Proceedings of the 3rd Croatian Conference on Earthquake Engineering - 3CroCEE
19–22 March 2025, Split, Croatia

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.49

OVERVIEW OF THE DEVELOPMENT, APPLICATION AND CHALLENGES OF NATURAL FIBER REINFORCED CEMENTITIOUS MATRIX (NFRCM)

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Abstract

Technological development in construction has brought significant advances in the application of materials, particularly composites such as fiber-reinforced polymers (FRP) and textile-reinforced concrete (TRC). These materials are widely used due to their excellent mechanical properties, including high strength and low weight, making them suitable for the refurbishment of damaged structures and the development of new building systems. However, they face challenges such as instability at high temperatures, which can lead to their degradation. In addition, the production of FRP and TRC often involves chemical processes that can have harmful effects on the environment and human health, raising questions about their sustainability and environmental impact.

In response to these challenges, current research is focusing on the development of natural composites, in particular the Natural Fiber Reinforced Cementitious Matrix (NFRCM). These composites use natural fibers as reinforcement in cementitious matrices, reducing the environmental impact while maintaining similar mechanical properties to conventional materials. NFRCMs represent a sustainable alternative to chemically produced materials, and their application can significantly reduce the impact of the construction industry's impact on the environment and human health.

This review aims to synthesize existing knowledge on NFRCMs, evaluate their advantages and limitations relative to conventional composites, and critically examine current research in the field. Particular attention is given to the challenges associated with the development of new matrices based on natural materials, including the evaluation of their mechanical properties and durability. The paper provides an overview of current materials and reinforcement processes using natural fibers, identifies key areas requiring further research and improvement, and offers guidelines for future research and development activities.

Keywords: NFRCM, TRM, FRP, Natural composites, Mechanical properties, Strengthening, Bridging, Ecological

1. Introduction

The development of society brings with it an ecological awareness and the need for sustainable development. Integrating sustainability principles into all sectors, particularly construction, is essential for future advancements. Extending the service life of buildings is one of the most pressing challenges for sustainability in construction, with the potential to prolong the usefulness of both new and historic structures. As a rule, retrofitting and reconstruction must be in line with conservation guidelines and environmental standards.

Many residential areas worldwide are located in seismically active areas. Table 1 shows the earthquakes in Croatia, highlighting the region's seismic activity [1]. Considering the fact that seismic activity can lead to disasters, as was the case in Turkey and Syria in 2023, Japan in 2011, Haiti in 2010, etc., new buildings need to be built according to modern standards. Additionally, inspections and retrofitting of existing buildings are necessary. Most historic buildings were built of natural stone or

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brick, usually without strong mortars or similar binders. However, due to architectural features such as arches, thick walls, and small openings, many of these historic structures are still in use today. Extensive research has focused on retrofitting historic buildings, as detailed in [2–7], with Fig. 1 showing a clear upward trend in publications on masonry strengthening from 2000 to 2023. Over the past four decades, this research has led to the development of numerous principles and materials for structural retrofitting, including micro-reinforced mortars, meshes, fibers, and various composite solutions.

Table 1. The strongest earthquakes in Croatia from the 17th century to 2021 [1]

Date	City	Magnitude (M_L)	Intensity (°MCS)
April 6th 1667.	Dubrovnik		IX-X
November 9th 1880.	Zagreb		VIII
July 2nd 1898.	Trilj		IX
October 8th 1909.	Pokuplje	5.8	VIII
March 12th 1916.	Vinodol	5.8	VIII_
March 27th 1938.	Novigrad Podravski	5.6	VIII
December 29th 1942.	Imotski	6.2	VIII-IX
January 11th 1962.	Makarska	6.1	VIII-IX
April 13th 1964.	Dilj Gora	5.7	VIII
September 5th 1996.	Ston-Slano	6.0	VIII
March 22nd 2020.	Zagreb	5.5	VII
December 29th 2020.	Petrinja	6.2	VIII

Reinforcement techniques remain crucial to advancements in construction, necessitating ongoing research to develop innovative concepts and broaden their practical applications.

