Implementing Performance Based Design in the Structural Engineering Industry

By

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ABSTRACT

In the structural engineering industry, the design of structures typically follows a prescriptive approach in which engineers conform to a series of code requirements that stipulate the design process. Prescriptive design is tested, reliable, and understood by practically every structural engineer in the industry; however, in recent history a new method of design has started to gain traction among certain groups of engineers. Performance-based design is a reversal of the prescriptive approach in that it allows engineers to set performance goals and work to prove that their proposed designs meet the criteria they have established. To many, it is an opportunity for growth in the structural design industry. Currently, performance-based design is most commonly utilized in regions where seismic activity plays an important role in the design process. Due to its flexible nature, performance-based design has proven extremely useful when applied to unique structures such as high-rises, stadiums, and other community-centric designs. With a focus placed on performance objectives and not on current code prescriptions, engineers utilizing performance-based design are more adept to implement new materials, design processes, and construction methods, and can more efficiently design their structures to exist on a specific area of land. Despite these many cited benefits, performance-based design is still considered an uncommon practice in the broad view of structural design. In order to ensure that structural engineers have the proper tools to practice performance-based design in instances where they see fit, a coordinated effort will be required of the engineers themselves, the firms of which they are employed, the professional societies to which they belong, and the educators who are preparing their

next generation. Performance-based design holds with it the opportunity to elevate the role of the structural engineer to which they are informed members of the community, where the structures they create not only perform according to design prescriptions, but also perform according to the needs of the owners, engineers, and society.

DEDICATION

Lezlie, Bob, Melissa, Danielle:

Thank you for your continual motivation and undying inspiration.

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PREFACE

In mid-2018 the Structural Engineering Institute's Task Committee on Performance-Based Design published a report advocating the benefits of utilizing performance objectives in the design of structures. According to the committee, these methods improve clarity, quality, and the overall innovation of the structural engineering industry. Despite this multitude of cited benefits outlined in this document, the committee also recognized that the concept of performance-based design "is unfamiliar to many engineers and other professionals and stakeholders in the construction industry." After speaking with a variety of structural engineers on their understanding of performance-based design both while working on my previous thesis project as well as in the workplace, it has become clear that many individuals do understand the benefits of updating their design methods in the appropriate scenarios, but they simply do not have a good idea of what steps to take to achieve an environment in which performance-based design is achievable. This inspired the following idea; whereas most documents on this subject detail the methods of performance design and their advantages, perhaps it would be helpful for modern engineers if there existed a document that provided practical steps towards achieving a performance-based environment in the workplace. The intention of this thesis is that it may serve as a roadmap to engineers looking to adopt innovative design methods in lieu of strictly adhering to prescriptive codes in scenarios that would benefit from some refreshing creativity and innovation.

CHAPTER 1

CHAPTER 1: INTRODUCTION

Performance-based design is a rational approach to the design of structures in which engineers identify key performance objectives focusing on the serviceability and strength of a structure and then design that structure to comply with the outlined objectives. This process is a complete reversal of typical prescriptive design, in which the engineer must conform to a series of code requirements that regulate design elements of the structure. By establishing explicit design goals early on, engineers have more flexibility and opportunity to add value and incorporate innovative solutions into their designs. While the structural engineering industry does have knowledge of the many benefits associated with performance-based design, its usage is significantly marginalized compared to that of the universally accepted prescriptive design. This thesis will delve into what performance-based design looks like in the modern workplace, why many engineering societies are working towards increasing its usage, and how structural engineers should pursue the implementation of performance-based design in their work.

Prescriptive Design

According to FEMA, the first building codes in the United States were developed and adopted as early as the late 1800s and early 1900s to protect public safety and welfare. Some of the first code restrictions sought to reduce the risk of urban conflagrations through limiting the usage of exposed wood frames, and the requiring of parapets to minimize fire spreading. These codes were largely restrictive, as their primary goal was to constrict engineers to keeping their designs within a safe threshold. Due to the success of these early building codes, the reach of their many design prescriptions continued to spread throughout the twentieth century. Now, modern prescriptive building codes exist to produce structures that are capable of achieving acceptable performance, without explicitly outlining these performance expectations. As identified by the Task Committee on Performance-Based Design in their report to the Structural Engineering Institute, typical design procedures evaluate design acceptability through conformance to prescriptive criteria on materials, configurations, detailing, strength, and stiffness. Through this method of conformity, the engineer does not explicitly verify that the structure will achieve desired performance, but instead verifies that the design parameters adhere to what is mandated by the code. Many believe that this process is constricting the evolution of the role of the structural engineer by placing an emphasis on knowledge of the code and navigation of prescriptive provisions rather than on one's ability to identify acceptable performance parameters and produce creative and innovate solutions to engineering problems.

Statement of the Problem

While technology and the practice of structural engineering has advanced significantly through recent years, the method in which building codes are implemented has not. Performance-based design is an opportunity for growth in the structural design industry, as it has been introduced to accommodate the design of new and innovative structures that flourish more from a complete reversal of the prescriptive design process.

