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SEISMIC ASSESSMENT AND PROPOSED STRENGTHENING OF A NON-DUCTILE BUILDING IN CALIFORNIA

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Abstract

Constructed in 1956, the building that was evaluated is a shared-use facility with the County of Los Angeles. The building is significantly undersized and has numerous functional problems that prevent the users from providing safe and efficient services. The building is a two story concrete shear wall building with steel framed penthouse which was designed to the 1955 Edition of Uniform Building Code (UBC) and is highly representative of public building types constructed within the same era of expansion in Southern California. Likely seismic performance of the existing building was assessed using ASCE 31-03 provisions and the outcomes were evaluated. Replacement and rehabilitation options, both for standard, enhanced and reduced performance requirements as compared to current building codes were studied. The likely risks associated with each option were presented in a manner that is more accessible to the non-engineering community than the approach that is ordinarily used by engineering standards.

Keywords: existing building; seismic assessment; seismic strengthening; seismic performance levels; ASCE 31-03

1. Introduction

Constructed in 1956, this public building was designed to the 1955 Edition of Uniform Building Code (UBC) and is highly representative of building types constructed within the same era in California. It consists of a two story concrete shear wall building with steel framed penthouse (Figure 1). There is a partial basement at the central portion of the building which consists of concrete walls laterally restrained by soil on all sides. The building plan is rectangular in shape with approximate dimensions of 62-ft by 264-ft and typical floor heights of 14.5ft. The building type as defined by ASCE 31-03 is S4, steel frames with concrete shear walls, based on the lateral-force resisting system and diaphragm type. The gravity system consists of 3.5-in thick concrete slabs on top of concrete joists and composite wide flange steel beams vertically supported by wide flange steel columns encased in concrete. The lateral system is comprised of reinforced concrete bearing/shear walls in both orthogonal directions.

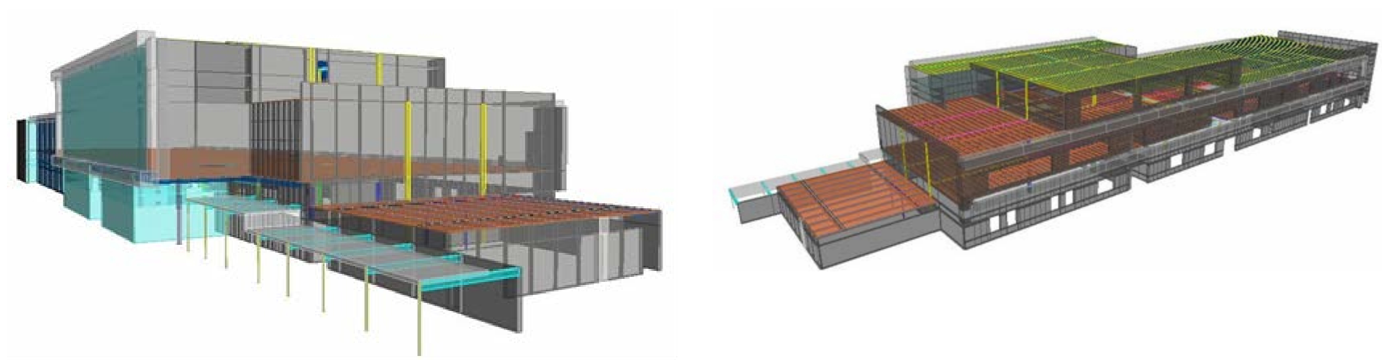


Figure 1. Main Building

The users of the facility recently concluded that the building has numerous deficiencies which prevent the facility from functioning in a safe and efficient manner. This conclusion led them to commission the architectural and engineering design team to conduct studies to evaluate various permutations of renovation ranging from full replacement to partial replacement combined with retrofit. As a component of these studies, the likely seismic performance of the building was evaluated based on the Tier-1 and Tier-2 methodologies of ASCE 31-03 Seismic Evaluation of Existing Buildings. The objective of the seismic assessment is to form a professional opinion on the likely seismic performance of the existing building based on the review of existing drawings, site visits, 3D computer analysis of the seismic system, and industry best practice in seismic engineering. Main non-conformances related to the structural system of the building together with seismic strengthening options are discussed.

