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Comprehensive Review of Unified Performance-Based Design (UPBD): An Advancement of Performance-Based Seismic Design

Kalpesh D. Baraiya [1], Dr. Gopal M. Tank [2],

[1] P.G. Student, Department of Applied Mechanics, L.D. College of Engineering, Ahmedabad, India

[2] Professor, Department of Applied Mechanics, L.D. College of Engineering, Ahmedabad, India

Corresponding Author Email: [1] kdbaraiya2601@gmail.com

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Abstract—

The field of earthquake engineering has evolved significantly from conventional Force-Based Design (FBD) towards Performance-Based Design (PBD), aimed at ensuring predictable structural performance under seismic events. While PBD offers flexibility in addressing multiple performance objectives, early Displacement-Based Design (DBD) methods, particularly Direct Displacement-Based Design (DDBD), often focused solely on inter-story drift, neglecting explicit member-level performance criteria such as plastic rotation. Additionally, DDBD required iterative sizing procedures, increasing computational effort. The Unified Performance-Based Design (UPBD) method was developed to overcome these limitations by simultaneously integrating drift and performance level criteria, providing non-iterative member sizing from the outset. This review examines the evolution from FBD to PBD and the emergence of UPBD, critically evaluates comparative studies, and highlights applications across RC frames, dual systems, high-rise buildings, and bridge piers.

The review identifies key advantages, limitations, and future research directions, including resilience-based extensions, probabilistic assessment, and AI/ML integration. UPBD demonstrates substantial benefits in cost efficiency, structural resilience, and design practicality, positioning it as a significant advancement in modern earthquake engineering.

Keywords— Unified Performance-Based Design (UPBD), Performance-Based Design (PBD), Displacement-Based Design (DBD), Inter-Storey Drift Ratio (IDR), Performance Levels (PL), Nonlinear Analysis, RC Dual Systems.

I. INTRODUCTION

Earthquake-resistant design historically relied on Force-Based Design (FBD), where design strength governed seismic performance, and code-based reduction factors simplified inelastic behavior. While time-tested, FBD primarily targets collapse prevention and fails to explicitly consider post-earthquake functionality, often resulting in significant economic losses, as observed in the 1994 Northridge earthquake (Priestley et al., 2007).

Performance-Based Seismic Design (PBSD) emerged to overcome these limitations by incorporating multiple performance objectives and control criteria such as drift and member rotation, making it particularly useful for critical facilities and tall buildings (Choudhury & Singh, 2013). Direct Displacement-Based Design (DDBD) gained popularity; however, it frequently overlooked explicit member performance levels (PLs) and necessitated iterative member scaling (Qi & Moehle, 1991; Priestley & Kowalsky, 2000).

Unified Performance-Based Design (UPBD) addresses these gaps by simultaneously incorporating inter-storey drift (IDR) and performance levels, enabling direct determination of member sizes without iterative procedures. This review presents the historical evolution, theoretical foundation, applications, advantages, and limitations of UPBD, highlighting its significance in contemporary seismic design practice.

II. LITERATURE REVIEW

The engineering community has over the decades been using force-based design (FBD) methodologies where calculations of base shear are taken seriously in order to maintain structural safety. But with the maturity of our seismic behavior, it has been realized that force is not a good measure of actual structural damage. This discovery gave rise to a paradigm shift to Performance-Based Seismic Design (PBSD) with the engineers being able to customize structures to certain performance targets. The Unified Performance-Based Design (UPBD) method has become a key improvement in the performance-based design compared to previous methods of Displacement-Based Design (DBD).

Conventional approaches such as the popular Direct Displacement-Based Design (DDBD) frequently use inter-storey drift as a design parameter only and involve the tedious trial and error processes to come up with sizes of the members. To overcome these challenges, Choudhury (2008) and Choudhury and Singh (2013) proposed the UPBD method that simultaneously supports target drift and an individual level of member performance (PL) as well as offers explicit formulas of member sizing in the beginning of the design process. This simplified methodology refuses the trial and error of more traditional design, so that planned performance goals, like Immediate Occupancy (IO), Life Safety (LS), or Collapse Prevention (CP) are achieved with high accuracy.

UPBD has proven to be versatile in a variety of structural systems. Mibang and Choudhury (2021) were able to apply the technique to reinforced concrete (RC) dual systems, where frames and shear walls are used in collaboration to resist lateral forces. Their study was based on layered shell elements to simulate shear walls with a confirmation that UPBD has the potential to deal with complicated interactions among structural elements to meet preset drift targets. Moreover, Chaudhary and Choudhury (2020) investigated the application of UPBD combined with the base isolator, namely the geotextiles as a cheap friction isolator. Their results showed that when building with UPBD, inter-storey drift and base shear is reduced considerably when using these types of isolation systems, which increases the structural strength of mid-rise RC frames.

