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Review Article

Improving Structural Resilience in Earthquake-Prone Areas through Seismic Retrofitting Strategies

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Abstract - *In the realm of structural engineering, the seismic resilience of building structures stands as a paramount concern, especially in regions prone to seismic activity. However, the absence of stringent seismic design requirements in current structural standards has left many existing structures vulnerable to the devastating effects of earthquakes. This review paper addresses this critical issue by exploring various seismic design strategies and analytical techniques for retrofitting pre-existing structures. Also, this paper discusses the shortcomings of current structural design standards in seismic considerations and the need for retrofitting measures. It explores various classification methods and discusses seismic analysis methodologies, including software tools and empirical approaches, and the integration of artificial intelligence (AI) to improve the accuracy and efficiency of monitoring building structures under seismic conditions. The paper also examines the economic aspects of retrofitting, conducting a comprehensive cost analysis to evaluate the financial implications against the potential benefits of enhancing structural resilience. The paper aims to analyze retrofit strategies by considering technical efficacy and cost-effectiveness, which are essential for researchers to facilitate informed decision-making and proactive measures to safeguard existing structures against the destructive forces of earthquakes.*

Keywords - *Machine Learning (ML), Earthquake engineering, Seismic hazard analysis, System identification and damage detection, Structural control, Seismic fragility assessment, Artificial Neural Network (ANN).*

1. Introduction

Undoubtedly the most destructive, unavoidable, and unforeseen natural calamity in human history, earthquakes are unavoidable. Every year, earthquakes destroy the lives of thousands of humans and wreak millions of dollars in property damage all over the world. They are also responsible for a wide variety of multi-hazard effects. The bulk of the time, structural injury is produced by the earthquake's magnitude, which imposes an excessively unanticipated lateral load on the structure.

An earthquake is the most dangerous and catastrophic type of damage, and it is extremely challenging to save people and build structures. To understand the seismic presentation of the buildings and take appropriate safeguards when a disaster strikes, it is essential to ensure that the structures endure recurring mild earthquakes [1]. Numerous such rules on this issue have been modified frequently worldwide. A building's ability to withstand the effects of seismic activity depends on several variables, including enough lateral strength, rigidity, flexibility, and a straightforward and consistent layout. Snow, living, and dead loads are typical gravity impact loads. A safe building frame must withstand vertical loads with enough rigidity. The presentation of a building during an earthquake (E) is related to various reaction characteristics such as appropriate lateral strength, plasticity, stiffness, and a simple as well as regular structure. An arrangement with uniformly distributed stiffness, mass in elevation and plan, and organized geometry sustains substantially less destruction than one with an unbalanced layout.

Because of the rapid global expansion, it is common to see irregular buildings being built in every nation.

- It is a regular structure when the arrangement across the whole axis is roughly regular.
- When a building has irregular plans, load-bearing elements or height must be considered unequal [2-3].

Today, most of the land is occupied by asymmetrical structures built to the specifications of the architecture. The part of the building that resists seismic pressures is known as a Lateral Force-Resisting System (LFRS). Shear walls and double frame-shear wall systems are examples of LFRS. A structural system within a building is designed to resist lateral forces, such as those from earthquakes or wind. LFRS components provide stability by counteracting horizontal loads and minimizing sway or deformation during an earthquake. Additionally, structural abnormalities in the building's rigidity, power, and mass are to blame for the structural vulnerabilities. Horizontal and vertical irregularities are the most common structural flaws [4].

Despite advancements in understanding earthquake impacts, a significant gap exists in addressing the vulnerabilities of irregular and asymmetrical buildings. These structures are often more susceptible to seismic damage due to their lack of uniform mass distribution and varying stiffness. Many existing buildings, especially those built in seismic zones with outdated standards, lack proper earthquake-resistant features. This gap emphasizes the need for more advanced techniques to predict and enhance the earthquake resilience of buildings with non-uniform designs, mainly when traditional seismic analysis tools fall short. Figure 1 depicts a line figure of numerous forms of perpendicular abnormalities. Different kinds of 2 2-dimensional frame approaches are displayed in Figure 2.

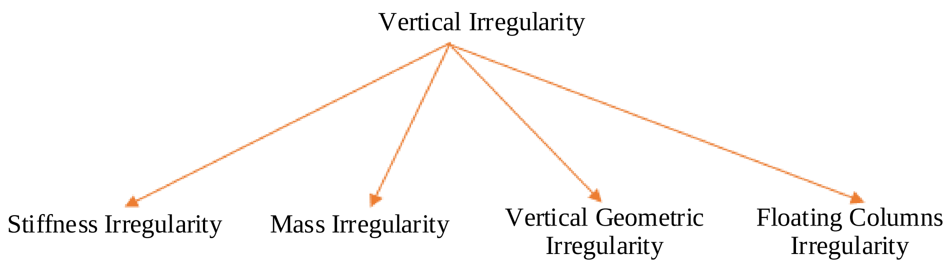


Fig. 1 Various forms of vertical irregularities [5]

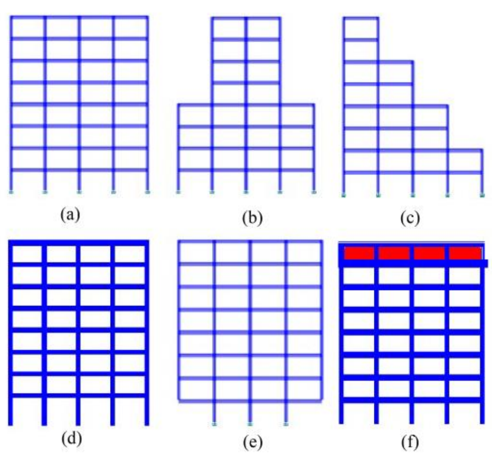


Fig. 2 Different models in 2-D (a) Regular building (b) Setback building (c) Stepped building (d) Stiffness irregular building (e) Floating columns building (f) Mass irregular building [6]

- It is possible that the structure was not planned and constructed with earthquake resistance in mind.
- Insufficient time is spent updating codes of practice and standards.
- Many existing structures need more earthquake resistance because they were not built by current building rules and accepted earthquake-resistant practices.
- Buildings on hilly slopes sometimes have columns of varying heights within the same story; as a result, short columns are more susceptible to damage during earthquake ground motion.
- In contrast to plain buildings, those on hills are torsionally linked, highly asymmetrical, and irregular with parallel and perpendicular planes. Consequently, they were susceptible to serious destruction when subject to earthquake ground motion.

In the field of E research, the term "Seismograph" describes equipment that is wise to seismic waves and may also be used to assess the impact of an earthquake. It is possible to estimate the strength of earthquakes using a variety of scales, including the Rossi-Forel Scale, the Mercalli Scale, and the Richter scale, among others. There are three different waves, which are explained as follows.

- P-waves, a type of longitudinal wave, are longitudinal waves that resemble sound waves in terms of their properties.
- Secondary or Transverse Waves (TW), commonly called S-waves, are TW with properties resembling those of light waves.
- Long-period waves, also known as surface waves or L-waves, are generated when the surface wave, or 'P' wave, strikes the surface.

