THE REPAIR OF EARTHQUAKE DAMAGED BUILDINGS

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SUMMARY

Procedures for the evaluation and repair of earthquake damaged buildings have been developed recently by the Applied Technology Council with funding by the Federal Emergency Management Agency. The methodology compares future seismic performance of a building in its pre-event, damaged, and repaired conditions. Global structural displacements from nonlinear static analyses serve as capacity indices related to selected performance levels (i.e. collapse prevention, significant damage, minimal damage). These capacities are compared to global displacement demands for predicted local seismic hazard levels. This paper uses an example building to illustrate these basic concepts and concludes with a philosophy for establishing performance-based evaluation and repair decisions.

INTRODUCTION

The Applied Technology Council has recently completed a project (ATC 43) funded by the Federal Emergency Management Agency (FEMA) addressing the evaluation and repair of earthquake damaged wall buildings. The results are presented in three documents. *FEMA 306: The Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings - Basic Procedures Manual* documents performance based evaluation procedures. The procedures address the investigation, documentation, and classification of damage caused by earthquakes to building components according to mode of structural behavior and severity. This information is used to evaluate of the effects of the damage on the performance of the building during future earthquakes. *FEMA 307: The Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings - Technical Resources* provides supplemental data that facilitates application of the procedures and includes an example application. *FEMA 308: Repair of Earthquake Damaged Concrete and Masonry Wall Buildings* addresses the use of a performance based methodology to select appropriate action to accept the damage as is, restore, or upgrade the earthquake damaged building.

In response to recent past earthquakes in California (CSSC, 1994; Holmes, 1994; and Russell 1994) and in Japan (Sugano, 1996) the affected communities have addressed the challenge of earthquake repair and reconstruction in their own way. A review of their experiences reveals several general observations. (1) The economic impact of an earthquake is a major influence on the implementation of policies for repair and upgrading after the event. The competing needs to restore the economic vitality of the community and to provide enhanced future earthquake resilience after a damaging earthquake present difficult and complex problem for individual building owners and the local government. Appropriate policies should balance the competing needs for public safety, private property rights, historic preservation, urban planning, economic development, ethical and legal considerations, among others. (2) There is a lack of adequate standards directed to the post-earthquake repair of damaged buildings. Most jurisdictions rely upon some adaptation of an existing code or model building ordinance for new building construction for these guidelines. Some jurisdictions have enacted emergency provisions developed after the event in a reactive manner. (3) There is a greater tolerance for damage and lower repair standards as the size of the damaging earthquake increases.

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The procedures of *FEMA 308* result in a policy framework that is capable of addressing and incorporating these and other issues for improved decisions on alternatives for damaged buildings or groups of buildings. Three alternatives are considered: (1) Accept the building for continued use in its damaged condition. (2) Restore the building to its pre-event condition. (3) Upgrade the building for improved seismic performance compared to its pre-event condition. The selection among these basic alternatives for a damaged building implies a capability to distinguish between the expected performance of the undamaged, damaged, restored (assumed to be the same as the undamaged), and upgraded building to some expected future seismic demand. This capability relies on the performance analysis procedures developed in *FEMA 306*. This paper illustrates this policy framework with the practical example contained in *FEMA 307*.

EXAMPLE BUILDING

The example is a reinforced concrete shear wall building evaluated and repaired after the 1994 Northridge earthquake. The building had also been damaged by and repaired after the 1971 Sylmar earthquake. The building is a two-story reinforced concrete building located on a sloping site. It is “T” shape in plan, Figure 1, with the stem of the tee on the downhill side with a lower story. The building was designed and constructed in the 1950s and is located about 4 miles from the epicenter of the Northridge earthquake. The overall plan dimensions of the building are 362 feet in the North-South direction by 299 feet in the East-West direction. Reinforced concrete walls in both directions of the building resist lateral forces. Some of the 26 feet long walls are solid and others have door openings 7.25 feet high by 6.5 feet wide (coupled walls). The building has four two-story solid walls and six walls with door openings in the North-South direction, and six solid walls and two walls with door openings in the East-West direction. In the three-story section of the building (the stem of the “T”), the walls do not continue at the lower level, but has one one-story solid wall in the north-south direction.

