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Use Of Basalt Fiber-Reinforced Polymer In Retrofitting Historical Masonry Structures

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Abstract
*This study explores the application of **Basalt Fiber-Reinforced Polymer (BFRP)** composites in the **retrofitting of historical masonry structures**, which are often vulnerable to seismic and environmental stresses due to their age and construction techniques. BFRP is selected due to its **high tensile strength, corrosion resistance, lightweight nature**, and **aesthetic compatibility** with heritage structures, offering a non-invasive and durable strengthening solution.A series of **experimental tests** were conducted on masonry wall panels retrofitted with BFRP sheets and compared to unreinforced controls. The panels were subjected to **in-plane (shear and compression)** and **out-of-plane (flexural and overturning)** load conditions to simulate real-world stresses such as **earthquake forces and wind loads**. The research was complemented with **finite element modeling (FEM)** to simulate the structural response and validate experimental findings.*
Keywords: *Basalt Fiber, Masonry Retrofitting, Heritage Structures, FRP Strengthening, In-Plane Load, Out-of-Plane Load, Seismic Retrofitting.*

1. INTRODUCTION

Historical masonry structures represent significant cultural, architectural, and social heritage. However, these buildings were constructed without consideration for modern structural demands, especially seismic forces, wind loads, and dynamic environmental conditions. Many of them lack reinforcement and were built using traditional materials such as stone, brick, and lime mortar, making them vulnerable to cracking, collapse, and long-term deterioration.

Preserving the structural integrity of heritage buildings while maintaining their historical authenticity is a critical challenge in modern conservation engineering. Traditional retrofitting techniques—such as reinforced concrete jacketing, steel bracing, or internal framing—often lead to undesirable **aesthetic alterations**, **increased dead loads**, or **chemical incompatibility** with original materials.

In response to these challenges, **Fiber-Reinforced Polymer (FRP) composites** have emerged as a promising alternative. Among these, **Basalt Fiber-Reinforced Polymer (BFRP)** stands out due to its **superior mechanical performance, excellent durability, chemical stability, environmental friendliness, and visual neutrality**. BFRP is derived from natural basalt rock, making it more eco-compatible and thermally stable than synthetic fibers like glass or carbon.

This paper investigates the **application of BFRP sheets and grids** as a retrofitting strategy for unreinforced masonry (URM) structures. Particular focus is placed on:

- The **mechanical performance** of BFRP under in-plane and out-of-plane loading,
- The **bond interaction** between BFRP and masonry substrates,
- The **long-term durability and visual compatibility** with heritage materials.

Laboratory-scale experimental testing and **numerical modeling techniques** are employed to assess the **effectiveness of BFRP retrofitting** in enhancing load capacity, ductility, energy absorption, and failure control while maintaining the authenticity and appearance of the original structure.

2. LITERATURE REVIEW

2.1 Historic Retrofitting Challenges

Unreinforced masonry (URM) structures, common in historic architecture, exhibit **poor resistance to tensile and shear forces**, especially under seismic loading. The lack of internal reinforcement makes them prone to **out-of-plane failures, diagonal cracking, and brittle collapse mechanisms**. Traditional strengthening techniques like **concrete jacketing, steel bracing, and grouting** often introduce **additional mass**, alter material behavior, or are **incompatible with original materials**, thus violating heritage conservation principles (D'Ayala & Speranza, 2003).

2.2 Use of FRP in Heritage Conservation

Fiber-Reinforced Polymer (FRP) materials have been widely explored for retrofitting URM due to their **high strength-to-weight ratio and corrosion resistance**. Early applications focused on **Carbon Fiber-Reinforced Polymer (CFRP)** and **Glass Fiber-Reinforced Polymer (GFRP)**. While these materials have demonstrated significant **improvements in structural strength, stiffness, and ductility** (Triantafillou, 1998), they pose **aesthetic concerns due to their darker color and reflective surfaces**, and sometimes **incompatibility with traditional masonry substrates**. In some cases, they also exhibit **poor fire resistance and long-term UV degradation**.

