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FEMA P-58: PERFORMANCE ESTIMATION TOOL AS A DESIGN AID

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Abstract

Following the publication of the FEMA P-58 methodology for seismic performance-based assessments, the Federal Emergency Management Agency commissioned a study to exercise the methodology on all possible design combinations (strength and stiffness) for selected building types, generating performance results including repair cost, repair time, and casualties associated with each building design. The results have proven to be a valuable tool for communicating performance goals of buildings with stakeholders. The data from the study have also formed the basis to develop a tool for engineers to initiate performance-based design work in terms of objectives communicated by stakeholders. This paper presents the FEMA P-58 *Performance Estimation Tool* (PET) highlighting its capabilities and providing an example of a performance-based design in line with objectives communicated by stakeholders. Furthermore, the paper presents the methodology that was developed and used to evaluate the performance of selected building types utilizing basic building design requirements, e.g., lateral strength and interstory drift. The methodology is general enough and can be easily extended to include building types outside of the scope of this project. Moreover, PET is designed to allow easy extension to include performance estimates of new building types.

Keywords: repair cost; repair time; casualties; performance-based earthquake evaluation

1. Introduction

Performance of code-conforming buildings is not uniquely defined. Building codes establish minimum criteria that must be followed, but structural engineers have latitude in applying design requirements, and can make design decisions that significantly influence the performance of buildings in an earthquake. Seismic force-resisting systems are selected from a variety of options. Although all buildings must meet certain minimum strength and stiffness requirements, structural engineers can choose to provide a structure that is stronger or stiffer than minimum requirements, or they can choose to design a structure that just meets code minimums. In the case of nonstructural systems, structural engineers can exert explicit control over the design, and select enhanced seismic criteria to improve expected performance.

Recently published FEMA P-58-5 [1], presents seismic performance-based assessment results for a large set of design combinations (strength and stiffness) for selected seismic-force resisting systems. The published results include a broad set of performance measures (e.g., repair cost, repair time, casualties), proven to be a valuable tool for communicating performance goals of buildings with stakeholders. The data from the study have also formed the basis to develop a tool for engineers to initiate performance-based design work in terms of objectives communicated by stakeholders.

This paper presents *Performance Estimation Tool* (PET) [2], an interactive tool that can be used as an interface for viewing system-specific results of FEMA P-58-5 seismic performance assessments on 1,755 archetypes across five structural systems representative of buildings conforming to the seismic design requirements of ASCE/SEI 7-10 [3] and applicable material design standards. Assessment results are organized to provide information on expected performance given different seismic-force resisting systems, design story drift ratios, lateral strengths, risk categories, hazard levels, building heights, and occupancy types. The paper demonstrates the use of PET as a design aid in performance-based design and presents the methodology that was developed and used to evaluate the performance of selected building archetypes.

2. Performance Evaluation Methodology

Assessment Approach

Assessments were performed using FEMA P-58 methodology and the *Performance Assessment Calculation Tool* (PACT) version 3.0.3. Performance is measured in terms of repair cost, repair time, probability of incurring an unsafe placard, probability of collapse, probability of unrepairable permanent drift, and casualty rate. In the FEMA P-58 methodology, performance assessment requires basic information on the building configuration, structural and nonstructural systems, site characterization, earthquake hazards at the site, and building response given exposure to different intensities of earthquake shaking. To assess a wide range of code-conforming parameters, it was necessary to develop the required information for a large number of archetypical buildings, using simplified design and analysis procedures, and design values that were parametrically varied for different systems, heights, hazard levels, occupancies, and combinations of lateral strength and stiffness. The overall design and assessment approach included the following steps:

- Determination of strength and stiffness combinations that bound a code conforming design space
- Simplified design and determination of structural and nonstructural properties for a wide range of archetypes
- Estimation of building response
- Assembly of building performance models
- Assessment and summary of performance results.

2.2 Building Archetypes and Seismic Hazard Levels

Design considerations that were anticipated to have a high impact on performance were primary factors considered in this study. These included the following: seismic force-resisting system, design strength, design stiffness (drift ratio), nonstructural design criteria, number of stories, occupancy, Risk Category, and Seismic Design Category. Other considerations, such as story height, bay spacing, floor area, redundancy, presence of irregularities, and site class were held constant to facilitate comparisons between archetypes with different seismic design criteria.

To quantify the performance capability of code-conforming buildings, the FEMA P-58-1 [4] methodology was used to assess a wide range of buildings and systems meeting ASCE/SEI 7-10 structural and nonstructural seismic design requirements. It is to be noted that the results of this study are valid for structures designed to ASCE/SEI 7-16, since there were only few significant revisions to the seismic provisions of the standard that influence the design of structural and nonstructural systems considered in this project. The following structural systems were considered: steel special moment-resisting frames (steel SMRF), reinforced concrete special moment-resisting frames (RC SMRF), steel buckling-restrained braced frames (BRBF), steel special concentrically-braced frames (SCBF), and special reinforced concrete shear walls (SRCSW). The seismic force-resisting systems considered in this study were selected to be representative of systems that would be used in commercial and healthcare design applications, across a range of low-, mid-, and high-rise structures, in regions of high seismicity. Preference was given to systems with a permissible height limit of at least 160 feet in Seismic Design Category (SDC) D to allow application across all building heights considered in the study.

