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Dynamic Pushover Analysis of a Reinforced Concrete Frame: Review Article

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Abstract: *This review article presents a comprehensive investigation into the dynamic pushover analysis of a reinforced concrete frame. The study delves into the essential aspects of seismic assessment and performance evaluation of structures using this advanced analytical technique. With seismic events posing significant threats to structures, accurate assessment methodologies are crucial for ensuring the safety and reliability of buildings. The paper begins by introducing the concept of pushover analysis, which involves subjecting the structure to a series of lateral loads, representing seismic forces, in a progressively increasing manner. The behavior of the reinforced concrete frame under these loading conditions is studied in detail to understand its seismic response and performance characteristics. Different parameters, such as lateral load patterns, strength distributions, and ductility capacities, are explored to assess their impact on the overall seismic behavior of the structure. Furthermore, the review article discusses the key advantages and limitations of dynamic pushover analysis in comparison to traditional linear static approaches. Various numerical models and software tools used to conduct such analyses are critically reviewed, along with case studies to illustrate real-world applications and outcomes. This review article emphasizes the significance of dynamic pushover analysis as an effective seismic assessment tool for reinforced concrete frames. The insights gained from this study can aid researchers, engineers, and professionals in making informed decisions for the seismic design and retrofitting of structures, ultimately contributing to safer and more resilient built environments.*

Keywords: *Dynamic pushover analysis, Reinforced concrete frame, Seismic assessment, Performance evaluation, Lateral load patterns, Ductility capacities.*

1. INTRODUCTION

In the context of engineering design, seismic hazard was generally defined as the predicted level of ground acceleration, which would have been exceeded with 10% probability at the site under consideration due to the occurrence of an earthquake anywhere in the region, in the next 50 years. Seismic hazard estimation involved a lot of complex scientific perception and analytical modeling. A computational scheme was employed, which involved the following steps: delineation of seismic source zones and their characterization, selection of an appropriate ground motion attenuation relation, and a predictive model of seismic hazard. While these steps were region-specific, certain standardization of the approaches was highly essential to ensure reasonably comparable estimates of seismic hazard worldwide, consistent across regional boundaries. The National Geophysical Research Institute (NGRI), Hyderabad, India, had been identified as one such center responsible for estimating the seismic hazard for the Indian region. Notably, earthquake catalogs and databases served as the first essential input for delineating seismic source zones and their characterization. Thus, preparation of a homogeneous catalog for a region under consideration was an important task. The data from historic time to recent had been broadly divided into three temporal categories: 1) since 1964, for which modern instrumentation-based data were available, 2) 1900-1963, representing the era of early instrumental data, and 3) pre-1900, consisting of pre-instrumental data primarily based on historical and macro-seismic information. In India, the scenario had been somewhat similar.

