Available online at www.CivileJournal.org

Civil Engineering Journal

Vol. 5, No. 6, June, 2019

Extreme Events design and Mitigation Methods: A Review

Lawali Moussa Laminou [a], Zhangjun Liu [a], Xinghua Chen [a*]

[a] *China Three Gorges University, College of Civil Engineering and Architecture,Yichang 443002, China.*

Received 13 March 2019; Accepted 07 June 2019

Abstract

Recently, extreme events have highlighted their potentially tragic effects on structural and infrastructure systems. Resilience of the Community to these extreme vents is an important issue of increasing more concern for developing design methods. Such extreme events scenarios involve many uncertainties, such as the intensity, location, and period. The extreme events may include those caused by various natural or manmade hazards, such as earthquake, strong winds, fire, blast, etc. Compared to other events, earthquake and wind are particularly critical due to their significant threats to the global structure performance and more challenges for design. Researchers have recognized that proper evaluation, modeling, and assessment of the effects of extreme events are fundamental to ensure the desired performance of structures. Therefore, the concern for developing appropriate methodologies to evaluate and design structures that can withstand the effects of extreme events has become a very active field of research in recent years. Improvement of building codes and development of new strategies are needed to mitigate the disastrous effects of extreme events. This paper presents a comprehensive review of literature surrounding designing building structures for extreme events. First, a general overview of the extreme events design and different objectives of approaches is conducted. Furthermore, a review related literature surrounding designing for earthquake resistance guidelines is presented, also highlights Performance-Based Seismic Design objectives. The available literature includes many studies for the provisions included in different design codes (China, United States and Europe). A review of literature related to wind resistance design with an overview of Performance Based Wind Design of building design method for the control of winds impacting on building structures is also presented.

Keywords: Extreme Events; Earthquake; Wind; Performance-Based Seismic Design; Performance-Based Wind Design.

1. Introduction

Latest disasters have shown that large parts of the world are subjected to multiple natural and manmade hazards. Despite the rarity of these events many examples exist of situations where disproportionately high levels of damage and loss of life have occurred from these extreme events. These have adversely affected the vital sectors of our development as agriculture, communication, irrigation, power projects and rural and urban settlements. Some disasters may be short lived and some other may be of long duration. However, irrespective of the duration of a disaster, the damage in the form of deaths, injuries and losses of property is immense. According to [1], extreme weather events are the top risk in terms of likelihood and second top risk in terms of impact, just after weapons of mass destruction. Worldwide, natural hazards are actively managed, but growing populations, land use change, development intensification and climate change impacts mean natural hazard risk appears to be increasing faster than it is being managed.

Extreme events actions such as earthquakes, strong wind and other severe natural hazards could cause local failure mechanisms that can propagate throughout the building and provoke collapse of partial or total building. Buildings are

* Corresponding author: chenxinghua@ctgu.edu.cn

http://dx.doi.org/10.28991/cej-2019-03091342

designed to withstand a number of frequently occurring specific expected hazard, but during construction and over their life, there is also a probability that the structures will be subjected to more than one unexpected hazard. While structures are generally not specifically designed for these unexpected events, this may probably cause collapse during their service-life. There is also a probability that the expected hazard nature will change throughout a building life span. So, the accelerating impacts of extreme events pose new significant challenges for the built environment and are increasingly becoming a design concern for many buildings. Such extreme challenges mean it's more important than ever to be able to design structures that can resist to these extreme events. Understanding the differences between various event conditions and the ways to help assess, quantify, and address the potential concerns is the key design standpoint. With an understanding of the design issues, code requirements, and standards for performance, the design professionals and developers address these challenges. Successfully doing so will appropriately allow the mitigation of the effects of the extreme events on buildings and more importantly protect the occupants by designing buildings that go beyond minimum life-safety requirements and incorporate the principles of resilient.

This paper presents a review of literature surrounding designing building structures for extreme events. It commences with a general overview of the extreme events design and highlights the different objectives of approaches. It furthermore reviews related literature surrounding designing for earthquake resistance guidelines, highlights the Performance-Based Seismic Design objectives includes many studies for the provisions included in different design codes*:* Chinese, United States and Europe Codes. This is followed by reviews literature related to wind resistance design; then goes into an overview of Performance Based Wind Design of building design method for the control of winds impacting on building structures.

2. Building Design for Extreme Events

2.1. General

Experience from past extreme events has demonstrated that structures and infrastructures suffer the most from extreme events in the world. Designing buildings to resist extreme events loads is probably the most challenging area of structural engineering. The evaluation procedure under such extreme loading scenarios involves many uncertainties, such as the intensity, location, and characteristics of primary and secondary hazards, properties and response of structural elements. However, the link between basic research and building codes, standards, and practices is weak [2]and due to the unconventional features of these extreme loading conditions, the behavior of the structures has not been well investigated. Zaghi et al. (2016) stated that several other deficiencies may be present in current design practice in designing for the effects of extreme events. However, many design experts still recognize that new and fundamentally different design approaches such as advanced analysis theories including structure interaction, high strain rate, nonlinear inelastic material behavior, low-cycle fatigue performance, and failure criterion need to be further developed to achieve the desired protection for society, and within targeted appropriate performance goals in most cases [3]. Facilitate design and construction of buildings with a realistic and reliable understanding of the risk of loss that might occur as a result of future extreme events is also a key target point. Understanding damage mechanisms of each hazard is integral to determining the best design and construction practices [4]. Most cities are exposed to multiple types of extreme events [5], sometimes simultaneously, and focusing on single events may lead to inadequate design recommendations. An improved method to estimate the probability of extreme events from independent observations was presented by Makkonen and Tikanmäki (2019) [6]. The method called VWLS since it combines minimization of the variance in x (V), Weibull plotting positions (W) and least squares (LS). It provides better prediction of the highest and smallest value in the data than presently available extreme value analysis (EVA) method. Chen (2012) [7] conducted a research about the structural response of mid- to high-rise buildings subject to wind and earthquake hazards using various types of analysis including static pushover and dynamic time history analyses, they stated that current design practices for tall buildings require the consideration of only the controlling load case for structural design while effective for areas where there is only the risk of one hazard, but this method underestimates the increased risk for multiple hazard regions and does not consider the differences in structural response to different load types. Figure 1 shows some conventional hazards that affect civil infrastructure, whenever the hazard`s range of effect intersects with another hazard, both the two would interact through the system and if the hazard zones do not interact in the space, it is expected that the two hazards to act independently [8]. To prevent structural collapse and enhance the community resilience in an environment exposed to these multi extreme events, Ngoc (2017) [9] stated that it is critical to understand the deterioration in structures so that proper prevention and/or mitigation practices can be undertaken to establish an accurate, efficient, and reliable analytical framework to quantify the performance of existing and new structures under extreme loading conditions both predictively and retrospectively; develop design and retrofit guidelines to improve the system resilience. Quiel et al. (2018) [10] investigated the performance of a semi-active damping device termed Variable Friction Cladding Connection (VFCC) under multi-hazard excitations that includes wind and seismic loads, comparing the performance of the VFCC against other connection strategies, Results showed that the VFCC provided better mitigation performance under different hazards and can improve structural resiliency against multi-hazards. Chulahwat and Mahmoud (2017) [11] proposed a combination of a linear algorithm – Nelder-Mead and a non-linear algorithm – CMA-ES multi-hazard optimization framework for wind and seismic of two suspended floor slabs isolation systems models. The results from the multi-hazard optimization tests showed the performance objectives satisfaction of both hazards at the same time and the proposed optimization framework can perform very well to other vibration isolation systems under multi-hazard loading. The performance of vibration control of structures with different methodologies is necessary for the safety and serviceability of the structures under multi-hazard loads, when single strategy fails in meeting the performance requirements [12].

The concept of superposition of different hazards cannot always accurately predict the risk of damage. The effects of multiple hazards, acting concurrently or over time, can significantly increase the damaging impact of individual hazards. Therefore, an explicit multi-hazard design is necessary to achieve robustness and resiliency at a large scale. Multi-hazard design requires an in-depth understanding of the nature of various hazards and their interactions. It must also include the effects that the hazards have on one another and on the behavior of structures or physical components of a system. According to Dubina and Zaharia (2010) [13], buildings should pose sufficient robustness to avoid progressive collapse and the Robust based design methodology may be generalized considering localized failures in models for specific of extreme events like fire, earthquake, Blast, impacts, Fire after blast, fire after earthquakes.