The Bureau of Indian Standards categorizes four regions of seismic activity: Zone-II, Zone-III, Zone-IV, and Zone-V, correspondingly, based on the country's seismic history (Table 1). Zone-V is the most seismically active area among the four zones, while Zone-II is the least seismically active.

Table 1. Types of zones and their intensity

Seismic Zone	Intensity on M.M Scale
Zone II (Low-Intensity Zone)	6 (or less)
Zone III (Moderate-Intensity Zone)	7
Zone IV (Severe-Intensity Zone)	8
Zone V (Very Severe - Intensity Zone)	9 (and above)

This research aims to bridge this gap by exploring AI-driven approaches to enhance earthquake resilience for buildings not fully considered by traditional seismic analysis methods. The potential of ML to forecast the behaviour of structures has led to its growing interest in seismic and Structural Engineering (SE). As an outcome, several studies have examined ML utilization in this area [7]. ANN based on AI has recently been developed as a novel method to handle these issues. It quickly discovered broad relevance spanning numerous regions. This has stimulated research into using such techniques to address real-life problems, highlighting the potential benefits and limitations [8].

In the modern world, design and construction are becoming more challenging in ensuring more economy and efficiency. Designers must, therefore, increase their knowledge and skills. Using 14 computer-based software programmes created by various software businesses, these issues can be solved more successfully with an Extended three-dimensional evaluation of a building (ETABS). It is true that the computer program is design-oriented and was created especially for the analysis of multi-story buildings [9]. The ETABS is an organizational strategy computer program well-suited for large-scale structural analysis. ETABS is primarily utilized in framework structures. Sequential construction, P-delta assessment, response spectrum assessment, pushover evaluation, and time history investigation may all be carried out using this software. ETABS analyses complex high-rise systems quickly using advanced numerical methods [10]. Steel frames, reinforced concrete frames, composite beams and columns, steel joists, and shear walls can all be designed with ETABS. The ETABS design allows easy access to the building’s components, immensely beneficial to the designer. Several investigations are performed to analyze the impact of numerous quake events on the seismic (S) presentation of the Reinforced Concrete (RC) framework.

The study’s scope provides information on how well structures perform during earthquakes. This review research is a framework: Segment 2 provides an elaborate literature survey. This section reviews the literature on seven classifications: base isolation system, base isolation materials, ground motion IMS and damage index, seismic analysis of numerous models, artificial intelligence methods, analytical investigation using software, and cost analysis for buildings/ structures. Segment 3 provides the summary of this review paper. Following that, future research is provided in Segment 4. Finally, Segment 5 concludes this review paper.

2. Literature Survey

A comprehensive literature survey has been conducted to spot the research problem, objectives, and outcomes to be gained from the research. The literature review is performed on seven classifications: base isolation system, base isolation materials, ground motion IMS and damage index, seismic analysis of numerous models, artificial intelligence methods, analytical investigation using software, and cost analysis. A detailed literature study is conducted to clearly and consistently recognize the research problem.

2.1. Base Isolation System

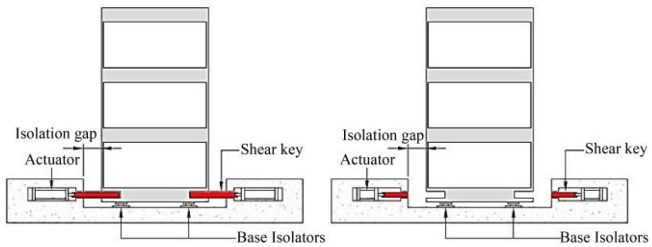
This section discusses several seismic isolation methods, including tuned mass dampers, rubber and lead rubber bearings, and rubber and bearings made of lead rubber.

Talaeitaba et al. (2021) examined the ideology of rubber bearings combined with steel rings, called the RRB. The study was carried out for three-to-six-story steel and concrete structures with RRB, Lead Rubber Bearing (LRB), and fixed Base. The modelling of the isolators is conducted in ANSYS software packages, which determines the hysteresis loop, effective stiffness, and damping values. The seismic responses, including base shear, drift, average damping, and effective stiffness, are computed. According to the authors, the effective stiffness of RRB and LRB is 82.48 ton/m and 110.88 ton/m, respectively. The damping values of RRB and LRB are determined as 47.02% and 18.44%, respectively, which is promising. RRB significantly reduces acceleration and drift compared to fix and LRB bases remarkably.

Pourmasoud and colleagues (2022) developed a novel Multi-Directional Seismic Isolation (MDSI) method to enhance structures’ stability when subjected to horizontal-vertical excitations. The Super-High-Damping Rubber (SHDR) device and isolation unit modify vertical stiffness without influencing horizontal movements. For steel frames three, five, eight, and twelve stories high, the system demonstrated efficacy under ten distinct seismic excitations, reducing maximum accelerations by up to 55% and 25%.

EEW systems detect fast-moving earthquake P-waves and alert the public before more destructive Swaves arrive.

Yan-Shing Lina et al. (2020) presented a study on the smart base isolation system with an earthquake warning mechanism (EEW system), which is used to give warning signals before the manifestation of earthquakes and is shown in Figure 3. This system uses a microcontroller to update the status of EEW via an internet connection and supports the key structure with sliding-type bearings for maximum vibration suppression. The framework could move freely in the horizontal plane because shear keys retract when a signal shows ground motion. Actuators renew the structure and engage the shear keys once the ground motion stops. Therefore, this approach was evaluated in three scenarios: fixed base, EEW-released, and sensor network-released.



(a) Off mode **(b) On mode**

Fig. 3 Earthquake warning system

The BIS-TMDI model by Yue and Han (2024) introduces a multi-objective optimization technique using NSGA-II to balance seismic vibration reduction and control force of the TMDI scheme in structures. Implemented to an 8-story structure, it reduces top displacement by 60% and control force by up to 60%, with robustness across varied seismic frequencies. The model achieves a 16-25% reduction in average control force under non-stationary excitations, though it results in slightly higher top displacement than single-objective approaches. In nonlinear cases, it stabilizes with 20% and 15% reductions in displacement and acceleration and up to 90% in control force. Figure 4 depicts a schematic illustration of the increased base isolation structure equipped with a tuned mass damper.

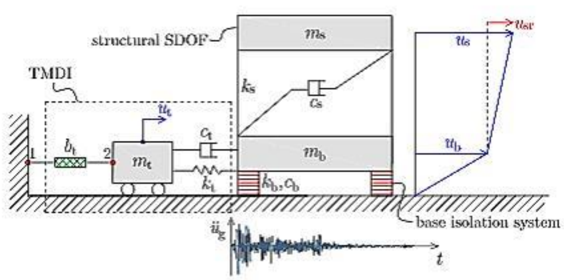


Fig. 4 Single-storey building with tuned mass damper

2.2. Base Isolation Materials

This section reviews different base isolation materials, from natural to recyclable materials. It discusses the literature based on natural materials such as pebble stones and limestone sand.

The study by Hashemi Jokar et al. generated 2D single-layer soil models using ABAQUSnite element software. 120 receivers recorded waves, with an active shot on two sides of the array. The data processing involved using windows of different lengths and tracings to determine the effect of windowing on dispersion curves. The double Fourier transform was used to obtain dispersion curves for each windowing. This allowed for accurate lateral variation location and phase velocity range determination, which was helpful in the inversion step and initial shear wave velocity range. This approach saves time and cost in specifying soil properties.