These methods emphasize the “output” rather than the “input,” and allow engineers to work towards an intended final result. Further expediated by rapid technological growth, performance-based methods are now more practical and achievable than ever. While it has been adopted in some specific areas, most engineering societies agree that performance-based design is underutilized by modern engineers. Despite countless articles and guidelines promoting the usage of performance-based design, its implementation into the workplace seems to be proving difficult for the majority of structural engineers. This difficulty could stem from a variety of reasons; a general lack of experience among engineers, the unproven track record of performance-based design, a daunting transition from the prescriptive approach, or even an apparent lack of benefit to the overall design process. While performance-based design might not be ideal for every design instance, it is important that structural engineers address these issues to ensure that both performance and prescriptive design approaches are equally attainable for every project. Once the roadblocks to performance-based design are universally leveled, engineering will become more efficient, cost-effective, and innovative at a global scale.

CHAPTER 2

CHAPTER 2: A BACKGROUND ON PERFORMANCE-BASED DESIGN

Performance-based standards are commonly praised for their many benefits to project cost, building performance, and the cultivation of innovative design and construction practices. This section will outline the framework of performance-based design, including a typical design process, potential applications of these processes, and where it is most prominently used in the modern day.

Typical Design Process

The first step in the performance-based design process is to establish performance objectives. In a typical prescriptive process these objectives are never explicitly outlined, and the designer will instead adhere to applicable code prescriptions. Conversely, in a performance-based environment the engineer will begin the process by identifying qualitative performance objectives. These objectives are simple statements of performance that assist both the engineer and any potential clients in understanding the goals of the design before it actually begins. It is here that emphases may be placed on safety, cost, or even use of innovative techniques. The Task Committee on Performance-Based Design, appointed by the Structural Engineering Institute to conduct research on performance-based design, has identified some examples of qualitative performance objectives, which are "the structure should have a low probability of being unusable following a design level event" and "occupants should have a high probability of being safe and able to exit the building given design level earthquake." Once statements such as these have been identified, the engineer must quantify the performance objectives into statements of exact probability so they can be explicitly designed. In a seismic design approach, this would be the stage where hazard levels are identified from acceleration time histories, and probabilities of risk events are evaluated. These are referred to as quantitative performance objectives, with examples from the Task Committee on Performance-Based Design being “the structure should have less than a ten percent chance of collapse given the occurrence of the Maximum Considered Earthquake,” “members or connections should have less than a $3x10^{-5}$ chance per year of structural failure as a result of live loading,” and “not more than one wind event in ten years should cause swaying troubling to occupants.”

Once quantitative performance objectives have been identified, the initial design process can proceed. One of the most common applications of performance-based design is in seismic design processes, where the “evaluation of the building performance during a seismic event is usually performed using ... nonlinear analysis” of which the goal is to “compute damage types and levels” in order to assess the consequences of any particular design (Tang 2008). According to their article on performance-based design with application to seismic hazard, Margaret Tang and her associates write that the computations of types, levels, and probabilities of damage due to earthquake motions is no easy task, and is currently undergoing extensive research and development. They go on to explain that fragility curves are often used in the design process to help simplify the process of assessing the consequences of design. These curves assist engineers in visualizing how selected vulnerabilities behave under different seismic hazard levels. The exact role of these curves can be observed in the following figure.

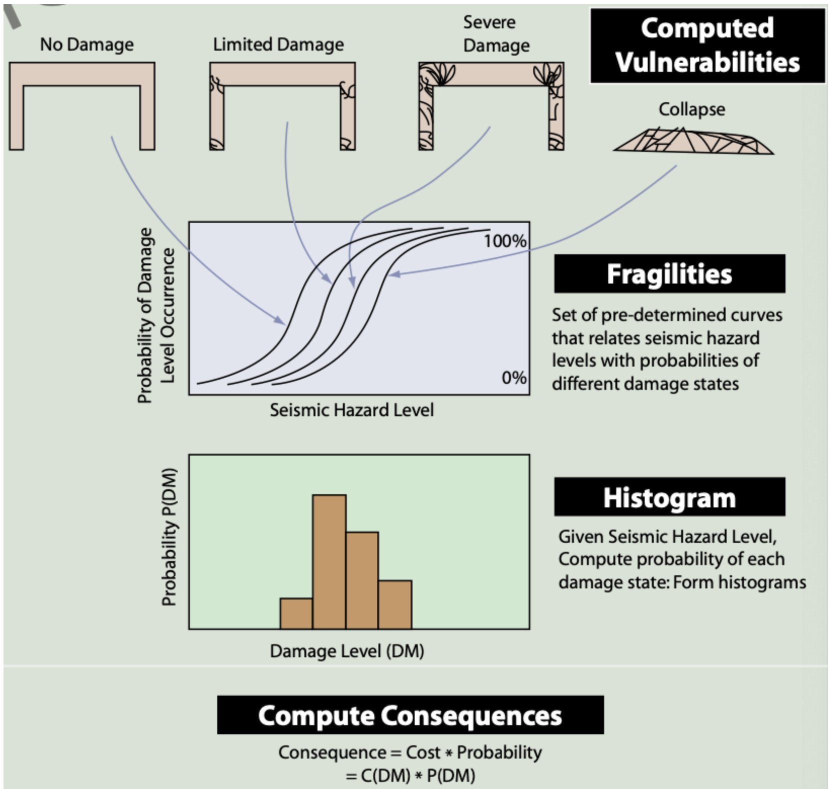

Figure 1: Computation of Risk (Tang, Castro, Pedroni, Brzozowski, Ettouney)

The computation of consequences is important in allowing engineers to compare the benefits and drawbacks to different design iterations. They can compare the design consequences to the set performance goals, and check to see if their goals have been met. FEMA classifies two distinct types of consequences, which are monetary (cost) and casualty (safety). As can be observed in the figure above, the probabilities of different types of damages can be estimated by the fragility curves, and these probabilities are used to compute cost and safety levels of the proposed structure. If the risks associated with the design can be accepted under the proposed performance standards, it is no longer necessary to repeat the design process. Once the design has been completed, the performance of the structure can then be verified through a variety of methods, with the most common being computer-based analytical simulations or the physical testing of prototypes.

