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Review on Performance Based Seismic Analysis & Design

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Abstract— Seismic design methodologies have significantly evolved, moving from traditional force-based approaches to performance-based paradigms focused on enhancing structural resilience and mitigating seismic risks. This review paper examines the seismic design landscape by comparing conventional force-based design (FBD) with performance-based seismic design (PBSD) methodologies. It delves into the development, principles, and applications of PBSD, highlighting its shift from prescriptive codes to performance-driven criteria. Emphasis is placed on techniques such as displacement-based design and performance-based plastic design, which prioritize structural performance and deformation management over peak forces alone. Additionally, the paper elucidates the role of advanced analysis methods, including nonlinear static and dynamic analyses, in accurately assessing structural behavior under seismic loading. By thoroughly exploring seismic design philosophies, this review underscores the critical importance of adopting performance-based approaches to create earthquake-resistant structures that prioritize occupant safety, property protection, and community resilience.

Keywords — Displacement based design, Forced based design, Non-linear analysis, Performance based seismic analysis, Pushover analysis, and target displacement.

I. INTRODUCTION

The seismic design philosophy for structures emphasizes the creation of earthquake-resistant buildings capable of withstanding seismic forces. A key element of this philosophy is ductility, enabling structures to sway during earthquakes. This design approach aims to balance responses to minor, moderate, and strong shaking events, ensuring that buildings remain operational with varying degrees of damage. Seismic-resistant structures are crucial for safeguarding lives, property, and communities in earthquake-prone regions by prioritizing occupant safety and minimizing the risk of collapse and potential injuries or fatalities. Additionally, these structures protect property and assets, enhance community resilience, and contribute to economic stability by supporting business continuity and preventing disruptions to local economies. Investing in seismic-resistant structures promotes long-term sustainability through resource conservation and reduces the need for frequent repairs or reconstructions, thereby fostering a safer and more resilient built environment [26].

Traditional seismic design, also referred to as force-based design, involves calculating the seismic forces that act on a structure and designing it to withstand these forces. This method uses simplified mathematical models to determine seismic forces based on parameters such as mass, stiffness, and seismic hazard. Structural elements are then sized and reinforced to resist these forces, with an emphasis on evenly distributing the forces throughout the building. Traditional seismic design includes safety factors to ensure that structures can reliably endure seismic events, thereby protecting occupants and assets during earthquakes. [10,13,14].

Performance-Based Seismic Design (PBSD) has become a leading approach in seismic design, focusing on achieving specific performance objectives rather than relying on traditional force-based methods. [10,13]. This shift represents a significant reevaluation of seismic design

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processes, moving from strength-centric methods to performance-oriented approaches [5,13]. Performance-Based Seismic Design (PBSD) enables the design of structures to achieve predefined levels of deformation and damage under specified seismic intensities, employing the substitute structure approach to precisely control building behavior [13,14]. By taking into account factors such as ductility, displacement, and energy dissipation through non-linear dynamic seismic analysis procedures, PBSD offers a more precise evaluation of a structure's behavior under seismic loads [13]. This precision results in designs that are more resilient and capable of effectively absorbing and dissipating seismic energy, thereby minimizing the risk of structural failure during earthquakes. The focus on innovation, research, and adherence to modern building codes reinforces PBSD as a dependable and effective method for designing earthquake-resistant structures. Consequently, PBSD has gained widespread acceptance as a preferred approach to seismic design globally [10]. Further design methods will be examined in detail.

II. FORCE BASED DESIGN METHOD

A. GENERAL

Conventional Force-Based Design (FBD) is a widely utilized structural design methodology implemented in many regions, focusing primarily on specifying exact forces and stresses within a structure to ensure its stability and safety. In the FBD design process, seismic forces are determined by considering factors such as stiffness, time period, and strength. This method relies on country-specific codes and standards, using normative, linear elastic analysis to calculate the lateral forces acting on the structure [13].

