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"Towards Earthquake Disaster Assessment Based On Seismic Vulnerability Analysis In Indore City"

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This research aims to present an in-depth analysis of earthquake vulnerability in various cities through a seismic vulnerability assessment framework. The proposed approach integrates multiple methodologies, including rapid visual screening, non-destructive testing (NDT) methodology, ultrasonic pulse velocity, and non-linear static analysis. The study evaluates existing seismic vulnerability research, identifies gaps, and introduces a novel framework for comprehensive earthquake disaster assessment. The outcomes of the experimental framework are discussed, highlighting key observations and recommendations for future studies.

Keywords: Seismic Vulnerability, Earthquake Disaster Assessment, Rapid Visual Screening, NDT Methodology, Ultrasonic Pulse Velocity, Non-Linear Static Analysis

1. Introduction

1.1Background

Earthquakes represent a formidable natural hazard, posing significant threats to urban environments worldwide. Understanding the vulnerability of cities to seismic events is paramount for disaster preparedness, response, and mitigation strategies. The complexity of urban structures and the intricate interplay between physical and social vulnerabilities necessitate a holistic approach to seismic vulnerability analysis.

To comprehend and address these challenges, extensive research has been conducted globally. Numerous studies (such as those by Sridharan and Gopalan (2022), Ulza and Idris (2022), and Sehili et al. (2020)) have delved into specific aspects of earthquake vulnerability, ranging from assessing the mobility of earthquake-induced landslides to understanding the unequal distribution of damages among cities [1], [2], [3].

1.2 Problem definition

Despite these valuable contributions, a comprehensive framework integrating various methodologies for earthquake vulnerability analysis is lacking. The existing literature emphasizes specific aspects, such as fragility curves, catastrophe theory, and rapid visual screening (RVS). However, a unified approach is necessary for a nuanced understanding of seismic vulnerability in diverse urban contexts. Identifying this gap becomes the cornerstone for our research endeavor.

1.3Research objectives

The primary objective of this study is to develop a cohesive earthquake disaster assessment framework based on seismic vulnerability analysis. Drawing inspiration from established methodologies (including RVS, catastrophe theory, and fragility curves) [4], [5], [6] our research aims to integrate these approaches into a unified model. Specific research objectives include:

Synthesis of Existing Techniques: Conduct a comprehensive review and synthesis of existing seismic vulnerability assessment techniques [4], [5], [6].

Methodological Integration: Develop an integrated seismic vulnerability analysis framework by adapting and combining methodologies such as RVS, catastrophe theory, and fragility curves, inspired by studies [7], [8].

Experimental Validation: Apply the proposed framework to diverse urban contexts, considering factors like building typology, geographical location, and socioeconomic factors. Validate the framework's effectiveness through experimental outcomes, building on insights from studies [9], [10].

1.4 Contributions of the study

This research aspires to make several contributions to the field of earthquake vulnerability analysis:

Methodological Synthesis: By synthesizing existing methodologies, our study aims to provide a unified approach that captures the multifaceted nature of seismic vulnerability. This addresses the limitations of isolated methodologies [1], [8].

Comprehensive Framework: The proposed framework intends to offer a holistic understanding of seismic vulnerability, taking into account various urban parameters. This addresses the need for comprehensive frameworks [3], [5].

Practical Applicability: Through experimental validation in diverse urban settings, our study aims to provide insights into the practical applicability and adaptability of the proposed framework. This aligns with the call for practical solutions in seismic vulnerability assessment, as emphasized [9], [10].

This introduction sets the stage for a research endeavor that seeks to bridge existing gaps in seismic vulnerability analysis, offering a novel and integrated approach for earthquake disaster assessment in urban environments. The subsequent sections will delve into a comprehensive literature review, detailing the state-of-the-art methodologies. Following this, proposal of the research methodology, results, and concluding remarks is done.

2. Literature survey

2.1Synthesis of existing techniques

The seismic vulnerability assessment landscape is rich with diverse methodologies, each offering unique insights into the complex nature of urban susceptibility to earthquakes. A thorough review of these approaches is vital for developing a comprehensive seismic vulnerability analysis framework.

