# A comparison study of Catastrophe Modeling vs. Performance-Based Design

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ABSTRACT: The paper presents the methodologies at the core of catastrophe modeling (CM) and performance-based design (PBD). Both CM and PBD are probabilisitic methods, in which the probability of achieving a certain hazard intensity is calculated and coupled with an estimate of the vulnerability or fragility of a certain building exposure to get an estimate of the exposure behavior, as well as of the expected damage and losses. Probabilistic CM is a well established field applied to all sorts of hazards, including the treatment of multi-hazards, whereas application of PBD to hazards other than seismic is a more recent development in structural engineering. CM is more oriented towards computing financial losses for the insurance industry and solving emergency management or community recovery issues, while PBD is oriented at guiding a particular building owner/designer in making the right design or retrofitting decisions. This paper explores similarities and differences between CM and PBD, especially regarding how the vulnerabilities or fragilities are derived in each case, how the uncertainties are treated, and how the two methodologies could benefit from each other.

## 1. INTRODUCTION

Risk is at the intersection of hazard, exposure, and vulnerability. Without hazard, there cannot be any damage, and hence any risk. Likewise, if there is no exposure, there will be no risk. For example, a wind storm in the middle of an inhabited region does not represent any risk. Finally, the hazard acting on the exposure represent a risk only if the exposure is vulnerable. For example, the pyramids of Egypt are probably invulnerable to wind storms, and therefore are not at risk. This paper concerns itself with treatment of risk in the two cases when the exposure is a large population of buildings, typically an insurance portfolio, or when on the contrary, the exposure is a single building. The first case corresponds to catastrophe modeling (CM). The second case corresponds to performance based design (PBD). This difference has significant implications on the definition of the vulnerabilities. In fact, in the case of CM, the vulnerabilities represent generic classes of buildings, with a corresponding large uncertainty, whereas in the case of PBD the vulnerabilities are representative of a specific structure. This paper explores the similarities and differences between the two methodologies.

## 2. CATASTROPHE MODELING

Catastrophe modeling (CM) is a computational methodology used to predict catastrophic events (such as hurricanes, earthquakes, and wildfires) in a probabilistic sense, and to estimate the losses that could be produced by these catastrophic events under unmitigated or mitigated conditions.

### *2.1. Purpose and basic characteristics of CM*

A natural disaster occurs when the damage due to a natural hazard, and its consequences, affect an entire community or society. The result of a natural disaster is a substantial economic loss for a community and possibly loss of life. For this to occur, the damage must affect a sufficiently large portion of the building exposure and infrastructure. Therefore, the modeling of natural disaster risk does not concern itself with detailed modeling of a single structure, but instead it deals with very large number of structures, sometimes in the order of millions. Typically, these structures are spread over a large geographical area affected by the natural disaster (e.g., the footprint of a hurricane at landfall, or the area with a certain shaking intensity in an earthquake).

The prediction of losses due to natural disasters is of compelling interest to the government, the insurance industry, and homeowners. The Federal and State governments are responsible for enacting policy for reducing the vulnerability of infrastructure (e.g., DMA, 2000), as well as, in some states, for regulating insurance rates (Klein, 2009). The insurance industry must assess its exposure to natural hazard risk losses to evaluate risk diversification, reinsurance, and mitigation incentives (Cardona, 2004). The public is concerned with the integrity of homes and the cost of insurance.

CM provides the necessary tools to predict these losses. Regardless of the type of hazard, all implementations of CM are composed of three main components: (1) a hazard model, (2) a vulnerability model, and (3) an actuarial model. A computing platform integrates all three. The input to the model is a certain exposure set, and the output is an estimate of the monetary losses for the exposure. The discussion that follows concentrates on the case of a hurricane wind risk model (see Figure 1), but the principles are the same for other types of CM.

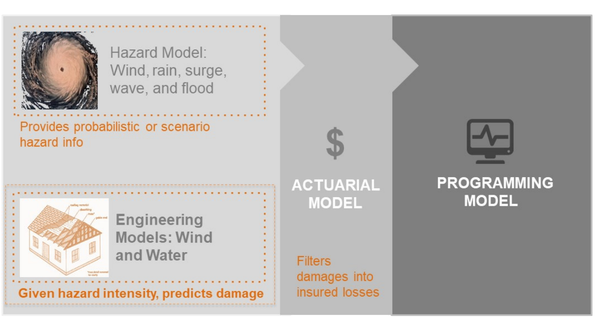



*Figure 1. Schematic of CM for the case of hurricane risk assessment.*

### 2.2. Applications of CM

CM is used for natural disaster risk analysis, including loss prediction, emergency management, mitigation studies, preparation, recovery and resilience evaluation. Catastrophe models provide the necessary tools to make informed or credible predictions of the risk, to estimate the effectiveness of mitigation measures and to gauge preparedness, recovery and resilience of communities to natural disasters. As such, risk models require the participation of scientists, engineers, disaster managers, policy makers, insurers and regulators, as well as social scientists.