Prescriptive vs. Performance

The benefits of performance-based design can be especially observed when compared to the alternative process of prescriptive design. Prescriptive methods typically revolve around "achieving an acceptable demand-to-capacity (D/C) ratio" while performance methods aim to "achieve a specified level of performance, as correlated to appropriate consequences" (Tang 2008). In this way, the two methods are fairly similar; they both feature a series of design iterations aimed at achieving a certain set of goals. These processes are visualized in the following figure.

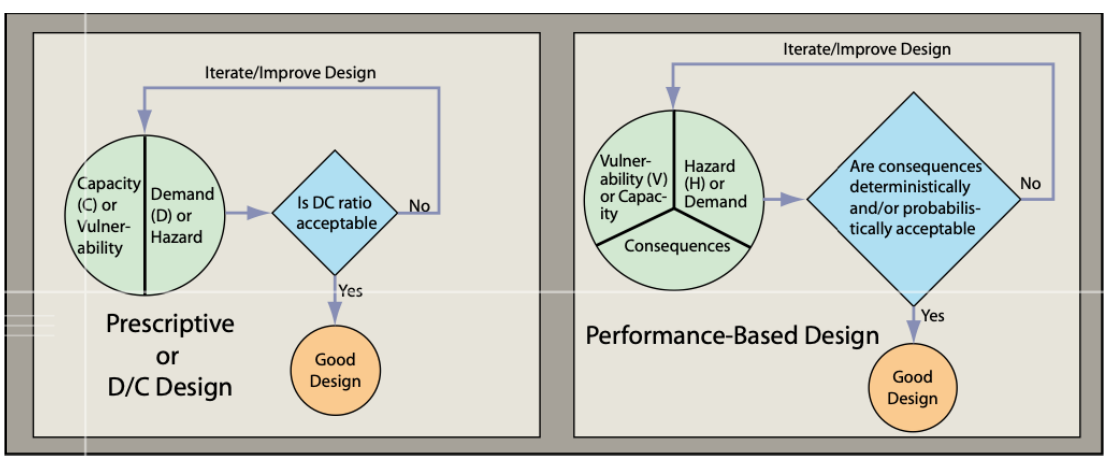

Figure 2: Prescriptive Design vs. Performance Based Design (Tang, Castro, Pedroni, Brzozowski, Ettouney)

Performance design differentiates itself in that its goals are flexible, versatile, and therefore more applicable to unique design environments. While prescriptive designs focus on capacity and demand, which relates directly to the reliability of the structure in question, performance methods “consider hazards, vulnerabilities, and consequences” (Tang 2008). In this way, performance-based design is able to adjust itself to any design scenario so that it behaves efficiently and allows engineers to design structures that work well with their surrounding environment. In order to properly execute this process, attention must be focused on early phases of the design process where the design goals are typically set. This early focus has proven to result in cost savings, optimal building performance, and a clear understanding of the consequences of risk events.

Prescriptive design methods are also quicky becoming increasingly problematic to use in areas of high risk from various natural and man-made hazards. Naveed Anwar, PhD, puts these issues into context by discussing potential conversations between a structural engineer and their clients. When asked if their building designs are safe, the best answer “structural engineers [who] follow the prescriptive provisions of the building and design codes...could offer is that ‘I am not sure, but I have designed this structure according to the building code.’” Anwar continues, conveying that this response is obviously not sufficient or acceptable, and that “clearer and more refined design approaches and methodologies” must be used in order to refine the response. Performance-based design is, of course, the solution to this issue. Performance objectives allow engineers to outline a required level of safety and carry out an explicit evaluation of the safety and reliability of a structure for various hazards, including earthquakes and other collapse scenarios. “This essentially allows the clients, building owners, and team carrying out the [performance-based design] to evaluate the explicit risks at the site, consider the purpose and usage of the building, and set the design for appropriate performance levels, in line with international guidelines and practices” (Anwar 2015).

Potential Applications

Perhaps the greatest benefit to learning effective performance-based design is that it is a highly adaptable process. While it does have the potential to be applied to nearly every design environment, there are a few specific areas in which performance-based design will especially flourish. First and foremost, performance-based design should be the go-to process for any structure or structural system that is considered to be essential to either the owner or surrounding community. Large high rises, public bridges, and community centers to name a few can be considered unique structures that serve essential purposes. By incorporating specific performance objectives into their design processes, engineers can ensure that community centers are the safest they can be for residents and guarantee that newly constructed skyscrapers stay cost-effective while maintaining structural integrity during earthquake events. With performance-based design, engineers will be able to implement additional safety measures where they are necessary, put extra emphasis on building strength when it is important to owners that their structure will survive earthquake events, and emphasize cost-efficiency when selecting materials to achieve these goals.

