Retrofitting Historic Structures: Evaluating Sustainable Materials Using Multi-Criteria Decision Analysis Approach

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ABSTRACT

Historic structures, representing rich cultural and architectural legacies, face gradual deterioration due to aging, environmental factors, and neglect. This study emphasizes the importance of retrofitting as a means to preserve these heritage buildings without compromising their structural safety or historical authenticity. It particularly focuses on the challenges faced in Indian states like Haryana, Rajasthan, and Jharkhand, where traditional materials are scarce and documentation is limited. A quantitative research methodology was adopted, utilizing Multi-Criteria Decision Analysis (MCDA) to assess the performance, compatibility, and sustainability of various retrofitting materials. Evaluation was based on key factors such as strength, durability, cost, environmental impact, and aesthetic compatibility. Through normalization and weighted scoring, the most suitable material was identified to guide future retrofitting practices. This research aims to bridge the gap between modern safety requirements and traditional values, contributing to the effective conservation of historic structures in urbanizing regions.

Key Words: *Retrofitting, Historic Structures, Multi-Criteria Decision Analysis (MCDA).*

1. INTRODUCTION

Historic structures serve as enduring symbols of cultural, architectural, and technological heritage. They offer deep insights into the craftsmanship and societal values of past civilizations. However, over time, these structures deteriorate due to natural aging, environmental conditions, and lack of maintenance. Retrofitting emerges as a vital method for preserving these buildings while ensuring their structural safety. Unlike conventional buildings, historic structures demand careful retrofitting that upholds both strength and authenticity. Materials like lime mortar and timber used in older buildings behave differently from modern materials like steel or FRPs, leading to challenges in compatibility and preservation. In regions like Haryana, Rajasthan, and Jharkhand, many heritage buildings suffer from neglect and are vulnerable to seismic and climatic risks. Limited documentation and scarce traditional materials complicate retrofitting efforts. Selecting suitable retrofit techniques requires a multidisciplinary approach involving structural analysis, material science, and cultural conservation. The aim of this study is to evaluate the performance, compatibility, and sustainability of retrofitting materials, providing guidelines for effective interventions. It also addresses socio-economic barriers such as funding and public awareness. By integrating modern safety standards with heritage values, this research supports the long-term conservation of historic structures, especially in the context of rapidly urbanizing regions in India.

2. RESEARCH METHODOLOGY

This study adopts a quantitative research methodology to evaluate materials used for retrofitting historic structures. The primary objective is to identify the most suitable material by analyzing various performance factors such as strength, durability, cost, and environmental impact. A Multi-Criteria Decision Analysis (MCDA) approach is employed to compare materials using a set of evaluation criteria. These criteria include strength, fire and seismic resistance, weight, durability, environmental impact, aesthetic compatibility, and cost. All data are normalized to a [0,1] scale to ensure comparability. For criteria where higher values are better (e.g., strength), a positive normalization formula is applied; for criteria where lower values are better (e.g., cost), a negative normalization formula is used. Each criterion is assigned a weight based on its importance to the project. A composite score is calculated for each material by aggregating the weighted normalized values. The material with the highest score is selected as optimal.

3. ANALYSIS AND RESULT

The importance of retrofitting historic structures has grown as urban environments face the challenges of preserving architectural heritage while meeting modern safety, durability, and sustainability standards. Retrofitting involves the careful selection and application of materials that enhance the structural integrity, fire resistance, seismic performance, and overall longevity of a building. It is also critical to choose materials that are compatible with the aesthetics of the existing structure, ensuring that modern modifications blend seamlessly with historical elements.

This analysis delves into the key materials used in retrofitting, examining their strength, fire resistance, seismic resistance, weight, durability, environmental impact, aesthetic compatibility, and cost. Through this detailed comparison, we aim to guide decision-making processes for engineers, architects, and conservationists involved in the rehabilitation and modernization of historic buildings. The materials analyzed in this report include Carbon Fiber Reinforced Polymer (CFRP), Fiber Reinforced Concrete (FRC), Epoxy-Coated Steel, Wood (Preserved Timber), Stone (Granite), Unburnt Rice Husk Fiber (URHF), Self-Compacting Concrete (SCC), and Reinforced Brick.