One of the main driver in the development of CM, which quantifies natural disaster risk, is the need of insurance and re-insurance companies to estimate their possible or expected losses. Another important application of CM is the study of the cost effectiveness of different mitigation measures under different catastrophe scenarios. Finally, CM is one of the main tools available to emergency managers, city engineers, and policy planners (among many other stakeholders) for preparation, response, rebuilding, and resilience assessment of communities, from the single town to the state and the nation levels.

In order to satisfy the requirement of the different possible applications, different types of CM can be used, e.g., a fully-probabilistic CM could be used to derive a probabilistic loss distribution for all possible catastrophic events in a given region (which is typically the approach of insurance and re-insurance companies), or a scenario-based CM could be used to predict/calculate the losses produced by a specific catastrophic event (which is the approach commonly used for emergency management, often through real-time or quasi real-time risk analyses of an impending or unfolding disaster).

## 3. PERFORMANCE BASED DESIGN

Performance-Based Design (PBD) is a general methodology for the design of new structures, as well as for the maintenance and/or retrofit of existing structures. This methodology explicitly defines the performance objectives for structural systems during their design life, provides criteria and methods for verifying the achievement of these performance objectives in a probabilistic sense, and offers appropriate approaches to improve the design and retrofit of structural systems. The performance objectives often correspond to higher requirements than those conventionally adopted by ordinary prescriptive design codes, and are generally defined through the interaction between the structural engineer and the other major stakeholders (e.g., owner for a private building, transportation state agency for a bridge).

*3.1. Purpose and basic characteristics of PBD*

PBD compares different design, retrofit, and/or maintenance solutions through the probabilistic evaluation of a set of decision variables (DV), where each DV represents different performance objectives and safety goals (from different serviceability levels to strength limit states). PBD was developed first for nuclear engineering and later was extended to performance-based earthquake engineering (PBEE) (Porter, 2003; FEMA, 2012), and in the last decade or so there has been an increased interest in this design philosophy in blast engineering (Hamburger and Whittaker, 2003), fire engineering (Lamont and Rini, 2008), tsunami engineering (Riggs et al. 2008), and wind engineering (Petrini, 2009; Van de Lindt et al., 2009; Griffis et al., 2012; Muthukumar et al., 2012; Judd et al., 2014). Recently, Barbato et al. (2013) extended the concept to the development of a performance-based hurricane engineering (PBHE) framework, and applied it to comparison studies of mitigation techniques for typical low-rise residential buildings (Unnikrishnan and Barbato, 2016).

PBD is based on a decomposition of the risk analysis problem into simpler component problems through the use of the total probability theorem. For example, in PBWE and PBHE (which represents the first PBD formulation for multiple interacting hazards) the structural risk is defined in terms of a given $DV$ as follows (Barbato et al., 2013):

$$
\begin{aligned}
G(DV) = \int\int\int\int\int & G(DV \mid DM)\cdot \\
& f(DM \mid EDP)\cdot \\
& f(EDP \mid IM, IP, SP)\cdot \\
& f(IP \mid IM, SP)\cdot f(IM)\cdot f(SP)\cdot \\
& \mathrm{d}DM\cdot \mathrm{d}EDP\cdot \mathrm{d}IP\cdot \mathrm{d}IM\cdot \mathrm{d}SP
\end{aligned}
\quad (1)
$$

where: $G(\cdot)$ = complementary cumulative distribution function (CDF), and $G(\cdot|\cdot)$ = conditional complementary CDF; $f(\cdot)$ = probability density function (PDF), and $f(\cdot|\cdot)$ = conditional PDF; $DM$ = damage measure (i.e., a parameter describing the physical damage to the structure, the distribution of which is obtained through damage analysis); $EDP$ = engineering demand parameter (i.e., a parameter describing the structural response for the performance evaluation, the distribution of which is obtained through structural analysis); $IM$ = vector of intensity measures (i.e., the parameters characterizing the environmental hazard, the distribution of which is obtained through hazard analysis); $SP$ = vector of structural parameters (i.e., the parameters describing the relevant properties of the structural system and non-environmental actions, the distribution of which is obtained through structural characterization); and $IP$ = vector of interaction parameters (i.e., the parameters describing the interaction phenomena between the environment and the structure, the distribution of which is obtained through interaction analysis). In other single-hazard PBD frameworks (e.g., performance-based earthquake, blast, fire, and tsunami engineering) the integration with respect to variables $SP$ and $IP$ is neglected (i.e., no structural characterization and interaction analysis are performed), but the general formulation is the same.