2. Site Description and Seismicity

The building is located in a region of high seismicity as defined by the current building code (Figure 2). According to a USGS (2002) seismic hazard deaggregation, the highest contributors to seismic hazard at the site are large events (M6.5-M7) on a fault system less than 10 miles from the site. These near faults are in seismic silence and are assumed as high risky by seismologists. In addition to that, there are some significant historic earthquakes on nearby faults in Southern California including the 1994 Northridge Earthquake (Magnitude 6.7, 22 miles away) and 1952 Kern County Earthquake (Magnitude 7.5, 42 miles away).

The ground shaking at the site due to previous large magnitude earthquakes was not severe and the building does not appear to have experienced any significant damage due to earthquakes and no damage was documented or reported since 1956. Parameters that are used to define the seismic hazard at the building site have been obtained from United States Geological Survey (USGS) Seismic Hazard Data. Short period and 1-second spectral acceleration values (S_s and S_1) have been given as 2.787g and 0.935g, respectively. The site class has been found as “Type C” (very dense soil and soft rock) per ASCE 7-05 classifications and USGS V_s Maps.

Site coefficients (F_a and F_v) have been found as 1.0 and 1.3, respectively. Based on site class C, short period and 1-second design spectral accelerations (S_{DS} and S_{D1}) have been calculated as 1.858g and 0.810g, respectively. The design basis earthquake (DBE) response spectrum (5% damping) is shown in Figure 4. Seismic Design Category (SDC) was determined to be “D” per ASCE 7-05.

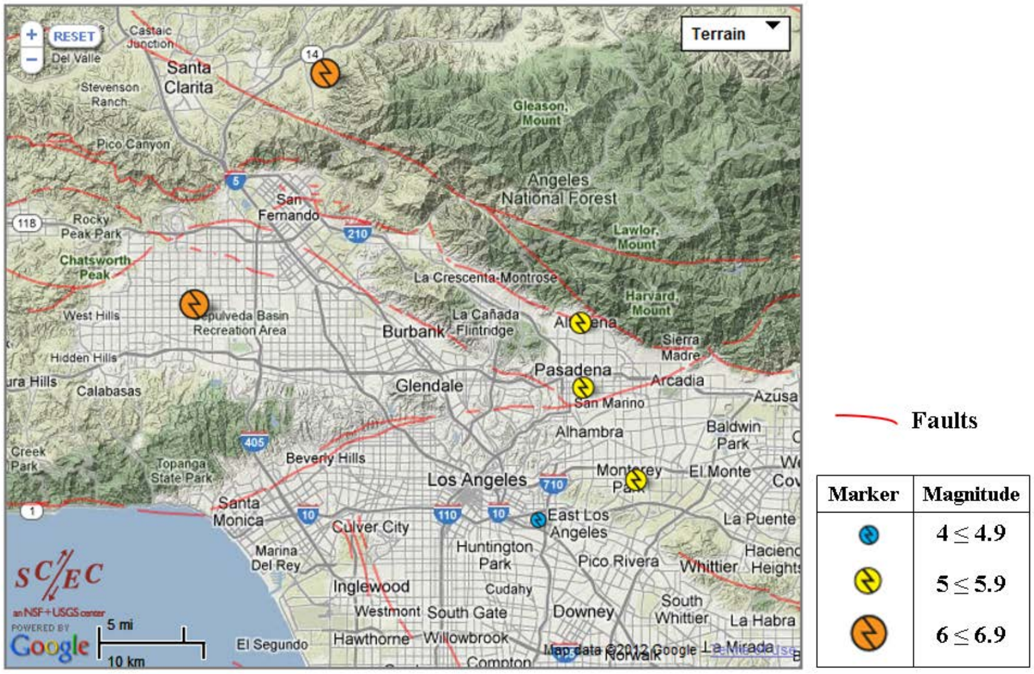


Figure 2. Significant earthquakes and faults in Southern California (Southern California Earthquake Center)

