

Seismic Performance Evaluation of Steel Moment-Resisting Frames Using Nonlinear Static and Dynamic Analysis – A Survey

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Abstract

The evaluation of seismic performance of structures is an essential aspect of modern structural engineering, particularly in regions vulnerable to earthquake hazards. Steel moment-resisting frames (SMRFs) are widely adopted due to their high ductility, flexibility, and ability to dissipate seismic energy. This review paper presents a detailed discussion of the theoretical and conceptual aspects of seismic behavior of steel moment-resisting frames using nonlinear static and nonlinear dynamic analysis approaches. The study is based entirely on secondary data and focuses on understanding the fundamental principles governing structural response under seismic loading. The paper explains the basic concepts of earthquake-induced forces, structural dynamics, and performance-based design philosophy. It further discusses nonlinear static (pushover) analysis as a method to estimate structural capacity and failure mechanism, and nonlinear dynamic (time history) analysis as a tool to capture realistic response under time-varying ground motion. Key response parameters such as base shear, storey displacement, storey drift, and hinge formation are also elaborated in detail. The review highlights the importance of ductility, stiffness distribution, and energy dissipation in ensuring structural safety. It also emphasizes the limitations of traditional linear methods and the advantages of nonlinear approaches in capturing actual structural behaviour. The study provides a simplified yet comprehensive understanding of seismic analysis methods, making it useful for both academic and practical applications. Overall, the paper consolidates theoretical knowledge and provides a clear framework for understanding the seismic performance of steel moment-resisting frames.

Keywords: Steel moment-resisting frame, nonlinear static analysis, pushover analysis, nonlinear dynamic analysis, seismic performance.

1. Introduction

Earthquakes are one of the most critical natural hazards affecting the safety and stability of structures. The forces generated during an earthquake are dynamic in nature and act primarily in the horizontal direction,

causing significant stress and deformation in structural systems. Unlike static loads, seismic forces vary with time and depend on the characteristics of ground motion as well as the dynamic properties of the structure. Steel moment-resisting frames have become a preferred structural system for seismic resistance due to their ability to undergo large deformations without failure. These frames consist of beams and columns connected through rigid joints, which enable them to resist lateral loads through bending action. The flexibility and ductility of steel allow the structure to absorb and dissipate seismic energy, thereby reducing the risk of collapse.

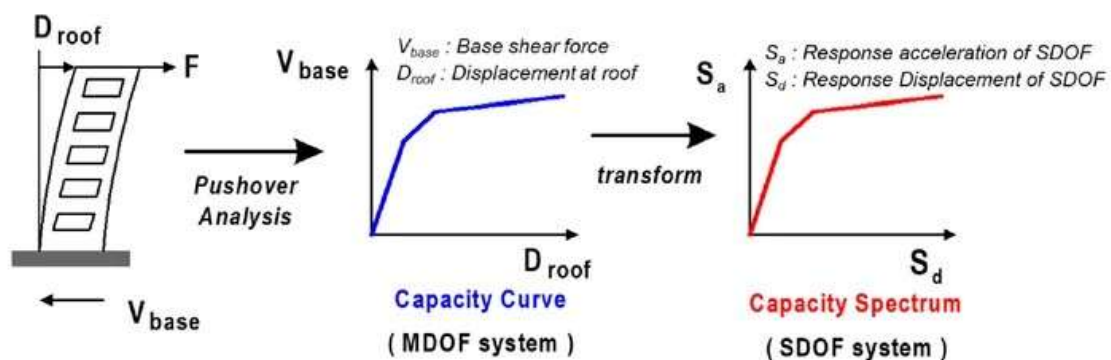


Figure 1.1: Typical steel moment-resisting frame system and seismic response behaviour

Traditional structural analysis methods were based on linear elastic assumptions, where the structure is expected to return to its original shape after the removal of loads. However, during strong earthquakes, structures often experience inelastic behaviour, leading to permanent deformations. This has led to the development of nonlinear analysis methods that can capture the actual behaviour of structures under extreme loading conditions. This review paper focuses on understanding the theoretical aspects of seismic performance evaluation using nonlinear static and dynamic analysis methods. The study does not involve any experimental or numerical results but is based on established concepts and methodologies used in structural engineering.