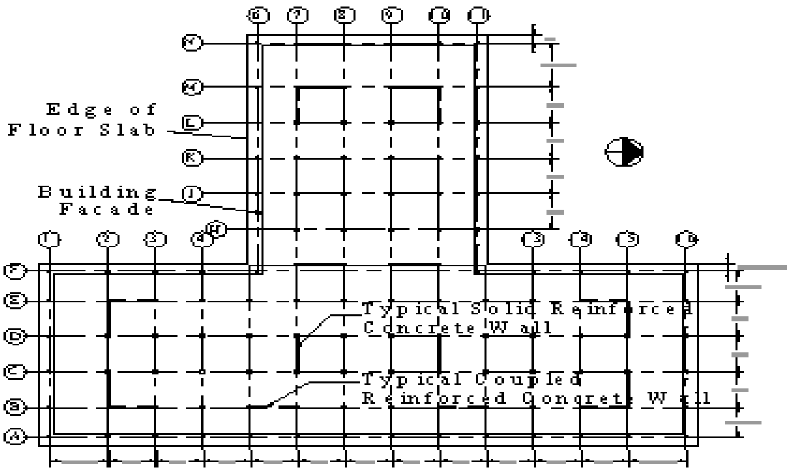


Figure 1. Example building plan. [from FEMA 307]

During the Northridge earthquake, the concrete walls experienced minor to moderate amounts of cracking. Based on the visual observations, component damage records were prepared for each of the walls in the building. These forms are included in *FEMA 306* along with guides for tests and inspection procedures for assessing damage. The most heavily damaged walls were the first-story-coupled walls in the stem of the T section of the building. These experienced heavy cracking in the coupling beams, including spalling and bar buckling in some locations. Damage to the other walls was less severe.

FEMA 306 includes extensive guidance on the identification of structural components and the classification of component damage according to behavior mode and severity. Structural components are identified by determining the inelastic lateral mechanism for the structure. This is done by comparison of expected strengths and by observation of the damage. The solid wall is considered as a single component. The wall with door openings is considered as a coupled wall with four components: two coupling beams and two, two-story, wall piers that where determined to be strong enough to fail the coupling beams.

Each of the structural wall components is evaluated to determine behavior mode and severity of damage. This is done again by a combination of calculations of governing strengths (e.g. shear vs. flexure) and by observation of the damage. Once the behavior mode is determined, the component damage is the assigned a severity of

Insignificant, *Slight*, *Moderate*, *Heavy* or *Extreme*. These designations are used, as discussed below, to modify the properties of the damaged component. *FEMA 306* provides an extensive set of Component Guides to facilitate this overall process.

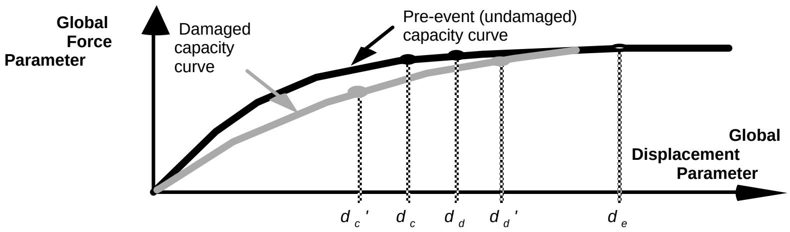
The typical solid walls in the example were determined to behave in a foundation rocking (or overturning) mode. Damage associated with this behavior may not be apparent based on observation of the walls. Damage to other structural and non-structural elements, such as the floor slab at the base or to the beams framing into the ends of the walls, were used to judge the severity of the mode. Because there was no significant damage to the adjacent structural and non-structural elements, the damage severity was judged to be *Insignificant* for all the solid walls. This behavior mode is considered to have moderate to high ductility.

The behavior mode for the coupling beams was determined to be pre-emptive diagonal tension. Damage for coupling beams with spalling, bar-buckling, and/or significant cracking was classified as *Heavy*. For coupling beams with shear cracking, but no bar-buckling or significant spalling, the damage was classified as *Moderate*. Three of the eight coupling beams at the first floor ceiling had *Heavy* damage and the remaining five had *Moderate* damage. Seven of the eight coupling beams at the second floor ceiling had *Moderate* damage and the remaining one had *Insignificant* damage. This behavior mode is considered as a brittle type.

The wall piers adjacent to the coupling beams were determined to behave in individual pier rocking mode. Similarly to the solid walls, the lack of adjacent structural or non-structural damage was used to classify their damage as *Insignificant*. This behavior mode is considered to have moderate to high ductility.

