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# Comparative Study on Externally Bonded Heat-Treated Jute and Glass Fiber Reinforcement for Repair of Pre-cracked High Performance Concrete Beams

Lysa BENADDACHE<sup>1</sup> | Ahmed Abderraouf BELKADI<sup>1</sup>, Oussama KESSAL<sup>1</sup>, Amirouche BERKOUICHE<sup>1</sup>, Ammar NOUI<sup>1</sup>, Salima AGGOUN<sup>2</sup>, Tarek CHIKER<sup>2,3</sup>, Taher TAYEBI<sup>4\*</sup>

<sup>1</sup>LMSE Laboratory, Department of Civil Engineering, Mohamed Elbachir Elibrahimi University, Bordj Bou Arreridj, Algeria

<sup>2</sup>CY Cergy Paris Université, L2MGC, F-95000 Cergy, France

<sup>3</sup>ESITC, Higher School of Engineering for Construction Works, France

<sup>4</sup>Mechanical Engineering Department, Faculty of Sciences and Technology, University Mohamed El Bachir El Ibrahimi of Bordj Bou Arreridj, Algeria

\*Correspondent author email: [tahartayebi@gmail.com](mailto:tahartayebi@gmail.com)

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# Comparative Study on Externally Bonded Heat-Treated Jute and Glass Fiber Reinforcement for Repair of Pre-cracked High Performance Concrete Beams

## Abstract

The adoption of natural fiber reinforced polymer (FRP) composites as an eco-friendly substitute for synthetic FRPs in structural strengthening applications is gaining substantial momentum. This study delves into the effectiveness of jute fabric reinforced epoxy composites in bolstering the flexural strength of impaired concrete beams. An array of variables, encompassing the number of fabric layers (ranging from 1 to 3), fiber heat treatment, externally bonded reinforcement (EBR) configuration (soffit vs. U-shape), and fiber type (jute vs. glass), underwent systematic scrutiny. The comprehensive analysis of 30 pre-cracked high-performance concrete beams yielded compelling findings. In particular, the application of heat-treated jute EBR, especially when employing two or three layers, resulted in significant increases in peak loads, translating to improvements ranging from 85% to 120% when compared to the control beam. This treatment significantly improves the bond between the fibers and the matrix, consequently enhancing the structural performance. Notably, jute composites can attain equivalent strengthening performance compared to glass FRP while offering substantial cost savings and significantly reducing carbon emissions, rendering them a more environmentally sustainable and economically viable choice.

## Key words

Concrete beam, reinforcement, jute fiber, heat-treatment, carbon footprint

## 1. Introduction

Glass fiber reinforced polymer (GFRP), carbon fiber reinforced polymer (CFRP), and aramid fiber composites are the primary materials utilized for reinforcing concrete structures [1]. However, it's essential to recognize that these composite materials come with significant environmental implications [2]. In the context of the ongoing shift towards more environmentally friendly structures, the composite industry is increasingly exploring the integration of natural fibers reinforced polymer (NFRP) into composite matrices, including fibers like flax, jute, or sisal [3]. Within the realm of sustainable development, a promising avenue involves tapping into the potential of jute fibers reinforced polymer (JFRP), which already find applications in various sectors such as aerospace and wind energy [4]. JFRP presents favorable mechanical properties, including notable strength and sufficient stiffness, positioning them as potential candidates for substituting synthetic fibers reinforced polymer (SFRP) in composite materials [5]. It has been introduced to the market as a promising alternative option for composite reinforcements, particularly glass fiber [6]. However, resins used for exterior concrete structural reinforcement must demonstrate optimal adhesion to both the concrete and reinforcement fibers, as well as proven resistance to weather conditions [7].

Research has been conducted on composites made from flax fiber reinforced polymer (FFRP) to investigate their properties. The findings from François Duc et al. [8] and Ben Ameer et al. [9] indicate that FFRP-based composites exhibit superior damping behavior in flexural fatigue tests compared to

CFRP. According to Di Luccio et al. [10], FFRP composites demonstrate an excellent energy dissipation capacity surpassing CFRP, especially in applications requiring ductility. A comprehensive comparative study conducted by Wenjie Wang and colleagues [11] analyzed the impact behavior of flax and glass-confined concrete composites. This study revealed that confining ordinary concrete with FFRP provides similar effectiveness to GFRP-confined concrete and that FFRP-reinforced material is less sensitive to deformation [12].