*3.2. Applications of PBD*

PBD is used for design, retrofit, and/or maintenance of specific structural/infrastructural systems. Since it requires a realistic and detailed understanding of the structural behavior in order to propagate accurately uncertainties from one analysis phase to the next, the use of PBD generally requires advanced finite element analysis (FEA), specifically calibrated fragility functions that are often obtained through expensive experimental testing, and specialized cost functions for each and all relevant components of the structural system under study. Therefore, application of PBD is relatively more expensive when compared to ordinary prescriptive design and is commonly limited to important and/or expensive structures (e.g., bridges, tall buildings, large industrial facilities, critical facilities), for which this additional cost can be justified by higher safety level or lower costs due to the avoidance of over-conservative designs.

## 4. SIMILARITIES BETWEEN CM AND PBD

Both CM and PBD are probability-based methodologies focusing on the performance of the built environment under extreme natural and/or man-made events. The striking similarity between the two approaches is due to their use of the total probability theorem to disaggregate a complex problem into elementary components, as it can be observed by comparing Figure 1 and Eq. (1). It is observed that: (1) the hazard model of CM corresponds to the result of the hazard analysis phase of PBD; (2) the vulnerability model of CM corresponds to the combination of the results of the structural analysis and damage analysis phases of PBD (with the addition of the structural characterization and interaction analysis phases for PBWE and PBHE), which is commonly known as fragility analysis; and (3) the actuarial model for CM corresponds to the results of the loss analysis phase of PBD. The following subsections provide additional details on the comparison of these different components of CM and PBD.

### *4.1. Hazard model/hazard analysis*

The hazard model is the probabilistic description of the hazard intensity within a region of interest. For example, in the case of hurricane CM/PBHE, the hazard model is a meteorology model (e.g., the probabilities associated to 3-second peak gust wind speeds corrected for the terrain roughness), and in the case of seismic CM/PBEE, the hazard model is a seismic activity model (e.g., maps of peak ground acceleration or spectral accelerations at different periods for a given return period). The hazard model provides the input for the vulnerability model in both CM and PBD.

The hazard models can be of different levels of complexity and accuracy. For example, in the case of the Florida Public Hurricane Loss Model (FPHLM) (Hamid et al., 2011), the meteorology component uses over 50,000 year simulations to generate a stochastic set of over 30,600 storms. Appropriate models determine translational velocity, central pressure, radius of maximum winds, etc. The storm track model generates tracks and intensities based on perturbations of historical storm conditions and motions. The initial seeds for the storms are derived from a database covering the period 1900-2017. Each simulated storm has an estimated track and intensity and a set of modeled wind fields at successive time intervals. The wind field model generates the 3-second peak gusts winds corrected for terrain roughness by using the gust wind model and the terrain roughness model for the storm at various locations on a 5 km grid, along its track. The wind swaths for each storm are computed on a roughly 1 km resolution grid and the 10 meter wind is interpolated from the saved swath grids for each storm to the policy location, for which a correction for terrain and gust factor are computed. The winds at various heights are computed using a modified log wind profile. Alternatively, for each location, an accounting could be made of all the simulated storms that pass through it. Based on the number of pass through storms and their peak wind speeds, a distribution of the wind speed could then be generated for the location. Based on this distribution, probabilities could be generated for each 5 mph interval of wind speeds, starting at 20 mph. A thorough discussion of a meteorology model can be found in Powell et al. (1995), whereas a discussion on how hurricane hazard models of different complexity can be used in

PBHE is provided in Unnikrishnan and Barbato (2017).

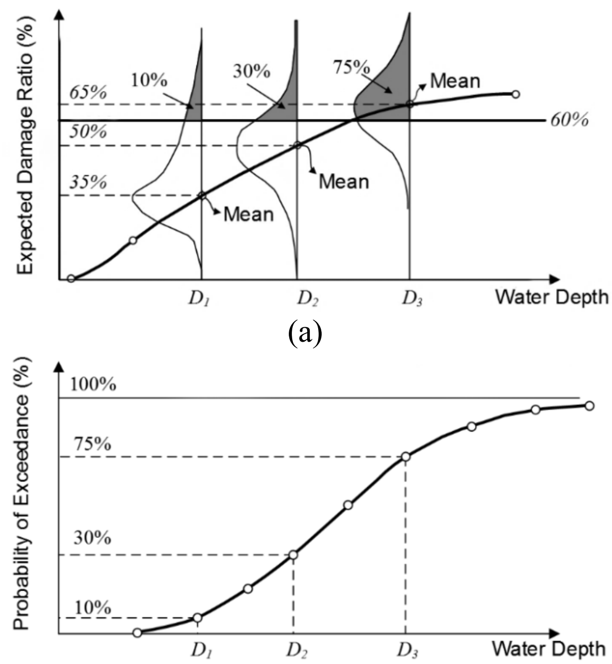
### *4.2. Vulnerability model/fragility analysis*

