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FROM RUIN TO A QUANTITATIVE RETROFITTING AND RESTORATION OF GRANITE COLUMNS AT HERMOPOLIS MAGNA, MINIA, EGYPT

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Abstract
This study focuses on the quantitative retrofitting and restoration of granite columns at Hermopolis Magna in Middle Egypt, addressing a gap in stone conservation. The study introduces a practical, tested solution for rejoining massive, scattered granite columns using a combination of diagnostic tools, structural analysis, and material characterization. It employs a multidisciplinary approach to assess suitable materials and mechanical strategies for reinforcing fractured stone elements, specifically in the context of the Basilica Church at the El-Ashmonein archaeological site. This site, affected by environmental factors like flooding and seismic activity, serves as an ideal case study for exploring sustainable retrofitting methods for vulnerable and displaced heritage structures.

Keywords: *Heritage conservation; Column retrofitting; Stone reassembly; Structural reinforcement; El-Ashmonein; Hermopolis Magna*

Introduction

The preservation and conservation of heritage structures are important aspects of cultural heritage management. Among the various structural components of historical buildings, columns are essential to both the aesthetic and functional duties of these monuments. Due to their prominent role in carrying loads, columns are particularly vulnerable to degradation over time, whether due to environmental factors, material fatigue, or previous inadequate interventions [1], [2]. In this regard, fractures and damage to columns in heritage structures not only threaten the stability of the building but also compromise its historical and cultural importance [3], [4].

The field of retrofitting fractured columns and reassembling heritage structures has gained a little considerable attention for quantitative solutions for interventive conservation. The retrofitting work involves strengthening and restoring the original structural stability of a component without altering its historic character. In this sense, this process typically includes the repair and rejoining of fractured elements to preserve the authenticity of the structure while improving its load-bearing capacity as well. In addition, different methods and materials have been explored to achieve effective and minimally invasive retrofitting solutions, ensuring that the interventions do not obscure the original fabric of the structure [5].

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An in-depth diagnosis of the fractured columns is essential before retrofitting to determine the causes, extent of damage, and material characteristics. For this, various diagnostic techniques are used to assess the structural behaviour of columns in heritage buildings. Common methods include visual inspection, laser applications, finite element anaylsis, ultrasonic pulse velocity (UPV) testing, ground penetrating radar (GPR), acoustic emission monitoring, X-ray and ultrasonic tomography, and endoscopic examinations [6], [7], [8]. These diagnostic tools help identify cracks, voids, and other internal damages that may not be visible on the surface. One of the most commonly used methods for identifying the extent of column fractures is the ultrasonic pulse velocity test. This technique allows for the measurement of the propagation speed of sound waves through the material, which is indicative of the material's homogeneity and density. For example, in columns made of stone or concrete, a reduced velocity of sound waves can indicate areas of weakness, such as fractures, voids, or deterioration of the material [9], [10], [11]. In the same context, Sarhosis et al. [12] employ the Discrete Element Method (DEM) to investigate the seismic response of ancient freestanding columns, particularly multi-drum configurations with dry ancient joints. Using numerical simulations performed in UDEC and 3DEC, the models account for large displacements, rotations, contact interactions, and potential detachment between drums. The results reveal that the dynamic stability of the columns is highly sensitive to ground motion frequency, joint friction, and initial geometric imperfections. Collapse mechanisms observed include rocking, sliding, and toppling, often occurring at lower acceleration thresholds than previously estimated by analytical models. In addition, Komodromos et al. [13] studied the seismic behavior of ancient multi-drum columns using custom-developed Discrete Element Method (DEM) software, capable of simulating rocking and sliding interactions between individual column drums under harmonic and earthquake excitations. Furthermore, numerical simulations were complemented by small-scale shake table experiments for qualitative validation. The study performed extensive parametric analyses, varying peak ground acceleration, excitation frequency, number of drums, and friction coefficients. Finally, the research indicates that higher excitation frequencies lower the threshold for initiating rocking or sliding, while columns are especially vulnerable to collapse under low-frequency excitations.

