RISK-BASED ANALYSIS FOR LIFE-SAFETY DECISIONS

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Abstract: Unmitigated risk of damage to buildings and property can lead to disastrous consequences to humans including loss of life and shelter. These consequences are compounded by the knowledge that they may have been avoidable with proper risk characterization. This paper explores the process by which the risk of building damage and collapse can be quantified for a given event (e.g., seismic or wind loading). The risk of building damage is determined based on such variables as building location, soil characteristics, selection and detailing of the lateral force resisting system, and construction quality. Once the risk is defined, a holistic approach is used to integrate structural modeling and calculations to determine the consequences of a disaster in terms of „deaths, dollars, and downtime." These metrics are then used by ownership to evaluate life-safety decisions including whether a retrofit is necessary and if so, what retrofit provides the most value. The paper presents a rational decision process associated with identified building defects/deficiencies and decisions on repair/retrofit to reduce the probability of casualties beyond society defined limits, and to secure an expected performance level at a justifiable cost. Performance-based analysis as a systematic approach to risk management is presented. The modeling of hazards at different levels is illustrated using a seismic hazard example.

Keywords: risk characterization; performance-based analysis; structural modeling; building damage

1. Introduction

While building codes provide minimum design standards for structures, designing according to the building code does not guarantee losses will not be excessive nor that the structure will remain operational after a natural disaster. The goal of performance-based engineering is to provide a building and a site-specific structural analysis that incorporates natural hazards and their likelihood of occurrence at the building site, structural performance specified demands, building component damageability, and damage consequences in financial costs, casualties, and downtime. These metrics can be used by building stakeholders to determine if the predicted performance is acceptable or if action must be taken to improve the expectation. In this paper, an analysis procedure for determining losses from earthquakes is outlined, though a similar procedure could be used for other hazards such as wind, flooding, or blast loading.

2. Characterization of Building Parameters

There are a number of parameters of a building and its environment which contribute to the risk for damage given a specific hazard. Five such parameters that will be discussed in this paper include building geographic location, soil characteristics, type of lateral force resisting system, construction quality, and building performance objectives. The significance of these parameters in respect to risk characterization can vary from building to building.

2.1. Geographic Location

The geographical location of the building often defines the types and severity of hazards to which it might be subject. Figures from the American Society of Civil Engineers' (ASCE) design standard titled Minimum Design Loads for Buildings and Other Structures are presented below for different hazards in the conterminous United States. Figure 1 shows a map of the wind speeds in miles per hour (meters per second) that are used for typical building design[1]. The majority of wind hazard to the United States is concentrated on states bordering the Gulf of Mexico and the Atlantic Ocean. The highest design wind speeds predicted in this map occur in the Southeastern tip of Florida with winds up to 180 mph (80 m/s).

