4. POST-EARTHQUAKE EVALUATION

Post-earthquake evaluation is the multi-step process conducted following an earthquake to: determine the extent and severity of damage experienced by a building; assess the implications of damage with regard to building safety; and determine appropriate occupancy, structural repair and modification strategies.

Detailed post-earthquake evaluations of buildings are costly. An initial screening (preliminary evaluation) process is recommended to identify those buildings most likely to have been damaged. Screening criteria include ground shaking severity estimates, proximity to other structures known to be damaged and significant observable damage to the building itself. Buildings identified by screening as likely to have been damaged should be subjected to detailed evaluation.

Analyses of damaged buildings show that although damage occurred at slightly higher frequency in locations predicted to have high strength and deformation demands, damaged connections tend to be widely distributed throughout the building frames, often at locations analyses would not predict. This approximates a random distribution. To detect all such damage, it would be necessary to subject each connection to detailed inspections. In order to reduce inspection costs, but still reliably detect damage, these Interim Guidelines recommend inspection of representative samples of connections and the use of statistical techniques to project damage observed in the samples to that likely experienced by the entire building.

In order to obtain valid projections of a building's condition, samples should be broadly representative of the varying conditions (location, member sizes, structural demand) present throughout the building and should be sufficiently large to permit confidence in the projection of overall building damage. Three alternative methods for sample selection are provided. When substantial damage is found within the sample of connections, additional connections are inspected to provide better, and more reliable information on building condition.

Once the extent of building damage is determined, the structural engineer should assess the residual structural integrity and safety, and determine appropriate repair and/or modification actions. General recommendations are provided, based on calculated damage indices. Direct application of engineering analysis may also be used. For individual structures, the structural engineer should confirm that the general recommendations are appropriate, based on evaluation of the specific structural characteristics of the damaged building and on engineering judgment.

4.1 Scope

This Chapter presents guidelines for:

1) identifying those WSMF structures likely to have been damaged in an earthquake;

2) development of a program of inspection for structures suspected of having been damaged;

3) assessing the implications of discovered damage; and

4) determining appropriate occupancy, repair, and/or structural modification actions to protect life safety.

Nothing in these Interim Guidelines should be deemed to preempt the judgment of the building official or to prevent individual structural engineers from adopting alternative approaches based on accepted engineering principles, rational criteria and sound reasoning. However, independent qualified third party review should be considered when such alternative approaches are adopted. Section 4.5 provides recommended criteria for such independent third party reviews.

Commentary: This Chapter provides a basic approach and suggested criteria for post-earthquake evaluation. This includes preliminary evaluation to determine if a building is likely to have been damaged and detailed evaluation to determine the actual damage experienced and the extent to which the building's lateral-force-resisting system has been compromised. In the detailed evaluation methodology, procedures are given for selecting a representative sample of building connections for inspection, and for interpreting the results of these inspections. Chapter 5 provides detailed recommendations on how to perform inspections. Chapter 6 provides guidance on damage repair as well as structural modification to improve future seismic performance.

4.2 Preliminary Evaluation

This section provides recommended criteria for determining which WSMF structures should be subjected to detailed post-earthquake evaluations and suggestions for the scheduling of such evaluations. It also provides recommendations (Section 4.2.4) for the acceptance of inspection and evaluation programs performed prior to the publication of these Interim Guidelines.

Following an earthquake, all WSMF structures that experienced ground motion having the potential to cause structural damage in these buildings, as indicated in Section 4.2.1, should be subjected to a detailed evaluation. Given that a detailed evaluation should be performed for a building, this evaluation should be completed prior to:

1) permanent occupancy of a building under construction at the time of the earthquake;

2) reoccupancy of a building closed for post-earthquake repairs that require a building permit; or

3) reoccupancy of a building where occupancy was limited by the building official as a result of apparent structural damage.

The results of all building evaluations should be transmitted to the building owner and filed with the building official as described in Section 4.3.9.

Commentary: This section provides guidelines for building officials and structural engineers to determine if a WSMF building should be subjected to detailed evaluations. An evaluation includes, as a minimum, assessment as to whether the building has experienced sufficient earthquake-induced structural demands to cause damage, and unless this is judged not to be the case, detailed structural evaluations should be performed. Given the high levels of uncertainty associated with the many issues involved in making such judgments, inspections should be performed for any building suspected of having damage, even when the provisions of these Interim Guidelines or the building official do not so require. It is particularly recommended that all buildings indicated by the preliminary evaluation of Section 4.2.1 as likely to have been damaged be subjected to detailed evaluations, regardless of whether or not the building official so directs.

4.2.1 Evaluation Process

Preliminary evaluation is the process of determining if a building should be subjected to detailed post-earthquake evaluations. Detailed evaluations should be performed for all buildings thought to have experienced strong ground motion, as indicated in Section 4.2.1.1 or for which the other indicators of Section 4.2.1.2 apply. Detailed post-earthquake evaluations include the entire process of determining if a building has experienced significant damage and if damage is found, determining appropriate strategies for occupancy, structural repair and/or modification. Except as indicated in Section 4.2.3, detailed evaluation should include inspections of a representative sample of moment-resisting (and other type) connections within the building.

4.2.1.1 Ground Motion

Within *UBC* Seismic Zone 4 {*NEHRP* Map Area 7}, detailed evaluation is recommended for all WSMF buildings when an earthquake of Magnitude greater than or equal to 6.5 has produced ground motion at the building site in excess of 0.20g, or when any earthquake has produced ground motion at the building site in excess of 0.30g. For buildings located in zones of lower seismicity, refer to Table 4-1, Section 4.2.2 for appropriate ground motion thresholds. Whenever feasible, ground motion estimates should be based on actual instrumental recordings in the vicinity of the building. When such instrumental recordings are not available, ground motion estimates may be based on empirical or analytical techniques. In all cases, ground motion estimates should reflect the site-specific soil conditions.

Commentary: A number of techniques are available for estimating the distribution of ground motion in an area, following an earthquake. In regions with a large number of strong motion accelerographs present, actual ground motion recordings produce the best method of mapping contours of ground motion. In other regions, empirical techniques, such as the use of standard *ground motion attenuation relationships (e.g. Joyner and Boore - 1994, Campbell and Bazorgnia - 1994) may be required. These can be supplemented with analytically derived estimates such as those obtained by direct simulation of the fault rupture and ground wave propagation. It should be noted, however, that lacking direct instrumental evidence, site-specific ground motion estimates are at best, uncertain, and subject to wide variations depending on the assumptions made. Therefore, the best indicator of the severity of ground motion at a site is often the performance of adjacent construction. The criteria of Section 4.2.1.2 are provided to help assure that sites which experienced strong ground motion are not overlooked as a result of inaccurate estimates of the ground motion severity.*

4.2.1.2 Additional Indicators

Regardless of the magnitude of the earthquake event, detailed evaluation should be considered for a building if any of the following apply:

1) significant structural damage is observed in one or more WSMF structures located within 1 kilometer of the building, on sites with similar, or more firm soil profiles;

2) significant structural damage is observed to one or more modern, apparently well-designed structures (of any material) within 1 kilometer of the building and on sites with similar, or more firm soil profiles;

3) for an earthquake having a magnitude of 6.5 or greater, the structure is either within 5 kilometers of the trace of a surface rupture or within the vertical projection of the rupture area when no surface rupture has occurred.

4) significant architectural or structural damage is observed in the building;

5) permanent interstory drift greater than 0.5% of story height is observed;

6) unexpected damage, or significant period lengthening of the building are observed in aftershocks; or

7) entry to the building has been limited by the building official because of earthquake damage, regardless of the type or nature of the damage.

Commentary: In the above, the term "significant" has been used without definition or quantification. The intent is to use known damage as an indicator of the severity of ground motion experienced. Damage is dependent not only on the strength of ground motion, but also on the quality and condition of the affected construction. Relatively moderate damage to buildings having regular configuration and adequate lateral-force-resisting systems may be a more significant indicator of strong ground motion than heavy damage to construction *in poor condition or having other poor earthquake resisting characteristics. The building official and/or structural engineer should use their own judgment in determining the significance of such damage.*

The absence of significant observable damage to WSMF structures on sites believed to have experienced strong ground motion, per Section 4.2.1, should not be used as an indication that detailed evaluations are not required. Many WSMF buildings that were structurally damaged by the Northridge Earthquake had little apparent damage based on casual observation.

The observed behavior of a building in repeated aftershocks may provide some clues as to whether it has experienced significant structural damage. In instrumented buildings it may be possible to observe a period shift in the instrumented response, as successive damage occurs. In buildings without instruments, the observation of unexpectedly large amounts of architectural damage could indicate the presence of structural damage.