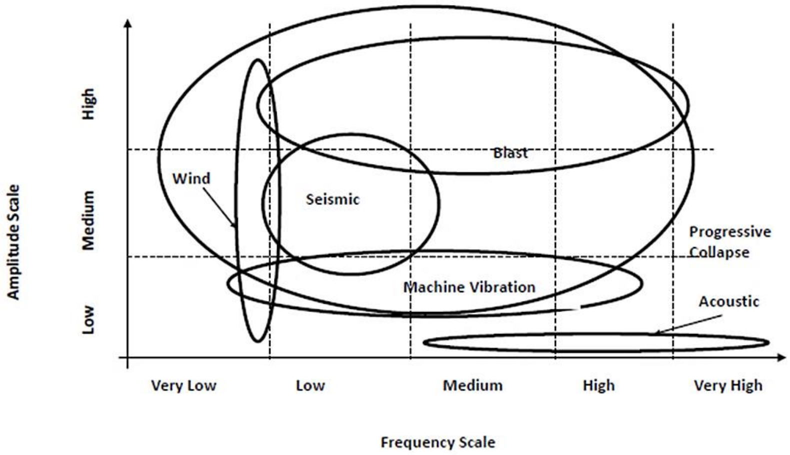

Figure 1. Qualitative Frequency-Amplitude distribution for different Hazards [8]

3. Earthquake Design

Large numbers of buildings may be significantly damaged and not only individual buildings but also entire cities may lose their function following extreme earthquake events. In recent large earthquakes, it has been observed that many properly designed and constructed buildings, which did not collapse, were no longer functional and were later demolished rather than being repaired. Most of the damages caused by earthquakes are mostly a consequence of the collapse and damage of existing buildings not the earthquake itself – meaning harm-reduction measures can make an impact [14]. A massive 7.1 magnitude earthquake shook Mexico’s capital city and in this quake, as in many others, collapsing buildings were the primary killer [15]. It is impossible to prevent earthquakes but it is possible to reduce the vulnerability of the population by the adoption of prevention measures. The availability of adequate and modern standards and guidelines for the design of new buildings is certainly a key element in the medium or long-term reduction of seismic risk. Achieving a seismic performance objective requires the coordination of structural and non-structural performance. According to Goldsworthy and Lam (2007) [16], the design of earthquake resistant buildings is not an exact science but it requires a certain artistry that is used to coax the building into behaving in a suitable manner. There are many uncertainties in both the demands being placed on the building and in the capacity of the building to meet these demands. The designer must have a good appreciation of these before embarking on the design. The architect should have completely knowledge of the conflict of architectural design in the risk of earthquake [17]. A properly engineered structure does not necessarily have to be extremely strong or expensive [18], it has to be properly designed to withstand the seismic effects while sustaining an acceptable level of damage. Basic concepts of the earthquake engineering, implemented in the major building codes, assume that a building should survive a rare, very severe earthquake by sustaining significant damage but without globally collapsing. On the other hand, it should remain operational for more frequent, but less severe seismic events. The consequences of an earthquake also depend on the resistance features of the buildings to the actions of a seismic shock. The more a building is vulnerable (by type, inadequate design, poor quality of materials and methods of construction, poor maintenance, type of soil on which the building is located), the greater will be the consequences.

According to Takagi and Wada (2019) [19], the seismic design philosophy for building and infrastructure should be changed from life-saving to business continuity for modern and resilient societies. Structures should be designed to be quickly restored to full operation with minimal disruption and cost following a large earthquake and proposed a new seismic design approaches in which Fundamental goals of seismic design against for small and moderate earthquakes and likely even for large earthquakes will be achieved, see Table 1. In order to achieve the goals of the new seismic design approach shown in Table 1, they again proposed an effective method of design which would allow structural components to play separate roles. The primary structure supports the gravity load and the seismic members mainly resist earthquake loads shown in Figure 2. Therefore, the seismic members protect the primary members against large earthquakes.

Table 1. Fundamental goals of seismic design against large earthquake

	Current seismic design approach	New seismic design approach
H	Human lives likely to be saved	Human lives surely to be saved
B	No certainty of future building use with repair	Building to be used with some repair
C	No continuous operation after earthquake	Continuous use even after earthquake

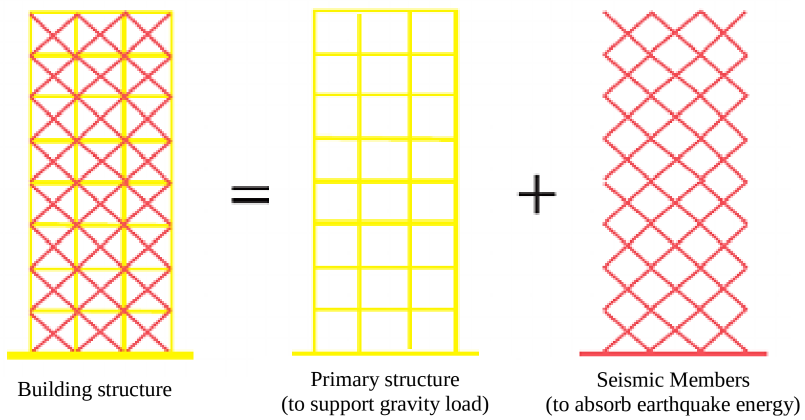

Figure 2. Separation of primary and seismic members

Given the fact that an engineer cannot predict and control the earthquakes phenomena but can govern the building performance through the designing procedure by introducing an upper-bound ground motion to design buildings against the collapse. An upper-bound ground motion should be used to assess every structural performance that involves the highest level of damage eligible for the building under design [20]. According to the importance of the structure, consideration is given to the Target Performance Level (TPL) which is the highest level of damage acceptable for the building. Targets of seismic design today are of great variety including life safety, functionality after seismic action, damage mitigation, etc. In addition, objects of design are not limited to structures but include all elements consisting buildings.

Recently with the advent of innovative structural systems, complex geometries and advanced construction techniques of building to handle earthquake resistant aspects also increased. The concept of box-type wall structures envisages a change of paradigm from the actual ductility-based Earthquake Engineering (centered on frame structures) toward a strength-based design, and this solution can easily yield to almost 100% safe buildings against earthquake [21]. According to Dixon (2017) [22], to make a structure more resistant to the lateral forces of an earthquake is to tie the walls, floor, and roof together to form a Super Structure and have an isolated foundation that becomes the Sub Structure. However, in order to nullify the vibrations and keep the equipment as safe as the human inhabitants, it is needed to look at what the building sits on. As each year buildings and other structures are designed and built with a continually improving understanding of their performance during earthquakes. The new design philosophies are grounded on the full exploitation of the non-linear deformation capacities, thus requiring a complete knowledge of structural and non-structural components behaviors. Eljajeh and Petkovski (2018) [23] presented a new optimization approach called Self Adaptive Optimization Approach (SAOA) in which the self-optimization of a semi-active system is used in the design stage and the resulting distribution of control forces is adopted as a passive system. The new optimization approach has both passive and semi-active control advantages to determine values of control forces in passively-controlled earthquake-resistant multi-storey buildings. A truss wall with the fuse-type connection was proposed by Ishikawa (2018) [24] and the study confirmed that the control of the dynamic collapse mechanism such as the steel bolt elongation in the dynamic elastoplastic analysis can avoid a brittle collapse mechanism such as a chain of member buckling. The use of The low-damage seismic design philosophy which can be achieved by activating rigid-like body movement of structural members and the movements cause less or no local deformation , not only provide safety of occupants but also the integrity of the structures will be achieved even reducing or avoiding the down time following a strong earthquake [25]. Lateral load resisting systems like chevron braces, knee braces in combination with aluminum shear links can considerably reduce the impact of earthquake on the structures with respect to its drift and economical and feasible passive and active control vibration systems like dampers, isolation techniques led to enhance the overall performance of high rise [26]. Figure 3 shows a wide spectrum of proposed simplifications in the overall seismic analysis process over last several decades [27]. Motion control of tall buildings, should take into consideration both static and dynamic loads. This can be accomplished by increasing the structural stiffness and damping while keeping the material amount at a minimum [28]. The probabilistic seismic hazard analysis method is also necessary to determine how rapidly the risk decays as resistance of the structure is increased [29].

