C.2 Performance-Based Design Methodology

The first step in PBD is to establish performance objectives described as the combination of an expected performance level with expected levels of hazard (*e.g.* ground motion, extreme wind). A performance level is an expression of the maximum desired extent of damage to a building. The Structural Engineers Association of California (SEAOC) defines four performance levels (SEAOC 1999):

1. **Fully Operational** where the facility continues in operation with negligible damage after frequent events.
2. **Operational** in which the facility sustains minor damage and minor disruption in non-essential services after occasional seismic events.
3. **Life Safe** where life-safety is substantially protected and damage to the structure is moderate to extensive after the rare event.
4. **Near Collapse** in which life-safety is at risk, damage to the structure is severe, but structural collapse is prevented after the very rare earthquake.

The second aspect to PBD is the definition of the expected hazard level that may occur at the given site. Four to five levels of earthquake hazard that have been suggested (ATC 1997; SEAOC 1999) are given in Table C-1.

Table C-1: *Probabilistic Seismic Hazard Events.*

	Seismic Hazard	
Event	**Recurrence Interval**	**Probability of Exceedance**
Frequent	43 years	50% in 30 years
Occasional	72 years	50% in 50 years
Rare	475 years	10% in 50 years
Very Rare	970 years	10% in 100 years
MCE	2,500	2% in 50 years

The performance objectives for a structure are the coupling of expected performance level with expected (probabilistic) hazard. The objectives for earthquake performance have been placed in matrix form as shown in Figures C-1.

The third and final ingredient necessary for PBE is a means to verify that the design is meeting the performance objectives. Some of the difficulty in implementing PBD in the past was the result of limited computational power and analytical tools. One can surmise that the analysis employed to validate achievement of the life-safe performance level during the very rare earthquake might involve a nonlinear static pushover analysis or nonlinear time-history analysis. To the contrary, assessment that the fully operational level is being met during the frequent earthquake may involve elastic time-history analysis or even a linear static lateral load analysis. Therefore, the verification of performance may require significantly different analysis methods and/or analytical assumptions (*e.g.* damping levels). Once these analyses have been carried out, the engineer is left with the need to assess satisfaction of performance objectives using information obtained through the analysis.

Efforts have been made in relating performance levels to structural and nonstructural damage. For example, damage descriptions are available (SEAOC 1999) to aid the designer in validating that performance levels are being met. These tables contain descriptions of behavior meeting an established performance level. For example, in the case of primary steel moment frames, the life safety seismic performance level includes "formation of plastic hinges; local buckling of some elements; severe joint distortion; isolated connection failures; and a few elements with a chance of experiencing fracture" (SEAOC 1999). While these tabular descriptions are very useful for qualitative assessment, the structural engineer needs much more quantitative performance measures. A relatively recent development in damage prediction is the HAZUS Loss Methodology (FEMA 1999) and it is very useful for quantifying damage to structural and non-structural components within buildings.

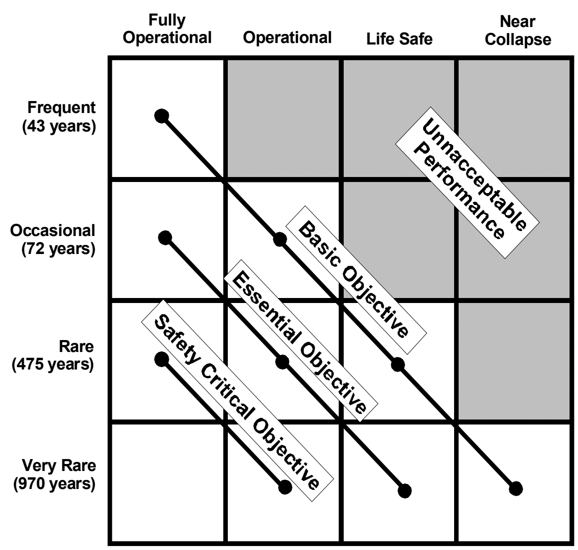

Figure C-1: Performance Objective and Hazard Level Matrix for Seismic Events (SEAOC 1999).

In general, damage to structural and nonstructural components is categorized by damage state: slight, moderate, extensive, and complete. Nonstructural elements are also classified as either drift-sensitive or acceleration-sensitive. Tables C-2 and C-3 give example descriptions (FEMA 1999) of damage states and the corresponding performance objectives (ATC 1997b) for nonstructural partition walls and structural steel components and skeletons, respectively.

Table C-2: Performance Objectives, Damage and Damage Descriptions for Partition Walls.

Performance Objective	Damage State	Damage Description
Fully Operational	Slight	A few cracks are observed at intersections of walls and ceilings and at corners of door openings.
Operational	Moderate	Larger and more extensive cracks requiring repair and repainting; some partitions may require replacement of gypsum board or other finishes.
Life Safe	Extensive	Most of the partitions are cracked and a significant portion may require replacement of finishes; some doorframes are also damaged and require re-setting.
Near Collapse	Complete	Most partition finish materials and framing may have to be removed and replaced; damaged studs repaired, and walls refinished. Most doorframes may also have to be repaired and replaced.

Table C-3: Performance Levels, Damage States and Damage Descriptions for Structural Steel Components and Skeletons.

Performance Objective	Damage State	Damage Description
Fully Operational	Slight	Minor deformations in connections or hairline cracks in a few welds.
Operational	Moderate	Some Steel members have yielded exhibiting observable permanent rotations at connections; few welded connections may exhibit major cracks through welds; or few bolted connections may exhibit broken bolts or enlarged bolt-holes.
Life Safe	Extensive	Most steel members have exceeded their yield capacity, resulting in significant permanent lateral deformation of the structure. Some of the structural members or connections may have exceeded their ultimate capacity exhibited by major permanent member rotations at connections, buckled flanges and failed connections. Partial collapse of portions of the structure is possible due to failed critical elements and/or connections.
Near Collapse	Complete	Significant portion of the structural elements have exceeded their ultimate capacities or some critical structural elements or connections have failed resulting in dangerous permanent lateral displacement, partial collapse, or collapse of the building.