PERFORMANCE BASED ANALYSIS

The *FEMA 306/307/308* performance-based approach utilizes structural analysis procedures that focus on inelastic displacements of the building. Nonlinear static procedures (NSPs) are used to generate a plot, called a capacity curve, Figure 2, relating a global displacement parameter (roof level displacement, for example) to the lateral force imposed on the structure (base shear force, for example). The nonlinear model of the building is an assembly of its individual structural components. The behavior of the structure in its undamaged, damaged and restored conditions is controlled by associated inelastic force-deformation relationships for each component. The force-deformation characteristics for individual components are monotonic idealizations of representative hysteretic behavior under cyclic loading conditions following the *FEMA 273/274* or *ATC 40* approach. For a given global displacement of a structure subject to a selected lateral load pattern, there is an associated deformation of each structural component of the building. Because inelastic deformation implies component damage, the maximum global displacement, d_d, to occur during an earthquake represents the structural damage state for the building in terms of inelastic deformations for each of its components. The capacity of given structure is represented by the maximum global displacement limit, d_c, at which the damage reaches the selected performance level. For example, the Collapse Prevention displacement limit capacity of a building might be the roof displacement at which the associated damage would result in collapse of one or more of the column components.



d_e = Estimate of maximum global displacement caused by damaging earthquake

d_c = Global displacement capacity for undamaged structure for specified performance level

d_c ' = Global displacement capacity for damaged structure for specified performance level

d_d = Global displacement demand for undamaged structure for specified seismic hazard

d_d ' = Global displacement demand for damaged structure for specified seismic hazard

Figure 2. Capacity curves from nonlinear static procedures. [from FEMA 308]

At the beginning of the damage evaluation procedure, the engineer identifies basic building components and documents the damage to each component as discussed previously. Using component properties for the pre-event structural conditions, Figure 3, the capacity curve and the global displacement parameters (d_c and d_d) are calculated for the building. Next, the structural properties of the components are modified to model the effects of the observed damage using λ-factors contained in *FEMA 306* supplemented by additional information contained in *FEMA 307*. The λ-factors are assumed based on the component mode of behavior and the severity of damage. They reduce the strength, stiffness, and allowable displacements for the damaged component. This then allows the calculation of the capacity curve and the global displacements parameters (d_c' and d_d') for the building in its damaged condition. The same basic approach is used to modify the component properties to account for repairs and/or upgrades on the capacity curve and global displacement parameters (d_c* and d_d*) for the building in a restored or upgraded condition.

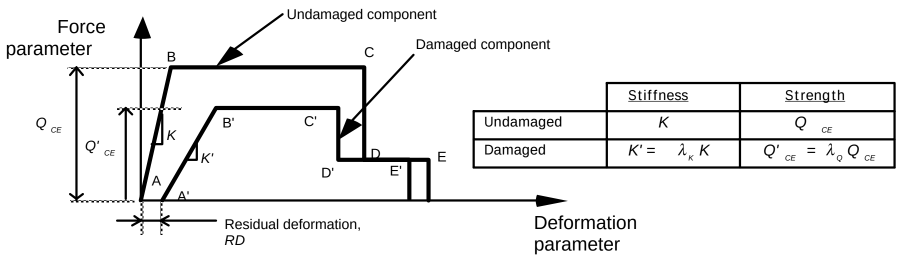


Figure 3. Undamaged and damaged component properties. [from FEMA 306]

The ratio of global displacement capacity limits (d_c, d_c', d_c*) for a selected performance level, illustrated in Figure 4, to the corresponding displacement demands (d_d, d_d', d_d*) for a selected seismic hazard are used to define indices (P, P', $P*$) of the capability of an undamaged ( ), damaged ('), or restored/upgraded (*) building to meet the selected performance objective. These can be expressed as:

$P = d_c/d_d$ Pre-event performance index,

$P' = d_c'/d_d'$ Damaged performance index,

$P* = d_c*/d_d*$ Restored/upgraded performance index.

