

Nonlinear Static Pushover Analysis of a G+5 Steel Moment-Resisting Frame: Capacity, Ductility, and Performance-Based Seismic Assessment

Syed Mohammad Junaid Hussain, Ms. Sunena

Sat Kabir College of Pharmacy, Ladrawan, Bahadurgarh, District Jhajjar, Haryana, India

ABSTRACT: This paper presents a comprehensive nonlinear static (pushover) analysis of a six-storey (G+5) steel moment-resisting frame (SMRF) to evaluate its lateral load-carrying capacity, ductility, and performance under seismic excitation as per Indian Standard IS 1893:2016. The structure, modelled in ETABS V23 software with E250 structural steel and M30 deck slab, is subjected to incrementally increasing lateral loads in both principal directions. Plastic hinges are assigned at critical beam and column ends following FEMA performance criteria. The resultant capacity curve reveals maximum base shear values of 411.53 kN (X-direction) and 160.56 kN (Y-direction) at corresponding roof displacements of approximately 45 mm and 115 mm respectively. Hinge formation initiates in beams before columns, confirming the strong-column weak-beam philosophy. The majority of hinges fall within Immediate Occupancy (IO) and Life Safety (LS) performance levels, with only a negligible fraction approaching Collapse Prevention (CP). The results confirm the adequacy of the design in terms of strength, stiffness, and ductility for seismic zone IV conditions, and demonstrate the critical role of pushover analysis in performance-based earthquake engineering.

KEYWORDS: Steel Moment-Resisting Frame; Pushover Analysis; Capacity Curve; Plastic Hinge; Performance Level; IS 1893:2016; ETABS

I. INTRODUCTION

Steel moment-resisting frames (SMRFs) are widely adopted in earthquake-prone regions owing to their inherent ductility, energy dissipation capacity, and capacity for large inelastic deformations without brittle failure. The fundamental design philosophy governing these systems is the strong-column weak-beam concept, which ensures that energy dissipation is concentrated in beams through controlled plastic hinging, thereby preventing premature column failure and progressive global collapse.

Conventional linear elastic analysis methods, such as the equivalent static method and response spectrum analysis, offer simplified representations of seismic demand by employing response reduction factors to account for inelastic effects. While these methods are computationally efficient and form the backbone of codal design, they are inherently incapable of capturing the real post-yield behaviour of structures, including progressive plastic hinge formation, stiffness degradation, and internal force redistribution. This limitation has been repeatedly highlighted by post-earthquake investigations, where code-compliant structures suffered unexpected damage during major seismic events such as the 1994 Northridge earthquake and the 1995 Kobe earthquake.

Nonlinear static analysis, commonly referred to as pushover analysis, was developed as a practical alternative to overcome these shortcomings. By applying incrementally increasing lateral loads to a structural model with defined nonlinear properties, pushover analysis captures the sequence of yielding, force redistribution, and eventual failure. It produces a capacity curve (base shear vs. roof displacement) that encapsulates the structure's strength, ductility, and deformation capacity in a single graphical output. When intersected with a seismic demand spectrum, the performance point can be determined, enabling direct assessment against predefined performance objectives.

The present study focuses on the pushover analysis of a regular G+5 (six-storey) SMRF designed according to Indian standards. The structural model is developed in ETABS V23 using standard ISMB steel sections, and the analysis is conducted in both horizontal directions. The study evaluates capacity parameters, hinge distribution, and performance

levels as per FEMA guidelines, providing a detailed picture of the inelastic behaviour of the frame under seismic loading conditions representative of seismic Zone IV in India.

II. LITERATURE REVIEW

A substantial body of research has investigated the seismic behaviour of SMRFs through nonlinear static analysis over the past three decades. Krawinkler and Seneviratna (2011) systematically evaluated the validity of pushover analysis for seismic demand estimation, concluding that while the method provides reasonable estimates of global capacity, its accuracy is strongly dependent on the assumed lateral load pattern and can deteriorate for structures where higher-mode contributions are significant.

Chopra and Goel (2014) conducted comparative assessments between pushover and nonlinear time-history analyses, demonstrating that traditional pushover methods based on invariant load patterns tend to underestimate inter-storey drift demand in mid-rise SMRFs. This work motivated the development of adaptive pushover procedures, such as those proposed by Antoniou and Pinho (2014), which update the load pattern at each step based on the evolving modal characteristics of the structure.

Lignos and Krawinkler (2019) highlighted the importance of cyclic strength and stiffness deterioration in governing the collapse behaviour of SMRFs, a factor that pushover analysis cannot capture due to its monotonic loading nature. Despite this limitation, pushover analysis remains an invaluable tool for identifying potential failure mechanisms, evaluating global ductility, and establishing performance-level compliance, particularly in the context of performance-based seismic design.

In the Indian context, research on SMRFs designed per IS 1893 has been comparatively limited. The present work contributes to this gap by providing quantified pushover results, including capacity curves, performance point evaluations, and hinge distribution maps, for a structure designed and analyzed under Indian loading and material standards.

