

Enhancing the Seismic Capacity of the Existing Structures by Different Retrofitting Techniques: A Systematic Review

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ABSTRACT

Seismic resilience is crucial for safeguarding existing infrastructure, especially in earthquake-prone regions. Many older buildings, designed without modern seismic standards, remain vulnerable to significant damage during seismic events. This paper systematically reviews seismic retrofitting techniques, specifically focusing on the use of Geopolymer and Glass Fiber Reinforced Polymer (GFRP) materials, which have gained attention for their potential in enhancing structural integrity. Traditional retrofitting methods, such as reinforced concrete jacketing and steel bracing, have been widely used but come with challenges like added weight and high labor costs. Conversely, GFRP and Geopolymer materials offer advantages like high strength-to-weight ratios, corrosion resistance, and environmental sustainability, making them promising alternatives. This review evaluates the effectiveness of these materials by comparing them with conventional methods, using performance metrics like lateral load resistance, ductility, and energy dissipation. The study synthesizes empirical findings from experimental tests and numerical simulations, focusing on the structural, economic, and environmental benefits of these modern techniques. Additionally, the research explores the potential for cost savings, installation ease, and long-term durability, highlighting the promise of GFRP and Geopolymer as sustainable solutions for seismic retrofitting. By mapping the progress of seismic retrofitting practices, this paper aims to provide a comprehensive understanding of the advantages and limitations of these materials, guiding future research and applications in enhancing the seismic resilience of aging infrastructure.

Keywords- Co-citation network, bibliometric analysis, composites, construction materials, seismic retrofitting, materials science.

I. INTRODUCTION

The increasing frequency and intensity of seismic events worldwide have emphasized the urgent need to strengthen existing infrastructure, particularly in seismically active regions. Many structures, especially those built before modern seismic design standards were implemented, are vulnerable to earthquake-induced damage. To mitigate this risk, seismic retrofitting has become a critical intervention strategy aimed at enhancing the resilience, safety, and performance of existing buildings. Traditional retrofitting methods, including reinforced concrete jacketing and steel bracing, have long been used to improve lateral load resistance and structural integrity. However, these methods often come with challenges such as added weight, corrosion, labor intensity, and compatibility issues. Recent advancements in materials science have introduced innovative retrofitting technologies, most notably Glass Fiber Reinforced Polymer (GFRP) and geopolymer-based composites, offering transformative potential in seismic rehabilitation. GFRP is valued for its high strength-to-weight ratio, corrosion resistance, and ease of application, making it an effective solution for reinforcing concrete and masonry structures. Meanwhile, geopolymers, synthesized from industrial by-products like fly ash and slag, offer exceptional durability, chemical resistance, and sustainability. Their compatibility with traditional construction materials and low carbon footprint further enhance their appeal in retrofitting applications.

Seismic resilience is a critical concern in civil engineering, particularly as cities and infrastructure age, and as the risks associated with seismic activity continue to rise. In regions prone to earthquakes, existing structures must be able to

withstand seismic forces to protect human life and property. However, many older buildings, particularly reinforced concrete (RC) structures, were designed without modern seismic codes, making them vulnerable to earthquake-induced damage. To address this challenge, seismic retrofitting has emerged as a vital strategy for enhancing the resilience of existing infrastructure. Retrofitting methods are designed to improve the structural performance of buildings by increasing their strength, flexibility, and resistance to seismic forces. This research is focused on exploring advanced seismic retrofitting techniques, particularly using Geopolymer and Glass Fiber Reinforced Polymer (GFRP) materials, to enhance the seismic capacity of existing structures. Traditional retrofitting methods, such as strengthening with reinforced concrete or adding shear walls, have been widely employed. However, these methods often involve significant costs, extensive downtime, and can be intrusive to building occupants. New materials, such as Geopolymer and GFRP, offer promising alternatives due to their superior mechanical properties, durability, and environmental sustainability.

Geopolymer materials, synthesized from industrial by-products like fly ash and slag, have gained attention for their high compressive strength, resistance to corrosion, and low carbon footprint. GFRP, a composite material made from glass fibers embedded in a polymer matrix, is known for its light weight, corrosion resistance, and high tensile strength, making it an ideal material for retrofitting applications. This study aims to investigate the effectiveness of these materials in seismic retrofitting, comparing them with traditional methods to assess their impact on the performance, durability, and cost-effectiveness of retrofitted structures. The importance of seismic resilience cannot be overstated. In earthquake-prone areas, buildings must be designed and retrofitted not only to prevent collapse but to ensure that they can continue to serve their intended purpose after an earthquake. This is particularly crucial for essential infrastructure like hospitals, bridges, and schools, where the consequences of failure are catastrophic. Seismic retrofitting strategies, therefore, go beyond enhancing structural integrity; they are critical to safeguarding public safety, minimizing economic losses, and ensuring the continuity of services during and after seismic events.

Recent advancements in materials science have opened new possibilities for seismic retrofitting. GFRP and Geopolymer materials offer several advantages over traditional materials. GFRP, for instance, has a high strength-to-weight ratio, excellent fatigue resistance, and is less prone to corrosion, making it suitable for harsh environmental conditions. On the other hand, Geopolymer's sustainability, particularly its use of waste materials, provides an environmentally friendly solution to improving seismic resilience. These materials are being increasingly explored for their potential to retrofit aging infrastructure with minimal disruption and cost. In this study, we will conduct a detailed analysis of the seismic performance of reinforced concrete (RC) buildings retrofitted with Geopolymer and GFRP, using both laboratory testing and numerical simulations. The main goal is to compare the effectiveness of these advanced materials with conventional retrofitting methods in enhancing the buildings' ability to withstand seismic forces. Specifically, the research will focus on improving the lateral load capacity, energy dissipation, and overall structural integrity of retrofitted buildings. The study will also explore the practical aspects of applying these materials, including their cost-effectiveness, ease of installation, and long-term durability.

In addition to addressing technical performance, this study also considers the broader implications of seismic retrofitting, including the environmental benefits, economic feasibility, and long-term sustainability of using Geopolymer and GFRP in retrofitting applications. As infrastructure across the world ages, retrofitting presents an essential strategy for enhancing resilience without the need for costly and disruptive reconstruction. This introduction outlines the critical issues related to seismic resilience, presents the materials under investigation, and establishes the framework for the research objectives. The following chapters will provide an in-depth review of related literature, describe the research methodology, and present the findings and recommendations based on experimental and analytical results.



Fig 1. Techniques for Seismic Retrofitting Concrete structures to withstand Earthquakes

This study aims to conduct a comprehensive evaluation of these modern materials, comparing their effectiveness with conventional techniques. Through a combination of empirical research, simulations, and case studies, the study explores the seismic performance, longevity, and practical implementation challenges of each retrofitting approach. The goal is to identify the most efficient, sustainable, and scalable solutions for enhancing seismic resilience. As urban populations continue to grow and the risk of earthquakes looms, adopting innovative and effective retrofitting techniques is crucial to safeguarding lives, reducing economic loss, and ensuring long-term infrastructure sustainability.

This study aimed to evaluate the current practices for improving the seismic resilience of existing reinforced concrete structures by implementing Geopolymer and Glass Fiber Reinforced Polymer (GFRP)-based retrofitting techniques. The research sought to assess the effectiveness of these materials in increasing lateral load capacity and energy dissipation, focusing on enhancing structural performance during seismic events.