Jokar et al. (2019) showed how MOPA may be easily applied to define heterogeneities in complex contexts, such as abandoned industrial sites, even at tiny spatial scales. This involved detecting subsurface lateral heterogeneities at a highly contaminated industrial site in Trieste, Italy, using a Multi-offset Surface Wave Analysis (MOPA). Characterization of the site is being done in preparation for remediation and reuse. One of the primary heterogeneities is a long submerged quay that separates the marine and continental deposits. Clear proof of the desired heterogeneities was produced by this analysis, which was backed by geo-electrical surveys, boreholes, and S surface waves. Ancillary data and synthetic modelling were used to support the interpretation of field data.

An evaluation of the application of Scrap Tire Pads (STPs) as a vibration control device for E-safety in residential buildings was conducted by Shirai and Park in 2020. An STP unit specimen was experimentally investigated, the seismic mass damper system's idea and benefits were explained, and the control effects were numerically evaluated. The STP specimen, without needing extra energy dissipation devices, was shown to have a modest damping capacity and stable hysteresis loops against lateral cyclic loadings. The impacts of the suggested mass damper system on response reduction were also assessed using earthquake response learning.

Munoz et al. (2019) proposed a bearing made of recycled tyre rubber. These recycled tyres are cut into square shapes, and each tyre layer is joined using a vulcanization process. The paper conducted a preliminary study by testing the specimens subjected to constant axial loads of 330 N/mm2, 270 N/mm2, and 220 N/mm2 for three specimens to check for shear deformation. From the investigation, the study reported that all three specimens undergo shear deformation, and a failure pattern is seen with a shear strain of 100%.

The research by Kumar et al. (2019) proposed a low-cost SI system using scrap rubber tyres to reduce seismic demand on structures using scrap tyres as a base. This study evaluated the assets of SI pads made from scrap automobile tyres, focusing on vertical and horizontal stiffness and shear modulus. The research was conducted at the IIT Bombay Heavy Structures Laboratory using a 200 x 200 x 130 mm sample. The steel plates, shim plates, and rubber pads were vulcanized together to create a composite structure. The shear coefficient was 0.8 MPa, the average horizontal stiffness was 4.4 × 105 N/m, or roughly 2% of the vertical stiffness, and the average vertical stiffness was 21.5 × 106 N/m. The findings demonstrated that the low-cost STRP base isolation technology is a desirable and practical substitute for isolation methods that are sold commercially.

A sand-rubber flexible, granular layer was used as an inexpensive seismic isolation technique for developing nations, and this was investigated in a 2019 study by Tsiavos et al. Direct shear testing was used to measure the friction angle of three distinct sand-rubber mixtures under varying vertical stress levels to investigate the mechanical properties of possible failure mechanisms within the sand-rubber layer. The frictional properties of sliding between a timber interface and a sand-rubber layer were determined. Additionally, the kinetic friction of various sliding interfaces against two distinct sand-rubber mixtures for varying sand-rubber layer heights was measured, and the dynamics of a rigid sliding block were examined. The results assist in determining the ideal grain size ratio and sand-rubber layer height to achieve a lower friction coefficient between the sand-rubber layer and the foundation.

Dhanya et al. (2019) proposed a base isolation method using a sand-tyre mix and geo-base isolation system placed underneath the foundation. To enhance the soil carrying capacity. This system is a model footing with a width of 100 millimetres and a thickness of 10 millimetres. The entire structure was located in a test tank filled with size 1mx1mx1m and occupied with sand up to a height of 0.9 m. The entire setup is subjected to static loadings, and geotechnical properties are obtained and studied. The test is varied for the number of geo-grid layers. From the investigation, the bearing ability of soil is improved three times with double-layer geo-grid layers. Furthermore, with single and double-layer geo-grid layers, a reduction in the soil's bearing capacity is increased by around 30% and 45%, respectively.

Banović et al. (2023) propose a low-cost geotechnical seismic isolation (GSI) system using natural stone pebbles (SP) (ASL-1) and a composite of SP with a geogrid layer (ASL-2) to reduce seismic forces in low-rise structures and small bridges. Tested under various accelerograms, ASL-2 was more effective than ASL-1, achieving up to 34% reduction in seismic forces at model failure, especially in stiffer structural models (M1 and M2). Although ASL-2 provides improved force reduction over conventional RB models, it performs less effectively in flexible structures and under specific excitation types, highlighting the need for further testing on realistic structures to validate efficiency across broader conditions.

Edinçliler and Yildiz (2023) propose a GSI solution using expanded polystyrene (EPS) beads mixed with sand to mitigate seismic forces on medium-rise buildings. Their study tested a 1/10 scale of a five-story structure with various EPS-sand layer thicknesses to observe reductions in peak accelerations and inter-story drifts. Results show that an EPS40 mix with a 15 cm isolation layer enhanced seismic performance. The model is sensitive to EPS content and earthquake input variations, indicating effective performance and potential limitations. Comparisons with rubber-sand mixtures affirm EPS-sand's promise but suggest further studies to refine its applicability.

2.3. Ground Motion IMS and Damage Index

Seismic ground motion IMS is a metric used to assess the strength or cruelty of seismic acceleration signals. These metrics are critical in determining a place's seismic danger, estimating seismic requests on structures, and constructing E-resistant models. Numerous IMS have proposed additional hours, each with its advantages and disadvantages.

Forcellini (2024) proposes designing Geotechnical Seismic Isolation (GSI) layers by assessing thickness and shear wave velocity through 3D OpenSees simulations on low-rise buildings. The approach reduces reliance on extensive simulations, providing practical guidelines for preliminary design. While effective for decoupling seismic forces, it is limited to low-rise structures and requires validation for mid-rise buildings and bridges.

Wang et al. (2023) propose an ML-driven framework for constructing a Probabilistic Seismic Demand Model (PSDM) for nuclear power plants using 33 Intensity Measures (IMs). The dataset comprises 300 ground motion records (100 near-fault and 200 far-fault) from the PEER database, representing active crustal earthquakes. Recursive Random Forest (RRF) identifies significant IMs, while 14 algorithms determine the optimal model. However, the method requires extensive computational resources for model training.

Li et al. (2023) propose a rapid evaluation model for earthquake-induced landslides based on Peak Ground Acceleration (PGA) and Arias Intensity (Ia), applied to the Luding Ms6.8 earthquake. The model utilizes the Newmark cumulative displacement method for landslide risk assessment. The model achieves an AUC value of 0.84, confirming its high accuracy in landslide prediction, especially using Ia. The outcomes highlight that the high-risk zones are concentrated along fault lines with steep slopes. However, the model's limitation lies in its dependency on accurate seismic data and geological conditions.

Pavel and Nica (2023) propose empirical models for assessing Ground Motion (GM) durations from Vrancea intermediate-depth E in Romania, using a database of 200 ground motions from five earthquakes (1977–2004). The models define significant durations with two Arias Intensity time intervals (5–75% and 5–95%). Results show that soil conditions and hypocentral distance influence duration, with D5-95 being larger than D5-75 by a ratio of 2.8. The model provides more accurate durations than the Eurocode 8 draft but faces limitations due to insufficient data for more significant peak accelerations and geographic trends.

