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A Comparative Evaluation of Geopolymer: Conventional and GFRP Retrofitting Techniques in Augmenting Seismic Robustness of RC Structures

Rahul Kumar*, D.I. Narkhede

Abstract

The requirement of retrofitting an existing old structure, rendered structurally unsafe (based on its structural health assessment) is observed to be a major challenge faced by engineers as it necessitates comprehensive and complicated repair procedures. It was further seen that during the earthquake, the main reason for failure of any structure was the failure of its beam column joints, thereby making it essential to strengthen them specifically. Until recently, the two most common methods for strengthening defective RC beam-column joints were concrete jacketing and steel reinforcement. Geopolymer and Fiber reinforced polymers, such as Carbon Fiber Reinforced Polymer (CFRP), Glass Fiber Reinforced Polymer (GFRP), and aramid FRP have recently emerged as new techniques for reinforcing the beam-column junction. In this study, using ANSYS Workbench 16, FEM analysis of T joints is carried out for comparative analysis of three retrofitting methods: Geo-polymer-based retrofitting, Conventional retrofitting, and retrofitting using GFRP. For this study, an existing G+3 RC building (1984 vintage) was chosen. To identify the critical joints of the building, its performance under static and seismic loading conditions was analyzed using STAAD.Pro and subsequently the retrofitting analysis of the critical joint was carried out by considering both the ends of column as hinged. Static load was applied at the free end of the cantilever beam to achieve results for key property attributes, such as deformation, equivalent stress and equivalent strain. The paper elucidates the material properties, application methodologies, and interaction with RC structures that make these techniques viable for seismic retrofitting.

Keywords: Geo-polymer, GFRP, retrofitting, seismic resilience, ANSYS

INTRODUCTION

The escalating threat of seismic activity in various regions has spurred a quest for retrofitting solutions that transcend the limitations of traditional methods to seek innovative retrofitting techniques in augmenting the seismic resilience of reinforced concrete (RC) structures. This research endeavors to conduct a comprehensive comparative evaluation of three distinct retrofitting methodologies, namely Geopolymer retrofitting, Conventional retrofitting, and Glass Fiber Reinforced Polymer (GFRP) retrofitting [1]. Each of these techniques brings their unique set of advantages and challenges, and understanding their comparative performance is imperative for selecting the most effective solution tailored to specific structural requirements. Conventional retrofitting techniques, reliant on standard concrete formulations, have served as the bedrock for decades. However, advancements in material science prompts a re-evaluation of these approaches, for optimizing resilience and longevity [2].

***Author for Correspondence**
Rahul Kumar
E-mail: rahul010101@gmail.com

Department of Civil Engineering, College of Military Engineering/Jawaharlal Nehru University, India

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The use of GFRP has expanded the options available for retrofitting, as GFRP wraps are highly suitable for various beam reinforcement applications due to their exceptional strength-to-weight ratio, excellent fatigue performance, and remarkable resistance to corrosion. This makes them a lightweight yet highly efficient alternative. However, the growing focus on geopolymer-based retrofitting is bringing about a significant shift in perspective. Geopolymers, derived from industrial by-products and characterized by exceptional strength and durability, hold the promise of not only fortifying structures against seismic forces but also aligning with sustainability imperatives.

The chemical intricacies of geopolymer formulations, including the synthesis of aluminosilicate gel through pozzolanic reactions, elevate these materials to the forefront of seismic retrofitting research [3]. This paper embarks on a journey of comparative analysis, employing a multi-faceted approach encompassing existing empirical data and advanced computational simulations to unravel the nuanced performance metrics of each retrofitting strategy, especially in terms of seismic resilience and structural integrity for long-term durability of a structure [2].

SEISMIC RESILIENCE AND ITS SIGNIFICANCE

Resilience is commonly described as the extent to which a system recovers from a damaged state to full operational capacity. Consequently, various studies have measured resilience using a recovery function (refer to Figure 1(a)), which illustrates how a building gradually regains its original functionality over time. Initially, the system – whether an individual structure or an entire community – operates at full capacity (i.e., 100% functionality or normal operations) until it is disrupted by a seismic event (an earthquake occurring at time T0E). Following the earthquake, the building's functionality declines to a specific level, which correlates with its seismic vulnerability. This loss ratio is influenced by the intensity of the earthquake and the structural and non-structural components' ability to withstand seismic forces. The horizontal axis denotes the building's recovery timeline, where any moment after T0E signifies a period of partial or complete operational downtime [3].