Retrofitting fractured columns in heritage structures is not without its challenges. For this, one of the primary concerns is maintaining the authenticity of the original structure. In this regard, interventions must ensure that any retrofitting work and technique can be done without damaging the original materials. Additionally, the materials used for retrofitting must be compatible with the existing column to avoid issues such as differential expansion, which can lead to further damage [14]. Another challenge in the retrofitting or rehabilitation process is the need to adhere to strict conservation guidelines [15], [16], [17]. Many heritage buildings are protected by law, and interventions must comply with regulations set forth by heritage protection organizations. This often limits the use of modern materials and techniques, which can be more effective but may not align with the guidelines for preserving the historic character of the building [18].

In supporting and restoring modern and ancient concrete columns, Eskandari-Naddaf et al. [19] used ETABS and MATLAB software to develop a cost-effective and safe retrofitting plan for corrosion-damaged reinforced concrete columns, considering externally bonded steel plates and concrete jacketing with various concrete compressive strengths. The study analyzed 30 retrofitting designs, revealing that while both methods are effective in certain situations, externally bonded steel plates are more suitable for the identified construction problems. The results emphasize the importance of considering safety factors in corroded structures to achieve optimal retrofitting designs. In the same context, Kaliyaperumal and Sengupta [20] investigated the flexural strength and performance of concrete-jacketed columns through a series of tests and analyses. Slant shear tests assessed the interface bond between old and new concrete. Column specimens were tested to determine strength, and beam-column-joint sub-assemblages were examined for ductility and energy dissipation. Analytical investigations, including lamellar approaches and incremental nonlinear analysis, were conducted to predict experimental results and determine the behavior of retrofitted columns. The study provides guidelines for retrofitting columns with concrete jacketing. In addition, Bournas and Triantafillou [21] investigated the effectiveness of textile-reinforced mortar (TRM) as a means of confining old-type reinforced concrete columns with limited capacity due to bar buckling or bond failure at lap splice regions, comparing it with fiber-reinforced polymer (FRP) jackets. Tests on full-scale columns under cyclic uniaxial flexure demonstrated that TRM jacketing effectively increases the cyclic deformation capacity of these columns. For this, TRM jacketing is a promising solution for confining poorly detailed reinforced concrete columns in seismic regions, showing comparable effectiveness to FRP jackets.

Fractured columns, due to their historical and cultural significance, present unique challenges to conservators and engineers working in heritage preservation. Accurate diagnosis, careful selection of retrofitting techniques, and a thorough understanding of material properties are essential for achieving successful and respectful interventions. This study offers one of the first quantitative assessments specifically focused on the reassembly of large archaeological stone fragments, addressing a significant gap in the field of stone conservation. It presents a practical, tested solution for the rejoining of massive, scattered granite columns using a combination of diagnostic tools, structural analysis, and material characterization. The research adopts a multidisciplinary approach to evaluate the most suitable materials and mechanical strategies for reinforcing fractured stone elements, particularly in the context of the Basilica Church at the El-Ashmonein archaeological site (ancient Hermopolis Magna) in Middle Egypt. This site has been heavily impacted by environmental factors such as flooding and seismic activity, making it an ideal case study for exploring sustainable retrofitting methods for vulnerable and displaced heritage structures.

Methodology

The methodology adopted in this study involves a multidisciplinary approach that combines *in situ* diagnostic assessments, laboratory testing, and structural modeling to evaluate the effectiveness of different rejoining bars for fractured granite columns at the archaeological site of El-Ashmonein, Minia, Egypt. The first phase focused on diagnostic investigations using non-destructive techniques to understand the internal condition of the damaged columns. Ultrasonic Pulse Velocity (UPV) testing was employed to assess the degree of internal fracturing and material homogeneity, alongside visual inspection and digital documentation of the column fragments. Physical properties of the granite were also considered, such as compressive strength, elastic modulus, and wave propagation velocities. Four bars were selected for structural rejoining, such as stainless-Steel Grade 304, titanium Grade 2, nylon 6/6 (30% glass fiber), and PEEK (30% glass fiber). Each of these materials was assessed based on mechanical performance (yield strength), corrosion resistance, weight, cost, and long-term compatibility with historical stone substrates. In preparation for the rejoining process, detailed measurements were taken, and holes were drilled into the fractured column sections to house the reinforcement bars. These were bonded using a reversible epoxy adhesive to allow for future disassembly, in line with heritage conservation principles.