FBD adheres to a prescriptive methodology, where the construction of a structure follows predetermined codes, standards, and regulations, emphasizing compliance over performance-based criteria [10,13]. In FBD, the predominant view of structural behavior is that it's primarily elastic, assuming a linear response to applied forces while overlooking non-linear effects. Typically, FBD relies on acceleration response spectrum analysis to determine base shear forces and design seismic loads, aligning with specified criteria [10].

In FBD-designed structures, their response to external forces is notably shaped by their initial stiffness and damping properties [10]. It's noteworthy that structures designed through FBD may demonstrate elevated base shear values in contrast to those designed via Performance-Based Seismic Design (PBSD). Additionally, they may display diverse performance levels regarding drift ratio, ductility demand, and base shear [13,14].

Essentially, Conventional Force-Based Design places significant emphasis on adhering to established guidelines and standards to uphold structural integrity. Its primary focus lies in effectively managing forces and stresses within the elastic range of materials [10,13,14].

B. FAILURE REASON OF FORCED BASED METHOD

Various challenges plague the traditional force-based seismic design method, which could potentially culminate in failures [25]. Relying on linear elastic analysis, the traditional force-based seismic design method frequently falls short in capturing the nonlinear behavior of structures under seismic loading. This can lead to designs that do not sufficiently meet performance objectives and underestimate seismic risk [13]. Failure to consider ductility in structures, crucial for absorbing energy during seismic events, can result in brittle failures and abrupt collapses. Additionally, force-based designs commonly lack redundancy, heightening the potential for progressive collapse [25].

Misalignments between drift limits and force reduction factors can yield structures with surplus strength and ductility, resulting in unnecessary material consumption. Furthermore, force-based design might not guarantee uniform damage distribution across structures or harmonize with performance-based seismic design goals, thereby affecting overall effectiveness [14]. Depending solely on code-prescribed forces without factoring in site-specific conditions may underestimate seismic forces and result in unpredictable performance during earthquakes [25].

Force-based design's downfall originates from prioritizing construction methodologies over structural performance during seismic events. It heavily leans on codes and regulations, sidelining direct considerations of structural behavior [10,25]. Ensuring the safety and resilience of structures during seismic events hinges on addressing crucial aspects like ductility, redundancy, and the actual structural response to seismic forces [25].

III. PERFORMANCE BASED DESIGN

A. DEVELOPMENT OF PERFORMANCE BASED DESIGN.

The seismic engineering field has witnessed a notable shift with the emergence of performance-based design (PBD), departing from conventional strength-based criteria to embrace a comprehensive approach focused on structural performance during seismic loading. This paradigm change, dating back to the mid-20th century, was catalyzed by seismic incidents such as the 1971 San Fernando earthquake in California. These events underscored the inadequacies of code-based design in safeguarding structural integrity during extreme conditions [24].

Historically, seismic design emphasized post-earthquake structural integrity by prescribing code requirements. Yet, this method didn't consistently ensure satisfactory performance [24,25]. In the 1970s, capacity design principles surfaced, highlighting the importance of

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distributing strength effectively across buildings to enhance seismic performance [24]. PBD continued to advance alongside progress in earthquake engineering research, computational tools, and an enhanced comprehension of structural behavior [24,25].

Following the Northridge Earthquake in 1992, the establishment of the Vision 2000 committee marked a pivotal moment in formalizing PBD recommendations. By 1995, the committee released a conceptual framework highlighting the possibility of designing buildings to different performance levels, considering factors like occupancy and economic feasibility [27].

ASCE 41-13, known as the Seismic Evaluation and Retrofit of Existing Buildings standard, represented a significant milestone in the development of PBD. It introduced a standardized process for assessing and retrofitting existing buildings, emphasizing a customized, performance-oriented approach rather than relying on generic code provisions [27].

The recognition of displacement ductility capacity as a vital indicator sparked the development of PBD concepts geared towards attaining precise performance goals rather than simply meeting minimum code requirements [20]. The PBD approach underwent refinement through progress in analytical tools, computational capabilities, and research. This evolution involved the integration of probabilistic methods, nonlinear analysis techniques, and risk assessment tools [24,25].