After the initial drop in functionality, there is a phase where no recovery occurs, known as the delay time (DT). This period accounts for all preliminary activities required before repair work can commence, including structural assessments, permit approvals, financial arrangements, and the restoration of essential utilities (such as electricity, water supply, and road access), which are necessary for the building to return to full functionality. Once these external factors are addressed, the repair phase begins, referred to as repair time (TRE). The recovery trajectory may be irregular in nature but is often approximated using different recovery models, such as linear, exponential, or trigonometric functions, as depicted in Figure 1(a). The mathematical formulations of these functions are provided in Equation (1) [4].

$$\text{Functionality function}\begin{cases} \text{Linear}: \ \text{frec} = (1 - \text{t} - \text{t0E}/\text{TRE}) \\ \text{exponential}: \ \text{frec} = \exp(-(\text{t} - \text{t0E})(\ln 200)/\text{TRE}) \\ \text{trigonometric}: \ \text{frec} = 0.5(1 + \cos(\pi(\text{t} - \text{t0E})/\text{TRE})) \end{cases} \quad (1)$$

STRUCTURAL HEALTH ASSESSMENT: CRUCIALITY IN RETROFITTING EXCELLENCE

Necessity of Structural Audit

The integration of a rigorous Structural Health Audit (SHA) is imperative to assess the technical viability and long-term effectiveness of Geopolymer retrofitting, Conventional retrofitting, and GFRP retrofitting methodologies. SHA serves as a multifaceted approach, encompassing advanced non-destructive testing (NDT) methods, dynamic analysis, and continuous monitoring, each playing a critical role in the comprehensive evaluation of structural interventions. These methods provide insights into the material's bond strength with existing substrates, potential voids, and variations in density. In the context of conventional retrofitting materials, SHA helps identify degradation mechanisms, such as corrosion of reinforcing elements, enabling a comparative assessment of material performance.

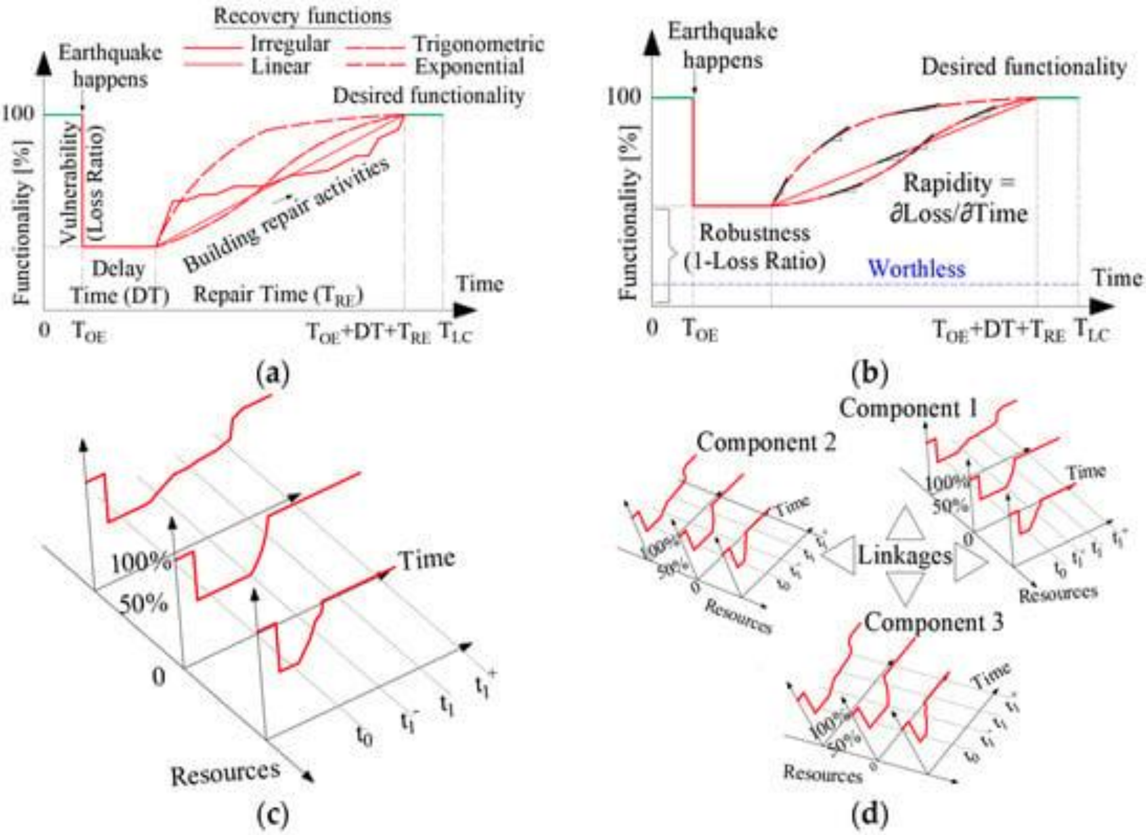


Figure 1. General components of resilience and main properties (4R), adapted from (a) Recovery function, (b) Robustness and Rapidity, (c) Resourcefulness, and (d) Redundancy [5].