In addition to greatly assisting with the design of particularly important structures, performance-based design is especially helpful when dealing with new or unusual design circumstances. Since performance goals are designed to be quite adaptable, they are particularly favorable for designing unique structural systems such as advanced tall building designs, innovative stadium structures, and so on. In addition to this, performance-based design can also assist in the implementation of new materials to the design process. Whereas these novel building tools might not be covered by typical prescriptive codes, they can be applied to design objectives in a performance-based environment. In this situation, the engineer can obtain test data for these materials and then verify that the structure in question can reach the outlined objectives through an analytical simulation that utilizes the new materials.

The final unique application to performance-based design is that this modified approach to structural engineering allows focus to be placed on the role of the structure in its surrounding environment. Structural engineers involved in performance-based design will be offered the rare opportunity to take a step back and analyze how the structures they are designing will affect the community as a whole. They will be able to look at issues such as sustainability, the robustness of the structure, and how the structure works together with the current built environment. As stated by engineer Stephen Szoke in his article on performance-based design, "the development of strategies and mechanisms to expand the acceptance of PBD tend to better reflect the interests of clients and jurisdictions while elevating structural engineers as design professionals." This application promises to advance the role of the structural engineer to a point where they are informed partners in the community, and provides an interesting look at the potential the future holds for this profession (Task Committee on Performance-Based Design).

History and Current Uses

While the benefits of performance-based design are beginning to be recognized in many areas of structural engineering, these methods have already found a home in the practice of seismic design. As high-rise construction continues to grow in scale and complexity, engineers have ascertained that performance-based design allows them to take a more modern approach and challenge the boundaries that prescriptive codes once limited them to. Usage of performance-based design for tall buildings dates back to the 1960s, when buildings such as the New York World Trade Center Towers, Chicago's John Hancock Building, and Sears Tower were being developed. In his article detailing the rise of performance-based seismic design, structural engineer Ron Klemencic describes this infancy of PBD; "the definition of suitable demand levels and commensurate acceptance criteria were developed from scratch…the basic framework stems from these early pioneering designs." While this was an important starting point for early performance-based design, these efforts primarily focused on wind effects and left the majority of the design process to be delegated by prescriptive provisions. It was not until the 1980s that performance-based seismic design was first developed, initially with the purpose of evaluating and enhancing the performance of existing structures. In 1997, FEMA introduced the first working seismic PBD design guide, republished in 2000 as

FEMA 356, “Prestandard and Commentary for the Seismic Rehabilitation of Buildings.” This document was eventually superseded in 2007 by ASCE 41-06, “Seismic Rehabilitation of Existing Buildings” with the document’s most recent update occurring in 2013 (Tang 2008). As these processes have continued to develop and grow over the years, engineers have become increasingly able to design entire structures around established performance objectives.

Performance-based design has been provided with the opportunity to thrive in seismic design primarily due to the ever-apparent limitations of the historic prescriptive approach. The boundaries imposed by code prescriptions tend to glance over framing systems that have been proven especially efficient in high-rise construction, and many characteristics of tall buildings “are not considered in current code provisions, and this may lead to less-than-desirable results” (Klemencic 2008). Through the usage of performance-based design, engineers can better understand site-specific conditions and how they directly impact building performance. Constraints on building form, framing systems, and construction materials make it difficult to design advanced modern structures, especially in areas of high seismic activity. With more breathing room in the design process, engineers are able to design buildings to perform optimally in seismic region they will be built in. The following chart details how structures are typically designed in seismic regions.

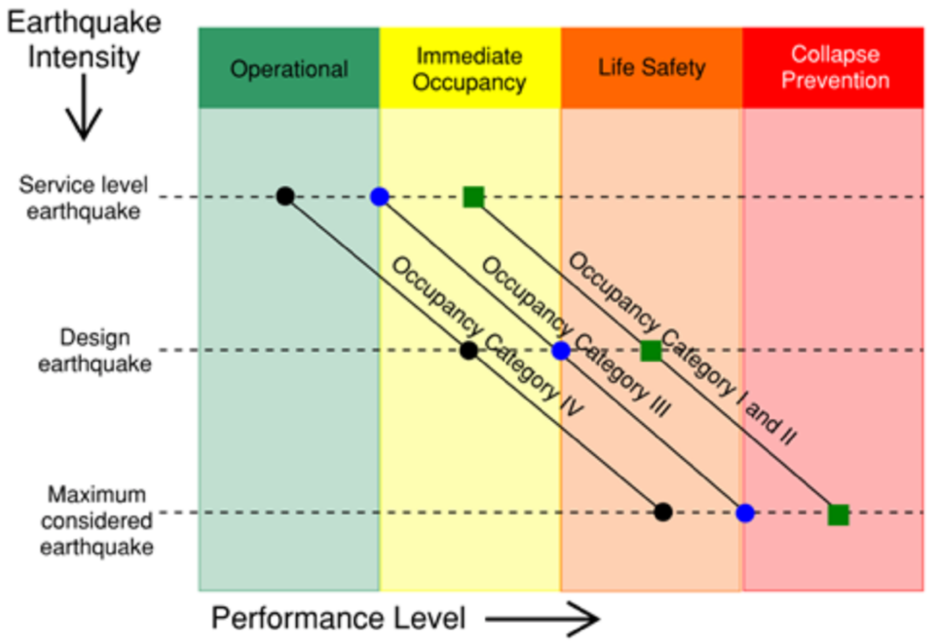

Figure 3: Seismic Design Categories (Doshi)

