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Performance Assessment of Current Practice and Enhanced Seismic Stability Design Methods

S, Shi[1], L. Fahnestock[2], R. Sabelli[3] and M. Speicher[4]

ABSTRACT

Seismic stability refers to a structure's ability to resist earthquake-induced forces and the destabilizing effects of gravity, particularly in the presence of large inelastic deformations. It goes beyond strength and ductility, focusing on a structure's capacity to sustain positive tangent stiffness and control deformation even after yielding. Recognizing the limitations of current design provisions in fully addressing these complex stability demands, recent research has explored enhanced methods that have the potential to improve seismic safety and resilience. In this study, performance of the current practice design method is compared to a baseline case that ignores P-Δ effects in design and to two enhanced design methods: 1) increasing the stiffness and strength of the primary seismic force-resisting system, and 2) adding a flexible elastic secondary stiffness moment frame as part of the seismic force-resisting system.

Introduction

The current practice (CP) provisions for addressing P-Δ effects in ASCE (American Society of Civil Engineers) 7-22 [1] rely on simplified models that may inadequately represent the inelastic seismic response of building structures. These provisions use elastic displacements to evaluate P-Δ effects when proportioning the seismic-force-resisting system (SFRS). The strength of the SFRS is increased to account for P-Δ effects that occur at elastic displacements under the design base shear. However, this approach does not account for the complex inelastic behaviors that arise during seismic events.

One potential modification to seismic stability design is to account for P-Δ effects that occur at inelastic displacements when proportioning the SFRS. The Direct Analysis Method in AISC (American Institute of Steel Construction) 360-22 [5] evaluates stability in nominally elastic systems using an elastic stiffness reduction factor (SRF) calibrated near member strength, but it may underestimate P-Δ effects in systems with significant inelastic drift. In such cases, an inelastic SRF can be used to approximate P-Δ effects [2]. The inelastic SRF increases the flexibility of the model, leading to larger P-Δ effects and concomitant strength

[1] Graduate Research Assistant, Civil and Environmental Engineering, Grainger College of Engineering, University of Illinois Urbana-Champaign, Urbana, IL 61801 (email: shi40@illinois.edu)
[2] Professor, Civil and Environmental Engineering, Grainger College of Engineering, University of Illinois Urbana-Champaign, Urbana, IL 61801
[3] Senior Principal and Director of Seismic Design, Walter P Moore, San Francisco, CA 94105
[4] Research Structural Engineer, Earthquake Engineering Group, National Institute of Standards and Technology, Gaithersburg, MD 20899

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requirements for the SFRS. This SRF method is illustrated schematically in Fig. 1(a) where the enhanced strength is intended to approximately account for the reduction in strength due to P-Δ effects at a target inelastic drift. Although the SRF method is relatively straightforward and easy to implement, it simply increases the stiffness and strength of the SFRS and does not directly address the inelastic response of the system.

In contrast, a flexible elastic secondary stiffness moment frame (SSMF) can be added to the primary SFRS [3]. The SSMF method directly considers the gravity-induced negative geometric stiffness (K_G) and proportions the SSMF stiffness (K_{SS}) to maintain a positive system stiffness, as depicted in Fig. 1(b). Although the SSMF method requires more design effort, it allows the primary SFRS to be proportioned without consideration of P-Δ effects and it can in many cases efficiently mobilize structural elements that are already in the building (e.g., the gravity framing).