The second phase of the methodology included structural simulations and engineering assessments to verify the efficacy of each bar material under critical load conditions. Finite element models and analytical calculations were used to evaluate the performance of the retrofitted column under a bending moment of 19 ton·m and a shear force of 6.3 tons, which represent typical mechanical factors acting on the base of a standing column. Two structural checks were conducted: 1) a shear friction check to determine whether the bars could resist lateral forces at the joint interface, and 2) a tensile stress check to evaluate their capacity under flexural loads. Calculations of the required reinforcement area were performed for each material type, considering a safety factor of 0.45 applied to the yield strength. The SP Column software was used to model stress distribution across the retrofitted joint and determine the bar dimensions required to withstand the applied forces. A comparative analysis was then conducted to determine the most suitable bar material based on strength-to-weight ratio, ease of installation, visual impact, and compatibility with conservation ethics. This methodological approach ensures that the recommended retrofitting solution is not only structurally viable but also aligns with the best practices in archaeological conservation and serves as a future guideline for the stone reassembling process.

This study is based on an unpublished chapter from my master's thesis titled "Geo-environmental and Seismic Response Analysis of Free-Standing Stone Columns at El-Ashmonein Archaeological Site-Minia, Egypt. With Practical Applications for Restoration and Preservation." In this paper, extended interpretations and comprehensive design approaches have been applied, incorporating broader analytical perspectives and updated methodological frameworks.

Results and discussion

Bars selection and their properties

Four selected bars were tested and evaluated for rejoining the scattered granite columns in the El Ashmonein archaeological site, Minia, Egypt. The first bar type is stainless steel grade 304. Stainless steel is widely used in structural applications due to its excellent corrosion resistance, high tensile strength, and good ductility [22]. With a yield strength of 240 MPa, it provides sufficient structural stability for retrofitting applications, particularly in environments prone to moisture and oxidation [23]. However, stainless steel has a higher density, which may increase the overall weight of the retrofitted column. The second selected bar for testing is titanium grade 2. Titanium is known for its high strength-to-weight ratio, corrosion resistance, and durability. With a yield strength of 275 MPa, it offers superior performance compared to stainless steel while being significantly lighter [24]. This makes it a favorable option for retrofitting historical structures where weight reduction is a priority. However, titanium is more expensive, which could be a limiting factor in large-scale applications. In addition, Nylon 6/6 (30% Glass Fiber) was also selected for assessment as a joining bar. In this regard, nylon reinforced with glass fiber provides a lightweight alternative to metal reinforcements. With a yield strength of 158 Mpa, it is considerably weaker than both stainless steel and titanium but offers excellent flexibility and resistance to chemical degradation [25]. This material might be suitable for less critical applications or when preserving the aesthetic integrity of historical structures is a concern. However, its long-term durability under heavy loads needs further evaluation. Lastly, PEEK (30% Glass Fiber) was tested and assessed, and it is considered an advanced polymer with exceptional mechanical and thermal properties [26]. With a yield strength of 172 MPa, it surpasses nylon in strength while maintaining lightweight and corrosion-resistant properties. PEEK is commonly used in aerospace and medical applications, demonstrating its reliability in demanding environments [27]. Its use in retrofitting would be advantageous in cases where non-metallic reinforcement is preferred. However, the cost of PEEK is higher than traditional materials, which could be a limitation for large-scale implementation.

Joining bars assessment for interventive conservation

Structural retrofitting is an important technique used to enhance the stability and longevity of historical and modern columns, especially when they have undergone severe damage or deterioration that led to scattering of the columns (Fig. **1**A-C).

Fig. 1. (A-C) the columns exhibit various types of damage, including surface erosion from weathering, mechanical breakage and fragmentation of shafts and drums, biological deterioration from surrounding vegetation, structural instability leading to displacement and toppling, and potential foundation issues causing uneven settling and misalignment

In this particular case, the indicated retrofitting method involves using reinforcement to reconnect the separated parts of a granite column with a height of 9.70 cm and a diameter of 140 cm (Fig. 2A and B). In addition, the elastic modulus of the granite is 2950 MPa. The compressional wave velocities are 2090 m/s and 2667 m/s, and the shear wave velocities are 1960 m/s and 2380 m/s [28]. The process entails drilling four holes in the fractured sections, filling them with an adhesive bonding material (such as epoxy) and inserting reinforcement bars to secure the two parts together. This technique aims to restore the column's strength and ensure its long-term stability under structural loads. One of the most vulnerable areas of a column is its bottom portion, as it experiences the highest straining action due to axial loads, bending moments, and shear forces [29], [30], and this is especially important in historical or ancient columns, where material degradation over time can further weaken the base (Fig. **1**). In this regard, the proposed retrofitting and interventive method must therefore be capable of withstanding these forces and maintaining the column's stability under both static and dynamic loads.