Each material has distinct advantages and limitations that make it suitable for specific applications. For instance, materials like CFRP and Epoxy-Coated Steel excel in strength and seismic resistance but come at higher costs. On the other hand, materials such as Wood and URHF provide aesthetic appeal at lower prices but may lack the strength required for more demanding retrofitting projects. The goal of this analysis is to provide a comprehensive overview, allowing professionals to make informed choices based on the specific needs of their projects, balancing performance, aesthetics, environmental impact, and budget constraints.

By understanding the unique properties of each material, stakeholders can ensure that historic buildings are preserved and modernized effectively, ensuring their longevity and relevance in the future.

Material Type	Strength (MPa)	Fire Resistance Rating (hrs)	Seismic Resistance (kg/m²)	Weight (kg/m²)	Durability (Years)	Environmental Impact (kg CO_2/m²)	Aesthetic Compatibility (1-10)	Cost (USD per m²)
Carbon Fiber Reinforced Polymer (CFRP)	600	2	500	1.2	50	3.0	8	45

Fiber Reinforced Concrete (FRC)	40	3	350	45.0	100	5.5	7	25
Epoxy-Coated Steel	250	3	700	50.0	75	4.2	6	30
Wood (Preserved Timber)	30	1	150	10.0	20	2.5	9	15
Stone (Granite)	150	2	400	200.0	200	1.8	10	50
Unburnt Rice Husk Fiber (URHF)	25	1	100	4.5	10	2.0	7	5
Self-Compacting Concrete (SCC)	50	2	350	50.0	75	3.2	6	20
Reinforced Brick	60	2	250	70.0	150	2.0	8	18

The data table presents a comparison of various materials used in retrofitting, highlighting key attributes such as strength, fire resistance, seismic resistance, weight, durability, environmental impact, aesthetic compatibility, and cost. Carbon Fiber Reinforced Polymer (CFRP) stands out for its high strength (600 MPa) and seismic resistance (500 kg/m²), making it suitable for high-load applications. However, it has a relatively high cost at $45 per m² and moderate environmental impact (3.0 kg CO_2/m²). Fiber Reinforced Concrete (FRC), while offering moderate strength and seismic resistance, provides good durability (100 years) and a more affordable cost of $25 per m². Epoxy-Coated Steel offers excellent seismic resistance (700 kg/m²) but is also one of the heavier materials, with a high cost of $30 per m². Wood (Preserved Timber) offers aesthetic appeal and low cost ($15 per m²) but has limited strength and durability compared to other materials. Granite, though highly durable (200 years) and aesthetically compatible, is the heaviest and most expensive material at $50 per m². Unburnt Rice Husk Fiber (URHF) is the most affordable option at $5 per m² but has low strength and durability. Self-Compacting Concrete (SCC) and Reinforced Brick offer balanced performance but come with moderate costs and environmental impacts.

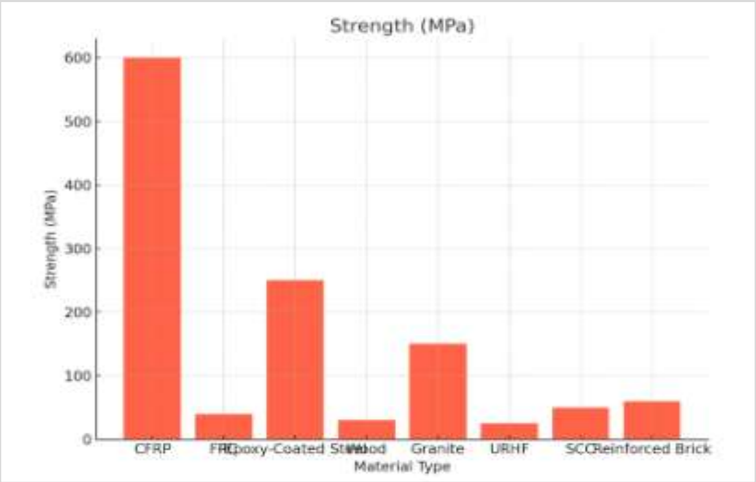

Figure 1: Strength (MPa)