In his article discussing the benefits of performance-based seismic design, engineer Jinal Doshi explains why PBD is so popular is regions of high seismic activity. In the figure above, occupancy categories I and II include common residential and office buildings, which are typically designed for life safety in a design earthquake scenario. However, if a building owner has particular interest in a property and wants to implement additional protections, they can request that the building is instead designed for immediate occupancy at the design earthquake level and for life safety at the maximum considered earthquake level (see Figure 4 below for a visualization of how these performance levels exist in regard to seismic design parameters). This will nearly ensure that the building will not collapse in the event of a rare high-magnitude ground motion. Buildings that are typically designed with these criteria are occupancy category IV, which includes structures such as hospitals and fire stations. With performance-based design, owners and engineers alike can set up their own criteria (as long as it is equal to or sterner than that of the code) to achieve custom seismic performance of structures.

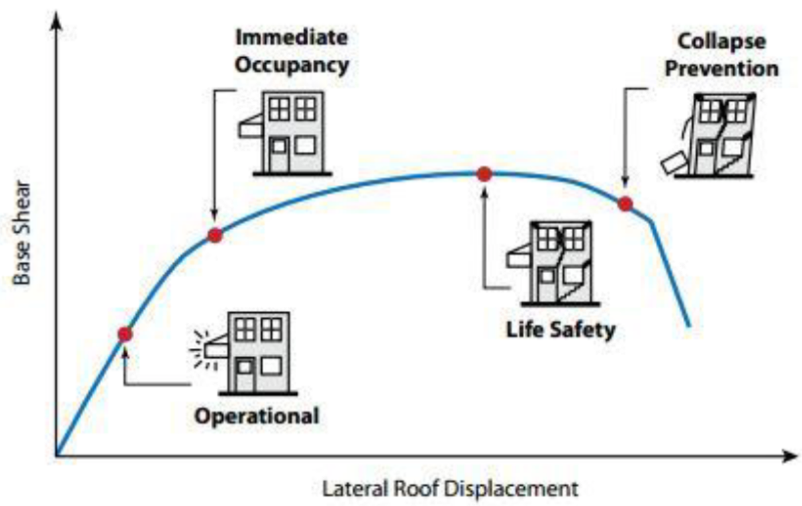

Figure 4: Performance Level Visualization (Doshi)

In addition to its usage in seismic design, performance-based design techniques can also be found in many special-case scenarios. For instance, performance-based design is commonly implemented into projects where new and innovative building materials or construction techniques not covered by typical building codes are being used. In these scenarios, performance-based design has proven useful in handling issues with progressive collapse, as well as in many full-scale bridge designs. Performance criteria is also often implemented in cases where the building owner might ask for special risk assessments, even in design scenarios with limited seismic activity. These requests are typically made when the owner wants to ensure that the structure can withstand extreme loading conditions without significant structural damage. Finally, performance-based design is useful when focus is placed on the economy of design, and allows for the consideration of atypical design and construction options that might reduce costs in particular scenarios (Szoke 2015). These unique applications include multi-hazard engineering (involving the consideration of more than one hazard event to increase safety and reduce cost), structural health monitoring (an essential tool for preserving the health of infrastructure), and life-cycle analysis (the evaluation of performance over the life of a structure as a result of anticipated loads, stresses, and hazards) (Tang 2008).

CHAPTER 3

CHAPTER 3: OPINIONS OF THE MODERN STRUCTURAL ENGINEER

While the benefits of performance-based design continue to be actively discussed within the structural engineering community, it is important to understand the sentiments of the engineers who hold the ability to practice it. Improvements to the applications of performance-based design serve no relevant purpose if these methods are not actually being practiced by engineers, and it is therefore of upmost importance to identify any roadblocks in the path of implementation and work to eliminate them.

Those Against

One of the largest cited benefits to performance-based design is that every uncertainty present in defining hazards, performing the design process, and estimating consequences is accounted for in the design structure. However, many engineers believe that these uncertainties are more adequately addressed in the heavily-tested prescriptive approaches. These concerns have led many to question whether performance-based design is worth the effort, considering that under-accounting for uncertainties could lead to concerns involving public safety and potential exposure to litigation for any engineers involved. It is true that “uncertainties are accommodated to a certain extent in prescriptive designs: Allowable Stress Design (ASD) utilizes factors of safety and Load and Resistance Factor Design (LRFD) accounts for load factors and strength reduction factors” (Tang, 2008). With this being said, performance-based design allows for freedom in allocating exceedance and probabilistic levels in the design process, and engineers are still free to implement their preferred methods of design when necessary. Performance-based design is regarded by many as a complete departure from historic methods of design, whereas in reality is should instead be looked upon as a method of enhancing prescriptive design so that its many methods can still be used, but with no more adverse restrictions. However, the issue for many is not a matter of which method provides the most freedom, but how much freedom is necessary to perform an adequate design. This leads into the final prominent issue with performance-based design, which is that many do not find that its added value and flexibility are necessary in most design processes. These impediments to performance-based design's implementation will be discussed in further detail later on.

