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SEISMIC RISK ASSESSMENT OF TILT-UP BUILDINGS USING THE FEMA P-58 METHOD

K.F. Wade[1], D.J. DeBock[2], J.W. Lawson[3], M. Koliou[4], D.T. Cook[5], C.B. Haselton[6]

ABSTRACT

Tilt-up structures have been a popular construction method in the United States during the last century for industrial and more recently commercial building structures. Since the 1970s, design requirements for tilt-up buildings have changed several times in response to observed performance in moderate earthquakes, making their seismic performance highly dependent on the building code era for which they were designed. A robust method for seismic assessment is needed to support the development of resilient communities; this method should support the assessment of all common building types including tilt-up buildings.

The FEMA P-58 method enables engineers to design and assess the seismic performance of buildings at a new level of detail using broadly understandable decision variables (repair cost, repair time, and casualties). Up to this point, the FEMA P-58 method has not been optimized for buildings in which the damage collects primarily in the flexible diaphragm or diaphragm to out-of-plane wall connections. This study extends the FEMA P-58 method for use on tilt-up buildings in two areas: (1) Estimation of standard engineering demand parameters (EDPs) for tilt-up buildings, such as interstory drift ratio, and tilt-up specific EDPs such as roof diaphragm ductility demand, and (2) Development of fragility curves for tilt-up specific building components.

[1] Research Engineer, Haselton Baker Risk Group, Chico, CA, 95928 (email: katie@hbrisk.com).
[2] Assistant Professor, Dept. of Civil Eng., CSU Chico, CA 95929 (email: ddebock@csuchico.edu).
[3] Associate Professor, Architectural Eng., Cal Poly, San Luis Obispo, CA 93407 (email: jwlawson@calpoly.edu).
[4] Assistant Professor, Zachry Dept. of Civil Eng., Texas A&M University, College Station, TX 77843 (email: maria.koliou@tamu.edu).
[5] PhD Candidate, CU Boulder, CO 80309 and Research Engineer, Haselton Baker Risk Group (email: dustin@hbrisk.com).
[6] CEO, Haselton Baker Risk Group, Chico, CA, 95928 and Professor, Dept. of Civil Eng., CSU Chico, CA 95929 (email: curt@hbrisk.com).

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Introduction

Over the past few years, the use of the FEMA P-58 method has increased dramatically, and FEMA P-58 is now being used by the majority of the large west coast structural earthquake engineering firms. This includes use of FEMA P-58 for many purposes such as resilient design, retrofit, and risk evaluation of existing buildings (for mortgage risk, insurance risk, and investment/ownership risk). During this adoption of the FEMA P-58 method in the structural engineering industry, it has become apparent that, due to the prevalence of tilt-up construction, the FEMA P-58 method needs

[1] Research Engineer, Haselton Baker Risk Group, Chico, CA, 95928 (email: katie@hbrisk.com).
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[4] Assistant Professor, Zachry Dept. of Civil Eng., Texas A&M University, College Station, TX 77843 (email: maria.koliou@tamu.edu)
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to be extended to cover tilt-up buildings. Specifically, there is need to enable the user to run the FEMA P-58 analysis without needing to create a nonlinear structural model of the building (since such modeling of tilt-up buildings is seldom done, and simplified response prediction methods do not work well for tilt-up buildings since their response is dominated by the flexible diaphragm). This extension has been completed, and the FEMA P-58 method can now be used to assess the seismic risk for tilt-up construction. This paper describes the development of this new FEMA P-58 tilt-up method, including the structural response prediction approach and the fragility functions specific to tilt-up construction. Benchmark results are then provided and compared with public-domain risk assessment methods.