In many cases in the past, buildings have initially been posted as unsafe without adequate investigation of their condition. Upon reconsideration and technical evaluation such buildings have subsequently been re-posted to allow occupancy. In such cases and for the purposes of item 7 above, the building need not be considered to have been posted.

4.2.2 Evaluation Schedule

When a detailed evaluation of a building is recommended, under Section 4.2.1, such evaluation should be completed as soon as practical and in any event, within a 12-month period from the date of the earthquake main shock, unless a shorter period is indicated in Table 4-1.

Table 4-1 - Suggested Time Limits for Post-Earthquake Evaluation[1]

Estimated PGA Range at Site[3]	$6.0<M\le 6.5$	$6.5<M\le 7.2$	$7.2<M$
$PGA>0.40g$[3]	6 months	6 months[2]	6 months[2]
0.3[3] $<PGA\le$ 0.4[3]	12 months	6 months	6 months[2]
0.2[3] $<PGA\le$ 0.3[3]	(1)	12 months	12 months

Notes:

1. Evaluation not required unless one or more of the conditions of Section 4.2.1.2 apply.
2. Buildings meeting this criteria are likely to have experienced significant damage and evaluations should be performed rapidly. If NDT technicians are not readily available, visual inspection, in accordance with Section 5.2.2 should proceed expeditiously. If in the course of such visual inspection, serious damage to connections is observed, then consideration should be given to the safety of the occupants in possible aftershocks.
3. The indicated PGA's are for modern buildings designed to *UBC* Zone 4 {NEHRP Map Area 7} criteria. For buildings designed to other criteria or for other seismic zones, the indicated PGA values should be reduced by the factor Z/0.4 (for localities that have adopted the *UBC*) {by the factor $A_a/0.4$ for localities that have adopted codes based on the *NEHRP* Provisions}. The indicated PGA's need not be reduced lower than 0.15g.

Commentary: It is important to conduct post-earthquake evaluations as soon following the earthquake as is practical. Aftershock activity in the months immediately following an earthquake is likely to produce additional strong ground motion at the site of a damaged building. If there is adequate reason to assume that damage has occurred, then such damage should be expeditiously uncovered and repaired. However, since adequate resources for post-earthquake evaluation may be limited, a staggered schedule is presented, with those buildings having a greater likelihood of damage recommended for evaluation first.

Large magnitude earthquakes are often followed by large magnitude aftershocks. Therefore, it is particularly urgent that post-earthquake evaluations be performed expeditiously following such events. If insufficient resources are available in the affected region to perform the NDT tests recommended by the Guidelines of Chapter 5, it is recommended that visual inspection, in accordance with Section 5.2.2, proceed as soon as possible. If visual inspection reveals substantial damage, consideration should be given to vacating the building until either an adequate period of time has passed so as to make the likelihood of very large aftershocks relatively low (e.g. 4 weeks for magnitude 7 and lower, and 8 weeks for magnitudes above this), complete inspections and repairs are made, or a detailed evaluation indicates that the structure retains adequate structural stiffness and strength to resist additional strong ground shaking. Preliminary visual inspections should not be used as an alternative to complete evaluation.

The table relates the urgency for post-earthquake building evaluation to both the magnitude of the earthquake and the estimated peak ground acceleration experienced by the building site. This is because large magnitude events are more likely to have large magnitude aftershocks and because buildings that experienced stronger ground accelerations are more likely to have been damaged. Except in regions with extensive strong motion instrumentation, estimates of ground motion are quite subjective. Following major damaging earthquakes, government agencies usually produce ground motion maps showing projected acceleration contours. These maps should be used when available. When such maps are not available, ground motions can be estimated using any of several attenuation relationships that have been published.

4.2.3 Connection Inspections

Detailed evaluations should include inspections of a representative sample of WSMF (and other) connections, except as indicated in Sections 4.2.3.1 and 4.2.3.2, below. Section 4.3.3 provides three alternative approaches to selecting an appropriate sample of connections for inspection.

4.2.3.1 Analytical Evaluation

Connection inspections need not be performed for buildings on sites meeting the criteria of Section 4.2.1.1, if conditions 4,5,6, and 7 of Section 4.2.1.2 are observed not to be present and a structural analysis indicates that estimated stresses in welded moment-resisting connections during the earthquake were all below the beam flexural design strength. For calculation of this strength, F_y should be taken as the minimum specified yield strength for the framing members. Such analysis should be performed using an estimated ground motion representation (response spectrum or acceleration time history) similar to that believed to have occurred at the site during the earthquake. For the purpose of this analysis, the ground motion and resulting stresses computed in the various framing elements should not be reduced by the lateral force reduction coefficients (R_w or R) contained in the building code.

Commentary: This section suggests that unless there is visible evidence that a building has been damaged, detailed connection inspections need not be performed for buildings which can be demonstrated by analysis to have experienced very low levels of stress. It will be possible to demonstrate this when ground motions at a site are low, or when the ground motion spectrum at a site was such that little excitation would have occurred at predominant modes for the building. A dynamic analysis, using site-specific estimates of the ground motion actually experienced by the building during the earthquake, is required to make such a determination. It should be noted that unless a building has been instrumented, it is very difficult to estimate the precise ground motions it experienced, with any accuracy. Since analyses do not provide any conclusive evidence as to whether a building has actually experienced damage, when the cost of such analyses approaches that of inspections, inspections should be performed.

4.2.3.2 Buildings with Enhanced Connections

For buildings designed in accordance with the recommendations of Chapter 7 of these Interim Guidelines, and not displaying any of the conditions 4, 5, 6, or 7 of Section 4.2.1.2, the scope of inspection may be reduced to 1/2 the number of connections recommended in Section 4.3.3. If in the course of this reduced scope of inspection, significant structural damage is found (damage to any connection with a damage index per Table 4-3(a or b) that is greater than 5), then full inspections in accordance with Section 4.3 should be performed.

Commentary: Structures designed in accordance with Chapter 7 of these Interim Guidelines are expected to be less susceptible to connection fractures than WSMF structures designed with the former prescriptive connection. However, the effectiveness of these Interim Guidelines in preventing such fractures, during real earthquakes, is not yet known. Therefore, inspection of some connections in buildings conforming to these Interim Guidelines is recommended, even if there is no obvious evidence of damage.

4.2.4 Previous Evaluations and Inspections

Many WSMF buildings have been evaluated prior to the publication of these Interim Guidelines. The following approach is recommended for these buildings:

1. The previous evaluation may be considered adequate if any of the following conditions is met:
    a. a building permit has been issued for repair of damaged connections; or
    b. the evaluation was performed following procedures contained in SAC Advisory No. 3 (SAC - 1995) and/or City Guidelines in force at the time of the inspection; or
    c. the number and distribution of connections inspected substantially complies with the recommendations of Section 4.3.3, and no connections with damage indices d_j (per Table 4-3a or b) greater than 3 were discovered.
2. Previous inspections may be considered adequate and their results interpreted using these Interim Guidelines if either of the following conditions is met:
    a. the number of connections inspected substantially meets the recommendations of Section 4.3.3 and the distribution of the inspected connections, as certified by the responsible structural engineer, is acceptable to the building official as meeting the intent of these Interim Guidelines.
    b. one and one half times the number of inspections recommended in Section 4.3.3 have been performed for each group of connections, regardless of the distribution of connections within the groups.

When a previous evaluation has been performed that does not meet the conditions of 1 or 2 above, the owner should be advised that the previous work does not comply with current recommendations and that additional connections should be inspected to provide adequate understanding of the building's condition. The additional connections should be selected so as to bring the total inspection program, including those inspections previously conducted, into substantial compliance with the recommendations of Section 4.3.3. Such additional inspections should be performed in a manner that minimizes disruption to building occupancy, but in accordance with a schedule acceptable to the building official.