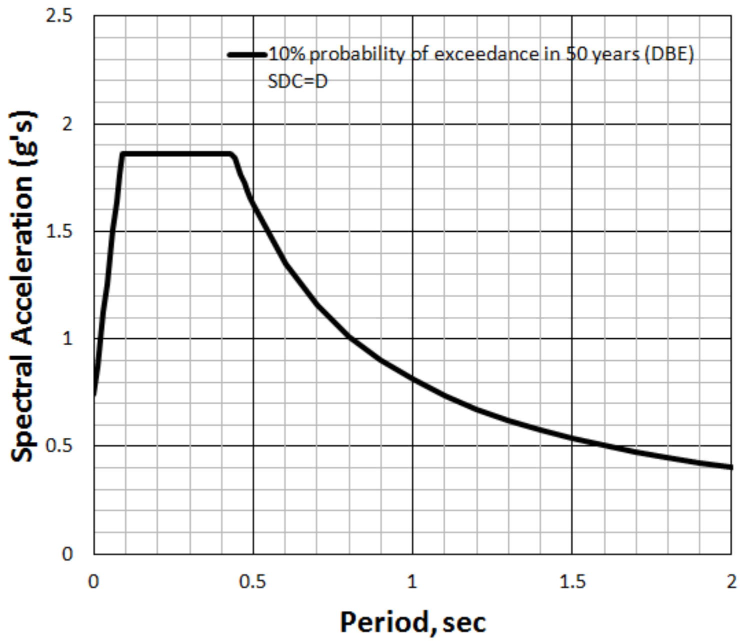


Figure 3. Design base earthquake (DBE) response spectrum function (5% damping)

3. Building Performance Level Objectives

The structural performance of a building during a seismic event can generally be categorized into four performance levels: (i) Operational (1A), (ii) Immediate Occupancy (1B), (iii) Life Safety (3C), and (iv) Collapse Prevention (5E). ASCE 31-03 and ASCE 41-06 documents provide descriptions for these performance levels of structural and non-structural elements. For reference, structural and non-structural performance levels are provided in Table 1.

The definition of Life Safety performance level per ASCE documents contains two performance criteria that require judgment to be exercised. The following guidance may be used to incorporate the two criteria in the design evaluation: (1) at least some margin against either partial or total structural collapse remains, or (2) injuries may occur, but the overall risk of life-threatening injury as a result of structural damage is expected to be low.

Immediate Occupancy Performance Level is defined as the post-earthquake damage state in which a structure remains safe to occupy (per ASCE 41-06). The definition of Immediate Occupancy Performance Level contains two performance criteria that require judgment to be exercised. The following guidance may be used to incorporate the two criteria in the design evaluation: (1) after a design earthquake, the basic vertical- and lateral-force resisting systems retain nearly all of their pre-earthquake strength and (2) very limited damage to both structural and non-structural components is anticipated during the design earthquake that will require some minor repairs, but the critical parts of the building are habitable.

Collapse Prevention is not a performance level defined in ASCE 31-03, however, ASCE 41-06 states "Structural Performance Level S-5, Collapse Prevention, means the post-earthquake damage state in which the building is on the verge of partial collapse. Substantial damage to the structure has occurred, potentially including significant degradation in the stiffness and strength of the lateral-force-resisting system, large permanent lateral deformation of the structure, and degradation in the vertical-load-carrying capacity. However, all significant components of the gravity-load-resisting system must continue to carry their gravity load demands. Significant risk of injury due to falling hazards from structural debris may exist. The structure may not be technically practical to repair and is not safe for re-occupancy, as aftershock activity could induce collapse."

Current US building codes imply a "Life Safety" performance level for "typical" buildings under code level seismic hazard (BSE-1 "rare" event with 10% probability of being exceeded in 50 years, a 475 year event). However, for the evaluation of existing structures, other performance levels can also be considered based on the type and associated (operational and/or safety) risks. For example, essential structures such as Hospitals, Fire Stations and Power Plants are generally designed to stay "operational" (1A) after BSE-1 level seismic hazard. Similarly, "Immediate Occupancy" (1B) performance objective could be selected for structures where extended disruption to the occupancy of the structure has substantial financial consequences to the client. For non-essential structures, it is usual to aim to achieve "Life-Safety" structural performance level when the building is subjected to a building code level earthquake. For the purposes of this evaluation, the main objective that was considered is a "Life Safety" performance level. However, other levels have also been considered as well if operational interruption after a seismic event is a concern.

Normal structural seismic performance objectives are met by through conformance with the principles and provisions of the applicable code using either mapped seismic acceleration parameters required by ASCE 7-05 Chapter 11 or site-specific seismic ground motions. This is categorized as "Life Safety (3C)" according to ASCE 31 and ASCE 41 documents.

Enhanced performance refers to controlling earthquake damage to a building in order to limit the expected loss of use. Enhanced structural performance objectives are met through approval of the seismic design criteria by the responsible authority. An independent peer reviewer may be appointed to review the criteria. This is categorized as "Immediate Occupancy (1B)" according to ASCE 31 and ASCE 41 documents.