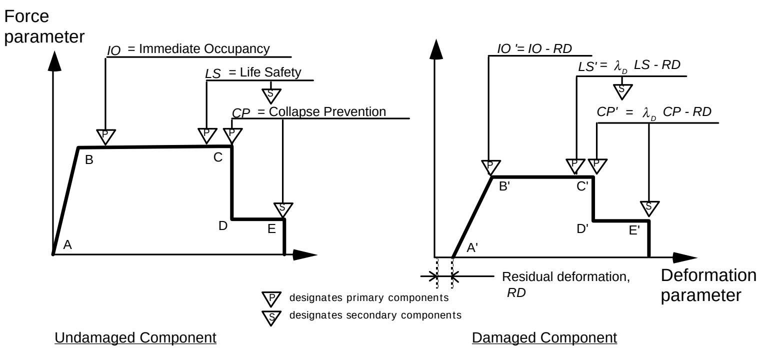


Figure 4. Undamaged and damaged component deformation acceptability limits. [from FEMA 306]

If the performance index is less than one, the implication is that the building does not have the capability to meet the selected performance objective. If the performance index is 1.0 or greater, the implication is that it does. Note that these indices are associated with a specific performance objective. The same building in the same condition may have different performance indices for different performance objectives. The ratio of the damaged performance index, P', to the undamaged performance index, P, for a building for a selected performance objective is a measure of the anticipated performance capacity of the damaged building relative to that for the building in its pre-event state. The loss in performance capacity caused by the damaging event can be defined as $L = 1 - (P'/P)$ Performance loss

For the FEMA 307 example a performance objective of life safety for an earthquake with 10 percent probability of exceedance in 50 years (a 475-year return period) results in a displacement demand of 1.68 inches for both the pre-event, d_d, and damaged, d_d', state. The life safety limit for the pre-event building was selected to be when the first floor coupling beam reached its shear capacity at 0.88 inches. Using the λ-factors for the damaged components (For the coupling walls, Heavy: stiffness = 0.4, strength = 0.5, displacement = 0.8; Moderate: stiffness = 0.5, strength = 0.8, displacement = 0.9), it was estimated that the damaged building first floor coupling beam will reach its shear capacity at 0.66 inches. Comparing the pre-event and post-event pushover curves in Figure 5, it can be seen that this estimate based on component criteria is conservative for overall system performance. It was estimated from the analyses and the observed damage that probable maximum roof displacement during the Northridge earthquake was d_e = 0.6 inches. Using these demand parameters and the global capacity calculated for the pre-event and damaged structural models the following relative performance data is generated for the example building:

$P = d_c/d_d = 0.88 / 1.68 = 0.52$ Pre-event performance index,

$P' = d_c'/d_d' = 0.66 / 1.68 = 0.39$ Damaged performance index,

$L = 1 – (0.39 / 0.52) = 0.25$ Performance Loss

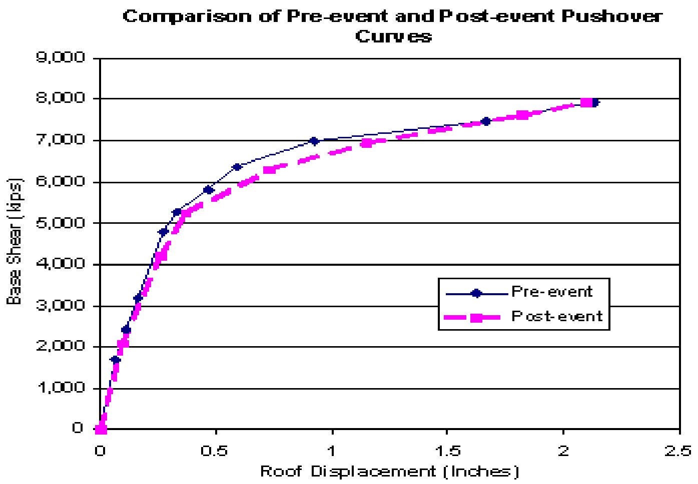


Figure 5. Comparison of pre-event and post-event pushover curves. [from FEMA 307]

THE DECISION TO ACCEPT, RESTORE, OR UPGRADE

The appropriate decision to accept, restore, or upgrade an earthquake damaged building depends on a number of interrelated factors including:

1. Relative severity of damaging ground motion - A building significantly damaged in a small earthquake is a good candidate for upgrading. However, similar damage caused by large ground motion may need only minor repair. The decision on repair and/or upgrading needs to consider the relative difference between the damaging earthquake and the selected design earthquake.