Zhen et al. (2024) propose a new GM intensity measure (IM) that accounts for numerous vibration modes and period elongation from roof isolation. Evaluating 37 IMs on a large-span roof-isolated structure, the proposed IM improves efficiency by up to 51.5%. While showing strong performance in correlation with structural responses, the study lacks consideration of scaling robustness, structural damage correlation, and certain seismic wave effects. Alcantara and Saito (2023) propose an ML-based method to forecast the injury state of RC resisting-moment frame buildings using 60,000 time-history simulations and 27 Intensity Measures (IMs). Seven ML methods were tested, with Gradient Boosting achieving the highest accuracy ($R^2 = 0.942$). The study found that including roof sensors was challenging and recommends expanding the dataset for improved prediction accuracy in future research.

Nguyen et al. (2020) identify key E IMs for assessing S injury in NPP structures, using the APR1400 NPP as a case study. The study finds that PGA, A95, and SMA are best for non-isolated structures under low-frequency ground motions, while SED, Ic, and Ia are better for high-frequency motions. For base-isolated NPPs, SED, Ia, and Ic are most effective. The study highlights that PGA and Sa may not be optimal for high-frequency regions, with a limitation in their focus on specific NPP configurations.

Nguyen et al. (2021) developed PSDMs to identify optimal E IMs for base-isolated NPP models. The study used a lumped-mass stick model and time-history analyses with 90 ground motion records focusing on seismic parameters. The results showed that velocity spectrum I (VSI) and Housner I (HI) are the greatest for MFD and MID, while PGA and A95 are efficient for MFA. However, some IMs, like Cumulative Absolute Velocity (CAV), were unsuitable for seismic performance evaluations.

An E IM based on modified spectral velocity was proposed by Lai et al. (2022) to evaluate the S stability of super high-rise structures. To maximize the number of modes, the IM uses the non-uniform Flexural-Shear Coupled Model (FSM-MS) to combine coefficients. The findings showed that compared to 19 other IMs, the suggested IM had higher stability and efficiency correlating with maximum Inter-Story Drift (ISD) ratios. However, the correlation with other structural demand measures and the impact on severe damage or collapse responses remains uncertain.

Abdalzaher et al. (2024) introduced a machine-learning model, 2S1C1S, for estimating earthquake intensity using a single station and component. Trained on the “INSTANCE” dataset from the Italian National Seismic Network, the model achieved 99.05% accuracy. It outperformed traditional methods and other machine learning models, showing promise for real-time earthquake early warning systems. Future work will focus on enhancing scalability, computational efficiency, and applicability in low-resource regions. The procedures for the studied IMs are specified in Table 2.

Table 2. Mathematical formulas for the examined IMs [21]

S.No	Name	Description
1	PGA	$\max\lvert a_g(t)\rvert$
2	PGV	$\max\lvert v_g(t)\rvert$
3	PGD	$\max\lvert d_g(t)\rvert$
4	I_A	$\frac{\pi}{2g}\int_0^{t_{end}} a_g^2(t)dt$
5	CAV	$\int_0^{t_{end}} \lvert a_g(t)\rvert dt$
6	PGA/PGV	$\frac{PGA}{PGV}$
7	I_{AS}	$\frac{I_A}{u_o^2}$
8	SMD_{TB}	$t(H_d = 95\%)$- $t(H_d = 5\%)$
9	SMD_{ROG}	$t(H_d = 97.5\%)$- $t(H_d = 2.5\%)$
10	SMD_{Bolt}	$t_{last}^{a_g>0.05g} - t_{1st}^{a_g>0.05g}$
11	P_{90}	$\frac{I_A(H_d = 95\%) - t(H_d = 5\%)}{SMD_{TB}}$
12	a_{rms}	$\sqrt{\frac{1}{SMD_{TB}}\int_{t_{5\%}}^{t_{95\%}} a_g(t)^2 dt}$
13	I_c	$a_{rms}^{1.5}.SMD_{TB}^{0.5}$
14	I_{FVF}	$PGV.SMD_{TB}^{0.25}$
15	I_{RG}	$PGD.SMD_{TB}^{\frac{1}{3}}$
16	SI_H	$\int_{0.1}^{2.5} PSV(T, \xi = 0.05)dt$

Structures suffer seismic damage as their resistance to external stresses deteriorates, which results in structural unpredictability. A reliable metric for determining structural injury is the Park and Ang damage index (DIPA), a linear combination of damage brought on by recurrent cyclic loading effects and excessive deformation. The energy absorbed by plastic hinges amplifies the maximal bending reactions during an E. The weight of each sub-damage is proportionate to the energy used by the structural participant linked with it, and the total damage index (DIG, PA) is calculated as an adjusted mean of sub-damage values. A low DIG PA number suggests minor damage and a flexible reaction, whereas a value around unity indicates the structure is about to collapse. Complete harm indices, including DIG and PA, provide a quantitative calculation of seismic injury to a model and have been used in several studies to analyze post-earthquake building conditions.

$$DI_{PA} = \frac{\delta_m}{\delta_u} + \frac{\beta}{Q_y\delta_u}\int dE$$

$$DI_{PA,component} = \frac{\theta_m - \theta_r}{\theta_u - \theta_r} + \frac{\beta}{Q_u M_y}E_h$$

$$the\ the\ the\ DI_{G,PA} = \frac{\sum E_i DI_{PA,component}}{\sum E_i}$$

Numerous variables related to fundamental element capacity and response are included in the damage index equation, including the maximum displacement (D) response δ_m, the ultimate D capacity δ_u, the strength deterioration model constant β Park et al. (1987), the absorbed cumulative hysteretic energy $\int dE$, the yield strength Q_y, the maximum rotation of the member throughout the response θ_m, the member's ultimate rotation capacity θ_u, and the recoverability θ_r.

2.4. Seismic Analysis of Various Structures

Zhang et al. (2022) compute the high storey drift of masonry structures subjected to M-A sequences using the non-iterative equivalent linearisation technique and the soft-storey failure mechanism. A finite element method was used to test the approach's efficacy. A parametric technique was used to study the effects of aftershock intensity, anti-seismic wall area ratio, site categorizations, the number of storeys, and mortar strength on S responses. The findings revealed that earthquakes significantly influenced masonry projects during the plastic period. The anti-overturning requirements and foundation shear force of maximum masonry constructions decrease with the number of stories, resulting in a minor maximum and less harm.

Micelli et al. (2022) studied a bell tower building, focusing on its stability and seismic vulnerability. They used a drone-based survey to compute the structure's geometry, reducing time and cost while maintaining accuracy. After that, the resultant item was entered into a structural modelling program using the Finite Element Method (FEM). Potential failure causes were found using a nonlinear kinematic assessment. A non-invasive reinforcing technique was used in the study to increase the bell tower's S strength.

Xu et al. (2019) designed the Vertical Inertia Force-Response D technique (VIF-RDM), which considers the soil's vertical inertia force. They fully described calculating the maximum vertical inertia force and basis spring values. The Integral Vertical Inertia Force-RD Method (IVIF-RDM) was developed to lower estimate error and computing complexity. The axial force of the central column differed significantly between the approach and the Time-History Analysis Method (THAM) in an actual underground construction.