2.1.1 Fragility curves

Analytical-based fragility curves, as explored in [2], present a quantitative method for evaluating vulnerability. The benefit lies in their ability to capture the probabilistic relationship between ground motion intensity and structural damage. However, drawbacks emerge in the sensitivity to the definition of damage intensities, as noted in the study. This emphasizes the need for a nuanced interpretation of damage criteria.

2.1.2 Catastrophe theory

The application of catastrophe theory, as demonstrated [7], introduces a novel perspective. By calculating the importance of criteria within a geographic information system, subjectivity is reduced. However, challenges arise in practical implementation, particularly in regions with a high degree of vulnerability due to factors like proximity to faults, steep slopes, and high population density.

2.1.3 RVS

RVS, is a widely adopted method for swift assessment. It offers a practical means of identifying vulnerable buildings, but falls short in providing detailed insights [9]. The method's drawback lies in the need for further, more detailed analysis. This is indicated in the study, reflecting the limitation of a quick visual assessment.

2.1.4 Expert-based approaches

The expert-based approach, showcases the significance of incorporating expert judgments. This method provides a valuable insight into vulnerability at the city scale [4]. However, challenges arise in predicting earthquakes accurately; the study acknowledges the limitations of ignoring interdependencies in the analytical hierarchy process (AHP) methodology.

2.2 Gaps in current research

While these methodologies offer valuable contributions to seismic vulnerability assessment, the existing literature reveals notable gaps that necessitate further exploration:

2.2.1 Comprehensive framework
Studies, such as emphasize the need for a comprehensive framework. The current methodologies often focus on specific aspects, overlooking the intricate interplay between physical and social vulnerabilities [3], [5]. This gap highlights the necessity for an integrated approach that considers various dimensions of seismic vulnerability.

2.2.2 Practical applicability
Several studies underscore the importance of practical applicability. While methodologies provide theoretical insights, their effectiveness in diverse urban settings remains a challenge. [9], [10]. This gap signals the need for methodologies that are not only robust in theory, but also adaptable and applicable in real-world scenarios.

2.3 Foundation for the proposed framework
The reviewed literature on seismic vulnerability assessment encompasses diverse methodologies and geographic locations. Studies focus on the examination of earthquake-induced landslides emphasize the correlation between landslide volume and mobility [1]. Research focuses on analytical-based fragility curves, revealing varying interpretations based on damage intensities [2]. The application of the catastrophe theory, assesses Tabriz city's vulnerability, emphasizing factors like space limitation and high seismic risk areas [7]. The 2003 Boumerdes earthquake, highlighting the intersection of social and physical vulnerability [3]. The expert-based approach proposes a method for city-scale vulnerability assessment [4]. The importance of design quality in reducing the vulnerability is also crucial [8]. The use of RVS was conducted in Malaysia and Coimbatore to assess the vulnerability through building typologies [9], [11]. A probabilistic seismic risk assessment focusing on old urban centers [6]. Screening procedures for tourist accommodations in Montreal Various methodologies, such as the Vulnerability Index Methodology [20] and exposure models [5], [10], [21]. Risk assessment in Nainital is explored by Rautela et al. (2020). Risk assessment in Mostaganem City was researched [14]. A new paper-based tool for damage assessment post-earthquakes [15]. These studies collectively contribute to understanding seismic vulnerabilities in diverse contexts.
The identified benefits and drawbacks of existing methodologies, coupled with the highlighted gaps in current research, form the foundation for our proposed seismic vulnerability analysis framework. The framework aims to address the limitations of individual methods by integrating diverse approaches, offering a comprehensive and practically applicable solution to seismic vulnerability assessment in urban environments. The subsequent section will delve into the specifics of our proposed methodology, drawing inspiration from the synthesis of existing techniques outlined in this literature survey.

3. Research methodology

3.1 Proposed earthquake disaster assessment
The methodology of this research study revolves around a multifaceted approach to seismic vulnerability analysis, incorporating and adapting various established techniques. The

proposed earthquake disaster assessment is designed to be a comprehensive framework that amalgamates the strengths of different methodologies, aiming for a nuanced understanding of seismic vulnerability in urban environments.