Dynamic analysis within SHA involves modal analysis to evaluate changes in natural frequencies, mode shapes, and damping ratios induced by retrofitting interventions. In the case of geopolymer-based retrofitting, dynamic studies are crucial to ascertain the impact of the material's stiffness and damping characteristics on the overall structural response. This dynamic assessment aids in ensuring that the retrofitting strategy does not compromise the structural dynamics or introduce resonances that could adversely affect the structure's performance. Ongoing monitoring systems are essential for assessing the long-term effectiveness of retrofitting solutions. Advanced sensor technologies, such as strain gauges, accelerometers, and environmental sensors, enable real-time data collection on structural performance. Additionally, non-destructive testing (NDT) methods, including ultrasonic testing and ground-penetrating radar, are utilized to evaluate the integrity and uniformity of geopolymer and GFRP applications. Continuous monitoring facilitates the observation of material behavior under different environmental conditions, temperature variations, and load-bearing situations [6].

Bye-Laws

According to Clause No. 77 of the revised Bye-Laws for Cooperative Housing Societies, a "Structural Audit" of the building must be conducted as follows:

For buildings aged between 15 and 30 years, the audit should be carried out once every five years. For buildings older than 30 years, the audit should be conducted once every three years. In this paper, the structural audit of an old G+3 RC residential building was carried out to assess its structural integrity by performing a series of tests. Based on the results achieved, it was established that the building being 40 years old has lost its structural integrity considerably and needs comprehensive repairs. It was therefore analyzed using all the three above-mentioned retrofitting methods. The gist of the test results is as under:

Rebound Hammer Test Results

In the selected locations, values were in the range of 26–30 indicating the quality of near surface concrete as "Satisfactory".

- *UPV Test Results:* Showed that the quality of concrete in majority of the tested RC Structural elements was "Doubtful".
- *Carbonation Depths:* The concrete core samples extracted from the RC structural elements range from 40 mm to 75 mm.
- *Chloride Content:* In samples drawn from the RC slabs, the values were in the range of 0.16 – 1.02 Kg/m^3 compared to a threshold limit of 0.6 kg/m^3 at the time of placing as specified in IS: 456-2000.
- *pH of the Concrete Samples:* In the RC Structural elements, the values were between 9.15 and 10.24 indicating a significant reduction in the alkalinity and were found consistent with carbonation test results.
- *Half Cell Potential Test:* In most RC slabs, results were between –200 mV & –300 mV indicating "Uncertain probability" of corrosion in reinforcement, occurring as per reference guidelines of ASTM C-876.
- *The Equivalent Cube Compressive Strength of Concrete:* The values obtained through the core samples as 10.4 Mpa were well below 20 MPa and, therefore, "do not satisfy" the present codal requirements.

THE IMPERATIVE OF RETROFITTING & DIVERSE TECHNIQUES: TECHNICAL EXPLORATION

The Need for Retrofitting

The need for retrofitting arises from various factors, including corrosion-induced deterioration, material fatigue, changes in occupancy or loading patterns, and the need to comply with evolving safety and environmental standards. Structural deficiencies, whether arising from initial design limitations or subsequent degradation, necessitate strategic interventions to bolster structural performance and mitigate potential risks. The seismic vulnerability of structures, in particular, underscores the urgency of retrofitting to enhance their ability to withstand seismic forces and minimize damage in the event of an earthquake [6].

Diverse Retrofitting Techniques

- *Conventional Retrofitting:* Conventional retrofitting encompasses a spectrum of techniques tailored to address specific structural deficiencies. This includes the addition of supplementary structural elements, such as braces, the strengthening of existing members through the introduction of steel elements, and the application of additional layers of concrete to enhance load-carrying capacity. The technique often involves a meticulous assessment of the existing structure's condition, identifying weaknesses, and subsequently implementing targeted retrofit measures [7].
- *GFRP Retrofitting:* GFRP retrofitting leverages the high strength-to-weight ratio and corrosion resistance inherent in fiberglass materials. GFRP composites find application in retrofitting scenarios through techniques, such as externally wrapping columns or beams with GFRP sheets. The objective is to enhance the load-carrying capacity of structural elements while minimizing additional dead load. The technical nuances of GFRP retrofitting, including its compatibility with existing structures and durability under diverse environmental conditions are key parameters in its selection as a retrofitting option [8].
- *Geopolymer-Based Retrofitting:* Geopolymer-based retrofitting introduces an innovative approach to structural enhancement. Geopolymers are synthesized through the activation of aluminosilicate materials with alkali activators, resulting in a material with excellent compressive strength, low shrinkage, and notable chemical resistance. Utilizing geopolymer composites for existing structures provides an eco-friendly and innovative alternative to traditional retrofitting materials. Numerical simulations to identify technical intricacies of geopolymer adhesion, homogeneity, and the long-term performance in retrofitting applications have been carried out [9].

METHODOLOGY

Research Methodology

To validate the findings of this study, a G+3 RC residential building constructed in 1984 was chosen for analysis. Firstly, the structural audit of this building was carried out to assess its structural integrity followed by its static as well as seismic analyses using STAAD.Pro software to identify the critical beam column joints. Thereafter using ANSYS software, FEM analysis of one of the critical T joints was carried out for comparative assessment of the three retrofitting methods: Geo-polymer-based, Conventional, and GFRP-based (Figure 2) [10]. The properties of Geopolymer and GFRP chosen for this analysis were selected after a thorough literature review of the empirically established database from various credible sources [11].