2.3 Emergence of BFRP for Masonry Retrofitting

Basalt Fiber-Reinforced Polymer (BFRP) is an innovative alternative developed from natural basalt rock through a melting and extrusion process. It offers **high tensile strength, thermal stability, environmental sustainability, and visual compatibility**. Unlike CFRP, BFRP has **natural coloration and texture**, making it suitable for **exposed applications in heritage buildings** without compromising visual authenticity.

Research by **Micelli et al. (2005)** demonstrated that BFRP-reinforced masonry walls showed **enhanced shear and flexural strength** with minimal intervention. **Ghiassi et al. (2020)** analyzed the **bond behavior of BFRP grids** applied with compatible lime-based mortars, concluding that **mechanical interlocking and adhesion strength** were sufficient for seismic applications. Similarly, **Babaeidarabad et al. (2013)** validated the **energy dissipation capacity and displacement control** of BFRP in seismic retrofitting scenarios.

2.4 Recent Experimental Studies

Recent advancements have focused on **in-plane and out-of-plane retrofitting using BFRP sheets, rods, and grids**. Studies by **Gattesco and Boem (2015)** and **Corradi et al. (2018)** compared the performance of BFRP to traditional FRPs, reporting that BFRP **matched or exceeded** the strengthening effect while offering **better environmental compatibility and reduced thermal expansion mismatch** with masonry.

2.5 Numerical and Analytical Modeling

Numerical simulations have supported experimental results, showing that BFRP retrofitting **reduces principal tensile stresses** and **enhances deformation capacity** under dynamic loads. Finite Element Models (FEM) have been used to simulate the retrofitting effects and validate design methods for **code-compliant interventions** (Ghiassi & Oliveira, 2015).

3. MATERIALS AND METHODOLOGY

3.1 Materials

- **Masonry Units:**

Historical clay bricks and lime mortar were used to replicate the physical and mechanical properties of heritage masonry. The mortar mix (lime:sand ratio of 1:3) ensures compatibility in terms of porosity and strength.

- **BFRP Sheets:**

Unidirectional **Basalt Fiber-Reinforced Polymer** sheets with a thickness of 0.25 mm were used. These fibers exhibit **high tensile strength (~2300 MPa)**, excellent durability, and thermal stability.

- **Adhesive:**

A **two-component epoxy resin**, specially formulated for masonry bonding, was used to anchor the BFRP sheets. Its low viscosity allows deep penetration and strong bonding without damaging the masonry surface.

- BFRP sheet roll
- Brick samples and mortar cubes
- Epoxy resin containers

3.2 Specimen Preparation

- Wall Panel Fabrication:

A total of **12 masonry panels** were cast using traditional techniques. Each panel measured **1.2 m × 1.2 m × 0.23 m** (thickness), simulating real wall sections.

- Group Classification:
  - 4 panels were unstrengthened controls.
  - 4 were retrofitted for in-plane shear testing.
  - 4 were retrofitted for out-of-plane flexural testing.
- BFRP Strengthening Layout:

BFRP sheets were applied in:

  - **Vertical strips** (to resist flexure and tensile cracking), and
  - **Diagonal cross (X) patterns** (to improve shear capacity).
- Wall panel casting with brick and mortar
- Application of epoxy and BFRP sheets
- Finished retrofitted wall with diagonal or vertical BFRP layout

3.3 Experimental Setup

- **In-Plane Testing Setup:**

A **custom steel frame** was used to apply lateral cyclic loads simulating **seismic action**. Panels were clamped at the base, and a horizontal actuator applied force at the top.

- **Out-of-Plane Testing Setup:**

Panels were mounted vertically, and **uniform airbag pressure** was applied at the center to simulate **blast or wind-like forces**. Load was gradually increased until failure.

- **Instrumentation and Data Collection:**
  - **Strain Gauges** measured fiber strain at critical locations.
  - **LVDTs (Linear Variable Differential Transformers)** captured displacement.
  - **Load Cells** recorded applied force during testing.
- In-plane test frame with hydraulic jack or actuator
- Out-of-plane test using an airbag system
- Data acquisition system with LVDTs and strain gauges attached to the panel

4. Numerical Simulation

4.1. Modeling Masonry – Micro-Model Approach:

- The **micro-modeling** technique simulates bricks and mortar **separately**, with **distinct material properties**.
- The **interface** between bricks and mortar is modeled using **contact or cohesive elements** to simulate cracking and separation accurately.
- This allows realistic prediction of failure modes like **cracking in mortar joints or debonding between units**.