Commentary: This section applies to buildings affected by the Northridge Earthquake that were evaluated, inspected, and/or repaired, prior to the publication of these Interim Guidelines. Two different cases are addressed: 1) buildings for which the post-earthquake evaluation/repair process has been completed, and 2) buildings which were inspected, but for which evaluation reports and repair actions have not been submitted to and accepted by the building official. If a building was evaluated and subsequently repaired under a permit issued by the building official, or evaluated according to procedures acceptable to the building official and found not to require repair, then no further *work is recommended. If a building was inspected, but no report was submitted to or accepted by the building official, then additional work may be appropriate if the inspections did not adequately address the condition of the building.*

In the months immediately following the Northridge earthquake, divergent opinions were held as to how building inspections should be performed. Some structural engineers required inspections of every connection in buildings while others selected a relatively small sample of connections upon which to perform preliminary inspections, proceeding to more inspections only if significant damage was found in the initial sample. This latter approach is essentially the same basic approach adopted by these Interim Guidelines, although these Guidelines may recommend a larger sample than was commonly used prior to their publication. By the fall of 1994, many structural engineering offices in the Los Angeles area had adopted the inspection procedure recommendations of a City of Los Angeles task group. Those suggested that for buildings with 7 stories or less, 15% of the connections should be included in the initial sample and for taller structures, 10% of the connections. It was suggested in those recommendations that connections be selected on a widely distributed basis, but biased towards those most likely to have been damaged, as indicated by rational analysis. Evaluations of building condition, based on inspections performed in accordance with those procedures should be deemed to comply with item 1b of this section and need not be supplemented by additional work.

If a building has been subjected to minimal inspection, meaning substantially less than both the criteria contained in these Interim Guidelines and the recommendations of the City of Los Angeles task group, and the building official requires submittal of an evaluation report, it is recommended that additional inspections be performed to meet the intent of these Interim Guidelines, prior to submission of the evaluation report.

If a building is not required to be inspected by the building official, but previous inspection has been performed at the request of the owner, the structural engineer should notify the owner if the program of inspection was not in substantial compliance with these recommendations. Note that under Section 4.3.4 of these Interim Guidelines, inspections conducted in a random manner may be terminated following inspection of 50% of the total number of connections recommended for inspection, if only minimal damage is found. It is anticipated that most previously conducted inspection programs, in which minimal damage was found, would surpass this minimum recommended amount. For those cases where this is not so, additional inspection should be performed if the owner and structural engineer desire reasonable confidence in their knowledge of the condition of the building. When the inspections were voluntary, and no current requirement from the building official exists, any additional inspections desired *could be performed over a long schedule, so as to result in minimal disruption of tenants.*

4.3 Detailed Evaluation Procedure

Where detailed evaluation is recommended by Section 4.2, assessment of the post earthquake condition of a building, its ability to resist additional strong ground motion and other loads, and determination of appropriate occupancy, structural repair and/or modification strategies should be based on the results of a detailed inspection and assessment of the extent to which structural systems have been damaged.

This Section presents one approach for making such assessments. In this approach, the results of the inspections are used to calculate a cumulative damage index, D, for the structure as well as the probability that the damage index at any floor of the structure has exceeded 1/3. General occupancy, structural repair and modification recommendations are made based upon the values calculated for these damage indices. In particular, a calculated damage index of 1/3 is used to indicate, in the absence of more detailed analyses, that a potentially hazardous condition may exist.

The structural engineer may use other procedures consistent with the principles of statistics and structural mechanics to determine the residual strength and stiffness of the structure in the as-damaged state and the acceptability of such characteristics relative to the criteria contained in the building code, or other rational criteria acceptable to the building official.

Commentary: The most reliable approach to determining the post-earthquake condition of a building and whether unacceptable damage has occurred would be to inspect and determine the condition of each of the moment-resisting connections in the structure. This is an expensive process, and is not warranted unless a structure is heavily damaged. Therefore, these Interim Guidelines recommend a process that includes initial inspections of a representative sample of the welded moment-resisting connections in the building. If the initial inspections indicate a significant amount of damage, then additional inspections are recommended. Based upon the observed condition of the total inspected sample of connections, the probable levels of damage throughout the structure are projected.

In this procedure, each inspected connection is assigned an individual connection damage index "d_j" ranging from 0 to 10. Judgmentally derived guidelines are provided for the assignment of these damage indices, based on the types of damage observed, with 10 indicating very severe damage and loss of ability to reliably participate in the lateral load resisting system, and 0 indicating no damage. An overall building damage index D is calculated by extrapolating the individual connection damage indices "d_j" for the connections actually inspected to the total number of connections in the structure. In this way, the *damage index D represents in a very approximate and rough manner, an indication of the loss of reliable capacity of the structure to resist future strong ground motion. A structural damage index of 1/3 has arbitrarily been taken as an indication, in the absence of more detailed analyses, that a potentially hazardous condition may exist.*

The procedure presented in these Interim Guidelines to estimate the level of damage does not include direct calculation of the remaining lateral strength and stiffness of the damaged building, or its residual displacement capacity, nor does it attempt to compare these characteristics to the requirements of the building code for new construction. Such an approach, if properly performed, should be very useful in assisting the structural engineer to understand the probable future performance of the building. However, it is important to note that no consensus has been reached yet with regard to appropriate modeling assumptions for the residual strength and stiffness of damaged connections. Also, unless all connections within a building have been inspected, the true condition of the building is subject to considerable uncertainty. Consequently, when such an approach is taken, qualified independent third party review, in accordance with Section 4.5, is strongly recommended.

It is recognized that many WSMF buildings have lateral strength and stiffness considerably in excess of that required by the building code. When analyses indicate that connection damage results in a building that still has more strength and stiffness than is required by the code, structural engineers should be cautious in making judgments that there is no requirement for structural repair or further modifications Such an approach could be permitted by these Interim Guidelines if such an engineering analysis is performed, and the building official approves. However, if a large number of building connections have been damaged, this may indicate the presence of conditions likely to result in excessive damage in future earthquakes, such as poor quality construction or an unfavorable configuration. Therefore, buildings which have experienced substantial damage should be carefully considered for repair and upgrade, regardless of their pre-earthquake design lateral strength and stiffness.

4.3.1 Eight Step Evaluation Procedure

Post-earthquake evaluation should be carried out under the direct supervision of a structural engineer. The following eight-step procedure may be used to determine the condition of the structure and to develop occupancy, repair and modification strategies:

Step 1: The moment-resisting connections in the building are categorized into two or more "groups" (Section 4.3.2 and 4.4) comprised of connections expected to have similar probabilities of being damaged.

Complete steps 2 through 7 below, for each group of connections.

Step 2: Determine the minimum number of connections in each group that should be inspected and select the specific sample of connections to be inspected. (Section 4.3.3)

Step 3: Inspect the selected set of connections using the technical guidelines of Section 5.2. and determine connection damage indices, d_j, for each inspected connection (Section 4.3.4)

Step 4: If inspected connections are found to be seriously damaged, perform additional inspections of connections adjacent to the damaged connections. (Section 4.3.5)

Step 5: Determine the average damage index (d_{avg}) for connections in each group, and then the average damage index at a typical floor. (Section 4.3.6)

Step 6: Given the average damage index for connections in the group, determine the probability, P, that the connection damage index for any group, at a floor level, exceeds 1/3, and determine the maximum estimated damage index for any floor, D_{max}. (Section 4.3.7)

Step 7: Based on the calculated damage indices and statistics, determine appropriate occupancy, structural repair and modification strategies (Section 4.3.8). If deemed appropriate, the structural engineer may conduct detailed structural analyses of the building in the as-damaged state, to obtain improved understanding of its residual condition and to confirm that the recommended strategies are appropriate or to suggest alternative strategies.

Step 8: Report the results of the inspection and evaluation process to the building official and building owner. (Section 4.3.9)

Sections 4.3.2 through 4.3.9 indicate how these steps should be performed.

Commentary: Following an earthquake structural engineers and technicians qualified to perform these evaluations may be at a premium. Prudent owners may want to consider having an investigation plan already developed (Steps 1 and 2) before an earthquake occurs, and to have an agreement with appropriate structural engineering and inspection professionals and organizations to give priority to inspecting their buildings rapidly following the occurrence of an earthquake.

4.3.2 Step 1—Categorize Connections by Groups

The welded moment-resisting connections participating in the lateral-force-resisting system for the building are categorized into a series of "connection groups." Each group consists of connections expected to behave in a similar manner (as an example, a group may consist of all those connections that are highly stressed by lateral forces applied in a given direction). As a minimum, two groups of connections should be defined - each group consisting of connections that primarily resist lateral movement in one of two orthogonal directions. Additional groups should be defined to account for unique conditions including building configuration, construction quality, member size, grade of steel, etc., that are likely to result in substantially different connection behavior, as compared to other connections in the building. Each connection in the building should be uniquely assigned to one of the groups, and the total number of connections in each group determined.

In buildings that have significant torsional irregularity, it may be advisable to define at least four groups—one group in each orthogonal direction on each side of an assumed center of resistance. Section 4.4 gives a procedure for defining groups where damage may accentuate torsional response, or where the structural engineer desires a more reliable characterization of the building's degree of damage. Such procedures should be considered when a building has significant torsional irregularity or when there is so little redundancy that failure of one connection at a floor level would exacerbate a torsional response.