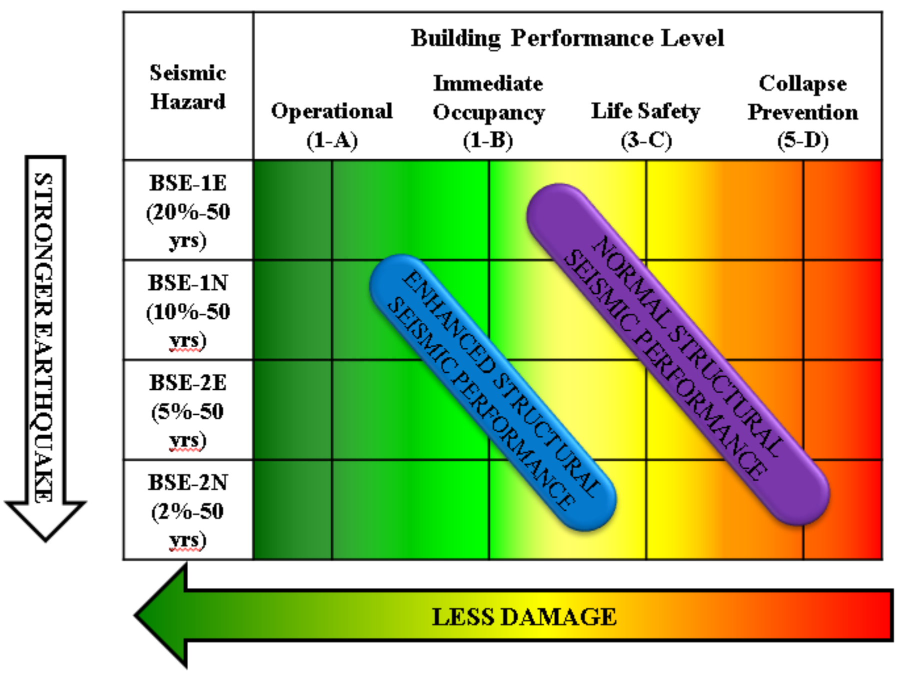


Figure 4. Building performance criteria

Table 1 – Damage control and target building performance levels

	Collapse Prevention Level (5-E)	**Life Safety Level (3-C)**	**Immediate Occupancy Level (1-B)**	**Operational Level (1-A)**
Overall Damage	Severe	Moderate	Light	Very Light
General	Little residual stiffness and strength, but load-bearing columns and walls	Some residual strength and stiffness left in all stories. Gravity-load-bearing	No permanent drift. Structure substantially retains original strength and stiffness.	No permanent drift. Structure substantially retains original strength and stiffness.

	function. Large permanent drifts. Some exists blocked. Infills and unbraced parapets failed or at incipient failure. Building is near collapse.	elements function. No out-of-plane failure of walls or tipping of parapets. Some permanent drift. Damage to partitions. Building may be beyond economical repair.	Minor cracking of facades, partitions, and ceilings as well as structural elements. Elevators can be restarted. Fire protection operable.	Minor cracking of facades, partitions, and ceilings as well as structural elements. All systems important to normal operation are functional.
Nonstructural components	Extensive damage.	Falling hazards mitigated but many architectural, mechanical, and electrical systems are damaged.	Equipments and content are generally secure but may not operate due to mechanical failure or lack of utilities.	Negligible damage occurs. Power and other utilities are available, possibly from standby sources.
Comparison with performance intended for buildings designed under the NEHRP Provisions for the Design Earthquake	Significantly more damage and greater risk.	Somewhat more damage and slightly higher risk.	Less damage and lower risk.	Much less damage and lower risk.

4. Seismic Assessment Methodology and Findings

The likely seismic performance of the building was evaluated based on Tier-1 and Tier-2 methodologies of ASCE 31-03 Seismic Evaluations of Existing Buildings. Tier-1 procedure includes a site visit where structural aspects of the building are compared against Tier-1 screening checklist to identify any non-conformances the building might have. A non-conformance does not confirm a deficiency, but it generally warrants a more detailed analysis/study per Tier-2 methodology.

4.1 Tier-1 Assessment

The initial assessment study based on Tier-1 methodology revealed several structural non-conformances in the building as outlined below. Specifically, lateral load resisting elements failed to comply with the requirements of ASCE 31-03 "Life Safety" (Normal structural seismic performance) and "Immediate Occupancy" (Enhanced structural seismic performance) criteria under BSE-1 level seismic hazard.