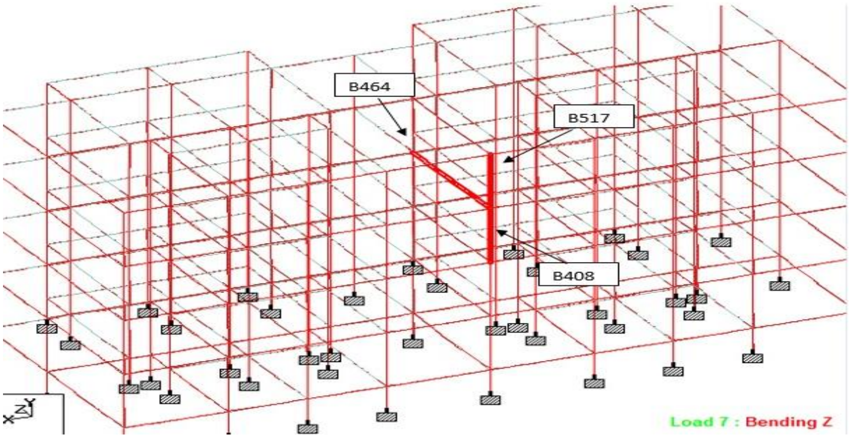


Figure 2. Exterior beam column joint modelled in STAAD Pro.

PROBLEM STATEMENT

An existing ground plus three-story RC residential building is considered.

- *Plan dimensions:* 15 m x 38 m.
- *Location considered:* Zone-IV.
- *Soil Type:* Medium soil.
- *Concrete Grade:* M20.
- *Steel Grade:* Fe 250, Fe 415.
- *Live Load:* 2 kN/m².
- *Brick Wall Thickness (both directions):* 230 mm.
- *Beam Dimensions (longitudinal & transverse):* 250 × 350 mm.
- *Column Dimensions:* 250 × 400 mm.
- *Concrete Density:* 25 kN/m³.
- *Brick Wall Density (including plaster):* 20 kN/m³.
- *Slab Thickness:* 120 mm.

Loading Details

The building under consideration was analyzed for the standard load combination 1.2 (DL+LL+EQX) and the beam with maximum bending moment (B-464) was identified for analysis in ANSYS Workbench 16.

MATERIAL PROPERTIES

The material properties for both steel as well as concrete are well established empirically and therefore have been used from existing databases whereas for both Geopolymer as well as GFRP, the material properties used in the paper were finalized based on literature review and thorough initial trials. Tables 1 and 2 below depict various elements as well as material properties utilized for the analysis in ANSYS Workbench (Figures 3 and 4).