Those in Favor

Perhaps the loudest voices on this topic in the modern structural engineering industry, the Task Committee on Performance-Based Design offers intricate insight on the many benefits that performance-based design has to offer to engineers. First, they identify the increased confidence and reliability that results from the creation of performance objectives. These objectives are the primary goal of the design process, and must be achieved to complete design. The verification of these objectives through analytical or physical means ensures that the designed structure will perform as intended. In addition to this increased reliability, explicitly defined performance targets also ensure that the structure in question will be designed appropriately for its purpose. Once a structure is completed in a performance-based design environment, its efficiency is ensured since the performance goals much be achieved to warrant a finalized design. Finally, the task committee conveys that performance-based design eliminates limitations imposed by prescriptive design approaches, allowing engineers to pursue innovative design solutions that might feature new materials and systems. In addition to these benefits outlined by the task committee, scholarly articles from a variety of prominent structural engineers and research professionals have identified a variety of additional advantages to the implementation of performance-based design. These include offering a more reliable attainment of intended seismic performance, reduced construction costs, eventual elimination of some prescriptive code requirements, accommodation of unique architectural features, and the usage of innovative structural systems and materials.

CHAPTER 4

CHAPTER 4: STEPS TOWARDS SUCCESSFUL IMPLEMENTATION

An effective implementation of performance-based design across all areas of structural engineering will require the efforts of structural engineers, the firms of which they are employed, the professional societies that represent them, and the educators that are raising their next generation. This implementation will not be deemed successful based on the number of designs that are completed using performance-based methods, but on the ability of engineers to have equal opportunity to choose between a performance approach or a prescriptive approach. In order to achieve this optimal design environment, the following responsibilities are required of individuals throughout the structural engineering industry.

Responsibilities of the Structural Engineer

One key impediment that has been cited by many is the resistance to change exhibited by many structural engineers when it comes to accepting a future rooted in performance-based design. As identified by the Task Committee on Performance-Based Design, this resistance can stem from a variety of places, including the fear of losing touch with long-lasting engineering standards, concerns involving public safety, and an increased potential for exposure to litigation. While these concerns do have their own merit, they are mostly rooted in an old way of thinking, one which has been taught to engineers in their youth and must now evolve along with methods of engineering. First, it is important to realize that the standards and codes that have been developed over the decades will not simply disappear. In fact, they will still serve an important role even in performance-based design approaches. Engineers will continue to reference codes, design examples, and standards during performance-based work, with the only difference being that they will no longer be constrained to any particular prescriptive requirement. In fact, most developments in performance-based design are rooted in expansions of existing codes, so that engineers are allowed to utilize performance-based design techniques under certain circumstances. This should also assist in demonstrating that public safety will continue to be ensured in a performance-based design environment. Structural engineers have years of experience working on complex design issues, and this knowledge has been stored for future generations to build and innovate on. Just as in any typical prescriptive design project, performance-based design will require the assistance of fellow engineers and will endure an intense series of checks, revisions, and verification.

The responsibility assigned to structural engineers is to recognize the criticisms of performance-based design, take the time to learn how they can be overcome, and share the knowledge of how to do so with fellow professionals. As identified by the Task Committee on Performance-Based Design, “not all structures need performance-based design to be efficient, sustainable, and robust.” The implementation of performance objectives is not a requirement, but instead an opportunity for innovation. It can be used for projects where lead engineers deem it to be useful, and from there its usage and acceptance in the industry will continue to grow. It is up to structural engineers to pioneer its usage and usher in a new way of thinking in which prescriptive design and performance-based design can co-exist in the workplace, allowing for both efficient designs and innovative ideas to flourish.

Responsibilities of Engineering Firms

While structural engineers practice the design of structures, it is the engineering firms that employ them and provide the necessary resources to succeed as an engineer. Engineering firms therefore hold an important responsibility in assisting with the implementation of performance-based design. One of the greatest impediments to the participation of firms in this cause is that they are profit-driven businesses by nature, and the current state of performance-based design has many costs associated with it. Whereas structural engineers are well-versed and have all the necessary means for a conventional prescriptive design approach, performance-based design would require additional education for engineers and more time spent learning the process. However, it is important to note that the extra time and money required for a firm's first few performance-based design processes is a one-time requirement, as with experience engineers will become more familiar with the process. With increased usage, performance-based design will evolve to become more efficient and could even promise to be more cost-effective than a traditional approach due to its ability to weed-out any unnecessary components of the design process. It is therefore the responsibility of engineering firms to support their engineers in pursuing the future of structural design. In order to combat the universal lack of proficiency with performance goals, it is up to engineering firms to offer time for education and implementation of necessary systems involved with performance-based design. This investment could include mandatory performance-based design education courses, as well as the supplying of necessary building codes that allow for the practice of performance-based design. While this may add some extra cost for the first few years of practice, the growth of the structural engineering profession to tackle new goals and design problems is worth the effort.