For buildings of two or more stories, the roof connections may be excluded from the initial inspection process. However, when Table 4-5 recommends inspection of all connections within a group or building, they should be inspected.

> *Commentary: Many base plates of columns in moment frames use the same basic connection detail as do the beam/column connections. When such base plates are not within the cast-in-place concrete floor and grade-beam system, then consideration should be given to their inspection. There is evidence from the 1995 Kobe earthquake that column splice damage can occur, with resulting severe impacts on the building's stability. Consideration should be given by the structural engineer to their inspection as well. Although these connections should also be inspected, they should not be included within the statistical calculations contained in this eight-step procedure. Any damage to such connections, should be repaired.*

4.3.3 Step 2—Select Samples of Connections for Inspection

Assign a unique identifier to each connection within each group. Consecutive integer identifiers are convenient to some of the methods employed in this Section.

For each group of connections, select a representative sample for inspection in accordance with any of Methods A, B, or C, below. A letter indicating the composition of the groups, and the specific connections to be inspected should be submitted to the building official prior to the initiation of inspection. The owner or structural engineer may at any time in the investigation process elect to investigate more connections than required by the selected method. However, the additional connections inspected may not be included in the calculation of damage statistics under Step 5 (Section 4.3.6) unless they are selected in adherence to the rules laid out for the original sample selection, given below.

Commentary: The purpose of inspection plan submittal prior to the performance of inspections is to prevent a structural engineer, or owner, from performing a greater number of inspections and reporting data only on those which provide a favorable economic result with regard to building disposition. The building official need not perform any action with regard to this submittal other than to file it for later reference at the time the structural engineer's evaluation report is filed. During the inspection process, it may be decided to inspect additional connections to those originally selected as part of the sample. While additional inspections can be made at any time, the results of these additional inspections should not be included in the calculation of the damage statistics, in Step 5, as their distribution may upset the random nature of the original sample selection. If the additional connections are selected in a manner which preserves the distribution character of the original sample, they may be included in the calculation of the damage statistics in Step 5.

4.3.3.1 Method A - Random Selection

Connections are selected for inspection such that a statistically adequate random sample is obtained. The minimum number of connections to be inspected for each group is determined in accordance with Table 4-2. The following limitations apply to the selection of specific connections:

1. Up to a maximum of 20% of the total connections in any sample may be pre-selected as those expected by rational assessment to be the most prone to damage. Acceptable criteria to select these connections could include:

   - Connections shown by a rational analysis to have the highest demand-capacity ratios or at locations experiencing the largest drift ratios.

   - Connections which adjoin significant structural irregularities and which therefore might be subjected to high localized demands. These include the following irregularities:

     - re-entrant corners
     - set-backs
     - soft or weak stories
     - torsional irregularities (connections at perimeter columns)
     - diaphragm discontinuities

   - Connections incorporating the largest size framing elements.

2. The balance of the sample should be selected randomly from the remaining connections in the group.

Up to 10% of the connections in the sample may be replaced by other connections in the group to which access may more conveniently be made.

Table 4-2 - Minimum Sample Size for Connection Groups

Number of connections in Group[1]	Minimum number of connections to be inspected	Number of Connections in Group[1]	Minimum number of connections to be inspected
6	2	200	27
10	3	300	37
15	4	400	45
20	5	500	53
30	7	750	72
40	8	1000	99
50	10	1250	104
75	13	1500	120
100	17	2000	147

Note: 1. For other connection numbers use linear interpolation between values given, rounding up to the next highest integer.

Commentary: The number of connections needed to provide a statistically adequate sample depends on the total number of connections in the group. The sample sizes contained in Table 4-2 were developed from MIL-STD-105D, a well established quality control approach that has been widely adopted by industry.

If relatively few connections within a group are expected, the standard deviation for the computed damage index will be large. This may result in prediction of excessive damage when such damage does not actually exist. The structural engineer may elect to investigate more connections than the minimum indicated in order to reduce the standard deviation of the sample and more accurately estimate the total damage to the structure. These additional inspections may be performed at any time in the investigative process. However, care should be taken to preserve the random characteristics of the sample, so that results are not biased either by selection of connections in unusually heavy (or lightly) damaged areas of the structure.

It is recognized that in many cases the structural engineer may wish to pre-select those connections believed to be particularly vulnerable. However, unless these pre-selected connections are fairly well geometrically distributed, a number that is more than about 20% of the total sample size will begin to erode the validity of the assumption of random selection of the sample. If the structural engineer has a compelling reason for believing that certain connections are most *likely to be damaged, and that more than 20% should be pre-selected on this basis, the alternative approach of Method C should be used.*

It is recognized that there is often a practical incentive to select connections that are in specific unoccupied or more accessible areas. It is suggested that no more than 10% of the total sample be composed of connections pre-selected for this reason. These connections, rather than having a higher disposition for damage, might well have a lower than average tendency to be damaged. An excessive number of this type of pre-selected connection would quickly invalidate the basic assumption of random selection. It is also recognized that during the inspection process conditions will be discovered that make it impractical to inspect a particular connection, e.g., the architectural finishes are more expensive to remove and replace than in other areas, or a particular tenant is unwilling to have their space disturbed. However, as discussed above, not more than 10% of the total connections inspected should be selected based on convenience.

There are a number of methods available for determining the randomly selected portion of the sample. To do this, each connection in the group (excluding pre-selected connections) should be assigned a consecutive integer identifier. The sample may then be selected with the use of computer spread sheet programs - many of which have a routine for generation of random integers between specified limits, published lists of random numbers, or by drawing of lots.

4.3.3.2 Method B - Deterministic Selection

Connections are selected to satisfy the following criteria:

1. At least one connection is selected on every column face of every line of moment-resisting framing in the group;

2. At least one connection is selected on every floor from every frame;

3. No more than 50% of the connections in a sample may be selected from any floor or column face than would be done if the number of inspected connections was equally apportioned among either the column faces or floors; and

Up to 10% of the connections in the sample may be replaced by other connections in the same frame and group to which access may more conveniently be made.

Commentary: It is recognized that in many cases the structural engineer may be reluctant to select connections in a random manner, as provided by Method A. For those cases, Method B is acceptable since it assures that every floor and every column is inspected at least once. The structural engineer may select any *combination of connections to be inspected that meets these criteria; notwithstanding, care should be exercised to assure that these allowances are not used to subvert the intent of the inspection process to determine the degree of damage to the building, if any.*

4.3.3.3 Method C - Analytical Selection

Connections are selected for inspection in accordance with the following criteria:

1. The minimum number of connections within the group to be inspected is as indicated in Table 4-2.

2. Up to 60% of the connections may be selected based on the results of rational analysis indicating those connections most likely to be damaged.

3. The remaining connections in the group to be inspected are selected such that the sample contains connections distributed throughout the building, including upper, middle and lower stories.

Prior to initiation of the inspections, the rational analysis and list of connections to be inspected should be subjected to a qualified independent third party review in accordance with Section 4.5. The peer review should consider the basis for the analysis, consistency of the assumptions employed, and to assure that overall, the resulting list of connections to be inspected provides an appropriate sampling of the building's connections.

During the inspection process, up to 10% of the connections in the sample may be replaced by other connections to which access may more conveniently be made. Substitution for more than 10% of the connection sample may be made provided that the independent third party reviewer concurs with the adequacy of the resulting revised sample.

Commentary: In analyses conducted of damaged buildings, there has been a generally poor correlation of the locations of damage and the locations of highest demand predicted by the analysis. However, there has been some correlation. Analysis is a powerful tool to assist the structural engineer in understanding the expected behavior of a structure. The specific analysis procedure used should be tailored to the individual characteristics of the building. It should include consideration of all building elements that are expected to participate in the building's seismic response, including, if appropriate, elements not considered to be part of the lateral-force-resisting system. The ground motion characteristics used for the analysis should not be less than that required by the building code for new construction, and to the extent practical, should contain the spectral characteristics of the actual ground motion experienced at the site. Qualified independent review is recommended to assure that there is careful consideration of the basis for the selection of the connections to be inspected and that a representative sample is obtained.

4.3.4 Step 3—Inspect the Selected Samples of Connections

Inspect the selected samples of connections in each group as indicated in Chapter 5. Characterize the damage at each inspected connection as described in Section 4.3.4.1

Inspections may be terminated when at least 50% of the connections selected for each sample have been inspected if:

1) the inspections have progressed in a manner that retains an adequately random nature and distributed geometry for those connections that are inspected (a distribution throughout the building that is acceptable to the building official); and

2) no connections with damage indices $d_j > 5$ (Table 4-3a or b) are discovered; and,

3) not more than 10% of the total connections inspected are discovered to have $d_j \geq 2$.