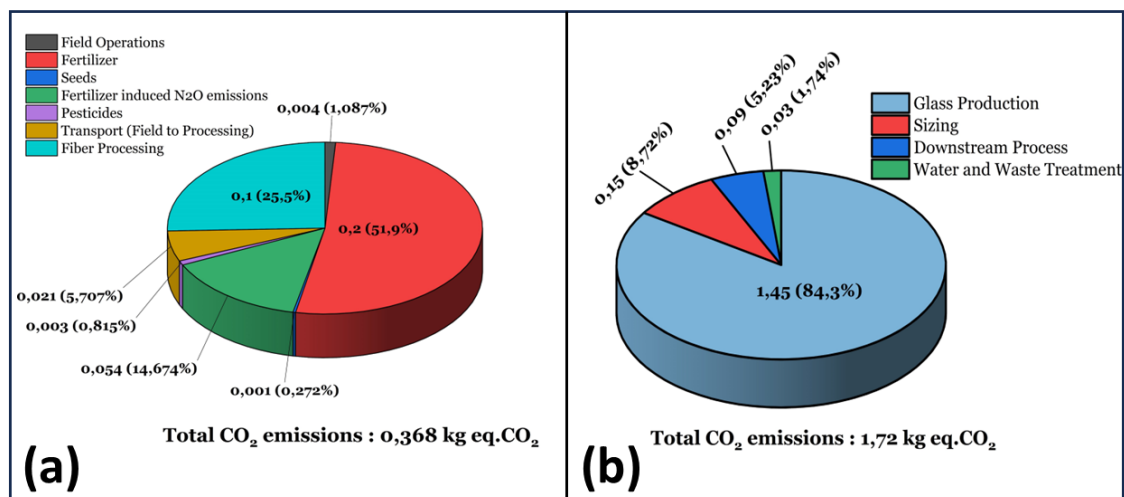
In addition, other researchers have explored the feasibility of FFRP and JFRP composites for external reinforcement of concrete structures, highlighting promising results in terms of flexural strengthening capacity [13]. E. Ferrier et al., [14] conducted a comparative study on the shear behavior of reinforced concrete beams using FFRP and CFRP, the results showed that FFRP exhibits a mechanical capacity equivalent to CFRP. Similarly, Yooprasertchai et al. [15] noted that columns reinforced with two layers of JFRP exhibited ductility levels similar to those of CFRP-reinforced columns.

In order to assess the feasibility of substituting SFRP with NFRP in external structural reinforcement, Cheng Chen and al. [16] established that the use of 8 layers of FFRP achieved reinforcement effects similar to those obtained with only two layers of CFRP. According to the work of A. Abdulla and al. [17], an improvement of 45%, 62%, and 71% was observed for beams reinforced with 2, 4, and 6 layers of JFRP laminates, respectively.

However, it is important to note that the efficiency of natural composites (cellulose, hemicellulose, and lignin) strongly depends on the adhesion between the fibers and the matrix [18]. Additionally, the thermal stability of natural fiber composites plays a crucial role in their mechanical properties [19]. As a result, surface modification methods and physical and chemical treatments have been developed and used for the production of NFRP [20]. One of the most commonly used physical treatments is heat treatment [21]. Y. Cao and al. [22] employed alkaline, enzymatic, and steam treatments at different temperatures to treat flax fibers and examined their effects on adhesive bonding. The results reveal that alkaline treatment and enzymatic treatment can significantly improve the thermal stability of flax fibers, while steam treatment does not affect the thermal stability. Research on the impact of heat treatment on NFRP composites has revealed improvements in thermal stability and mechanical properties, resulting from the removal of moisture, waxy layers, and other surface impurities [23]. As a result, heat-treated natural fibers develop enhanced mechanical properties and significant adhesion [24].

The findings from A. Azadeh and al. [25] showed that exposing bamboo fibers (BFRP) to a temperature of 175°C for 24 hours increased compressive strength by nearly 30%. In a similar line of research, Cui et al. [26] examined the tensile strength, modulus of elasticity, fracture modes, and micromechanical properties of cell walls in the fibers. The outcomes confirmed those of A. Azadeh and al. [25], demonstrating that the modulus of elasticity of BFRP increases with increasing temperature, and there is a positive correlation between the modulus of elasticity and the hardness of the bamboo fiber cell wall. Heat treatment's influence on the mechanical attributes of JFRP has been the focus of recent investigations by T. Voravutvityaruk et al [27]. Their research illuminated a significant improvement in the compressive strength of concrete reinforced with JFRP after subjecting it to heat treatment at 80°C. In concurrence with this investigation, T. Jirawattanasomkul et al. [28] determined that the optimal heat treatment conditions for jute fabric were achieved at 80°C for a duration of 24 hours. Additionally, Campana et al. [29] performed an investigation to evaluate the effects of heat treatment on the mechanical properties of unidirectional FFRP fabrics after post-curing at temperatures ranging from 100 to 150°C. Their study revealed that at 80°C, flax fibers retained only 5% moisture, with this moisture evaporating at temperatures exceeding 86°C. This observation indicates that 80°C is approximately the curing temperature. However, temperatures exceeding 120°C could result in the degradation of specific components within the cell wall.