Background

FEMA P-58 method for Building Specific Seismic Risk Evaluation

The P-58 method is a rigorous building specific method for estimating building seismic performance [1]. The method is rooted in the performance-based earthquake engineering framework developed by the Pacific Earthquake Engineering Research Center (PEER) [2]. The PEER framework addresses successively the site hazard, structural performance (quantified by Engineering Demand Parameters, EDPs), damage, and finally loss, to produce decision variables that inform design, construction, and retrofit decisions. The FEMA P-58 method implements a multi-layer Monte Carlo Simulation [1], varying the input based upon an estimated distribution at each iteration to obtain a probabilistic estimation of economic loss, repair time, and safety. The process by which losses are estimated is outlined in Figure 1.

The FEMA P-58 framework includes a structural response method for estimating EDPs and building component fragilities critical to the loss assessment for several building types. This study develops, for the first time, a specific response method and component fragilities for tilt-up concrete buildings commonly found in the seismically active West Coast of the United States.

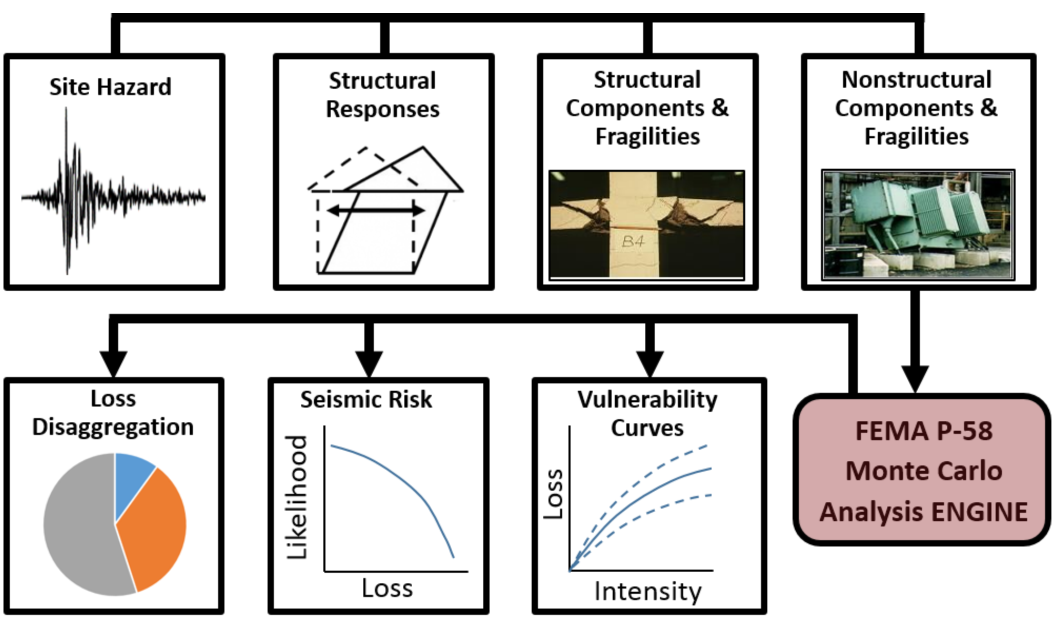


Figure 1. Schematic of FEMA P-58 seismic risk assessment methodology.

Structural Response and Damage to Tilt-up Buildings from Seismic Ground Shaking

Unlike conventional building structures, the yielding occurs in the diaphragm rather than the in-plane walls (Figure 2). Therefore, fragilities specific to tilt-up buildings and a unique method for EDP prediction are necessary for the accurate assessment of these buildings.

Tilt-up buildings accumulate damage primarily in the roof diaphragm itself and (particularly in buildings designed prior to the 1994 Northridge Earthquake) in the connections between the diaphragm and out-of-plane (OOP) wall resulting in early partial diaphragm collapse (e.g. Figure 3). The in-plane shear walls typically provide shear resistance beyond what is required by seismic demand without significant damage or deflection. In the out-of-plane direction, the walls respond much like a simply supported beam spanning between the ground and the roof diaphragm, as illustrated in Figure 4. Out-of-plane wall responses may become significant in strong seismic events, causing concrete cracking and steel yielding; however, OOP wall deformation has been observed as a relatively small source of damage/loss in tilt-up buildings.