Two types of occupancies were considered in this study: office and healthcare. Office and healthcare occupancies were each designed as standard occupancy (Risk Category II) and essential (Risk Category IV) structures, as follows: (1) Office archetypes in Risk Category II representing standard commercial office buildings; (2) office archetypes in Risk Category IV representing an emergency operations center or other essential facility, with contents and occupancy similar to an office environment; (3) healthcare archetypes in Risk Category II representing medical buildings that perform outpatient diagnostic imaging and outpatient surgical services, in which patients stay less than 24 hours; and (4) healthcare archetypes in Risk Category IV representing general acute care hospital buildings that provide in-patient surgical, imaging, and laboratory services, in which patients stay more than 24 hours.

In all cases, the structural configuration is a regular, redundant system, with well-distributed seismic force-resisting elements (identical in two orthogonal directions), without the presence of plan or vertical irregularities, and mass uniformly distributed over the height. Diaphragms were assumed to be rigid, and torsion and foundation flexibility were ignored. The geometric configuration of all archetypes is a rectangular floor with consistent bay spacing and identical overall dimensions of 100 feet wide by 140 feet long. Story heights are a constant 13 feet, but the number of stories varied from low-rise (2-story and 3-story), to mid-rise (5-story), and high-rise (12-story) archetypes. Office occupancies were configured to include all three height variants. Healthcare occupancies utilized only low- and mid-rise variants.

Archetypes have been located in three seismic settings, all considered to be regions of high seismicity. Locations were selected with mapped spectral response acceleration parameters resulting in design values corresponding to three seismic hazard levels: Low SDC D (just above the SDC C/D boundary; $S_{DS} = 0.5g$, $S_{D1} = 0.35g$), SDC D ($S_{DS} = 1.0g$, $S_{D1} = 0.6g$), and SDC E/F (near active faults; $S_{DS} = 1.33g$, $S_{D1} = 0.75g$). Default Site Class D was assumed for all sites. For each of the seismic hazard levels, five intensity levels were considered, each expressed as a percentage of the Maximum Considered Earthquake shaking: 20% MCE, 40% MCE, 67% MCE (Design), 80% MCE, and 100% MCE.

In summary, archetypes are defined by lateral system type, height, lateral strength, lateral stiffness, occupancy, and design ground motion. Archetypes were designed for five different seismic force-resisting systems, two Risk Categories, and three levels of seismic hazard.

2.3 Design Space

All structures must conform to the minimum strength, stiffness, and seismic detailing requirements of the building code. In theory, all buildings could be designed to just meet the minimum base shear strength and maximum allowable drift limits specified for the selected system, configuration, height, and Risk Category. In practice, however, most structures exceed code minimums in one way or another, and for a variety of reasons.

Practical constraints on the combinations of lateral strength and stiffness for different seismic force-resisting systems can result in buildings that are stronger or stiffer than required. For example, steel special moment-resisting frames are typically governed by story drift limits, but the actual strength of frames with the required stiffness often significantly exceeds the code design base shear. Conversely, steel braced frame systems are typically governed by strength requirements, but braced frames are often stiffer than the minimum stiffness required, and actual drifts are far less than code allowable drift limits.

Structural engineers can also make a conscious decision to provide a structure that is stronger or stiffer than required. For these reasons, the concept of a code-conforming design space was developed to bound the range of possible archetype designs. The design space is intended to represent a reasonable range of lateral strengths and stiffnesses that would be expected in typical modern buildings designed in accordance with ASCE/SEI 7-10 seismic design requirements. Seismic requirements, however, only specify the minimum strength and maximum allowable drift boundaries of the design space. Assumptions for upper bound strength and lower-bound drift limits were established by a diverse group of practicing structural engineers [5].

A schematic representation of the design space is shown in Fig. 1, which illustrates typical upper and lower bound assumptions for strength and stiffness. Lateral stiffness, in terms of story drift ratio, is presented on the horizontal axis, and lateral strength, as a multiple of the minimum design base shear strength, is presented on the vertical axis. Thirteen points are used to characterize archetypes with different strength and stiffness combinations throughout the design space. Different systems have different upper and lower bound assumptions for strength and stiffness. The resulting design space for each system varies based on Risk Category, building height, and bounding assumptions for strength and stiffness. Limits for the design space of each system are provided in FEMA P-58-5.

For each combination of occupancy, Risk Category, and building height, archetypes were created at each of three levels of seismic hazard, for each of the 13 combinations of lateral strength and stiffness representing the design space. Each system is, therefore, represented by a combination of 195 office and 156 healthcare archetypes (351 total archetypes per system), for a total of 1,755 archetypes across all five seismic force-resisting systems.