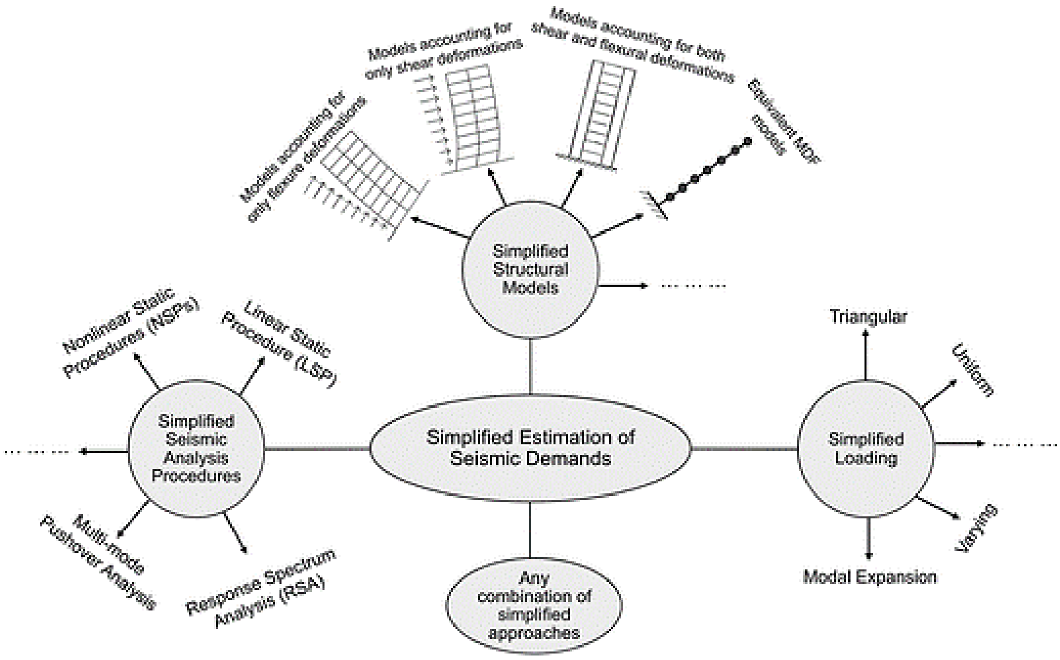

Figure 3. Some proposed simplifications in the overall seismic analysis

4. Performance Based Seismic Design

Researching for new solutions for seismic resistant buildings design is important concept behind in order to provide cost-effective and sound designs. In the traditional seismic design, the performance objectives are considered implicitly. But satisfying one design level does not ensure that other design levels will be satisfied as well. Performance-based Design (PBD) approach refers to the methodology in which structural design criteria are expressed in terms of achieving a set of performance objectives or levels [30]. It ensures that the structure as a whole reaches a specified demand level including both service and strength design levels. Performance Based Seismic Design (PBSD) involves a large number of probabilistic considerations, relating to variability of seismic input of material properties, dimensions, gravity loads, and of financial consequences associated with damage, collapse or loss of usage following seismic attack, among other things. The main idea in this new seismic design approach is to correlate the level of structure's damage to measurable engineering demand parameters as show on Figure 4. The PBSD procedure consists of two design phases. In the first phase, after the preliminary design is completed with the basic configuration and structural layout selected, the code-exceeding conditions are identified, and the seismic performance objectives are determined accordingly. Furthermore, the key structural components which are crucial to the seismic safety of overall structure are identified and laid particular emphasis. The design criteria are established to achieve the desired performance objectives. Different performance requirements are proposed for different types of structural components. The seismic effects under the frequent earthquake and the effects of other actions are determined on the basis of linear-elastic behavior. In the second phase, the seismic performance of the target building is evaluated by comprehensive numerical analysis. For tall buildings which greatly exceed the height limit or have very complex or unique as well as innovative structural system without design experience and referential bases, structural testing on the joint, member, or full structural model is highly recommended to conduct in order to study the structural behavior and check the seismic performance directly. If the predefined seismic performance objectives cannot be satisfied, design iteration should be done until satisfied. There is overstrength in designing based on current code, especially in Life safety level, so using performance-based codes lead to more optimum design [31].

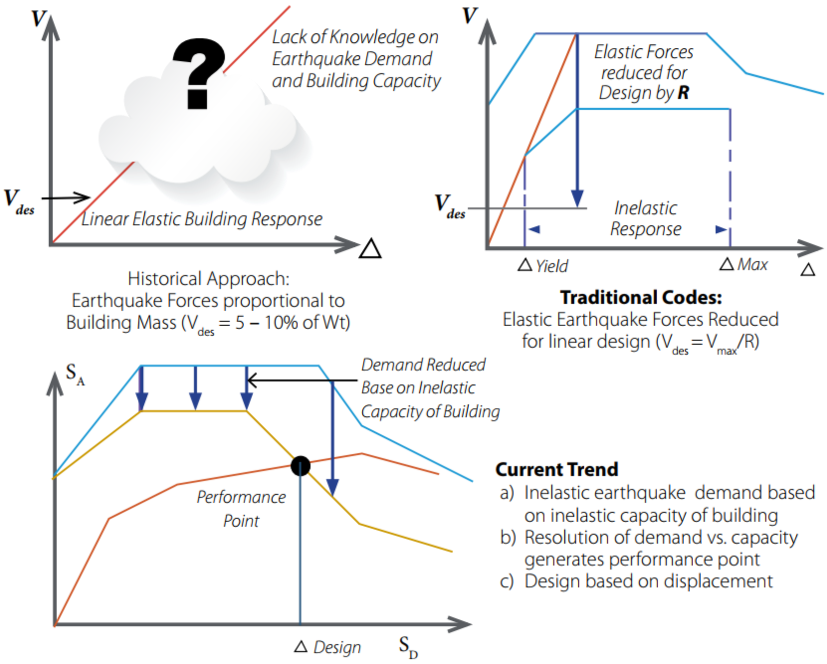

Figure 4. The progression of seismic design approach [32]

After some recent extreme earthquakes, it is considered necessary to review and re-analyze the seismic hazard, considering more recent geological and seismological input, in combination with consideration of recent advances in seismic hazard and site-response analysis (SRA). New concept in the seismic design criteria is introduced in ASCE-SEI-7-10 and PEER Guidelines for Performance-Based Seismic Design of Tall Buildings 2010, that the seismic criteria are not only based on seismic hazard as previously adopted by many building codes, but based on probability of collapse of the buildings. The ground motions derived from this concept is called risk-targeted ground motion (RTGM). The analysis developed herein is based on risk-target maximum considered earthquake (MCE_R) defined as 1% probability of collapse of the building in 50 years, in reference to ASCE-SEI-7-10. These objectives are achieved by performing nonlinear response history analysis using a suitable suite or suites of ground motions representing MCE_R shaking[33]. The 1 percent in 50-year collapse risk objective is the result of integrating the hazard function (which is different for each site) and the derivative of the hypothetical collapse fragility defined by the 10 percent conditional probability (and an appropriate amount of collapse uncertainty).

4.1. Performance Objectives

As stated previously, most of the current seismic design codes for building systems claim, either explicitly or implicitly, that design of buildings' structures based on their requirements leads to Life Safety (LS) as their minimum Performance Level (PL) [34]. Some buildings, designed based on the current codes provisions and constructed based on high standards, under good supervision, have shown unacceptable Performance Levels (PLs), even collapse in some recent earthquakes. In many cases the level of damage in the earthquake stricken buildings has been so high, that the demolishing and reconstruction of the building have become inevitable. PBSD defined a key parameter as performance objective, which is the acceptable level of damage selected for a specified earthquake intensity level. A building may be designed based on one or multiple performance objectives. The selected performance objectives will depend on the intended use of the structure; for example, safety-critical buildings, such as hospitals and fire halls, are required to remain operational (light damage, most operations can resume immediately) after a severe earthquake event. Performance objective for a design should more correctly be stated as a certain level of confidence (i.e. 95%) that the structure will provide Collapse Prevention or better performance for earthquake hazards. The PBPD method uses predetermined target drift and yield mechanisms as important performance objectives. These two limit states are directly dependent on the degree and distribution of structural damages, respectively [35]. Different seismic codes have established goals for building performance levels during earthquakes in order to assure life safety and to limit property damage. These performance levels reflect those codes expectation of both the level of damage to a facility and the ability to continue operations. The levels account for both structural and non-structural elements. Following are some codes description on the performance objectives.

Chinese code: The current Chinese seismic design code seems conservative because the buildings show marginal potential of suffering serious damages endangering life when subjected to the seismic hazard level higher than it was designed by Yu et al. (2017) [36]. In mainland China in recent years, a large number of code-exceeding tall buildings, whether their heights exceed the limit for the respective structure type or the extent of irregularity is violated, have been constructed. PBSD approach has been highly recommended and become necessary to demonstrate the performance of code-exceeding tall buildings at least equivalent to code intent of safety. Technical specification for concrete structures of tall building [37], suggest that the performance objective of tall buildings is dividing into four grades named A, B, C and D. In addition, the aseismic performance level is divided into five levels named 1, 2, 3, 4 and 5 each performance objective corresponds to a group of aseismic performances under different earthquake levels see Table 2.