The Midas/Civil finite element software process evaluation examines the Chengdong Hanjiang Bridge in Ankang City, a multi-span continuous beam-arch combination system. Mei and colleagues (2020) study concentrated on how the internal force of the bridge structure was affected by the traveling wave effect and the SI scheme. The results showed that the travelling wave effect increases each hole's displacement and bending moment, and the fixed pier's IF rises. The travelling wave effect strengthens the structure's seismic response, and with increasing wave velocity, the structure's response approaches uniform excitation. Using friction pendulum seismic isolation support reduces the bending moment of Pier No.32, improves bridge stiffness, and enhances the isolation effect.

2.5. Artificial Intelligence Methods

Yariyan et al. (2020) suggested that a Fuzzy-Analytic Hierarchy Process and ANN generated an E-risk valuation map for Sanandaj City in Iran. This method employed a GIS to apply weights to earthquake risk criterion layers, producing an earthquake forecast map with 95% accuracy. The MLP model is integrated into the IDRISI programme, and 250 points are approved for grades 0 and 1. The biggest disadvantage is the lengthy construction and deployment process necessary because of the vast training data required.

Domadzra et al. (2024) examine the seismic response of base-I buildings using Lead Rubber Bearings (LRBs) and Friction Pendulum Systems (FPSs). The study highlights key isolator properties like friction coefficient and lead core diameter that affect performance. The proposed model reduces inter-storey displacement and base shear by dissipating energy through friction and rubber elasticity. While effective for critical structures, the paper suggests further research to optimize designs for varying ground conditions and structural scenarios.

The study by Aydin et al. (2024) proposes an integrated approach using Interpretive-Structural-Modeling (ISM), Decision-Making-Trial, and Evaluation-Laboratory (DEMATEL), along with Neutrosophic Fuzzy Sets (NFSs) to assess and prioritize barriers to managing post-E debris waste. The results show that inadequate recycling techniques and regulatory issues are major impediments. While the model effectively identifies and prioritizes barriers, it is limited by the subjective nature of the data inputs and the complexity of the integrated methodologies.

Aghamohammadi et al. (2024) proposed a fuzzy logic-based model to estimate the survivability of people trapped in collapsed buildings after earthquakes, considering time elapsed and building type. Applied to Tehran's district 11 for Mercalli intensities 7 and 9, the model revealed a significant decrease in survivability in northern areas with rapid building collapses. The key advantage is its timeliness, estimating injuries and life expectancy within 0 to 72 hours after an earthquake. The model provides accurate predictions, though future building classification and rescue optimization improvements are recommended. Shadmaan and Popy (2023) used the Analytical Hierarchy Process (AHP) to assess earthquake vulnerability in Sylhet, Bangladesh, focusing on social, structural, and physical distance factors. The study revealed a high vulnerability in 55% of the area socially, 48% structurally, and 38% regarding physical distance. Data limitations, such as missing information on soil liquefaction, were noted. The model offers valuable insights for earthquake risk assessment and mitigation planning.

Using socio-economic data and multivariate statistical analysis, Sauti et al. (2021) developed a GIS-based Exposure Vulnerability Index (EVI) for seismic risk valuation in Sabah, Malaysia. The EVI map and seismic hazard data identified high-risk areas like Kota Kinabalu and Sandakan. While the model aids in risk planning, it is limited by reliance on census data and lacks consideration of resilience and capacity factors. Future work should integrate these components for a more comprehensive seismic risk assessment.

Hait et al. (2020) created a multi-objective seismic damage evaluation process for low-rise residential buildings using Reinforced Concrete (RC) frames. The study focused on the roof and GF disasters and employed an improved technique to determine the Global Damage Index (GDI) for regular and irregular structures. They also adopted an ANN-based forecast model to minimize errors. The study described the variables influencing the GDI of RC-framed structures and provided a neural interpretation diagram to show how input parameters and GDI relate. This could help designers quickly estimate GDI as an evaluation criterion.

Payan-Serrano et al. (2024) proposed using deep learning models (ANNs) to predict the seismic performance of RC buildings, including those with RC-BRBs, under earthquake ground motions. The model uses fundamental period and earthquake intensity to predict maximum interstory drift. The dataset is based on actual ground motion records. Results showed high accuracy with an R^2 of 95%, making it suitable for seismic predesign. However, the model faces challenges like overfitting with too many hidden layers, which increases computational demands. Future work will compare different neural network architectures for improved efficiency.

Hansapinyo et al. (2020) created a model for the Adaptive Neuro-Fuzzy Inference System (ANFIS) to forecast building seismic damage on an urban scale. This method obtained 57,648 training data from six earthquake magnitudes, eight structural kinds, and 1,201 distances using the Capacity Spectrum Method (CSM) to evaluate buildings. Using the data, a useful ANFIS model for seismic damage prediction was subsequently created. There were minor differences between the CSM and ANFIS results when the model was evaluated in Chiang Mai Municipality under five potential earthquake scenarios. The ANFIS model is appropriate for E-prone regions with little seismic data, such as developing nations, because it can effectively predict seismic building damage.

Nguyen et al. (2021) Created an ML method capable of predicting the seismic reactions of planar steel moment-resisting frames subjected to ground motions. Two of the most potent machine learning approaches, ANN and Extreme Gradient Boosting (XGBoost), are used to achieve this goal. In the first three natural times, ground motion significantly influenced seismic drift response prediction more than earthquake and soil properties and spectrum accelerations. Furthermore, sophisticated behaviours at the section and system levels, modelling irresolution, and additional essential seismic reactions of the arrangement will be considered in future studies.

Huang et al. (2022) created fragility curves for circular tunnels in soft soils using a probabilistic framework and an ANN. The framework estimates tunnel response under ground shaking using a two-dimensional dynamic approach considering ground motion parameters and soil-structure interaction. The ANN produced probabilistic seismic demand models and compared them to conventional linear regression models. The findings demonstrated that the ANN-based framework lowers computational costs while producing dependable fragility models with comparable capabilities to traditional methods. This method can support risk management and decision-making for a more robust transportation infrastructure.

Rachedi et al. (2021) suggested a technique that uses NN to evaluate a viaduct's seismic risk while considering the various soil classifications, the Soil-Structure Interaction, and the seismic intensity levels. The structural response of the viaduct was effectively predicted using the Back-Propagation NN. Unseen instances were used to evaluate the ANN's generalization abilities.

Three soil classes were considered when creating fragility curves for a structural limit state. It was shown that using ANN to generate fragility curves numerically was efficient in accuracy and time. SSI could considerably raise the exceedance probability of damage states across all fragility curves. More numerical studies are necessary to examine the effectiveness of the suggested strategy for further structural and foundation systems.

Mekaoui et al. (2022) developed a hybrid seismic analysis that integrated analytical and RNN models into an explicit temporal integration technique to calculate the entire response of a building structure. Every computing time step had a nonlinear response of interest predicted by the MLM. A thorough methodology for creating synthetic data, enhancing network architecture and hyper-parameters, developing MLM, and testing it was suggested. To verify the effectiveness of the suggested hybrid analysis, numerical simulations of three separate buildings—5, 10, and 15 stories—subjected to four GMs with varying amplitudes, frequency contents, and durations were carried out. The created MLM connected the displacement time history of the buildings under study to the matching shear force-time history, simulating such structures' isolation layer (NRB + LRB + Oil Damper).