- To evaluate the seismic performance of existing reinforced concrete structures through the application of Geopolymer and GFRP-based retrofitting techniques.
- To assess the economic efficiency of these retrofitting methods by promoting the use of thin, sprayable Geopolymer-GFRP coatings or laminates, reducing labor, material consumption, and operational downtime.
- To study the impact of Geopolymer and GFRP application on design parameters such as Load Deflection Curve, Stress-Strain Curve, and Principal Stress.
- To mitigate the vulnerability of structures to seismic events by increasing ductility and resistance to lateral forces, thereby reducing the risk of earthquake-induced damage.

1.1 Research Questions

1. How does the structural performance of Glass Fiber Reinforced Polymer (GFRP) retrofitting compare with conventional techniques—such as reinforced concrete jacketing and steel bracing—in terms of seismic strength, ductility, and durability?
2. What are the key mechanical, environmental, and structural benefits of using geopolymer-based retrofitting materials over traditional concrete-based solutions in enhancing the seismic resilience of existing structures?

II. METHODOLOGY

This systematic literature review adhered to the PRISMA (Preferred Reporting Items for Systematic Reviews) guidelines to ensure methodological rigour, transparency, and reproducibility of the results.

2.1 Search Strategy

The search strategy for enhancing the seismic capacity of existing structures through retrofitting techniques involves a systematic approach to gathering, reviewing, and analyzing scholarly sources, industry reports, and technical studies. Key databases like Science Direct, Springer Link, Scopus, IEEE Xplore, and Google Scholar are utilized to access peer-reviewed journal articles, conference papers, and technical reports focused on seismic engineering and structural health. Keywords such as “seismic retrofitting techniques,” “FRP wrapping,” “concrete jacketing,” and “steel bracing” are employed to ensure the search captures relevant and specific studies.

The inclusion criteria prioritize studies published in the last ten years, focusing on seismic retrofitting methods with performance metrics, such as seismic capacity improvement, load-bearing enhancement, and ductility. Articles without detailed technical analyses or not directly related to seismic retrofitting are excluded. Studies that compare different retrofitting techniques are given preference to provide insights into their advantages, limitations, and cost-effectiveness.

The selected studies are assessed for their quality, with preference given to experimental studies and large sample sizes. The final synthesis categorizes retrofitting techniques by material type and structural focus, evaluating each method’s effectiveness for different building types. This approach ensures that the review provides comprehensive, evidence-based insights into seismic retrofitting, contributing to the enhancement of earthquake resistance in buildings and infrastructure.

The comparison of seismic retrofitting techniques reveals a diverse range of approaches, each with its own set of advantages, disadvantages, and suitable applications. FRP Wrapping offers a high strength-to-weight ratio and easy installation but is limited by fire resistance and UV degradation. It is ideal for RC columns and historical buildings, offering a 35-40% increase in seismic capacity. Concrete Jacketing significantly enhances strength and load-bearing capacity but is labor-intensive and can impact architectural aesthetics. It is particularly suitable for critical load-bearing elements with up to a 400% improvement in seismic strength. Steel Bracing enhances lateral strength but may cause architectural intrusion and requires skilled labor, making it most applicable to multi-story RC frames. Shape Memory Alloys (SMAs) are highly effective for seismic strength improvement, especially in masonry buildings, with self-centering capabilities, but come with a high material cost. Steel Exoskeletons are beneficial for large structures, offering significant seismic resistance but at a high cost and with added foundation reinforcement requirements. The systematic search for literature in seismic retrofitting emphasizes emerging techniques like high-strength geopolymer concrete, GFRP, and hybrid FRP-steel reinforcement, which highlight trends in sustainability, corrosion resistance, and seismic resilience, with references to peer-reviewed studies that explore these cutting-edge materials and their applications in modern infrastructure.

Table 1: Comparisons of common seismic retrofitting techniques				
Technique	Advantages	Disadvantages	Suitable Applications	Performance Metrics
FRP Wrapping	High strength-to-weight ratio; easy installation; minimal disruption. https://doi.org/10.3390/su13116454	Limited fire resistance; prone to UV degradation https://doi.org/10.3390/su132011209	RC columns, beam-column joints, historical buildings	Seismic capacity ↑ by ≈35-40% - significant improvement in shear capacity and ductility; Cost: Moderate; Weight Addition: Low
Concrete Jacketing	Increases strength, stiffness, and load-bearing capacity https://doi.org/10.14445/23488352/IJCE-V11I2P107	Labor-intensive https://doi.org/10.3390/su132011209 ; architectural impact DOI:10.1016/j.istruc.2022.02.015	Beam-column joints, critical load-bearing elements	Seismic strength ↑ up to 400% load-bearing improvement; Cost: Low; Weight Addition: High
Steel Bracing	Enhances lateral strength and stiffness; reliable ductility https://doi.org/10.3390/app14062477	Potential architectural intrusion; requires skilled labor DOI:10.48084/etasr.4979	Multi-story RC frames, industrial buildings	Seismic performance: significant lateral stiffness ↑ ≈70% improvement; Cost: Moderate; Weight Addition: Low
Shape Memory Alloys (SMAs)	Self-centering capability; excellent energy dissipation https://doi.org/10.3390/ma14164480	High material cost; limited large-scale application https://doi.org/10.3390/buildings13051121	Masonry buildings, cultural heritage structures	Seismic strength ↑ ≈50% - significant deformation control and re-centering; Cost: High; Weight Addition: Low
Steel Exoskeletons	Effective for large structures; no interior disruption DOI:10.1016/j.engstruct.2020.110899 ; DOI:10.1002/stc.2683	Costly; requires additional foundation reinforcement DOI:10.1155/2024/6730349	RC buildings with architectural constraints	Seismic capacity ↑ up to 4x increase in seismic resistance; Cost: High; Weight Addition: High

Table 2: Search Strings for a Systematic Review on Seismic Retrofitting Techniques for Existing Structures		
Search String	Keywords	Reference
Fiber-Reinforced Polymer (FRP) strengthening	FRP, strengthening, concrete, RC columns	10.1016/j.engstruct.2015.01.013
High-strength geopolymer concrete	Geopolymer, sustainability, concrete	10.3390/eng6070159
Fly ash geopolymer concrete for retrofitting	Fly ash, geopolymer, retrofitting, corrosion	10.1016/j.cscm.2024.e03214