3.2 Approaches

3.2.1 RVS

RVS is a widely recognized technique for swiftly assessing the seismic vulnerability of structures. This approach involves visual inspection of buildings and their categorization based on observed damage or potential risk factors. The simplicity and efficiency of RVS make it a valuable tool for preliminary assessments [16]. However, its limitations lie in the inability to provide detailed insights into the structural integrity. Thus arises the need for subsequent, more detailed analyses for a comprehensive understanding.

3.2.2 NDT methodology

Non-Destructive Testing (NDT) methodology offers a non-intrusive means of evaluating the structural health of buildings. Techniques such as ground-penetrating radar, infrared thermography, and acoustic emission testing are utilized to assess material properties and detect hidden anomalies. NDT helps provide valuable information without causing damage to the structure [17]. However, its applicability may be limited in certain situations, and interpretation of results requires expertise.

3.2.3 UPV

Ultrasonic Pulse Velocity (UPV) is an advanced method that measures the speed of ultrasonic pulses through a material. This is done to determine its elastic properties. This approach is particularly useful for assessing the integrity of concrete structures. UPV helps to identify internal defects, cracks, or deterioration in concrete. It also offers insights into the structural soundness of a structure [18]. However, interpretation of UPV results requires specialized knowledge. Moreover, its effectiveness can be influenced by the composition of the building material.

3.2.4 Non-linear static analysis

Non-linear static analysis involves subjecting building structures to simulated seismic forces. This helps in analyzing the non-linear behavior of materials and components of a building structure. This method provides a more detailed assessment of structural response compared to linear methods. It is effective in evaluating the performance of structures under different levels of seismic loading [19]. However, it demands computational resources and expertise in structural engineering for accurate implementation.

3.3 Integration and adaptation

The strength of the proposed methodology lies in the integration and adaptation of these approaches. RVS provides a quick overview, NDT methodology offers non-intrusive insights, ultrasonic pulse velocity delves into material properties, and non-linear static analysis ensures a detailed structural assessment. By combining these methodologies, the earthquake disaster assessment framework aims to overcome the limitations of individual approaches and offer a more comprehensive understanding of seismic vulnerability in urban settings.

3.4 Application and validation

The application of the proposed methodology will involve case studies in diverse urban environments, drawing inspiration from studies like Kassem et al. (2021) and Pavić et al. (2020). The outcomes will be validated through experimental results and compared with existing methodologies, ensuring the practical applicability and effectiveness of the earthquake disaster assessment framework.

4. Proposed results and analysis

4.1 Indore: RVS statistics for Indore

RVS conducted in the vicinity of Bhawarkua (Indore) focused on assessing the seismic vulnerability of structures with a predominant type of construction made of reinforced concrete (RCC). The survey covered 101 buildings, distributed across commercial (52), residential (22), mixed-use (23.), and other categories (4 nos.). Fig. 1 shows the distribution of the building types among the total number of buildings considered for the survey.