In addition to technical efficiency, recent literature has paid attention to economic and safety advantages of UPBD. Das et al. (2024) conducted a comparison between the RC frames designed by UPBD and the ones designed based on the traditional Indian Standard (IS) codes. They found that not only does UPBD result in structures with better performance measures but also it is less expensive, consuming comparatively less concrete and steel. In an attempt to further quantify the safety, researchers have developed a strong logarithmic relationship between the Inter-storey Drift Ratio (IDR) with the Global Damage Index (GDI). With these parameters connected to modified Park and Ang damage models, engineers are now able to predict structural damage with a reduced level of computational complexity.

the development of the unified performance-based methodology out of the force-based codes is a significant move to creating safer, predictable, and cost-effective environments. The combination of the performance at the member level as an inseparable part of the design stage gives UPBD a strong platform in the contemporary seismic engineering.

Table I. Key Differences of UPBD from FBD and DDBD

Method	**Design Criterion**	**Performance Consideration**	**Application**
FBD	Strength	Only collapse prevention	Conventional RC/steel buildings
DDBD	Inter-storey Drift	Drift only	RC frames/dual systems
UPBD	Drift + PL	Drift + Member rotation	RC/steel frames, dual systems, bridges

III. METHODOLOGY

The methodology for evaluating UPBD is centered on a comparative structural simulation framework that utilizes advanced nonlinear analysis techniques. The research design typically begins with the creation of prototype buildings designed initially according to traditional force-based codes (e.g., IS 1893:2016) to establish a baseline for performance and cost respectively. These buildings are then redesigned using the UPBD methodology to match identical performance objectives, ensuring a standardized benchmark for comparison.

The fundamental design procedure of UPBD differentiates itself through the direct calculation of member sizes. Using yield strain, beam length, and the desired performance level (Immediate Occupancy, Life Safety, or Collapse Prevention), engineers use Equation (6) to determine beam depth (h_b) at the inception of design. The actual multi-degree of freedom (MDOF) structure is then converted into an Equivalent Single Degree of Freedom (ESDOF) system using the fundamental mode shape profile and the total building mass. This conversion allows for the determination of target spectral displacements and equivalent viscous damping based on system ductility.

Data collection for performance validation is conducted through Nonlinear Static Pushover Analysis (POA) and Nonlinear Time History Analysis (NLTHA). POA is utilized to identify the structure's Performance Point (PP) and construct capacity curves to verify if target performance states are met. For more realistic assessment, NLTHA is performed using a suite of Spectrum Compatible Ground Motions (SCGMs), often sourced from databases like PEER NGA etc. These ground motions are spectrally matched to the design spectrum using tools like Seismomatch to ensure the building is tested at the appropriate seismic hazard level. Modeling is typically executed in software like SAP2000, with user-defined moment (M3) hinges for beams and axial-biaxial moment (P-M-M) hinges for columns, adhering strictly to ASCE 41 and FEMA 356 guidelines. Finally, if study requires structural damage, then quantified using the modified Park and Ang Damage Index (DI), which integrates ductility damage and hysteresis energy dissipation to provide a numerical damage scale from 0 to 1.

Force based design, based on elastic analysis and force reduction factors, has been globally employed but lacks accuracy in predicting inelastic structural response. Early PBD concepts appeared in the 1927 Uniform Building Code (UBC) and matured through FEMA and ATC guidelines, including FEMA 273/274, FEMA 356, and ASCE 41, defining operational, life safety, and collapse prevention performance levels (Park & Ang, 1985; ATC, 1996). DDBD further refined PBD but focused primarily on drift, ignoring plastic rotation criteria and requiring iterative sizing (Qi & Moehle, 1991; Priestley & Kowalsky, 2000). DDBD disregards member plastic rotation and lacks preliminary member sizing recommendations, resulting in repeated, resource-demanding design processes (Choudhury, 2008).

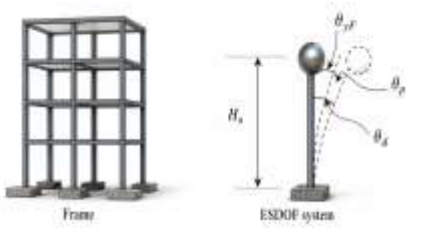

Figure 2. Equivalent SDOF System (Choudhury and Singh 2013)

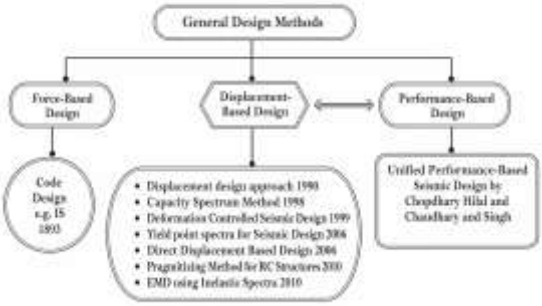

Figure 1. Types of Seismic Design Methods

Standard Frameworks:

FEMA/ATC: Introduced capacity spectrum approaches and specific performance levels for seismic evaluation.