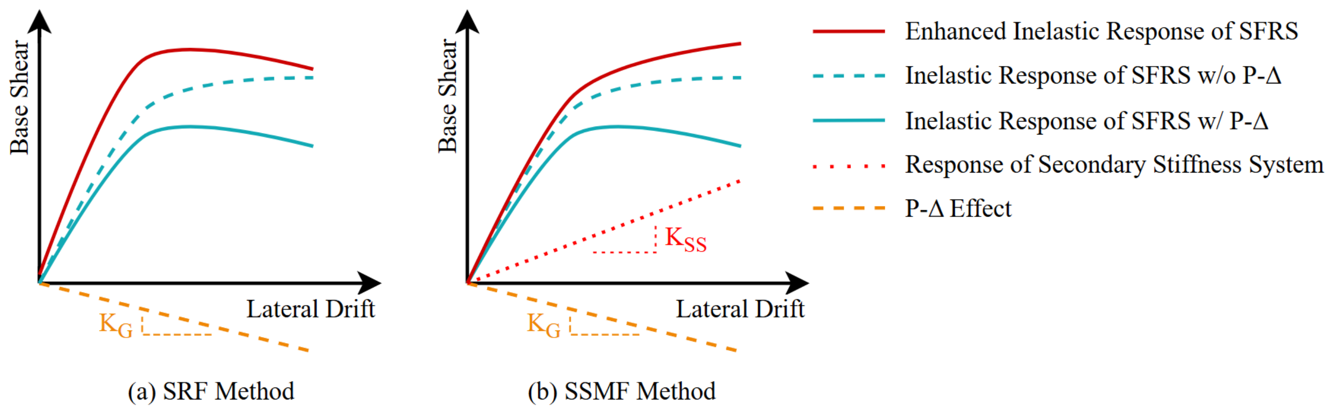


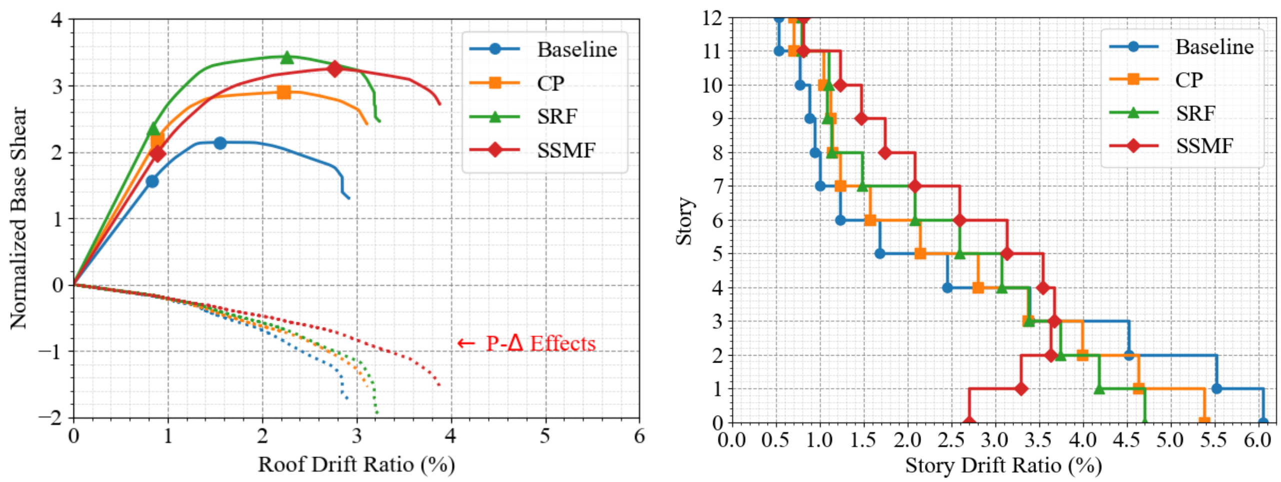
Figure 1. Schematic static pushover curves illustrating seismic stability design methods

Case Study

This case study focuses on a 3-bay, 12-story steel special moment frame (SMF) adapted from prior research [4]. The design adheres to the latest standards: AISC 360-22 [5] for strength requirements of structural components; ASCE 7-22 [1] for drift and stability requirements for SMF, gravity and Equivalent Lateral Force (ELF) load definitions, and strength, drift and stability load combinations; AISC 341-22 [6] for seismic design requirements specific to the SMF; and AISC 358-22 [7] for reduced beam section (RBS) requirements. Four design cases were developed and analyzed: Baseline, CP, SRF, and SSMF. The Baseline case disregards stability requirements and employs first-order elastic analysis for proportioning. The CP case follows code-compliant second-order elastic analysis, incorporating stability provisions. The SRF case enhances the design, with SRF equal to 0.25 applied to the elastic modulus in the analysis model used for proportioning the SMFs. The SSMF case augments the Baseline SMF with a SSMF companion, designed to remain elastic up to 2.5 % target story drift, and positioned in gravity bays adjacent to the SMF to enhance seismic stability.

The OpenSees computational platform [8] was used for nonlinear static and dynamic analyses. The numerical models for both SMF and SSMF systems are two-dimensional and assume a rigid diaphragm to ensure uniform lateral displacement across all floor levels. Beams and columns in the SMF and SSMF are represented as elastic elements with nonlinear rotational springs at their ends to simulate inelastic behavior, with parameters defined based on established methodologies [9]. Nonlinear panel zone behavior is explicitly included at all beam-column connections to account for localized deformations. A leaning column is incorporated into the model to simulate the destabilizing effects of gravity loads. A modal damping ratio of 2 % is applied and supplemented by 0.1 % stiffness-proportional damping. The load combinations used in the analyses align with ASCE 7-22 stability requirements to ensure a consistent evaluation of seismic stability, differing slightly from the FEMA (Federal Emergency Management Agency) P695 approach [10].