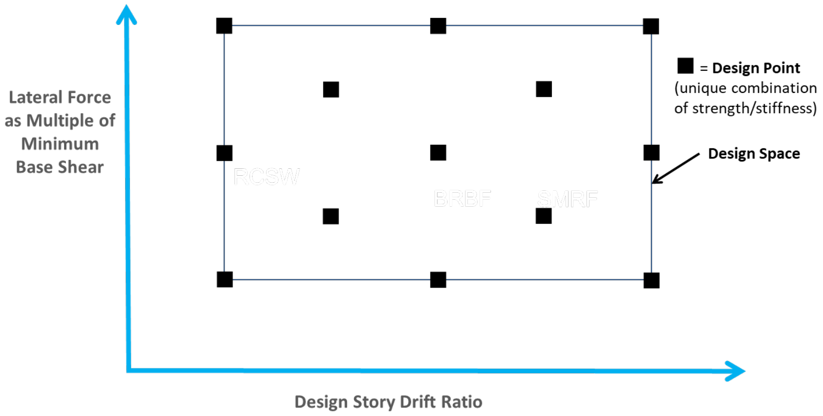


Fig. 1 – Schematic representation of the design space

2.4 Evaluation of Engineering Demand Parameters

Because of the large number of archetypes considered, a simplified design and analysis approach was used to determine structural properties associated with each archetype, and to estimate structural response quantities (drifts, accelerations, and velocities) for performance assessment at each intensity of shaking for every seismic hazard. Furthermore, the residual drift ratios were estimated for each archetype using the simplified residual drift model in FEMA P-58-1, in which residual drift is predicted as a function of the peak transient drift and yield drift. While this section describes the method used to calculate the peak transient drift of an archetype, a reader is referred to FEMA P-58-5 for more information on calculation of the yield drift ratios.

The simplified analysis procedure in FEMA P-58-1 was used to calculate median estimates of drift, acceleration, and velocity demands for each point in the design space of an archetype. Structural information needed to implement the simplified analysis procedure include the effective fundamental period, first mode shape, total seismic weight, first mode effective weight, and expected yield strength of the archetype.

Median estimates of story drift ratios, floor accelerations, and floor velocities, for a point in design space of an archetype were computed using FEMA P-58-1 simplified analysis procedure as follows:

- Elastic displacement profile was calculated from the pseudo lateral force, V, distributed over height. These story displacements were divided by corresponding story heights to obtain elastic story drift ratios.
- Elastic story drift ratios were corrected to account for inelastic behavior and higher mode effects using simplified analysis correction factors for drift from FEMA P-58-1.
- Peak floor acceleration was estimated at each floor from peak ground acceleration using simplified analysis correction factors for acceleration from FEMA P-58-1.
- Peak floor velocity was estimated at each floor from peak ground velocity using simplified analysis correction factors for velocity from FEMA P-58-1.

2.4.1 Estimation of Dynamic Properties of Archetypes: Mode Shape and Effective Fundamental Period

Dynamic properties for each archetype were determined based on the design story drift at the point of interest in the design space, using an approximate procedure for estimating mode shape and Rayleigh's quotient for estimating period.

First mode shape of an archetype was estimated using an approximate method presented in Miranda and Taghavi [6]. In this procedure, buildings are modeled as an equivalent continuum structure consisting of a flexural cantilever beam and shear cantilever beam pin-connected by axially rigid links. Estimated mode shapes are functions of the total height of the building and structural stiffness parameters α and δ, which control the response of the structure. Value of α represent variations in the behavior of the structure from a pure flexural response ($\alpha = 0$), to a pure shear response ($\alpha = 30$). Value of δ represent variations in lateral stiffness over the height of the structure. While $\delta = 1.0$ represents a structure with uniform stiffness over height, $\delta = 0.5$ represents a structure with a 50 percent reduction in lateral stiffness between the base and the top of the structure.

Values of structural stiffness parameters used to estimate first mode shapes for each archetype are different for different combinations of building height and seismic force-resisting system. Selected values of α and δ are summarized in Table 1 by system and building height. The selected values were determined by calibrating estimated first mode shapes to mode shapes obtained in two-dimensional structural analyses conducted on a series of typical building models for selected systems. The resulting values indicate that responses were flexurally dominated; furthermore, low-rise archetypes had a uniform stiffness over height, and mid- and high-rise archetypes had a 50% reduction in stiffness over height.

Table 1 – Stiffness parameters used to estimate first mode shape

Seismic Force-Resisting System	Stiffness Parameters	2-story, 3-story	5-story	12-story
Steel SMRF	α	4	6	6
	δ	1.0	0.5	0.5
RC SMRF	α	4	6	6
	δ	1.0	0.5	0.5
Steel BRBF	α	4	6	3
	δ	1.0	0.5	0.5
Steel SCBF	α	4	4	2
	δ	1.0	0.5	0.5
Special RCSW	α	1	2	2
	δ	1.0	0.5	0.5

Given the seismic force-resisting system, building height, and hazard level, the bare-frame fundamental period, $T_{1,BF}$, was calculated such that the maximum story drift is equal to the design drift at the point of interest in the design space. The bare-frame fundamental period corresponding to the design drift target was determined using Rayleigh's quotient (see Eq. (1)). In this method, the fundamental period is calculated by equating the maximum strain and kinetic energy generated by external lateral forces on assumed lateral displacements.

$$T = 2\pi\sqrt{\frac{\sum_{j=1}^{N} u_j^2 w_j}{g\sum_{j=1}^{N} u_j f_j}} \tag{1}$$

In Eq. (1) g is the gravitational constant, w_j is the portion of the total effective seismic weight of the structure (W) located or assigned to level j, u_j is the lateral displacement at level j, f_j is the corresponding lateral force at level j, and N is the total number of levels (i.e., floors) where the ground level is excluded from counting.