2. Performance characteristics of the building after the damaging earthquake - If the damaged building is capable of meeting reasonable performance objectives in its damaged state, repair or upgrading may be unnecessary. It is also possible that short-term performance objectives, lower than those appropriate for the longer term, may be acceptable while other alternatives are considered.

3. Performance characteristics of the building before the damaging earthquake - It is not logical to restore a building to a poor level of expected performance.

4. The change in performance characteristics of the building caused by the damaging earthquake - If the damaging earthquake causes a large decrease in the performance characteristics of a building, restoration or upgrading are needed. Small loss in capacities, particularly for large earthquake ground motions, is acceptable.

5. Nonseismic issues related to the condition and use of the building - Nonseismic deficiencies (e.g. disabled access, fire and life safety, programmatic, maintenance) are important considerations. The anticipated future use of a building can change its seismic performance objectives. It makes little sense to extend the life of a building significantly without addressing seismic deficiencies. Nor is it reasonable to address seismic problems while ignoring other considerations. The proper scope of a restoration or upgrading project is balance among many goals.

First, consider whether the damage is acceptable for this example building. The Damaged Performance Index (0.39) is substantially less than one, indicating that the damaged building is rather deficient with respect to the selected performance objective. The size of the damaging ground motion in this example was not particularly large compared to that for the performance event ($S = d_e/d_d = 0.36$). It is concluded from the relative performance analysis that the damage should not be accepted for this example. If, however, the performance objective was different the conclusion might change. Assume, for example, that the desired performance level was Collapse Prevention for an event with a 10% chance of exceedance in 100 years and that the performance indices and loss were:

$P = d_c/d_d = 0.95$	Pre-event performance index,
$P' = d_c'/d_d' = 0.71$	Damaged performance index,
$L = 1 - (0.71 / 0.95) = 0.25$	Performance Loss
$S = d_e/d_d = 0.65$	Damage to performance ground motion ratio

In this case, it might be reasonable to conclude that the building need not be repaired since the damaged performance index is moderately high (0.71), the performance loss (0.25) is not extreme, and the damaging ground motion is significant (0.65). The propriety of this conclusion increases as the size of the event damaging ground motion compared that for the performance ground motion, *S*, increases.

The three decision parameters controlling whether the damage is acceptable without repair are:

$L_{r(min)}$=	Performance loss threshold below which restoration is not required regardless of the damaged performance index
P'_{max} =	Damaged performance index threshold above which restoration is not required regardless of the performance loss
$S = d_e/d_d$ =	Size of the damaging ground motion relative to the performance ground motion

The interaction of these parameters is illustrated three dimensionally in Figure 6. Note that there is a gradual transition of control of the decision from the loss threshold to the damaged performance index.

Similar logic can be used to develop the three decision parameters controlling whether the damaged building should be restored to its pre-event performance or upgraded. In the decision to restore or upgrade performance, the pre-event performance index replaces the damaged performance index. *FEMA 306/307/308* include guidelines for formulating repair measures to restore the damaged building to its pre-event performance capability ($P^* = P$) or to upgrade performance to a selected performance objective ($P^* = 1.0$). Restoration and/or upgrade strategies may take several different forms:

1. Component restoration entails the repair of individual elements to restore structural properties that were diminished as a result of the earthquake damage. For example, cracks in shear walls might be injected with grout to restore component strength and/or stiffness. Outline specifications for typical repairs for concrete and masonry wall buildings are included in *FEMA 308*.