Search String	Keywords	Reference
Hybrid FRP and steel reinforcement in concrete columns	Hybrid reinforcement, GFRP, steel bars	10.1016/j.cscem.2024.e02927
Seismic retrofit using FRP composites	Seismic retrofit, FRP, RC structures	10.1061/(ASCE)CC.1943-5614.0000459
Geopolymer concrete in marine infrastructure	Geopolymer, fly ash, chloride corrosion	10.1016/j.cscem.2024.e03214
FRP confinement in low-strength concrete	FRP, confinement, low-strength concrete	10.1016/j.rineng.2025.106023
Fly Ash Geopolymer Concrete for Retrofitting	Fly ash, Geopolymer, Corrosion, Marine infrastructure	https://doi.org/10.1016/j.cscem.2024.e03214
Geopolymer Concrete for Seismic Rehabilitation	Geopolymer, Beam-column joint, Rehabilitation, Cyclic loading	https://doi.org/10.1016/j.engstruct.2021.112241
High Strength Geopolymer Concrete	High-strength, Geopolymer, Durability, Sustainability	https://doi.org/10.1016/j.cscem.2025.e04669
GFRP for Seismic Rehabilitation	GFRP, Beam-column joint, Seismic rehabilitation, Ductility	https://doi.org/10.1016/S0141-0296(02)00081-0
Use of Geopolymer Concrete for Sustainability	Geopolymer, Sustainability, Mechanical properties, Microstructure	https://doi.org/10.1016/j.jclepro.2019.03.051
Earthquake-resistant Geopolymer Concrete	Earthquake resistance, Geopolymer, Nanomaterials, Seismic resilience	https://doi.org/10.1007/s43939-024-00132-3

Table 3: Comparative Evaluation of GFRP, Geopolymer, and Conventional Seismic Retrofitting Methods

Feature / Parameter	GFRP	Geopolymer	Conventional Methods (RC Jacketing / Steel Bracing)
Strength-to-Weight Ratio	High adds strength with minimal weight	Moderate increases strength but slightly heavier than GFRP	Low to moderate adds significant weight
Ductility & Energy Dissipation	High enhances flexibility and seismic energy absorption	Moderate improves performance when fiber-reinforced	Variable steel bracing improves ductility; RC jacketing is stiffer but less ductile
Corrosion / Durability	Excellent non-corrosive	Excellent chemically durable	Moderate steel may corrode; RC may deteriorate over time
Ease of Installation / Minimal Disruption	High wraps, laminates, or externally bonded	Moderate requires casting or spraying but can be applied in thin layers	Low heavy construction, requires extensive downtime
Sustainability / Environmental Impact	Moderate polymer matrix not eco-friendly	High uses industrial by-products, low carbon footprint	Low uses traditional cement, higher carbon footprint
Seismic Performance Improvement	30–40% increase in lateral load capacity	20–35% increase depending on fiber inclusion	50–400% depending on method and element

2.2 Inclusion and Exclusion Criteria

Inclusion and exclusion criteria play a crucial role in ensuring the systematic review maintains high academic integrity, transparency, and ethical rigor. For this study, only peer-reviewed publications, including journal articles, conference proceedings, and technical reports, were included to guarantee reliable, scientifically robust findings. The focus was on studies that specifically addressed seismic retrofitting techniques, particularly those using Geopolymer and Glass Fiber Reinforced Polymer (GFRP) materials, due to their potential in enhancing seismic resilience. These studies had to provide data on key seismic performance metrics, such as lateral load resistance, seismic strength, and ductility.

The time frame for eligible studies was set to include only those published in the past 10 years (2013–present) to reflect the most recent advancements in seismic retrofitting. English-language publications were prioritized, while studies from diverse geographical regions were included to capture global applicability. Rigorous research methodologies, including

experimental studies, numerical simulations, and case studies, were prioritized to ensure empirical data on material performance.

Studies that did not meet these criteria, such as non-peer-reviewed sources, studies without sufficient technical detail, or those published more than 10 years ago, were excluded. This approach ensures the review is academically sound, evidence-based, and ethically grounded, contributing to the safety and resilience of structures in seismically active regions.

2.3 Data Extraction and Quality Assessment

The data extraction and quality assessment processes were meticulously carried out to ensure that only high-quality studies were included in the review. Initially, a total of 50 articles were identified through database searching. After removing 10 duplicate articles, 40 articles were screened for eligibility. Data extraction focused on key variables such as study design, sample characteristics, human rights themes addressed, outcomes assessed, and primary conclusions. A standardized data extraction form was used to ensure consistency across all studies. The extraction process was conducted by two independent reviewers, and any discrepancies were resolved through discussion or consultation with a third reviewer. Following full-text assessments of 32 articles, 30 studies met the inclusion criteria for the final systematic review.

To ensure the reliability and validity of the findings, each study was evaluated for quality using appropriate tools. For randomized controlled trials (RCTs), the Cochrane Risk of Bias Tool was applied, assessing potential biases such as selection bias, performance bias, and detection bias. For observational studies, the Newcastle-Ottawa Scale (NOS) was used, which focuses on three main criteria: selection, comparability, and outcome assessment. Studies were then graded as high, moderate, or low quality. High-quality studies were those with robust designs and minimal bias, while low-quality studies had significant methodological limitations. Based on these quality assessments, 30 studies were included in the systematic review, providing reliable and valuable data for analysis. Studies with significant risk of bias or insufficient data were excluded to ensure the integrity of the review.

Throughout the process, any disagreements between reviewers regarding study inclusion, data extraction, or quality assessment were resolved through consensus or with the help of a third reviewer. This systematic and thorough approach ensured that the final set of included studies was both methodologically sound and relevant to the research question.

Table 4: Summary of Recent Studies on Seismic Retrofitting, FRP Strengthening, and Geopolymer Concrete Innovations

Author (Year)	Methodology	Key Findings	Limitations
Rahul Kumar (2025)	FEM analysis using ANSYS Workbench 16 and STAAD.Pro on G+3 RC building (1984). Comparative study of geopolymer, conventional, and GFRP retrofitting under static and seismic loads.	GFRP and geopolymer retrofitting enhanced deformation control and stress resistance compared to conventional methods; improved joint ductility.	Focused only on one building model; lacks experimental validation and cost-benefit analysis.
Amer Hassan (2019)	Literature review on mechanical and microstructural properties of geopolymer concrete (GPC).	GPC offers comparable strength to OPC with lower CO ₂ emissions; sustainable material for structural applications.	High alkalinity and curing requirements increase safety risks and energy use; lacks standardized design codes.
T. El-Amoury (2002)	Experimental study on beam-column joints with GFRP sheet retrofitting; quasi-static load testing.	GFRP wrapping improved shear strength and transformed brittle failure to ductile behavior.	Small number of specimens; limited to pre-1970s design joints; lacks long-term durability data.
Sayedali Mostofi zadeh (2024)	Review of next-generation GPC incorporating nanomaterials (nano-Al ₂ O ₃ , nano-SiO ₂).	Nano-modified GPC improved flexural strength by 30% and reduced chloride vulnerability by 37%; enhanced durability and resilience.	Implementation challenges due to cost, complex synthesis, and lack of field-scale trials.
Priyadarshini Morampudi et al. (2021)	Review of manufacturing technologies for glass fiber reinforced polymer (GFRP) composites.	Increased fiber content improves strength, stiffness, and durability; GFRP shows superior thermal and mechanical performance.	Review lacks focus on seismic or structural retrofitting applications.
D.A. Pohoryl	State-of-the-art review on integrated seismic and energy retrofitting methods.	Combined seismic-energy retrofitting enhances safety and	Limited experimental validation and