Lateral displacement profile, u, was developed by scaling the amplitudes of the first mode shape so that the story drift at the floor with the highest drift demand equals the design story drift target. Such scaling of the mode shape should closely approximate displacement profile determined by ASCE/SEI 7-16, where the elastic displacement profile generated by the equivalent lateral forces distributed along the building height is scaled by C_d/I_e (where C_d is the displacement amplification factor and I_e is the importance factor). Therefore, the lateral force f_j that corresponds to lateral displacement u_j should be closely approximated by equivalent lateral force at level j, scaled by C_d/I_e. Since the equivalent lateral force profile depends on the fundamental period of the structure, the bare-frame fundamental period corresponding to the design drift was determined using Rayleigh's quotient in an iterative procedure as outlined below:

1) Calculate displacement profile, u, by scaling the amplitudes of the first mode shape so that the story drift at the floor with the highest drift demand equals the design story drift at the point of interest in the design space.
2) Set the estimated period, T, to T_{max}, where T_{max} is the code upper limit of period used for the strength check in ASCE/SEI 7-16.
3) Use the estimated period, T, to calculate the equivalent lateral forces per ASCE/SEI 7-16.
4) Scale the equivalent forces by C_d/I_e factor to get lateral forces f_j.
5) Use Eq. (1) to calculate fundamental period and designate it as $T_{computed}$.
6) If $|T - T_{computed}| \leq 0.05$, then the values converged, and the fundamental bare frame period, $T_{1,BF}$, is taken as $T_{computed}$. If not, T is set to $T_{computed}$, and steps 3 through 5 are repeated until the values converge.

In the FEMA P-58 methodology, analytical models of buildings should include all elements that contribute to lateral strength or stiffness. In this study, the fundamental bare frame period, $T_{1,BF}$, was modified to reflect the period stiffening effects associated with the presence of gravity framing and nonstructural components that contribute to lateral stiffness. The effective fundamental period, T_1, is given by: $T_1 = (MF)\ T_{1,BF}$ where values of the modification factor, MF, are based on comparisons between computed and measured fundamental periods in instrumented buildings described in Harris et al. [7]. The modification factors for the different systems considered in this study are summarized in FEMA P-58-5.

2.4.2 Expected Yield Strength of Archetypes

The base shear strength of an archetype is a function of the point of interest in the design space, which is a multiple of the code minimum base shear, V_b (calculated per ASCE/SEI 7-1 Eq. 12.8-1). In this study, the multiple of code minimum base shear at each point in the design space is a form of overstrength, termed the design space overstrength factor, OF (i.e., y axis of the design space; see Fig. 1). Assuming that the yield strength of an archetype corresponding to the lower bound of the design space is 1.5 times the code minimum base shear, the yield strength of any building of interest in the design space is therefore given by Eq. (2).

$$V_y = 1.5(OF)V_b \tag{2}$$

2.4.3 Median Estimates of Story Drift Ratios

The simplified analysis procedure of FEMA P-58-1 uses a pseudo lateral force, V, distributed over the height on the building model to compute story drift ratios. Pseudo lateral force computations are similar to those found in ASCE/SEI 41-17 [8] and calculated using Eq. (3):

$$V = C_1 C_2 S_a(T_1) W_1 \tag{3}$$

where C_1 and C_2 are adjustment factors for inelastic displacements and cyclic degradation, both function of strength ratio, S, provided in Eq. (4) and effective fundamental period of the building, T_1 (determined using the simplified structural analysis procedures in Section 2.4.1); $S_a(T_1)$ is the 5 percent damped spectral acceleration at the effective fundamental period of the building at the intensity level of interest; and W_1 is the first modal effective weight, taken as not less than 80 percent of the total seismic weight, W. If the value of the strength ratio, S, is less or equal to 1.0, then C_1 and C_2 are taken as 1.0. V_y in Eq. (4) is the expected yield strength of an archetype calculated using Eq. (2).

$$S = \frac{\mathrm{S}_a(T_1)W}{V_y} \tag{4}$$

The displacement profile of the building at level j that corresponds to the pseudo-lateral force, V, distributed over the height of the building can therefore be calculated following the basic principles of dynamics of MDOF systems using Eq. (5):

$$D_j = C_1 C_2 \Gamma_1 \phi_{j1} (S_a(T_1)/\omega^2) g \tag{5}$$

where ϕ_{j1}, is the jth ordinate of the first mode shape (determined using the simplified structural analysis procedures in Section 2.4.1), $\Gamma_1$is the modal participation factor, ω is the first circular frequency of vibration, and g is the gravitational constant.

For uniform weight over the building height, the modal participation factor, Γ_1, is provided in Eq. (6):

$$\Gamma_1 = \frac{W_1}{L_1^h} = \frac{W_1}{\sum_{j=1}^{N} \frac{W}{N} \phi_{j1}} = \frac{\sum_{j=1}^{N} \phi_{j1}}{\sum_{j=1}^{N} \phi_{j1}^2} \tag{6}$$

Because W_1 may not be taken as less than 80 percent of the effective seismic weight, the modal participation factor Γ_1 cannot be less than $\Gamma_{1,min}$ provided in Eq. (7).

$$\Gamma_{1,min} = \frac{0.8W}{L_1^h} = \frac{0.8N}{\sum_{j=1}^{N} \phi_{j1}} \tag{7}$$

The uncorrected story drift ratio Δ_i at story i can then be calculated using Eq. (8):

$$\Delta_i = (D_j - D_{j-1})/h_i \tag{8}$$

where D_j and D_{j-1} are lateral displacements of the floor levels immediately above and below the story and h_i is the story height of story i. These drift ratios were corrected to account for inelastic behavior and higher mode effects using simplified analysis correction factors for drift from FEMA P-58-1.