Table 2. Anticipated performance objective of PBSD of Tall buildings

Performance Objective Performance Level Seismic demand Level	A	B	C	D
Frequent earthquake	1	1	1	1
Design earthquake	1	2	3	4
Rare earthquake	2	3	4	5

Chinese national seismic design code (Ministry of Construction of China 2010) consider three levels of seismic hazards, minor or frequent earthquake with the exceeding probability of 63.2% in 50 years (50 year return period), moderate or basic earthquake with the exceeding probability of 10% in 50 years (475 year return period), and strong or rare earthquake with the exceeding probability of 2% in 50 years (2475 year return period). The minimum seismic performance objectives for ordinary buildings (including tall buildings) specified in the code are summarized as fully operational under minor earthquake, repairable under moderate earthquake, and collapse prevention under strong earthquake. Zhou et al. (2017) [38] proposed a performance objective system for earthquake-resilient structures for the Chinese seismic code, see Figure 4, Tables 3 and 4. The system incorporates four earthquake levels namely minor, moderate, major and mega earthquakes which have an exceeding probabilities of 63.2%, 10%, 2~3% and 0.01% in 50 years, respectively. Performance objectives are set as "No damage under minor and moderate earthquakes", "Replaceable under major earthquakes" and "Repairable under mega earthquakes".

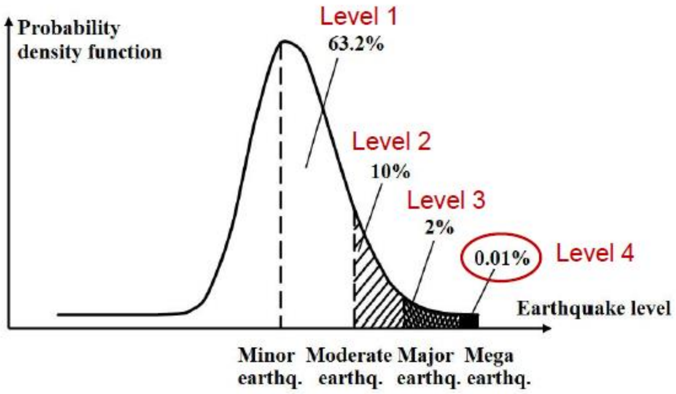

Figure 5. Proposed Performance Objectives for earthquake-resilient structures

Table 3. Proposed seismic performance objectives

Structure system	Seismic performance level			
	Level 1 Minor earthquake	**Level 2 Moderate earthquake**	**Level 3 Major earthquake**	**Level 4 Mega earthquake**
Traditional structures	No damage	Repairable	No collapse	-
Earthquake-resilient structures	No damage	No damage	Replaceable	Repairable

Table 4. Description of the seismic performance levels

Seismic performance level	Description
No damage	No damage in the structure ,functional without any repair
Minor damage	Minor damage in the structure ,the main vertical and lateral resisting components maintain their capacities, the building function is disturbed but can quickly recover after slight repair
Functional after replacement	The structure is partially damaged but the damage part is replaceable, the building function can quickly recover after replacing the damaged components
Functional after repair	The structure is partially damaged and the building function is affected, moderate repair cost is needed to recover the structure`s function
Life safety	The structure is severely damaged but does not lose its bearing capacity, collapse and other failure mode that can endanger human life are prevented

For tall buildings beyond the scope of design codes, Jiang and Zhu (2012) [39] proposed performance objectives. The relationships between the performance levels and earthquake design levels are summarized in Table 5. The seismic protection category is classified into four grades according to the importance of the building and the consequence of earthquake disasters. Type I is the highest grade. For tall buildings, the lowest grade, Type IV, is excluded. In Chinese code for concrete structures of tall buildings (Ministry of Construction of China 2002), there are two classes of structural height specified, Class A and B. The height limit for Class B is much larger than Class A. If the height is larger than the limit for Class A or the extent of irregularity is violated, the building is classified as the type beyond the scope of design codes. The performance level of operational defined here means the post-earthquake damage state in which very limited structural damage occurs. The basic vertical and lateral force resisting structural systems retain most of their pre-earthquake characteristics and capacities. Although some minor structural repairs may be appropriate, there would generally not be required prior to re-occupancy.

Table 5. Seismic performance objectives for code –exceeding tall buildings

Aseismic protection category	Seismic performance level		
	Frequent earthquake	**Basic Earthquake**	**Rare earthquake**
I	Fully operational	Fully operational	Operational
II	Fully operational	Operational	Repairable
III (RC structures with Height class B and irregularity within the code)	Fully operational	Repairable	Collapse prevention
III (structures except above)	Fully operational	Operational	Repairable

United states code: Four performance levels govern performance objective of seismic design of building throughout most of the United States as show on Fig.5, this represents the graphical representation of a performance objective matrix that matches selected earthquake hazard levels (y axis) with chosen target building performance levels (x axis). The three diagonal lines represent the performance objectives for different groups of building structures. Group I represents a basic commercial structure, while Groups II and III represent structures that require a higher level of protection such as hospitals, fire stations, data centers, key manufacturing facilities, etc. Building structures need to meet these objectives as a minimum which depend on earthquake intensities. According to ASCE/SEI 7-10 (2013) [40] buildings and other structures must satisfy strength limit states in which members and components are proportioned to safely carry the design loads specified in this Standard to resist buckling, yielding, fracture, and other unacceptable performance. This requirement applies not only to structural components but also to non-structural elements, the failure of which could pose a substantial safety or other risk.

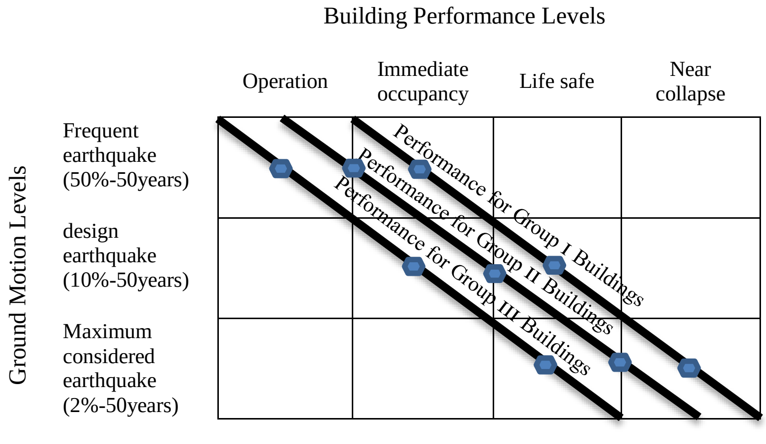

Figure 6. Performance objectives for United States

ASCE/SEI 7-10 adopted design-level earthquake shaking for purposes of evaluating strength and deformation that is 2/3 of the intensity of MCE_R shaking. This has been followed by ASCE/SEI 7-16 and this 2/3 reduction in the design earthquake is in recognition that the response modification factors (R factors) traditionally contained in the older codes incorporated an inherent margin of at least 1.5. That is, buildings designed using these R factors should be able to resist ground shaking at least 150% of the design level without significant risk of collapse. Building structures must be demonstrated, through appropriate nonlinear analyses and the use of appropriate detailing to have a suitably low probability of collapse under MCE shaking. A service-level performance check is also incorporated into the procedure to reasonably assure that buildings are not susceptible to unreasonable damage under the more frequent, low-intensity shaking, likely to be experienced by the building one or more times during its life. Protection of non-structural components and systems is reasonably assured by requirements that such components and systems be anchored and braced to the building structure in accordance with the prescriptive criteria of the building code. ASCE/SEI 7-16 (2016) [41] defines expected performance in the form of acceptable probabilities of collapse based on the occurrence of risk-target maximum considered earthquake shaking, see Tables 6 and 7.

Table 6. Collapse Performance Goals in ASCE/SEI 7-16

Risk Category	Tolerable Probability of Total or Partial Structural Collapse	Tolerable Probability of Individual Life Endangerment	Ground Motion Level
I or II	10%	25%	MCE_R
III	6%	15%	MCE_R
IV	3%	10%	MCE_R

Table 7. Anticipated reliability (maximum probability of failure for earthquake)

Risk Category I and II	
Total or partial structural collapse	10% conditioned on the occurrence of Maximum Considered Earthquake shaking
Failure that could result in endangerment of individual lives	25% conditioned on the occurrence of Maximum Considered Earthquake effects
Risk Category III	
Total or partial structural collapse	6% conditioned on the occurrence of Maximum Considered Earthquake shaking
Failure that could result in endangerment of individual lives	15% conditioned on the occurrence of Maximum Considered Earthquake shaking
Risk Category IV	
Total or partial structural collapse	3% conditioned on the occurrence of Maximum Considered Earthquake shaking
Failure that could result in endangerment of individual lives	10% conditioned on the occurrence of Maximum Considered Earthquake shaking

For ordinary buildings, Federal Emergency Management Agency [42] recommended the following performance objectives: *Life Safety Performance Objective*, for an event that has a 10% probability of occurring in the next 50 years. *Collapse Prevention Performance Objective*, for an event that has a 2% probability of occurring in the next 50 years. The following performance objectives are recommended by FEMA for essential facilities (buildings which are required to be operational after the design level seismic event): *Continued Operations Performance Objective*, for an event that has a 10% probability of occurring in the next 50 years. *Life Safety Performance Objective*, for an event which has a 2% probability of occurring in the next 50 years.