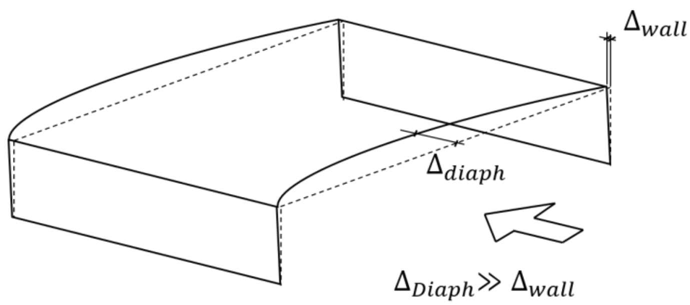


Figure 2. Illustration of diaphragm displaced shape for tilt-up construction.

Figure 3. Photo of tilt-up building with the first bay of diaphragm caved in due to out-of-plane wall connection failure [source: EERI].

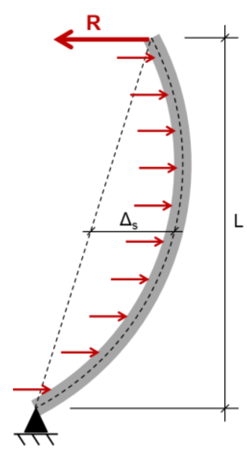


Figure 4. Illustration of out-of-plane (OOP) wall response with diaphragm translation.

The design of tilt-up buildings has evolved over the years based upon lessons learned from damage to buildings subjected to past earthquakes; as a result, the damageability of tilt-up building components depends on building age. In buildings designed prior to the 1997 Uniform Building Code (UBC) [3], failure of the connection between the roof diaphragm and out-of-plane wall has been observed as the dominant failure mode causing partial diaphragm collapse (right side of Figure 3) and even wall collapse (lower side of Figure 3). The progression of design requirements for OOP wall connection capacity is outlined in Figure 5, for further detail on the progression of design requirements please see [4]. The earliest code updates require direct connections that do not rely upon wood cross-grain bending. The most recent updates in the 1990s increase the connection design force to maximum expected levels without reliance upon material ductility [5]. The code-level design requirements have remained relatively consistent from 1997 to present [6, 7]. In strong seismic events, it is now expected that new tilt-up buildings will experience more damage to the diaphragms and less damage to the OOP wall connection compared with past events.

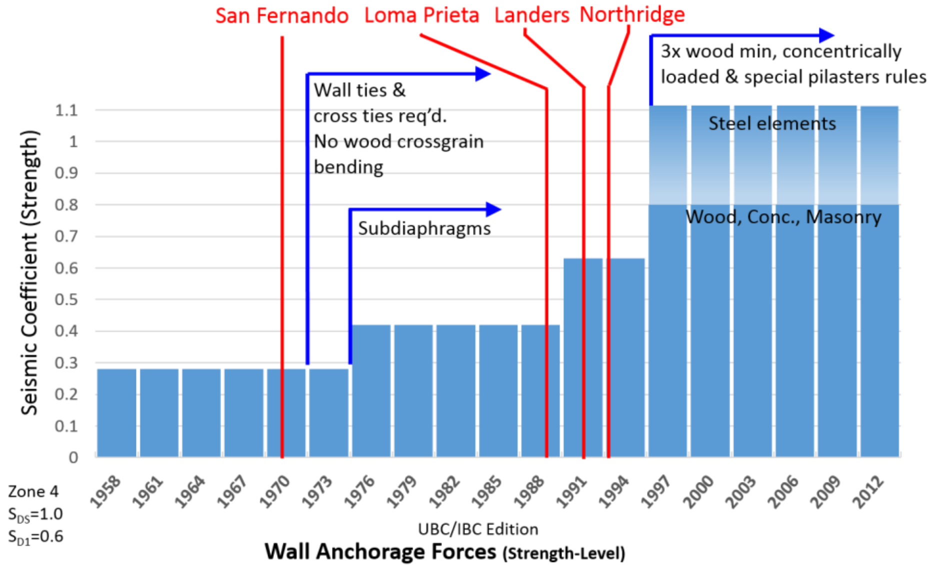


Figure 5. Evolution of code design forces for tilt-up construction [4].