2.5 Collapse Fragility

The possibility of building collapse was considered through the development of collapse fragilities. In this study, collapse fragilities were developed using judgment-based procedure in FEMA P-58-1. For each archetype, the inferred median collapse capacity, $\hat{s}_a(T_1)$, at the fundamental period, T_1, was determined using Eq. (9):

$$\hat{s}_a(T_1) = 3(OF)\frac{V_b}{W}R \geq 4\frac{V_b}{W}R \tag{9}$$

where V_b is the code minimum base shear (per ASCE/SEI 7-16); *OF* is the design space overstrength factor (as defined in Section 2.4.2); *W* is the seismic weight; and *R* is the response modification coefficient for the structure, as defined in ASCE/SEI 7-16. For the purpose of calculating collapse fragility, the design space overstrength factor, *OF*, was never taken less than 4/3 at any point in the design space.

2.6 Building Performance Models

For each archetype, a PACT building performance model was created that includes project information, building information, population data, component structural and nonstructural fragilities, performance groups, collapse fragilities, structural analysis results (drift, acceleration, and velocity), residual drift information, and hazard curves.

Structural and nonstructural fragilities used in the building performance models were selected from the updated and revised PACT fragility database [2], which includes many options for each type of structural and nonstructural system. However, custom fragilities for fixed and mobile medical equipment were developed for the purposes of this study and developed fragilities are provided in FEMA P-58-5.

Structural fragility quantities were determined for each Seismic Design Category (SDC), building height, risk category, and seismic force-resisting system, based on design story forces and structural fragility capacity assumptions. Structural systems for each archetype were designed based on extrapolation from analytical studies on preliminary designs. These studies were used to establish strength and stiffness properties for determining the number of bays of lateral bracing, or length of shear wall, needed. Situations where design drift, rather than lateral strength, governed the size of the structural elements were also considered.

General types and typical quantities of nonstructural components in each archetype were based on information from the *Normative Quantity Estimation Tool* in FEMA P-58-3 [2]. For a given building height and occupancy, typical fragilities (e.g., partition walls, ceiling, piping) and their nonstructural normative quantities are uniform across all archetypes, regardless of the seismic force-resisting system. However, there are several nonstructural components whose median capacity must be defined by the user. These include anchored mechanical and electrical equipment, egress stairs and exterior curtain walls. For these components, median capacities were calculated using the code-based limit state procedures in FEMA P-58-1, Section 3.8.4, and the seismic design provisions of ASCE/SEI 7-16. Seismic design criteria for nonstructural components depend on many factors, including seismic hazard level, risk category, design story drift, and the location over the height the structure. As a result, nonstructural components and systems required multiple fragilities with different lateral capacities to account for different combinations of factors. Details on how the building performance models were assembled are provided in FEMA P-58-5.

2.7 Limitations

The FEMA P-58 methodology employs analysis techniques that characterize building performance metrics in a probabilistic manner, recognizing the many uncertainties that can affect building performance. Results for each metric are provided in the form of a probability distribution, and performance metrics at any confidence level can be reported. However, the *Performance Estimation Tool* provides only median, mean, and 90th percentile values. Median values provide the expected performance in the middle of the distribution, with half of the possible values higher, and half of the possible values lower than the reported value. Mean value provides an average and 90th percentile value provides a high confidence that the reported performance metric will not be exceeded as 90% of possible values lower and 10% of the possible values higher than the reported value.

Properties of the structural seismic force-resisting systems and nonstructural component seismic bracing and anchorage were proportioned to comply with the seismic provisions of ASCE/SEI 7-16. Structural members and connections are assumed to comply with the requirements in ANSI/AISC 360, Specification for Structural Steel Buildings [9], ANSI/AISC 341-10, Seismic Provisions for Structural Steel Buildings [10], and ACI 318-11, Building Code Requirements for Structural Concrete and Commentary [11]. The performance evaluations presented herein apply only to buildings that fully comply with all structural and nonstructural seismic design requirements in ASCE/SEI 7-10 and applicable material design standards.

The possibility of building collapse was included in the performance assessments in an approximate manner. A fundamental assumption in this study is that life safety performance, as measured by an acceptably low probability of collapse, is achieved by designing and constructing buildings in accordance with the requirements in ASCE/SEI 7-16. Collapse fragilities were developed using judgment-based procedure in FEMA P-58-1, which is based on a 10 % probability of collapse for standard occupancy structures, given the occurrence of maximum considered earthquake shaking. A lower (i.e., 5 percent) collapse probability was assumed for the structures represented by the design space in this study, as most of the buildings in the design space exceed the code minimum strength.

Foundation elements were not included in the performance models. For some seismic force-resisting systems, foundations may be vulnerable to damage that has not been considered in this study.