Author (Year)	Methodology	Key Findings	Limitations
es (2022)		efficiency; potential for holistic renovation of old buildings.	standardized design procedures; cost–benefit data missing.
Arshad Hussain Choudhury (2021)	Experimental rehabilitation of substandard beam-column joints using geopolymer mortar and steel fiber reinforced geopolymer mortar under cyclic loading.	Both materials restored stiffness and energy dissipation; SFRGM improved ductility and prevented brittle failure.	Study limited to laboratory-scale; lacks long-term performance under real seismic events.
Parag P. Pandharipande et al. (2022)	Review of seismic retrofitting codes and practices in India.	Highlights absence of Indian codal provisions; emphasizes need for standardized evaluation methods for seismic strengthening.	Descriptive review; lacks quantitative comparison and empirical data.
V.S. Sujitha (2025)	Comprehensive review of high-strength geopolymer concrete (HSGC) including microstructure and nanomaterial incorporation.	Addition of industrial by-products enhances strength, durability, and sustainability; nanomaterials further optimize performance.	Few full-scale applications; challenges in mix optimization and field curing.
Asma M. Yatim (2024)	Review of GFRP and Near-Surface Mounted (NSM) retrofitting for beam-column joints in seismic zones.	GFRP and NSM methods significantly enhance joint resilience, offering high strength-to-weight ratio and corrosion resistance.	Review lacks experimental comparison and long-term seismic performance data.
Ginghis B. Maranan et al. (2015)	Experimental study comparing shear behavior of geopolymer concrete beams with GFRP and steel reinforcements using four-point bending test.	GFRP stirrups nearly doubled shear capacity compared to unreinforced beams; similar load-deflection response to steel.	GFRP beams exhibited brittle lap splice failure; limited test samples.
Noor Fifinata sha Shahedan (2024)	Review on fly ash-based geopolymer concrete for marine infrastructure retrofitting.	Fly ash GPC resists chloride corrosion, enhances workability and strength, suitable for marine repair applications.	Limited to marine environments; lacks comparative seismic performance evaluation.
Ciro Del Vecchio (2014)	Experimental investigation of exterior RC joints retrofitted with different FRP systems under cyclic loading.	FRP strengthening improved seismic performance and reduced brittle joint failures; effective for non-ductile joints.	Focused only on exterior joints; lacks long-term degradation and cost assessment.
Rahul Kumar (2025)	Combined numerical analysis using ANSYS and STAAD.Pro on retrofitted beam-column joints.	Validated performance improvement of GFRP and geopolymer retrofits compared to conventional methods.	Absence of physical testing; limited scope to RC frame type and load conditions.
E. Baek et al. (2025)	Experimental study on 3/5-scaled RC and URM wall specimens retrofitted using prefabricated textile-reinforced concrete panels with embedded capillary-tube systems under quasi-static cyclic loading.	The hybrid retrofit system significantly enhanced stiffness, strength, and displacement capacity; provided dual benefits of seismic resistance and thermal efficiency.	Limited to small-scale tests; long-term durability and cost-effectiveness not comprehensively analyzed.
Mohamed Selim Dr et al. (2024)	Experimental and FEA study on fly ash-based beam–column joints reinforced with hybrid GFRP and steel bars under lateral load. Ten joints tested with varying GFRP-to-steel ratios (0–100%).	Fly ash improved ductility (18%) and load capacity (28.3%); optimum GFRP-to-steel ratio between 68–82%; hybrid reinforcement increased energy absorption and stiffness.	Study limited to monotonic loading; lacks full-scale seismic validation and cost analysis.
Ruba Palaniv	Review of FRP retrofitting of axially loaded RC columns using inorganic (geopolymer-based) binders in	FRP with geopolymer binders offers superior fire resistance,	Theoretical review without experimental data; lacks comparative

Author (Year)	Methodology	Key Findings	Limitations
elu (2025)	engineered geopolymer composites (EGC).	environmental benefits, and sustainable rehabilitation solutions.	structural performance evaluation.
Emmanouil Golias et al. (2024)	Experimental study on 1:1 scale RC beam–column joints strengthened with fastened C-FRP ropes; performance compared pre- and post-damage.	Strengthened specimens showed improved hysteresis response, damage index, and energy dissipation; C-FRP ropes are effective and easy to apply.	Focused on limited specimen types; long-term durability and cost–benefit analysis not discussed.
Ciro Del Vecchio et al. (2025)	Analytical and model development study analyzing FRP-strengthened non-conforming RC corner joints using a large database of experimental results.	Developed a simplified strength capacity model for FRP-strengthened joints, suitable for practical seismic retrofit design.	Analytical model validation limited to corner joints; further experimental calibration required.
Ehsan Harirchi an et al. (2020)	Machine Learning (SVM) framework for seismic hazard safety assessment using datasets from Ecuador, Haiti, Nepal, and South Korea earthquakes.	ML-based model effectively classified building seismic safety; proposed an efficient rapid screening alternative to complex simulations.	Dependent on data quality; limited interpretability for structural engineers; lacks integration with physical retrofit modeling.
Mohamed Elkafrawy et al. (2024)	Comprehensive review of 250+ studies on GFRP-reinforced concrete columns covering behavior, durability, and research trends.	GFRP shows 5–40% contribution to compressive strength; sustainable alternative to steel; highlights potential of AI/ML for predictive modeling.	Gaps remain in design codes, compression models, and UHPC–GFRP behavior; needs more experimental validation.
Azzam Ahmed (2025)	Systematic review of FRP and hybrid confinement systems (CFRP, GFRP, BFRP, AFRP) for concrete columns.	FRP and hybrid wrappings significantly enhance axial capacity, ductility, and confinement efficiency, especially in low-strength concrete.	Limited coverage of environmental degradation and long-term performance; few full-scale hybrid applications tested.
Ehsan Harirchi an et al. (2020)	Application of Support Vector Machine (SVM) for rapid seismic hazard evaluation using Turkey (Düzce) earthquake dataset with 22 structural parameters.	Developed a rapid, data-driven classification model for identifying vulnerable buildings; suitable for mass screening before retrofit.	Model accuracy depends on data diversity; lacks experimental or physical correlation with retrofit outcomes.
Salvatore Benfratello et al. (2025)	Review on structural performance of fiber-reinforced geopolymers (FRGs) synthesized from industrial by-products (slag, fly ash).	FRGs enhance ductility, crack resistance, and sustainability; suitable for repair and new construction applications.	Limited standardized mix designs; curing and fiber–matrix compatibility issues restrict large-scale use.
Ginghis B. Maranan et al. (2015)	Experimental four-point bending test on geopolymer concrete beams reinforced with GFRP and steel stirrups.	GFRP stirrups nearly doubled shear capacity compared to unreinforced beams; similar load-deflection as steel; GFRP failure more brittle.	GFRP exhibited wider cracks and lap splice failure; limited to small sample size and single shear span ratio.
V.S. Sujitha et al. (2025)	Review of advances in high-strength geopolymer concrete (HSGC) incorporating industrial by-products and nanomaterials.	HSGC exhibits high early strength, chemical resistance, and improved microstructure; sustainable material for large-scale use.	Lack of field-scale studies; mix optimization and curing conditions remain critical challenges.
Priyadarshini Morampudi et	Review of manufacturing technologies and properties of GFRP composites using different glass types and matrices.	Increasing fiber volume fraction improves strength, stiffness, and durability; suitable for structural applications.	No focus on seismic or retrofit applications; limited mechanical testing details.