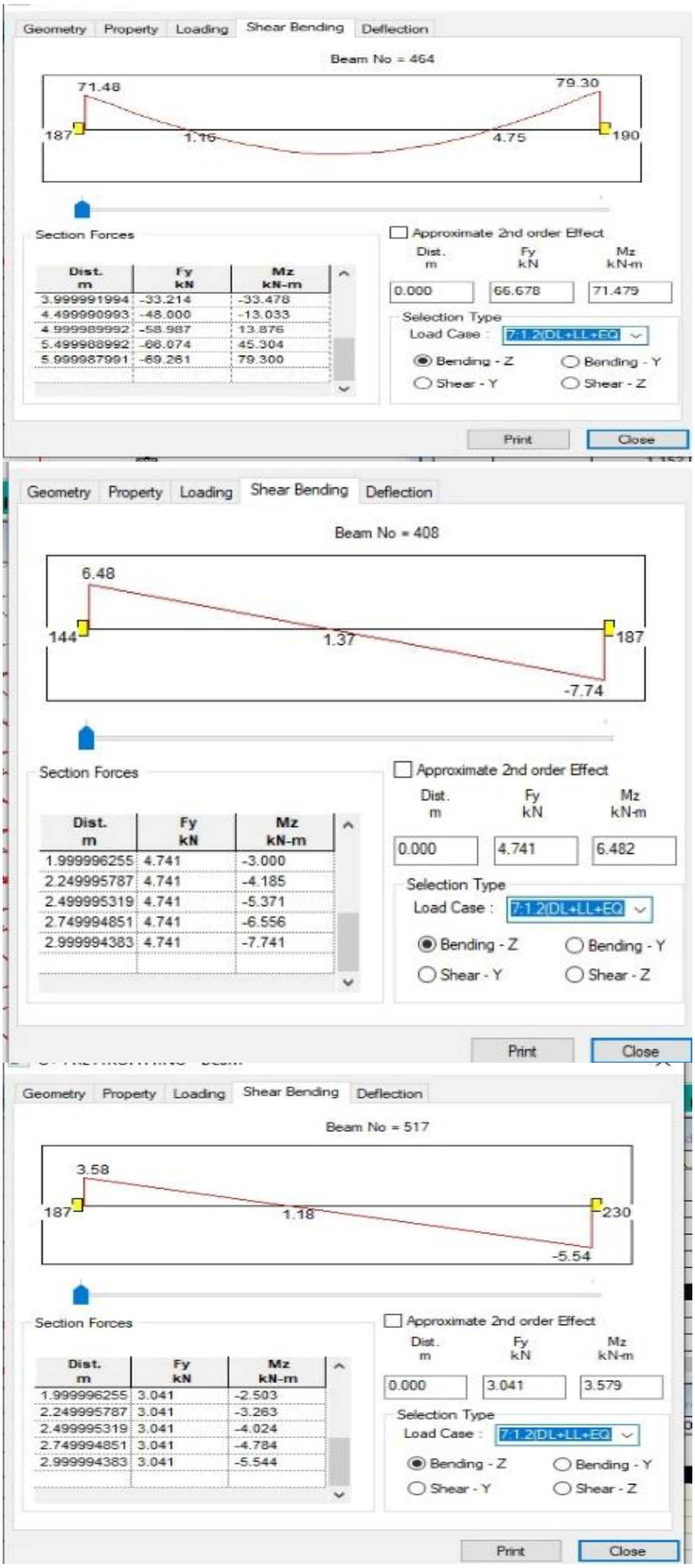


Figure 3. Identifying critical joints (analyzed using STAAD.Pro software).

Table 1. Material properties.

Property	GFRP	Geopolymer
Modulus of elasticity in KN/m^2	2.1 * 105	$3.0 * 10^5$
Poisson's ratio	0.26	0.3
Shear modulus in KN/m^2	1520	1500
Density in KN/m^3	17.3	26.5

Table 2. Elements used.

S.N.	Material/Purpose	Element Type	No of Nodes
1	Concrete, Geopolymer & GFRP	Solid 186	20
2	Steel	Link 180	2
3	Interaction between materials	CONTA174 and TARGET 170	8

MODELLING

Finite Element Modelling

For the analytical study on the behavior of reinforced beam-column joint, the finite element method was adopted. In retrofitted portions, GFRP as well as Geopolymer properties are provided for their retrofitting applications respectively. The Young's Modulus and Poisson's ratio of concrete and GPC are different, therefore to have bond between old concrete and new concrete, nodes were merged. Various properties of the T joint were studied using ANSYS. The two elements were linked at adjacent nodes of the concrete solid element, ensuring that both materials had common nodal connections.

Loading and Boundary Conditions

A cyclic load is applied at the beam's tip, while a constant load is exerted on one end of the column, with the opposite end remaining fixed. The same loading conditions are used for all retrofitted specimens.

Element used

Various elements employed in the paper are discussed as under:

- *Link180 element:* It is utilized for modeling steel reinforcement.
- *Solid 186:* It was used for modelling Geopolymer/GFRP.
- *Meshing:* For meshing of conventional beam column joint, the quadrilateral meshing was done with nodes 24713 and elements 9410 whereas for GFRP and Geopolymer, the quadrilateral meshing was done for RCC section and Triangular meshing was used for layers.
- *Interaction:* For connections between GFRP and Geopolymer, CONTA174 and TARGET 170 elements are used.

COMPARATIVE ANALYSIS OF RETROFITTING TECHNIQUES: SEISMIC RESILIENCE AND STRUCTURAL ENHANCEMENT

Seismic events pose a significant threat to structures, necessitating robust retrofitting strategies to enhance seismic resilience and overall structural performance. The following comparative analysis critically evaluates the three mentioned retrofitting techniques by examining key technical parameters and performance indicators. These observations will subsequently be attempted to correlate in the upcoming sections of the paper using analytical results.

Material Properties

- *Conventional:* Typically involves the addition of steel elements or reinforced concrete, with properties that may not be optimized for seismic resilience.
- *GFRP:* Provides a high strength-to-weight ratio and excellent corrosion resistance; however, it may

exhibit limited ductility [12].

- *Geopolymer-Based:* Exhibits excellent compressive strength, low shrinkage, and superior chemical resistance, contributing to enhanced seismic resilience [2].

Conventional Retrofitting Technique | Retrofitting with GFRP bars | Retrofitting with Geopolymer

Figure 4. An illustration of retrofitting with various techniques.

Adhesion and Homogeneity

- *Conventional:* Adhesion depends on surface preparation; homogeneity may be challenging, especially with varied substrate materials.
- *GFRP:* Adhesion is generally good, but achieving homogeneity across complex geometries may pose challenges.
- *Geopolymer-Based:* Demonstrates strong adhesion to various substrates and can be applied homogeneously, ensuring uniform seismic performance.

Durability Under Seismic Loading

- *Conventional:* May exhibit performance degradation over time due to corrosion and fatigue.
- *GFRP:* Resilient against corrosion but may lack ductility, impacting seismic performance [8].
- *Geopolymer-Based:* Shows promise in long-term durability, with resistance to chemical degradation and excellent seismic ductility [7].