Responsibilities of Professional Societies

Professional engineering societies have a diverse history of setting standards, goals, and objectives in order to assist their respective professions in evolving and modernizing their practices. Structural engineering societies therefore have the opportunity to assist in the implementation of performance-based design techniques. So far, the resolve of professional societies when it comes to this matter has been the most prominent of all the groups to be mentioned. For example, the Structural Engineering Institute oversaw the creation of the Task Committee on Performance-Based Design, whose 2018 report to SEI on the current state of its implementation exists as one of the most useful modern documents to characterize performance-based design in the structural engineering industry. In addition to the efforts of this SEI-sanctioned committee, the American Society of Civil Engineers has identified performance-based design standards as one of the four areas of focus under the “ASCE Grand Challenge.” The purpose of this program is to challenge engineers to rethink the possibilities of structural engineering, and ASCE adeptly identifies performance standards as a way to “dramatically improve performance while creating more efficient costs” and to “encourage innovation across the civil engineering profession.”

While structural engineering societies have already recognized and begun to promote the many benefits to performance-based design, it is important that their responsibility does not end there. As stated by the Task Committee on Performance-Based Design, “to change the design paradigm will take time – many years, if not decades.” The ad-campaign being run by these societies has been effective in establishing performance-based design as a goal, but the real challenge of profession-wide integration is yet to begin. In their report, the Task Committee asks for the support of the Structural Engineering Institute on the following key issues, which will be cited in their entirety:

1) Identify collaborations and partnerships within the social, economic, natural and built environments that can be leveraged so that ongoing PBD activities can be fully aligned.
2) Promote PBD principles through education and engagement of professionals and stakeholders to the design process.
3) Develop a consensus framework, or umbrella approach, for PBD that can guide ongoing and future PBD documents and committees.
4) Actively pursue development of PBD documents with code authorities and agencies.

These tasks focus on infrastructure, and on the future implementation of performance-based design in the workplace and the engineering profession as a whole. The committee focuses on education, future reports and committees, and the work to be done with code enforcement officials. It is the responsibility of professional engineering societies to assist in the completion of items on this list, as well as with any industry-wide issues that must be addressed in order to facilitate the implementation of performance-based design.

Responsibilities of Educators

The ideas discussed in this report, as well as in many similar discussions on performance-based design, have been primarily rooted in the modern engineering workplace. Previously-mentioned responsibilities were established for the engineers themselves, the firms to which they are employed, and the engineering societies to which they belong. However, the future generation of structural engineers, those which will be leading the industry in just a few decades, do not yet belong to any of these groups. The young engineers of today are graduating primary school, earning their degrees, and performing research at universities. It is up to the educators – the teachers, lecturers, and professors – to provide these students with the knowledge they require to succeed in their future careers.

As discussed, one of the primary issues facing the implementation of performance-based design in the workplace is the current lack of knowledge among engineers, and the unwillingness of many firms to implement educational programs focusing on the topic. According to Naveed Anwar, essential knowledge and skill sets "are generally not imparted to structural engineers in a typical undergraduate civil engineering program" and are typically "acquired through specialized master's degree programs or through extensive training and experience in PBD applications." In order to assist with these issues, educators could integrate performance-based design principals into their current undergraduate coursework so that students will graduate with an established familiarity with the topic. The nature of performance-based design is more challenging than prescriptive approaches, and would serve as an excellent educational tool. Instead of having students create sample designs by following prescriptive code standards, perhaps they could be tasked with generating a set of performance goals and designing a structure to achieve those goals. These designs could even be compared against similar prescriptive designs to allow students to comprehend the advantages to each approach. By establishing this critical link between prescriptive and performance-based design techniques in their students' minds, educators will be defeating a major roadblock to the successful implementation of performance-based design in the structural engineering industry. As structural design technologies continue to advance, it is important to ensure that the students of today have the proper tools and knowledge to continue to innovate and take on the problems of tomorrow.

Additional Considerations

In addition to these four essential constituent groups, building owners and regulators also serve as two essential stakeholders in the effort to effectively implement performance-based design. Currently, many building owners looking to construct new developments or improve their existing structures might not have adequate knowledge of performance-based design or of the benefits its usage could provide for their construction ambitions. With public education programs geared towards these individuals, building owners could themselves advocate for performance objectives to be set for their structures. As discussed earlier, there are many occasions in which building owners could benefit from the inclusion of performance goals, including increasing factors of safety, utilizing innovative materials and construction methods, and improving the role of their structures in the surrounding community. Regulators also serve an important role, as they are the parties who develop building codes which need to allow performance-based design to be practiced. While many building codes are already evolving to include language that permits the practice of performance design methods, it is important that this evolution continues its current trend well into the future.

While every stakeholder discussed in this chapter serves an important role in advancing the structural engineering profession towards performance-based design, it is structural engineers themselves that serve the most important role and will lead the ensuing effort. All of these groups exist because of structural engineers; firms employ them, professional societies are made up of them, educators teach them, building owners require their services, and regulators provide guidelines for them. Structural engineers must buy into the usage of performance-based design in order to inspire a reaction from each of these groups. Once engineers begin to show interest for and implement performance methods more prominently in their work, firms will begin to show more support, educators will implement performance methods more prominently in education, and the structural engineering profession as a whole will begin to advance towards a future rooted in performance design.

CHAPTER 5

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

In their report to the Structural Engineering Institute, the Task Committee on Performance-Based Design adeptly outlines the issues at hand when it comes to the over-utilization of the prescriptive approach to design.