Quantities of nonstructural components and systems were developed using the Normative Quantity Estimation Tool in FEMA P-58-3. Components deemed rugged (i.e., not subject to significant damage for credible levels of seismic demand) in FEMA P-58-1, were excluded from the performance models. Building contents, such as furniture and electronic equipment (not designated as medical equipment) were also excluded from the performance models because they are not permanently attached to the structure, and are, therefore, exempt from the seismic provisions of the building code.

Healthcare occupancy performance models include judgement-based fragilities for fixed and mobile medical components developed specifically for this study. Median capacities for medical components were determined based on the seismic design forces required by ASCE/SEI 7-10 and the procedures for calculation-based fragilities in FEMA P-58-1. Repair costs and repair times associated with the damage of medical equipment are rough order-of magnitude, judgement-based estimates that consider component cost and perceived complexity. Repair costs consider only the cost of the component, and do not include any ancillary work required to access or reinstall the damaged component. Mobile components (i.e., components commonly installed on rollers for easy transport) are velocity-controlled. Median capacities were based on assumptions of how far a component can move before it impacts another component and becomes damaged. Performance estimates for healthcare occupancies are provide insight about the potential influence of design decisions, especially Risk Category, on performance. Because of the diverse nature of healthcare facilities, and the approximate nature of the assumed medical component fragilities, the resulting performance estimates should be used for comparative purposes only.

2.8 Work-flow analysis

To assess performance of 1,755 archetypes, it was necessary to automate calculation process by developing a work-flow algorithm that systematically loops through input parameters (e.g., Seismic Design Category, Occupancy Type, Risk Category, Lateral-Load Resisting System, a point in the design space) to initiate an architype. For a current architype the algorithm then does the following:

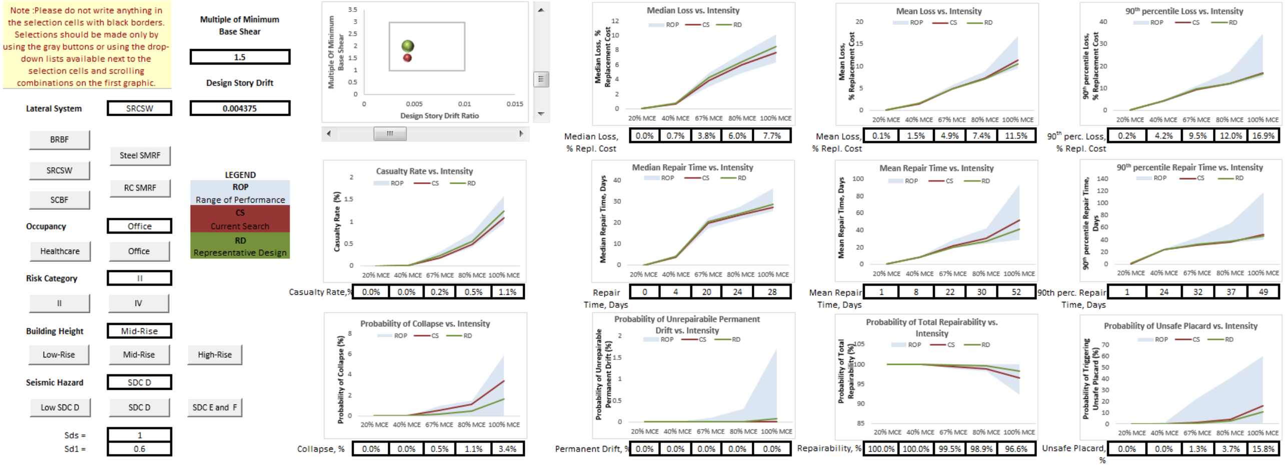
1. Estimates building responses and collapse fragility (per procedure described in Sections 2.4 & 2.5),
2. Opens PACT building performance model (developed as described in Section 2.6),
3. Updates the PACT model of the archetype with the estimated building responses and collapse fragility,
4. Does the performance assessment (i.e., runs PACT model) in a batch mode,
5. Saves the results in the folder designated for the current archetype.

Furthermore, an algorithm for postprocessing of the generated results was developed to generate the data that will be graphed with the *Performance Estimation Tool.*

3. Selection of the Performance-Based Design Requirements for a Building utilizing Performance Evaluation Tool

3.1 Performance Estimation Tool

Performance Estimation Tool (PET), as shown in Fig. 2, is an interactive tool that serves as a repository of all assessment results and provides an interface for viewing the results for a given system and set of design assumptions. It can also be used as a design aid for preliminary performance-based design as described in Section 3.2. The tool is provided in FEMA P-58-3. It was created in Microsoft Office 2013 as a macro enabled Excel file (.xlsm). The tool uses Excel macros; therefore, macros must be enabled for the tool to run.



Note :Please do not write anything in the selection cells with black borders. Selections should be made only by using the gray buttons or using the drop-down lists available next to the selection cells and scrolling combinations on the first graphic.