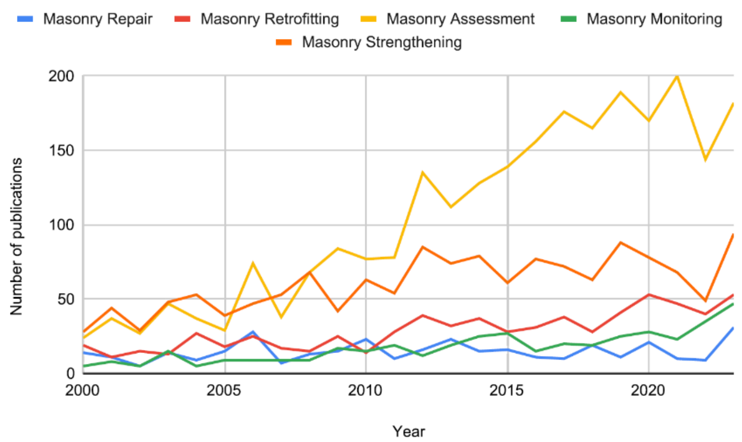

Figure 1. Presentation of the representation of works published from 2000 to 2023 that contain words in the title ''Masonry Repair'', ''Masonry Retrofitting'', ''Masonry Assessment'', ''Masonry Monitoring'', and ''Masonry Strengthening''[8]

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With the increasing emphasis on environmental sustainability, the focus is on awareness of the impact of materials on human health. Currently materials such as basalt and glass fibers, carbon tape, and polymer resin are widely used in retrofitting and research [9–13]. Although these materials are widely used, they are synthetic and pose significant challenges in terms of their environmental impact and end-of-life disposal. As a sustainable alternative, composite materials based on natural fibers, such as flax, hemp, sisal, and viscose, are gaining popularity in structural repair [14–20]. Beyond their ecological benefits, the use of natural fibers could have a transformative effect on global economic structures. The economic and ecological benefits of using natural fibers are discussed in [21]. India, for example, which currently has an underdeveloped timber industry, could potentially establish itself as a leading exporter of natural fibers on the world market. This paper presents a comprehensive review of previous research and experimental tests on natural fiber-based composites for retrofitting and repair in the construction industry. It also provides an objective comparison of the mechanical properties of natural fiber-based composites with those of synthetic composites, highlighting their potential as sustainable solutions.

2. Fibers, Matrices and Composites in the Construction Industry

The combination of the matrix and fibers creates a composite material. A composite material consists of a matrix that is either inorganic or chemically processed, strengthened by embedded fibers. The main task of the matrix is to transfer the load to the fibers and bind them together. The most common inorganic matrices include cement-based or hydraulic lime mortars, while chemically synthesized matrices often involve epoxy resins. Unreinforced matrices, especially inorganic ones, are prone to brittle failure due to crack propagation after initial cracking. This challenge has led to the development of composite materials. Fibers are thin filaments introduced into the matrix to improve the mechanical properties. Fig. 2 shows the classification of fibers, partially based on categorizations presented in [22,23]. The most commonly used natural fibers in the construction industry are flax, sisal, viscose, coir, cotton, banana, and hemp, among others. Synthetic fibers such as carbon, steel and plastic, on the other hand, are processed chemically.