The bar graph illustrates the strength (in MPa) of various materials used in retrofit applications for historic structures. The material with the highest strength is Carbon Fiber Reinforced Polymer (CFRP), which stands at an impressive 600 MPa. This material significantly outperforms others in terms of strength, indicating its suitability for applications requiring high load-bearing capacity. Epoxy-Coated Steel follows, with a considerably lower strength of around 250 MPa. Materials such as Granite, Reinforced Brick, and Self-Compacting Concrete (SCC) exhibit moderate strength values between 150 MPa and 50 MPa. The remaining materials, including Wood, URHF, and Fiber Reinforced Concrete (FRC), have significantly lower strength values, highlighting their limitations when it comes to supporting heavy loads or withstanding high-stress environments. The variation in strength emphasizes the importance of selecting materials that align with the structural demands of retrofitting historic buildings while ensuring long-term safety and stability.

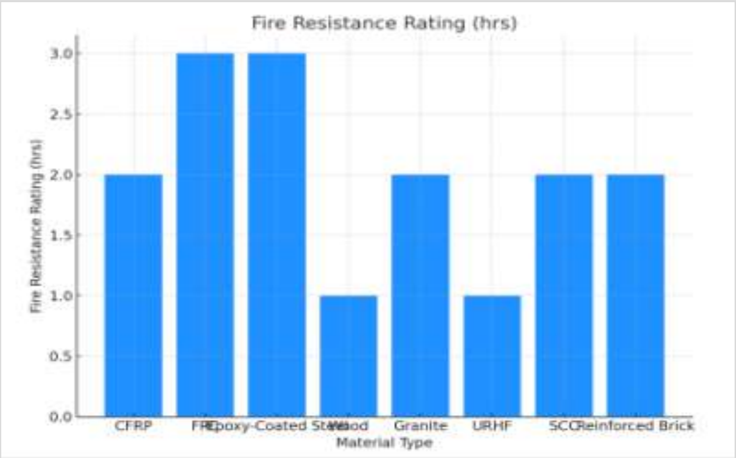

Figure 2: Fire Resistance Rating (hrs)

The bar graph presents the fire resistance rating (in hours) for various materials. The materials with the highest fire resistance are CFRP and Fiber Reinforced Concrete (FRC), both of which have a fire resistance rating of 2-3 hours. This makes them highly suitable for applications where fire protection is critical. Epoxy-Coated Steel follows closely with a rating of approximately 2 hours, offering moderate fire resistance. Wood, Granite, URHF, and Reinforced Brick all show a lower fire resistance rating, with values ranging from 1 to 2 hours. These materials, while durable, may not provide as much fire protection as CFRP or FRC. The graph indicates that materials with higher fire resistance ratings are better suited for environments where fire safety is a primary concern. In contrast, the materials with lower ratings may require additional protective measures to meet modern safety standards.

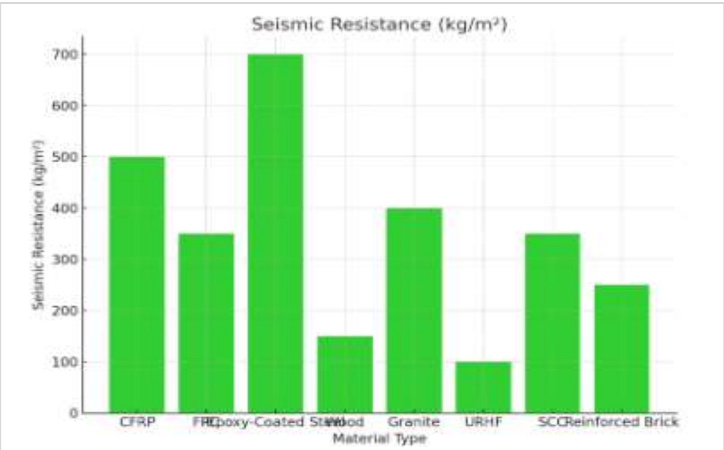

Figure 3: Seismic Resistance (kg/m²)

