DEVELOPMENT OF SEISMIC FRAGILITY CURVES FOR STEEL TOWERS

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Abstract:

Seismic fragility curves play a crucial role in assessing the vulnerability of structures to earthquake-induced damage and informing risk mitigation strategies. This project presents a comprehensive study on the development and application of fragility curves for steel towers subjected to seismic loading. The research aims to provide insights into the seismic performance of steel towers, enhance understanding of their vulnerability characteristics, and facilitate informed decision-making for risk reduction and structural resilience enhancement. The study begins with a review of relevant literature, including previous research on fragility analysis methods, seismic behavior of steel structures, and applications of fragility curves in seismic risk assessment. This literature review serves as the foundation for identifying research gaps, defining the scope of the study, and establishing the methodology for fragility curve development. The methodology encompasses several key steps, including data collection, structural modeling, seismic hazard analysis, and fragility curve generation. Real-world data on steel tower properties, seismic ground motions, and historical earthquake events are collected and analyzed to inform the development of representative structural models and input parameters for fragility analysis. Advanced numerical modeling techniques, such as finite element analysis and probabilistic seismic hazard analysis, are employed to simulate the dynamic response of steel towers under seismic loading and assess the probability of various damage states. The primary focus of the study is on defining damage states and quantifying the probability of occurrence for each state at different levels of seismic intensity. Damage states are defined based on observable structural performance criteria, such as drift ratios, member deformations, and connection capacities. Threshold values for each damage state are established through iterative analysis and validation against empirical data, expert judgment, and engineering standards. The fragility curves generated in this study provide valuable insights into the vulnerability characteristics of steel towers and their response to seismic hazards. By visualizing the probability of damage or failure as a function of seismic intensity, stakeholders can assess the relative risk posed by different seismic events, prioritize mitigation measures, and optimize resource allocation for risk reduction efforts. Future research directions include extending the applicability of fragility analysis to other types of structures, integrating multi-hazard risk assessment approaches, and exploring innovative strategies for enhancing structural resilience to seismic hazards. In summary, this study contributes to the advancement of seismic risk assessment practices for steel towers and provides a framework for evaluating and mitigating the impacts of earthquakes on critical infrastructure. By enhancing understanding of structural vulnerability characteristics and facilitating informed decision-making, fragility curves play a crucial role in building resilient communities and ensuring the safety and sustainability of built environments in earthquake-prone regions.

Keywords: Seismic fragility curve, seismic capacity, pushover analysis, time-history analysis, steel cellular tower.

Introduction:

Steel towers stand tall as iconic structures in our modern landscape, serving a diverse array of functions critical to our infrastructure and daily lives. From supporting telecommunications networks to transmitting electrical power and harnessing renewable energy, these towering structures play an indispensable role in facilitating communication, commerce, and connectivity on a global scale. However, amidst their towering presence, steel towers also face formidable challenges, particularly in their susceptibility to environmental forces, with earthquakes representing one of the most significant threats.

The seismic vulnerability of steel towers poses a complex and multifaceted challenge, as earthquakes have the potential to unleash devastating consequences on these structures, leading to widespread damage, disruption, and loss of life. Understanding the seismic behaviour of steel towers is therefore paramount, not only for ensuring the structural integrity and resilience of these vital assets but also for safeguarding the safety, security, and well-being of communities worldwide.

In response to the pressing need for comprehensive risk assessment and mitigation strategies, seismic fragility analysis has emerged as a pivotal tool in the field of structural engineering and earthquake risk assessment. By quantifying the probability of structural damage or failure at different levels of seismic intensity, fragility analysis provides valuable insights into the vulnerability characteristics of steel towers, enabling engineers, policymakers, and stakeholders to make informed decisions regarding risk management, emergency preparedness, and infrastructure resilience.

The development and application of fragility curves for steel towers represent a significant advancement in the field of earthquake engineering, offering a systematic framework for assessing the seismic vulnerability and performance of these structures under varying environmental conditions. Fragility curves serve as predictive tools, allowing engineers to evaluate the likelihood and severity of structural damage or failure in response to seismic events, thereby guiding the design, maintenance, and retrofitting of steel towers to enhance their resilience and mitigate the potential impacts of earthquakes.

The journey towards developing fragility curves for steel towers begins with a comprehensive understanding of the structural dynamics, material properties, and environmental factors that influence their seismic response. Real-world data on steel tower properties, including geometry, material composition, and construction methods, serve as the foundational basis for modelling and analysis. Additionally, seismic hazard data, such as ground motion records and historical earthquake events, provide crucial insights into the dynamic forces that steel towers may encounter during seismic events.