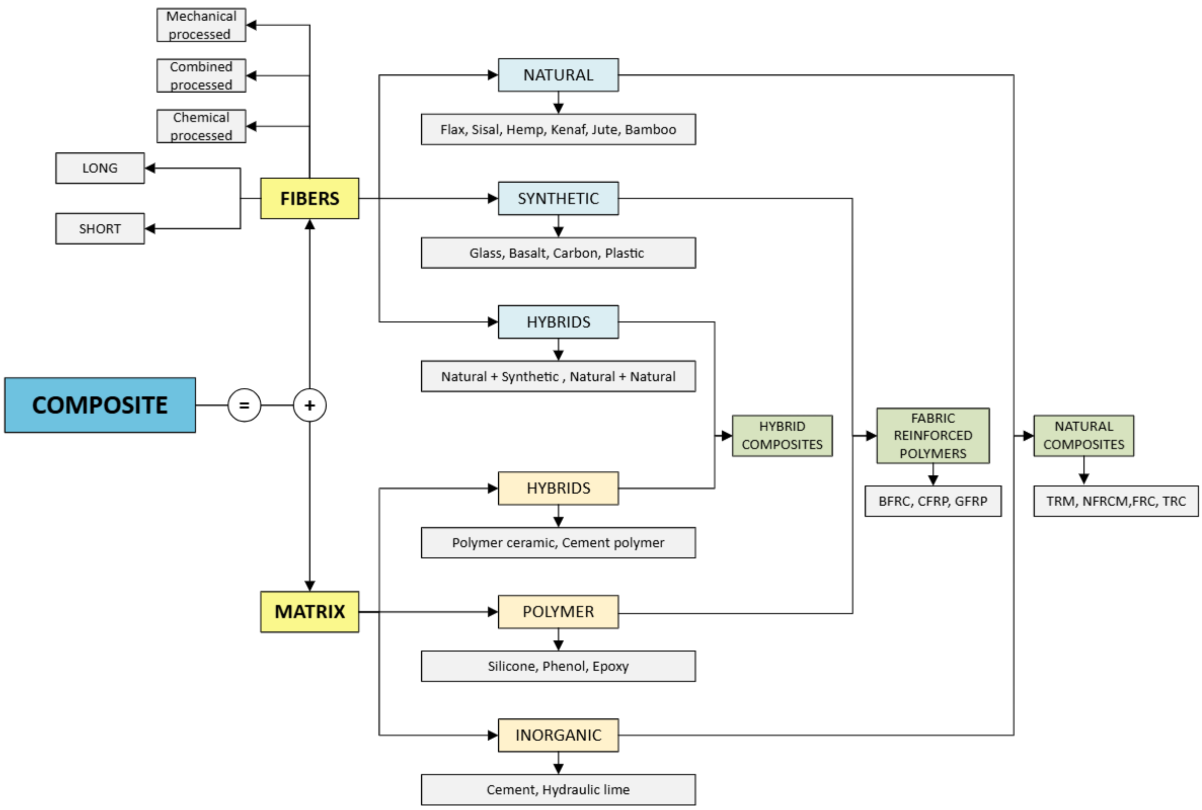

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Figure 2. Classification of the composites

The optimization of synthetic fibers has resulted in high tensile strength, low weight, and versatile applications in structural repairs. These fibers are designed to be resistant to corrosion and chemicals proving beneficial across industries such as construction [24], automotive [25], and aerospace [26]. Their production involves chemical processes that ensure stable pricing and consistent availability. The disadvantages of these fibers include susceptibility to high temperatures, decreased permeability in construction, and suboptimal adhesion to bonded surfaces. Furthermore, controlling the distribution and orientation of fibers in micro-reinforced mortars is crucial, as it significantly affects mechanical behavior and failure patterns. Brittle failure is typical for composites with lower fiber content, whereas ductility depends on the fiber amount and spatial distribution, as shown in [27]. On the other hand, natural fibers have high tensile strength and low weight, along with a mesh structure aiding load distribution in orthogonal planes. In addition, they are viable and environmentally friendly with better adhesion and enhanced breathability in construction compared to their synthetic counterparts. Research [28] demonstrated that the use of natural fibers can reduce total construction weight by 10% and production energy requirements by 80%, thereby cutting CO_2 emissions significantly. Ultimately, the most important fact is that work environments with natural fibers have no negative impact on human health. However, natural fibers have inherent limitations, such as susceptibility to biodegradation, thermal limits (around 200 °C for most fibers), pest attacks, and UV-induced deterioration [29].

Additionally, the quality and availability of natural fibers vary with seasonal and climatic factors, causing annual price fluctuations. The global material representation reflects cost trends, although different quantities are required for equivalent performance. Therefore, material cost should not be the sole determinant in overall economic assessments. For example, Fig. 3, based on [21] shows a cost comparison for fibers achieving a tensile load resistance of 100 kN.

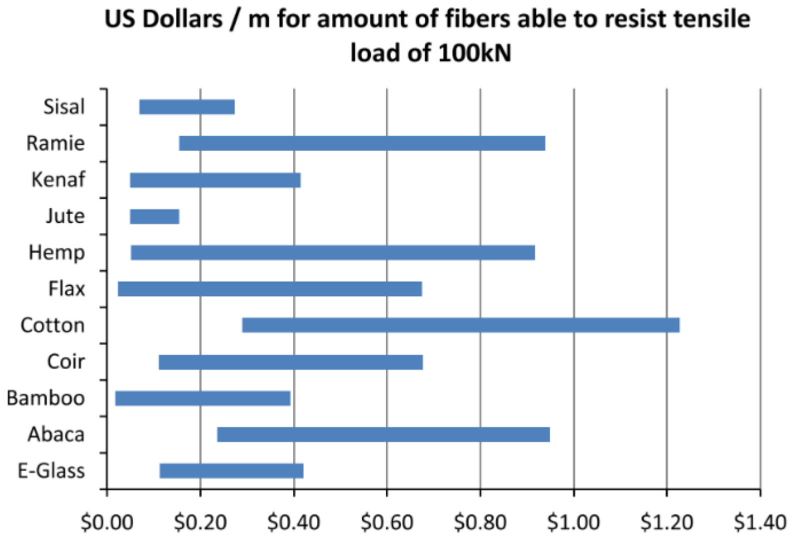

Figure 3. Cost comparison of fibers per unit length [21]