If all of these conditions are not met, then inspections should be completed for all connections contained in all samples.

Commentary: The sample size suggested for inspection in the methods of Section 4.3.3 are based on full inspection using both visual (Section 5.3.1) and NDT techniques (Section 5.3.2) at all connections in the sample. Other methods of selection and inspection may be used as provided in Section 4.3, with the approval of the building official. One such approach might be the visual-only inspection of the bottom girder flange to column connection, but with the inspection of a large fraction of the total connections in the group, possibly including all of them. If properly performed, such an inspection procedure would detect almost all instances of the most severe damage but would not detect weld defects (W1a), or root cracking (W1b), nor lamellar damage in columns (C5). The occurrence of a few of these conditions, randomly scattered through the building would not greatly affect the assessment of the building's post-earthquake condition, or the calculation of the damage index. However, if a large number of such defects were present in the building, this would be significant to the overall assessment. Therefore, such an inspection approach should probably include confirming NDT investigations of at least a representative sample of the total connections investigated. If within that sample, significant incidence of visually hidden damage is found, then full NDT investigations should be performed, as suggested by these Interim Guidelines. Similarly, if visual damage is found at the bottom flange, then complete connection inspection should be performed to determine if other types of damage are also present.

4.3.4.1 Damage Characterization

Characterize the observed damage at each of the inspected connections by assigning a connection damage index, d_j, obtained either from Table 4-3a or Table 4-3b. Table 4-3a presents damage indices for individual classes of damage and a rule for combining indices where a connection has more than one type of damage. Table 4-3b provides combined indices for the more common combinations of damage.

Table 4-3a - Connection Damage Indices

Type	Location	Description[1]	Index[2] d_j
G1	Girder	Buckled Flange	4
G2	Girder	Yielded Flange	1
G3	Girder	Top or Bottom Flange fracture in HAZ	8
G4	Girder	Top or Bottom Flange fracture outside HAZ	8
G5	Girder	Top and Bottom Flange fracture	10
G6	Girder	Yielding or Buckling of Web	4
G7	Girder	Fracture of Web	10
G8	Girder	Lateral-torsional Buckling	8
C1	Column	Incipient flange crack (detectable by UT)	4
C2	Column	Flange tear-out or divot	8
C3	Column	Full or partial flange crack outside HAZ	8
C4	Column	Full or partial flange crack in HAZ	8
C5	Column	Lamellar flange tearing	6
C6	Column	Buckled Flange	8
C7	Column	Fractured column splice	8
W1a	CJP weld	Minor root indication - thickness <3/16” or $t_f/4$; width < $b_f/4$	1
W1b	CJP weld	Root indication - thickness > 3/16” or $t_f/4$ or width > $b_f/4$	4
W2	CJP weld	Crack through weld metal thickness	8
W3	CJP weld	Fracture at girder interface	8
W4	CJP weld	Fracture at column interface	8
W5	CJP weld	Root indication—non-rejectable	0
S1a	Shear tab	Partial crack at weld to column (beam flanges sound)	4
S1b	Shear tab	Partial crack at weld to column (beam flange cracked)	8
S2a	Shear tab	Crack in Supplemental Weld (beam flanges sound)	1
S2b	Shear tab	Crack in Supplemental Weld (beam flange cracked)	8
S3	Shear tab	Fracture through tab at bolt holes	10
S4	Shear tab	Yielding or buckling of tab	6
S5	Shear tab	Damaged, or missing bolts[4]	6
S6	Shear tab	Full length fracture of weld to column	10
P1	Panel Zone	Fracture, buckle, or yield of continuity plate[3]	4
P2	Panel Zone	Fracture of continuity plate welds[3]	4
P3	Panel Zone	Yielding or ductile deformation of web[3]	1
P4	Panel Zone	Fracture of doubler plate welds[3]	4
P5	Panel Zone	Partial depth fracture in doubler plate[3]	4
P6	Panel Zone	Partial depth fracture in web[3]	8
P7	Panel Zone	Full (or near full) depth fracture in web or doubler plate[3]	8
P8	Panel Zone	Web buckling[3]	6
P9	Panel Zone	Fully severed column	10

Notes To Table 4-3a:

1. See Figures 3-2 through 3-6 for illustrations of these types of damage.
2. Where multiple damage types have occurred in a single connection, then:
   a. Sum the damage indices for all types of damage with d=1 and treat as one type. If multiple types still exist; then:
   b. For two types of damage refer to Table 4-3b. If the combination is not present in Table 4-3b and the damage indices for both types are greater than or equal to 4, use 10 as the damage index for the connection. If one is less than 4, use the greater value as the damage index for the connection.
   c. If three or more types of damage apply and at least one is greater than 4, use an index value of 10, otherwise use the greatest of the applicable individual indices.
3. Panel zone damage should be reflected in the damage index for all moment connections attached to the damaged panel zone within the assembly.
4. Missing or loose bolts may be a result of construction error rather than damage. The condition of the metal around the bolt holes, and the presence of fireproofing or other material in the holes can provide clues to this. Where it is determined that construction error is the cause, the condition should be corrected and a damage index of "0" assigned.

Table 4-3b - Connection Damage Indices for Common Damage Combinations[1]

Girder, Column or Weld Damage	Shear Tab Damage	Damage Index	Girder, Column or Weld Damage	Shear Tab Damage	Damage Index
G3 or G4	S1a	8	C5	S1a	6
	S1b	10		S1b	10
	S2a	8		S2a	6
	S2b	10		S2b	10
	S3	10		S3	10
	S4	10		S4	10
	S5	10		S5	10
	S6	10		S6	10
C2	S1a	8	W2, W3, or W4	S1a	8
	S1b	10		S1b	10
	S2a	8		S2a	8
	S2b	10		S2b	10
	S3	10		S3	10
	S4	10		S4	10
	S5	10		S5	10
	S6	10		S6	10
C3 or C4	S1a	8			
	S1b	10			
	S2a	8			
	S2b	10			
	S3	10			
	S4	10			
	S5	10			
	S6	10			

1. See Table 4-3a, footnote 2 for combinations other than those contained in this table.

More complete descriptions (including sketches) of the various types of damage are provided in Section 3.1. When the engineer can show by rational analysis that other values for the relative severities of damage are appropriate, these may be substituted for the damage indices provided in the tables. A full reporting of the basis for these different values should be provided to the building official, upon request.

Commentary: The connection damage indices provided in Table 4-3 (ranging from 0 to 10) represent judgmental estimates of the relative severities of this damage. An index of 0 indicates no damage and an index of 10 indicates very severe damage.

When initially developed, these connection damage indices were conceptualized as estimates of the connection's lost capacity to reliably participate in the building's lateral-force-resisting system in future earthquakes (with 0 indicating no loss of capacity and 10 indicating complete loss of capacity). However, due to the limited data available, no direct correlation between these damage indices and the actual residual strength and stiffness of a damaged connection was ever made. They do provide a convenient measure, however, of the extent of damage that various connections in a building have experienced.

4.3.5 Step 4—Inspect Connections Adjacent to Damaged Connections

Perform additional inspections of moment-resisting connections near connections with significant damage as follows:

1) when a connection is determined to have a damage index $d_j > 5$, inspect all moment-resisting connections immediately adjacent (above and below, to the left and right) to the damaged connection in the same moment frame (See Figure 4-1). Also inspect any connections for beams framing into the column in the transverse direction at that floor level, at the damaged connection.

2) when a connection is determined to have a damage index $d_j > 9$, inspect the <u>two</u> moment-resisting connections immediately adjacent (above and below, to the left and right) to the damaged connection in the same moment frame (See Figure 4-2). Also inspect any connections for beams framing into the column in the transverse direction at that floor level at the damaged connection.