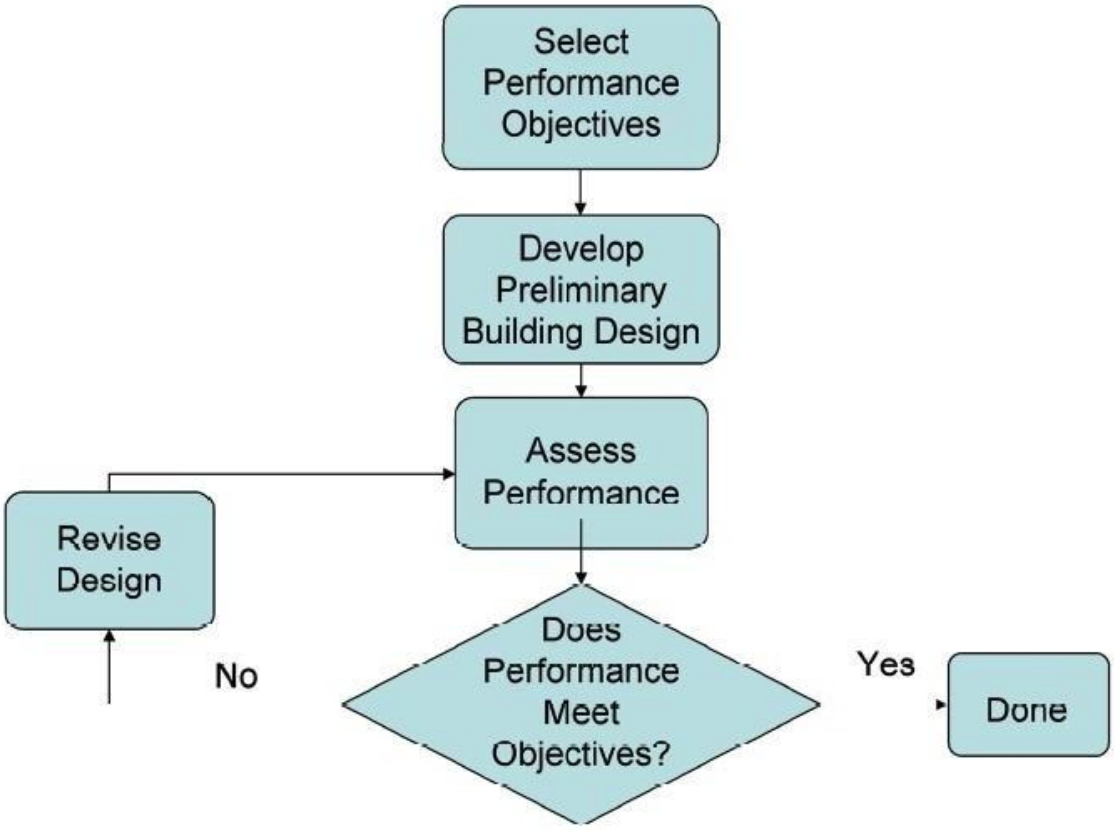

Figure 1: Performance-Based Design Flow Diagram (ATC, 1997a)

2. PURPOSE OF DOING PUSHOVER ANALYSIS

The pushover analysis offers valuable insights into various response characteristics that cannot be obtained from elastic static or dynamic analyses. These include determining realistic force demands on potentially brittle elements like axial forces on columns, force demands on brace connections, moment demands on beam-to-column connections, and shear force demands in reinforced concrete beams. Additionally, the method provides estimates of deformation demands for elements that must undergo inelastic behavior to dissipate the energy imparted to the structure. It also helps understand the consequences of individual element strength deterioration on the overall behavior of the structural system. By identifying critical regions with high deformation demands, pushover analysis guides the focus of detailing efforts. Moreover, it pinpoints strength discontinuities in plan elevation that may alter dynamic characteristics within the elastic range. The analysis also yields estimates of interstory drifts, accounting for strength or stiffness discontinuities, enabling the control of damages and evaluation of P-Delta effects. Lastly, pushover analysis verifies the completeness and adequacy of the load path, encompassing all structural elements, connections, stiff non-structural elements of significant strength, and the foundation system. (Source: www.architectjaved.com).

3. DIFFERENT HINGE PROPERTIES IN PUSHOVER ANALYSIS ON SAP2000

In SAP2000, there are three types of hinge properties: default hinge properties, user-defined hinge properties, and generated hinge properties. Frame elements can only be assigned default hinge properties or user-defined hinge properties. When these hinge properties are assigned, the program automatically generates a separate hinge property for each hinge. Default hinge properties cannot be modified or viewed because they depend on the section of the frame element. To observe the effect of default properties, they must be assigned to a frame element, and then the resulting generated hinge property can be viewed. These default properties are typically based on FEMA-273 and/or ATC-40 criteria. User-defined hinge properties can either be based on default properties or be entirely customized. When they are based on default properties, they cannot be viewed due to their section dependency. However, non-default user-defined properties can be viewed and modified. Generated hinge properties are utilized in the analysis and follow an automatic naming convention, using the frame element label and a hinge number. These properties can be viewed but cannot be altered. The program sequentially assigns hinge numbers, starting from 1, for each hinge applied to the frame element. The distinction between defined properties (default and user-defined) and generated properties is essential because hinge properties are often section-dependent. Different frame sections in the model could require numerous hinge properties, making it more practical for the program to automatically generate them based on the applied conditions.

4. LITERATURE REVIEW

Comprehensively covering the entire literature related to structural modeling would be challenging within the scope of this chapter. Hence, a concise review of previous studies pertaining to the application of pushover analysis of structures is presented in this section. The literature review primarily focuses on recent contributions concerning pushover analysis and highlights past endeavors that are most relevant to the current research objectives.