Eurocode: The level of the protection that can be provided is expected to vary from country to country, depending on the relative importance of the seismic risk and on the global economic resources. Generally, in Eurocode8 [43], the fundamental requirements for seismic performance are no collapse performance level, which requires that the structure retains its full vertical load bearing capacity after a rare seismic action with a recommended return period of 475 years; longer return periods are given for special structures, such as hospitals, see Table 8 as shows the acceptance criteria for collapse prevention and life safety. After the earthquake, there should also be sufficient residual lateral strength and stiffness to protect life even during strong aftershocks. The second main requirement is to meet a damage limitation performance level, which requires that the cost of damage and associated limitations of use should not be disproportionately high, in comparison with the total cost of the structure, after a frequent earthquake event with a recommended return period (for normal structures) of 95 years. The no-collapse performance level is achieved by dimensioning and detailing structural elements for a combination of strength and ductility that provides a safety factor between 1.5 and 2 against substantial loss of gravity load capacity and lateral load resistance. The damage limitation performance level is achieved by limiting the overall deformations (lateral displacements) of the system to levels acceptable for the integrity of all its parts (including non-structural ones) and through (non-engineered) measures for the integrity of (masonry) infills.

Another objective is to prevent global collapse during an extremely strong earthquake, of the order of the MCE of US codes. For structures of ordinary importance, the recommendation of EC8 is for a 10% exceedance probability in 50 years (design) seismic action for collapse prevention (mean return period: 475 years). A 10% in 10 years serviceability action for damage limitation (mean return period: 95 years). Enhanced performance of essential or large occupancy facilities is achieved not by upgrading the performance level for given earthquake level, as in United States codes, but by modifying the hazard level (the mean return period) for which collapse prevention or damage limitation is pursued. For essential or large occupancy structures it is recommended to increase the seismic action at both performance levels, corresponding to an exceedance probability lower than 10% in 50 or 10 years, respectively. According to Beyer (2015)

[44], The Eurocode should include provisions for new structural systems constructed from Reinforced Concrete elements that have the potential to reduce damage and therefore costs, in particular also during small and frequent events. Then, suggested systems such as post-tensioned rocking wall systems or fiber reinforced concrete elements systems to provide adequate performance, but with re-evaluation of the classical Reinforced Concrete elements design practice aiming at reinforcement details that limit, for example, crack widths in small events.

Table 8. Acceptance Criteria for Life Safety and Collapse Prevention

Performance Level	Primary Component	Second Component
Life safety	75% of the deformation at which significant loss of lateral force resisting strength occurs	100% of the deformation at which significant loss of lateral force resisting strength occurs
Collapse Prevention	75% of the deformation at which loss of vertical load earing capacity occurs, but not more than the deformation at which significant loss of lateral force resisting strength occurs	100% of the deformation at which loss of vertical load bearing capacity occurs

5. Wind Design

Due to the increase population in the urban societies, the evolution of the high-rise buildings as show in Figure 6, becomes a unique solution to the land area economization. In general, these buildings with considerable height are exposed to lateral forces resulting from wind loads which will affect them by the extent that such forces will play a major role in the design process. By previous experience, a large number of buildings were severely damaged or completely destroyed due to the lack of wind resistance in design and poor construction standards [45]. For example, January 2011, a residential building called Real Class, with 13,400 m² area and about 105 m high, which was under construction in the city of in the city of Belem, Para, Brazil collapsed during a heavy rain, where intense winds were registered in the city. After different studies carried out about the case, it was showed that the wind load was not properly considered in the design [46]. Most wind damage to buildings occurs during strong winds, the high-rise buildings are built to sustain extreme wind loads within an expected long lifespan. In recent years due to increase of global warming, Typhoons and strong local winds are becoming more frequent, so it is important to continually develop more accurate methods for structural design of tall buildings as the collapse of such buildings can lead to catastrophic consequences with a loss of many human lives and mitigating the impacts of strong or extreme winds at the building and urban city scale is key to urban resilience.

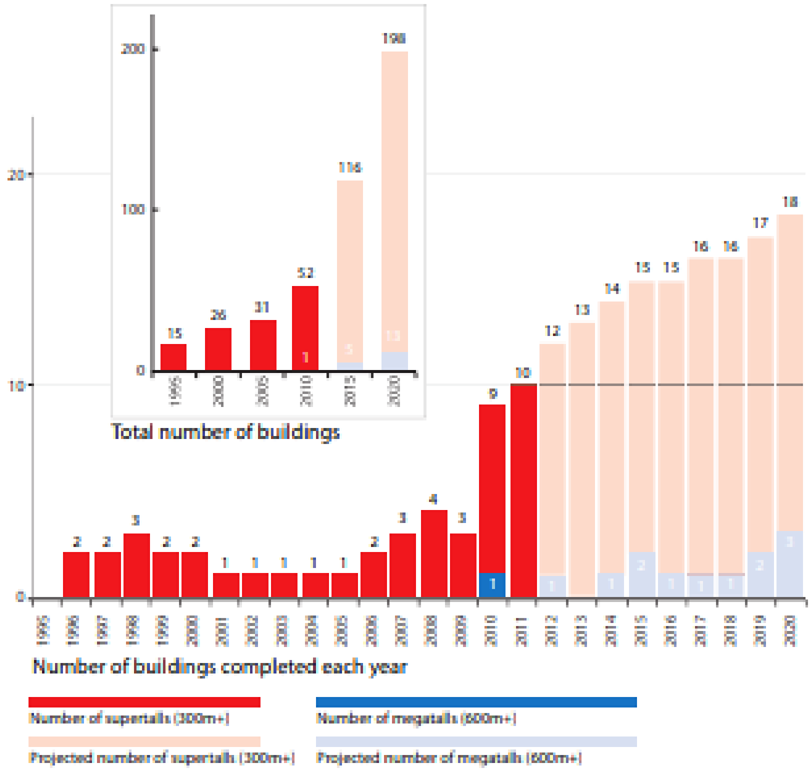

Figure 7. Supertall and Megatall building completion showing a significant projected increase [47]

In the structural design, the wind is physically represented by a speed profile reaching a building. Its characteristics and the effects it generates depend on the velocity of the wind, the geometry of the building, and of the protection caused by the terrain and surrounding obstacles. Figure 7 shows how the different wind forces are acting on building structures. As the damage occurred during strong winds depends not only on wind speed but also on the strength or quality of structures. However, the structure must have sufficient strength to resist the wind-induced forces, adequate stiffness to satisfy human comfort and serviceability criteria, and the wind may produce a dynamic response of the structure. Current wind design procedures require that structural behavior remains elastic under wind loading corresponding to a specific return period unlike seismic codes that set some specifications to account for the ductile behavior of structures [48]. And as stated by Mendis et al. (2007) [49], simple quasi-static treatment of wind loading, which is universally applied to design of typical low to medium-rise structures, can be unacceptably conservative for design of very tall buildings.

With tall buildings of today continuing to increase in height the mitigation of wind-induced vibration is one of the critical key points for designing tall buildings. The Wind-induced vibrations in structures increases the importance of structural design as the use of high-strength, lightweight materials, longer floor spans, and more flexible framing systems are used [50]. The most important factor for the evaluation of the wind-induced vibration is to choose appropriate wind load level [51]. It is also important to consider the theory of dynamic shakedown as an efficient means for describing the collapse probability of the main wind force resisting system [52].