- Weak story: The strength of the lateral-force resisting system of the penthouse level is less than 80 percent of the strength of the level below.
- Vertical discontinuities: There are vertical shear wall elements in the lateral-force resisting systems that do not continue to the foundation.
- Shear stress checks: Inadequate shear strength of the lateral load resisting system exists. Shear stress on concrete walls is greater than the allowable 100-psi per ASCE 31-03.
- Foundation dowels: For some wall members, existing 2#4 dowels @ 10 on center are not adequate to resist uplift forces.
- Opening at shear walls: There are diaphragm openings immediately adjacent to the shear walls that are larger than the 25 percent of the wall length allowed by the code.

4.2. Tier-2 Assessment

ASCE 31 Tier-2 assessment was conducted as a result of Tier-1 non-conformances. ASCE 31-03 Tier-2 procedure consists of creating a linear model of the building and conducting analysis to estimate the seismic demands on the structural components. Capacities of the lateral load resisting members are computed based on the site investigations and the material strength values provided by the structural drawings. Demand capacity ratios are calculated and compared to the acceptable values given in ASCE/SEI 31-03.

A 3-D model of the building was created using ETABS structural analysis software (Figure 1). The analysis model includes all members of the lateral load resisting system and the primary gravity load carrying members. The 3-D building model wasanalyzed under combinations of horizontal seismic and vertical gravity loads laid out by ASCE 31-03. The capacities of the lateral load resisting members were derived and checked against ASCE 31-03 acceptance criteria under an earthquake hazard level with 10% probability of being exceeded in 50 years (475 year event).

Material strengths were based on the information available on the structural drawings and ASCE 31-03 default values. The following strengths were used in seismic evaluation:

- Concrete strength, f'_c = 2,000 psi (Main building) and f'_c = 3,000 psi (Probation wing)
- Yielding strength of reinforcing steel, f_y = 40 ksi (ASTM A305)
- Yielding strength of structural steel, F_y = 33 ksi (ASTM A7)

Load demand due to gravity loads (Q_G) is a combination of dead (Q_D) and live (Q_L) loads on the structure as follows:

$$Q_D = 1.1(Q_D+Q_L+Q_S) \quad (1)$$

$$Q_G = 0.9Q_D \quad (2)$$

Seismic loads (Q_E) acting on the components were based on the linear static procedure outlined in Section 4.2.2.1.3 of ASCE 31-03. Gravity and seismic forces were then combined using equation 4-8 of ASCE 31-03.

$$Q_{UD} = Q_G \pm Q_E \quad (3)$$

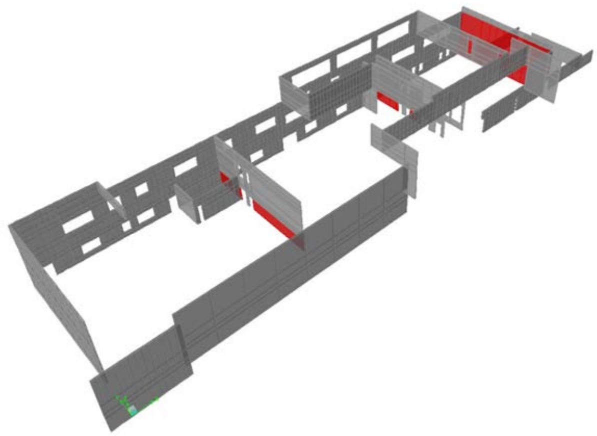
Per ASCE 31-03 linear analysis procedure, components are grouped as deformation or force controlled. Equation (3) is used for the assessment of deformation-controlled components. Q_{UD} represents the load demand on these members. As shown in Equation (4) below, force demand on the elements is reduced by factor m, which accounts for the inelastic response of the components.

$$Q_{CE} \geq Q_{UD}/m \quad (4)$$

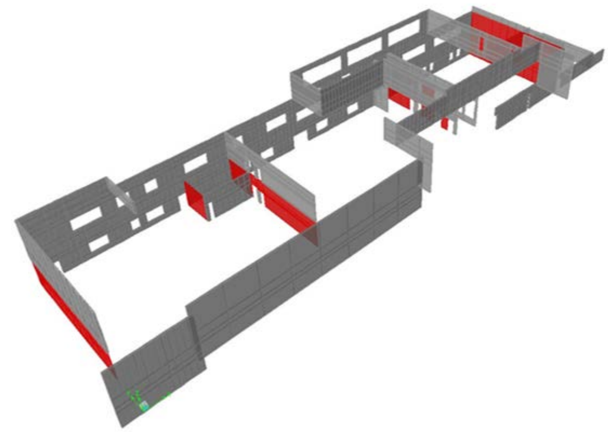
Expected strength of the structural elements, Q_{CE}, is then compared against the force acting on the element, Q_{UD} using Equation 4. The expected strength is assumed to be equal to the nominal strength multiplied by 1.25 per Section 4.2.4.4 of ASCE 31-03.