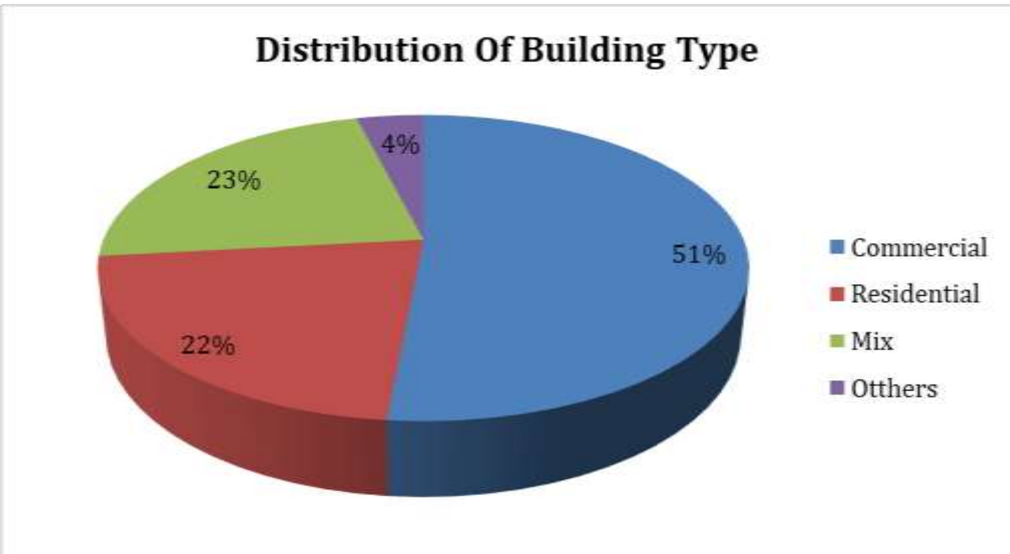


Fig. 1 Distribution of building type in the surveyed houses

4.1.1 Statistical analysis

- Mean Seismic Vulnerability Index: The mean vulnerability index for the surveyed structures was found to be 99.52.
- Standard Deviation: The standard deviation, indicative of the variability in vulnerability, was calculated at 32.06.
- Range: The vulnerability index ranged from a minimum of 3.34 to a maximum of 195.71.

A large number of buildings were featured in the center of the performance score range (68–132). Out of the total number of buildings examined, 101 buildings had mean and standard deviation ratings of 99.52 and 32.06, respectively. These scores assist in the selection of high-vulnerability buildings for examination.
Therefore, these scores are valuable in identifying buildings with a higher vulnerability for detailed evaluation. In the Building Vulnerability Map, building damage states such as no damage, slight damage, moderate damage, severe damage, and collapse state are classified based on μ-3σ, μ-2σ, μ-σ, μ, μ+σ, μ+2σ, and μ+3σ.

Table 1. Various Damage States

Damage State	Scores	
No damage	μ-3σ	3.34
Slight damage	μ-2σ	35.39
Moderate damage	μ-σ	67.46
Severe	μ+σ	131.58
Very severe	μ+2σ	163.65
Collapse	μ+3σ	195.71

