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Evaluating Seismic Response of a G+6 Structure using PBD and FBD

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***Abstract*— Earthquakes keeps on causing damage which continue to be a concern when we look past the data and it makes it essential to study their effects and evaluate structural performance. This study focuses on Performance Based Design (PBD), a method that inspects how structures actually respond during earthquakes, especially in the inelastic range. While many studies consider only elastic behaviour, inelastic performance still needs deeper exploration. PBD determines the required frame strength based on a chosen yield mechanism and target deformation, ensuring controlled and uniform damage distribution—unlike Force-Based Design (FBD), which often leads to localized failures and overlooks post-yield behaviour. Although FBD is widely used due to its simplicity, it may result in conservative designs with limited post-elastic performance.**

In this study, target drifts representing performance levels- Immediate Occupancy, Life Safety, and Collapse Prevention are used to compare PBD and FBD for RC structures under lateral loads. Through pushover curves, hinge formation, and performance points, PBD provides a clearer understanding of structural response across different performance levels. Findings indicate that PBD allows engineers to define desired performance more accurately, improves distribution of seismic damage, and helps ensure both safety and functionality. Despite needing further research for broader practical adoption, PBD remains a promising and effective approach for designing resilient and economical structures.

***Index Terms*— Performance-Based Design (PBD), Energy based method, Force Based Design (PBD), reinforced concrete (RC).**

I. Introduction

Earthquake is among the most damaging natural disasters which grounds vast amount of assets loss and human life injury resulting in devastating impact. It has always resulted in financial criticalness along with loss of life depending on its intensity. The ground motion intensity and the structures subjected to the earthquake waves decide the damage that might occur. While the arrival of the same is enduring, it considers both damages-structural and non-structural components. This study focuses mainly on comparing the level of structural damage due to such earthquakes on structure which were designed by both FBD and PBD. As it is the need of the hour to provide seismic-resilient design solutions, one focuses on the same. In current decades, engineers and scientists have engrossed on generating structural systems that can withstand seismic loads while curtailing damage and ensuring post-earthquake functionality [1]. Earlier more focus was given to the conventional code-based methods for designing the seismic resistant structures but now Performance based metho is in advance due to its constructive facts which are discussed throughout this study.

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It is being seen that PBD is beneficial in many terms. Two of the most widely used techniques that represent two distinct seismic design approaches are the Force Based Design (FBD) method and the Performance Based Design (PBD) method. In PBD, three levels are considered- Immediate occupancy, life safety and collapse prevention [2]. In the force-based method, lateral forces are obtained by considering the structure's mass, stiffness, and seismic coefficients using elastic analysis. FBD tries to make sure that a structure has enough strength to endure the design seismic forces, even though code-specified detailing criteria indirectly address ductility and deformation capabilities. As FBD seems not to provide precise results in terms of controlling structural performance or inelastic deformation when subjected to large ground vibrations, this principle often prevents in achieving the intended performance goals [3][4].
Performance Based Design (PBD) aims at attaining the performance objectives by controlling the plastic mechanisms and guaranteeing reliable, ductile performance. This approach is based on energy-based principles and the intended yield mechanism. This helps in dispersing the energy during seismic events. When PBD is compared with FBD, it is observed that the latter is less rational and provides less accessible framework for designing earthquakes. PBD emphasizes on the parameters like drift control, ductility demand and energy dissipation [5-7].
In PBD, the combination of site-specific variables such as soil conditions, material properties, and planned performance goals can be combined and as a result of which it provides more strong and ideal structural systems. Force based method follows a combined regulatory guideline, which might result in extra cautious designs or might fail to capture a structure's inelastic response. PBD provides more flexibility by merging energy dissipation, post-yield deformation, internal force redistribution and uniform damage distribution. This flexibility is spread across a range of seismic intensities [8-11]. Here, a G+6 reinforced concrete structure is done under FBD and PBD techniques. To study the hinge formation and performance point behaviour under lateral seismic loads, nonlinear pushover analysis is done. Results were obtained and it was validated that PBD provides adaptable, cost effective and reliable system compared to FBD. Future research should aim to develop PBD techniques by examining more extensive performance goals and a range of structural designs under different seismic hazard scenarios.