Extension of Rapid FEMA P-58 method to Tilt-up Buildings

For the purpose of creating a method to predict tilt-up EDPs, a set of tilt-up designs are created and analyzed using OpenSEES [8]. Specific details of these designs and the modeling are explored in the following sections.

Archetype Designs

Archetype designs are binned into three eras based upon the code requirements and design practices common in each era. These designs are representative of common tilt-up buildings in the seismically active United States West Coast; they are single story, having fully-blocked wood structural panel roof diaphragms spanning with aspect ratios of 1:1 and 1:2, and intermediate precast (tilt-up panels) concrete shear walls. An example of the diaphragm design for a new era building is provided in Figure 6. All of the designs are created for a seismic design category D_{max} (S_{DS} = 1.0g) or UBC Zone 4 site, depending upon the design era. Details unique to the archetypes representing each design era are given in Table 1.

Table 1. Design properties, by era, for the archetype tilt-up designs.

	Old Era 1973 UBC and Earlier	**Intermediate Era** 1976-1994 UBC	**New Era** 1997 UBC and After
Wall dimensions	24’ tall, 6” thick	27’ tall, 7.5” thick	30’ tall, 9.25” thick
Wall reinforcing	#4 GR 60 @ 12” o.c.	#5 GR 60 @ 16” o.c.	#5 GR 60 @ 10” o.c.
Wall anchorage	1973 UBC: 0.20W_p (ASD); Pre-1973 no direct anchorage	0.30W_p (ASD)	0.80W_p (Strength)
Wall force (out-of-plane)	0.20W_p (ASD)	0.30W_p (ASD)	0.40W_p (Strength)
Base shear	V=0.133W (ASD)	V=0.183W (ASD)	V=0.224W (Strength)
Diaphragm force	F_p=0.133Wp (ASD)	F_p=0.183Wp (ASD)	F_p=0.25Wp (Strength)
Subdiaphragm	No	Yes	Yes

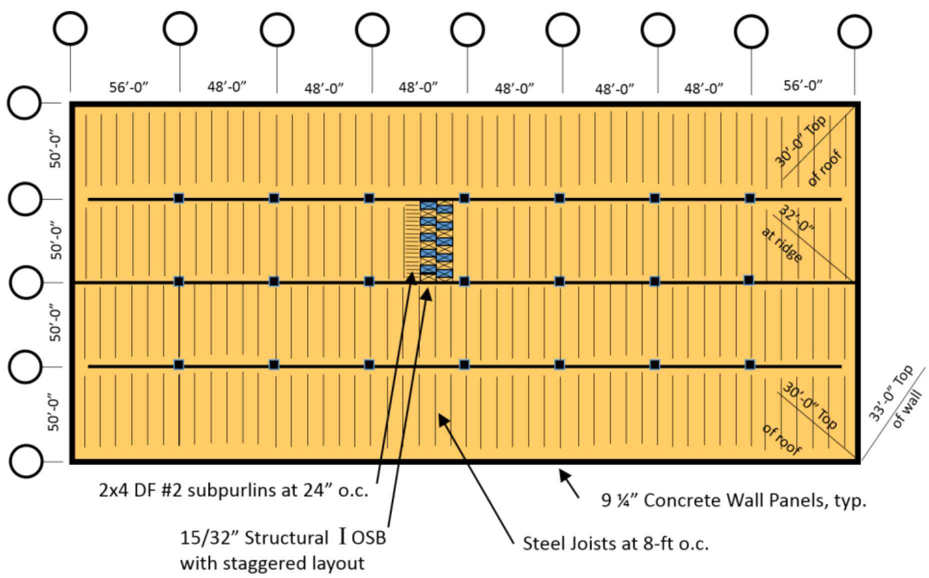


Figure 6. Plan view of an archetype tilt-up building representing modern era construction.