The bar graph illustrates the seismic resistance (in kg/m²) of various materials. The material with the highest seismic resistance is Epoxy-Coated Steel, which can withstand up to 700 kg/m² of seismic forces, making it highly suitable for earthquake-prone regions. Fiber Reinforced Concrete (FRC) follows closely with a seismic resistance of around 500 kg/m², also demonstrating strong resistance to seismic activity. Carbon Fiber Reinforced Polymer (CFRP) shows moderate seismic resistance at approximately 400 kg/m², offering a good balance between strength and weight. Materials like Granite, Reinforced Brick, and Self-Compacting Concrete (SCC) exhibit lower seismic resistance, ranging from 100 to 300 kg/m². Wood and Unburnt Rice Husk Fiber (URHF) have the least seismic resistance, suggesting they may not be ideal for areas with high seismic activity unless supplemented with additional reinforcing materials. This highlights the importance of choosing materials based on the specific seismic requirements of the location.

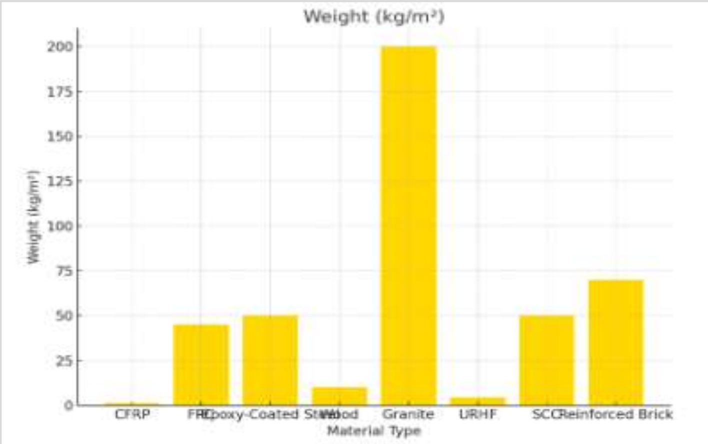

Figure 4: Weight (kg/m²)

The bar graph represents the weight (in kg/m²) of various materials used for retrofitting. Granite stands out significantly as the heaviest material, with a weight of approximately 200 kg/m², making it the least ideal for applications where weight is a concern. In comparison, Carbon Fiber Reinforced Polymer (CFRP), Fiber Reinforced Concrete (FRC), and Epoxy-Coated Steel are much lighter, with weights ranging between 1 and 50 kg/m². This makes these materials highly suitable for projects that require lightweight solutions without compromising on strength. Wood and Unburnt Rice Husk Fiber (URHF) are relatively light, with wood having a weight of around 10 kg/m², which is beneficial for non-load-bearing applications. Self-Compacting Concrete (SCC) and Reinforced Brick have moderate weights, which can be appropriate depending on the structural requirements. Overall, the graph emphasizes the importance of considering material weight in retrofitting, especially in weight-sensitive environments.