II. Performance-based Plastic Design (PBD)

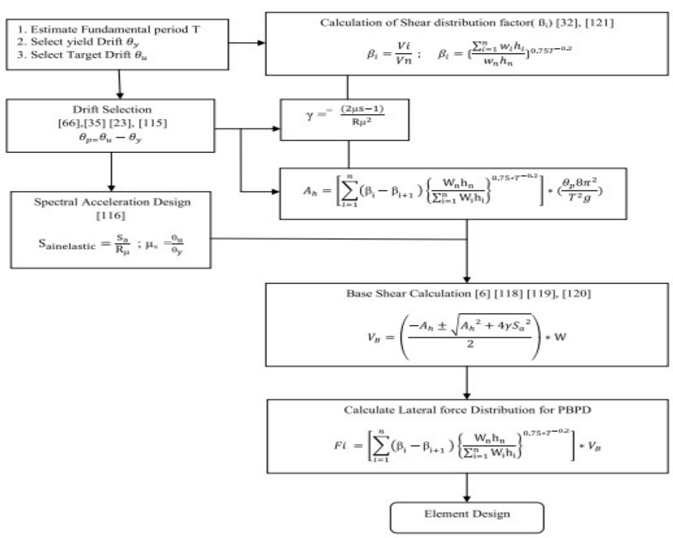

Figure 1 Steps in PBD

As an alternative of relying solely on theoretical models or procedural conformity, Performance Based Design (PBD) assesses systems and structures based on quantifiable outcomes. [5] developed PBD, an advanced method of seismic design that pursues to promptly reach a specified level of performance under specific seismic conditions. At the beginning of PBD design, the intended performance standards are clearly defined, including target drift, yield mechanism, and ductility demand. identifying the energy loss factor, selecting an ideal drift level that resembles with a desired performance objective (like collapse prevention or life safety), and carefully positioning plastic hinges to create a controlled yield mechanism are all steps in the procedure. Instead of using

the traditional code-based coefficients , PBD makes use of work energy equation for the design base shear calculation[6,7]. It is ensured by this methodology that the structure will behave in a ductile and stable mannerwith clearly defined performance outcomes during designlevel-earthquake. The steps of PBD are summarized in Figure 1 [12].
As it can be seen in figure 2 (FEMA 356, 2000; ASCE 41-17, 2017), the three levels which are specified: Immediate occupancy (IO), Life Safety (LS) and collapse prevention(CP) , they characterize the predetermined objectives which are designated for acceptable damage prevention of a sructure under various intensities and magnitudes of earthquake. If these minimum levels are incorporated right from the design stage, engineers can effectively manage ductility demands and reduce the residual deformation and limit the interstory drift ultimately improving resilience and predictability.
It is seen how well the structure behaves by checking the metrics like- target achievement, resource efficiency, and product quality [11] [15–19]. PBD provides engineers with rational insights by carefully gathering data and evaluating outcomes to predefined standards for optimizing material consumption, energy dissipation and design economy.

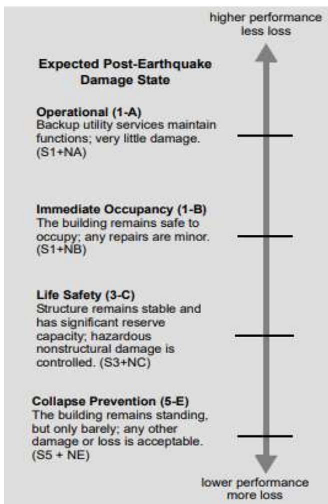

Figure 2 Target building performance levels

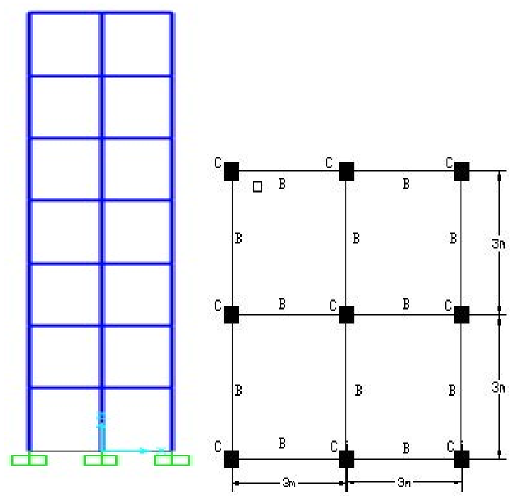

Figure 3 Plan and Elevation

PBD controls the inelastic behaviour and energy dissipation which helps in achieving the performance directly.
PBD incorporates the performance objectives such as drift limits, ductility demands and yield mechanisms in the design process which ultimately produces predictable and ductile structure reactions while undergoing earthquake, which are not considered in the FBD process. PBD considers the harmonization of input and dissipating energy through plastic deformation so that it results in safe and efficient operation of structure across various seismic intensity level ranges. Therefore, as PBD considers material efficiency along with other benefits, it is considered as an optimistic advancement in modern seismic design practices and it thus acts as a robust alternative to FBD.