Dhileep. M et al., (2011) The non-linear direct numerical integration of the equations of motion in seismic analysis poses practical difficulties, leading to the adoption of non-linear static pushover analysis for structures. Pushover analysis has gained popularity due to its simplicity, but its effectiveness in capturing the contribution of higher modes and non-linear effects in stiff and irregular structures is not fully developed. This paper aims to address the behavior of high frequency model responses in non-linear seismic analysis of structures. Non-linear static pushover analysis has become a standard tool worldwide, serving as an approximation to non-linear time history analysis for engineers, researchers, and professionals. In particular, high frequency modes may significantly impact the seismic analysis of irregular and stiff structures. To consider the contribution of higher modes, structural engineers can incorporate high frequency modes into the non-linear static pushover analysis. The study focuses on investigating the behavior of high frequency modes in non-linear static pushover analysis for irregular structures. Notably, at high frequencies, the responses of non-linear dynamic analysis tend to converge with the results obtained from non-linear static pushover analysis. Understanding the behavior of high frequency modes in this context is crucial for accurate and efficient seismic analysis of structures.

Amar et al.(2015) The results obtained from the comparison of non-linear static pushover and incremental dynamic analyses were examined. It was observed that in the case of non-linear static pushover analysis, the seismic behavior factor decreased with an increase in the number of stories in the structure. However, in the case of non-linear incremental dynamic analysis, a different trend was observed: the seismic behavior factor increased as the number of stories increased. This finding indicated that the seismic behavior factor's value was influenced by various parameters, including the height of the structure, which was not accounted for in the seismic design codes. Based on the information obtained from incremental dynamic analyses, it was evident that the seismic behavior factor adopted by the seismic design code RPA 99/Version 2003 was overestimated, particularly for low-rise frame structures. The paper also presented conclusions drawn from the study's findings and outlined the limitations encountered during the research.

Bracci and Joseph. (2015) The adaptive pushover analysis played a crucial role in the methodology, relying on a reasonable estimation of the structure's failure modes. The proposed technique was applied to a one-third scale three-story reinforced concrete frame model building, which underwent repeated shaking table excitations. Subsequently, the structure was retrofitted and subjected to further testing at the same intensities. The study demonstrated that the procedure yielded reliable estimates of story demands versus capacities, serving as valuable input for seismic performance assessment and retrofit evaluation of structures.

Occhipinti and Giuseppe. (2017) The proposed solution was thoroughly investigated using a high fidelity model implemented in the software ADAPTIC. The numerical results obtained from the high fidelity 3D nonlinear dynamic simulations revealed a significantly poor seismic performance of the existing structure. However, the numerical simulations for the retrofitted structure confirmed that the proposed solution had a substantial positive impact on the response under earthquake loading. This enhancement enabled the structure to withstand the design earthquake with minimal damage to the original RC beams and columns, thus demonstrating the feasibility of retrofitting for this typical multi-story RC building structure.

Oyguc et al. (2018) The results of previous reconnaissance studies, involving one of the present authors, were discussed. Capacities of the considered reinforced concrete frames (RCFs) were determined using a 3D single-run adaptive pushover procedure capable of accounting for plan irregularities. The performance assessment procedure based on the 2007 Turkish Earthquake Code was then applied to these investigated buildings. Furthermore, nonlinear dynamic time history analyses were conducted using the previously selected time histories. The hysteretic behavior of the considered buildings was examined as a consequence of the analyses, and the seismic response of the buildings was evaluated in terms of interstory drifts, considering various sets of selected ground motions. None of the buildings were found to satisfy the expected performance level. Additionally, the numerical results exhibited a strong correlation with the field observation findings.

Liu et al. (2018) In this paper, collapse fragility curves were obtained by conducting incremental dynamic analysis on nonlinear equivalent single degree of freedom (ESDOF) systems for reinforced concrete (RC) frame structures. A five-story three-span reinforced concrete frame structure was chosen as a case study, and it was represented by ESDOF systems using pushover curves. The nonlinear ESDOF systems employed the modified Ibarra-Krawinkler (I-K) hysteretic model within the OpenSees platform. To assess the applicability and accuracy of the nonlinear ESDOF systems quantitatively, 20 real ground motion records were selected as inputs and compared with the results obtained from seismic collapse fragility analysis of the original structure. To account for the effects of modeling uncertainties on collapse fragility, random pushover analysis considering modeling uncertainties was conducted on the nonlinear ESDOF systems. The results indicated that the developed ESDOF systems efficiently evaluated the collapse-resistant capacity of the prototype structure while maintaining the accuracy of the approximate model. The collapse margin ratios of the ESDOF systems were found to agree quite well with the original structure. Furthermore, the collapse margin ratios of the ESDOF systems, considering modeling uncertainties, were larger than those not considering modeling uncertainties.