Analysis results indicate that structural components on the lateral load resisting system of the building fall into both force and deformation controlled categories. Per Table 4-6 of ASCE 31-03, S4 type building types, the value of m factor for deformation controlled actions is taken as 3.0 for Life Safety and 2.0 for Immediate Occupancy performance levels. Values of m factor for force-controlled actions are taken as 2.5 for Life Safety and 2.0 for Immediate Occupancy performance levels.

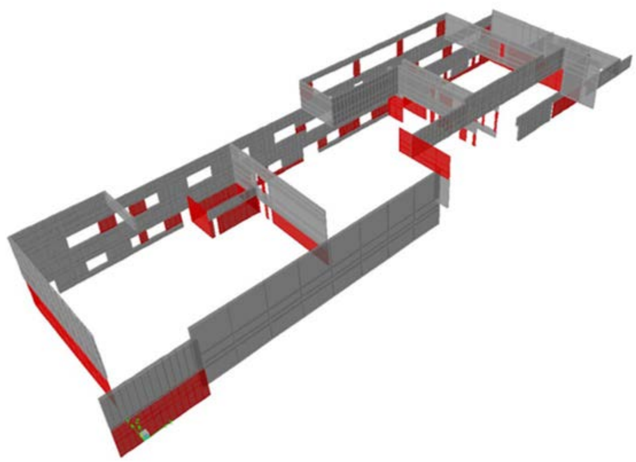
Figure 5 Highlights the members with non-conforming shear and flexural strength under Life Safety and Immediate Occupancy criteria.



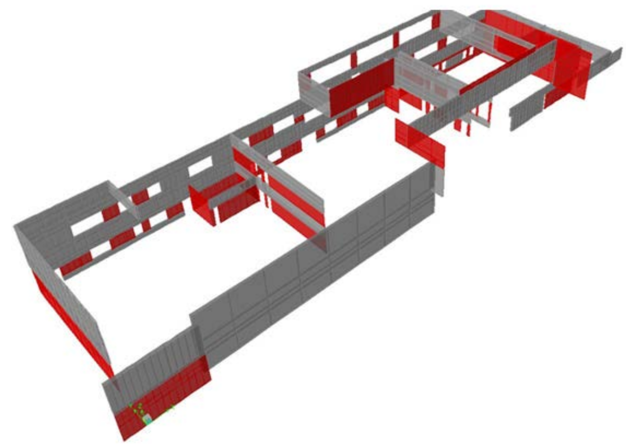
(a) Shear – Life safety



(b) Shear – Immediate occupancy



(c) Flexure – Life safety



(d) Flexure – Immediate occupancy

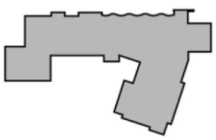
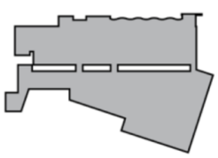
Figure 5. Building conformance check for shear and flexural behavior of reinforced concrete walls (non-conformances are highlighted in red)

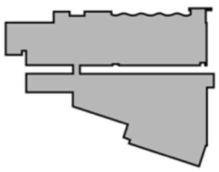
5. Structural Strengthening Options

Various facility upgrade strategies were evaluated for consideration by the building owner. Requirements for structural strengthening options for Life Safety and Immediate Occupancy performance levels for the Building were provided along with similar guidelines appropriate for the design of replacement buildings. These are indicated in Table 2.

Figure 6 provides graphical representation of the strengthening options studied for Life Safety, Immediate Occupancy, as well as Collapse Prevention performance levels.