III. METHODOLOGY

In this study, a G+6 structure is investigated by using both FBD and PBD and this is done by using non-linear pushover analysis. The stability of structure is evaluated by considering the hinge formation, performance point analysis and by checking the complete seismic resistance of structure under subjected lateral loads.

A. Reinforced Concrete (RC) Structural Behaviour

A Reinforced concrete structure has stability of both steel and concrete that helps protect the structure in the way that's possible. RC structure has compressive strength of concrete and tensile strength of steel which makes the structure helpful in bearing both lateral and gravity loads [20]. The structure is subjected to cyclic loading during the seismic excitation which ultimately causes yielding, cracking and inelastic deformations in the structure. Therefore, to prevent the brittle failure of the structure, ductile detailing such as concrete confinement, suitable reinforcement anchorage and controlled hinge formation is essential to ensure energy dissipation as well [21].

The aim of seismic design is to reserve the functionality and security of the structure across a range of earthquake magnitudes. As here, we have considered three levels: Immediate occupancy, Life safety and collapse prevention, so depending on the intensity of the earthquake, the structure can be seen to fall under one of the levels. For lighter earthquakes, the structure shall behave elastic, for moderate ones, repairable damage is acceptable and for severe earthquakes, the primary objective is to avoid collapse with significant inelastic deformation. In PBD, one specifically links target performance levels with deformation capacity and energy dissipation [5].

B. Performance Categories and Evaluation

It can be seen in Figure 2, and as discussed in above para, three targets are considered: Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). Figure 2 shows the plan and elevation of the model considered here. These categories specify the expected levels of post-earthquake damages ranging from operational (minimal damage and full functionality) to collapse prevention (severe damage with limited stability) [13].

IV. Results and Discussion

For checking the structural behaviour and its performance, a G+6 Reinforced Concrete (RC) structure is subjected to lateral loads and gravity loads and compared using both approaches (FBD and PBD). In accordance with the standard code conventional practices, the structure was designed using the FBD approach, wherein the design base shear was calculated using seismic coefficients prescribed in IS 1893 (Part 1):2016 and distributed along the height based on the fundamental mode shape of the structure. This study considers three target levels: Immediate Occupancy (IO), Life safety (LS) and collapse Prevention (CP) [13][14]. Further investigation has revealed that there are significant differences in the lateral force distribution patterns obtained from the two design approaches. It was observed that the lateral forces in FBD produced stronger forces at the base and weaker or smaller at the top. This doesn't directly explain the structure's inelastic behaviour under extreme seismic loads. In PBD, a nonlinear lateral force distribution which is based on the energy balance principle and intended yield mechanism is obtained. Seismic demands in PBD were uniformly distributed across the height of the structure which resulted in larger stresses in the regions that were expected to undergo greater energy dissipation and plastic deformation [5][6]. The PBD method has worked better than FBD method in terms of drift management and plastic hinge creation. The brittle behaviours were reduced in PBD method as the inelastic deformations were concentrated in the predetermined ductile zone [7][21]. The G+6 structure was inspected using the FBD and PBD techniques. The target performance levels that were taken into consideration for the study are defined systematically in the methodology section. The primary analytical outcomes for the FBD and PBD frames are shown in Table 1.

TABLE I: IMPORTANT PARAMETERS OF THE STUDY

Parameter	FBD	PBD_IO	PBD_LS	PBD_CP
W (kN)	5720.57	5720.57	5720.57	5720.57
θ_u	-	0.01	0.02	0.04
θ_y	0.0033	0.0033	0.00377	0.00663
θ_p	-	0.0067	0.01623	0.03337
μ_s	-	3.03	5.305	6.033
Γ	-	0.645	0.3844	0.3074
S_a	2.2295	0.7963	0.446	0.3716
A_h	-	2.2602	5.477	11.259
V_B	46.804	963.375	79.66	21.56
V_B/W	0.0082	0.1684	0.0139	0.00377

TABLE II: LATERAL FORCES OF THE FRAMES

Story	F_i (IO)	F_i (LS)	F_i (CP)
7	289.615	23.946	6.481
6	193.043	16.458	4.454
5	131.368	10.866	2.941
4	83.375	6.891	1.865
3	47.967	3.967	1.074
2	22.491	1.856	0.5023
1	6.211	0.5136	0.1391

Further investigation revealed that the lateral force distributions varied, as seen in Table 2.