> "We, the structural engineering community, are confounded by a situation we created for ourselves. As structural engineers, we operate in a design environment with easy access to information, have the ability to collect and analyze more data than we have ever had in the past, and have access to robust and reliable analysis and design software. Nevertheless, we are prevented from fully leveraging these advantages by prescriptive codes and standards that restrict innovation and are increasing prescriptive requirements at an unsustainable rate. In an era when we face multiple demands on our designs – safety, economy, serviceability, sustainability, robustness, and unreasonable schedule demands – we are constrained to follow a prescriptive path to a solution that often does not optimally satisfy expectations.
>
> As a result, the societies we serve are not getting maximum value from their limited resources of time, money, energy, and materials. Rather, they are getting designs that are constrained by prescriptive codes that are generic, with uncertain reliability because design by prescription neither quantifies nor directly evaluates performance."

For the reasons outlined above, structural engineers and the communities they serve can no longer afford to be limited by prescriptive design. It is time to implement change and grow the profession of structural engineering to the modern and innovative statue of which present-day designs demand.

Current Progress of Implementation

Performance-based design is already permitted by many modern building codes, including the International Code Council International Building Code (IBC) and the International Code Council Performance Code (ICCPC). Most derived building codes are based on IBC, for which the official language "includes alternative means and methods to allow the use of materials, design techniques, or construction methods not specifically prescribed by the code." Likewise, ICCPC "permits innovation and deviations from the prescriptive criteria while maintaining the intent of the building code" (Szoke 2015). These parameters within modern building codes have allowed for the current state of performance-based design, and demonstrate the true potential for growth that it holds. As far as building codes go, there are no significant restrictions on performance-based design as long as certain safety parameters are still being met. As stated in the official ICCPC, the purpose of the code is "to provide appropriate health, safety, welfare, and social and economic value, while promoting innovative, flexible and responsive solutions that optimize the expenditure and consumption of resources." The language of these codes is also evolving through the years, with the release of ASCE 7-16 allowing for "the removal of some of the extra conservatism built into the current building code" and offering engineers the ability to further implement new performance-based methods (HartCrowser 2018). In allowing the early adoption of performance-based design, these building codes are paving the way for a more modern approach to structural engineering. For a complete list of additional standards and guidelines that assist in the implementation of performance-based design, refer to Appendix A.

Despite the fact that performance-based design is allowed by building codes, it is still infrequently practiced by most structural engineers. To this end, its implementation is not assured by simply allowing the process to occur, but instead in promoting its use. Ron Klemencic mentions the rise of volunteer efforts in his article on performance-based design, citing many recent articles that support PBD of tall buildings published by the likes of the Los Angeles Tall Buildings Structural Design Council, the Structural Engineers Association of Northern California, the San Francisco Department of Building Inspection, the PEER Applied Technology Council, and the Council on Tall Buildings and Urban Habitat. The efforts being made by these groups are helping to increase public awareness of performance-based design, especially when it comes to one of its most beneficial engineering applications. However, throughout the effort to raise awareness of performance-based design and increase its usage in the structural engineering industry, one of the most difficult tasks has been to articulate exactly what it means to perform performance-based design so that engineers will know where to start and what steps to take. While it is helpful that so many entities have sought to publish documents focused on performance-based design, this process of increasing publicity would benefit greatly from a more skilled articulation of clear steps to take. Top experts in the field agree that this task is extremely difficult to achieve effectively, and it is therefore a major roadblock in allowing performance-based design to gain traction among willing engineers.

The Future of Structural Engineering

The large potential for growth in the structural engineering profession has been made abundantly clear in recent years. As building designs continue to grow in height and overall quantity, there is a clear necessity "for more skilled engineers, equipped with better tools to evaluate and guarantee the safety and performance of such buildings" (Anwar 2015). Throughout this document, it has been made clear that performance-based design offers numerous advantages compared to traditional design methods, and this tool could very well be the key to many more years of innovation in the structural engineering industry. With that being said, the road ahead is not without many setbacks and challenges. As stated by Margaret Tang and her research team, "the challenges of implementing performance-based design include smooth multidisciplinary integration and the added expertise of professionals. The advantages of PBD make meeting these challenges a worthwhile goal."

The intention of this research paper is for it to serve as a starting point; a culmination of information including the challenges, the payoffs, and the necessary steps to be taken if performance-based design is to become a prominent part of structural engineering. As summarized by Stephen Szoke, "This effort, while invaluable, is a complex, multi-faceted and long-term project for the advancement of structural engineering as a profession." The implementation of performance-based design will take time and resources to execute correctly. In addition to this, there will be no way to know when the effort has concluded. Adoption of performance standards will be gradual, but as history has shown, engineers will continue to become more and more comfortable with these new methods of design. As predicted by many of the reputable engineers whose voices have been cited in this paper, performance-based design presents the opportunity to elevate the role of the structural engineer to a point where they are essential members of the community. Structural design can serve many unique purposes and solve a variety of problems. With the right objectives set in the design process, the future of any design holds infinite possibilities.

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APPENDIX A

GUIDELINES FOR IMPLIMENTING PERFORMANCE-BASED DESIGN

The following is a collection of guidelines that support the implementation of performance-based design. These documents allow for the practice of performance-based design and should serve as a starting point for engineers looking to begin implementing these practices into their work. Credit to Naveed Anwar who published the first iteration of this list in his article “Performance-based Design: An Approach towards Safer, Reliable Structures” (2015).

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