Vulnerability is the susceptibility to physical damage induced by a natural hazard (Pita et al. 2013; 2015). The vulnerability depends on both the structure, or structural component under investigation, and the types of natural hazard and their effects on structures. Since, typically, a natural hazard varies in intensity, the vulnerability will be a function of the intensity of the natural hazard: the less intense a hazard, the lesser the vulnerability. In other words, the vulnerability of an element is a measure of the damage caused by a certain intensity of the natural hazard.

The concept of vulnerability is applicable to any kind of natural hazard, and the vulnerability is a function of the intensity of the hazard. The most common hazards include wind storms (e.g., hurricanes, tornadoes), rain events, coastal flood or storm surge, inland flood, earthquakes, tsunamis, and fire. In each case, more than one parameter can define the intensity of the hazard, which affects the vulnerability. Some of these parameters for the case of wind related hazards are wind speed and direction, debris impact, rain, and tree damage. It is common for more than one hazard to affect a structure at a time. For example, windstorms come with rain, and in some cases with storm surge or inland flooding. Earthquakes can trigger tsunamis and fires. In each case, multiple parameters define the intensity of the different hazards, which affect the vulnerability. The result is a multi-dimensional vulnerability, which generally requires some simplifications in order to be modeled and used.

Typically, after a natural hazard impacted a structure, the structure will present a level of physical damage, defined qualitatively as some gradation of no visible, minor, moderate, and severe damage up to complete collapse. To reduce the subjectivity of the damage evaluation, physical damage to the different components of a building can be characterized quantitatively by assigning ascending threshold levels of damage, or so-called damage (limit) states. Individual component damage states can then be combined to assign an overall structure damage state.

The results of a vulnerability model are usually expressed in two different forms: (1) vulnerability curves, which provide the expected damage intensity (e.g., damage ratio) as a function of the hazard intensity; and (2) fragility curves, which yield probabilities of exceedance of a given damage state as a function of the hazard intensity. Figure 2 illustrates the relationship between vulnerability and fragility curves for the case of flood hazard under the simplifying hypothesis that the hazard can be fully described by a single *IM*.




(a)

(b)

*Figure 2: Example of vulnerability model for flood hazard: (a) vulnerability curve and (b) fragility curve.*

Figure 2(a) plots the vulnerability curve (i.e., *DM* = expected damage ratio vs. hazard *IM* = water depth) of a building together with the PDFs of the damage ratio at different hazard intensities. The mean value of each PDF makes up the vulnerability curve, as shown. The shaded sections of the PDFs represent the probability of meeting or exceeding the damage state of interest, which in this example corresponds to 60% damage. Figure 2(b) plots the fragility curve corresponding to the 60% damage state, which is obtained by reporting the probability of meeting or exceeding the damage state of interest (i.e., the shaded areas) for each *IM* value. The process can be repeated for any other damage state of interest by simply moving up or down the threshold value in Figure 2(a) and building the corresponding fragility curve, similar to that shown in Figure 2(b).

### *4.3. Actuarial model/loss analysis*

The actuarial model provides a probabilistic description of the losses associated with a given hazard. These losses are most commonly expressed in monetary terms, but they could also measure other parameters, e.g., life losses, downtime related losses, or a combination thereof. The actuarial model can also be used to evaluate the expected benefits from different hazard mitigation, retrofit, and maintenance measures, in order to allow a rigorous comparison of different solutions in terms of their expected performance.

Expected losses are usually modified to account for insurance deductibles and limits, total replacement costs, and additional collapse consequences, as well as to discount losses or benefit that are expected in the future (e.g., during the entire design life of a structure) when compared to cost incurred in the present. All of these components contribute to the uncertainty of the losses, so that often a policy implementation or a design decision cannot be based only on the expected value of the losses, but it would require knowledge of the entire loss PDF.