Methods such as the capacity spectrum approach and direct displacement-based design empower engineers to evaluate existing structures and engineer new ones, prioritizing the attainment of specific performance thresholds [21]. In essence, the evolution of PBD marks a transformative shift towards a refined and precise design methodology, bolstering both building safety and community resilience in earthquake-prone areas [21,27]. Through the collaborative endeavors of industry professionals, researchers, and standards organizations, PBD has emerged as an indispensable element within contemporary seismic design methodologies [27].

B. CHARACTERISTICS OF PERFORMANCE BASED SEISIC DESIGN.

Pioneered by the Pacific Earthquake Engineering Research Center (PEER), performance-based seismic analysis seeks to elevate decision-making in seismic risk assessment and design methodologies. This approach deconstructs the evaluation and design phases into coherent components within a unified probabilistic framework. Performance-based seismic design (PBSD) centers on attaining precise performance goals, departing from the exclusive reliance on conventional code-based criteria [17,21]. It encompasses assessing a structure's ability to withstand seismic forces by taking into account factors like strength, stiffness, and deformability [19]. Within PBSD, seismic hazard analysis, structural simulations, damage assessment, and the determination of decision variables such as displacement capacity, ductility, and energy dissipation are integrated. This comprehensive approach aims to guarantee safety, functionality, and reparability both during and after seismic events [17].

Sophisticated methodologies like push-over analysis, capacity spectrum methods, and nonlinear analyses offer intricate insights into how structures react to seismic activity. Through simulating a structure's performance under diverse seismic conditions, engineers gauge its capacity to fulfill specific performance objectives such as ensuring life safety and preventing collapse [19,21]. Designing structures with performance-based criteria aims to attain consistent levels of seismic resilience by accounting for factors such as foundation compliance and variations in seismic intensity. Through thorough analysis, potential vulnerabilities are identified, allowing for tailored retrofitting or design adjustments to bolster seismic resilience [19].

Within PBSD, defining precise performance goals aligned with the building's intended function holds paramount importance. These objectives may encompass minimizing damage, averting collapse, and safeguarding occupants. Evaluating seismic hazard entails analyzing earthquake scenarios, ground motion attributes, and soil conditions. Engineering Demand Parameters quantify the structure's reaction to seismic forces, aiding in decisions regarding performance across various seismic occurrences. Damage assessments inform strategies for repair and retrofitting, while decision variables translate structural performance into tangible outcomes, often within a probabilistic context to address uncertainties [17].

By integrating standards like ATC-40 and FEMA 273/274, PBSD presents a customized and efficient framework for earthquake engineering, empowering informed choices in seismic risk reduction. It furnishes a dependable methodology for crafting structures capable of enduring and recuperating from seismic events, thereby bolstering seismic resilience in both buildings and infrastructure [19].

C. DISPLACEMENT BASED SEISMIC DESIGN.

Displacement-based seismic design transforms structural engineering by placing greater emphasis on projected displacements of structures over conventional force-based evaluations during seismic events [10]. Direct Displacement Based Design (DDBD) embodies this methodology, centering on performance metrics related to displacements and drifts rather than solely prioritizing peak forces [13]. Displacement-based design provides a nuanced comprehension of structural behavior under seismic loads by highlighting displacement control and deformation

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management as focal points [22].

In DDBD, detailed linear elastic analysis is performed to evaluate resulting displacements against established allowable drift limits. This shift in methodology emphasizes understanding a structure's capacity to endure inelastic deformation, a factor often overlooked in force-based approaches [14]. By representing inelastic structures as equivalent linear elastic systems, displacement-based design offers a logical approach to ensuring structural integrity and performance under seismic loading conditions [22].