Li et al. (2021) created a technique for determining the Maximum Inter-story Drift Ratio (MIDR) using a deep learning approach and the inter-story drift spectrum. To account for discrepancies among the spectrum and actual responses, the approach first approximated the interstory drift spectrum. The first approximation for forecasting the MIDR under novel seismic occurrences was then fine-tuned using a Deep Convolutional NN (DCNN). The technique's potential for precise MIDR estimate was demonstrated by comparison with four ANN models and one support vector machine approach.

Gharehbaghi et al. (2020) investigated how well feedforward, backpropagation ANN and wavelet weighted least squares SVM (WWLSSVM) predicted inelastic seismic reactions of structures. The first three natural periods served as inputs for this study, which examined the force- and displacement-based seismic responses of an 18-story reinforced concrete frame. Although the prediction capabilities of both models were satisfactory, the ANN model demonstrated somewhat higher accuracy, mainly when fewer data were employed. Additionally, the study discovered that responses based on D and force were most sensitive to the first and second natural periods.

Mehrabi et al. (2021) investigated the mechanical efficiency and dynamic response of fibre-reinforced concrete columns using hybrid numerical techniques. They integrated metaheuristic methods with AI to determine the strength factor under seismic loads. The study employed Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and the ANFIS as AI using 317 real test data. The results showed that ANFIS–PSO had promising evaluation indexes [R^2 (test) = 0.86, R^2 (train) = 0.90] for predicting the lateral load. The results demonstrated promising assessment indices for compressive strength and lateral load prediction. The dependable performance of the ANFIS-GA and ANFIS-PSO approaches encouraged researchers to substitute predictive utilities for expensive experimental testing.

An ANN-based surrogate method was proposed by Yoon et al. (2020) to predict the system-level seismic risk of bridge transport networks effectively. To effectively assess a high-dimensional network using probabilistic seismic hazard analysis (PSHA), an ANN-based surrogate approach is added to the total system trip time (TSTT), which is designed as a presentation measure for evaluating network efficiency. Bridge component damage states were used as input training data to generate training information, and TSTT was chosen as output data. However, the approach presented in this research was expected to be used for optimal decision-making and earthquake resilience in civil infrastructure networks, which will need several iterative studies. Therefore, it will be possible to analyze the network structure's operation in a powerful way before earthquakes and to create conservation measures immediately after an earthquake, even in a high-dimensional bridge transportation network.

2.6. Comparisons Focusing on the Structural Complexity of AI Models

Table 3 summarises the techniques mentioned above, focusing on earthquake risk assessment, seismic response analysis, earthquake vulnerability assessment, and seismic damage prediction. Table 3 includes information on the AI models used, the application context, key findings, and their advantages or disadvantages.

Table 3. Comparison based on the structural complexity of AI models

Reference	Models	Application Context	Key Findings	Advantages/Disadvantages
Yariyan et al. (2020)	FAHPANN (Fuzzy-Analytic Hierarchy Process and ANN)	Earthquake risk assessment for Sanandaj City, Iran	95% accuracy in earthquake forecast map	Lengthy construction and deployment process due to vast training data
Domadzra et al. (2024)	LRB, FPS	Seismic response of base-isolated buildings	Key isolator factors like friction coefficient, lead core diameter, and hysteretic behavior are crucial for a seismic response.	Effective in reducing inter-storey displacement and base shear, more research is needed for optimal performance under different ground conditions.
Aydin et al. (2024)	ISM, DEMATEL, Neutrosophic Fuzzy Sets	Post-earthquake debris waste management	Lack of legal enforcement and lack of environmental awareness are key barriers.	It provides insights for policymakers to prioritize barriers in waste management but relies on subjective data inputs and complex integrated methods.

Alizadeh et al. (2018a)	ANN and ANP models	Earthquake vulnerability assessment in urban areas	Varying levels of safety in different metropolitan areas	enhance earthquake vulnerability assessment, and prioritize risks in urban areas.
Hait et al. (2020)	ANN-based forecast approach	Estimating global DI for RC-framed buildings	Ground floor sustains most damage: roof sustains least	Visualized neural interpretation diagram for input parameters
Payán-Serrano et al. (2024)	Deep Learning (ANN)	Seismic efficiency forecast of RC, BRB, and SDOF structures	The model predicts maximum interstory drift with high accuracy (R^2 = 95%) using fundamental period and earthquake intensity as inputs.	High accuracy, suitable for seismic predesign. However, overfitting with many hidden layers increased computational demands.
Hansapinyo et al. (2020)	ANFIS	Predicting building damage at the metropolitan scale	It uses earthquake magnitudes, structural types, and distances	Plans to employ technology for future seismic data generation
Nguyen et al. (2021)	ANN and XGBoost	Predicting seismic reactions of steel moment-resisting frames	Ground motion has a more significant influence on drift response prediction	Considers sophisticated behaviors and additional seismic reactions
Huang et al. (2022)	ANN-based probabilistic seismic demand method	Fragility curves for various damage states	Reliable fragility methods with lower computing cost	Lower computing cost compared to classic linear regression models
Rachedi et al. (2021)	ANN-based strategy for nonlinear dynamic behaviour	Predicting nonlinear dynamic response with varying intensities, soil variability, and SSI	Significant in seismic structural damage and risk assessment analysis	More numerical analyses are needed for different systems and foundations
Mekaoui et al. (2022)	Analytical and RNN models	Hybrid seismic analysis for the entire building response	Effective integration for various building heights and ground motions	Thorough methodology for creating synthetic data, enhancing network, testing
Li et al. (2021)	Deep learning method (DCNN)	Estimating maximum interstory drift ratio (MIDR)	Potential for accurate MIDR estimation	Compared with other AI models, it showed promising performance
Gharehbaghi et al. (2020)	WWLSSVM and ANN	Forecasting seismic reactions of arrangements	ANN model attained higher accuracy with fewer samples	Outperforms WWLSSVM in predicting seismic reactions but may require more data for accurate predictions, potentially increasing data collection efforts.
Mehrabi et al. (2021)	ANFIS, PSO, and GA	Dynamic response and mechanical performance of fiber-reinforced concrete columns	Reliable performance in lateral load and compressive strength prediction	Encourages replacing costly experimental tests with predicting utilities
Yoon et al. (2020)	ANN-based surrogate method	System-level seismic risk of bridge transport networks	Efficiently estimates high-dimensional network performance	Anticipated for earthquake resilience and optimal decision making

2.7. Analytical Investigation Using Software

For instance, the applications of various SE software such as ETABS, SAP 2000, MATLAB, REXEL, and SEISMOMATCH were studied concerning linear and nonlinear analysis of buildings with different profiles, such as regular and irregular buildings. Furthermore, the Fast Nonlinear Analysis (FNA) concept was performed for conventional bearings rather than STRP bearings. Finally, apart from FNA, the concept of applying pushover analysis for buildings with and without seismic isolation is discussed.