Ayşegül et al. (2020) The aim of this study was to assess the impact of steel plate shear walls (SPSWs) on the earthquake response of reinforced concrete (RC) moment resisting frames. Two types of RC frames, namely, ductile and nominally ductile RC frames, were utilized, each consisting of five storeys and three bays. The first storey had a height of 4 meters, while the remaining storeys were 3 meters in height. To improve the seismic performance of the existing structures, a special unstiffened SPSW system was integrated into the middle bays of each frame. The SPSWs included an infill steel plate and horizontal and vertical boundary elements such as beams (HBEs) and columns (VBEs). Analytical modeling of the structures was conducted using the finite element method, and they were evaluated using both nonlinear static (pushover) and time history analyses. In the pushover analysis, two load distribution methods were considered: first mode load distribution and uniform load distribution. For the dynamic time history analysis, a set of ground motion records was employed, considering a seismic hazard level with a 2% probability of exceedance in a 50-year period. The seismic response of the ductile and nominally ductile RC frames, with and without SPSWs, was compared. The results indicated a significant improvement in the earthquake performance of both the ductile and nominally ductile RC frame structures when SPSWs were incorporated.

Yüksel et al. (2020) The objective of this paper was to explore the various effects of reinforcement corrosion on reinforced concrete buildings. To achieve this, a hypothetical five-storey reinforced concrete building frame was designed. Three different modes of action were selected, including corrosion on the ground floor alone, corrosion on one facade, and corrosion on two neighboring facades of the building. Each mode of action was subjected to different corrosion scenarios, ranging from zero to 15% mass loss in 3% increments. Pushover analyses were conducted for each corrosion scenario, and the results were utilized to perform a structural performance evaluation in accordance with Eurocode 8. The findings revealed a general decrease in structural performance with significant changes in the building's dynamic characteristics. The extent of the decrease varied depending on the corrosion scenarios and modes of action. Notably, important alterations in structural behavior and instances of premature damage were observed, along with a reduction in the building's displacement ductility. In severe-corrosion scenarios, reductions in moment and curvature capacities could cause a shift in the structural behavior of load-bearing members from ductile to non-ductile. Overall, the study demonstrated the detrimental effects of reinforcement corrosion on the structural integrity and performance of reinforced concrete buildings.

Huseyin et al. (2021) This study focused on applying Static and Dynamic nonlinear analyses to an old moment-frame reinforced concrete building. The selected case study was a template building designed in 1982, typical of the structures constructed in the Albanian region during the communism era, using outdated standards (KTP 2-78) and lacking shear walls. The capacity calculation involved conducting Pushover analysis with an inverse triangular load pattern. For the demand calculation, Incremental Dynamic Analysis (IDA) was employed, providing the response behavior of the structure from the elastic range to collapse. A set of 18 earthquakes without directivity marks was used for the dynamic analysis. Both Pushover and IDA analyses were performed based on the FEMA 356 guidelines, and limit states were defined accordingly. The mathematical model was prepared using the Zeus-NL software, specifically designed for earthquake applications. The IDA analysis considered parameters such as 5% damped first mode spectral acceleration (Sa(T1,5%)) as the intensity measure (IM) and maximum global drift ratio (ϴmax) as the damage measure (DM). For the Pushover curve, the limit states were Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). Similarly, for the IDA curve, the limit states were IO, CP, and Global Instability (GI), as per FEMA guidelines. The IDA curves were summarized into 16%, 50%, and 84% fractiles, following the literature's suggestions. A comparison was made between the Pushover and IDA median (50% fractile) to illustrate the correlations between performance levels. Finally, the structural performance was interpreted based on the obtained outcomes.