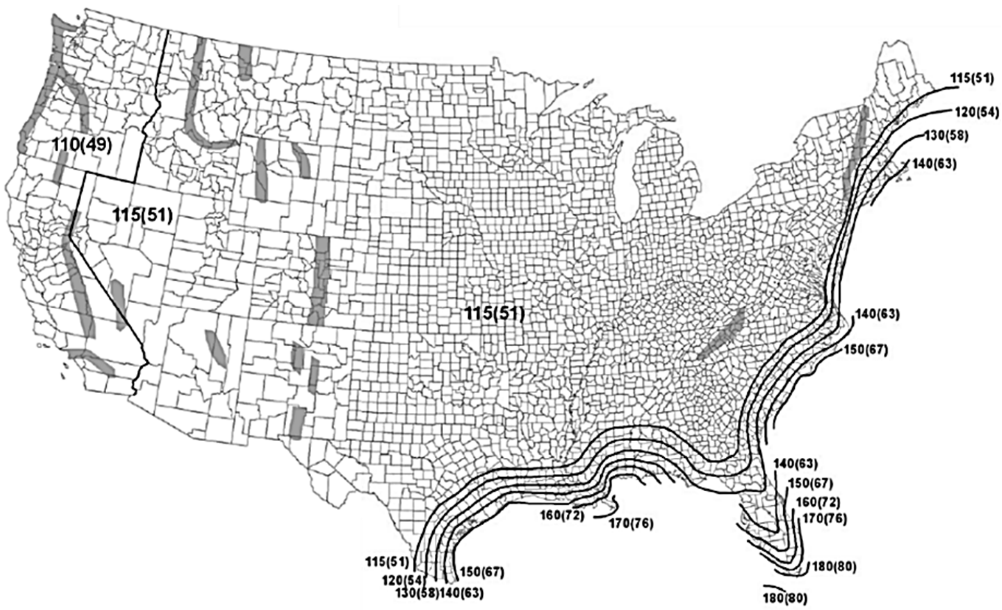

Fig. 1. Wind Speed Maps in miles per hour (meters per second) [1]

Figure 2 is the long-term seismic hazard map indicating relative intensities based on a probability of return of 2% in fifty years [2]. The west coast of the US, including Alaska and Hawaii have the highest potential for seismic demands. Also, the New Madrid Fault Zone in western Tennessee and the surrounding states could also be subject to significant earthquakes.

Although hazard to a building can come in many forms and all pertinent hazards should be evaluated to determine which one may control the design, the example used in this paper focuses on the risk and damage modeling related to seismic hazard specifically.

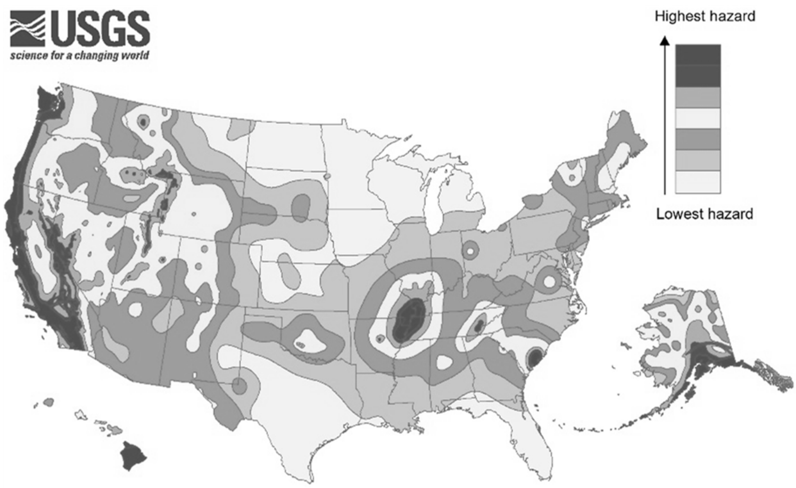

Fig. 2. 2014 Long-term Seismic Hazard Map, 2% in 50 years [2]

2.2. Soil Characteristics

Related to the risk for seismic ground movement at a given site is the characterization of the soil on which the building is founded. For tall or flexible structures with longer fundamental periods subjected to earthquakes, founding the building on softer soils leads to larger expected spectral accelerations and larger seismic design forces in the members. ASCE 7–10 accounts for differing seismic forces in buildings depending on soil type by applying site coefficients, Fa and Fv, to the spectral ordinate used for design, where the coefficients are determined by the shear wave velocity of the underlying soil [1].

2.3. Lateral Force Resisting System

In order to protect a building and its contents from damage given loading other than gravity, a competent lateral force resisting system must be designed and constructed. For the case of seismic design, varying levels of ductility may be sought to mitigate structural damage and to prevent loss of life through the selection of a lateral system and appropriate detailing.

An excerpt from ASCE 7–10, Table 12.12–1 is shown below in Figure 3 for reference[1].

Seismic Force-Resisting System	ASCE 7 Section Where Detailing Requirements Are Specified	Response Modification Coefficient, R^a	Overstrength Factor, Ω_0^g	Deflection Amplification Factor, C_d^b	Structural System Limitations Including Structural Height, h_n (ft) Limits[c] — Seismic Design Category				
					B	C	D^d	E^d	F^e
C. MOMENT-RESISTING FRAME SYSTEMS									
5. Special reinforced concrete moment frames[n]	12.2.5.5 and 14.2	8	3	5½	NL	NL	NL	NL	NL
6. Intermediate reinforced concrete moment frames	14.2	5	3	4½	NL	NL	NP	NP	NP
7. Ordinary reinforced concrete moment frames	14.2	3	3	2½	NL	NP	NP	NP	NP

Fig. 3. Excerpt from Table 12.2–1, Design Coefficients for Seismic Force-Resisting Systems [1]

This figure shows the various seismic design parameters for reinforced concrete moment frames. The required level of ductility and expected inelastic demands increase when moving from ordinary to intermediate to special moment frames. Furthermore, as the inelastic demand on the system increases, the detailing requirements become more demanding.