Multiple of Minimum Base Shear: 1.5
Design Story Drift: 0.004375
Lateral System: SRCSW
Occupancy: Office
Risk Category: II
Building Height: Mid-Rise
Seismic Hazard: SDC D
Sds = 1
Sd1 = 0.6

Median Loss, % Repl. Cost: 0.0% 0.7% 3.8% 6.0% 7.7%
Mean Loss, % Repl. Cost: 0.1% 1.5% 4.9% 7.4% 11.5%
90th perc. Loss, % Repl. Cost: 0.2% 4.2% 9.5% 12.0% 16.9%
Casualty Rate,%: 0.0% 0.0% 0.2% 0.5% 1.1%
Repair Time, Days: 0 4 20 24 28
Mean Repair Time, Days: 1 8 22 30 52
90th perc. Repair Time, Days: 1 24 32 37 49
Collapse, %: 0.0% 0.0% 0.5% 1.1% 3.4%
Permanent Drift, %: 0.0% 0.0% 0.0% 0.0% 0.0%
Repairability, %: 100.0% 100.0% 99.5% 98.9% 96.6%
Unsafe Placard, %: 0.0% 0.0% 1.3% 3.7% 15.8%

Fig. 2 – User Interface tab of Performance Estimation Tool

The *Performance Estimation Tool* requires, as input, the selection from available seismic force-resisting system, occupancy type, Risk Category, building height, and seismic hazard from the available options. It also requires selection of design story drift and design strength in terms of a multiple of minimum base shear. Based on the selected parameters, the tool will return associated graphs and data for a considered set of performance measures (see Fig. 2).

3.2 Selection of Design Drift and Base Shear to Meet Desired Performance Objectives

One of the main features of the PET is its capability to be used as an aid in performance-based design. For the set of the performance objectives set by stakeholders, PET provides design requirements, and maximum interstory drift and base shear values that shall be used in place of ASCE/SEI 7-10 requirements to achieve desired building performance. It is to be noted that design requirements suggested by PET shall only be used in the preliminary phase of the design. A full assessment of a building performance accounting for all unique features of the building shall be conducted following the final design of the building to verify building conformance to performance objectives.

The selection of design requirements can be streamlined by following the following procedure:

1. In the *User Interface* tab of PET choose seismic force-resisting system, occupancy type, Risk Category, building height, and seismic hazard.
2. Go to the *Detailed Plots* tab of PET to check if the desired performance can be achieved utilizing the considered system. This check requires the following steps:
    - 2.1. For each performance metric of interest, extract and tabulate values associated with the two most extreme design options within the design space: best performing building (BPB) (designated as Lower Bound in PET) and the least performing building (LPB) (designated as Upper Bound in PET).
    - 2.2. Compare the performance of the two considered designs, best performing and least performing, with the performance objectives. The following outcomes are possible:
        - 2.2.1. If the best performing building does not meet the objectives, try another structural system.
        - 2.2.2. If only the best performing building meets the objectives, the optimal design requirements can be found within a design space.
        - 2.2.3. If the least performing building meets all performance objectives, ASCE/SEI 7-10 design requirements are sufficient.
3. In case of outcome 2.2.2, find optimal design solution. This step includes the following:
    - 3.1. Isolate performance measures for which the least performing building (i.e., Upper Bound) does not meet the performance objectives.
    - 3.2. For the isolated performance measures, find the percent difference in performance between the best performing building (i.e., Lower Bound) and performance objectives.
    - 3.3. Announce the performance measure with the smallest percent difference (i.e., smallest buffer) the critical performance measure.
    - 3.4. In the *User Interface* tab, move the *Current Search* (red dot in the design space, Fig. 2) throughout the design space while monitoring the performance outcome of the critical performance measure. Announce the point in the design space that most closely meets the critical performance objective the optimal design solution.
    - 3.5. For the identified optimal solution compare its performance outcomes across all performance measures with the performance objectives. If all performance objectives are met, report the associated design requirements. Otherwise, investigate solutions in the vicinity of the optimal design solution until you find one that satisfies all performance objectives.
4. Report the design requirements, maximum interstory drift and base shear, and associated performance.

The outlined procedure for finding the design requirements that will most likely achieve the desired building performance is next demonstrated on an example of a 5-story office building (Risk Category II) located on the site class D characterized with the SDC D ($S_{DS} = 1.0g$, $S_{D1} = 0.6g$). For the set of performance objectives specified at two intensity levels, design earthquake and MCE as presented in Table 2, the special reinforced concrete shear wall (SRCSW) system is selected and its design requirements are identified.

Table 2 – Performance objectives for the set of performance measures at two intensity levels: design earthquake and MCE

Performance Measure	**Design Earthquake**	**MCE**
Median Repair Loss Ratio	5%	10%
90th percentile Repair Loss Ratio	10%	20%
Probability of Unrepairable Permanent Drift	1%	3%
Probability of Unsafe Placard	5%	10%
Probability of Collapse	2%	5%

Table 3 is generated by extracting values associated with the best and least performing buildings within the design space for the case where the seismic force-resisting system is set to SRCSW, occupancy type to Office, Risk Category to II, building height to mid-rise, and seismic hazard to SDC D. Notice that while the best performing building meets all performance objectives (i.e., goals), the least performing building does not. This means that the minimum design requirements of ASCE/SEI 7-10 are not sufficient; however, a design solution exists within the design space. To find an optimal design solution, it is first recognized that LPB does not meet performance objectives 1, 2, 4, and 5. From these performance measures, BPB has the smallest percent difference for the 2nd performance measure (90th percentile Repair Loss Ratio) at the design earthquake; therefore, that is the critical performance measure. Focusing on the 90th percentile Repair Loss Ratio, the *Current Search* is moved through the design space to find the optimal design solution. It is found that the design that utilizes interstory drift of 0.625% and base shear of $2V_b$ (i.e., two times the minimum base shear per ASCE/SEI 7-16) meets the 2nd performance objective. However, this design does not meet the 4th performance measure (Probability of Unsafe Placard). The *Current Search* is then moved towards the top-left corner of the design space (stronger and stiffer system) to find the optimal design solution that meets all performance objectives. The final design solution requires interstory drift of 0.44% and base shear of $2.5V_b$. Table 4 compares the performance of the optimal design to the set performance objectives, showing that all performance objectives are met.