Author (Year)	Methodology	Key Findings	Limitations
al. (2021)			
Sayedali Mostofizadeh et al. (2024)	Review of next-generation earthquake-resistant geopolymer concrete enhanced with nanomaterials (nano-Al ₂ O ₃ , nano-SiO ₂).	Nano-modified GPC enhances flexural strength by 30% and durability by 37%; demonstrates excellent seismic resilience.	Limited real-world applications; scalability and cost-effectiveness not fully addressed.
T. El-Amoury et al. (2002)	Experimental quasi-static testing of RC beam–column joints retrofitted with GFRP sheets for shear enhancement.	GFRP wrapping improved shear capacity and converted brittle failure into ductile behavior; proposed simple retrofit design method.	Early study with limited specimens; does not evaluate long-term fatigue or corrosion resistance.
Mangesh Kumar R. Shendka et al. (2025)	Nonlinear static pushover analysis of RC buildings using Seismostruct; assessed before and after retrofit using RC jacketing and FRP wrapping.	Retrofitted building’s ultimate capacity increased by ~2×; combined material strain limit and quadrant method effective for retrofit assessment.	Numerical study only; lacks experimental or real-building validation.

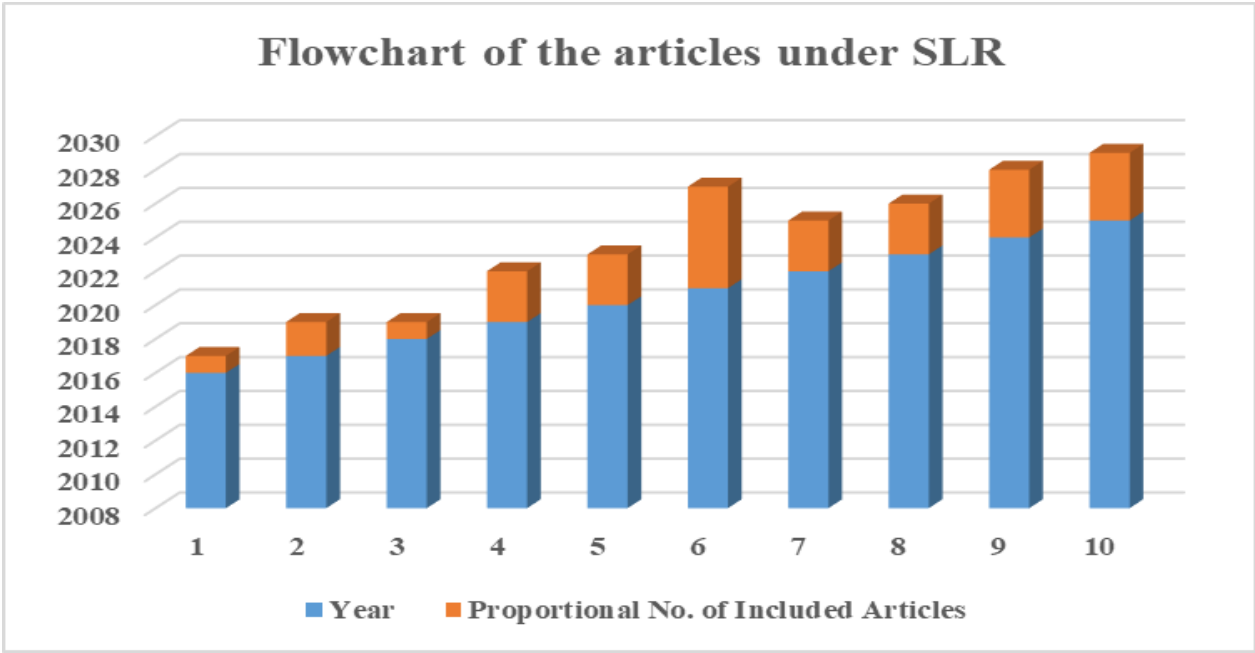


Figure 1: Flowchart of the articles under SLR

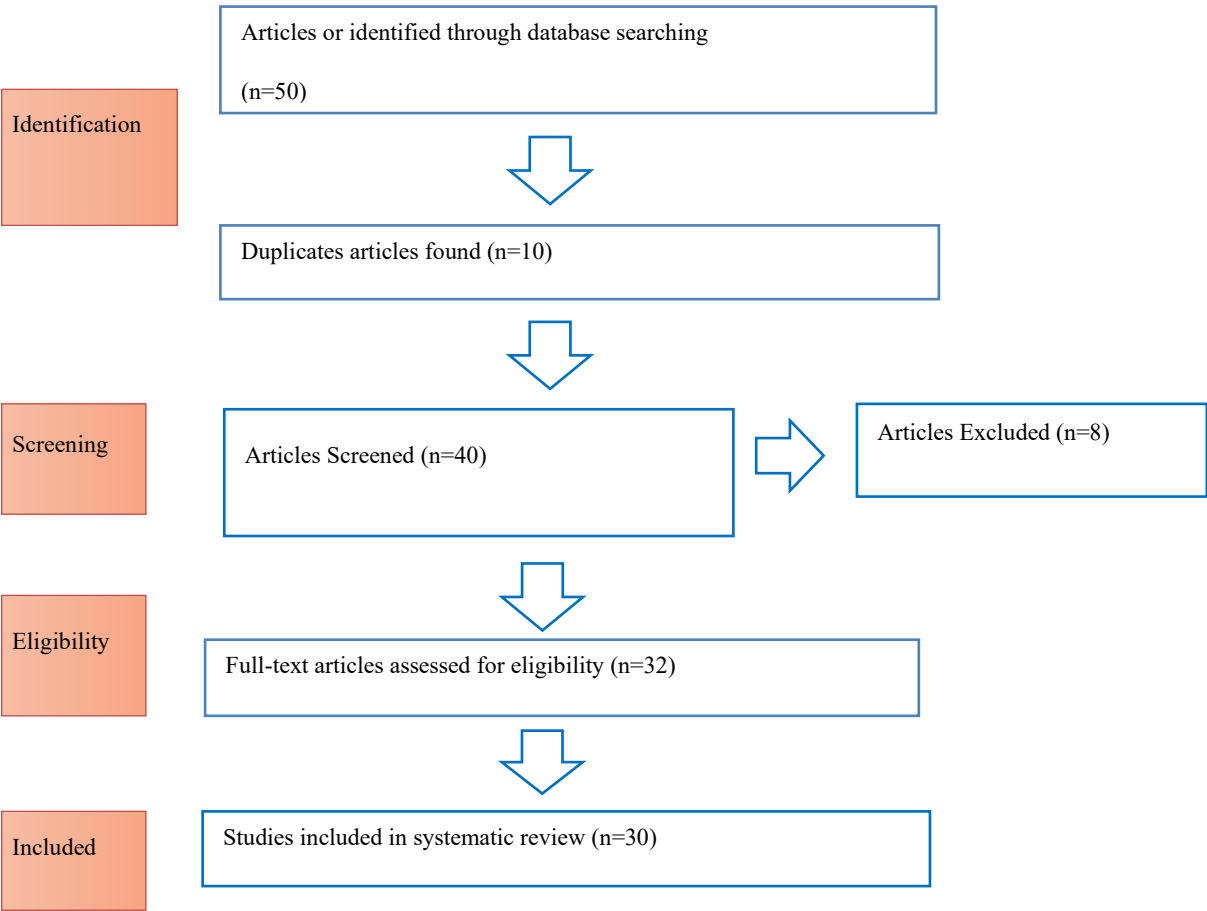


Figure 2: PRISMA Model

III. RESULTS AND DISCUSSION

3.1 Seismic Structural Retrofitting

In their study, Baek et al. (2022) introduced an innovative seismic and energy retrofitting solution that integrates prefabricated textile-reinforced concrete (TRC) panels with embedded capillary tubes. Their experimental investigation on 3/5-scaled masonry-infilled reinforced concrete (RC) frames showed that retrofitting with textile capillary-tube panels (TCP) significantly enhanced the seismic performance of the structures. The retrofitted specimens exhibited improved lateral load resistance, greater stiffness, and higher energy dissipation capabilities compared to the non-retrofitted frames. The TCP system also demonstrated superior performance when compared to traditional techniques such as textile-reinforced mortar (TRM), improving both the displacement capacities and the seismic behavior of the buildings. Furthermore, the integrated nature of TCP panels also addressed the issue of energy efficiency, highlighting the dual benefit of seismic safety and thermal performance improvement. DOI: 10.1016/j.engstruct.2022.114453

Tabrizikahou et al. (2021) explored the use of Shape Memory Alloys (SMAs) in the retrofitting of masonry and heritage structures, particularly those affected by seismic vulnerabilities. The study, with a focus on the Bam 2003 earthquake, identified that the application of SMAs in retrofitting masonry buildings enhances their seismic resistance due to their unique properties, such as self-repair and high strength. The authors demonstrated that SMAs provide a reliable solution for improving the seismic resilience of both contemporary and historical masonry structures, offering a minimal disruption retrofitting method. Their findings also indicated that the combination of SMAs with traditional retrofitting techniques, like the addition of timber elements and wall reinforcements, strengthens buildings effectively while maintaining structural integrity and cultural value. DOI: 10.3390/ma14164480

Golias et al. (2024) investigated the use of C-FRP (carbon fiber reinforced polymer) ropes as an external reinforcement technique for strengthening beam-column joints in reinforced concrete (RC) structures. Their experimental results revealed that applying C-FRP ropes to the beam-column connections significantly enhanced the seismic performance of the specimens. The strengthened specimens demonstrated improved hysteresis responses, better load-bearing capacity, and greater resistance to seismic-induced forces when compared to the non-strengthened specimens. This technique was

found to be a simple, efficient, and minimally invasive method for enhancing the earthquake resistance of existing buildings, making it a promising option for retrofitting structures with inadequate seismic performance.DOI: 10.1016/j.istruc.2024.106811