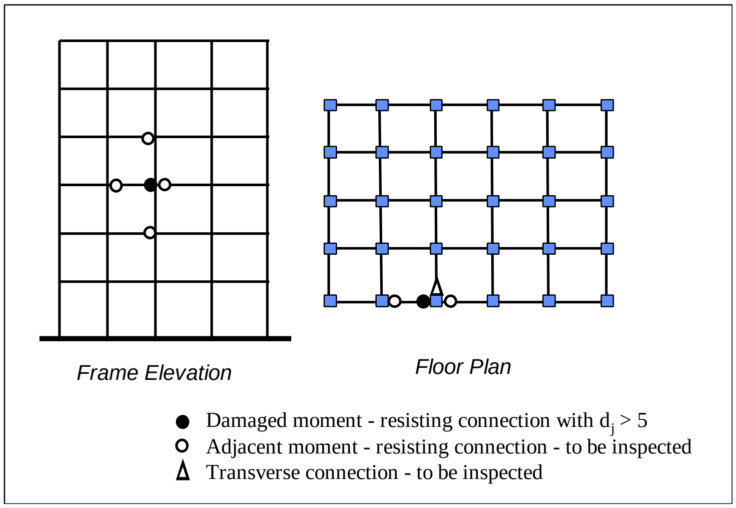

Figure 4-1 - Inspection of Connections Adjacent to Damaged Connection (d_j > 5)

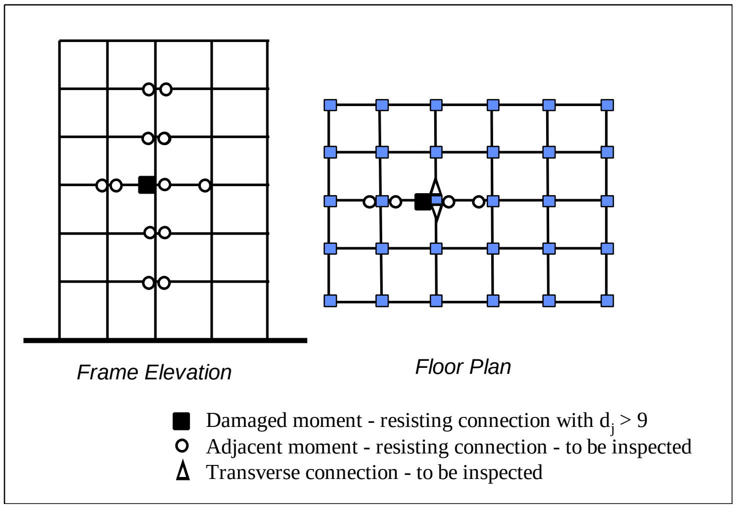

Figure 4-2 - Inspection of Connections Adjacent to Damaged Connection (d_j > 9)

Assign damage indices, d_j, per Section 4.3.3, to each additional connection inspected. If significant damage is found in these additional connections (dj > 5), then inspect the connections near these additional connections, as indicated in 1) and 2) above. Continue this process, until one of the following conditions occurs:

a) The additional connection inspections do not themselves trigger more inspections, or

b) All connections in the group have been inspected.

The results of these added connection inspections, performed in this step are not included in the calculation of average damage index d_{avg} per Section 4.3.6 but are included in the calculation of the maximum likely damage index D_{max} and probability of excessive damage, P, per Section 4.3.7.

4.3.6 Step 5—Determine Average Damage Index for Each Group

For each group of connections, determine the estimated average value of the damage index for the group (d_{avg}) and its standard deviation (σ) from the equations:

$$d_{avg} = \frac{1}{n}\sum_{j=1}^{n}\frac{d_j}{10} \tag{4-1}$$

$$s^2 = \frac{1}{n-1}\sum_{j=1}^{n}\left(\frac{d_j}{10} - d_{avg}\right)^2 \tag{4-2}$$

where: “n” is the number of connections in the sample selected for inspection under step 2 (Section 4.3.3), and

“d_j” is the damage index, per Table 4-3 for the “jth” inspected connection in the sample

The additional connections selected using the procedure of Section 4.3.5 (Step 4) are not included in the above calculation.

4.3.7 Step 6—Determine the Probability that the Connections in a Group at a Floor Level Sustained Excessive Damage

Two procedures are provided. The first procedure (Section 4.3.7.1) is used in the typical case, when some connections in the group have not been inspected. In this case, the maximum damage index at a floor “D_{max}” is estimated based on the damage indices determined for the connections actually inspected, and the probability “P” that D_{max} exceeds a value of 1/3 is determined. The second procedure (Section 4.3.7.2) is used when all connections in the group have been inspected. In this case, the maximum damage index at any floor “D_{max}” can be calculated directly from the known values of the damage indices of the inspected connections.

4.3.7.1 Some Connections in Group Not Inspected

If some connections in the group have not been inspected, determine the expected maximum damage index at a floor “D_{max}” and the probability that at least one floor has a damage index exceeding 1/3.

First determine the average damage index at a typical floor “D” and its standard deviation “S” from the equations:

$$D = d_{avg} \tag{4-3}$$

$$S = \frac{s}{\sqrt{k}} \tag{4-4}$$

where "k" is the total number of connections (both inspected and not inspected) in the group at a typical floor.

Then, determine the probability P that the set of connections within the group at any floor has had a cumulative damage index that is greater than or equal to 1/3. This may be done by using the parameters D and S to calculate a factor "b", which represents the number of multiples of the standard deviation of a Normal distribution above the mean that would be required to exceed 1/3. The factor "b" is calculated from the equation:

$$b = (1/3 - D)/S \tag{4-5}$$

Using the value of "b" calculated from equation 4-5, determine P_f, from Table 4-4. P_f is the probability that if all connections had been inspected, the cumulative damage index at any floor would have been found to exceed 1/3. This strongly suggests the possibility that there has been a reduction in seismic resisting capacity of a similar amount.

Then determine the probability P that if all connections within the group had been inspected, the connections within the group on at least one floor (out of "q" total floors in the group) would have been found to have a cumulative damage index of 1/3 or more from the equation:

$$P = 1 - (1 - P_f)^q \tag{4-6}$$

Table 4-4 - P_f as a function of b

b	P_f - (%)	b	P_f - (%)
-1.2816	90	1.2265	11
-0.8416	80	1.2816	10
-0.5244	70	1.3408	9
-0.2533	60	1.4051	8
0.0000	50	1.4395	7.5
0.2533	40	1.4758	7
0.5244	30	1.5548	6
0.8416	20	1.6449	5
0.8779	19	1.7507	4
0.9154	18	1.8808	3
0.9542	17	1.9600	2.5
0.9945	16	2.0537	2
1.0364	15	2.1701	1.5
1.0803	14	2.3263	1
1.1264	13	3.0962	.1
1.1750	12	3.7190	.01

* Note - Intermediate values of P_f may be determined by linear interpolation

Finally, for each floor "i" in the group for which an inspection has been performed, determine the cumulative damage index, "D_i", from the equation:

$$D_i = \frac{(k_i - m_i)d_{avg}}{k_i} + \left(\frac{1}{k_i}\right)\sum_{j=1}^{m_i}\frac{d_j}{10} \qquad (4\text{-}7)$$

where: k_i is the total number of connections in the group at floor "i"
m_i is the number of inspected connections in the group at floor "i" including the additional connections inspected under step 4

Take "D_{max}" as the largest of the "D_i" values calculated for each floor of the group.

4.3.7.2 All Connections in Group Inspected

If all connections in a group have been inspected, determine the damage index for each floor "i" in the group from the equation:

$$D_i = \frac{1}{k_i}\sum_{j=1}^{k_i}\frac{d_j}{10} \qquad (4\text{-}8)$$

where: "k_i" is the total number of connections in the group at floor "i"

Take "D_{max}" as the maximum of the "D_i" values calculated for each floor of the group.

Commentary: The criterion for damage evaluation used in this Guideline is to assume that a cumulative damage index of 1/3 marks the threshold at which a structure may become dangerous. Such a damage index could correspond to cases where 1/3 of the connections in a building have been severely damaged; cases where all of the connections have experienced moderate damage; or some combination of these, and therefore represents a reasonable point at which to begin serious consideration of a building's residual ability to withstand additional loads.

Given the current limited understanding of steel moment frame damage, the probability distribution for connection damage is not known. However, since the damage index for a floor is the sum of the damage indices for each connection at the floor, then, by the Central Limit Theorem, as the number of connections increases, the distribution tends to a normal distribution, regardless of the form of the distribution for individual connections. Therefore, the probability that a damage index of 1/3 has been exceeded at a floor, in a group with k connections may be approximated by determining how many multiples ("b") times the standard deviation (S), when added to the mean damage index (D) equals 1/3. Or, in equation form :

$$D + bS = 1/3 \qquad (4\text{-}9)$$

Solution of this equation for the multiplier "b" results in the required relationship of equation 4-5.

Damage Indices (from Table 4-3) that are largely judgmental are used to characterize the loss of reliable seismic performance capability of individual connections. These indices are added, averaged and otherwise statistically manipulated for use as an indication of the average damage index for groups of connections, entire frames and ultimately of the lateral system itself. It should be clear that use of such an approximate, judgmentally defined characterization of strength cannot rigorously calibrate the loss of lateral resistance, or the residual strength and stiffness of the building.