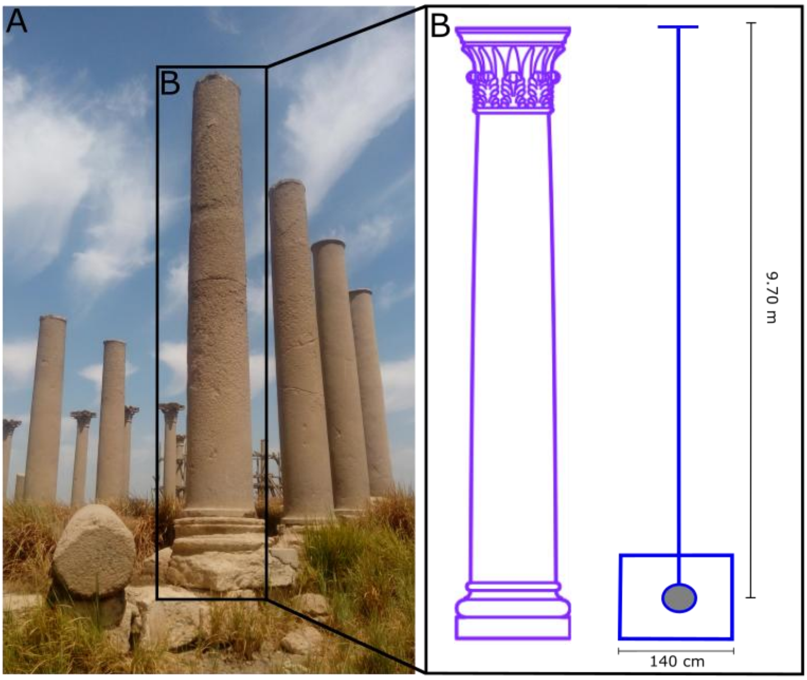

Fig. 2. The standing damaged scattered granite column at the El-Ashmonein archaeological site, Minia, Egypt (A). The section and plan of a column and its dimension (B)

To verify and validate the effectiveness of this retrofitting approach, several structural checks were conducted. These assessments included material testing, stress analysis, and load-bearing capacity evaluation. The primary goal was to determine whether the inserted bars and epoxy bonding could sufficiently restore the column's load-bearing capability and prevent further displacement or failure at the joints. For this, a variety of materials were considered for the reinforcement bars to determine their suitability for use in this retrofitting method. The tested materials included 1) stainless steel grade 304, 2) titanium grade 2, 3) Nylon 6/6 with 30% glass fiber, and 4) PEEK (polyether ether ketone) with 30% glass fiber. Each of these materials has distinct mechanical properties, particularly in terms of yield strength, which is an important factor in ensuring the stability of the retrofitted column. In this context, Figure 3 summarizes the yield strength values for these evaluated materials.

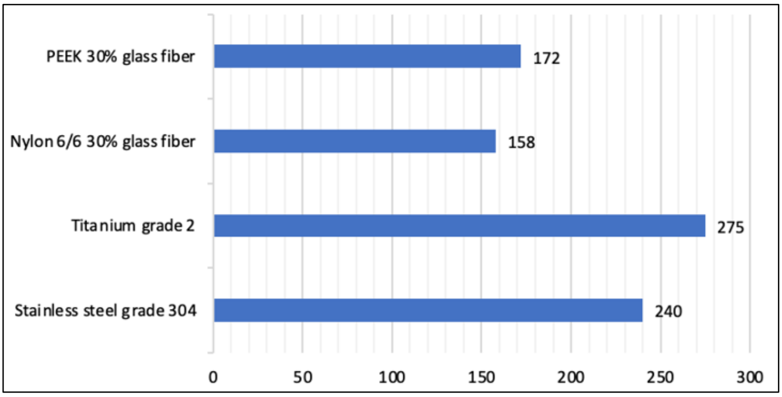

Fig. 3. Yield strength (MPa) values for the tested materials as jointers for scattered granite