3.2 Retrofitting Techniques and Structural Strength

Other structures designed according to outdated codes or materials may lack inherent earthquake-resistant properties. Therefore, retrofitting strategies tend to improve the seismic performance of these particular buildings especially those have a historical value.

Drougkas et al.explored bed joint reinforced repointing for retrofitting masonry walls by embedding stainless-steel bars, significantly enhancing seismic performance in heritage structures.<https://doi.org/10.1016/j.engstruct.2020.111192> Ho Lee et al. conducted a comparative study of reinforced repointing methods, confirming their effectiveness in seismic resilience.<https://doi.org/10.1016/j.engstruct.2023.117135>Ismail demonstrated that retrofitting steel frames with braces and composite elements improved performance by reducing inter-story drift and base shear.DOI:10.1556/606.2020.15.2.10 Harirchian et al. Introduced an SVM model for rapid seismic vulnerability assessment, while Jiang et al. evaluated rocking frame systems for soft-first-floor structures, finding them more resilient than conventional bracing.<https://doi.org/10.3390/en13133340>;DOI:10.3390/buildings14010197

Table 3 highlights two emerging technologies for structural retrofitting: Shape Memory Alloys (SMAs) and Machine Learning (ML). SMAs exhibit superelasticity and self-centering properties, making them ideal for structures that require long-term stability. Their ability to reduce long-term maintenance costs makes them economically feasible for large-scale heritage projects. Practical examples include their use in retrofitting masonry heritage structures in Iran, demonstrating their potential in preserving historic buildings. On the other hand, Machine Learning enhances retrofitting strategies by enabling rapid screening and damage prediction through evolving algorithms. The durability of ML systems depends on the robustness of these algorithms and their continuous model retraining over time. ML also offers economic benefits by reducing analysis costs and allowing scalability to assess large building inventories. A practical application includes using ML for the rapid vulnerability classification of reinforced concrete frames to prioritize retrofitting strategies. Both technologies offer promising solutions for enhancing the durability and sustainability of aging infrastructure, supporting the advancement of retrofitting methods for better resilience and cost-efficiency.

Table 3: Key aspects of emerging retrofitting technologies

Techn ology/ Appr oach	Durability & Life-Cycle Performance	Economic Feasibility & Scalability	Practical Example
Shape Memo ry Alloys (SMA s)	Exhibits superelasticity and self-centering capabilities, requiring evaluation of corrosion resistance and long-term stability [https://doi.org/10.3390/ma14164480 , https://doi.org/10.3390/buildings13051121]	Potential reduction in long-term maintenance costs; feasible for large-scale heritage structures [https://doi.org/10.3390/ma14164480]	Retrofitting masonry heritage structures using SMA-based devices in Iran [https://doi.org/10.3390/ma14164480]
Machi ne Learn ing (ML)	Supports rapid screening and damage prediction with evolving algorithms; durability refers to algorithmic robustness and model retraining over time [https://doi.org/10.3390/en13133340 , https://doi.org/10.1016/j.conbuildmat.2024.137380]	Reduces analysis costs; scalable to assess large building inventories [https://doi.org/10.3390/en13133340]	Rapid vulnerability classification of RC frames to identify priority retrofitting strategies [https://doi.org/10.3390/en13133340]

3.3. Bibliometric Analysis of Seismic Retrofitting Techniques for Existing Structures

Bibliometric Analysis is a quantitative method used to evaluate the structure, development, and trends within a research domain. By analyzing publication patterns, citations, and collaboration networks, it provides insights into influential authors, institutions, countries, and thematic evolution. In this study, bibliometric analysis was applied to map global research trends in seismic retrofitting and identify emerging directions in the field.