Habib et al. (2021) As illustrated in Figure 5, a nonlinear time history analysis was performed on RC bordered buildings in four cases: regular type, heavy mass, soft storey, and stepped type. The SAP 2000 software package was used for the analysis, and the seismic responses of the building with and without LRB were collected and compared. The buildings are subjected to seismic excitations from low PGA to high PGA, such as the Imperial Valley E and the Lome Prieta E. The results reported from this study show that the reduction in roof acceleration is significantly seen during this Loma event at about 30%, 15%, 21%, and 39% in regular, soft-story, heavy-story, and stepped types with LRB base. Also, the results concluded that the performance of buildings with heavy masses is lower than that of other building types. Moreover, low PGA events have a more significant influence in bringing out long periods.

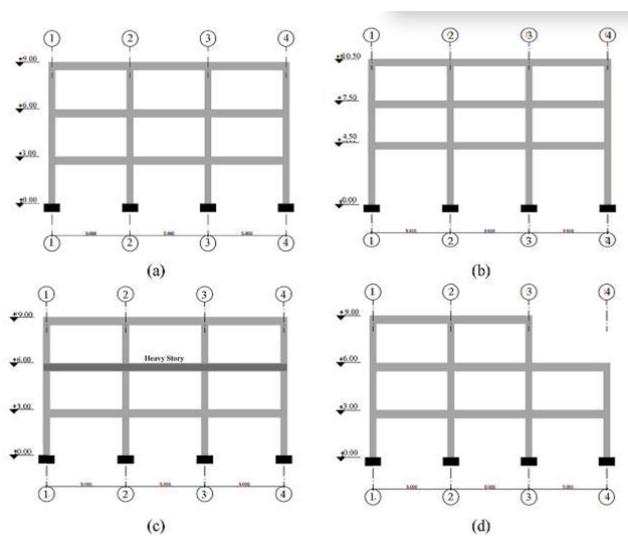


Fig. 5 Analytical investigation using SAP 2000 (a) Regular building (b) Soft story building (c) Heavy mass storey (d) Stepped type building

In order to increase the accuracy of analyzing the time of statistical analysis utilizing the FNA approach to the Nonlinear Time History Analysis (NLTHA) in Sap2000 software, Alilou and Pouraminian et al. conducted a study. They looked into two seismic-resistant methods for an RC frame: Moment Resistant Frame (MRF) and MRF with visco-elastic dampers. The results showed a 7-9 times decrease in analysis time, but the seismic fragility curves did not accurately estimate frame damage. Moreover, with the visual investigation of the fragility curves, it is perceived that FNA's consequences are less reliable than NLTHA. Nevertheless, irrespective of limited nonlinear elements, FNA has acceptable results compared to NLTHA with isolators.

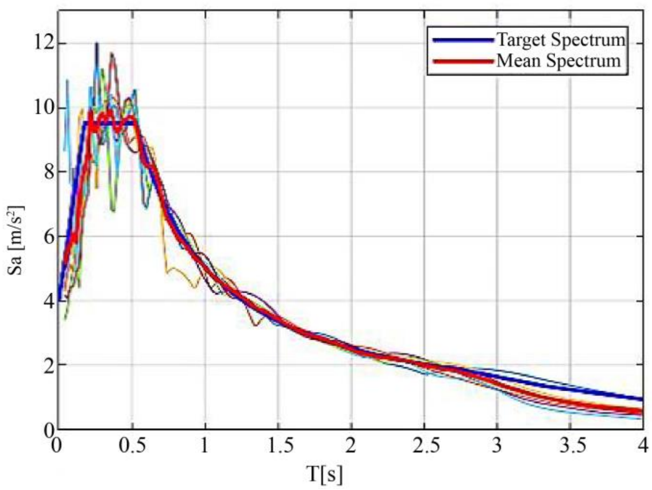
Khan et al. (2019) examined the efficacy of three distinct types of passive base isolators: Lead Core Rubber Bearing (LCRB, Damping Ratio: 25%), Low DRB (LDRB, Damping Ratio: 3%), and High Damping Rubber Bearing (HDRB, Damping Ratio: 13%). under field earthquakes, both distant and close. They used the state space method in MATLAB to evaluate an eight-story building. According to the study, the excitation source affects the structure's dynamic response, which designers must consider for effective design. For far-field earthquakes, the inter-story drift varies between 22 and 52 mm, and in all three isolation systems, it varies between 5 and 60 mm. In order to limit both transmissibility and deformation ratios, the base isolator's damping should be modified; in certain situations, an array of dampers may be employed.

Narjabadifam et al. (2019) conducted a study on the effects of inherent structural characteristics on the performance of SI systems. The study differed from earlier research that concentrated on the impacts of extra mass and dampening or stiffening the superstructure to assess performance enhancement. In contrast to earlier research that concentrated on the effects of ageing, the study sought to comprehend how intrinsic structural features affected the practical efficacy of isolation systems.

Furinghetti et al. (2019) conducted a Nonlinear Modal Time History Analysis for a three-storey RC outlined case study structure as exposed in Figure 6 (a), situated at L'Aquila, Italy, using the REXEL software package. The base-isolated building is modelled as per the Italian Building Code. For instance, seven seismic events that occurred in Italy are checked for convergence in SEISMOMATCH software packages, as shown in Figure 6 (b). After that, the accelerograms are applied to the building, and the corresponding seismic responses are determined. From the study, a predominant decrease in base shear, acceleration, storey drift and improved roof movement is achieved with base isolation.

Nanda and Majumder (2019) carried over NLPOA on four-story RC-framed buildings using the SAP 2000 software package. Buildings are classed into bare frames with and without isolators and infilled frames with and without isolators. The building is situated in seismic zone V as per IS 1893 (part 1): 2002. The pushover analysis was conducted in two cases, FEMA 273 and ATC-40.

(a) Three- storey building modelling



(b) Matching in SEISMOMATCH
Fig. 6 (a-b): Analytical study using REXEL

2.8. Cost Analysis

Cost is the primary issue to be measured. Therefore, the cost comparison of the constructions with and without seismic isolation is studied in this section. Most researchers proposed that significant cost reduction is attained by installing seismic isolation in buildings.

Saiful Islam and Sodangi (2020) study investigated the effectiveness and feasibility of base isolation systems in reducing seismic demands on buildings of varying elevations. They found that isolators in low-rise to high-rise structures significantly decrease seismic responses, promoting structural flexibility and good structural health. The study also found that incorporating base isolators increases the initial outlay but significantly reduces the total structural cost despite the initial increase in the initial outlay. Furthermore, though an initial cost is required for the isolator unit (including installation cost), the gross savings in cost reduction is about 19.78% compared to the fixed base. Moreover, the minimal cost increase due to the isolator/isolator installation depends on the dimensions of the bearings.

3. Overall Summary of the Review

The comprehensive literature survey undertaken in this review paper defines the overarching aim of identifying pertinent research problems within seismic resilience enhancement. Section 2.1 initiates this exploration by scrutinizing various base isolation methods and dampers proposed by researchers. Notably, some instances highlight the synergistic coupling of base isolation devices with dampers to bolster the seismic responses of structures. While conventional seismic isolation systems thrive in developed nations, a notable gap exists in their adoption within developing countries, prompting an extension of the literature survey to identify suitable seismic isolation materials tailored to their needs.