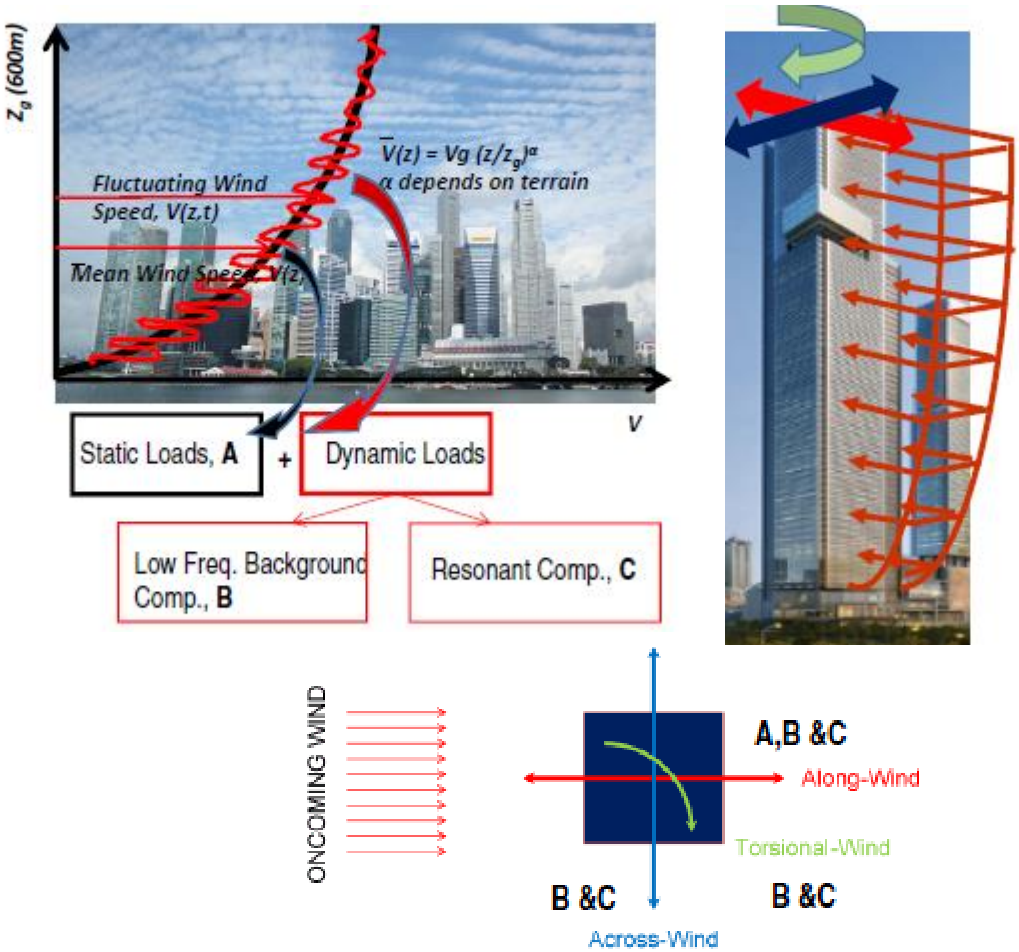

Figure 8. A & B: Dependent on building geometry & turbulence environment; C: Dependent on building geometry. Turbulence environment & Structural dynamic properties (mass, stiffness, damping)

According to Chan et al. (2009) [53], the structural design of modern tall buildings is generally governed by the need to provide adequate strength and stiffness against dynamic movement induced by strong wind. In addition to the strength-based safety design considerations, the major design effort of a tall building is related to the assessment of the wind-induced serviceability design requirements. However, serviceability with respect to occupier perception of lateral vibration response can become the governing design issue necessitating the introduction of purpose-designed damping systems in order to reduce these vibrations to acceptable levels. To yield adequate structural robustness, as well as to provide required comfort satisfaction to occupants, excessive acceleration under wind loads should always be avoided. According to the human comfort specifications in some countries such as China, North America and Europe countries, wind acceleration at the highest occupied level should below the limits specified in Table 9.

Table 9. Acceleration limits

Type of Use of Building	Peak acceleration (m/s^2)		
	China	North America	Europe
Residential	0.15	0.10-0.15	0.14
Office building, Hotel	0.25	0.20-0.25	0.21

For high-rise buildings, especially those with more complex geometry, the wind tunnel test procedure is alternatively recommended to determine the design wind loads since it yields more precise definitions of design loads, and more economical and risk consistent structural designs than code calculation methods. The response of tall buildings to wind forces is a critical design criterion and it requires both conventional forces based designs as well as performance based solutions [54]. Cui and Caracoglia (2018) [55] proposed a simulation framework for tall buildings that combines fragility analysis with local wind climate information to evaluate structural vulnerability and the study provides a desired solution to examine the building failure probability, considering both wind speed and wind direction.

6. Performance-based Wind Design

Similar to the seismic performance based evaluation approach, the wind performance based design approach enables the designers to design buildings efficiently according to the desired performances in various hazard levels. A set of performance objectives related to several discrete hazard levels (depending on the building's type) is required. Meeting the performance requirements leads to acceptable functionality and resilience of the building during extreme wind events. As the current wind design excludes the development of any nonlinearity in structural members, utilization of the performance-based design in wind engineering for tall building becomes a priority. It may suggest that the serviceability performances are the governing criteria in performance-based wind design.

Nonlinear analysis to predict inelastic building behavior and the risk of collapse for wind loads is the key challenge in performance-based wind engineering (see Figure 8). However, the wind tunnel test procedure is alternatively recommended to determine the design wind loads for complex buildings, Moustafa and Irwin (2017) [56] stated that current wind tunnel testing methods that utilize rigid or flexible linear elastic models are important but insufficient to ultimately develop performance-based wind engineering frameworks and an approach that combines computational nonlinear dynamic analysis with wind tunnel testing of nonlinear/inelastic building models is desirable. As such approach can help to understand the aerodynamic response and inelastic structural response of buildings under wind hazards develop, more accurate dynamic loading histories, and redefine or develop realistic target performance levels that span serviceability and strength objectives all the way to collapse.

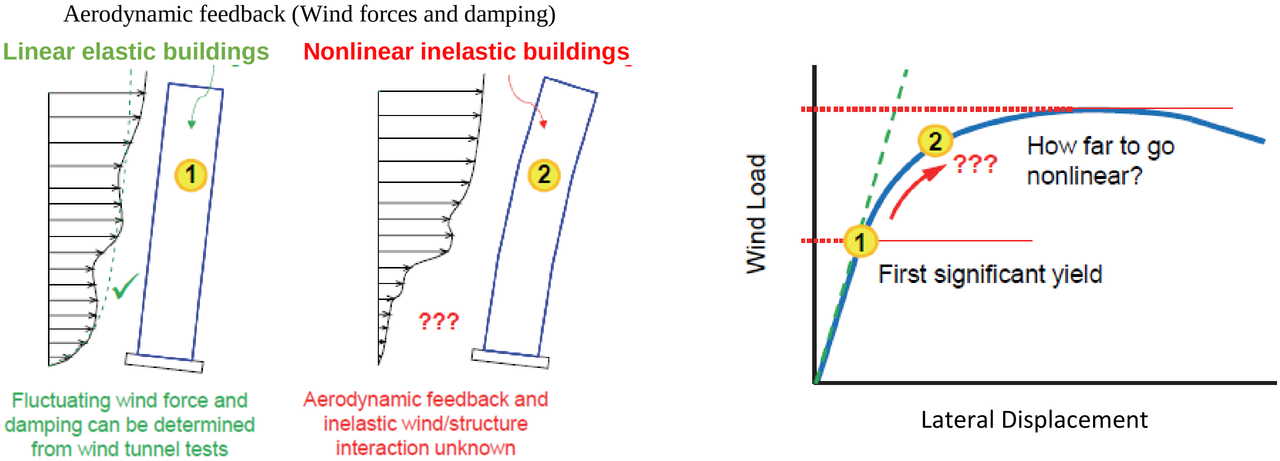

Figure 9. Challenges facing performance-based wind engineering and nonlinear inelastic design of buildings

Mohammadi (2016) [57] proposed wind performance-based engineering framework considered four performance levels as described in Table 10, and each performance level with its corresponding level of functionality interruption and damage to the building. The table also relates a wind hazard range in terms of Mean Recurrence Interval (MRI) to each performance objective. In order to undertake a wind performance based design, the framework requires the building to meet those four performance level objectives for windstorm and hurricanes events with 1-10 years, 50-100 years, 700-1700 years and 10,000 years return period respectively.

Table 10. Proposed performance levels

	Performance Levels			
Building Element	**Collapse prevention (CP)**	**Life Safety (LS)**	**Limited operations (LO)**	**Fully operational (FO)**
Storm Level (MRI Range)	10,000 Yr	700-1700 Yr	50-100 Yr	1-10 Yr
General Overall Building Performance	Building survives but unrepairable	Repair likely required before occupancy	Building repairs minor	No water infiltration
		Significant cost and time to repair	Minor disruption to access & egress	All systems important to normal operational remain functional
		Access & egress compromised but generally functional	Immediate re-occupancy expected	Access & egress unaffected
		Relocation of occupants likely required within building	Significant occupant discomfort during storm event	Continuous occupancy & use of building expected
		Severe level of occupant discomfort expected	All MEP & other systems repairable	Minor effect to occupant comfort

Micheli et al. (2017) [58] introduced a novel performance-based design (PBD) methodology for structures equipped with high-performance control systems (HPCS) exposed to multi-level wind excitations. A PBD objective matrix is proposed for structures subjected to wind excitation as presented in Figure 9. Three general performance objectives are defined: basic, essential and critical performance. The basic performance objective corresponds to the design level that the majority of buildings should satisfy to ensure serviceability during daily operations. The essential performance criteria are associated with specialized structures that require tighter acceleration thresholds to maintain operations. The critical performance objective is used for buildings that must remain fully functional during extreme events. Four wind mean recurrence intervals (MRI) are associated in the matrix. The acceleration thresholds associated with each performance objective are relaxed with increasing wind hazard levels.