Advanced numerical modelling techniques, such as finite element analysis (FEA) and probabilistic seismic hazard analysis (PSHA), play a central role in simulating the dynamic behaviour of steel towers under seismic loading conditions. These computational tools enable engineers to predict the structural response of steel towers, including deformation patterns, stress distributions, and failure modes, allowing for the identification of critical vulnerabilities and the formulation of targeted mitigation strategies.

A key component of fragility curve development is the definition of damage states and their corresponding probabilities of occurrence across different levels of seismic intensity. Damage states represent the spectrum of structural damage or degradation that steel towers may experience during seismic events, ranging from minor impairments to catastrophic collapse. By defining clear criteria for each damage state based on observable performance metrics, such as deformations, member capacities, and overall stability, engineers can assess the resilience of steel towers and prioritize mitigation efforts accordingly.

The capacity of steel towers to withstand seismic loading is influenced by various factors, including tower height, slenderness ratio, structural system, and foundation design. Taller towers may exhibit increased stability and robustness, while shorter towers may be more susceptible to damage or failure under certain seismic conditions. Thus, engineers must carefully consider these design parameters and environmental variables when developing fragility curves, ensuring a comprehensive assessment of seismic resilience across different types of steel towers.

Beyond the realm of structural engineering, fragility curves have broader implications for risk management, emergency response planning, and policy development. By quantifying the probability of structural damage or failure under seismic loading, fragility curves empower stakeholders to make informed decisions regarding infrastructure investment, disaster preparedness measures, and community resilience initiatives. Through interdisciplinary collaboration and continuous refinement, fragility curves for steel towers hold the potential to enhance the safety, sustainability, and resilience of our built environment in the face of seismic hazards.

Need for study:

The need for this study arises from the critical role of cellular steel towers in communication infrastructure and the inherent vulnerability of such infrastructure to seismic hazards. With the increasing reliance on wireless communication networks for emergency response, public safety, and everyday communication, ensuring the resilience of these towers against earthquakes is paramount. However, there is a lack of comprehensive understanding regarding the seismic performance of cellular steel towers, particularly in diverse geographical settings such as India. By investigating the behaviour of towers of varying heights under seismic loading, this study addresses this knowledge gap and provides valuable insights into their vulnerability and capacity limits. Furthermore, with the frequency and intensity of earthquakes expected to rise in seismic-prone regions, including India, there is a pressing need to develop proactive measures to mitigate the risks posed to communication infrastructure. By identifying potential failure modes, evaluating structural vulnerabilities, and developing fragility curves, this research equips engineers, policymakers, and stakeholders with the necessary tools to enhance the seismic resilience of cellular steel towers. Ultimately, the findings of this study contribute to the development of robust and resilient communication networks capable of withstanding seismic events, thereby ensuring uninterrupted communication and facilitating effective disaster response and recovery efforts.

Objectives of this paper:

The main objectives of this study are:

- To select the type of tower based on its functions and specifications.
- To perform push-over analysis to define the damage states.
- To perform time-history analysis with ground motion records using ETABS.
- To develop damage fragility function for a specific location based on its seismic records.
- To plot fragility curves for different stages of damage with respect to ground motion for three towers with varying heights.

Methodology:

1) **Introduction**

The introduction sets the stage for the study, highlighting the importance of understanding structural behaviour under seismic loading conditions. It outlines the objectives of the research and provides a brief overview of the methodology to be employed.

2) **Literature Review**

In this section, a comprehensive review of existing literature is presented. The review covers seismic design principles, steel tower structures, pushover analysis, time-history analysis, and fragility curves. Emphasis is placed on summarizing key findings from previous studies and identifying gaps in current knowledge.

3) **Tower Selection and Design**

Tower Selection

The rationale behind selecting cellular steel towers as the focus of the study is discussed in detail. The advantages of these towers in seismic-prone regions are highlighted, along with their relevance to the research objectives.

Tower Design

The tower design process is outlined, starting with the selection of towers of varying heights (30m, 40m, 50m). The fixation of section properties using I-sections of different sizes is explained, along with considerations for structural integrity and compliance with relevant standards.

4) **Pushover Analysis**

This section delves into the methodology and objectives of pushover analysis using ETABS software. The significance of defining five damage states (DS0, DS1, DS2, DS3, DS4) to capture the progressive failure behaviour of the towers under seismic loading is discussed in detail.

5) **Time-history Analysis**

Ground Motion Selection

Criteria for selecting ground motion records from previous earthquakes in India are presented, including considerations such as magnitude, distance from the epicentre, and soil conditions. The rationale behind these criteria is explained to justify the choice of ground motion records.

Analysis Procedure

The steps involved in performing time-history analysis using ETABS are outlined, covering input parameters, simulation settings, and output data collection. Special attention is given to the interpretation of results and their relevance to the study objectives.