A key aspect of displacement-based design is deriving design parameters from displacement spectra, which incorporate a structure's response to ground motions [13,23]. This approach addresses both elastic and inelastic responses during earthquakes, effectively handling challenges like torsion and higher vibration modes [23]. Engineers strive to achieve a target displacement profile that aligns with a reference response spectrum, controlling performance levels by determining appropriate values for maximum displacement and inter-storey drift [13,23].

As a performance-based design methodology, DDBD emphasizes flexibility and deflection, exceeding the safety and resilience benchmarks of Force-Based Design (FBD) structures. Validation through nonlinear time history analysis reveals that DDBD-designed structures offer superior seismic resistance, showcasing greater flexibility and lower ductility demands compared to their FBD counterparts [13].

Performance evaluation in displacement-based design directly correlates a building's performance with the damage it sustains during seismic events. This represents a significant shift from strength-based to displacement-based criteria for assessing structural integrity [10]. Overall, displacement-based seismic design provides a thorough understanding of structural response to seismic forces, allowing engineers to develop resilient designs that protect occupants and infrastructure from earthquake impacts [10,23].

D. PERFORMANCE BASED PLASTIC DESIGN.

Performance-based plastic design transforms structural engineering by focusing on a structure's performance during seismic events rather than merely complying with code requirements [12,16]. This methodology anticipates a structure's behavior under seismic loading, aiming to minimize damage while enduring earthquake forces. It carefully considers factors such as expected ground shaking, structural characteristics, and desired performance objectives. The design process begins with assessing lateral forces based on anticipated ground motion, which are then allocated to various structural elements to achieve performance goals [11,16].

At the heart of performance-based plastic design lies the integration of plastic hinges, designated areas within the structure where controlled yielding or plastic deformation is allowed during seismic events. This deliberate integration empowers the structure to dissipate energy and alleviate transmitted forces. The design of these hinges centers on the principles of target drift and yield mechanism, whereby predetermined maximum allowable displacement and specific yielding locations are established in advance [15,16].

At the core of the methodology lies the energy concept introduced by Housner, which equates the work necessary to push the structure to the target drift with the energy demanded by the equivalent single degree of freedom (EP-SDOF) system. This correlation extends to multi-storey structures through equivalent modal single degree of freedom oscillators [15]. Practical implementation involves detailed plastic design of frame members and connections to achieve the desired yield mechanisms accurately [15,16].

The design of structural members is contingent upon the intended yield mechanism, whereby members expected to yield, such as steel concentric braced frames, are engineered to deliver strength, ductility, and the desired behavior. The comprehensive design process involves establishing the design base shear, allocating lateral forces according to inelastic dynamic responses, and implementing plastic design techniques to meticulously detail connections and members, ensuring they align with performance objectives [11].

Performance-based plastic design provides several benefits, including a precise assessment of seismic performance, optimized material usage, and the consideration of secondary effects such as the P-Δ effect [12] Validation entails conducting thorough nonlinear dynamic analyses utilizing ground motion records. In summary, performance-based plastic design offers a holistic approach to seismic design, acknowledging the real structural response to earthquake forces, marking a notable progression in structural engineering practice [11,15,16].

IV. ANALYSIS METHODS

A. NONLINEAR STATIC ANALYSIS

In structural engineering, pushover analysis, also known as nonlinear static analysis, holds significant importance for evaluating seismic performance [18,20]. Pushover analysis facilitates performance-based seismic design by adjusting the stiffness matrices of frame elements to accommodate nonlinear behavior under both gravity and lateral loads. Structures undergo incremental lateral force application until reaching a predetermined displacement target, accounting for material plasticity. This methodology provides an accurate assessment of the structure's response to seismic loading by tracking progressive plastic behavior, essential for comprehending diverse seismic intensities [7,18].

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Nonlinear static analysis computes the structure's response across various displacement levels, assisting in determining force and deformation distribution. It identifies failure mechanisms, evaluates seismic force resistance, and assesses overall performance under a range of loading scenarios [20]. Sequential elastic analyses approximate the force-displacement curve by iteratively adjusting stiffness as lateral forces escalate. This methodical process involves comprehensive structural modeling and load-deformation diagrams until reaching the specified control displacement or detecting structural instability [6,9].