In spite of the somewhat arbitrary nature of the 1/3 damage index criterion and the judgmental nature of the suggested way of testing whether that criteria has been exceeded, it is believed that the results of these procedures will lead to reasonable conclusions in most cases. However, it is always the prerogative of the responsible structural engineer to apply other rational techniques, such as direct analyses of the remaining structural strength, stiffness, and deformation capacity as a verification of the conclusions provided by these procedures. Particularly in anomalous or marginal cases, such additional checks based on engineering judgment are strongly encouraged .

4.3.8 Step 7—Determine Recommended Recovery Strategies for the Building

Recommended post-earthquake recovery strategies are as indicated in Table 4-5, based on the calculated damage indices and statistics determined in the previous steps. For those groups in which all connections have been inspected, the statistic P in the table is neglected.

Table 4-5 - Recommended Repair and Modification Strategies

Observation[6]	Recommended Strategy (Cumulative)	Note
P>0 or D_{max}>0	Repair all connections discovered to have $d_j > 5$	1,2
P > 5% or D_{max} > 0.1	Repair all connections discovered to have $d_j > 2$	1,2
P > 10 % or D_{max}> 0.2	Inspect all connections in the group. Repair all connections with $d_j > 2$	2
P > 25 % or D_{max}> 0.33	A potentially unsafe condition may exist. Carefully evaluate the earthquake resistance of the building and the safety of its occupants and if not satisfied that adequate vertical stability, lateral strength and stiffness exists, notify the building owner of the potentially unsafe condition. Inspect all connections in the building. Repair all connections with $d_j > 1$. Consider modification of all repaired connections and others as appropriate.	3
D_{max} > 0.50	An unsafe condition probably exists. Notify the building owner of this unless more detailed evaluations indicate otherwise. Inspect all connections in the building. Repair all damaged connections and modify all connections for better performance, or modify the building's lateral-force-resisting system for improved performance.	4,5

Notes to Table 4-5:

1. Includes damage discovered either as part of Step 2 or Step 3.
2. Although repair is recommended only for the more seriously damaged connections, the repair of all connections that are damaged or otherwise deficient should be considered.
3. The determination that an unsafe condition may exist should continue until either:
   a. full inspection reveals that the gravity system is not compromised, and that the damage index at any floor does not exceed 1/3, or
   b. detailed structural analyses indicate that a dangerous condition does not exist, or
   c. recommended repairs are completed for all connections having $d_j > 3$.
4. An unsafe condition probably exists. The building is almost certainly too severely damaged to provide adequate occupant safety in a strong earthquake. The structural engineer should either recommend that the building be vacated, or, alternatively, demonstrate by analysis that the risks to occupant safety, while repairs are conducted, are acceptable. If a decision is made to accept the short-term risks of continued occupancy, an independent third party review of the basis of this decision is recommended.
5. Repairs required to the building are extensive. In addition to repair, strong consideration should be given to performing systematic modifications of the building's lateral-force-resisting system to provide more reliable performance in the future.
6. The more restrictive observation governs the recommendation. If all connections in the group were inspected, than do not apply the criteria pertaining to P.

Commentary: The value of P (the probability that the connections on at least one floor have a cumulative damage index of 1/3 or more) and D_{max} (the maximum damage index at a floor level within a group) were determined in Method A by using a random selection process, and thus represent a statistically valid basis for the characterization of the damage index for the group of connections, and thus for the building. Method B selects the connections by using a specified distribution throughout the building based on forcing selection of connections in every column line and floor. Method C selects the connections, based on engineering characterization of those most likely to have been damaged, modified to reflect a distribution throughout the structure. While the connections selected by Methods B and C are not truly random, they are widely distributed and have some characteristics of a random distribution. Such selections are judged to be sufficiently "random-like" to warrant processing as if the connections were selected randomly. Thus regardless of whether method A, B, or C was used, decisions on disposition of the building, and the need for repair measures can defensibly be based on the values of these two key parameters, as determined for each group of connections.

For buildings that have experienced relatively limited levels of damage, Table 4-5 recommends repair of damaged connections, without further modification. This is not intended to indicate that buildings that experienced only slight damage have been demonstrated to be seismically rugged. In fact, if a building experienced light damage as a result of being subjected to relatively low levels of ground motion, it may have substantial vulnerability. This recommendation is made based on economic considerations and the fact that modification of buildings which are only slightly damaged entails a significant increase in the *required investment. It should be made clear to the owner of such buildings that even an undamaged or fully repaired welded steel moment frame building still carries risk of damage, and to an uncertain extent, risk to life safety in subsequent large earthquakes.*

When damage is moderate (D_{max} < 33%) consideration should be given to modification of those connections which are being repaired, to provide improved reliability in the future. However, the structural engineer is cautioned that modification of only those connections which have been damaged could unintentionally create an undesirable condition such as a weak story or torsional irregularity. Therefore, care should be taken that such conditions are not created by connection modifications. Modification of the entire structural lateral force-resisting system is strongly recommended when D_{max}>0.50. This is not because the extent of damage indicates that the building is particularly vulnerable, although this may be the case, but because the work required to repair the building is extensive enough that a relatively small incremental investment will allow substantial improvement in the building's future potential performance.

If a decision to structurally modify a building is made, and it can be demonstrated that the structural modifications will reduce the earthquake demands on the existing WSMF connections from the original design levels, it may be acceptable not to repair some conditions. In such cases, analyses should be performed to demonstrate the adequacy of the modified structure assuming either that the affected connections have no moment-resisting capacity, or by including an estimate of their reliable post-elastic behavior in the damaged state. In no case should conditions that affect the gravity load-carrying capacity of the structure be left unrepaired.

Recommendations to close a damaged building to occupancy should not be made lightly, as such decisions will have substantial economic impact, both on the building owner and tenants. A building should be closed to occupancy whenever, in the judgment of the structural engineer, damage is such that the building no longer has adequate lateral-force-resisting capacity to withstand additional strong ground shaking, or if gravity load carrying elements of the structure appear to be unstable.

4.3.9 Step 8 - Evaluation Report

When an evaluation of a WSMF building has been performed, the responsible structural engineer should prepare a written evaluation report and submit it to the owner, upon completion of the evaluation. When the building official has required evaluation of a WSMF building, this report should also be submitted to the building official. This report should directly or by attached references, document the inspection program that was performed, provide an interpretation of the results of the inspection program, and a recommendation as to appropriate repair and occupancy strategies. The report should include but not be limited to the following material:

1) Building Address

2) A narrative description of the building indicating plan dimensions, number of stories, total square feet, occupancy, the type and location of lateral-force-resisting elements. Include a description of the grade of steel specified for beams and columns, and if known, the type of welding (SMAW, FCAW, etc.) present. Indicate if moment connections are provided with continuity plates. The narrative description should be supplemented with sketches (plans and elevations) as necessary to provide a clear understanding of pertinent details of the building's construction. The description should include an indication of any structural irregularities, as defined in the Building Code.

3) A description of nonstructural damage observed in the building, especially as relates to evidence of the drift or shaking severity experienced by the structure.

4) If a letter was submitted to the building official before the inspection process was initiated, indicating how the connections were divided into groups and the specific connections to be inspected; a copy of this letter should be included.

5) A description of the inspection and evaluation procedures used, including documentation of all instructions the inspectors, and of the signed inspection forms for each individual inspected connection.

6) A description, including engineering sketches, of the observed damage to the structure as a whole (e.g. - permanent drift) as well as at each connection, keyed to the damage types in Table 4-3; photographs should be included for all connections with damage index $d_j>5$. (Refer to Section 5.3.5)

7) Calculations of d_{avg}, D_i, and D_{max} for each group, and if all connections in a group were not inspected, P_f and P.

8) Calculations demonstrating the safety of the building where D_{max} > 33% and the structural engineer has determined that an unsafe condition does not exist.

9) A summary of the recommended actions (repair and modification measures and occupancy restrictions). Any recommendations which represent significant departures from the requirements of Section 4.3.8 should be carefully and completely explained.

The report should include identification of any potentially hazardous conditions which were observed, including corrosion, deterioration, earthquake damage, pre-existing rejectable conditions, and evidence of poor workmanship or deviations from the approved drawings. In addition, the report should include an assessment of the potential impacts of observed conditions on future structural performance. The report should include the Field Inspection Reports of damaged connections, as an attachment and should bear the seal of the structural engineer in responsible charge of the evaluation.

Commentary: Following completion of the detailed damage assessments, the structural engineer should prepare a written report. The report should include identification of any potentially hazardous conditions which were observed, including earthquake damage, pre-existing rejectable conditions, and evidence of poor workmanship or deviations from the approved drawings. In addition, the report should include an assessment of the potential impacts of observed conditions on future structural performance. The report should include the field inspection, visual inspection and NDT records, data sheets, and reports as attachments.