2.4. Quality of Construction

Another key aspect in the evaluation of risk to a given structure is the quality of construction. An engineer may design an elegant and efficient solution only to have the vision not realized due to poor craftsmanship. In seismic and wind design, it is critical that the facility be constructed as to provide a complete load path from the point(s) of load application (e.g., masses for seismic loading or surfaces for wind loading) through the structure and into the foundation and ground. If poor workmanship affects any component of this load path, the performance of the structure under the applied lateral loading will be diminished.

Deficiencies in construction manifest themselves in many forms. For example, concrete may be understrength or reinforcing bars could be missing. Steel beams may be erected in the wrong location or supplied in the wrong material grade. Connections may be missing fasteners or missing altogether. Whatever the deficiency may be, there is often a negative effect on structure performance. Part of the strategy of using performance-based evaluation is to characterize subtleties in the construction process that may dramatically affect the intended performance of the building system as a whole.

2.5. Targeted Performance Objectives

ASCE 7, like many building design standards, specifies the minimum requirements for a building design to perform to an acceptable level of risk. ASCE 7 is based on the performance objective that given a Maximum Considered Earthquake (MCE), the probability of collapse of a typical structure will be less than 10% [3]. This level of risk corresponds roughly to a seismic event which has a 2% probability of occurrence in 50 years. The MCE is then reduced to design values (known as the Design Basis Event or DBE), which has approximately a 10% probability of occurrence in 50 years. To meet code requirements, the lateral force resisting system must withstand the design level (DBE) lateral forces reduced by a response modification coefficient (R, see Figure 3) while still having elastic behavior. ASCE-7 also sets limits on inter-story drift ratio for buildings subjected to the design level lateral forces [1].

2.6. General Procedure for Quantifying Damage

For seismic hazard, the general procedure for assessing the risk of damage and/or collapse to a specific structure is as follows:

– Create a numerical model that incorporates the important components of the designed structure. The model should include accurate representations of the lateral force resisting system and associated components, floor masses, and material and geometric nonlinearities.
– Apply a lateral force pattern to the model structure and apply increasing deformations until the lateral force resisting system can no longer carry vertical load (collapse). The pushover curve can be created by plotting, for example, the roof deformation on the abscissa and the base shear force on the ordinate.
– Use the backbone curves to create fragility curves predicting collapse, and
– Estimate damage through approximation of the structural system response to a given demand level.

It is worth noting that performance-based engineering is not just limited to seismicity. Other local natural hazards such as wind, hurricanes/typhoons, tornados, blast, or floods can also be characterized for inputs into a performance-based analysis. Once the numerical model is created, the steps proceed similar to that outlined above in order to estimate the anticipated damage given the specified event. The following sections detail how this process is performed for assessing seismic hazards.

3. Structural Modeling

The lateral force-resisting system consists of potentially many different structural components which, when acting together, are able to resist the demands on the system as a whole. For example, consider an exterior façade wall acted on by wind perpendicular to its face. The wall must be able to transmit the wind forces through connectors into the floor diaphragm. Next, the floor diaphragm must distribute the forces to the lateral load-resisting elements, say a steel moment frame. Finally, the moment frame must be able to transmit the loads down to the foundation. In this load path, each of the elements has a backbone curve that dictates the element's force-displacement response when increasing deformations are applied. As a whole, the system also has a backbone curve, which dictates global response due to the combination of all of these elements which make up the structural load path.