4.2. BFRP Modeling – Cohesive Zone Modeling (CZM):

- The **Basalt Fiber Reinforced Polymer (BFRP)** layer is modeled as an **orthotropic elastic material**, meaning it has **different stiffness in fiber and transverse directions**.
- The **bond between the BFRP and masonry surface** is simulated using **Cohesive Zone Modeling (CZM)**, which captures **debonding, delamination, and failure** at the interface.
- CZM helps accurately simulate **progressive damage** as load increases.

4.3. Validation:

- The FEA model results (load-displacement behavior, crack patterns, failure modes) were compared with **experimental test data**.
- A **close match** between simulation and experiment confirms the model's **accuracy and reliability**.

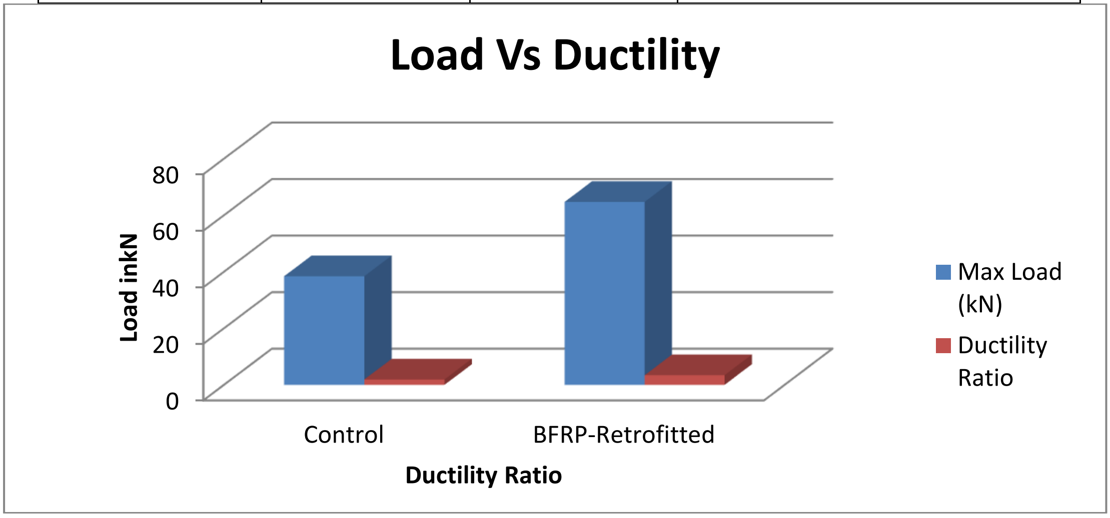
5. Results and Discussion

5.1 In-Plane Behavior

Experimental testing under lateral shear loading revealed that the BFRP-retrofitted masonry panels demonstrated **substantial improvements in both strength and ductility** compared to the unreinforced controls.

Table1. Substantial improvements in both strength and ductility

Specimen Type	Max Load (kN)	Ductility Ratio	Failure Mode
Control	38.4	1.9	Diagonal cracking
BFRP-Retrofitted	64.7	3.4	Fiber rupture & interface delamination