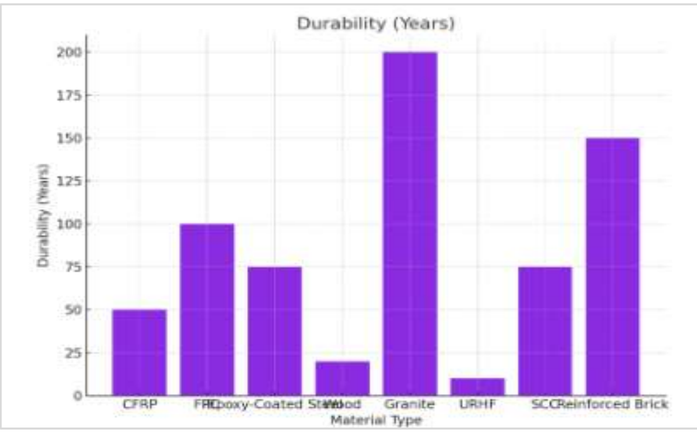

Figure 5: Durability (Years)

The bar graph illustrates the durability (in years) of various materials used in retrofitting applications. Granite stands out as the most durable material, with an impressive lifespan of approximately 200 years. This makes granite an ideal choice for long-term applications where the material's endurance is crucial. In comparison, materials such as Fiber Reinforced Concrete (FRC) and Epoxy-Coated Steel show durability in the range of 50 to 100 years, indicating they offer moderate long-term durability for retrofitting projects. Carbon Fiber Reinforced Polymer (CFRP) shows a similar level of durability, contributing to its use in structures requiring reinforcement over extended periods. Wood, Unburnt Rice Husk Fiber (URHF), and Reinforced Brick display lower durability, ranging from 10 to 50 years. These materials may need more frequent maintenance or additional protection in harsh environments. Overall, the graph emphasizes the importance of selecting durable materials to ensure long-lasting performance in retrofitting projects.

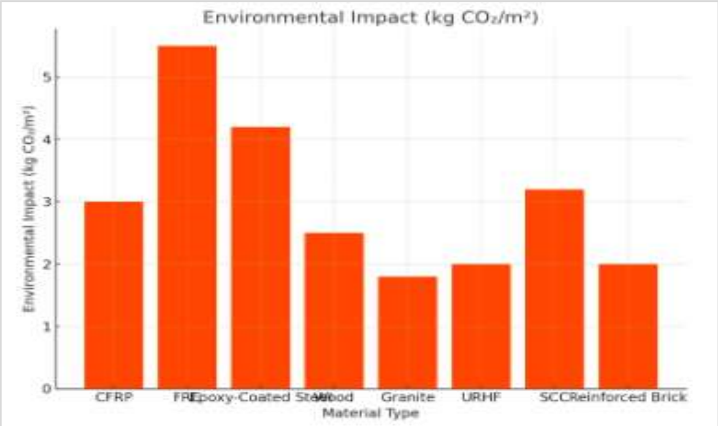

Figure 6: Environmental Impact (kg CO_2/m^2)

The bar graph illustrates the environmental impact (measured in kg of CO_2 per m^2) of various materials. Fiber Reinforced Concrete (FRC) and Epoxy-Coated Steel have the highest environmental impact, emitting over 4 kg of CO_2 per m^2. This indicates that their production processes contribute significantly to carbon emissions, which could be a concern for projects focused on sustainability. Carbon Fiber Reinforced Polymer (CFRP) also has a relatively high environmental impact, just under 3 kg CO_2 per m^2. In contrast, materials like Granite, URHF (Unburnt Rice Husk Fiber), and Self-Compacting Concrete (SCC) show a lower environmental impact, ranging between 1.5 to 3 kg CO_2 per m^2. These materials are more eco-friendly in comparison, making them suitable choices for projects with sustainability goals. Wood and Reinforced Brick are the least impactful, with the lowest CO_2 emissions, aligning them with environmentally conscious construction practices.