Structural Modeling

Diaphragm

A numerical modeling framework, based on a three step sub-structuring modeling approach, is considered for modeling the in-plane response of the roof diaphragm [9,10], which served as the basis for developing building archetype models. In Step 1, the framework focuses on the modeling of the roof diaphragm connectors (e.g., common nails) in order to archive hysteretic properties of the connectors [11] to be used in the second step of the framework. In Step 2, an inelastic roof diaphragm analytical model is developed. In this roof diaphragm model, each deck panel is modeled as a deep shear beam, and the hysteretic model (previously developed in Step 1) is used to represent the inelastic cyclic response of each roof diaphragm connector. In this model, the continuity ties are assumed adequate. The total in-plane flexible roof diaphragm displacement is computed as the sum of: (i) the elastic shear deformation of each individual panel, (ii) the inelastic deformations (slippage) of connectors and (iii) the elastic flexural deformations of the chord members. In Step 3 of the numerical framework, a two-dimensional building model is generated in the general-purpose RUAUMOKO2D [12] software, representing the three-dimensional building without accounting for torsion. The vertical wall responses are considered in this model and are addressed more completely in the next section. All three steps of this numerical framework were validated with analytical and experimental studies available in the literature [9], while all modeling parameters were identified through a set of sensitivity studies [10]. The RUAUMOKO building model served as the basis for generating and calibrating OpenSEES models of the building archetypes considered in this study.

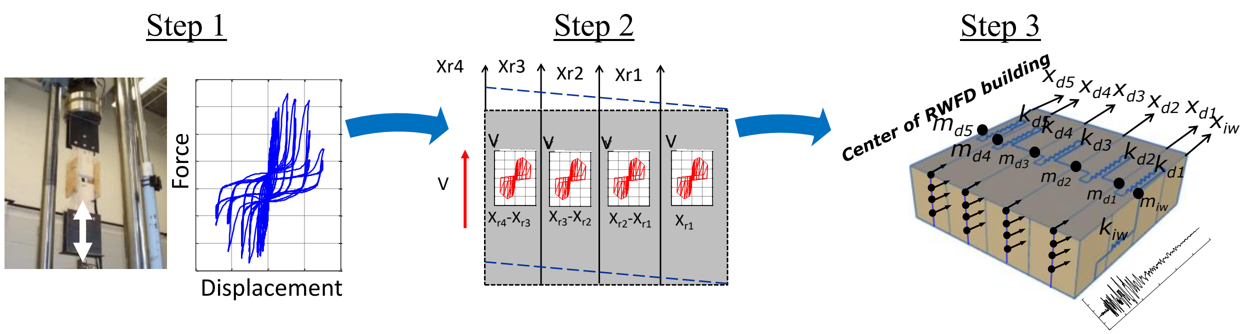


Figure 7. Process for modeling the roof diaphragm [9].

Tilt-up Concrete walls

Tilt-up concrete walls are modeled as linearly elastic for deformations in the plane of the wall. Out-of-plane, the walls are modeled with linear beam-column elements connected by three equally spaced trilinear plastic hinges with pinched response. Plastic hinge strengths are computed from expected material properties, using a concrete rupture modulus $f_r = 5\sqrt{f'c}$ [13]. Rotation capacity is calibrated to match the UBC deflection equations, which align well with test data [14]—moment amplification due to axial loading of the walls is considered when computing the UBC displacements. Figure 8 shows a comparison of the OpenSEES out-of-plane wall moment-displacement relationship and the target displacement curve for the new era archetypes. P-Δ effects are explicitly included in the OpenSEES models.