Structural Dynamics

- *Conventional:* May alter structural dynamics significantly, potentially introducing undesirable resonances.
- *GFRP:* Moderate impact on dynamics but lacks the ductility needed for effective energy dissipation.
- *Geopolymer-Based:* Tends to maintain or improve structural dynamics, with inherent ductility providing effective energy dissipation during seismic events [2].

Sustainability

- *Conventional:* Often involves resource-intensive materials with environmental implications.
- *GFRP:* Fiberglass production has environmental concerns, although it offers a lightweight alternative [12].
- *Geopolymer-Based:* Environmentally friendly, utilizing industrial waste and exhibiting a lower carbon footprint compared to conventional materials [9].

Energy Dissipation Capacity

- *Conventional:* Limited capacity for energy dissipation during seismic events, leading to potential structural damage.
- *GFRP:* Moderate energy dissipation capabilities but may exhibit brittle failure under high seismic forces.
- *Geopolymer-Based:* Demonstrates superior ductility, allowing for effective energy dissipation and minimizing seismic damage [6].

Crack Propagation and Self-Healing
- *Conventional:* Prone to crack propagation and lack inherent self-healing mechanisms.
- *GFRP:* May exhibit cracks under seismic loading, with limited self-healing potential.
- *Geopolymer-Based:* Shows resistance to crack propagation and possesses inherent self-healing properties, contributing to sustained structural integrity.

Construction Speed and Minimal Disruption
- *Conventional:* Often involves extensive construction activities, leading to significant disruption.
- *GFRP:* Generally faster than conventional methods but may require careful surface preparation.
- *Geopolymer-Based:* Rapid application due to its one-step curing process, minimizing downtime and disruption during retrofitting [9].

Cost-Effectiveness Over the Lifecycle
- *Conventional:* The upfront costs might be lower, but the long-term maintenance expenses can be substantial.
- *GFRP:* Initial costs can be moderate, but potential durability concerns may contribute to long-term expenses [8].
- *Geopolymer-Based:* While initial costs may be marginally higher, the superior durability and minimal maintenance contribute to long-term cost-effectiveness [9].

Compatibility with Existing Infrastructure
- *Conventional:* Compatibility depends on the type of material and technique used, requiring careful consideration.
- *GFRP:* It is typically compatible with different structures; however, surface preparation may be necessary to ensure optimal adhesion.
- *Geopolymer-Based:* Exhibits high compatibility due to strong adhesion properties, allowing for effective application on diverse substrates.

ANALYSIS AND RESULTS

The major goal of this research is to undertake a full structural analysis using ANSYS software to compare and assess models made of three different materials (as shown below) to determine the most effective material in terms of structural performance, seismic resilience and efficiency. This section meticulously dissects key parameters, such as deformation, equivalent stress and equivalent strain, offering a comprehensive and quantifiable assessment of the seismic resilience and structural enhancement achieved through these retrofitting techniques. The incorporation of ANSYS not only enhances the precision of the study but also establishes a scientific basis for the conclusions drawn, bolstering the credibility and significance of the research findings (Figures 5–7).

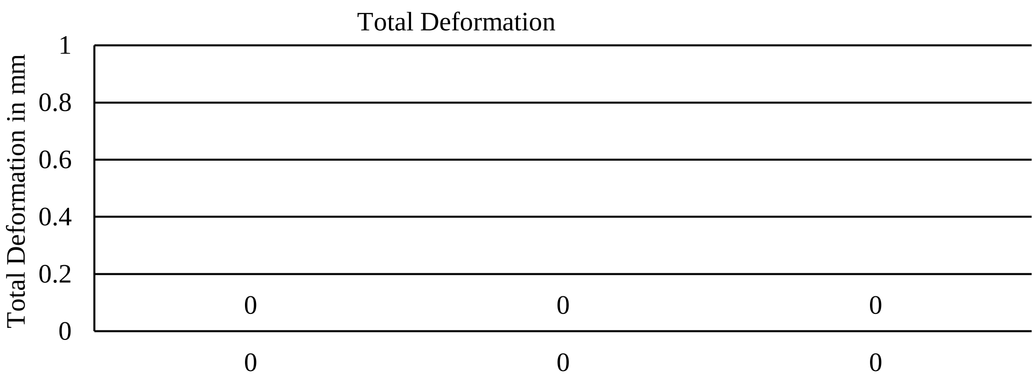


Figure 5. Total deformation (mm).