Construction details and their execution in the field as well as the operational conditions can also lead to unintended consequences[4, 5, 6, 7, 8]. On January 17, 1994 at 4:30 in the morning, a magnitude 6.7 earthquake struck in Northridge, CA, about 20 miles west-northwest of Los Angeles. The blind thrust event led to significant damage throughout the region including freeway collapses as well as significant damage and collapse in office buildings and parking decks [9]. In addition to the catastrophic collapses, a number of steel moment frames also experienced unrepairable damage. The construction of the beam-to-column joints in the moment frames led to a number of defects in the welds. These defects were exploited by the earthquake and caused fractures through the columns in many buildings. A backbone curve for the moment-plastic rotation response of a pre-Northridge connection is shown in Figure 4 [10]. Conversely, Figure 5 shows a similar Northridge-type connection that has been modified to increase ductility [10].

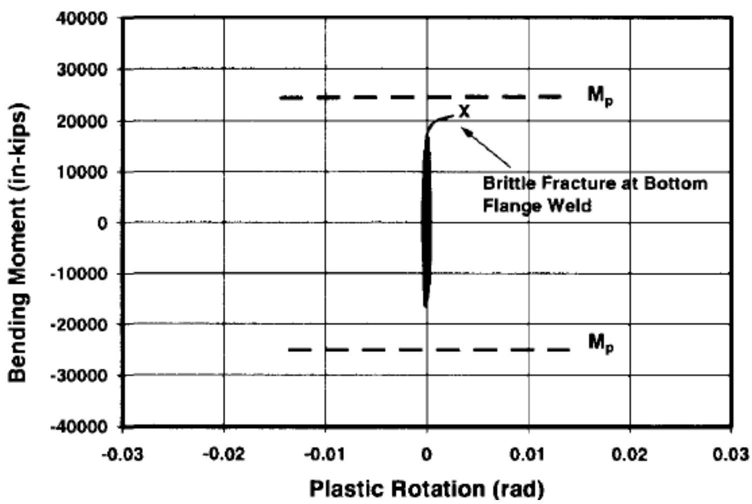

Fig. 4. Moment-plastic rotation response of pre-Northridge connection [10]

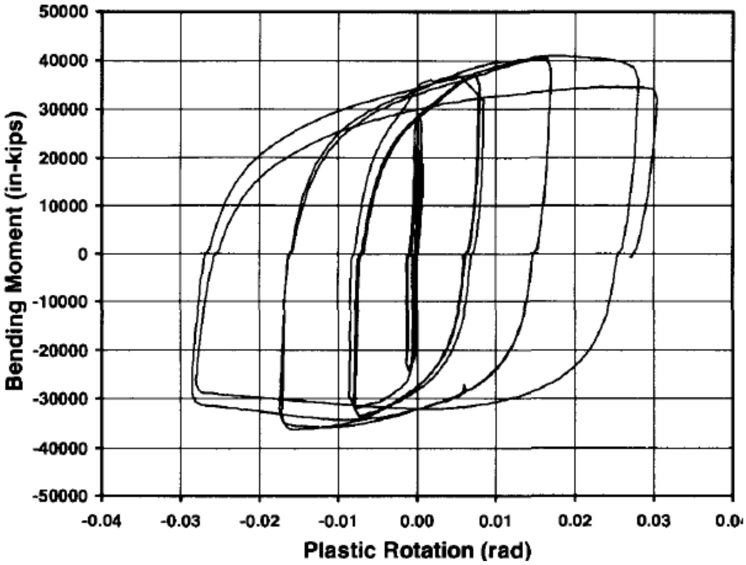

Fig. 5. Moment-plastic rotation response of modified Northridge connection [10]

The plots show that the modified moment connection is able to resist much larger plastic rotations than the pre-Northridge connection. The area within the hysteretic loops, which represents plastic energy dissipation, is also much larger for the modified connections when compared to the pre-Northridge connection. These results suggest that the modified connections would be able to undergo much larger deformations during an earthquake before fracture of the member and loss of load carrying capacity.

When selecting a method for modeling the building to be analyzed, it is important to select a software that will capture the behavior of the structure at large deformations. Material and geometric nonlinearities (P-Δ and P-δ effects) should be built into the model to ensure that the resulting pushover curve is accurate. Many analysis packages are capable of capturing these effects.