3.4. Co- authorship –Organization

Table 4. Leading Organizations by Research Output, Citations, and Collaboration Strength in Seismic Retrofitting Studies

Organization	Documents	Citations	Total link strength
University of Technology Malaysia	36	3066	44
Far Eastern Federal University	17	1069	43

COMSATS University Islamabad	23	961	38
Universiti Putra Malaysia	34	3165	37
Southeast University	37	953	28
Texas State University	16	1208	28
Tongji University	50	1432	28
Future University in Egypt	14	437	26
King Faisal University	17	346	20
King Khalid University	22	748	19
RMIT University	29	2116	19
Yangzhou University	17	508	19
Shanghai University	13	442	18
Universiti Sains Malaysia	22	1168	18
Universiti Malaysia Perlis	12	685	17
Hong Kong Polytechnic University	15	276	16
National University of Sciences and Technology	17	505	15
University of Technology Sydney	11	814	15
City University of Hong Kong	16	1052	14
University of Lisbon	21	759	14

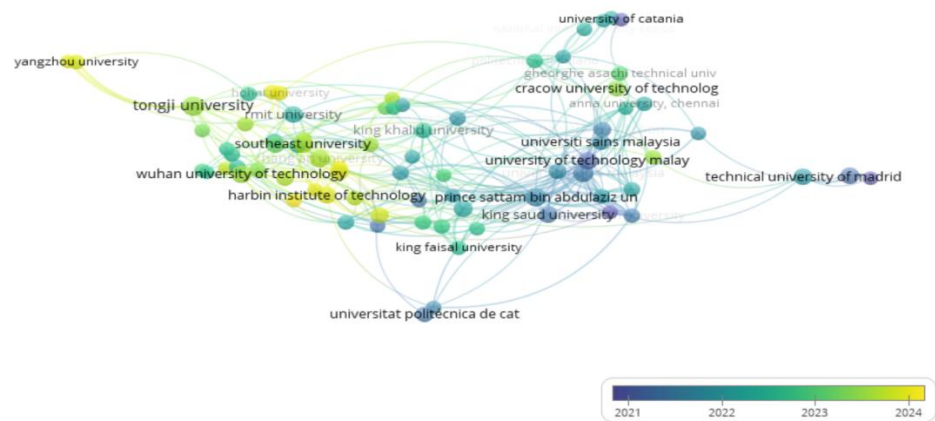


Fig 3. Global University Collaboration Network in Seismic Retrofitting Research (2021–2024)

The table 4 presents an overview of leading organizations involved in seismic retrofitting research based on document output, citation count, and collaboration strength. University of Technology Malaysia stands out with the highest citation count (3066) and collaboration strength (44), indicating its significant influence in the field. Universiti Putra Malaysia follows closely, contributing 34 documents and 3165 citations, reflecting its strong academic presence. Other notable institutions like Tongji University and RMIT University also demonstrate substantial research output and citation impact, with Tongji University leading in document count (50). In contrast, universities such as King Faisal University and Future University in Egypt contribute fewer documents but still maintain meaningful citation counts, indicating specialized research efforts. The collaboration strength metric further highlights the global network, with institutions such as Far Eastern Federal University and Southeast University maintaining robust collaborative ties, as evidenced by their citation and link strength. Overall, the table underscores a diverse range of institutions contributing to advancing seismic retrofitting research, with varying degrees of research output and academic influence.

3.5. Bibliographic coupling – Documents

Table 5. Most Cited and Highly Linked Documents in Seismic Retrofitting and Related Research

Document	Citations	Total link strength
Amran (2022a)	146	1508
Farooq (2021)	255	1259

Document	Citations	Total link strength
Amran (2022b)	68	1119
Riaz (2023)	54	918
Rehman (2021)	225	892
Zaid (2024a)	36	885
Ricciotti (2023)	26	876
Qaidi (2022)	149	875
Farhan (2020)	127	866
Liew (2017)	325	849
Lu (2024)	25	841
Ming (2021)	25	815
Ünal (2023)	21	803
Salman (2021)	70	794
Amin (2022a)	53	787
Jindal (2023)	31	771
Amran (2023a)	98	761
Abbas (2022)	89	739
Amran (2022c)	110	733
Xie (2021a)	52	720

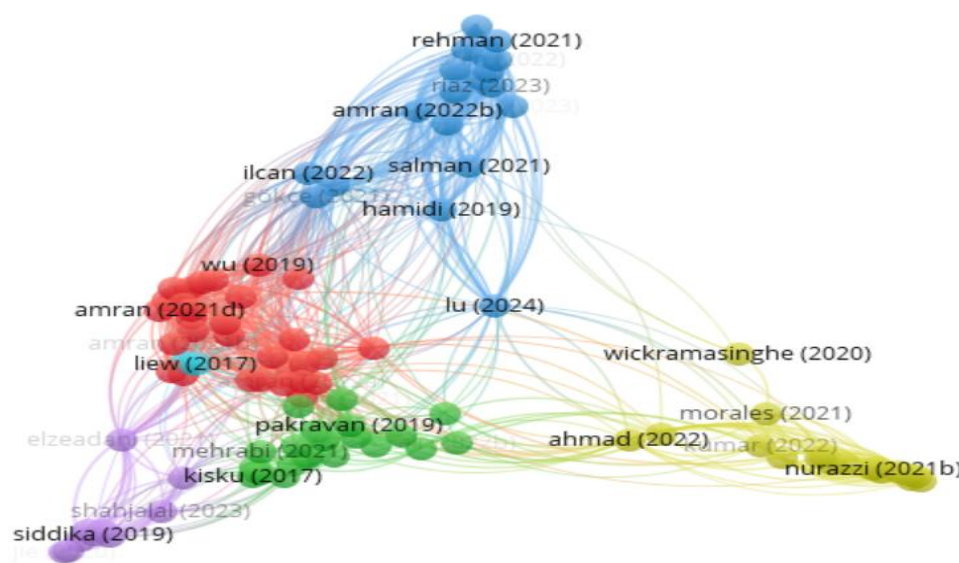


Fig 5. Co-Citation Network of Authors in Seismic Retrofitting Research

The table 5 highlights the most cited and highly linked documents in seismic retrofitting research, showcasing influential works in the field. Liew (2017) stands out as the most cited document with 325 citations, followed by Farooq (2021), which has the highest citation count in recent years (255 citations). Documents by Amran (2022a, 2022b, 2022c) collectively reflect a strong contribution to the field, with citation counts ranging from 68 to 146 and a total link strength of 1508. Rehman (2021) and Qaidi (2022) also have notable citations, indicating their impact in the domain. Ricciotti (2023), Farhan (2020), and Zaid (2024a) demonstrate a balanced citation and link strength, further emphasizing their importance in seismic retrofitting research. Despite being relatively newer, authors like Riaz (2023) and Ming (2021) are gaining recognition, showing their contributions are becoming increasingly significant. The total link strength metric reveals the degree of scholarly collaboration and reference within the academic community, with documents like Amran (2022a) having the highest total link strength. This data collectively underscores the influential role these authors and their works play in shaping ongoing research in seismic retrofitting.

3.6. Co- citation – Cited References

Table 6. Most Frequently Cited References and Their Collaboration Strength in Seismic Retrofitting Research

Cited Reference	Citations	Total link strength
Anonymous (2023). Materials Today Proceedings	120	102
Anonymous (2006). Journal of Materials Science, 42(9), ...	54	79
Anonymous (1991). Journal of Thermal Analysis and Cal...	59	78
Anonymous (2012). Progress in Polymer Science, 37(11)...	61	77
Anonymous (2021). Advances in Civil Engineering, 2021...	59	77
Anonymous (2020). Cement and Concrete Composites, ...	46	69
Anonymous (2018). Advances in Civil Engineering, 2018...	50	68
Anonymous (2016). Composites Part A: Applied Science ...	51	64
Anonymous (2007). Journal of Polymers and the Environ...	38	61
Anonymous (1997). Cement and Concrete Composites, ...	39	58
Anonymous (2015). Construction and Building Materials...	36	57
Anonymous (2015). Composites Part B: Engineering, 74...	34	56
Anonymous (2019). Polymers, 11(1), 1667	31	56
Anonymous (2020). Advances in Civil Engineering, 2020...	58	55
Anonymous (2013). Construction and Building Materials...	47	51
Anonymous (2020). Advances in Materials Science and ...	53	51
Anonymous (2013). Materials & Design, 47:424-442	33	48
Anonymous (2019).	45	46
Anonymous (2018). Advances in Materials Science and ...	37	45
Anonymous (2020). Journal of Cleaner Production, 251...	33	44