This analysis provides insights into behavior beyond elastic limits, offering information about strength, ductility, and potential vulnerabilities [14,16]. This analysis provides insights into behavior beyond elastic limits, offering information about strength, ductility, and potential vulnerabilities [8,18].

Findings from the analysis, including the static pushover curve and details such as deformed shapes and hinge outcomes, guide structural design and retrofitting strategies. Engineers utilize this information to improve seismic performance and assess various design alternatives [9,18]. Although fundamental, nonlinear static pushover analysis is enhanced by dynamic time history analysis to achieve a comprehensive grasp of seismic behavior. Software applications such as SAP-2000 enable precise simulation [8,9].

To summarize, pushover analysis plays a crucial role in structural engineering by providing a robust methodology for assessing seismic performance and bolstering resilience against earthquakes [20]. By integrating nonlinear behavior and progressive plasticity, pushover analysis ensures structural safety and effectively mitigates seismic risks [8,12].

B. NONLINEAR DYNAMIC ANALYSIS

Nonlinear dynamic analysis serves as a crucial computational tool for examining structural behavior under dynamic loads, notably seismic events such as earthquakes. Unlike linear analysis, which simplifies the response, nonlinear dynamic analysis captures the complex nonlinear behavior of materials and structural elements. This method employs mathematical equations to model the structure, accounting for material and geometric nonlinearities, thereby offering a more precise depiction of real-world response [6,11].

Nonlinear dynamic analysis evaluates the structure's response by simulating the authentic time history of ground motion during seismic events [11,13,14]. This entails numerically solving mathematical equations over time, accounting for the time-varying characteristics of applied loads [11]. Through time history analysis, the dynamic response is assessed by considering the actual time-varying forces and displacements encountered during seismic events [11,15].

A key aspect of time history analysis is the use of recorded or simulated ground motion inputs, represented as a time history of acceleration, velocity, or displacement. This ground motion drives the calculation of structural response, incorporating properties such as mass, stiffness, and damping to accurately model dynamic behavior [15].

Nonlinear dynamic analysis offers a more accurate prediction of structural response compared to linear methods by capturing phenomena such as material yielding, stiffness degradation, and energy dissipation. However, it necessitates detailed modeling and can be computationally intensive [6,11].

The insights gained from nonlinear dynamic analysis are crucial for evaluating structural safety, informing design decisions, and pinpointing areas for improvement. This method is extensively employed in designing structures to withstand extreme loading conditions, ensuring their integrity and performance [11,15,16].

In summary, nonlinear dynamic analysis is an essential tool for accurately predicting and assessing structural behavior under dynamic loads. It is crucial in improving the safety and performance of structures in seismic-prone areas and other dynamic environments [11,15].

V. FINDINGS

This study thoroughly examines seismic design methodologies, highlighting the evolution from traditional force-based approaches to performance-based paradigms. It underscores the critical importance of seismic-resistant structures in safeguarding lives, property, and communities in earthquake-prone areas, emphasizing the key role of ductility in enhancing structural resilience. The comparison between traditional force-based design (FBD) and performance-based seismic design (PBSD) reveals the limitations of FBD, particularly its reliance on linear elastic analysis and insufficient consideration of ductility, which hampers its ability to meet performance objectives and mitigate seismic risks. In contrast, PBSD offers a comprehensive approach that focuses on achieving specific performance goals through techniques such as displacement-based design and performance-based plastic design. Advanced analysis methods, including nonlinear static and dynamic analyses, are essential for accurately evaluating structural responses to seismic loading. The study advocates for the widespread adoption of PBSD methodologies to develop earthquake-resistant structures. It emphasizes the need for collaboration among industry professionals, researchers, and standards organizations to enhance building safety, improve community resilience, and contribute to a safer, more sustainable built environment in earthquake-prone regions.

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