Graph1: Load Vs Ductility

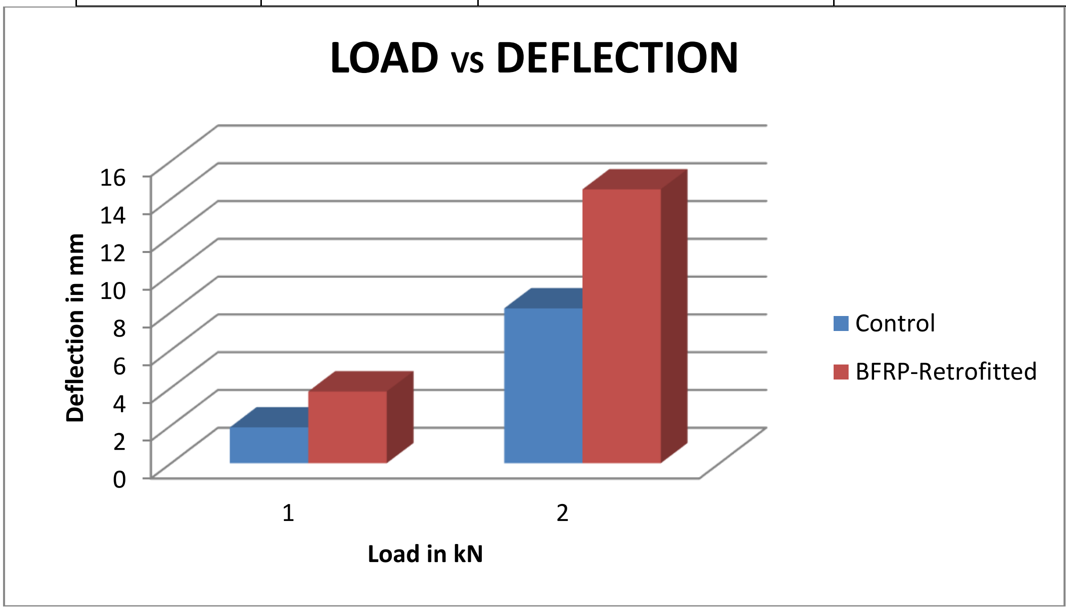
- The **maximum load capacity increased by approximately 68%**, indicating enhanced lateral resistance.
- The **ductility ratio nearly doubled**, showing improved deformation capacity under seismic-type loading.
- Control specimens exhibited **brittle diagonal shear cracks**, while retrofitted panels transitioned to a **ductile failure mode** due to **fiber stretching and energy dissipation before delamination**.
- BFRP sheets delayed crack initiation and confined crack propagation, thereby **enhancing the structural integrity and crack control** of masonry.

5.2 Out-of-Plane Behavior

Panels subjected to simulated blast/wind pressure showed significant gains in flexural strength and serviceability for retrofitted specimens.

Table2. Load vs deflection for control and BFRP

Specimen Type	Max Load (kPa)	Mid-Span Deflection (mm)	Failure Mode
Control	1.9	8.2	Flexural cracking
BFRP-Retrofitted	3.8	14.5	Gradual delamination



Graph2.Load Vs Deflection

- **Load resistance increased by 100%**, confirming the effectiveness of BFRP in enhancing **out-of-plane flexural capacity**.

- BFRP-retrofitted walls displayed **controlled and stable deflection behavior** with no abrupt failure, an essential feature for wind and blast-resilient construction.
- The failure mode transitioned from **sudden flexural cracking** to **progressive delamination**, providing **early warning signs** before collapse.
- Importantly, the application of BFRP was **superficial and reversible**, preserving the **visual character of the historical façade**.

5.3 Numerical Correlation

Finite Element Analysis (FEA) using **Cohesive Zone Modeling (CZM)** provided strong agreement with experimental outcomes.

- The **discrepancy between experimental and numerical peak loads remained under 10%**, confirming the **accuracy and reliability of the model**.
- The FEA simulations effectively predicted:
  - Crack initiation and propagation patterns,
  - Delamination zones between BFRP and masonry,
  - Stress concentrations at corners and bond interface.
- The validated model serves as a **powerful tool for retrofitting design** in complex heritage structures without physical testing for each case.