4. Quantification of Damage

4.1 What is Damage?

In general, quantification of damage occurs by assessing the structural response for different levels of demand. After characterizing the inherent hazards to the system (including, for example, building location, expected natural hazards, and construction defects) and determining the combined system backbone curve, it is now paramount to create a predictive model which can assess the metrics associated with damage.

One other aspect that must be discussed before an example can be given is what is meant by the word „damage." Damage prevention in a structural engineering sense, is often attributed to preventing loss of life (which is the base to code philosophy). While the building maintains sufficient integrity to prevent collapse, it could still be subject to significant structural and nonstructural damage. Ultimately, this could terminate the useful life of the building or result in loss of building use an extended period of time. Overall, „damage" can be represented by „deaths, dollars, and downtime."

Researchers have invested great effort into quantifying damage and collapse potential in structures over ranges of seismic hazard levels. In 2012, the United States Federal Emergency

Management Agency (FEMA) published FEMA P-58, a document which outlines a method for the seismic assessment of buildings [3]. The document outlines a methodology in which a structural model of the building is subjected to nonlinear analysis (either response history or pushover). The fragilities of each component in the building (e.g., cladding, partition walls, structural elements, plumbing), which represent the expected damage levels at different structural demand levels, have been compiled from test data. For example, aggregated test data may show that interior partition walls undergo cracking that would require repair at a median drift level of 0.2%, while more extensive damage requiring replacement of the gypsum board would occur at a median drift level of approximately 0.7%. The FEMA P-58 methodology further relates costs with these repair procedures for each component in the building. Collapse fragility, which characterizes the probability of building collapse at different seismic hazard levels, is determined from the nonlinear model analysis. The methodology uses numerical integration to combine the effects of the seismic hazard at the building location with the nonlinear response from the model and the component fragilities and associated repair costs to characterize the expected building performance in terms of overall repair cost („dollars"), loss of building functionality („downtime"), and casualties („deaths").

Since this method of determining seismic losses is onerous to perform manually, those in research and industry have devised software packages to perform the analysis, though the user must input seismic hazard information from the building site and results from nonlinear structural analysis, which are performed separately. As part of the FEMA P-58 project, researchers produced a tool called Performance Assessment Calculation Tool (PACT) to integrate the building response with the seismic hazard and component fragilities. More recently, Professors Jack Baker and Curt Haselton created a web-based analysis software called Seismic Performance Prediction Program (SP3)[11], which provides a convenient user interface and also implements REDi [12] repair time analysis and a USRC rating system [13] to evaluate the considered structure.

4.2 Example Damage Model

The example used to describe this process only varies the performance objective to illustrate the effects on damage detection and decision making. The example case explores the damage to a 12-story reinforced concrete moment frame building given various hazard levels. This example building is part of those included in the SP3 analysis package[3].

4.2.1 Building Location, Parameters, and Seismic Hazard

The example structure is hypothetically located in Commerce, California, near downtown Los Angles. The building is assumed to be commercial occupancy, with moment frames placed on the perimeter, 4 m. floor heights, and total floor area of approximately 16,000 sq. m. Using the simplified analysis approach, which approximates the building performance based on an equivalent single-degree-of-freedom (SDOF) system, the building period, base shear coefficient, and yield drift ratio are given as 1.67 seconds, 0.067, and 0.75%, respectively. The median spectral acceleration at collapse was provided as 3.3 g. Building components which have fragilities that are considered in the analysis include the special moment frames, the slab connections, exterior curtain walls, partition wall finishes, suspended ceilings, piping, HVAC systems, and stairs, among others. The story drift as a function of building height is plotted for the 2% in 50 year event and 10% in 50 year event in Figure 6. Stories where this plot indicates a drift larger than 0.75% should expect yielding of the system, which can be an indicator for significant damage and/or collapse.