Nonlinear static (pushover) analysis results shown in Fig. 2(a) demonstrates that all design cases reach the end of the elastic range at a roof drift ratio around 0.9 %. The Baseline and CP cases achieve maximum base shear at roof drift ratio of approximately 1.6 % and 2.2 %, respectively. The SRF case exhibits similar performance to the CP case, with a maximum base shear occurring at a roof drift ratio of 2.3 %. In contrast, the SSMF case demonstrates the longest range of positive stiffness, achieving its maximum base shear at a roof drift ratio of 2.8 %. The band of negative P-Δ effects, with each color corresponding to the associated case, shows that the SSMF case is most effective at controlling the destabilizing effects of gravity. Each P-Δ line in Fig. 2(a) shows a steeper negative slope as inelastic drift concentrates in the lower stories and the ratio of the average lateral movement of the mass to the roof drift increases. This response is illustrated by the story drift distributions in Fig. 2(b) at a 2.5 % roof drift ratio. The SSMF system effectively controls drift at the lower stories, while the other three cases exhibit their largest drift at the bottom.



(a) Pushover Curves (b) Story Drift Distribution

Figure 2. Normalized monotonic static responses

Table 1 summarizes key response parameters for the four design cases, including the fundamental period (T_1), system overstrength factor (Ω_0), period-based ductility factor (μ_T), normalized SFRS weight and adjusted collapse margin ratio (ACMR). The Baseline case, with the longest fundamental period of 4.02 seconds, represents the most flexible structure and serves as the reference for steel weight comparison. The CP case reduces the fundamental period to 3.46 seconds, indicating increased primary stiffness, with a 12% increase in SFRS weight relative to the Baseline. The SRF case has the shortest fundamental period of 3.21 seconds, associated with a 19 % increase in SFRS weight compared to the Baseline. The SSMF case is slightly more flexible than the CP case, with a fundamental period of 3.64 seconds, and slightly lighter than the SRF case. The SRF case exhibits the largest overstrength and the SSMF case achieves the largest ductility. Both the SRF and SSMF cases show expected improvements in nonlinear response over the Baseline and CP cases based on static analysis, with further insights into their effectiveness provided by dynamic analysis results.

Table 1. Response parameters from nonlinear analysis

Case	**T_1 (s)**	**Ω_0**	**μ_T**	**Normalized SFRS Weight**	**ACMR**
Baseline	4.02	2.14	2.99	1.00	2.51
CP	3.46	2.90	3.24	1.12	2.68
SRF	3.21	3.44	3.25	1.19	3.02
SSMF	3.64	3.25	3.30	1.16	3.02

For the nonlinear response history analysis, the first-story drift ratio responses to the 7.5M 1999 Kocaeli, Turkey earthquake, recorded at the Duzce Station (KOCAELI/DZC180), are presented in Fig. 3 as a representative example. Among the design cases, the Baseline, CP, and SRF cases exhibit significant transient first-story drift ratios that exceed 7.5 % at approximately 15.6 seconds, indicating likely seismic instability and the development of weak-story collapse mechanisms. Toward the end of the record, the responses of these three cases oscillate beyond the 7.5 % threshold, trending toward complete sidesway collapse. The SSMF case also develops large first-story drift, but demonstrates improved performance (peak near 6 %). Similar trends are observed across other ground motion records, where the SSMF case consistently exhibits enhanced stability and, in some instances, avoids collapse under conditions that lead to failure in the other design cases.

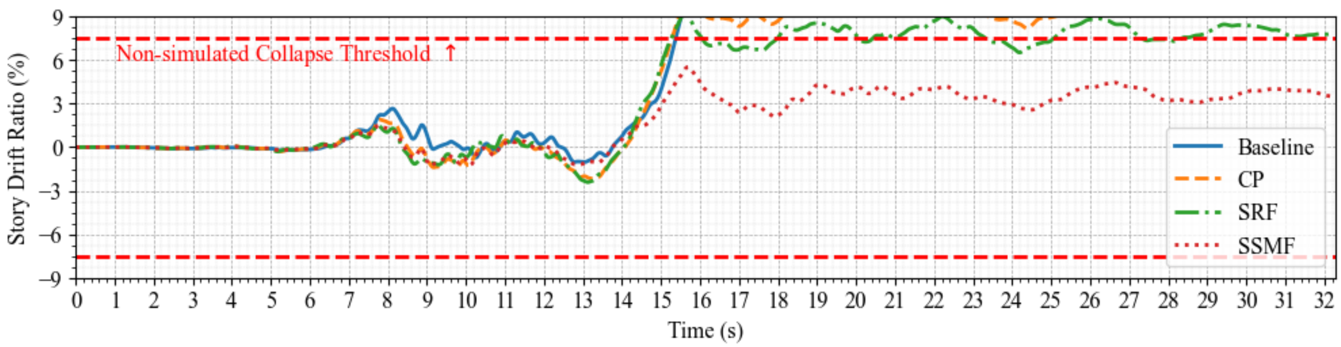


Figure 3. First-story drift ratio response history for SMFs subjected to the 7.5M 1999 Kocaeli, Turkey earthquake, recorded at the Duzce Station (KOCAELI/DZC180) and scaled to MCE_R