Table 2 - Structural strengthening requirements for the Building

		NORMAL "LIFE SAFETY" PERFORMANCE	ENHANCED "IMMEDIATE OCCUPANCY" PERFORMANCE
Strategy A 	**Existing Building**	• Retain North façade only. • Inspect and evaluate the attachment of existing North façade to the structural system. Mitigate where necessary. • Construct new building within footprint of existing	• Retain North façade only. • Inspect and evaluate the attachment of existing North façade to the structural system. Mitigate where necessary. • Construct new building within footprint of existing
	New Building	• Design new building per current building code.	• Design new building using Performance Based Seismic Design methodology to achieve Immediate Occupancy under a BSE-1 level seismic hazard.
Strategy B 	**Existing Building**	• Add 280-ft of 10-in. thick reinforced shotcrete walls in the short direction (3,800 ft^3). • Add 160-ft of 12-in. thick reinforced concrete shear walls in lieu of the demolished existing walls in the long direction (4,640 ft^3). • Inspect and evaluate the attachment of existing North façade to the structural system. Mitigate if necessary. • Existing foundations to be assessed.	• Add 350-ft of 10-in. thick reinforced shotcrete walls in the short direction (4,750 ft^3). • Add 160-ft of 14-in. thick reinforced concrete shear walls in lieu of the demolished existing walls in the long direction (5,400 ft^3). • Inspect and evaluate the attachment of existing North façade to the structural system. Mitigate if necessary. • Existing foundations to be assessed
	New Building	• Separate new construction from existing courthouse with a seismic joint. • Design new building per current building code. • Provide seismic expansion joints at the bridges connecting the existing building to the new building.	• Separate new construction from existing building with a seismic joint • Design new building using Performance Based Seismic Design methodology to achieve Immediate Occupancy under a BSE-1 level seismic hazard. • Provide seismic expansion joints at the bridges connecting the existing building to the new building.

Strategy C 	**Existing Building**	• Add 280-ft of 10- in. thick reinforced shotcrete walls in the short direction (3,800 ft^3). • Add 160-ft of 12-in. thick reinforced concrete shear walls in lieu of the demolished existing walls in the long direction (4,640 ft^3). • Inspect and evaluate the attachment of existing North façade to the structural system. Mitigate if necessary. • Existing foundations to be assessed	• Add 350-ft of 10-in. thick reinforced shotcrete walls in the short direction (4,750 ft^3). • Add 160-ft of 14-in. thick reinforced concrete shear walls in lieu of the demolished existing walls in the long direction (5,400 ft^3). • Inspect and evaluate the attachment of existing North façade to the structural system. Mitigate if necessary. • Existing foundations to be assessed
	New Building	• Separate new construction from existing courthouse with a seismic joint • Design new building per current building code.	• Separate new construction from existing buildingwith a seismic joint • Design new building using Performance Based Seismic Design methodology to achieve Immediate Occupancy under a BSE-1 level seismic hazard.