Further, a broad spectrum of analytical investigations forms a cornerstone of the literature review. Researchers have conducted exhaustive analyses using diverse software platforms, encompassing varied isolator types, building configurations, and seismic excitations. Concurrently, the review examines cost analyses derived from these investigations, shedding light on factors such as isolator type and building typology.

Moreover, existing research primarily concentrates on advancing ANN active and semi-active control approaches. However, the review underscores the need for exploring additional sophisticated learning techniques, including reinforcement learning. These methodologies are essential for achieving robust control amidst multifaceted uncertainties, such as seismic variations and time delays. Furthermore, while various control devices, including active tuned mass dampers and distributed actuators, are under investigation, the review posits the potential of integrating machine learning into operational controllers for extended efficacy.

4. Discussion

While current structural design standards have significantly advanced construction safety and performance, inherent limitations may compromise their efficacy under specific circumstances. Some of the most notable shortcomings include:

Inflexibility to evolving materials and technologies limits the full potential of advanced construction. For instance, new materials like carbon fibre composites and self-healing concrete offer improved performance but are not fully integrated into current design standards focused on steel and concrete. A notable case is the Millau Viaduct in France, where high-performance concrete and steel cables created certification delays and design adjustments. This highlights the gap in standards adapting to modern materials, slowing down innovation in structural engineering.

Overreliance on historical data in design standards can overlook evolving risks, assuming past performance will match future conditions. This is problematic in areas facing rapid urbanization, seismic shifts, or climate changes. A stark example is the 1995 Sampoong Department Store collapse in South Korea, where outdated codes and reliance on historical data contributed to the disaster. The building's reinforced concrete structure could not support added weight and altered load-bearing walls, underscoring the critical need for evolving standards with changing stress factors.

Current design standards often underestimate dynamic loads like wind, earthquakes, and human activity, relying too much on static load assumptions. This can overlook the complex behaviour of structures under dynamic forces. A key example is the 2018 Ponte Morandi bridge collapse in Genoa, Italy, where structural deficiencies and failure to account for rising traffic and stress contributed to the disaster. This incident highlights the importance of updating standards to address dynamic load impacts on modern infrastructure.

Structural design standards often prioritize safety, cost, and functionality but fall short on sustainability and resilience in light of climate change. With rising demand for sustainable development, standards must integrate resilience to extreme weather, eco-friendly materials, and energy efficiency. After Hurricane Katrina, it was evident that many buildings in New Orleans lacked the resilience to withstand severe weather. The absence of flood-proofing guidelines and energy-efficient materials in standards contributed to extensive damage, underscoring the need for updated, sustainability-focused regulations.

Structural design standards often assume a 30-50-year lifespan, overlooking maintenance needs and retrofitting for ageing infrastructure. This gap is critical as much of the existing infrastructure now exceeds these limits, lacking long-term fatigue and degradation provisions. The 2007 collapse of the I-35W Mississippi River Bridge in Minneapolis, caused by corrosion and structural wear, highlights this issue. The bridge's design did not accommodate extended use or rigorous inspections, underscoring the need for evolving standards with ageing infrastructure in mind.

Structural design codes often simplify load distributions, treating them as static or uniform despite real-world complexities like material anomalies, construction flaws, and external dynamics. This can lead to severe vulnerabilities, as seen in London's 1968 Ronan Point Tower collapse. The building's design underestimated the impact of a gas explosion, causing a cascading structural failure. This event underscores the risks of oversimplifying load predictions in design standards, which must account for complex, dynamic loads to ensure structural resilience.

Modern structural design standards often focus more on technical aspects than human factors like user behaviour, error, and modifications. This oversight can compromise safety, as seen in the 2001 collapse of the World Trade Center in New York City. While the crash caused the initial damage, the lack of consideration for human activity and emergency evacuation impacts exacerbated the structural failure. The event led to significant changes in design standards, particularly in fireproofing and evacuation protocols, highlighting the need to prioritize human factors alongside technical specifications.

5. Future Research

Future research in seismic analysis for reinforced buildings should focus on advancing our understanding of seismic behaviour, improving design methodologies, and enhancing the resilience of structures.

- Develop more sophisticated and accurate numerical modelling techniques, such as finite element analysis and computational fluid dynamics, to better simulate the dynamic behaviour of reinforced buildings during earthquakes.
- Investigate new resources and construction approaches that can enhance the seismic presentation of reinforced buildings, including high-performance concrete, advanced steel alloys, and composite materials.
- Explore innovative retrofitting methods for existing reinforced buildings to improve their seismic performance and extend their service life. This could involve using new materials, dampers, or base isolation systems.
- Integrating AI into seismic analysis for reinforced buildings holds great promise for improving seismic assessment and design efficiency, accuracy, and reliability.
- Utilize AI to optimize retrofitting strategies and structural design. Machine learning can analyze historical seismic data and building performance to suggest cost-effective design modifications that enhance seismic resilience.

The limitations of current structural design standards highlight several critical areas that require improvement to address the evolving challenges in construction and infrastructure effectively. By focusing on these areas, future standards can enhance the safety, sustainability, and resilience of buildings and structures, ensuring they are better equipped to meet the demands of modern environments and unforeseen conditions.

- Update standards to incorporate advanced materials like carbon fibre composites and self-healing concrete for better performance and adaptability.
- Shift from static load assumptions to models that account for dynamic forces such as wind, earthquakes, and human activity to address evolving risks.
- Focus on sustainability by integrating climate resilience, eco-friendly materials, and energy efficiency to withstand extreme weather and reduce environmental impact.
- Develop standards for retrofitting and maintaining ageing infrastructure, emphasizing long-term maintenance, fatigue, and regular inspections.

- Integrate human factors, error prevention, and evacuation procedures into design codes while utilizing AI, machine learning, and IoT for predictive maintenance and real-time monitoring.

By embracing these future directions, structural design standards have evolved to address the challenges posed by modern construction, climate change, and the needs of a rapidly changing world. The result will be a more resilient, sustainable, and adaptable infrastructure that better withstand predictable and unpredictable stresses.

6. Conclusion

This review paper examines seismic resilience enhancement strategies for retrofitting existing structures to mitigate earthquakes. It examines seismic design, analysis techniques, and control methodologies, highlighting advancements and gaps in the field. The paper emphasizes the importance of seismic isolation methods and dampers in improving structural responses to seismic events. Conventional base isolation systems have been successful in developed countries, but their adoption in developing countries is limited. Analytical investigations across different software platforms provide valuable insights into structures' behaviour under seismic loading, with cost analyses being crucial for retrofitting projects. The review also highlights the evolving landscape of control methodologies, particularly ANNs and the integration of advanced learning techniques like reinforcement learning. The paper serves as a valuable resource for researchers, engineers, and policymakers in seismic risk mitigation efforts, aiming to contribute to developing effective strategies for enhancing seismic resilience and ensuring the safety and security of communities in earthquake-prone regions. Future research should focus on integrating artificial intelligence, enhancing sensor technology, and advancing seismic-resistant design for sustainable and energy-efficient solutions. Also, incorporating emerging seismic assessment techniques, such as next-generation monitoring, nonlinear dynamic analysis, and AI-driven predictive models, could further enhance structural resilience.

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