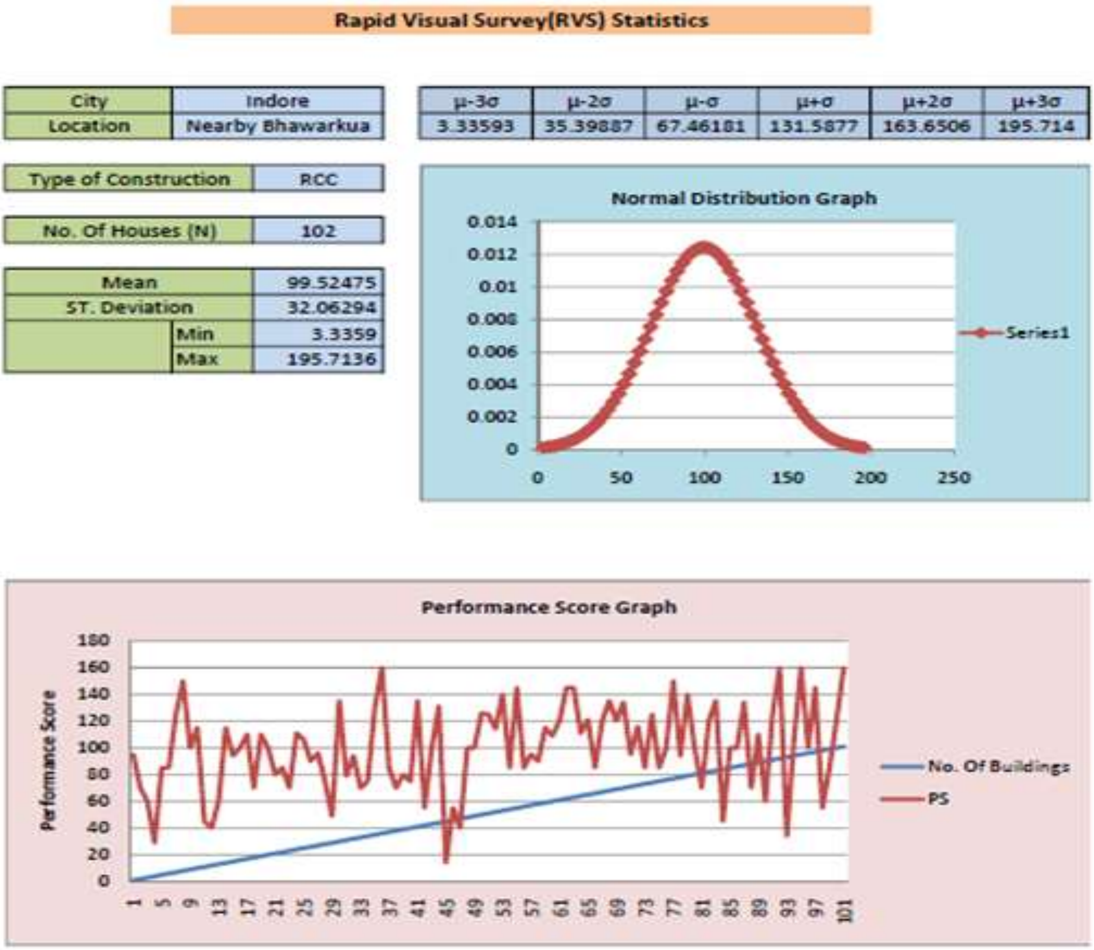


Fig. 2 Normal distribution graph statistical analysis

4.1.2 Vulnerability Factors

- Plan Irregularity: Twenty one structures exhibited plan irregularity, while 80 structures did not.
- Vertical Irregularity: Vertical irregularity was observed in 36 structures, and 65 structures did not display this characteristic.
- Soft Story: Soft story conditions were identified in 67 structures, with 34 structures lacking this vulnerability.
- Pounding: Pounding vulnerability was detected in 29 structures, while 72 structures did not exhibit this characteristic.
- Falling Hazard: Falling hazard vulnerability was prevalent in 100 structures, with only 1 structure devoid of this risk.
- Apparent: Apparent vulnerability was found in 46 structures, while 55 structures did not show this characteristic.

- Heavy Overhang: Heavy overhang vulnerability was identified in 6 structures, while 95 structures did not possess this risk.

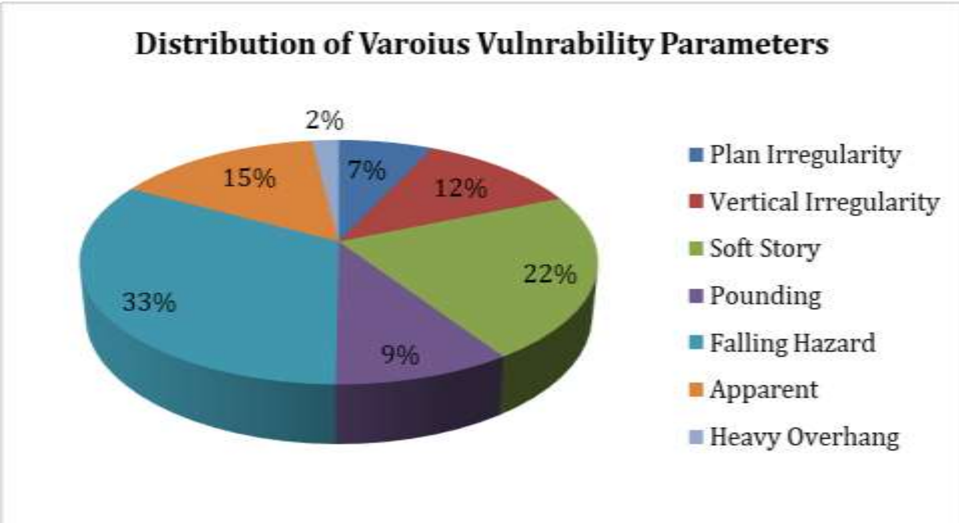


Fig. 3 Distribution of various vulnerability parameters

4.1.3. Observations from results

1. RVS of 101 buildings of ward no (63, 64, and 65) of Indore was carried out. In this screening, the performance scores of 14 buildings were found to be less than the cut-off score obtained by the normal distribution method for Indian methodology; 70 buildings needed level 2 analysis as per FEMA 154 methodology.
2. Maximum buildings with soft stories and pounding effects were discovered to be vulnerable and require additional detailed analysis. FEMA methodology does not consider the effect of height in deciding the vulnerability of a building. However, when Indian methodology scores decrease substantially with increasing height. As the maximum number of buildings in the area of the study were three or four storied, they were found safe as per Indian form.