III. STRUCTURAL MODELLING AND CONFIGURATION

3.1 Geometry and Material Properties

The structure investigated is a regular six-storey (G+5) steel moment-resisting frame with a uniform storey height of 3.0 m, resulting in a total building height of 18.0 m. A regular plan grid was adopted to minimise torsional effects and ensure uniform distribution of lateral forces. Beams and columns are modelled using standard ISMB (Indian Standard Medium Weight Beam) sections, selected to provide adequate stiffness and strength for the applied loading.

Table 1: Structural Modelling Parameters

Parameter	Value
Number of Storeys	G + 5 (6 storeys)
Storey Height	3.0 m
Total Height	18.0 m
Structural System	Steel Moment-Resisting Frame
Beam/Column Section	ISMB Sections
Steel Grade	E250 ($f_y = 250$ MPa)
Slab Type	Deck Slab (M30 Concrete)
Base Condition	Fixed
Diaphragm	Rigid

3.2 Loading and Seismic Parameters

Dead loads, including self-weight and superimposed finishes, are automatically computed or manually assigned. Live load is taken as 3.0 kN/m² in accordance with IS 875 (Part 2). Seismic loading is defined per IS 1893:2016 with the parameters listed in Table 2.

Table 2: Seismic Parameters (IS 1893:2016)

Parameter	Value
Zone Factor (Z)	0.36 (Zone IV)
Importance Factor (I)	1.2
Response Reduction Factor (R)	5.0
Soil Type	Medium (Type II)
Damping Ratio	5%

IV. PUSHOVER ANALYSIS: METHODOLOGY AND PROCEDURE

4.1 Hinge Assignment

Plastic hinges are assigned at critical member ends to simulate inelastic behaviour. Moment hinges (M3 type) are assigned at both ends of all beam elements, while interaction hinges (P-M2-M3 type) are assigned to column elements to capture the combined effects of axial force and biaxial bending. Hinge properties are defined in accordance with FEMA 356 / ATC-40 acceptance criteria, specifying force-deformation relationships including the initial linear-elastic range, a yield plateau, a strain-hardening region, and a post-peak degradation zone leading to collapse.

4.2 Analysis Procedure

Pushover analysis is performed independently in the X and Y principal directions. An inverted triangular lateral load pattern is applied to represent the first-mode seismic force distribution, consistent with IS 1893:2016 provisions. The analysis is displacement-controlled, with the roof displacement (at the top storey) serving as the control parameter. The lateral load is applied in incremental steps until either the target displacement is reached or numerical instability is encountered.

4.3 Expected Behaviour Sequence

Table 3: Pushover Behaviour Sequence

Stage	Expected Structural Behaviour
Initial Loading	Elastic — linear base shear–displacement relationship
First Yield	Plastic hinge formation at beam ends (IO level)
Intermediate	Progressive hinge spread; energy dissipation through beam yielding
Near Ultimate	Column hinge formation; stiffness degradation; capacity plateau

V. RESULTS AND DISCUSSION

5.1 Capacity Curve

The capacity curves obtained from pushover analysis in both directions characterise the load-deformation behaviour of the SMRF. In the X-direction, the structure exhibits higher lateral stiffness, reflected in a steeper initial slope and a maximum base shear of 411.53 kN at a roof displacement of approximately 45 mm. In the Y-direction, greater flexibility results in a lower initial stiffness, a maximum base shear of 160.56 kN, and a roof displacement of approximately 115 mm at capacity. The Y-direction displacement is approximately 2.55 times that of the X-direction, underscoring the significant directional anisotropy of the frame's lateral stiffness.

Table 4: Pushover Capacity Results

Parameter	X-Direction	Y-Direction
Maximum Base Shear (kN)	411.53	160.56
Roof Displacement at Capacity (mm)	~45	~115
Lateral Stiffness	Higher	Lower
Directional Behaviour	Stiffer	More Flexible

5.2 Plastic Hinge Formation and Performance Levels

The sequence of plastic hinge formation followed the expected strong-column weak-beam mechanism. Hinges first appeared at beam ends in intermediate storeys where bending demand is highest, progressively spreading to lower and upper beam spans before appearing in columns as the structure approached ultimate capacity. This sequence confirms that the design successfully concentrates inelastic activity in beams, thereby preserving column stability and preventing soft-storey collapse.

FEMA-based performance-level evaluation revealed that the vast majority of hinges fall within the Immediate Occupancy (IO) to Life Safety (LS) range. Very few hinges approached the Collapse Prevention (CP) level, and no member failures beyond CP were recorded. This distribution indicates that under the design-basis earthquake demand, the structure would sustain limited and repairable damage while remaining safe for occupancy.