A building's deformation pattern and overall seismic performance are greatly influenced by the lateral load distribution along its height in seismic design. The Force Based Design (FBD) method distributes the lateral loads according to code-specified formulas that primarily rely on the mass and height of structure. The largest lateral force occurs at the bottom level because the lateral force strength usually rises linearly from the top to the base. This distribution is based on the fundamental mode shape of the structure and assumes an elastic response. The nonlinear inelastic behaviour that happens during large earthquakes is not adequately captured by this straightforward and practical method [19][20]. The lateral force distribution as per storey level is as shown in Figure 4.

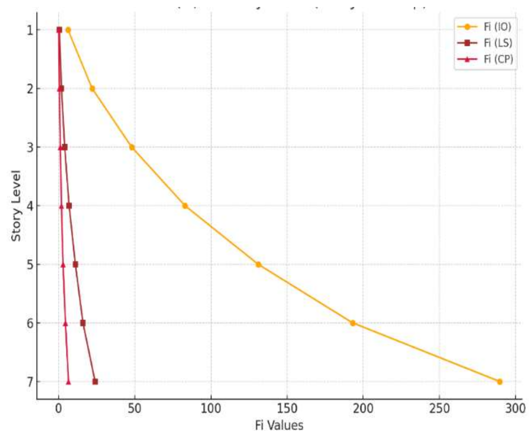

Figure 4 Lateral Storey Distribution

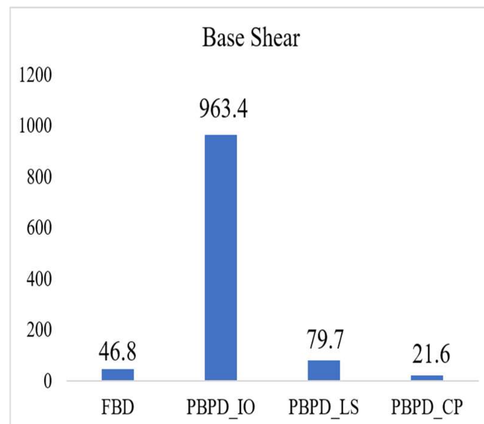

Figure 5 Base Shear Calculations

Nomenclature

θ_y = Selected Yield drift

θ_u = Targeted Drift

V_B=Base shear

R_μ = Ductility Reduction

μ_s = Structural Ductility Factor

θ_p = Inelastic Drift

γ= Energy modification factor

W=Seismic Weight

g = Acceleration due to Gravity

Fi=Lateral force at level i

Ah=Design horizontal seismic coefficient

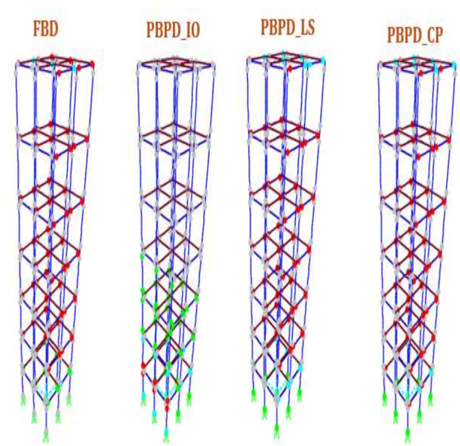

Figure 6 Hinge creation patterns

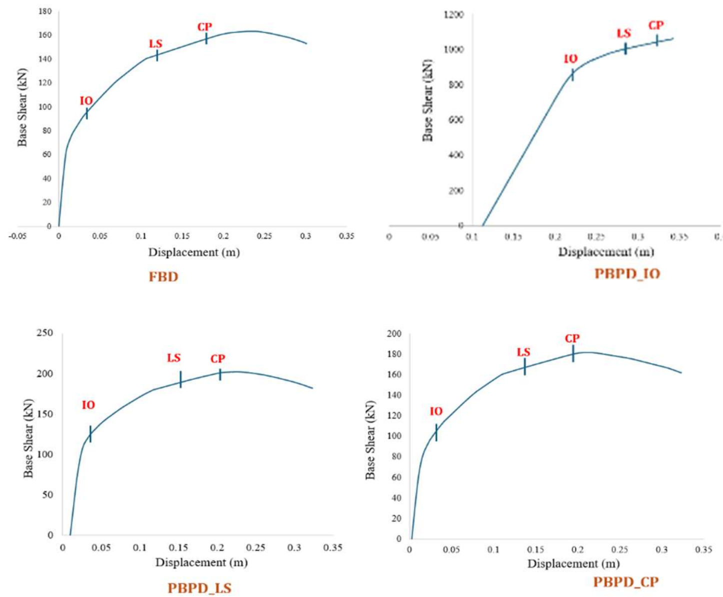

Figure 7 Capacity Curves

On the other hand, rather than using predefined empirical formulae, the Performance Based Design (PBD) approach practices energy balance and goal performance objectives to determine the lateral load pattern. In order to achieve a predetermined yield mechanism and consistent energy dissipation throughout the structure, the distribution of seismic forces is created. In the PBD method, the lateral load pattern obtained is nonlinear and is less concentrated at the base which guarantees the plastic hinge formation in planned ductile regions rather than in critical or brittle parts. This allows the controlled distribution of lateral forces so that the structure functions in a more reliable way during strong seismic excitations. It was observed that FBD based load distribution led to higher shear demands in the lower storeys which raised stiffness concentration near the base. But in PBD, the load pattern decreased the stiffness irregularities throughout the height of the structurer which in turn explains the advancement of this approach as the energy dissipation is proper in this.

Overall seismic demand of the building can be governed by checking the base shear distribution of the structure as shown in figure 5. In FBD, base shear is governed by various factors such as fundamental period, seismic zone, importance factor and response reduction factor (R) of the structure. The resultant base shear is spread subsequently throughout the building's height in accordance with empirical or mode shaped based calculations [19][20]. Although this approach guarantees adherence to code regulations, it does not accurately represent the structure's inelastic energy dissipation properties under significant ground motions.

When we talk about the PBD approach, it uses the energy balance concept for the estimation of base shear value. The value is lower compared to the FBD method. In PBD, the total seismic energy equals the elastic strain energy and the energy lost during plastic deformation. PBD provides seismically reliable and economically efficient structure as it provides efficient method for calculating seismic design forces.