4.2 Non-linear static pushover analysis and NDT results

In this section, we present the results of Non-Destructive Testing (NDT) and the Non-Linear Static Pushover Analysis, which were conducted as part of this study. The NDT results offer valuable insights into the structural integrity and health of the buildings, while the Pushover Analysis provides information about their seismic performance.

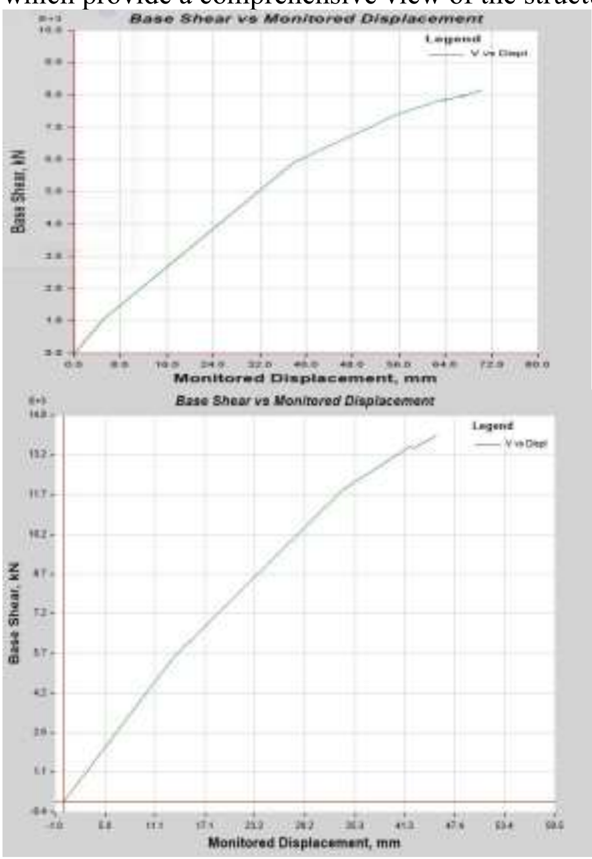
4.2.1. Non-destructive testing results

Rebound Hammer Test: The Rebound Hammer Test was conducted to assess the concrete strength of the structures. It is important to note that the Rebound Hammer Test provides an indication of concrete strength. However, it may not be highly precise due to various

influencing factors, such as the type of cement used. In our study, the accuracy of predicting concrete strength in a structure was found to be approximately 25%. This test helps identify potential weaknesses but may not reveal internal fractures or defects.
Ultrasonic Pulse Velocity Test: The Ultrasonic Pulse Velocity Test is a valuable tool for evaluating the quality of building structures. However, in some cases, we encountered challenges where the velocity readings were out of range, indicating potential issues such as gaps between concrete and plaster. These tests revealed variations in the compressive strength of the structures, particularly as we moved closer to the base of the columns.