Awayo et al. (2022) The primary objective of this study is to develop seismic fragility curves that illustrate the probability of exceeding a damage limit state for a specific structure type subjected to seismic excitation. To achieve this, three distinct buildings were selected as case studies, namely a seven-story, eleven-story, and sixteen-story building, each with a typical floor plan. For each building, two different models were considered: one as a bare frame and the other with horizontal concrete block (HCB) infill configurations, with varying percentages of infill. All building models were analyzed using Seismo-Struct software to assess their seismic vulnerabilities. Non-linear dynamic time history and pushover analyses were employed to generate fragility curves. In the non-linear dynamic time history analysis, 30 artificial accelerograms were utilized. To develop the fragility curve, non-linear dynamic analyses were conducted for each of the 30 building models under different ground motion scenarios, and the maximum roof displacement (ID) was recorded for each ground motion. The results of the study revealed that the bare frame had the highest probability of failure, while building models with a larger percentage of infill configurations showed lower failure probabilities compared to slightly infilled building models. The infill configurations significantly contributed to reducing large lateral deflections, resulting in lower and more tolerable story displacements during earthquake excitations. This ultimately led to a reduced probability of failure for the structure at life safety and collapse prevention limit states.

Awchat et al. (2023) This paper presented the results of an IDA and seismic fragility analysis conducted on a ground storey + 7-floor (G + 7) reinforced concrete frame subjected to a suite of eleven ground motions. The primary objective of the study was to perform equivalent static and linear-dynamic analyses to meet the requirements of both National and International seismic design codes. Subsequently, pushover analysis was carried out by introducing parametric auto hinges based on ASCE 41-13 tables, considering both geometric and material non-linearity. For the pushover analysis, suitable criteria for seismic intensity were utilized to select strong ground motions. IDA was then conducted using SeismoStruct 2022 software, and based on the IDA curves, the fragility analysis was performed. The study's results were found to be valuable for researchers in predicting the probability of structural damage under earthquake events. The use of IDA and seismic fragility analysis provided important insights into the behavior of the reinforced concrete frame, enabling a better understanding of its seismic performance and vulnerability.

Mincigrucci et al.(2023) The main objective of this study was to assess the response of Glass Fiber Reinforced Polymer (GFRP) under dynamic conditions, specifically seismic loads, and compare its performance with two traditional building materials: reinforced concrete and structural steel. For this purpose, a finite element analysis was conducted on a two-dimensional frame modelled using steel, reinforced concrete (RC), and GFRP pultruded materials, and subjected to seismic input. The dynamic response of the structure was evaluated for all three building materials in terms of displacements, inter-storey drift, base shear, and stress. The results demonstrated that the GFRP frame exhibited a favorable performance, with stress distribution and displacements falling between those of RC and steel. Most notably, the GFRP frame outperformed the other materials in terms of reduced weight, leading to significantly lower base shear (a reduction of 40% compared to steel and 88.5% compared to RC). Overall, the study showed promising results for the use of GFRP as a building material under dynamic conditions, particularly in seismic-prone regions. The lightweight nature of GFRP contributed to its improved seismic performance, making it a viable alternative to traditional materials like steel and reinforced concrete in certain structural applications.

5. SUMMARY

This review article provides an extensive investigation into the dynamic pushover analysis of a reinforced concrete (RC) frame, focusing on seismic assessment and performance evaluation. Seismic events pose significant threats to structures, necessitating accurate assessment methodologies to ensure safety and reliability. The paper introduces the concept of pushover analysis, subjecting the RC frame to a series of lateral loads representing seismic forces in a progressively increasing manner. Detailed examination of the structure's behavior under these loading conditions helps understand its seismic response and performance characteristics. Various parameters, such as lateral load patterns, strength distributions, and ductility capacities, are explored to assess their impact on the structure's overall seismic behavior. The advantages and limitations of dynamic pushover analysis are discussed in comparison to traditional linear static approaches. The review critically assesses numerical models and software tools used for such analyses, alongside real-world case studies illustrating practical applications and outcomes. Emphasizing dynamic pushover analysis as an effective seismic assessment tool for RC frames, the study provides valuable insights for researchers, engineers, and professionals in making informed decisions for seismic design and retrofitting of structures. The comprehensive exploration of dynamic pushover analysis ensures safer and more resilient built environments in earthquake-prone regions.

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