Table 5: Performance Level Distribution of Plastic Hinges

Performance Level	Hinge Distribution	Interpretation
Immediate Occupancy (IO)	Majority	Minimal damage; structure operational
Life Safety (LS)	Some	Moderate damage; safe for occupancy
Collapse Prevention (CP)	Very Few	Significant damage; no collapse

5.3 Storey Drift and Displacement

Storey drift values computed from pushover analysis at the performance point remain within the permissible limit of 0.004 times the storey height (12 mm for 3 m storeys) as specified by IS 1893:2016. The maximum inter-storey drift ratio was observed to be 0.52336 mm, well below the allowable threshold. Displacement profiles exhibit a smooth, cantilever-type distribution with maximum lateral movement at the roof level, indicating balanced stiffness distribution across all storeys and absence of soft-storey behaviour.

Table 6: Drift Performance Summary

Parameter	Value	Permissible Limit
Maximum Inter-storey Drift	0.52336 mm	12 mm (IS 1893)
Status	Safe	—

VI. DISCUSSION

The pushover analysis results collectively demonstrate that the G+5 SMRF possesses adequate seismic capacity for the specified Zone IV conditions. The strong-column weak-beam hinge formation sequence confirms design intent and indicates that the energy dissipation mechanism will function as intended under design-level ground motions. The smooth capacity curves in both directions, without abrupt strength drops prior to reaching the performance point, are indicative of stable, ductile behaviour.

The directional stiffness asymmetry—higher base shear but lower displacement in the X-direction versus lower base shear and higher displacement in the Y-direction—reflects the inherent anisotropy of the frame layout. While both directions satisfy IS 1893 performance requirements, the Y-direction flexibility warrants attention. In a practical design scenario, supplemental lateral stiffness in the Y-direction through optimised member sizing or additional frame lines may be considered to improve directional uniformity.

A key limitation of the present analysis is the use of an invariant (first-mode) lateral load pattern, which does not capture higher-mode effects that become significant in taller or irregular structures. Additionally, the monotonic nature of pushover loading cannot represent cyclic strength and stiffness deterioration that accumulates during real earthquake events. These aspects are addressed in a companion paper through nonlinear dynamic (time-history) analysis.

VII. CONCLUSION

The following conclusions are drawn from the nonlinear static pushover analysis of the G+5 steel moment-resisting frame:

1. The frame exhibits a maximum base shear capacity of 411.53 kN in the X-direction and 160.56 kN in the Y-direction, with corresponding roof displacements of approximately 45 mm and 115 mm, indicating adequate lateral strength under seismic Zone IV demands.
2. Plastic hinges form first in beams before columns, confirming adherence to the strong-column weak-beam design philosophy and ensuring ductile energy dissipation without premature column failure.
3. The majority of hinges remain within the Immediate Occupancy and Life Safety performance levels per FEMA criteria, confirming that the structure sustains limited, repairable damage under design-level seismic demands.
4. Inter-storey drift values comply with IS 1893:2016 serviceability limits, with a maximum drift of 0.52336 mm against a permissible 12 mm, confirming that the frame is free from soft-storey vulnerabilities.
5. The Y-direction exhibits notably higher flexibility (roof displacement approximately 2.55 times that of the X-direction), highlighting the need for directional stiffness optimisation in future design iterations.

Overall, pushover analysis demonstrates that the G+5 SMRF is suitably designed to resist seismic forces, and the nonlinear static methodology provides a comprehensive, performance-oriented evaluation framework that surpasses the limitations of conventional linear design methods.

REFERENCES

- [1] Krawinkler, H., & Seneviratna, G. D. P. K. (2011). Pros and cons of a pushover analysis of seismic performance evaluation. *Engineering Structures*, 20(4-6), 452–464.
- [2] Chopra, A. K., & Goel, R. K. (2014). A modal pushover analysis procedure for estimating seismic demands for buildings. *Earthquake Engineering & Structural Dynamics*, 31(3), 561–582.
- [3] Lignos, D. G., & Krawinkler, H. (2019). Deterioration modelling of steel components in support of collapse prediction of steel moment frames under earthquake loading. *Journal of Structural Engineering*, 137(11), 1291–1302.
- [4] Antoniou, S., & Pinho, R. (2014). Development and verification of a displacement-based adaptive pushover procedure. *Journal of Earthquake Engineering*, 8(5), 643–661.
- [5] Bureau of Indian Standards. (2016). IS 1893 (Part 1): Criteria for Earthquake Resistant Design of Structures. New Delhi, India.
- [6] FEMA 356. (2000). Prestandard and Commentary for the Seismic Rehabilitation of Buildings. Federal Emergency Management Agency, Washington D.C.
- [7] ATC-40. (1996). Seismic Evaluation and Retrofit of Concrete Buildings. Applied Technology Council, Redwood City, California.
- [8] Bureau of Indian Standards. (2003). IS 875 (Part 2): Code of Practice for Design Loads – Imposed Loads. New Delhi, India.



INTERNATIONAL
STANDARD
SERIAL
NUMBER
INDIA



INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH

IN SCIENCE | ENGINEERING | TECHNOLOGY

 9940 572 462  6381 907 438  ijirset@gmail.com



www.ijirset.com

Scan to save the contact details