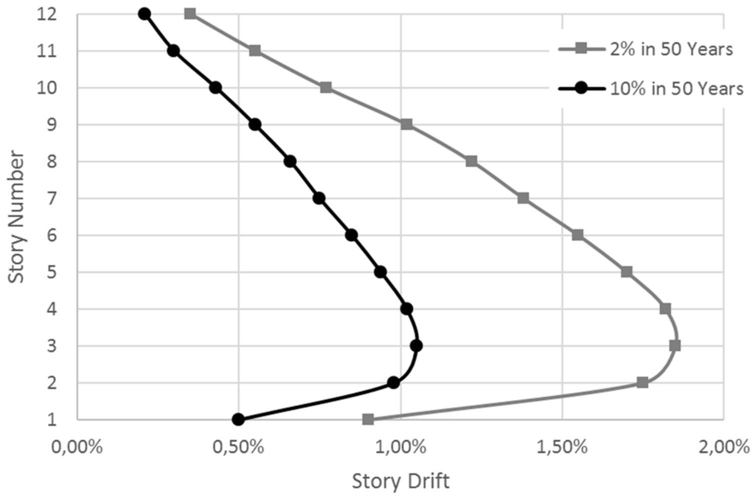

Fig. 6. Example Building – Story Drift

4.2.2 Damage Characterization

Integrating the seismic hazard with the building demand parameters, damage states, and associated costs, the analysis determines that in an earthquake with a 10% probability of occurrence in 50 years (approximately the DBE), the mean repair cost is 7.1% the cost of the building, while the comparable cost at a rarer event with a 2% probability of occurrence in 50 years (approximately the MCE) is 18.7% the cost of the building. The analysis predicts a 0.1% probability of collapse under the more common hazard and a 1.5% probability of collapse under the stronger ground motion. The REDi analysis results, as shown in Figure 7, suggest that these events are associated with functional recovery times of 287 days and 245 days for the events with a 2% and 10% probability of occurrence in 50 years, respectively. These damage levels are associated with approximately 4 casualties in the more common event and 10 casualties in the rarer event, based on building occupancy.

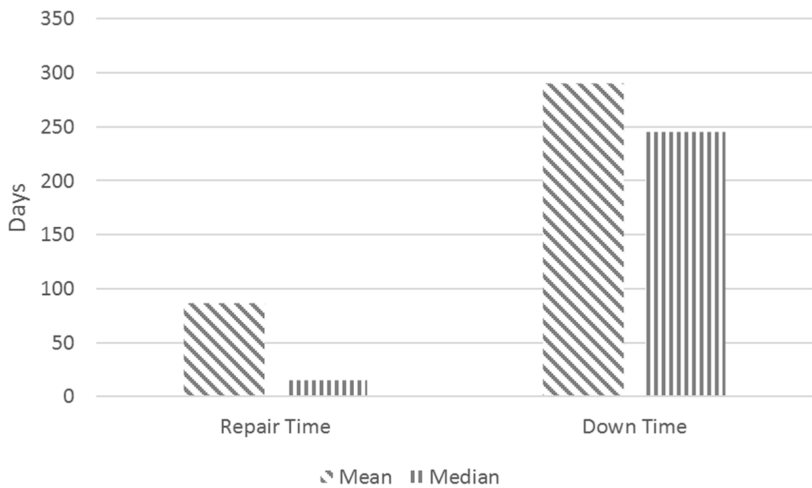

Fig. 7. Example Building – REDi Down Time and Repair Time

5. Making the Decision

Performance-based engineering such as that outlined in FEMA P-58 allows engineers, owners, and other stakeholders to make building-specific decisions based on analysis results and on desired building performance. The probabilities of collapse for the example structure are quite small, however, if it had been found that the probability of collapse were large under the Design Basis Earthquake and Maximum Considered Earthquake, the owner may decide to carry-out a retrofit to reduce the collapse probability and associated casualties. Additionally, if a structure with known defects and deficiencies was modeled, the results of the analysis could help the owner decide if repair of the defects would yield worthwhile results. Repair and retrofit costs can be balanced with expected financial, downtime, and casualty losses. For example, if performing $XM retrofit would lead to a reduction in building damage under the MCE significantly greater than $XM, a reduction in downtime of multiple months, and a lowering of the number of casualties by half, the building stakeholders may well decide that the retrofit is worth their investment. Conversely, if results of the analysis show little benefit to implementing a repair on improving life safety and limiting damage and downtime, the building stakeholders may well decide that the repair is not worth the required costs. Performance-based engineering gives building stakeholders the tools and results steeped in rigorous analysis to make these important decisions.

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