Table 3 – Performance of the least performing building (LPB) and best performing building (BPB) in the design space

Performance Measure	**Design Earthquake**			**MCE**		
	Goal	**LPB**	**BPB**	**Goal**	**LPB**	**BPB**
1. Median Repair Loss Ratio	5%	**4.9%**	**3.1%**	10%	**10.1%**	**6.3%**
2. 90th percentile Repair Loss Ratio	10%	**11.1%**	**9.2%**	20%	**35.0%**	**15.0%**
3. Probability of Unrepairable Permanent Drift	1%	**0.1%**	**0.0%**	3%	**1.7%**	**0.0%**
4. Probability of Unsafe Placard	5%	**23.0%**	**0.0%**	10%	**60.0%**	**0.2%**
5. Probability of Collapse	2%	**1.0%**	**0.0%**	5%	**6.0%**	**0.0%**

LPB - least performing builidng; BPB - best performing builidng

Table 4 – Performance of the optimal design

Performance Measure	**Design Earthquake**		**MCE**	
	Goal	**Optimal Design**	**Goal**	**Optimal Design**
1. Median Repair Loss Ratio	5%	**4.6%**	10%	**9.0%**
2. 90th percentile Repair Loss Ratio	10%	**9.8%**	20%	**15.7%**
3. Probability of Unrepairable Permanent Drift	1%	**0.0%**	3%	**0.0%**
4. Probability of Unsafe Placard	5%	**0.1%**	10%	**5.2%**
5. Probability of Collapse	2%	**0.0%**	5%	**0.4%**

4. Summary

This paper presents *Performance Estimation Tool*, an interactive tool that can be used as an interface for viewing system-specific results of FEMA P-58-5 seismic performance assessments on 1,755 archetypes across five structural systems, two risk categories, three hazard levels, three building heights, and two occupancy types. One of the main features of the PET is its capability to be used as an aid in performance-based design allowing engineers to initiate performance-based design work compliant with objectives communicated by stakeholders. The paper suggests a procedure for finding optimal design requirements (design interstory drift and base shear) within the scope of the performance-based design and demonstrates its efficiency with an example of a 5-story office building. To provide content to the assessment results contained within PET, the paper also presents the methodology that was developed and used to evaluate the performance of selected building archetypes highlighting all simplifying assumptions. While the presented tool has limited capabilities, the presented methodology has a potential to be extended to include building types outside of the scope of this project.

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6. References

[1] FEMA (2018): Seismic Performance Assessment of Buildings, Volume 5 – Expected Seismic Performance of Code-Conforming Buildings. *FEMA P-58-5*, prepared by the Applied Technology Council for the Federal Emergency Management Agency, Washington, D.C.

[2] FEMA (2018): Seismic Performance Assessment of Buildings, Volume 3 – Supporting Electronic Materials and Background Documentation, Third Edition. *FEMA P-58-3*, prepared by the Applied Technology Council for the Federal Emergency Management Agency, Washington, D.C.

[3] ASCE (2010): Minimum Design Loads and Associated Criteria for Buildings and Other Structures, Provisions. *ASCE/SEI 7-10*, American Society of Civil Engineers, Reston, Virginia.

[4] FEMA (2018): Seismic Performance Assessment of Buildings, Volume 1 – Methodology, Second Edition. *FEMA P-58-1*, prepared by the Applied Technology Council for the Federal Emergency Management Agency, Washington, D.C.

[5] ATC (2014): Proceedings of FEMA-Sponsored Workshop on Design Guidelines and Tools to Implement Next-Generation Performance-Based Seismic Design. *ATC-58-5 Report*, Applied Technology Council, Redwood City, California.

[6] Miranda E, Taghavi S (2005): Approximate Floor Acceleration Demands in Multistory Buildings. I: Formulation. *Journal of Structural Engineering*, American Society of Civil Engineers, **131** (2), 203-211.

[7] Harris A, Naeim F, Zareian F (2016): Development of Fundamental Period Adjustment Factors for Buildings in Low-To-Moderate Seismic Excitation. *FEMA P-58/BD-3.7.17 Report*, Applied Technology Council, Redwood City, California.

[8] ASCE (2017): Seismic Evaluation and Retrofit of Existing Buildings. *ASCE/SEI 41-17*, American Society of Civil Engineers, Reston, Virginia.

[9] AISC (2010): Specification for Structural Steel Buildings. *ANSI/AISC 360-10*, American Institute of Steel Construction, Chicago, Illinois.

[10] AISC (2010): Seismic Provisions for Structural Steel Buildings. *ANSI/AISC 341-10*, American Institute of Steel Construction, Chicago, Illinois.

[11] ACI (2011): Building Code Requirements for Structural Concrete and Commentary. *ACI 318-11*, American Concrete Institute, Farmington Hills, Michigan.