Per FEMA P695 [10], collapse performance was assessed using the ACMR, as shown in Table 1. The acceptance value of ACMR corresponding to a 10 % probability of collapse is 1.96. All design cases, including the baseline case that ignores P-Δ effects in design and thus is not code compliant, exceed the ACMR threshold. While the CP and the SRF cases exhibit similar ductility based on nonlinear static analysis, the SRF case shows a 13 % improvement in collapse performance, but the CP case shows similar performance to the Baseline case. The SRF and SSMF cases demonstrate comparable collapse performance, and the SSMF case is slightly more economical in terms of steel weight.

Summary

This paper compares current practice (CP) seismic stability design provisions to Baseline (no consideration of P-Δ effects) and to two enhanced design methods: 1) increasing the stiffness and strength of the primary seismic force-resisting system (SFRS), and 2) adding a flexible elastic secondary stiffness moment frame (SSMF) as part of the seismic force-resisting system. The stiffness reduction factor (SRF) method is used to approximately account for the reduction in strength due to P-Δ effects at a target inelastic drift, and to increase the stiffness and strength of the SFRS accordingly. The SSMF method directly considers the gravity-induced negative geometric stiffness and proportions the SSMF stiffness to maintain a positive system stiffness. The results show that CP provides only slight performance improvement over Baseline, and notably, neglecting the current seismic stability requirements does not significantly affect overall performance. The SRF method improves seismic performance by increasing system strength, but it does not directly address inelastic responses. In contrast, the SSMF method introduces post-yield stiffness directly into the design framework, enabling greater control over nonlinear behavior and improving global stability. This research also reinforces that ductility alone does not guarantee stability during seismic events [11]; rather, sustained positive tangent stiffness is essential to resist destabilizing gravity forces at large drifts. Both the SRF and SSMF methods outperform the Baseline and CP cases, with the SSMF method offering a slightly more economical solution. These outcomes highlight the value of incorporating enhanced stability-focused design strategies to improve resilience and reduce collapse risk in seismic regions.

Acknowledgments

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References

1. ASCE. *Minimum Design Loads for Buildings and Other Structures*. ASCE/SEI 7-22. American Society of Civil Engineers, Reston, VA, 2022.
2. Fahnestock LA, Shi S, Speicher MS. Building Seismic Stability - Code Provisions vs. Inelastic Behavior. *Proceedings of the 18th World Conference on Earthquake Engineering*, Milan, Italy, 2024.
3. Fahnestock LA, Shi S, Sabelli R, Speicher MS. Practical Techniques for Elastic Secondary Stiffness Design to Provide Seismic Stability and Enhance Seismic Resilience. *Proceedings of the 18th U.S.-Japan-New Zealand Workshop on the Improvement of Structural Engineering and Resilience*, San Diego, CA, USA, 2024.
4. Harris III JL, Speicher MS. *Assessment of First Generation Performance-Based Seismic Design Methods for New Steel Buildings, Volume 1: Special Moment Frames*. NIST Technical Note 1863-1. National Institute of Standards and Technology, Gaithersburg, MD, USA, 2015.
5. AISC. *Specification for Structural Steel Buildings*. ANSI/AISC 360-22. American Institute of Steel Construction, Chicago, IL, USA, 2022.
6. AISC. *Seismic Provisions for Structural Steel Buildings*. ANSI/AISC 341-22. American Institute of Steel Construction, Chicago, IL, USA, 2022.
7. AISC. *Prequalified Connections for Special and Intermediate Steel Moment Frames for Seismic Applications*. ANSI/AISC 358-22. American Institute of Steel Construction, Chicago, IL, USA, 2022.
8. McKenna F, Scott MH, Fenves GL. Nonlinear Finite-Element Analysis Software Architecture Using Object Composition. *Journal of Computing in Civil Engineering* 2010; **24** (1): 95-107.
9. NIST. *Guidelines for Nonlinear Structural Analysis and Design of Buildings: Part IIa - Steel Moment Frames*. NIST GCR 17-917-46v2. National Institute of Standards and Technology, Gaithersburg, MD, USA, 2017.
10. FEMA. *Quantification of Building Seismic Performance Factors*. FEMA P695. Federal Emergency Management Agency, Washington, DC, USA, 2009.
11. Fahnestock LA. Seismic Stability from Low Ductility to Enhanced Resilience. SDSS 2022 – *The International Colloquium on Stability and Ductility of Steel Structures*, Aveiro, Portugal, September 2022.