2.1. Selection of Composite

Selecting the optimal combination of fibers and matrix materials can significantly improve both the mechanical properties and durability of composite materials. Fig. 2 illustrates the structural configurations of different composite systems. However, challenges such as fiber length, geometry, and surface adhesion with the matrix remain and require further study. The texture and chemical composition of fibers may impair adhesion at the fiber-matrix interface. (For instance, natural fibers degrade when exposed to alkali in cement-based matrices (C). As a result, composites with a natural hydraulic lime (NHL) matrix show superior resistance, as demonstrated by experimental data [30]. The effects of C

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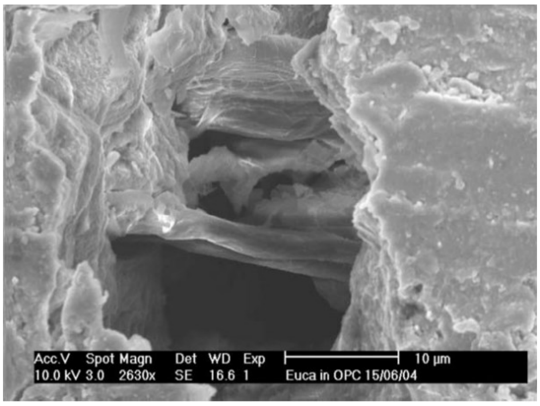
and NHL matrices on fiber durability were studied in [31]. It was found that fibers embedded in cement matrices exhibited lower durability than fibers embedded in hydraulic lime matrices, leading to significant variations in experimental results. The alkali-induced degradation of fibers in composites can be minimized using fiber impregnation techniques. For example, flax fibers impregnated with curaua fibers reduced the crack width by 20% in tensile tests. Impregnated fibers show better performance due to improved adhesion and a more gradual failure mode, as shown in [32]. The failure mode of a composite depends on its fibers; after an initial crack occurs due to the matrix's limited tensile strength, fibers assume the load-bearing role, deform significantly, and stop crack propagation through "bridging" [33]. Surface adhesion can also be improved by modifying fiber geometry or length. Pull-out tests, as described in [34], have shown that triangular, hollow, and circular cross-sections improve mechanical properties by increasing the force required to dislodge fibers. Moreover, [35] concluded that the performance of Steel Fiber Reinforced Concrete is heavily influenced by the bond between fibers and the concrete matrix. Insufficient fiber length can cause fiber pull-out, diminishing load transfer efficiency. Conversely, optimal fiber length reduces concrete shrinkage and postpones initial cracking [22]. Bonding is often improved by treating fibers mechanically, chemically, or with a combination of methods. As reported in [22] these treatments fall into physical, chemical, or hybrid categories. Treatment intensity is critical since excessive treatment can weaken fibers' mechanical properties [23]. It was also found that mechanical or drying treatments have minimal impact on composites' mechanical properties. Similarly, the fiber-to-matrix ratio is a key determinant of composite performance. In [36], adding 1% curaua fibers by mass improved mortar flexural strength but reduced workability. Raising fiber volume fractions can lower composite compressive strength due to higher pore volume and uneven fiber distribution [22]. Moreover, adjusting fiber content can reduce shrinkage by up to 70%, although it increases surface cracks and decreases their average width.