Retrofitting the column under flood risk Load conditions and structural assessment

Ensuring the stability and safety of a retrofitted column requires careful consideration of the forces acting upon it, especially under extreme loading conditions such as flooding. Flooding at the archaeological site was one of the most important factors for structural damage. In structural assessment, two primary structural checks were conducted to validate the effectiveness of the proposed retrofitting method and jointers' materials. These include a shear friction check to determine whether the inserted reinforcement bars can safely resist the shear forces acting on the critical section of the granite column. On the other hand, check tensile stress in bars due to bending moments to verify that the selected reinforcement bars can sustain the tensile stresses induced by bending moments. The retrofitted column has been subjected to a bending moment of 19 ton.m and a shear force of 6.3 tons at its most critical section, which is at the bottom due to maximum straining actions. The effectiveness of different bar materials in handling these forces was examined, with a particular focus on stainless steel (grade 304) and titanium (grade 2), which exhibited superior structural performance.

In this context, the primary goal of the shear friction check is to confirm that the reinforcement bars inserted into the retrofitted column can effectively resist the applied shear force. The shear friction capacity depends on the mechanical properties of the selected material, particularly its yield strength, as well as the bond strength provided by the epoxy. The required cross-sectional area of the bars was calculated using the following formula (Fig. 4):

$$A_{bars} = \frac{V_{ultimate}}{0.45 \times \mathrm{f_y}}$$

where: A_{bars} = Required reinforcement area (cm²); V_{ultimate} = Ultimate shear force (tons); f_y = Yield strength of the reinforcement material (MPa); 0.45 is a safety factor applied to the yield strength

From this analysis, it is evident that stainless steel grade 304 and titanium grade 2 require significantly smaller bar areas compared to fiber-reinforced polymer (FRP) materials such as nylon and PEEK. This is due to their higher yield strength, which allows for efficient load distribution with fewer or smaller bars. In addition, and based on the shear friction check, stainless steel grade 304 and titanium grade 2 are the most suitable materials for the reinforcement bars, as they require the least cross-sectional area, thereby minimizing material usage and potential drilling damage to the column.

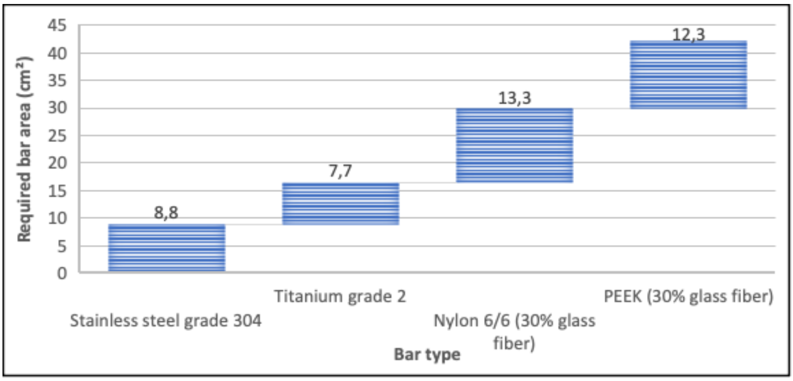

Fig. 4. Required bar area due to shear friction check

Moreover, the second structural check focuses on the tensile stresses induced in the reinforcement bars due to the bending moment at the critical section of the column. The bending moment in this case is 19 ton·m, and it must be resisted effectively by the inserted bar to prevent failure. To determine the required reinforcement area, SP Column Software was utilized to simulate the stress distribution within the retrofitted column. The software accounts for the elastic behavior of materials, ensuring an accurate estimation of the necessary bar cross-section.