The formation of hinge is different for both FBD and PBD as is shown in Figure 6. It can be observed that hinge formation focuses on base columns and beam-column joints for lower stories as seen in FBD which indicates that there are high concentration of load and a possibility of stiffness. This behaviour is commonly seen in FBD structures as the lateral force distribution is significantly skewed towards the base which causes localized yielding and early failure of important members of the structure. When we compare the results of PBD, a more controlled and dispersed hinge creation can be seen, which correlate to the Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) performance levels. As seen in the PBD model with IO level target, it exhibits limited inelastic action and good performance at low to moderate seismic waves action as it shows smaller hinge formation mostly near beam end. In PBD LS, reasonable number of hinges are formed mostly at beam ends and a few at column bases. In PBD CP model, the structure experiences significant energy dissipation without global instability by showing hinge formation that extends to more members while remaining well-distributed along the height. The capacity curves are as shown in Figure 7.

The achievement of Performance based design in attainment of the intended goal performance levels is demonstrated by the progressive and predictable hinge development in PBD designed frames. In PBD, plastic hinges are specifically formed at the designated ductile regions which improves the buildings overall seismic performance, energy dissipation capacity and structural resilience. These results demonstrates that PBD provides a more logical and performance-oriented framework for seismic design. It resulted in increased ductility, less damage concentration, and better post- earthquake functionality [23-32].

V. Conclusions

The entire motive of this study is to examine a G+6 Reinforced Concrete (RC) frame structure designed using both FBD and PBD method. The results that were obtained for each Structural Model highlighted the differences in Seismic behaviour produced using the two design methodologies. The comparative assessment which was done illustrated how the selected design influenced the critical response parameters including base shear, inter-storey drift, plastic hinge formation and overall energy dissipation. Through this evaluation, the study elaborated about the benefits of adopting PBD for mid-rise RC buildings subjected to seismic forces. This methodology can be broadened by incorporating structures with plan and elevation irregularities. The building feature elements such as setbacks, re-entrant corners, or uneven mass and stiffness distributions often behave differently under seismic loading, leading to torsional effects and localised demand concentrations. Including these irregular configurations would enable more holistic investigation of PBD's ability to deliver reliable and predictable performance across a wider range of structural conditions. Additionally, the target drift levels which are used in PBD can be adjusted depending on the type of structure used. Also depending on the design objectives and required performance criteria of the building. The structure of higher importance might require lower drift limits to minimize the damage or the conventional building may permit higher drift values so that can be incorporated accordingly. By modifying these parameters, designers can fine-tune the seismic response to meet both functional and safety demands, thereby enhancing the adaptability and practicality of the PBD framework.

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