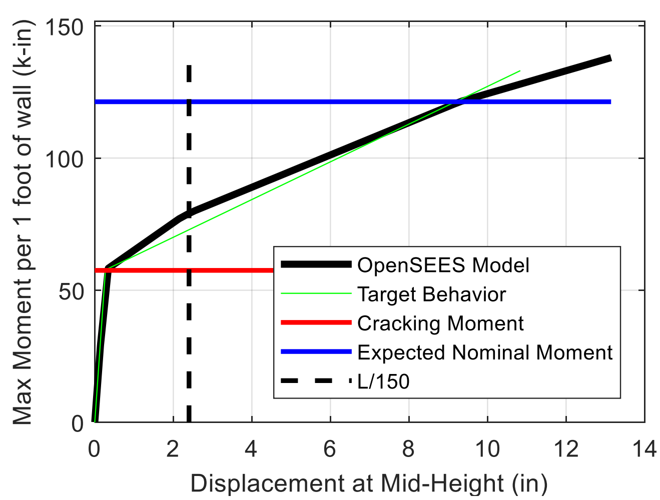


Figure 8. Moment-deflection curve for the new era out-of-plane walls, subjected to a uniformly distributed out-of-plane wall force.

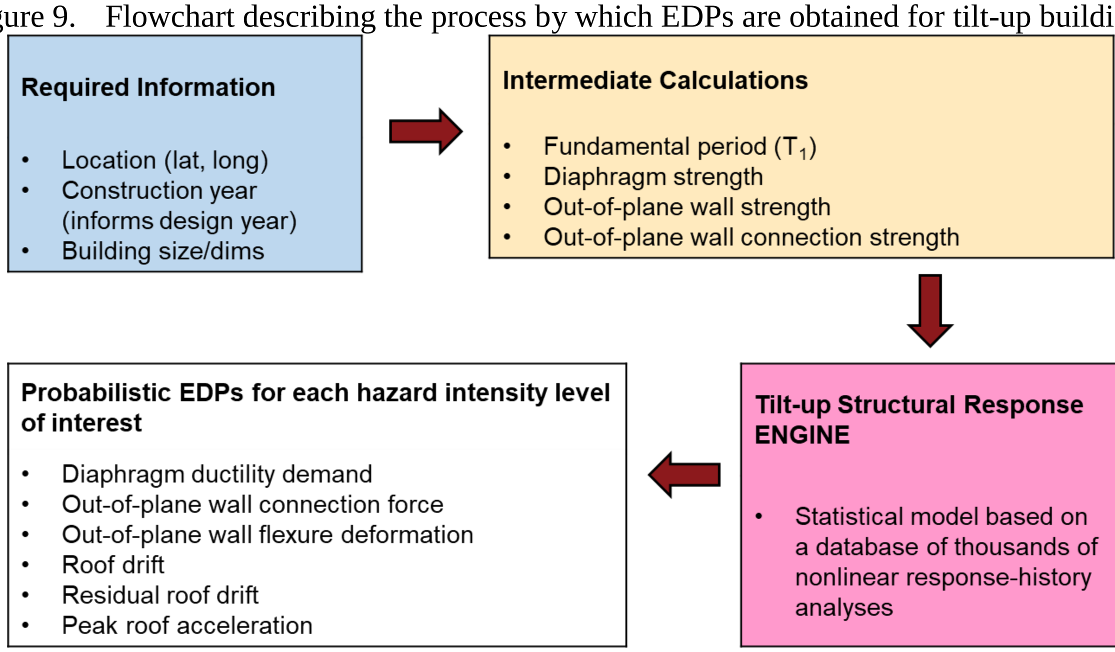
Structural Analysis: Engineering Demand Parameters (EDPs)

The archetype models are subjected to a series of incremental dynamic analyses with a suite of 44 far-field ground motion recordings from strong events [15], scaled to a broad range of intensity levels. The following EDPs are tracked at intervals along the length of the OOP wall:

1. Diaphragm ductility demand (μ)—ratio of diaphragm deflection demand to the deflection at which the diaphragm yields.
2. Out-of-plane wall connection force demand—force in the connection between the roof diaphragm and OOP wall, measured in units of g.
3. Out-of-plane wall flexure demand—ratio of relative deflection at the mid height of the wall to the wall span height, Δ_s/L (Figure 4).
4. Roof drift ratio—ratio of horizontal displacement at the roof to the roof height.
5. Residual roof drift ratio—ratio of residual horizontal displacement at the roof to the height at the roof.
6. Peak roof acceleration—peak acceleration at the roof, measured in units of g.