This analysis further reinforces the advantage of using stainless steel grade 304 and titanium grade 2, as they require significantly smaller bar areas compared to Nylon and PEEK. The higher yield strength of these metals allows them to handle bending-induced tensile stresses with fewer and smaller reinforcement bars. In this context and due to their superior mechanical properties and lower required reinforcement area, titanium grade 2 and stainless-steel grade 304 are the most suitable materials for resisting bending moments in the retrofitted column (Table 1). The results from both the shear friction check and the tensile stress check indicate that stainless steel grade 304 and titanium grade 2 are the most effective materials as reinforcement bars for restoration (Table 2).

Table 1. Required bar area due to bending moments

Material	Required bars area (cm^2)	Number and size of bars
Stainless steel grade 304	32.16	4 ϕ 32
Titanium grade 2	25.00	4 ϕ 32
Nylon 6/6 (30% glass fiber)	45.00	4 ϕ 40
PEEK (30% glass fiber)	38.00	4 ϕ 40

Table 2. Evaluation criteria of bars selection for interventive conservation process

Evaluation Criteria	Stainless Steel Grade 304	Titanium Grade 2	Nylon 6/6 (30% Glass Fiber)	PEEK (30% Glass Fiber)
Yield strength (Mpa)	240	275	158	172
Shear friction required area (cm^2)	8.8	7.7	13.3	12.3
Bending moment Required area (cm^2)	32.16	25.00	45.00	38.00
Recommended bar size	4 ϕ 32	4 ϕ 32	4 ϕ 40	4 ϕ 40
Weight (Density Factor)	Moderate	Low	Very Low	Very Low
Cost factor	Moderate	High	Low	High

Comparison with other retrofitting method and global examples

The proposed method of drilling, bonding, and reinforcing with bars is not the only technique available for column retrofitting. Other common approaches include Steel Jacketing method, where steel plates or casings are wrapped around the column to enhance its strength. This is commonly used in seismic retrofitting but may alter the historical appearance of ancient structures. In addition, the FRP (Fiber Reinforced Polymer) wrapping method is a noninvasive technique where composite materials like carbon or glass fiber wraps are applied to provide additional tensile strength. This method is effective for increasing ductility but may not be ideal for severe structural fractures. The grouting and injection method involves injecting cementitious or polymer-based grout into the material to restore the resistance. While useful for filling voids, it does not provide the same level of reinforcement as embedded bars.

"Anastylosis" is a term derived from the Greek word meaning “restoration” or “re-erection of columns" and refers specifically to the process of reconstructing a ruined structure by reassembling its original, surviving components [31]. Over time, the term has come to signify a particular methodology within architectural conservation, one that focuses on the precise reintegration of dismembered architectural elements, typically in cases involving dry masonry, stone blocks, or timber-frame constructions. It is generally not applied to monolithic or bonded structures such as mortared brick walls, where disassembly and accurate repositioning of original components is less feasible or less historically appropriate. As a highly specialized form of restoration, anastylosis seeks to recover the spatial, aesthetic, and historical legibility of a ruined structure, reinstating its lost original form to the greatest possible extent. This is achieved by using the original materials that are still available on-site and are in a condition suitable for reintegration. When conducted properly, anastylosis respects the authenticity of the structure, avoids conjecture, and refrains from introducing excessive new material or modern interventions that could distort the historical narrative. The process must be guided by archaeological, architectural, and historical evidence. Decisions regarding placement, orientation, and connection of fragments must be based on firm documentation and scholarly consensus. Where original components are missing or incomplete, the introduction of new materials should be minimal and clearly distinguishable upon close inspection, ensuring that the intervention remains both legible and reversible. International conservation charters, such as the Venice Charter (1964) and guidelines established by UNESCO and ICOMOS, recognize anastylosis as the preferred method of structural reassembly, especially in the context of World Heritage Sites [32]. In such sensitive and historical contexts, in some cases, it is considered the only acceptable form of reconstruction method, as it balances the goals of structural stabilization, historical fidelity, and visual comprehensibility, all while safeguarding the authenticity and integrity of cultural heritage.

Santos et al. [5] applied the ties and lateral confinement method as effective techniques for column restoration. These measures often involve wrapping the structure with metallic sheets or advanced composite materials such as Carbon Fiber Reinforced Polymer (CFRP), Glass Reinforced Concrete (GRC), and similar reinforcements. The optimal choice among these techniques depends largely on the specific conditions of the structure, including its materials, geometry, and degree of damage and displacement. In another common scenario, particularly with unstable architectural elements like towers and chimneys, structural strengthening can be achieved by applying horizontal ties, typically using steel strips or tensioned cables, to prevent outward displacement or collapse. Alternatively, these elements can be encased or wrapped with bonded composite materials like CFRP or GRC, which provide added tensile strength and improve resistance against seismic or wind-induced forces.