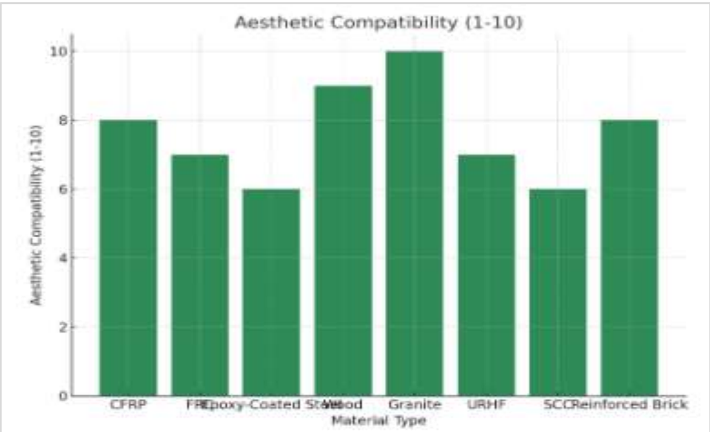

Figure 7: Aesthetic Compatibility (1-10)

The bar graph illustrates the aesthetic compatibility (on a scale of 1 to 10) of various materials used in retrofitting. Granite stands out as the most aesthetically compatible material, scoring a perfect 10. This makes it highly suitable for applications where visual appeal is crucial, especially in preserving the historical integrity of a structure. Wood follows closely with a score of 9, offering natural beauty and warmth, making it an attractive choice for aesthetic applications. Materials like CFRP (8) and FRC (7) have moderate aesthetic compatibility, indicating they are somewhat suitable for integration into existing structures, though they may not blend as seamlessly as granite or wood. Epoxy-Coated Steel, URHF, and SCC show lower scores, reflecting their less natural appearance, which may require additional design efforts for aesthetic integration. Reinforced Brick scores the lowest, suggesting that while functional, it may need more work to maintain aesthetic harmony.

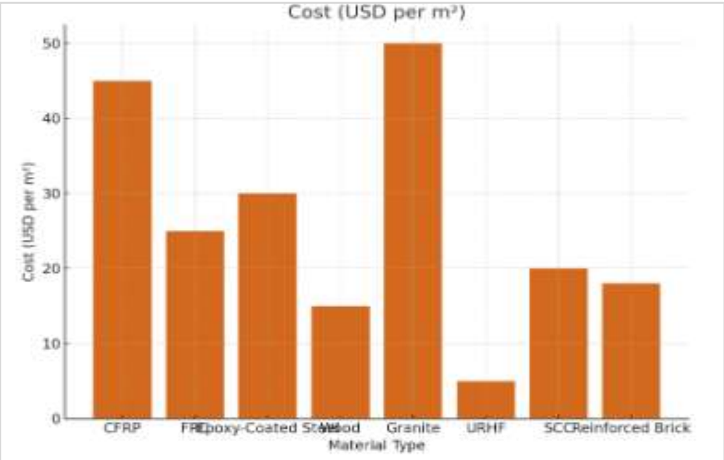

Figure 8: Cost (USD per m²)

The bar graph shows the cost (in USD per m²) of various materials used in retrofitting applications. Granite is the most expensive material, with a cost of around \$50 per m², which reflects its high durability and aesthetic appeal. CFRP and FRC are also relatively costly, with prices ranging from \$40 to \$45 per m², indicating their advanced properties and high performance in structural applications. Epoxy-Coated Steel is moderately priced, costing approximately \$30 per m². Wood, while an attractive material aesthetically, has a lower cost at about \$20 per m², making it a more affordable option for certain applications. Materials like URHF, SCC, and Reinforced Brick are among the least expensive, with prices ranging from \$10 to \$20 per m², offering budget-friendly alternatives for retrofitting. Overall, the cost factor plays a crucial role in material selection, with more expensive options typically offering better durability or aesthetic benefits.

4. CONCLUSION

The study demonstrated that retrofitting historic structures requires a balanced integration of structural integrity, material compatibility, and cultural preservation. Through the MCDA approach, it was possible to objectively compare materials and identify the optimal choice for sustainable retrofitting. The findings highlighted the necessity of multidisciplinary collaboration and the importance of considering both technical and socio-economic factors. By offering a structured evaluation framework, this research supports informed decision-making in heritage conservation, especially in regions with limited resources and rapid urban development.

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