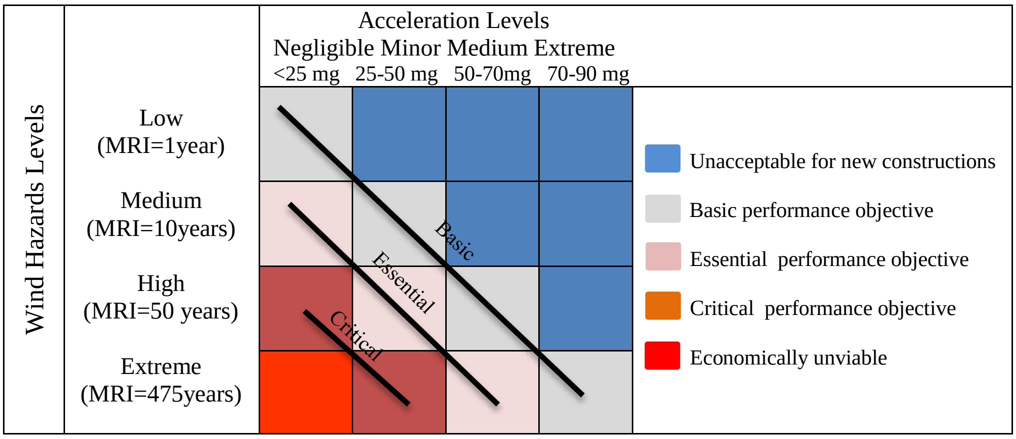

Figure 10. Performance-based matrix for wind excitations

7. Conclusion

Climate change and over land use has worsen the effects of extreme events and is only expected to rise in the future. Designing building structures for extreme events is an important role for the resilience of the community. These extreme loading develop high stresses, produce sway movement or cause vibration. Therefore, it is very important for the structure to have sufficient strength against vertical loads together with adequate stiffness to resist lateral forces. Even for the cases where the wind demands control the design of lateral load-resisting system, the detailed performance-based seismic evaluation should be carried out to ensure the overall structural safety and integrity [59]. This paper provides an overview of the design of different extreme events. A comprehensive review of literature surrounding designing building structures for extreme events is discussed. First, a general overview of the extreme events design and different objectives of approaches is conducted. Guidelines for earthquake resistance were also discussed. Performance-Based Seismic Design objectives were presented with support of different design codes (China, United States and Europe). Wind resistance design with an overview of Performance Based Wind Design was also presented.

This paper seeks to identify a general performance based design concept, Moreover, a consistent realization of this design concept requires the consideration of probabilistic approaches and ultimately leads to a reliability based design. However, it is demonstrated how this performance based design approach can add value to engineering decision making compared to standard design approaches, and that its application can potentially lead to more economical designs. But even with the recent advance of performance-based engineering approaches, improvement of building codes, and development of new mitigation strategies, structures remain vulnerable to threats from extreme hazards at large. So the codes provisions still need improvement by developing new insights to create sufficient confidence in the engineering community and this need the involvement of all stakeholders concerned with the built environment.

8. Conflicts of Interest

The authors declare no conflict of interest.

9. References

[1] Forum, W.E., Global Risks Report 2017, in 978-1-944835-07-1. 2017: Geneva.

[2] Thompson, Kristy D. "Structural Performance for Multi-hazards Program.", (NIST), N.I.o.S.a.T. (2011).

[3] Zaghi, Arash E., Jamie E. Padgett, Michel Bruneau, Michele Barbato, Yue Li, Judith Mitrani-Reiser, and Amanda McBride. "Establishing Common Nomenclature, Characterizing the Problem, and Identifying Future Opportunities in Multihazard Design." Journal of Structural Engineering 142, no. 12 (December 2016): H2516001. doi:10.1061/(asce)st.1943-541x.0001586.

[4] McCullough, Megan, and Ahsan Kareem. "Anatomy of damage to coastal construction: A multi-hazard perspective." In 2009 Structures Congress. Reston, VA: ASCE, 2009: San Juan, Puerto Rico.

[5] Wisetjindawat, Wisinee, Amirhassan Kermanshah, Sybil Derrible, and Motohiro Fujita. "Stochastic Modeling of Road System Performance during Multihazard Events: Flash Floods and Earthquakes." Journal of Infrastructure Systems 23, no. 4 (December 2017): 04017031. doi:10.1061/(asce)is.1943-555x.0000391.

[6] Makkonen, Lasse, and Maria Tikanmäki. "An Improved Method of Extreme Value Analysis." Journal of Hydrology X 2 (January 2019): 100012. doi:10.1016/j.hydroa.2018.100012.

[7] Chen, Elisa. "Multi-hazard design of mid-to high-rise structures." University of Illinois at Urbana-Champaign, (2012).

[8] Ettouney, Mohammed M. "Multihazard Considerations in Civil Infrastructure" (November 30, 2016). doi:10.1201/9781315373959.

[9] Ngoc, T.D., Damage Assessment and Collapse Simulations of Structures under Extreme Loading Conditions, in Civil and Environmental Engineering. 2017, University of California: UC Berkeley. p. 235.

[10] Quiel, Spencer, James Ricles, Liang Cao, Yongqiang Gong, Laura Micheli, and Simon Laflamme. "Performance Evaluation of a Semi-Active Cladding Connection for Multi-Hazard Mitigation." Edited by Alper Erturk. Active and Passive Smart Structures and Integrated Systems XII (March 15, 2018). doi:10.1117/12.2295933.

[11] Chulahwat, Akshat, and Hussam Mahmoud. "A Combinatorial Optimization Approach for Multi-Hazard Design of Building Systems with Suspended Floor Slabs under Wind and Seismic Hazards." Engineering Structures 137 (April 2017): 268–284. doi:10.1016/j.engstruct.2017.01.074.

[12] Said Elias Rahimi, Aly-Masoud Aly, Vasant Matsagar, and Rajesh Rupakhety "Vibration Control of Structures under Multiple Hazards", 2019 EMI International Conference. 2019: INSA Lyon, Villeurbanne, France.

[13] Dubina, D. and R. Zaharia. Common philosophy for design under extreme loadings in COST TU0604 2010. Barcelona.

[14] Knight, Sophie. "What would an entirely flood-proof city look like?" The Guardian. Retrieved from http://www.theguardian.com/cities/2017/sep/25/what-flood-proof-city-china-dhaka-houston (2017).

[15] Ossola, A. Built-In Damage Prevention. How Engineering Earthquake-Proof Buildings Could Save Lives 2017; Available from: https://futurism.com/new-research-shows-how-the-brain-processes-our-experiences.

[16] Goldsworthy, Helen, and Nelson Lam. "Earthquake Resistant Design of Buildings and Education in Australia." In Australian Earthquake Engineering Society Conference, (2007): 23-25.

[17] Hussain, Shaimaa Hameed, and Maraim Safa Hussain. "The Strategies of Architectural Design Resisting Earthquake in Tall Buildings." Al-Nahrain Journal for Engineering Sciences 20, no. 2 (2017): 436-445.

[18] Kokona, E., H. Kokona, and H. Cullufi, Comparative analysis of dynamic solutions using Albanian Seismic Code KTP-89 and Eurocode 8, in 3rd International Balkans Conference on Challenges of Civil Engineering, 3-BCCCE. 2016: Epoka University, Tirana, Albania.

[19] Takagi, Jiro, and Akira Wada. "Recent Earthquakes and the Need for a New Philosophy for Earthquake-Resistant Design." Soil Dynamics and Earthquake Engineering 119 (April 2019): 499–507. doi:10.1016/j.soildyn.2017.11.024.

[20] Fasan, M., A. Magrin, C. Amadio, G. F. Panza, F. Romanelli, F. Vaccari, and S. Noè. "A possible revision of the current seismic design process to overcome the limitations of standard probabilistic seismic input definition." In 16th World Conference on Earthquake, 16WCEE 2017. 2017.

[21] Laghi, Vittoria, Michele Palermo, Tomaso Trombetti, and Martijn Schildkamp. "Seismic-Proof Buildings in Developing Countries." Frontiers in Built Environment 3 (August 25, 2017). doi:10.3389/fbuil.2017.00049.

[22] Ian Dixon, C. Building data centers that can handle seismic activity. 2017; Available from: www.datacenterdynamics.com.

[23] Eljajeh, Yasser, and Mihail Petkovski. "Self-Adaptive Approach for Optimisation of Passive Control Systems for Seismic Resistant Buildings." Bulletin of Earthquake Engineering 16, no. 7 (January 13, 2018): 3171–3194. doi:10.1007/s10518-018-0309-9.

[24] Ishikawa, Koichiro. "Earthquake Response Control of Double-Layer Truss Walls by Means of Innovative Fuse Connections." Advances in Civil Engineering 2018 (August 15, 2018): 1–9. doi:10.1155/2018/1425672.