2. Review of Literature

In recent decades, earthquake engineering research has progressively shifted from conventional force-based design philosophies toward performance-based seismic evaluation methodologies that emphasize realistic simulation of structural behaviour under severe ground motion. This transition has been largely driven by post-earthquake observations and analytical evidence demonstrating that structures designed using simplified linear elastic approaches may experience significant inelastic deformation, localized damage concentration, and unexpected performance deficiencies. As a result, nonlinear analytical techniques such as nonlinear static (pushover) analysis and nonlinear dynamic (time-history) analysis have become central to contemporary seismic performance assessment of steel moment-resisting frames (SMRFs). These methods enable engineers and researchers to investigate critical response characteristics including plastic hinge development, stiffness degradation, cyclic energy dissipation, and redistribution of internal forces beyond the elastic range. Comparative investigations reported in recent literature consistently highlight the limitations of pushover analysis in accurately predicting seismic demand, particularly for multi-storey steel frame systems where higher-mode effects significantly influence response behaviour.

While pushover analysis provides valuable insight into global lateral load-carrying capacity and potential failure mechanisms, it typically relies on predefined lateral load patterns and monotonic loading assumptions. Consequently, it may underestimate inter-storey drift demand, cumulative damage effects, and deformation concentration in specific storeys. Nonlinear time-history analysis, in contrast, captures the time-dependent nature of seismic excitation, including cyclic loading and unloading, inertia force variation, and interaction among structural modes. These dynamic characteristics are crucial in determining peak displacement demand, residual deformation, and overall structural stability during strong ground motion events. Another important aspect emphasized in recent research is the influence of record-to-record variability in ground motion characteristics. Differences in frequency content, duration, and amplitude of earthquake excitation can lead to significant variation in structural response even for buildings with identical geometric and material properties. Such variability is inherently addressed through nonlinear dynamic analysis but remains largely unaccounted for in conventional pushover-based evaluation procedures. Similarly, cyclic deterioration of strength and stiffness, which plays a decisive role in governing collapse potential and post-earthquake reparability, cannot be realistically simulated using monotonic static loading frameworks.

These limitations collectively underscore the necessity of adopting integrated analytical strategies that combine capacity-based and demand-based assessment approaches. The reviewed dissertation identifies several critical research gaps within the existing body of knowledge. One major gap is the limited integration of nonlinear static and nonlinear dynamic analyses within a unified performance evaluation framework.

Although many studies employ either pushover or time-history analysis independently, comparatively fewer investigations systematically correlate capacity estimates obtained from static procedures with demand predictions derived from dynamic simulations. This lack of integration restricts the ability to comprehensively evaluate seismic performance and may lead to incomplete or unconservative design conclusions. Another significant gap pertains to the insufficient utilization of quantitative response parameters extracted from advanced structural analysis software. While modern computational tools enable detailed modelling of material nonlinearity, geometric effects, and plastic hinge behaviour, numerous studies still focus primarily on qualitative interpretations rather than rigorous data-driven assessment. Parameters such as base shear capacity, peak roof displacement, inter-storey drift ratios, hinge rotation demand, and residual deformation provide valuable insight into structural performance but are not consistently analysed in a systematic manner.

Furthermore, existing literature often lacks detailed examination of drift concentration phenomena and potential soft-storey mechanisms that may develop under nonlinear response conditions. Such localized deformation patterns can critically influence damage progression and collapse vulnerability, particularly in steel moment-resisting frames where stiffness distribution and connection detailing govern inelastic behaviour. Additionally, there remains a notable need for localized performance-based seismic evaluation studies that reflect regional seismic hazard characteristics, design practices, and codal provisions applicable to specific contexts such as Indian seismic zones. By addressing these identified gaps, the reviewed work contributes to advancing the understanding of seismic performance of SMRF systems through comprehensive analytical investigation. The adoption of realistic modelling strategies, systematic extraction of response parameters, and performance-based evaluation criteria enables a more accurate and holistic assessment of structural behaviour under earthquake loading. Consequently, the study strengthens the foundation for integrating advanced nonlinear analysis techniques into practical seismic design and assessment methodologies.

3. Fundamentals of Seismic Forces

Seismic forces are generated due to ground motion caused by tectonic activities. When the ground moves, the base of the structure moves along with it, while the upper portion tends to remain in its original position due to inertia. This difference in motion creates internal forces within the structure. The magnitude of seismic force depends on several factors, including the mass of the structure, stiffness, damping, and characteristics of ground motion. Heavier structures tend to experience higher forces, while flexible structures experience larger displacements. The interaction between mass and stiffness determines the natural frequency of the structure, which plays a crucial role in seismic response. Seismic forces are not uniformly distributed along the height of the structure. Typically, higher storeys experience greater displacement and acceleration compared to lower

storeys. This variation leads to the development of storey shear and bending moments, which must be carefully considered in design.

4. Structural Dynamics and Response

The behavior of structures under seismic loading is governed by the principles of structural dynamics. A structure can be modeled as a dynamic system with mass, stiffness, and damping properties. When subjected to ground motion, the structure vibrates, and its response depends on its natural frequency and damping characteristics.