In summary, the selection of a high-performance composite is an iterative process that involves the optimization of the matrix and fiber combination, supported by experimental testing to verify their mechanical properties and behavior. By varying the matrix and fiber types, several composite variants with distinct properties are developed. The structure of composites varies, and [37] provides a classification based on strengthening systems, such as wet lay-up, prefabricated, and specialized systems. Fiber Reinforced Polymers (FRP) are further subdivided into Glass Fiber Reinforced Polymers (GFRP) and Carbon Fiber Reinforced Polymers (CFRP), which are typically homogeneous composites consisting of short fibers embedded in a polymer matrix. Furthermore, Textile Reinforced Mortars (TRM) are systems composed of an inorganic matrix (e.g., cement or hydraulic lime) reinforced with a knitted mesh of natural fibers. Modern natural composites include Textile Reinforced Concrete (TRC), Textile Reinforced Mortars (TRM), Fabric Reinforced Cementitious Matrix (FRCM), and Natural Fiber Reinforced Matrix (NFRCM).

a)



b)

Figure 4. a) Bridging effect [38], b) Application of TRM [39]

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3. Experimental Testing of Composites for Application in Construction

To understand the systems and approaches for strengthening structures, it is important to recognize the possible failure modes. Structural collapse can result from global instability or in-plane shear of walls subjected to significant horizontal loads [37], as well as from local failure of the weakest structural element. The characteristic failure modes of masonry are detailed in [40], concluding that diagonal cracking is typical under moderate compressive forces, whereas stepped cracking occurs in masonry subjected to tensile stresses perpendicular to the face planes and along multiple horizontal planes. Planar failure, on the other hand, results from exceeding the principal tensile stresses within the component. Failure of composite reinforcements can occur within the composite matrix, at the interface between the reinforcement and the substrate, or through fracture of the base material of the structure. To ensure the suitability of a specific composite for application, its effect on the mechanical properties of masonry must be demonstrated through comparisons with unreinforced specimens. To ensure reliable and reproducible results, tests should be conducted on samples with uniform geometric characteristics and boundary conditions. Standardized test methods and guidelines are outlined in various international standards. Test protocols for masonry that comply with European standards can be found on the official website of the Croatian Standards Institute [41]. Croatian standards provide parameters for evaluating of masonry specimens under compression, out-of-plane bending, and shear resistance. For tensile resistance, commonly assessed through diagonal compression tests, studies have primarily adhered to RILEM or ASTM standards [42].

A detailed review of prior experimental research is presented in the following sections, offering critical insights into the state-of-the-art in this field.

3.1. Testing Shear Resistance and Bonding of Composite

Structural reinforcements commonly used in construction today possess significantly higher tensile strength than those of the base structure. For example, unreinforced masonry has a tensile strength of less than 1.0 MPa, while carbon fiber meshes exhibit a tensile strength of approximately 3500 MPa and glass fiber meshes of about 1500 MPa. Failure typically occurs at the interface between the masonry surface and reinforcement, highlighting the importance of determining whether the full potential of the reinforcement can be effectively utilized. To evaluate bond strength, the pull-off test is most commonly used, as it is indirectly correlated with the shear strength between the reinforcement and the base material. Numerous studies have been conducted on this topic [43–47], with variations in matrix composition, fiber types, or loading methods. Furthermore, in [31] it was demonstrated that the high stiffness of PBO (polyparaphenylene benzobisoxazole) fibers relative to the substrate causes delamination of the composite from the substrate. Additionally, it was concluded that flax fibers enhance ductility, causing crack formation in the matrix before delamination from the structure.

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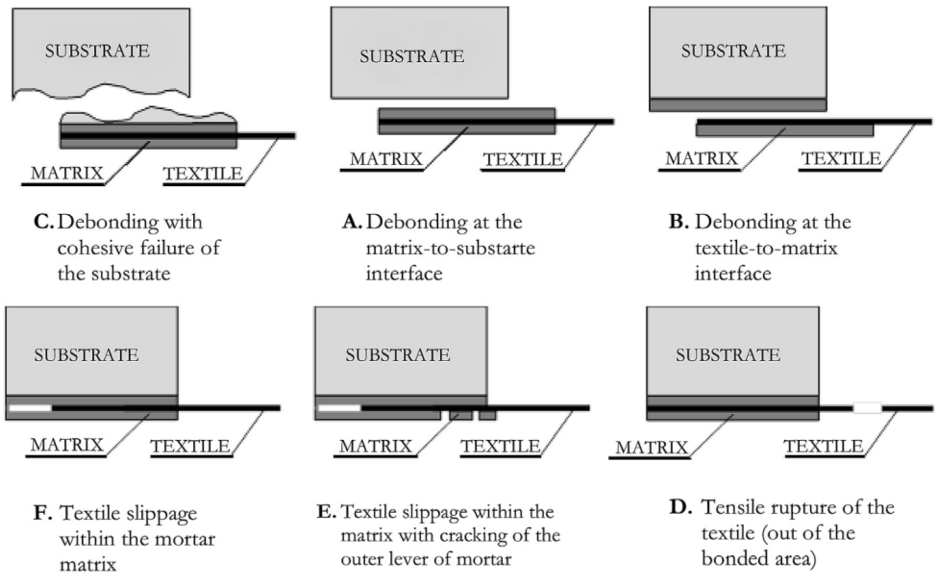