ADVANTAGES AND DISADVANTAGES OF THE THREE RETROFITTING TECHNIQUES [13]

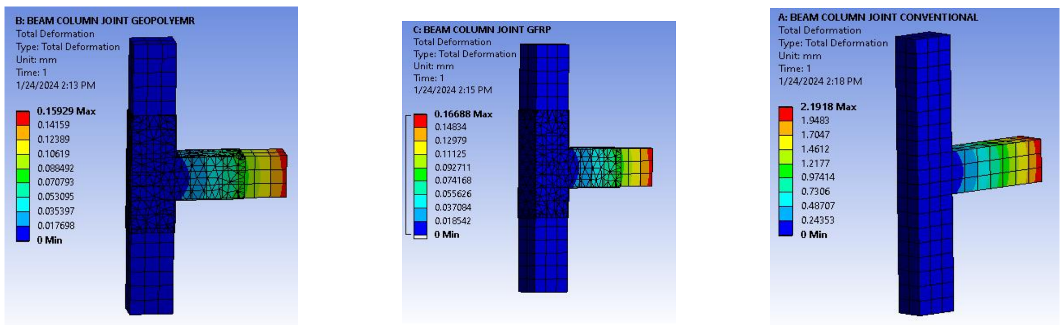
GFRP Retrofitting: Advantages

- *High Strength-to-Weight Ratio:* Enhances structural strength without adding significant weight, reducing seismic forces.
- *Ductility:* Provides ductility, allowing the structure to absorb and dissipate seismic energy.
- *Corrosion Resistance:* It offers corrosion resistance, contributing to long-term structural durability.
- *Ease of Installation:* Lightweight nature facilitates easier handling and installation.

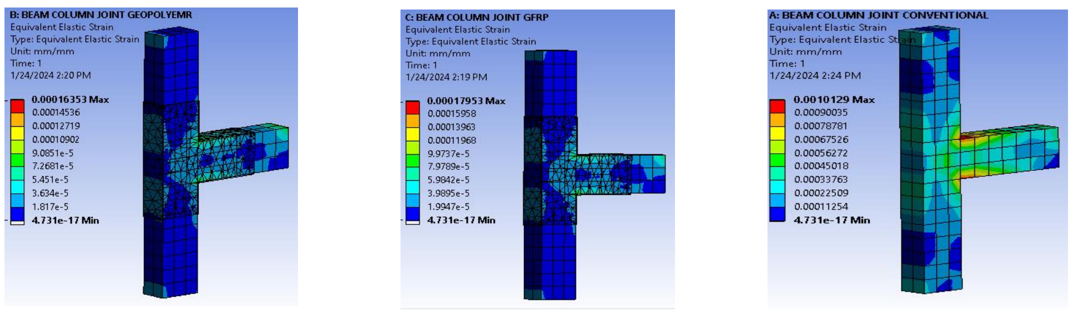
GFRP Retrofitting: Disadvantages

- *Cost:* Initial material costs may be higher compared to conventional methods.
- *Limited Temperature Resistance:* May have limitations in high-temperature environments during seismic events.
- *Compatibility Issues:* Careful designing is required to ensure compatibility with existing materials.

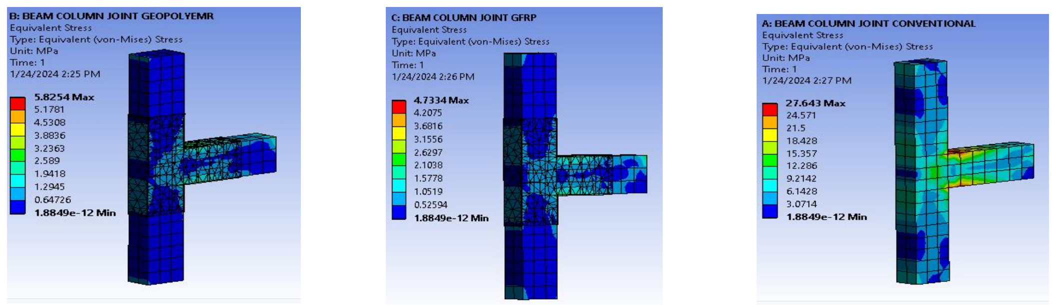
Model With Geopolymer **Model With GFRP** **Conventional Model**



Total Deformation



Equivalent Elastic Strain



Equivalent Stress

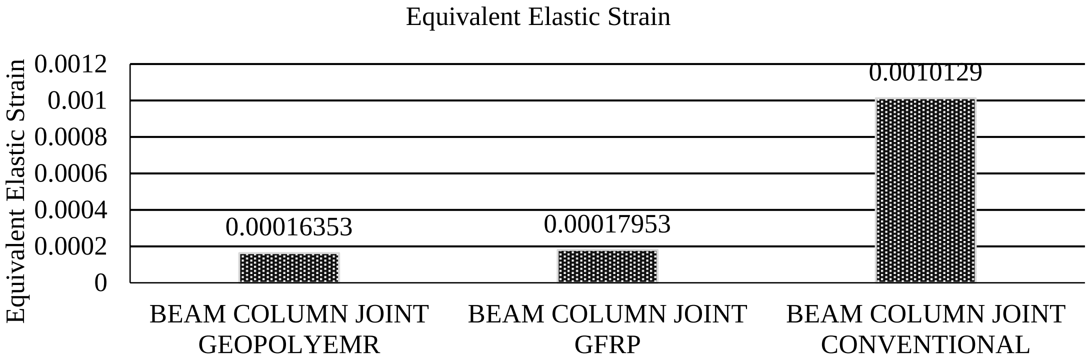


Figure 6. Equivalent elastic strain.