[25] Chouw, Nawawi. "Low-Damage Design Philosophy for Future Earthquake-Resistant Structures." Volume 8: Seismic Engineering (July 16, 2017). doi:10.1115/pvp2017-65273.

[26] Patil, R, A Naringe, and J S Kalyana Rama. "Novel Techniques for Seismic Performance of High Rise Structures in 21st Century: State-Of-The Art Review." IOP Conference Series: Materials Science and Engineering 330 (March 2018): 012126. doi:10.1088/1757-899x/330/1/012126.

[27] Najam, Fawad Ahmed. "Nonlinear Static Analysis Procedures for Seismic Performance Evaluation of Existing Buildings – Evolution and Issues." Sustainable Civil Infrastructures (July 12, 2017): 180–198. doi:10.1007/978-3-319-61914-9_15.

[28] Lago, A., A. Wood, and D. Trabucco. Damping Technologies for Tall Buildings: New Trends in Comfort and Safety. 2015; Available from: https://www.elsevier.com/physical-sciences-and-engineering/engineering/journals/damping-technologies-for-tall-buildings-new-trends-in-comfort-and-safety.

[29] Khan, Abdul Arafat, Hafsa Farooq, and Syed Suhaib. "Structure Analysed for Maximum Considered and Design Basis Earthquake in Northern India." International Journal of Civil Engineering 4, no. 5 (May 25, 2017): 119–125. doi:10.14445/23488352/ijce-v4i5p121.

[30] Thilakarathna, Shilpa Nirman, Naweed Anwar, Pramin Norachan, and Fawad Ahmed Naja. "The Effect of Wind Loads on the Seismic Performance of Tall Buildings." Athens Journal of Technology & Engineering 5, no. 3 (August 31, 2018): 251–276. doi:10.30958/ajte.5-3-3.

[31] Allahvirdizadeh, R., M. Khanmohammadi, and M. Marefat, Local and Global Design Criteria in Performance-Based Seismic Design of New R.C Buildings, in the 4th International Conference on Seismic Retrofitting. 2012: Tabriz, Iran.

[32] Anwar, Naveed, Thaung Htut Aung, and Fawad Najam. "From Prescription to Resilience: Innovations in Seismic Design Philosophy." Technology (2016): 8.

[33] Tall Buildings Initiative. "Guidelines for performance-based seismic design of tall buildings." Pacific Earthquake Engineering Research Center (PEER) (2010).

[34] Hosseini, Mahmood, Banafshehalsadat Hashemi, and Zahra Safi. "Seismic Design Evaluation of Reinforced Concrete Buildings for Near-Source Earthquakes by Using Nonlinear Time History Analyses." Procedia Engineering 199 (2017): 176–181. doi:10.1016/j.proeng.2017.09.225.

[35] Xiong, Ergang, Qian Zhang, Xingwen Liang, and Xiaoyu Miao. "Performance-Based Plastic Design Method of High-Rise Steel Frames." Journal of Vibroengineering 19, no. 3 (May 15, 2017): 2003–2018. doi:10.21595/jve.2016.17687.

[36] Yu, Xiao-Hui, Da-Gang Lu, and Bing Li. "Relating Seismic Design Level and Seismic Performance: Fragility-Based Investigation of RC Moment-Resisting Frame Buildings in China." Journal of Performance of Constructed Facilities 31, no. 5 (October 2017): 04017075. doi:10.1061/(asce)cf.1943-5509.0001069.

[37] National Standard of the People's Republic of China. "Technical specification for concrete structures of tall building (JGJ 3-2010)." (2010).

[38] Zhou, Y., et al., Performance-based Seismic Design of a Controlled Rocking Frame, in International Workshop On Performance-Based Seismic Design Of Structures (Resilience, Robustness), D.E. Beskos, et al., Editors. 2017: Shanghai,China. p. 41-51.

[39] Jiang, Huanjun, Xilin Lu, and Jiejiang Zhu. "Performance-Based Seismic Analysis and Design of Code-Exceeding Tall Buildings in Mainland China." Structural Engineering and Mechanics 43, no. 4 (August 25, 2012): 545–560. doi:10.12989/sem.2012.43.4.545.

[40] American Society of Civil Engineers (ASCE). "Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 7-10)." (2013).

[41] American Society for Civil Engineers (ASCE). "Minimum Design Loads and Associated Criteria for Buildings and Other Structures (ASCE/SEI 7-16)." (2016).

[42] Council, Building Seismic Safety. "NEHRP recommended seismic provisions for new buildings and other structures." Rep. FEMA P 750 (2009).

[43] European Committee for Standardization (CEN). "Design of structures for earthquake resistance. Part 1: General rules, seismic actions and rules for buildings." Eurocode 8 (2004).

[44] Beyer, Katrin. "Future directions for reinforced concrete wall buildings in Eurocode 8." In Proceedings of the SECED 2015 Conference, no. CONF. (2015): 1-6.

[45] Gopu, Vijaya VJ. "Performance of Light-frame Structures Subject to Extreme Wind Loads." In The Eighth Asia-Pacific Conference on Wind Engineering. 2013. Research Publishing Services: Chennai, India.

[46] Tapajós, L.S., J. A .T. Ferreira, A. F. Lima Neto, M. R. Teixeira, and M. P. Ferreira. "Effect of Wind in the Design of Reinforced Concrete Buildings." Revista IBRACON de Estruturas e Materiais 9, no. 6 (December 2016): 883–910. doi:10.1590/s1983-41952016000600005.

[47] Hollister, Nathaniel, and Antony Wood. "Tallest 20 in 2020: Era of the Megatall: The Projected World's Tallest 20 Skyscrapers in the Year 2020." CTBUH Journal (2012): 44-47.

[48] Sabbek, T., S. Langlois, and F. Légeron, Influence of damping and force hypotheses for evaluating ductility demand of structures subjected to time history wind loading, in The 13th Americas Conference on Wind Engineering (13ACWE). 2017: Gainesville, Florida USA.

[49] Mendis, Priyan, Tuan Ngo, N. Haritos, Anil Hira, Bijan Samali, and John Cheung. "Wind loading on tall buildings." Electronic Journal of Structural Engineering (2007): 41-54.

[50] Vikram.M.B, C.G. P, and K.G. B.S, A Study on Effect of Wind on the Static and Dynamic Analysis. International Journal of Emerging Trends in Engineering and Development, 2014. 3(4): p. 885-890.

[51] Zhaoa, X., J.M. Ding, and H.H. Suna. "Structural Design of Shanghai Tower for Wind Loads." Procedia Engineering 14 (2011): 1759–1767. doi:10.1016/j.proeng.2011.07.221.

[52] Chuang, Wei-Chu, and Seymour M.J. Spence. "A Performance-Based Design Framework for the Integrated Collapse and Non-Collapse Assessment of Wind Excited Buildings." Engineering Structures 150 (November 2017): 746–758. doi:10.1016/j.engstruct.2017.07.030.

[53] Chan, C. M., M. F. Huang, and K. C. S. Kwok. "Stiffness Optimization for Wind-Induced Dynamic Serviceability Design of Tall Buildings." Journal of Structural Engineering 135, no. 8 (August 2009): 985–997. doi:10.1061/(asce)st.1943-541x.0000036.

[54] Gunawardena, T., et al., Wind Analysis and Design of Tall Buildings, The State of The Art, in 8th International Conference on Structural Engineering and Construction Management. 2017: Kandy, Sri Lanka.

[55] Cui, Wei, and Luca Caracoglia. "A Unified Framework for Performance-Based Wind Engineering of Tall Buildings in Hurricane-Prone Regions Based on Lifetime Intervention-Cost Estimation." Structural Safety 73 (July 2018): 75–86. doi:10.1016/j.strusafe.2018.02.003.

[56] Moustafa, M.A., P. Irwin, "Vision for Hybrid Simulation Testing of Buildings under Wind Loading", 7th International Conference on Advances in Experimental Structural Engineering (7AESE), September 6-8, 2017, Pavia, Italy.

[57] Mohammadi, A., Wind Performance Based Design for High-Rise Buildings, in Civil Engineering, Florida International University: FIU Electronic Theses and Dissertations (2016): 262.

[58] Micheli, Laura, Liang Cao, Yongqiang Gong, Alessandro Cancelli, Simon Laflamme, and Alice Alipour. "Probabilistic Performance-Based Design for High Performance Control Systems." Edited by Gyuhae Park. Active and Passive Smart Structures and Integrated Systems 2017 (April 11, 2017). doi:10.1117/12.2261449.

[59] Thilakarathna, S.N., et al., The Effect of Wind Loads on the Seismic Performance of Tall Buildings, in 2nd Annual International Conference on Structural Engineering and Mechanics. 2018: Athens, Greece.