The nature and scope of the evaluations performed should be clearly stated. If the scope of evaluation does not permit an informed judgment to be made as to the extent with which the building complies with the applicable building codes, or as to a statistical level of confidence that the damage has not exceeded an acceptable damage threshold, this should be stated.

4.4 Alternative Group Selection for Torsional Response

This Section provides an optional procedure to that of Section 4.3.2, Step 1, that may be appropriate in selected situations where the structural engineer wants more reliable determination of the building’s susceptibility to excessive torsional response. If a building responds in a torsionally dominated manner, one side of the structure may experience substantially more damage than the other side. Such a situation would result in a building that is even more susceptible to torsional response in future strong ground shaking. In the group selection procedure of Section 4.3.2, the connections on opposite sides of a building are included in the same group. If the building responds torsionally, connections on one side will experience more damage and connections on the other side less damage, but the average damage statistics calculated for the group will mask this behavior. In this optional procedure a connection group is established on each side of the building’s center of lateral resistance so that if one side of the building has experienced greater damage, due to torsional response, this will be detected by the damage statistics calculated for the different groups. Typically, under this procedure, at least 4 groups of moment-resisting connections will be designated for the building, one on each of the north, south, east and west sides of the center of rigidity. Buildings with unusual plan shapes (triangular, hexagonal, etc.) may require more (or possibly fewer) groups of connections to adequately capture torsionally induced damage.

For each group of connections, the following assumptions are made:

1. All of the connections in a group are expected to perform in the same statistical manner;

2. The probability of damage to each connection is uniform over the group, that is, all connections have the same probability of failure; and,

3. Prior to inspection, whether an individual connection in the group is damaged or not is independent of the damage state of any other connection in the group.

The number of groups should be increased as is required to meet these objectives.

To reflect torsional response, resulting either from the structural response characteristics of the undamaged building or a chance concentration of damage that creates such an imbalance, each moment-resisting frame connection is assigned to a group according to the following procedure:

a. Determine the approximate center of rigidity for torsional response of the first floor (assuming the building is in its pre-earthquake, original condition). Draw two orthogonal lines in the plan principal directions of the moment frames and extend these vertically as planes. These planes should be adjusted so that all of the connections along a given structural frame are assigned to the same group and that all frames on higher floors are unambiguously assigned to a group. Where the seismic system does not have an orthogonal system, the principal axes can be drawn skewed, or as appropriate to give approximately equal classes of connections assigned to one or the other directions. The following discussion assumes a building with principal orthogonal axes aligned with the north-south and east-west directions.

b. All of the connections providing north-south lateral force resistance and located to the west of the center of resistance on all floors (and expected to perform in a similar manner) are assigned to the same group (No. 1). Both weak and strong axis connection connections are included. Similarly all of the connections providing north-south lateral force resistance and located to the east of the center of resistance are assigned to a second group. A similar procedure is followed to assign connections providing east-west lateral force resistance to one of two additional groups.

c. Sample selection from these groups may be made by any of Methods A, B, or C. In keeping with the suggestion in Section 4.3.3.1 paragraph 1, several of the connections in each group having the greatest distance from the assumed center of rotation should be included in each sample.

Commentary: It is well known that torsion can play an important role in the distribution of loads on a building's frame. The eccentricity of the damaged building, either by its design or the chance occurrence of damage to individual connections, has major implications for its response in future earthquakes. It is also clear that the building's response in orthogonal directions is important. Therefore, for buildings with moment frames in both principal directions, it is recommended that the investigation procedure include at least four distinct groups of connections to reflect the torsional and orthogonal loading conditions.

For buildings with moment frames in only one direction, it is recommended that the investigation procedure have at least two distinct groupings of connections.

4.5 Qualified Independent Engineering Review

Independent third party review, by qualified professionals, is recommended throughout these Interim Guidelines when alternative approaches to evaluation or design are taken, or where approaches requiring high degrees of structural engineering knowledge and judgment are taken. Specifically, it is recommended that qualified engineering review be provided in any of the following cases:

1. Where an engineer elects to select connections for inspection by a method other than Methods A or B of Section 4.3 of these Interim Guidelines.

2. Where the calculated damage index D_{max} exceeds 33% and the engineer has determined that an unsafe condition does not exist.

3. Where an engineer has decided not to repair damage otherwise recommended to be repaired by these Interim Guidelines.

4. When any story of the building has experienced a permanent lateral drift exceeding 1% of the story height and proposed repairs do not correct this condition.

5. When an engineer elects to design connections for plastic rotation capacities determined by analysis.

6. When an engineer elects to design connection configurations by calculations only, without the use of, or reference to, qualification tests for a connection prototype.

Where independent review is recommended, the analysis and/or design should be subjected to an independent and objective technical review by a knowledgeable reviewer experienced in the design, analysis, and structural performance issues involved. The reviewer should examine the available information on the condition of the building, the basic engineering concepts, and the recommendations for proposed action.

Commentary: The independent reviewer may be one or more persons whose collective experience spans the technical issues anticipated in the work. When more than one person is collectively performing the independent review, one of these should be designated the review chair, and should act on behalf of the team in presenting conclusions or recommendations.

Independent third party review is not a substitute for plan checking. It is intended to provide the structural engineer of record with an independent opinion, by a qualified expert, on the adequacy of structural engineering decisions and approaches. The seismic behavior of WSMF structures is now *understood to be an extremely complex issue. Proper understanding of the problem requires knowledge of structural mechanics, metallurgy, welding, fracture mechanics, earthquake engineering and statistics. Due to our limited current state of knowledge, even professionals who possess such knowledge face considerable uncertainty in making design judgments. Third party review should not be performed by unqualified individuals.*

4.5.1 Timing of Independent Review

The independent reviewer(s) should be selected prior to the initiation of substantial portions of the design and/or analysis work that is to be reviewed, and review should start as soon as sufficient information to define the project is available.

4.5.2 Qualifications and Terms of Employment

The reviewer should be independent from the design and construction team. The reviewer should have no interest of any kind with the work being reviewed other than the performance of tasks required by this section.

a. The reviewer should have no other involvement in the project before, during, or after the review.

b. The reviewer should be selected and paid by the owner and should have an equal or higher level of technical expertise in the issues involved than the structural engineer of record.

c. The reviewer (or in the case of peer review teams, the review chair) should be a structural engineer who is familiar with governing regulations for the work being reviewed.

d. The reviewer should serve through completion of the project and should not be terminated except for failure to perform the duties specified herein. Such termination should be in writing with copies to the building official, owner, and the structural engineer-of-record.

4.5.3 Scope of Review

Review activities related to evaluation of the safety condition of a building should include a review of available construction documents for the building, all inspection and testing reports, any analyses prepared by the structural engineer of record, the method of connection sample selection and visual observation of the condition of the structure. Review should include consideration of the proposed design approach, methods, materials and details.

4.5.4 Reports

The reviewer should prepare a written report to the owner and building official that covers all aspects of the structural engineering review performed including conclusions reached by the reviewer. Such reports should include statements on the following:

a. Scope of engineering review performed with limitations defined.

b. The status of the project documents at each review stage.

c. Ability of selected materials and framing systems to meet performance criteria with given loads and configuration.

d. Degree of structural system redundancy, ductility and compatibility, particularly in relation to lateral forces.

e. Basic constructability of structural members and connections (or repairs and modifications of these elements).

f. Other recommendations that would be appropriate to the specific project.

g. Presentation of the conclusions of the reviewer identifying any areas which need further review, investigation and/or clarifications.

h. Recommendations, if any.

4.5.5 Responses and Corrective Actions

The structural engineer-of-record should review the report from the reviewer and develop corrective actions and other responses as appropriate. Changes during the construction/field phases that affect the seismic resistance system should be reported to the reviewer in writing for action and recommendations.

4.5.6 Distribution of Reports

All reports, responses and corrective actions prepared pursuant to this section should be submitted to the building official and the owner along with other plans, specifications and calculations required. If the reviewer is terminated by the owner prior to completion of the project, then all reports prepared by the reviewer, prior to such termination, should be submitted to the building official, the owner, and the structural engineer-of-record within (10) ten working days of such termination.

4.5.7 Engineer of Record

The structural engineer-of-record should retain the full responsibility for the structural design as outlined in professional practice laws and regulations.

4.5.8 Resolution of Differences

If the structural engineer-of-record does not agree with the recommendations of the reviewer, then such differences should be resolved by the building official in the manner specified in the applicable Building Code.

This Page Intentionally Left Blank