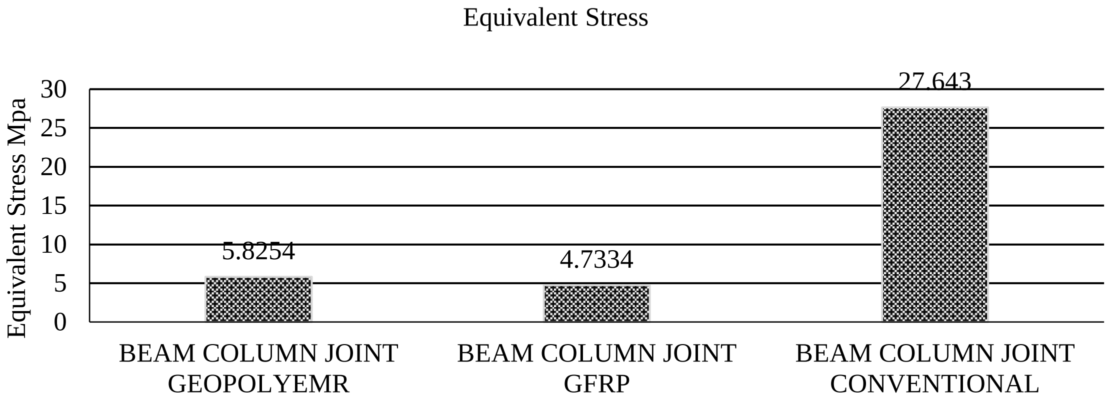


Figure 7. Equivalent stress [Mpa].

Geopolymer Retrofitting: Advantages
- *Tailorable Properties:* Can be designed for specific seismic performance requirements.
- *Rapid Strength Development:* Achieves high early strength, enhancing immediate seismic resilience.
- *Corrosion Resistance:* It resists corrosion, enhancing longevity and structural integrity over time.
- *Low Environmental Impact:* Potential for reduced carbon footprint compared to conventional methods.

Geopolymer Retrofitting: Disadvantages
- *Limited Data for Seismic Design:* Limited established standards and data for seismic design with geopolymer.
- *Material Availability:* Limited commercial availability may affect widespread adoption.
- *Curing Time:* Some formulations may have specific curing requirements, affecting construction timelines.

Conventional Retrofitting: Advantages
- *Proven Seismic Performance:* Well-established methods, like steel bracing and concrete jacketing, have proven seismic performance.
- *Familiarity:* Widely understood and implemented, reducing potential design errors.
- *Availability of Materials:* Conventional materials, like steel and concrete, are readily available.

Conventional Retrofitting: Disadvantages
- *Additional Weight:* Added weight from conventional materials may increase seismic forces.

- *Corrosion Potential:* Susceptible to corrosion, requiring ongoing maintenance for resilience.
- *Intrusiveness:* Retrofitting conventional materials may be more intrusive and disruptive.

In summary, geopolymer retrofitting offers high compressive strength and durability but faces challenges with standards and potential shrinkage. GFRP retrofitting is characterized by a high strength-to-weight ratio and corrosion resistance but may be more expensive and has limited fire resistance. Conventional techniques, like steel reinforcement, are widely accepted with predictable performance but come with corrosion issues and increased deadload. The selection of a retrofitting method is influenced by factors like structural needs, environmental conditions, cost implications, and material availability. Evaluating long-term durability and performance is essential in the decision-making process.

CONCLUSIONS

Identification of Critical Beam-Column Joint

Using STAAD.Pro software, the critical RC beam-column joint of an existing 40 year old G+3 RC building (duly structurally audited) was identified based on maximum shear force and bending moment conditions.

The Comparative Analysis

Various property attributes of above-mentioned retrofitting techniques were studied to select the key aspects to be used for comparative study using FEM analysis.

Minimum Equivalent Stress

It was established analytically that the minimum equivalent stress among the three retrofitting techniques was achieved using GFRP, followed by marginal increase with Geopolymer, whereas considerable increase was observed using Conventional technique for the same applied load.

Minimum Equivalent Strain

The minimum equivalent strain worked out to be the least for the Geopolymer based retrofitting, followed by a negligible increase with GFRP, however the value was found maximum with Conventional technique.

Total Deformation

The total deformation as calculated was found to be the least for the Geopolymer based retrofitting followed by slight increase with GFRP, however the same was found maximum for Conventional technique.

Load Carrying Capacity

The load carrying capacity of the structure is considerably increased after retrofitting with GFRP and Geopolymer based solutions when compared with conventional techniques.

Structural Strength

It is assessed that the structural strength of the retrofitted building using any of the above-mentioned techniques is adequately augmented based on the increase in its seismic resilience. It is safe to assume that it enhances the lifespan of the structure by about 08–10 years comfortably.

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