### *4.4. Differences between CM and PBD*

The most important and evident difference between CM and PBD is that the former focuses on a large portfolio of structures (on the orders of thousands or even hundreds of thousands), whereas the latter considers a single structure. This major difference produces several other differences in terms of inputs, methodologies, and outputs, which Table 1 summarizes.

*Table 1: Differences between CM and PBD*

| **Feature** | **CM** | **PBD** |
| --- | --- | --- |
| Focus | Portfolio of structures | Single structure |
| Applications | Policy making, insurance, emergency management | Design, retrofit, maintenance |
| Hazard | Regional level | Single location |
| Vulnerability | Generic (for families of buildings) | Detailed (for specific buildings) |
| Fragility | Based on statistics and post-disaster reconnaissance surveys, or simplified engineering models | Based on FE analyses and experimental tests |
| Loss variability | Controlled by type/# of buildings | Controlled by cost/discount rate variability |

As a results of the different goals of the two methodologies, their output are necessarily different. In general, the uncertainties associated with CM are higher than those associated with PBD. However, this is not a limitation but a feature of CM, which is not concerned with an accurate description of specific structures. In addition, PBD is not necessarily associated with lower levels of uncertainties than CM, as a naïve analysis would suggest. This phenomenon can be explained by considering that CM seeks an overall risk and, thus, benefits from an "averaging effect" based on the law of large numbers; whereas the uncertainties in PBD can become very large when "hit-or-miss" conditions are present (i.e., when a hazard is very intense but also localized, so that a structure is almost intact in most of the cases and almost completely destroyed when directly hit). For example, Unnikrishnan and Barbato (2016) showed that the performance-based assessment of a single-family house located in Pinella County, FL, and subject to wind hurricane hazard can produce standard deviations of annual losses that are more than 20 times larger than the expected annual losses for the same building.

## 5. SYNERGIES BETWEEN CM AND PBD

Owing to the fact that both CM and PBD are based on the same probabilistic principles and use the same probabilistic tools, it is apparent that important synergies could be exploited to advance simultaneously CM and PBD toward the goal of a safer and more resilient built environment. A detailed investigation of how both methodologies could benefit from each other is outside the scope of this paper; however, some suggestions are briefly discussed below.

Current state of the art CM, especially for seismic and wind risk, already uses engineering models to derive physics-based fragility curves for different classes of structures with the help of Monte Carlo simulation methods (Pita et al, 2013; 2015). However, the engineering models used in CM could benefit from the potentially more sophisticated models used in PBD. This application is particularly important for new construction technologies and innovative structure typologies, for which the statistical data is not yet available or is insufficient to build reliable fragility curves. The use of numerically-derived and/or experimentally-based fragility curves in conjunction with information on the distribution of different structural typologies reduces some of the uncertainty and avoid potential bias associated with CM estimates of regional risk and expected losses.

At the same time, results from CM could inform and validate structural and component models used in PBD. This application would be particularly useful in the development of new types of PBD procedures (e.g., new types of hazards and or multihazard approaches), as well as in the calibration of loss analysis models. It is noted here that information at the single building level is often insufficient to derive a fully-probabilistic loss model and that in many cases engineers employ several simplifying heuristic assumptions that are not necessarily based on statistical data.

Finally, a field in which the joint use of CM and PBD could be beneficial is mitigation cost-benefits analyses, emergency management and post-disaster recovery planning. In fact, for this type of applications, the statistically-based approach of CM for large portfolios of buildings could be complemented by a structure-specific assessment developed using PBD for critical structures (e.g., bridges, first responder buildings, hospitals) in order to develop real-time strategies for disaster mitigation and recovery.

## 6. CONCLUSIONS

This paper presents a brief comparison of catastrophe modeling (CM) and performance-based design (PBD) in terms of similarities and major differences. These two subfields of Risk Engineering have been traditionally considered as two fundamentally different entities. This interpretation has been supported by the very different types of applications for these two approaches: (1) policy making, insurance loss prediction, emergency management, mitigation studies, preparation, recovery and resilience evaluation based on large portfolios of structures for CM; and (2) design, retrofit, maintenance of single (usually important) structures for PBD. However, notwithstanding the evident differences between CM and PBD, their similarities are even more striking. In particular, the two methodologies share the same probabilistic basis, employ the same disaggregation of the problem through the use of the total probability theorem, and make use of conceptually identical hazard, vulnerability, and fragility curves.

This study also identifies a few potential opportunities for synergy between CM and PBD studies. While a comprehensive investigation of possible interactions between CM and PBD researchers and practitioners is beyond the scope of this paper, it is hoped that this work will stimulate future discussions to advance promising collaborations within and across these two important subfields of Risk Engineering.

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