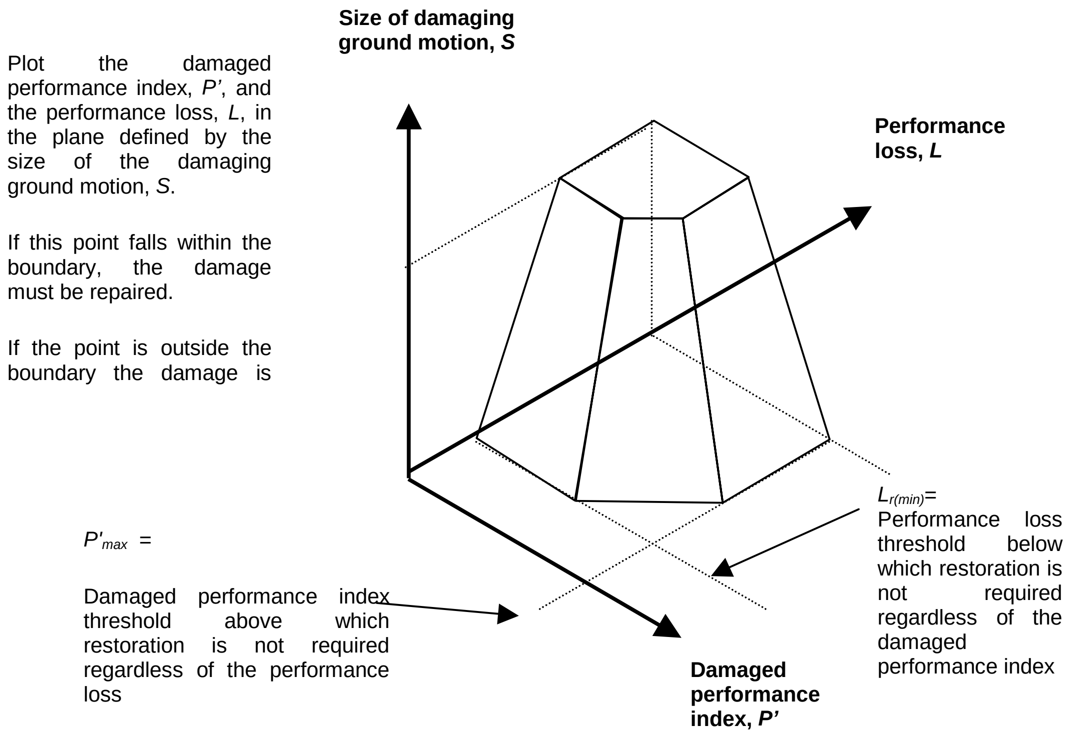


Figure 6: Decision parameters for acceptance or restoration of a damaged building.

2. An extreme case of component repair is complete replacement. A severely damage wall section might be completely removed and replaced with a similar or improved component. In some cases, this is the only alternative. In other cases it may be an economic alternative.

3. Performance can also be restored or upgraded by the addition of new supplemental lateral resisting elements or components. Instead of repairing or replacing a damaged section of wall, a new wall component might be installed in another location.

The process of repair and/or upgrade design involves developing a component level strategy including one, or a combination, of the above alternatives. The proposed strategy is then tested by analyzing the performance of the modified structure and recalculating the measures until the performance is approximately the same as the pre-event building ($P^* = P$), or if desired, the selected performance objective ($P^* = 1.0$).

In the example the performance can be restored with the repair of the heavily damaged coupling beams by removal of the concrete, placement of additional reinforcing steel to meet current code detailing requirements, and replace the concrete. This provides ductile coupling behavior for these five locations but does not change the behavior for the remaining coupling beams. This provides only a slight increase in performance capabilities over the pre-event building.

CONCLUSIONS

The performance base methodology for the evaluation and repair of earthquake damaged buildings provides the opportunity to use limited financial resources wisely. As noted, criteria for decisions to repair and/or upgrade damaged buildings have not been established. While the loss and performance values can be calculated for a specific building using the procedures described in the previous sections, the limiting parameters in Figure 7 need to be defined in a realistic manner by the local building jurisdiction. Selection of inappropriately high loss and low performance limits can result in too many post-earthquake potentially hazardous buildings, while selection of too onerous upgrading requirements can stall or destroy the local economy. Communities need to prepare for the future earthquake by:

1. Establishing seismic performance objectives for existing buildings in the community. Selection of appropriate objectives should be based on the size, age, occupancy, and function of the individual building.

2. Adopting a seismic hazard demand standard. These can be based on some proportion of the demand for new buildings or can be more detailed based on regional or local conditions.

3. Adopting loss thresholds for repair and upgrading that are a function of the local intensity of damaging earthquake. Research on loss estimation and economic recovery after earthquakes is needed to identify appropriate levels of tolerable damage.

4. Establishing a relationship between mandatory upgrading of existing buildings and the repair/upgrade of damaged buildings. Seismic performance objectives and repairs and modifications required to meet them are best incorporated into long-term facility planning and replacement process. Buildings and their systems and furnishings deteriorate over time. Additionally, the programmatic needs of the owner or occupant also evolve. Modifications toward improved seismic performance should fall into the same category, unless extraordinary life safety problems are identified.

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