end of the sloping portion of the restoration boundary represents the limit (P'_{min}). As the loss increases there is logically less tolerance for a lower damaged performance index (*P′*). As the loss increases further, there comes a point $L_{r(max)}$, at which the damaged performance index must be greater than P'_{max} ($P' > P'_{max}$) if damage is to be acceptable regardless of the loss. If the damaged performance index (*P′*, *L*) is within the restoration boundary, then either restoration or upgrading is required.

The parameters affecting the decision between upgrade or restoration are illustrated in Figure 3-7b. The decision between upgrade or restoration is controlled by the loss (*L*) and the pre-event performance index (*P*). The upgrade boundary is delineated similarly to the restoration boundary using the parameters in Table 3-2.