Figure 5. Failure modes of composites subjected to shear testing [48]

3.2. Experimental Testing of Out-of-Plane Bending Resistance

Failure at the interface between the reinforcement and the structure is not the only mode of failure for composites. In [49], experimental tests on reinforced concrete slabs and beams demonstrated various failure modes of composites, such as fiber sliding through the mortar, debonding of the reinforcement from the substrate, partial debonding of the reinforcement from the substrate, and cracking of the TRM due to bending exposure. The same study [49] identified two types of delamination at the concrete-reinforcement interface in concrete beams: from the middle towards the ends and from the ends towards the middle. These failure modes highlight the importance of properly anchoring the reinforcement to prevent premature, ensuring the activation of composite fibers under load. Additionally, bending tests perpendicular to the plane and the comparison of reinforcement contributions to unreinforced specimens were presented in [50–53]. In [54], 27 samples were tested using a simplified procedure to observe out-of-plane bending of walls. In [55] was demonstrated that the use of FRP reinforcement increased bending resistance by 2.5 times, significantly reducing deformability and enhancing structural performance.

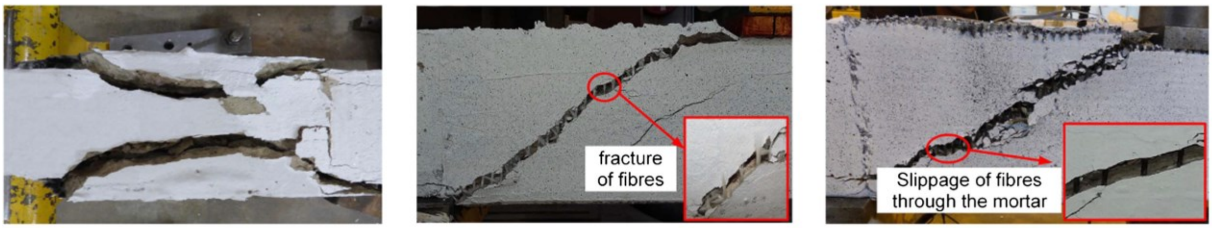

Figure 6. Failure modes of samples subjected to bending load [49]

3.3. In-Plane Testing (Compressive Loading and Diagonal Test)

Diagonal tests are a commonly used technique in experimental research to evaluate the mechanical properties of masonry structures. Specimens subjected to diagonal tests may fail due to exceeding either shear or tensile stresses. Consequently, direct tensile testing of composite materials often precedes diagonal testing to better understand their mechanical behavior. Research presented in [56] investigates the tensile behavior of composites under load, with Fig. 7 illustrating the failure mechanisms identified.

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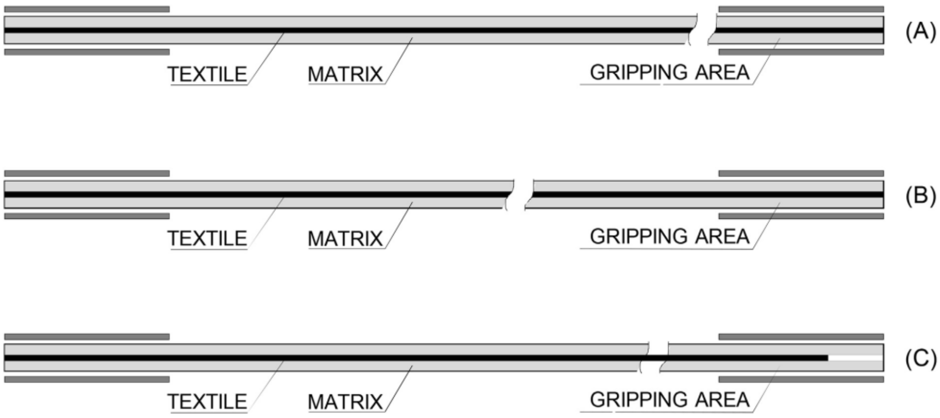