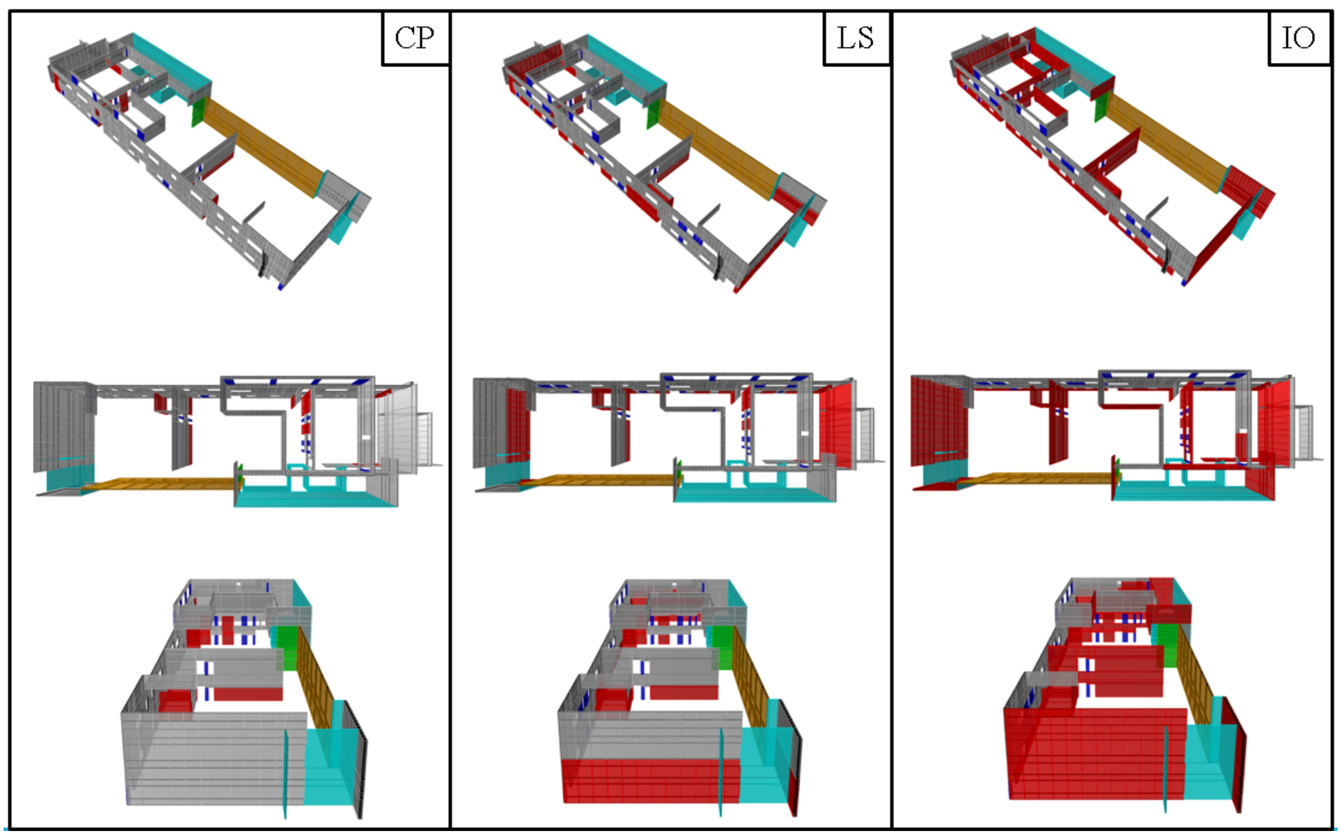


Figure 6. Strengthening options for (a) Immediate Occupancy, (b) Life Safety, and (c) Collapse Prevention performance levels

While various planning strategies were explored, for those which included retention and/or rehabilitation of the existing facility, three levels of seismic rehabilitation were evaluated along with the possible outcome of not executing seismic rehabilitation (where this would be permissible under the provisions of the building code). Costs were developed by the project's cost consultant corresponding to each rehabilitation option. It was important that the owner (who is not a structural engineer) would be able to consider the relative risks of these 4 possible options. As a result of this, the approach of describing a "failure to achieve life safety in an event having a probability of exceedence of x% in y years" was determined to be inappropriate for conversations about seismic risk with non-engineers. Therefore the performance options and the level of relative risks were re-stated and a % chance that a particular outcome (Immediate occupancy, Life Safety, Collapse Prevention) would not be achieved at some point in 50 years. These data are presented in Table 3.

Table 3 – Rehabilitation options expressed as chance of failing to achieve various possible performance objectives in 50 years.

Option	**Failure to achieve Immediate Occupancy**	**Failure to achieve Life Safety**	**Failure to achieve Collapse Prevention**
No Retrofit	86% chance in 50 years	70% chance in 50 years	46% chance in 50 years
Collapse prevention	31% chance in 50 years	20% chance in 50 years	7% chance in 50 years
Life Safety	16% chance in 50 years	10% chance in 50 years	2% chance in 50 years
Immediate Occpancy	10% chance in 50 years	5% chance in 50 years	1% chance in 50 years

6. Conclusions

Based on the findings from analysis and evaluation studies, existing drawings of the structural system, and experience from past Southern California earthquakes as it relates to this building type, it is our opinion that buildings of this common type of construction and vintage are likely to perform poorly under a seismic event similar to the seismic hazard prescribed in the current California Building Code. This particular example did not satisfy the ASCE 31-03 Tier-1 and Tier-2 Life Safety performance objective when subjected to a fraction (2/3) of the current BSE-2 level seismic hazard.

When presenting findings such as these to help building owners select from various rehabilitation options, many of which may be voluntary under local laws and building code provisions it is important to consider presenting risks in a manner that is easier understood by the non-engineer. This may require departing from the routine engineering presentation of outcomes as failure (or not) to achieve a level of performance in an event having a probability of exceedence of x% in y years.

7. References

[1] ASCE/SEI 31-03. 2003. *Seismic Evaluation of Existing Buildings*. American Society of Civil Engineers-Structural Engineering Institute, Reston, VA.

[2] ASCE/SEI 41-06. 2006. *Seismic Evaluation and Retrofit of Existing Buildings*. American Society of Civil Engineers-Structural Engineering Institute, Reston, VA.

[3] ASCE/SEI 41-13. 2013. *Seismic Evaluation and Retrofit of Existing Buildings*. American Society of Civil Engineers-Structural Engineering Institute, Reston, VA.