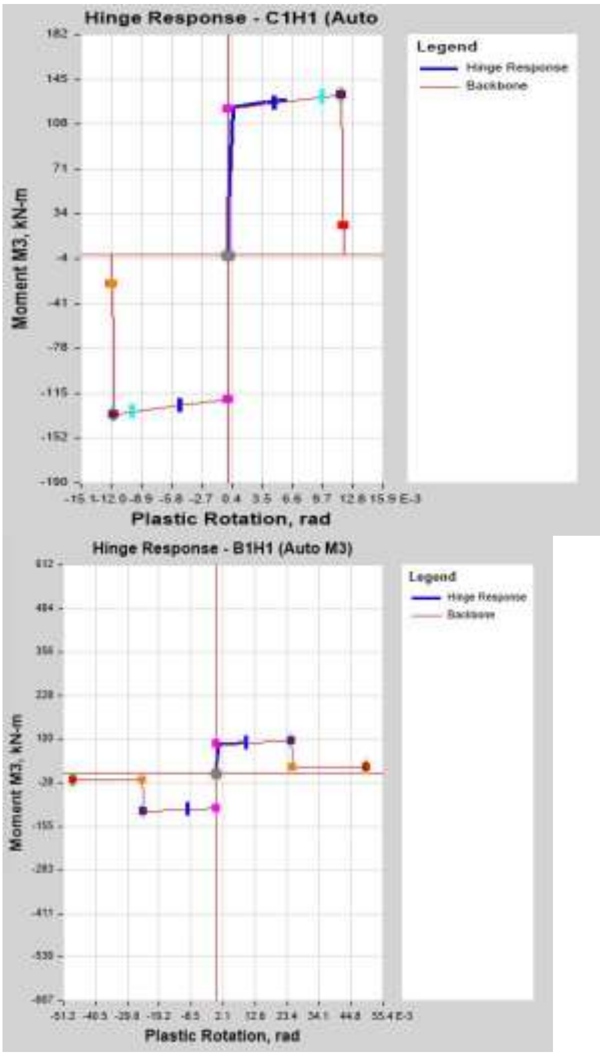
4.2.2. Non-linear static pushover analysis

The non-linear static pushover analysis is a critical component of this study to assess the seismic response of the structures. The analysis is conducted according to the seismic zone classification provided by the Indian Code for the region.
Pushover hinges were assigned to beams and columns, and lateral forces were applied at the design center of mass at each floor level. Fig. 8 (a) and (b) illustrate the pushover curves, which provide a comprehensive view of the structural performance under seismic loading.



(a) (b)

Fig. 4 Pushover curve



(Column) (Beam)

Fig. 5 Hinge responses for pushover by beam and column.

Fig. 9 showcases the hinge responses for pushover by beam and column and the demand spectrum curves for both models, with and without shear walls.

4.2.3 Analysis of pushover results

Pushover curves

The pushover curves demonstrate the relationship between base shear and displacement during the lateral loading of the structure.

For models with and without a shear wall, the curves show a gradual increase in base shear with increasing displacement. This gradual increase indicates a more ductile response to lateral forces.
The presence of hinges in the inelastic over strength (IO), local strength (LS), and collapse prevention (CP) ranges indicates potential areas of concern, where inelastic deformations and yielding may occur.

Visual representations of hinge formations
The figures illustrating hinge formations in beams and columns visually highlight potential weak spots in the structure.
Locations where hinges form suggest areas of the building that may undergo significant deformations or exhibit reduced strength during a seismic event.
The presence and type of hinges provide insights into the structural vulnerabilities and help in identifying areas that may require reinforcement or retrofitting.
Overall, the observations suggest that the structure exhibits a ductile response to lateral forces, allowing for a gradual redistribution of stresses and deformations. However, the specific locations and types of hinges formed in beams and columns indicate potential areas of vulnerability that should be carefully considered in structural assessments and retrofitting strategies.

4.2.4. Observation

- NDT results show that the majority of structural elements such as columns, beams, and slabs of NC (Navlakha complex) buildings, particularly those located in the outer plan or exposed to weather have been severely deteriorated and their strength has decreased significantly.
- On the NC building, a non-linear static pushover analysis was performed. The model was examined with and without a shear wall. The performance point for the model with shear wall was at base shear 6144.96 KN, with an effective time period of 0.739 sec. The performance point for model without a shear wall was at base shear 1998.73 KN with an effective time period of 0.816 sec. The percentage variation is calculated to be 67.47 %.
- Collapse hinges in beams and columns were observed in both cases. Following that, appropriate repair and retrofitting techniques were suggested.