Results Analysis

Results from the time-history analysis, including Peak Ground Acceleration (PGA) values and corresponding drift ratio percentages, are presented and analysed. The implications of these results for the structural response and performance of the towers under seismic loading are discussed.

6) **Fragility Curve Development**

Data Analysis

The process of calculating the mean and standard deviation from the PGA and drift ratio percentage data is explained. The significance of cumulative distribution probability functions in quantifying structural fragility is discussed, along with their role in developing fragility curves.

Fragility Curve Generation

The methodology of plotting fragility curves for each of the five damage states using the mean and standard deviation values obtained is presented. The interpretation of these curves in assessing the vulnerability of the towers to seismic events is discussed in detail.

7) Comparative Analysis

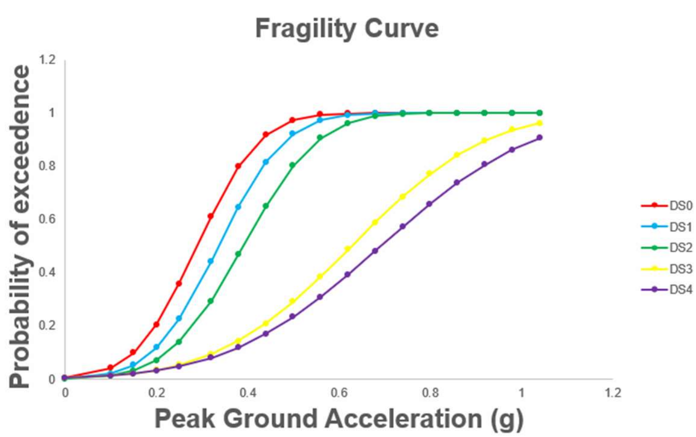
A comparative analysis of the fragility curves generated for the different tower heights is conducted. Trends, differences, and similarities in the seismic vulnerability profiles of the towers are identified and discussed, providing valuable insights into their structural behaviour.

8) Conclusion

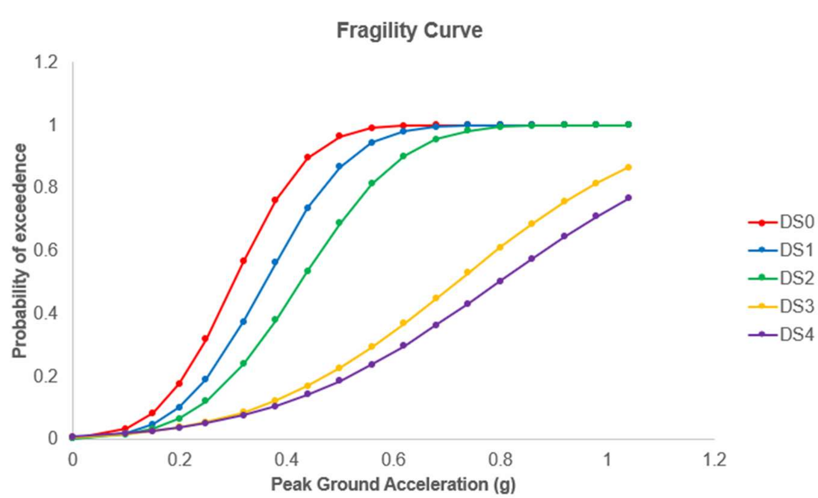
The conclusion summarizes the key findings of the study and their implications for seismic design and risk assessment of cellular steel towers. Limitations and areas for future research are identified, concluding with reflections on the significance of the research in advancing knowledge in the field.

Results and Discussions:

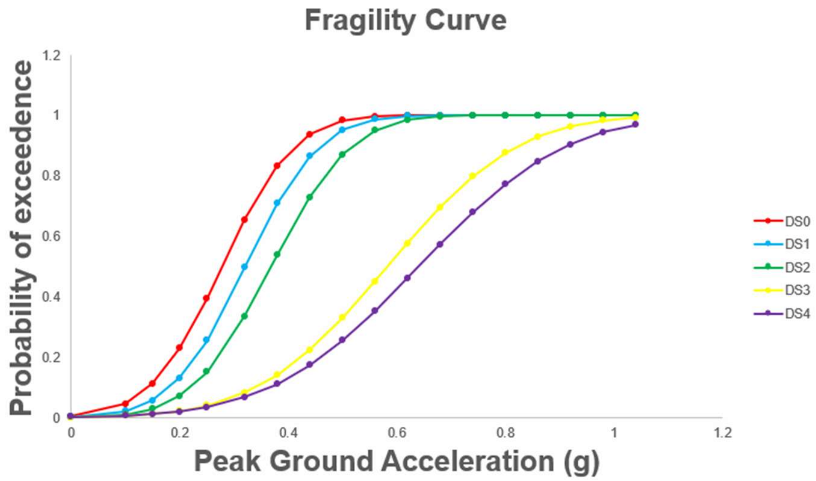
Fragility curve – 40m tower



Fragility curve – 30m tower



Fragility curve – 50m tower



Conclusion:

- The development of a fragility curve for the steel tower has provided valuable insights into its seismic vulnerability and performance characteristics.
- Through rigorous analysis and modeling, the relationship between structural response and earthquake intensity has been defined, enabling a comprehensive understanding of the tower's behavior under seismic loading.
- In terms of the capacity, the 30m tower has a higher capacity when compared to other towers.
- This is due to the slenderness ratio of the tower. The story heights of the tower have been modified with respect to the same base dimension.
- In the damage states DS0 and DS1, the probability of exceeding the damage state increases when there is an increase in the tower height.
- In the damages states DS2, DS3 and DS4, the probability of exceeding the damage state is higher for the 30m tower when the PGA is low.
- This is due to the increased stability, robust foundation design, and reduced likelihood of resonance for the 50m tower.
- In the damages states DS2, DS3 and DS4, the probability of exceeding the damage state is higher for the 50m tower when the PGA is high.

- This is due to increased lateral deformation, increased dynamic response, higher lateral forces and susceptible to settlement or tilting for the 50m tower.
- Taller structures have longer natural periods of oscillation, making them more prone to resonating with certain frequencies of the earthquake waves.
- Engineers can use fragility curves to optimize structural design parameters such as material properties, construction techniques, and foundation design.
- Apart from height, structural system, foundation properties, soil conditions and maintenance are some of the factors that affect the fragility curve of the structure.
- Overall, this study contributes to the ongoing efforts to enhance the safety, sustainability, and resilience of built environments, ensuring the protection of lives and property in the face of seismic events.

Future Scope:

- Validation and Calibration: Moving forward, continued research and collaboration will be essential to refine and validate the fragility curve, as well as to extend its applicability to other types of structures.
- Machine learning: With the mean and variance values obtained from the cumulative distribution function for different towers, the fragility curves for towers between the height 30m and 50m can be plotted using machine learning.
- Extension to other hazards: Expanding the scope of the fragility curve to consider other hazards beyond earthquakes, such as windstorms, floods, or blast events or developing multi-hazard fragility curve.
- Application to Existing Infrastructure: Applying fragility curves to assess the seismic vulnerability of existing infrastructure and prioritize retrofitting or mitigation measures.

References:

- A.M. Salman, Y. Li, Age-dependent fragility and life-cycle cost analysis of wood and steel power distribution poles subjected to hurricanes, Struct. Infrastruct. Eng. 12 (8) (2016) 890–903, https://doi.org/10.1080/15732479.2015.1053949.

- K.R. Karim, F. Yamazaki, A simplified method of constructing fragility curves for highway bridges, Earthq. Eng. Struct. Dynam. 32 (10) (2003) 1603–1626, https://doi.org/10.1002/eqe.291.
- J. Liu, L. Tian, X. Meng, M. Yang, Seismic fragility assessment of a transmission tower considering mainshock-aftershock sequences, J. Constr. Steel Res. (2022), https://doi.org/10.1016/j.jcsr.2022.107344, 194 107344.
- H.S. Park, B.H. Choi, J.J. Kim, T.H. Lee, Seismic performance evaluation of high voltage transmission towers in South Korea, KSCE J. Civ. Eng. 20 (2016) 2499–2505, https://doi.org/10.1007/s12205-015-0723-3.
- L. Ma, M. Khazaali, P. Bocchini, Component-based fragility analysis of transmission towers subjected to hurricane wind load, Eng. Struct. (2021) 242 112586, https://doi.org/10.1016/j.engstruct.2021.112586.
- X. Fu, H.N. Li, L. Tian, J. Wang, H. Cheng, Fragility analysis of a transmission line subjected to wind loading, J. Perform. Constr. Facil. 33 (4) (2019), 04019044, https://doi.org/10.1061/(ASCE)CF.1943-5509.0001311.
- V.K. Singh, A.K. Gautam, Analysis of transmission line tower subjected to wind loading, Mater. Today Proc. 65 (2) (2022) 1739–1747, https://doi.org/10.1016/ j.matpr.2022.04.791.
- C. Li, H. Pan, L. Tian, W. Bi, Lifetime multi-hazard fragility analysis of transmission towers under earthquake and wind considering wind-induced fatigue effect, Struct. Saf. 99 (2022), 102266, https://doi.org/10.1016/j.strusafe.2022.102266.