Retrofitting was performed on some of the ancient columns of the Pantheon (Rome, Italy) using stainless steel and titanium reinforcements to maintain structural stability while preserving historical authenticity. This highlights the effectiveness of metal reinforcements in restoring ancient structures. The structural retrofitting using non-metallic materials such as PEEK and fiber-reinforced polymers has been explored in Greek temples, including the Parthenon (Athens, Greece), to minimize the visual impact while ensuring long-term durability. Furthermore, in contemporary buildings and bridges, reinforcement bars of stainless steel and titanium are frequently used to strengthen structural components that experience high stress. These applications demonstrate the feasibility of using similar materials in column retrofitting for both historical and modern structures.

Bansal [18] discussed the retrofitting of historic buildings, focusing on the structural retrofitting methods used in the Hearst Greek Theatre in California as a different case study. The retrofit strategy can be approached through two main concepts: 1) the exposed retrofit concept and 2) the concealed retrofit concept. The Exposed Retrofit Concept (ERC) involves reinforcing the exterior of the colonnade by installing steel walers, struts, and frames anchored of the rear stage wall, providing visible structural support. In contrast, the Concealed retrofit concept (CRC) aims to preserve the visual integrity of the structure by integrating reinforcement within the existing architectural elements. This method entails detachment, removal, and replacement of the existing stage to construct a new concrete mat foundation supported by micropiles, along with the addition of internal reinforcement within the columns [33]. In this case, drilling holes for epoxy-anchored dowels was tested for the restoration of the historic colonnade with extreme caution.

Conclusion

The conservation of fractured columns in heritage structures represents a delicate balance between structural rehabilitation and the preservation of historical authenticity. This study demonstrates that retrofitting ancient columns, particularly those composed of massive granite, requires a holistic methodology, one that integrates diagnostic investigation, material science, and engineering principles. Through detailed assessment of the column's condition using non-destructive techniques such as ultrasonic testing, combined with knowledge of the physical properties of the stone, a clear understanding of the structural weaknesses was established. These inputs guided the design of a retrofitting intervention that respects the historical value of the site while ensuring structural stability. The process of drilling, bonding with epoxy, and inserting rejoining bars offered an interventive approach option and adhered to the international standards of cultural heritage conservation.

The comparative analysis of four different reinforcement materials of Stainless-Steel Grade 304, Titanium Grade 2, Nylon 6/6 (30% glass fiber), and PEEK (30% glass fiber) highlighted the complexities involved in selecting suitable materials for such interventions. While metallic options like stainless steel and titanium exhibited superior mechanical performance, particularly in yield strength and resistance to shear and tensile stresses, they also came with higher weight and cost considerations. On the other hand, polymer-based alternatives offered lighter and potentially less visually intrusive solutions, though with trade-offs in mechanical capacity and long-term durability. Structural assessments under bending and shear loads confirmed that both titanium and stainless steel required smaller bar cross-sections and offered higher reliability in supporting the retrofitted column under dynamic and static conditions. These results provide practical data that bridge the gap between theoretical conservation strategies and their real-world applications, particularly in archaeological contexts where empirical, field-tested solutions are often lacking.

Ultimately, this research contributes to an initial step toward quantitative and scientifically grounded approaches in the field of architectural conservation, particularly for reassembling and stabilizing fragmented stone elements. The proposed method and materials not only ensured the mechanical functionality of the reconstructed granite column but also preserved the archaeological durability of the site. In doing so, this study serves as a model for future conservation projects involving fractured or displaced stone elements, especially in regions exposed to environmental factors like flooding or seismic activity. Moreover, the documentation and engineering evaluation presented in the paper can inform policy and guidelines for cultural heritage authorities and conservation professionals, enabling more informed decision-making. As heritage conservation continues to evolve with technological advancement, it is important to integrate empirical data, structural modeling, and ethical conservation principles to safeguard historical structures for future generations.

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