Based on the suite of nonlinear response history analyses conducted for this study, a statistical model was developed to make probabilistic predictions of the EDPs based on building properties and ground shaking intensity at the fundamental period of each archetype, $Sa(T_1)$. The flowchart in Figure 9 illustrates the process by which EDPs are obtained using this process. The component strengths that are used to predict EDPs are *expected* strengths, i.e. the design strength with an appropriate overstrength factor applied. Design strength is computed based on the building code that was in effect when the building was designed and the seismic zone/category and site class for the building. The elastic fundamental period of the building is computed using the relationship developed by [16], which depends on properties of the rigid concrete (tilt-up) shear walls and the flexible wood roof diaphragm. This is much different than the empirical equations in ASCE/SEI 7, which are inaccurate for buildings whose primary response is in the roof diaphragm [17, 18].

Figure 9. Flowchart describing the process by which EDPs are obtained for tilt-up buildings.



Tilt-up Component Fragilities

FEMA P-58 fragilities are families of cumulative distribution functions representing the likelihood of reaching or exceeding a set of damage states. Figure 10 shows a fragility function for wood diaphragms considered in this study. In total, 42 fragilities are created to represent damageable structural components in tilt-up buildings across the three archetype eras considered in this study.

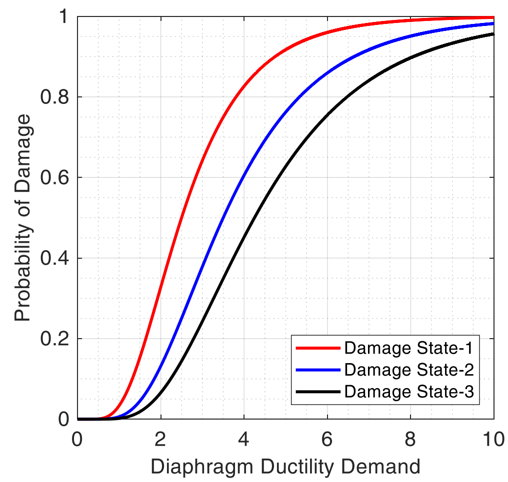


Figure 10. Wood diaphragm fragility functions.

Development of tilt-up fragilities is guided by [7]; OOP connections are identified as the primary cause of partial or complete collapse in buildings designed before the 1994 Northridge Earthquake. [7] goes on to identify other damageable components in tilt-up buildings and rates them in order of importance for retrofit, i.e. identifying the components most likely to damage and cause serious repercussions. The threshold for damage as well as the associated repair consequences are estimated according to the FEMA P-58 method for each component using the design code era and damage state specific repair schedules. Table 2 summarizes three fragility types, specific to tilt-up buildings that are developed in this study.

Example Results

Tilt-up test buildings at several Southern California sites, having varying layouts and design eras, are analyzed with the FEMA P-58 method using the Seismic Performance Prediction Program (SP3, [19]). The FEMA P-58 approach gives site-specific, building specific, age specific results, as evidenced by the vulnerability functions shown in Figure 11. For comparisons to existing methods that give loss in an average sense (rather than building specific), results for HAZUS [21] and ATC 13 [22] are also shown. The source of the losses computed with the FEMA P-58 method may be further disaggregated to identify the components and associated EDPs that dominate total loss. For example, in early era archetypes, failures of the OOP wall connection to the diaphragm dominate loss. The loss sensitivity to EDPs across eras are examined qualitatively in Table 3.

Conclusion

Performance of tilt-up buildings is deeply dependent upon the code year for which the building is designed and location of the building. This makes simplified assessment of seismic performance for tilt-up buildings difficult. The FEMA P-58 method is distinctive in its capacity to probabilistically examine the effect on seismic performance of building variables from site conditions to building component detailing. This capacity of the FEMA P-58 method has been unlocked for existing and new design tilt-up buildings by the creation of a probabilistic method for structural response prediction and the creation of fragilities unique to these tilt-up structures.