PEER: Developed probabilistic frameworks emphasizing reliability and risk-informed design (Cornell & Krawinkler, 2000).

Tall Building Guidelines: Los Angeles Tall Buildings Structural Design Council LATBSDC (2008) and Structural Engineers Association of Northern California SEAONC (2007) incorporated PBSD for high-rise irregular structures.

CONCEPT AND FRAMEWORK OF UPBD:

UPBD converts multi-degree-of-freedom (MDOF) systems into Equivalent Single Degree-of-Freedom (ESDOF) systems, accounting for nonlinear behavior. Its theoretical foundation ensures accurate prediction of both global drift and member-level performance (Choudhury, 2008). UPBD simultaneously incorporates:

- Inter-storey Drift Ratio (IDR)
- Performance Level (PL), representing ductility capacity and damage-based criteria.

Unlike DDBD, UPBD eliminates iterative member sizing by deriving dimensions directly from combined IDR and PL criteria for beams, shear walls (Choudhury & Singh, 2013).

The study follows a comparative research design, initially developing a set of three-dimensional reinforced concrete (RC) frame and dual-system prototype buildings using traditional Indian Standard (IS) force-based codes (IS 1893:2016). These structures are then redesigned using the UPBD method to achieve identical target performance objectives Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) to establish a standardized benchmark for comparison. Prototype buildings vary in height (ranging from 3 to 15 storeys) and floor plans to test the method's versatility across different structural scales.

UPBD Design Procedure

The core design method involves a systematic procedure that differentiates it from traditional Displacement-Based Design (DBD):

- **Member Sizing:** Unlike iterative methods, UPBD utilizes direct theoretical formulas to determine beam depths and shear wall dimensions at the start of the design process, based on target inter-storey drift and average plastic rotation.
- **System Conversion:** Multi-degree of freedom (MDOF) structures is converted into an equivalent single degree of freedom (ESDOF) system using fundamental mode shape profiles and total building mass.
- **Effective Damping:** Equivalent viscous damping is computed as a function of system ductility (μ) to generate displacement spectra corresponding to specified seismic hazard levels (0.36g or 0.45g).

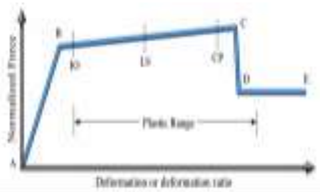

Figure 3. Force-deformation Behavior (FEMA-356)

Data collection is performed through numerical simulations rather than physical surveys. To represent realistic seismic hazards, Spectrum Compatible Ground Motions (SCGMs) are utilized. A suite of eleven ground motions, sourced from PEER NGA and COSMOS databases, is spectrally matched to target design spectra (IS1893 or Eurocode 8).

Table II. Summary of Key UPBD Case Studies

Year	**Structure Type**	**Analysis Type**	**Findings**	**Cost/Material Saving**	**Reference**
2008	RC Frame-Wall Dual	NSPA/NLTHA	Drift & PL satisfied	12–15%	Choudhury, 2008
2013	RC Frame	NSPA/NLTHA	Optimized beams & columns	13%	Choudhury & Singh, 2013
2021	Steel Frame	NLTHA	PL achieved	N/A	Mibang & Choudhury, 2021
2023	Bridge Piers	NLTHA	Drift & PL within ±20%	N/A	Mibang & Choudhury, 2023

The software is used for matching, ensuring the mean response spectrum remains within ±10% of the target.

Analysis Techniques

- **Nonlinear Static Pushover Analysis (POA):** Used to identify the Performance Point (PP) and construct capacity curves to verify if the structure meets the predefined damage states.
- **Nonlinear Time History Analysis (NLTHA):** Used to extract inelastic rotation, Inter-storey Drift Ratio (IDR), and hysteresis energy for every member across each ground motion.

Statistical Analysis and Validation

To establish a predictive relationship between structural response and damage, regression analysis is conducted on the simulated data. A logarithmic correlation equation was developed to predict the Global Damage Index (GDI) based on the maximum IDR, achieving a robust coefficient of correlation (R2) of approximately 98%. This model was further validated through a separate set of 6- and 10-storey buildings under different hazard levels (0.45g) to ensure accuracy and generalizability.