4.3 Seismic retrofitting suggestions

The study recommends several retrofitting methods for enhancing the seismic resilience of buildings:

4.3.1. Jacketing method

- Purpose: To strengthen weak columns prone to failure under load
- Implementation: To reinforce and fortify vulnerable columns

Fig. 6 Column jacketing

4.3.2. FRP

- Purpose: To increase or expand the capacity of reinforced concrete beams
- Implementation: To utilize fiber reinforced polymer (FRP) as an axial strengthening system for beams

Fig. 7 FRP for retrofitting of building

4.3.3. Epoxy injection method

- Purpose: To repair non-moving cracks in concrete walls, slabs, columns, and piers
- Implementation: To repair minor cracks in structural elements using epoxy injection, in a cost-effective manner

Fig. 8 Epoxy injection for retrofitting of building

4.3.4. External plate bonding

- Purpose: To reinforce concrete beams (especially beneficial for repairing damaged beams)
- Implementation: To apply external plates or strips to enhance the strength and integrity of beams

Fig. 9 External plate bonding for column and beam repair

4.3.5 Grouting and re-casting or plastering

- Purpose: To repair damaged plaster on walls and ceilings and to re-cast damaged chajja or slab cantilever edge projections
- Implementation: To utilize grouting and re-casting methods for effective repair work

Fig. 10 Grouting and re-casting or plastering of (existing) damaged ceiling plaster

4.3.6. Corroded structural member's retrofitting

- Purpose: To address corrosion in structural members by removing weakened concrete and exposing reinforcing steel
- Implementation: To use wire brushes or sandblasting to remove rust, and to apply polymer or epoxy resin-based bonding compounds as a tack coat

These retrofitting methods provide diverse solutions to strengthen and repair different structural elements, addressing vulnerabilities identified in the seismic assessment.

Implementing these recommendations can significantly improve the overall seismic performance and safety of the studied buildings.

5. Conclusion and future scope

The comprehensive seismic assessment conducted in Indore and Dhamnod reveals crucial insights into the vulnerability of structures, providing a foundation for informed decision-making and retrofitting strategies. The analysis involved RVS, vulnerability factors, NDT, and non-linear static pushover analysis.

1. Pushover Analysis Results: The pushover analysis demonstrated a gradual increase in base shear with displacement, indicating a ductile response to lateral forces. Hinge formations in beams and columns highlighted potential weak spots in the structures, guiding retrofitting recommendations.
2. Specified Performance Points of Buildings: In Indore, the performance point for buildings with shear walls was at a base shear of 6144.96 KN, with an effective time period of 0.739 sec. However, buildings without shear walls had a performance point at a base shear of 1998.73 KN, with an effective time period of 0.816 sec. The percentage variation between the two scenarios was calculated to be 67.47 %.
3. Vulnerability in Indore: In Indore, RVS of 101 buildings in wards 63, 64, and 65 revealed the following findings: Of the buildings surveyed, 14 had performance scores below the Indian methodology cut-off and 70 buildings required a level 2 analysis per FEMA 154 methodology. The vulnerability factors such as soft stories and pounding effects were found to be significant contributors.
4. Indian and FEMA Scores: The analysis underscores the disparity between Indian and FEMA methodologies in assessing vulnerability. While the Indian methodology considers the effect of height, resulting in fewer vulnerable buildings in areas with predominantly low-rise structures, the FEMA methodology focuses on other factors, contributing to a higher vulnerability rate.

5.1 Overall conclusions

- The study emphasizes the urgent need for comprehensive evaluation and retrofitting in both cities due to the substantial vulnerability identified.
- Common issues such as irregularities in structure, poor construction practices, and unfavorable soil conditions were identified as major contributors to vulnerability.
- The complex nature of seismic vulnerability assessments highlights the importance of expert insights and detailed evaluations, despite the associated challenges in terms of time and cost.
- Seismic retrofitting suggestions include various methods such as column jacketing, FRP strengthening, epoxy injection, external plate bonding, grouting, re-casting or plastering, and addressing corroded structural members.

In conclusion, the study provides a holistic understanding of the seismic vulnerability of structures in Indore,offering valuable recommendations for enhancing the structural integrity and safety of buildings. The findings underscore the significance of proactive measures to mitigate seismic risks and ensure the resilience of the built environment in these regions.

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Competing interests
The authors have no relevant financial or non-financial interests to disclose.

Data availability
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