Table 2. Tilt-up specific building component fragility summary.

Building component	**EDP**	**Damage state**	**Description**
Out-of-plane connections	OOP force	DS 1	Connection failure, partial diaphragm collapse.
		DS 2	DS 1 + OOP wall collapse.
Precast tilt-up wall out-of-plane	OOP wall deflection	DS 1	Residual cracking.
		DS 2	DS 1 + residual drift requiring re-alignment.
Wood diaphragm	Diaphragm ductility	DS 1	Roof material tearing at in-plane walls.
		DS 2	DS 1 + nail pull-out, framing splitting, plywood/OSB tearing.
		DS 3	DS 2 + plywood/OSB panels pull free, framing splitting.

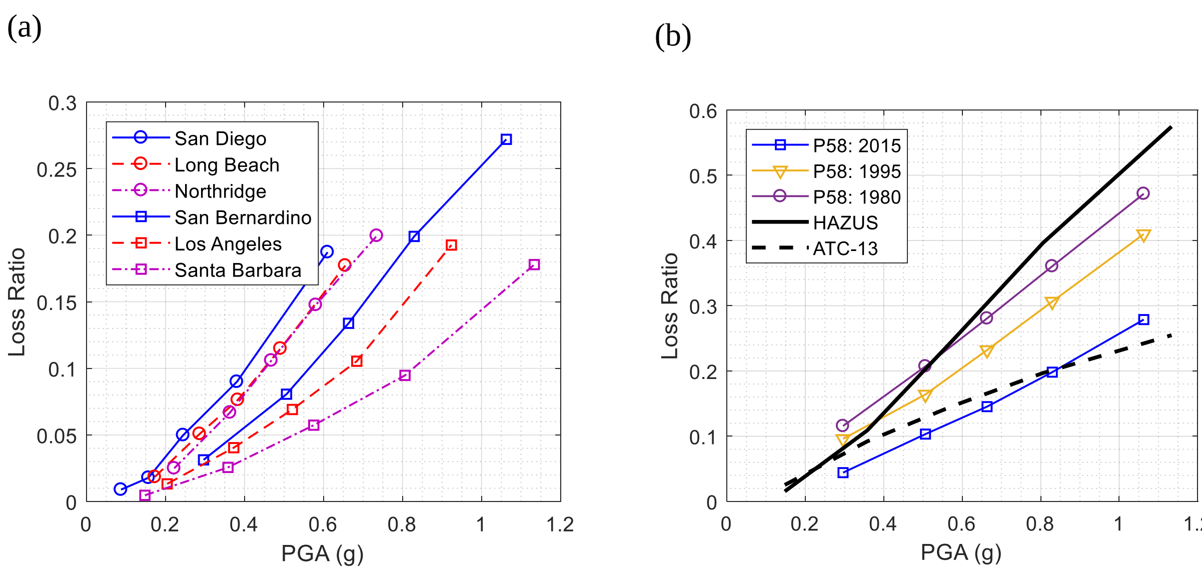


Figure 11. Vulnerability functions for tilt-up buildings: (a) 400’x400’ modern era design at various locations, (b) Three different design eras at a site near San Bernardino.

Table 3. Summary of EDPs for calculating tilt-up building losses.

EDP	**Unique to tilt-up bldgs?**	**Relative contribution to loss, by era**		
		Early era	*Intermediate era*	*New era*
Diaphragm ductility demand	YES*	Low	Moderate	High
Out-of-plane wall connection force demand	YES*	High	High	Low/ Moderate
Out-of-plane wall deformation	YES*	Low	Low	Moderate
Roof drift ratio	NO	Low	Low	Low
Residual roof drift ratio	NO	Low	Low	Low
Peak roof acceleration	NO	Low	Low	Moderate

* EDPs categorized as “unique” to tilt-up buildings also occur in other building types, but their contribution to damage in other buildings is often of little significance.

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