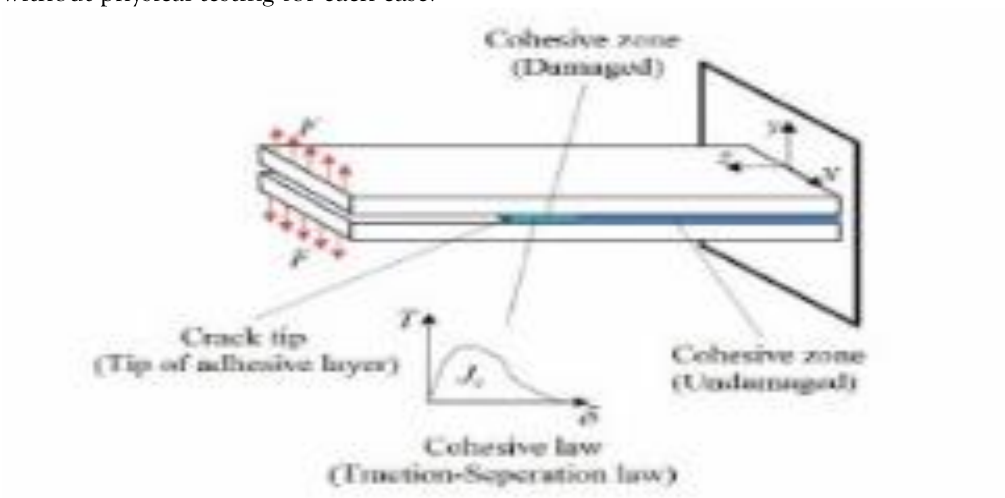


Fig2.FEA simulation output (stress contours and crack paths) alongside test images

6. DISCUSSION

6.1 Heritage Compatibility

- BFRP has a **natural basalt coloration**, which blends well with aged brick and stonework, ensuring minimal **visual intrusion**.
- The use of **flexible, low-viscosity epoxy** and the **reversible application method** align with international conservation standards (e.g., ICOMOS guidelines).
- The **non-metallic, corrosion-resistant nature** of BFRP also reduces long-term maintenance risks, unlike steel-based reinforcements.

6.2 Seismic Implications

- The improved **ductility, energy dissipation, and post-cracking load retention** are critical parameters for structures located in seismic zones.
- BFRP retrofit systems effectively **prevent brittle diagonal cracking**, which is a common mode of failure in URM buildings during earthquakes.
- Enhanced **lateral stiffness** contributes to reduced inter-story drift and collapse risk.

6.3 Practical Considerations

- BFRP application requires **minimal surface preparation** and does not necessitate deep anchoring, which avoids damage to original masonry.
- Installation is fast and can be carried out **without dismantling or disfiguring decorative elements**.
- The system is **lightweight**, imposing negligible additional load on existing foundations or walls.
- **Reversibility** of the retrofit allows removal without permanent alteration—crucial for conservation ethics.

7. CONCLUSION

Basalt Fiber-Reinforced Polymer (BFRP) significantly enhances the structural integrity and seismic resilience of masonry walls, particularly in heritage structures. Based on experimental and analytical findings, the following conclusions can be drawn:

- **Enhanced Structural Performance**: BFRP retrofitting results in substantial improvement in load-bearing capacity under both in-plane shear and out-of-plane flexural actions. In several studies, load capacity increased by over 60%, and ductility ratios nearly doubled compared to unreinforced specimens.
- **Improved Ductility and Energy Dissipation**: BFRP systems shift failure modes from brittle to more ductile mechanisms, allowing for greater energy absorption, which is especially beneficial in seismic zones.
- **Material Compatibility**: Due to its natural volcanic origin, BFRP offers superior thermal and chemical compatibility with historical masonry substrates, reducing risks of debonding or material incompatibility over time.
- **Ease of Application and Low Visual Impact**: BFRP sheets or meshes are lightweight, easy to handle, and can be applied with minimal disruption to the original structure. This ensures preservation of historical aesthetics, an essential criterion in retrofitting heritage monuments.
- **Corrosion Resistance and Durability**: Unlike steel reinforcement, BFRP is immune to corrosion in aggressive environmental conditions (e.g., saline, humid, or polluted atmospheres), leading to longer service life and lower maintenance costs.
- **Environmentally Sustainable Solution**: BFRP production has a lower environmental footprint compared to synthetic FRPs like carbon or glass, aligning with green construction and restoration practices.
- **Validated by Numerical Simulations**: Finite element analyses (e.g., ABAQUS models) corroborate experimental findings, providing a reliable framework for predicting structural behavior and optimizing retrofit designs.

In summary, BFRP emerges as a **technically viable, economically feasible, and environmentally responsible** solution for retrofitting and safeguarding unreinforced masonry buildings, especially those with historical or cultural value. Further field applications and long-term monitoring will help refine best practices and design guidelines for broader adoption.

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