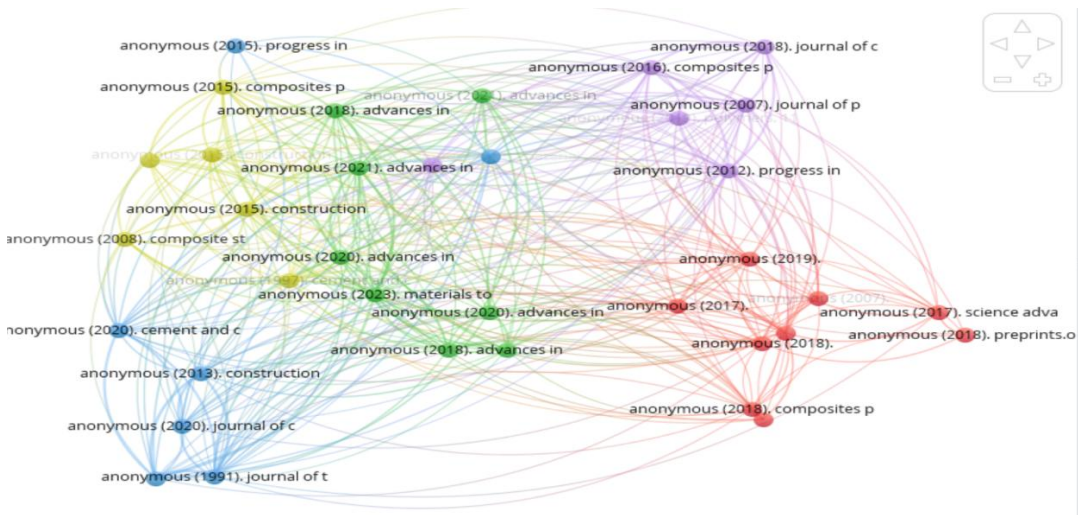


Fig 6. Co-citation Network of Research Publications

The table presents a list of highly cited and influential references in seismic retrofitting and material science research, each contributing to advancements in the field. The most cited reference, Anonymous (2023) from Materials Today Proceedings, with 120 citations and a total link strength of 102, indicates its pivotal role in shaping recent research trends. Other notable references such as Anonymous (2006), Anonymous (2012), and Anonymous (2018) show consistent contributions to the academic discourse, particularly in polymer science, materials engineering, and construction. The total link strength metric highlights the degree of interconnectedness between these references, with documents like Anonymous (2020) in Advances in Civil Engineering and Journal of Cleaner Production reflecting strong collaborative ties. While some older references, such as those from 1991 and 1997, continue to be cited for their foundational contributions, recent works

(e.g., Anonymous (2021)) demonstrate a continued focus on materials and engineering advancements. The distribution of citations and link strength reveals the enduring relevance of both classic and contemporary sources in seismic retrofitting, providing a broad spectrum of insights for ongoing research and innovation.

IV. CONCLUSION

The research conducted on seismic retrofitting techniques for reinforced concrete (RC) structures, particularly using Geopolymer and Glass Fiber Reinforced Polymer (GFRP), has provided valuable insights into modern approaches to enhancing seismic resilience. The increasing frequency of seismic events worldwide emphasizes the need for effective retrofitting strategies, especially for aging infrastructure that was not designed to meet contemporary seismic standards. This study has evaluated the efficacy of innovative materials such as GFRP and Geopolymer in improving the lateral load resistance, ductility, and overall structural integrity of existing buildings.

The findings indicate that GFRP, with its high strength-to-weight ratio and corrosion resistance, significantly enhances the seismic performance of structures, especially when used in retrofitting critical elements such as beam-column joints. Similarly, Geopolymer, derived from industrial by-products like fly ash, has proven to be a sustainable and durable solution for retrofitting, offering an environmentally friendly alternative to traditional materials while providing superior strength and resistance to corrosion.

Moreover, the research has highlighted the economic feasibility of these retrofitting techniques, with both GFRP and Geopolymer offering cost-effective solutions by reducing labor and material consumption, as well as minimizing disruption during installation. The study also emphasizes the importance of evaluating performance metrics such as energy dissipation, load-bearing capacity, and structural longevity to assess the long-term benefits of these materials in seismic applications.

In conclusion, the adoption of advanced materials like GFRP and Geopolymer for seismic retrofitting represents a significant step forward in the construction industry. By combining high-performance materials with innovative techniques, these solutions not only improve the safety and resilience of existing structures but also contribute to the sustainability and cost-efficiency of seismic retrofitting practices. Future research could explore further optimization of these materials, particularly in terms of scalability, environmental impact, and application to various building types.

LIMITATION OF THE STUDY

Despite the valuable insights provided by this study on seismic retrofitting techniques using Geopolymer and Glass Fiber Reinforced Polymer (GFRP), there are several limitations that must be acknowledged. First, the study primarily focuses on the performance of these materials in reinforced concrete (RC) structures, which may limit the applicability of the findings to other types of building materials or structural systems. Additionally, while the study utilized both experimental testing and numerical simulations, it did not explore the full spectrum of real-world variability in seismic events, such as ground motion variability or structural complexities in different geographical locations.

Another limitation is the scope of the materials considered. Although Geopolymer and GFRP have shown promising results, there are other innovative materials and techniques that could have been examined for comparative analysis. Moreover, the economic assessments in this study are based on current market conditions, which may fluctuate over time, affecting the cost-effectiveness of the retrofitting solutions.

Lastly, the study does not fully account for the long-term performance and durability of these retrofitting methods under real-world conditions, such as exposure to extreme weather, corrosion, or other environmental factors, which could impact their effectiveness over time. Future studies should consider these variables for a more comprehensive evaluation of seismic retrofitting techniques.

FUTURE SCOPE

The future scope of this study on seismic retrofitting using Geopolymer and Glass Fiber Reinforced Polymer (GFRP) presents numerous opportunities for further research and development. One key area is the exploration of these materials in diverse building types, such as historical monuments, multi-story commercial buildings, and industrial structures. Expanding the scope to include various structural systems will provide a broader understanding of the adaptability and effectiveness of GFRP and Geopolymer across different construction contexts. Furthermore, long-term durability studies are essential to assess the performance of retrofitted structures over time, particularly in regions exposed to harsh environmental conditions such as extreme temperatures, humidity, and seismic activity. Investigating the degradation mechanisms of these materials in real-world scenarios will offer valuable insights into their sustainability and longevity. Additionally, the integration of advanced technologies such as Machine Learning (ML) and Artificial Intelligence (AI) for predictive maintenance and damage detection in retrofitted structures could revolutionize the monitoring process, enhancing the efficiency of retrofitting strategies. Cost optimization is another important avenue, where future research could focus on the

development of more affordable and scalable retrofitting solutions using locally available materials. Lastly, a comparative study with other emerging retrofitting technologies, such as Shape Memory Alloys (SMAs), could provide a more comprehensive evaluation of various approaches to seismic resilience.

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