The equation of motion for a single-degree-of-freedom system is given by:

$$M\ddot{u} + C\dot{u} + Ku = F(t)$$

This equation represents the balance between inertia force, damping force, restoring force, and external force. The solution of this equation provides the displacement response of the structure over time. In multi-storey buildings, the behaviour becomes more complex due to the presence of multiple degrees of freedom. Each storey can move independently, resulting in different mode shapes. The overall response of the structure is a combination of these modes.

5. Steel Moment-Resisting Frames

Steel moment-resisting frames are structural systems designed to resist lateral loads through bending of beams and columns. The connections between beams and columns are rigid, allowing moments to be transferred effectively. This results in a continuous load path and improved structural performance. One of the key advantages of SMRFs is their ductility. Ductility refers to the ability of a material or structure to undergo large deformations without losing its load-carrying capacity. In seismic design, ductility is essential because it allows the structure to absorb energy and prevent sudden failure. The concept of strong-column weak-beam is fundamental in the design of SMRFs. According to this principle, beams are designed to yield before columns, ensuring that the structure undergoes controlled deformation rather than collapse.

6. Nonlinear Behaviour of Structures

Under seismic loading, structures often exhibit nonlinear behavior, where the relationship between force and displacement is no longer linear. This occurs when the stress in the material exceeds its elastic limit, leading to plastic deformation. Nonlinear behaviour is characterized by stiffness degradation, energy dissipation, and hysteresis. As the structure undergoes repeated cycles of loading and unloading, energy is dissipated through

plastic deformation, reducing the overall response. Understanding nonlinear behaviour is essential for accurate seismic analysis, as it provides insight into the actual performance of the structure under extreme conditions.

7. Nonlinear Static Analysis (Pushover Analysis)

Pushover analysis is a simplified method used to evaluate the nonlinear behavior of structures. In this method, lateral loads are applied incrementally until the structure reaches a target displacement. The resulting force-displacement relationship is known as the capacity curve. The capacity curve provides valuable information about the strength and deformation capacity of the structure. It also helps identify the formation of plastic hinges, which indicate the onset of inelastic behaviour. Although pushover analysis is relatively simple and easy to perform, it has limitations. It does not account for dynamic effects and may not accurately represent the response of complex structures. However, it is widely used for preliminary assessment and performance evaluation.

8. Nonlinear Dynamic Analysis (Time History Analysis)

Time history analysis is a more advanced method that involves the application of actual ground motion records to the structural model. This method captures the variation of response with time, providing a detailed understanding of structural behavior. In time history analysis, the equation of motion is solved numerically to obtain displacement, velocity, and acceleration at each time step. This allows for a realistic representation of the response under seismic loading. The accuracy of time history analysis depends on the selection of appropriate ground motion records. It also requires significant computational effort and expertise.

9. Performance-Based Seismic Design

Performance-based design is an approach that focuses on achieving specific performance objectives under different levels of seismic demand. Instead of designing for a single load case, this method considers multiple scenarios, such as minor, moderate, and severe earthquakes. The performance of a structure is evaluated in terms of predefined levels, such as immediate occupancy, life safety, and collapse prevention. These levels represent different states of damage and functionality. Performance-based design provides a more realistic and flexible approach to seismic design, allowing engineers to optimize the structure based on desired performance criteria.

10. Influence of Structural Parameters

The seismic performance of steel moment-resisting frames is influenced by various factors, including geometry, material properties, and load distribution. Regular structures with uniform mass and stiffness

distribution tend to perform better than irregular structures. The height of the structure also affects its response. Taller buildings generally experience larger displacements and are more sensitive to dynamic effects. Damping plays a crucial role in reducing the response by dissipating energy.

11. Advantages and Limitations

Nonlinear analysis provides a more accurate representation of structural behavior compared to linear methods. It captures inelastic deformation, stiffness degradation, and energy dissipation, which are essential for realistic seismic assessment. It also helps in identifying critical regions where failure is likely to occur, enabling better design and strengthening measures. Despite its advantages, nonlinear analysis has certain limitations. It requires detailed modeling and accurate input data, which may not always be available. The computational effort is also higher compared to linear analysis. Additionally, the interpretation of results can be complex, requiring a thorough understanding of structural behaviour.

13. Conclusion

This review paper presents a detailed discussion on the seismic performance of steel moment-resisting frames using nonlinear analysis methods. The study highlights the importance of understanding structural dynamics, nonlinear behavior, and performance-based design concepts. Nonlinear static and dynamic analysis methods provide valuable insights into structural performance and help in designing safer structures. Steel moment-resisting frames continue to be an effective solution for seismic resistance due to their ductility and energy dissipation capacity. The concepts discussed in this paper provide a strong theoretical foundation for further research and practical applications in the field of seismic engineering.

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