Figure 7. Failure modes of composites subjected to direct tensile testing: (A) tearing failure near the grip surface of the sample, (B) failure at the center of the sample due to exceeding the tensile strength, and (C) slippage of the textile at the grip surface without tensile failure

The failure mechanisms identified in these tests have led to various terminologies in the literature, including terms such as "diagonal shear test," "diagonal tensile test," and "diagonal compressive test," the latter reflecting the specific loading conditions applied during the test. The diagonal test has served as the basis for numerous comparisons and conclusions regarding the contribution of natural-material composite reinforcements to structural performance in masonry. For instance, experimental results in [57] demonstrate that the failure mode of the sample is influenced by factors such as the type of masonry unit (solid bricks of standard format or hollow blocks), mortar strength, and the reinforcement approach (unilateral or bilateral). In [58], a combined analytical and experimental analysis was conducted following RILEM guidelines and certain Italian recommendations. Results from these diagonal tests showed that the load-bearing capacity of samples reinforced with natural-material meshes increased twofold relative to unreinforced ones. Interestingly, there was no significant difference in the load-bearing capacity between samples reinforced with one layer versus two layers of reinforcement. Diagrams further indicated that failure of reinforced elements was not catastrophic, as the fibers within the reinforcement were able to sustain load after initial cracking. In tests conducted on adobe bricks using the diagonal method, it was concluded that the ductility of the masonry primarily depends on the tensile strength of the elements located in the central part of the wall [59]. Additionally, research on masonry samples reinforced with flax fabric and lime-based hydraulic mortar revealed that the composite exhibited ductile behavior in post-peak phase, regardless of the sample configuration [60]. Compression testing, alongside diagonal testing, is one of the most frequently used in-plane evaluation techniques for masonry structures. Compression stresses are ever-present in masonry, either due to self-weight or additional loads, making it critical to monitor stress levels resulting from these forces. In reinforced masonry, failure under in-plane compressive loading occurs when the tensile stresses in the composite fibers exceed their capacity, preventing the propagation of cracks within the structure [61]. Full utilization of textile-reinforced mortar (TRM) fibers occurs only when failure propagates through them [49]. In [62], tests were performed on reinforced and unreinforced masonry samples subjected to compressive loads parallel and perpendicular to the mortar joints. Results indicated that compression parallel to the bed joints leads to brittle failure, producing a single compressive strength value in this direction. Conversely, a relatively linear relationship between axial strain and compressive stress was observed in the perpendicular direction up to approximately 50% of the ultimate load.

These findings collectively highlight the effectiveness of diagonal testing as a diagnostic tool for understanding the mechanical behavior of masonry, particularly when enhanced with natural-material reinforcements. Further, the integration of analytical and experimental approaches offers a robust framework for advancing sustainable and resilient construction practices.

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4. Conclusion

In addition to the widely used synthetic fibers such as steel, glass, carbon, basalt and plastic, natural fibers such as flax, jute, sisal, viscose and cotton are also gaining importance in scientific research. Current findings underline the great potential of natural fiber composites in the construction industry. They offer advantages such as high mechanical performance, rapid biodegradability and environmentally friendly disposal at the end of their service life. To maximize their structural benefits, it is crucial to carefully select the fiber types, optimize their treatment processes and combine them with suitable matrix materials. However, there are still some challenges. Key areas for improvement include enhancing the fiber-matrix interface and improving fire and weathering resistance to meet the stringent requirements of the construction sector. Future research must focus primarily on standardized testing of mechanical properties in compliance with relevant guidelines to establish natural fiber composites as viable, sustainable alternatives to synthetic materials. The use of natural fibers in construction offers additional socio-economic benefits. It promotes the industrial development of underrepresented regions, improves living standards and boosts the local economy. Furthermore, its integration is in line with global efforts to reduce the environmental and health risks associated with synthetic composites. The further development of natural fiber composites requires a multidisciplinary approach. Planned experimental studies will provide crucial insights into their performance in the reinforcement of masonry and provide a basis for reliable and scalable applications. By overcoming these challenges, the construction industry can move towards more sustainable, resilient and environmentally friendly practices.

5. Acknowledgements

This work has been supported through project *"Development of a new technology for strengthening masonry structures with construction quality certification"* [IP.1.1.03.0109], project co-financed by the Croatian Government and the European Union through the European Regional Development Fund-the Competitiveness and Cohesion Operational Programme.

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