APPLICATIONS ACROSS STRUCTURAL SYSTEMS:

The method allows for accurate prediction of seismic performance at both global and member levels. Its non-iterative member sizing approach reduces design time, while offering cost-effectiveness with material savings. It is applicable to a wide range of structures, including RC frames, dual systems, high-rise buildings, base-isolated structures, and bridges.

- RC Frames and Dual Systems: UPBD validated for frames, dual systems, and URM-infilled walls (Choudhury, 2008; Singh & Choudhury, 2014).
- Steel and Composite Structures: Recent formulations adapt UPBD for steel frames, linking target drift with yield and plastic rotation (Mibang & Choudhury, 2021).
- Base-Isolated Buildings: Applied for buildings and geotextile-isolated RC structures (Chaudhary, A. K., & Choudhury, S.2019).
- Bridges: Adapted for circular bridge piers using drift and PL criteria without iterations (Mibang & Choudhury, 2023).

Although the adoption of these methods remains limited due to a lack of awareness and training among practitioners. Verification analyses often demand significant computational effort, which can be a barrier to widespread use. Further development is needed to extend these approaches to non-building structures and steel frames. Additionally, integration into national codes and routine engineering practice is still limited, which restricts their broader application.

UPBD increasingly correlates drift and plastic rotation with damage indices (DI/GDI), enhancing predictive efficiency and supporting resilience-based design. Research efforts are extending

UPBD applications to energy dissipation devices, high-rise irregular buildings, and fragility-based probabilistic assessments. Widely used software tools such as ETABS, SAP2000, PERFORM-3D, and MIDAS GEN facilitate these analyses, while emerging AI and machine learning techniques are being explored to optimize UPBD, reduce computational demands, and enable more effective predictive design.

IV. RESULTS AND DISCUSSION

The results of numerous studies consistently highlight that UPBD-designed buildings successfully achieve their target performance objectives with high precision. Nonlinear static and dynamic analyses show that achieved inter-storey drifts typically fall within a tolerable ±15% deviation from the design targets. This confirmation is critical because it validates the robustness of the initial theoretical formulas for member sizing, proving that the method accurately predicts structural behavior without the need for multiple redesign cycles.

Economically, the data provides a compelling case for the adoption of UPBD. Comparative analyses between IS code-designed frames and UPBD redesigns reveal an average reduction of 12% in concrete weight and 14% in reinforcing steel weight. This leads to an overall cost saving of approximately 13%. The results suggest that prescriptive codes often lead to "over-design" due to conservative assumptions and simplified methodologies, whereas UPBD's explicit consideration of nonlinear behavior and ductility allows for a more efficient and optimized distribution of forces. This optimization does not come at the expense of safety; UPBD structures consistently show an average 11% reduction in the Global Damage Index (GDI) compared to FBD counterparts, even when achieving identical performance levels.

A standout technical achievement in the results is the establishment of a strong logarithmic correlation between maximum inter-storey drift and structural damage. This simplified model allows engineers to predict seismic damage with minimal computational effort, which is invaluable for rapid post-earthquake assessments. Furthermore, for specialized systems like base-isolated frames, results show base shear reductions of up to 40%, proving that UPBD can be successfully paired with innovative technologies to create highly resilient structures at a fraction of the cost of traditional isolation methods.

IX. CONCLUSION

The shift from prescriptive force-based codes to the Unified Performance-Based Design (UPBD) method represents a transformative leap in earthquake engineering. By integrating member-level performance targets directly into the initial design phase, UPBD effectively eliminates the cumbersome trial-and-error iterations characteristic of previous methodologies. The synthesized research confirms that UPBD is a versatile, high-precision framework applicable across a wide range of structural configurations, from simple RC frames to complex dual systems and base-isolated buildings.

The method's advantages are quantified through both safety and economic metrics. UPBD structures are not only 13% more cost-effective than those designed with traditional codes but also exhibit an 11% reduction in global damage, proving that structural optimization and seismic resilience are not mutually exclusive. The development of highly accurate logarithmic correlation equations further empowers engineers to predict structural damage with minimal computational overhead, enhancing our ability to design and evaluate resilient built environments.

Despite its proven efficacy, the path toward global industry adoption requires further efforts in dissemination and training. Future research should prioritize investigating the impact of structural irregularities, different energy dissipation devices (like viscous or tuned mass dampers), and more extensive fragility studies to refine the method's predictive capabilities. Ultimately, the transition to Unified Performance-Based Design offers a clear pathway toward building cities that are not just collapse-resistant, but truly resilient and economically sustainable for future generations.

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