Considering its biodegradability and inherent natural qualities, the manufacturing of natural fibers often requires less energy and chemical treatments than that of synthetic fibers. Soil health is improved, and carbon dioxide levels are reduced by the natural absorption of carbon dioxide by jute throughout its growth, for example [30]. On the other hand, the production of glass fibers often involves operations that are energy-intensive, meaning they need greater temperatures and use more resources [31]. Consequently, they leave a relatively bigger carbon footprint and affect the environment. A comparison of CO<sub>2</sub> emissions during production (**Fig. 1**) highlights the environmental impact difference between jute and glass fibers. The comparative life cycle assessment distinctly showcases that biobased jute holds a carbon footprint four times lower than that of glass fiber, attributed to its renewable, low-impact origins.



**Fig. 1** Comparison of carbon footprint: (a) Biobased jute [30], (b) Glass fiber [31].

However, despite the growing interest in the utilization of natural fibers as reinforcement materials in concrete structures, limited research has ventured into exploring the impact of heat treatment on the mechanical properties and adhesion of JFRP as reinforcement materials for damaged reinforced concrete structures. This study aimed to fill this research gap by conducting comprehensive experimental investigations into the effectiveness of jute fabric-reinforced polymer composites applied using various externally bonded reinforcement (EBR) techniques on pre-cracked concrete beams. The primary focus of this research was to evaluate the influence of critical parameters, including the number of fabric plies, heat treatment, wrapping scheme, and fiber type, on the overall structural performance, failure modes, and fiber-matrix bonding behavior. To achieve these goals, an experimental program was conducted on high-performance concrete beams, which were strengthened using both untreated and heat-treated jute fabrics as well as glass fibers. A total of 30 specimens underwent three-point bending tests to characterize their flexural response, ductility, damage tolerance, and load-carrying capacity under various strengthening systems. Through a detailed investigation of the fundamental mechanics and bonding interactions, this research seeks to pave the way for the broader adoption of sustainable jute-based composites as alternatives to synthetic FRPs for structural reinforcement and rehabilitation. The comprehensive experimental dataset allows for a quantitative assessment of how these critical parameters impact key performance metrics compared to unstrengthened and glass fiber-strengthened beams. The findings provide valuable technical insights into the design of durable jute reinforcement solutions for infrastructure engineering applications.

## 2. Materials and methods

### 2.1. Materials

#### 2.1.1. Concrete beams

This study involved the casting of high-performance concrete (HPC) beams, each measuring 400 x 100 x 100 mm. The beam dimensions were taken from prior literature [32]. The HPC was formulated to achieve a target compressive strength of 60.4 MPa at 28 days. It was prepared using several key components, including Portland Cement CEM I/42.5R (with a Blaine fineness of 3400 cm<sup>2</sup>/g and a density of 3.2 g/cm<sup>3</sup>), fine aggregate with a maximum particle size of 5 mm, coarse aggregate with a maximum particle size of 15 mm, water, and silica fume at a proportion of 10% by weight of cement. The silica fume possessed a Blaine fineness of 8755 cm<sup>2</sup>/g and a density of 2.2 g/cm<sup>3</sup>. The adjuvant used is a high water-reducing superplasticizer marketed under the name, its density is 1.07 with a dry extract of 30%. The specific mix proportions employed are detailed in **Table 1**. Post-casting, the HPC beams were demolded after 24 hours and subsequently subjected to controlled curing at a temperature of 23 ± 2°C for a duration of 28 days to ensure adequate strength gain and material properties.

**Table 1** HPC formulation

	Cement	Silica fume	Sand (0/5)	Coarse aggregate 3/8	Coarse aggregate 8/15	Water	Superplasticizer
<b>Proportion (kg/m<sup>3</sup>)</b>	406.9	40.6	761.52	356.1	676.22	139.2	5.5

At 28 days, a 30 mm deep x 5 mm wide notch was cut in the center of each beam using a concrete saw to simulate damage [33], as shown in **Fig 2**. The notch was cut perpendicular to the longitudinal axis on the tension side of the beam. Identical notches were cut in all beams to create uniform damage conditions prior to strengthening.



**Fig 2** Notch creation procedure

#### 2.1.2. Composite materials

Jute fabric (230 g/m<sup>2</sup>), epoxy resin, and E-glass fibers were used to strengthen the damaged concrete beams. Prior to application, both treated and untreated jute fabric samples were prepared for experimentation. The untreated jute fabric remained in its original state without undergoing any specific heat treatment. Conversely, the treated jute fabric was subjected to a heating process in an oven at 80°C for 1 hour to enhance bonding between the fibers and the epoxy resin. The microscopic observations (**Fig. 3**) reveal an increase in surface roughness and a reduction in the thickness of jute fibers treated at 80°C compared to untreated fibers. According to Sen et al. [34], this can be attributed to two primary

mechanisms. Firstly, the increase in fiber crystallinity after heat treatment induced by the partial degradation of certain structural components of the walls, especially the hemicelluloses, and to a lesser extent, the lignin. Secondly, the heat treatment causes dehydration of the cellulose walls, resulting in the loss of water present in the amorphous regions. The combination of these two phenomena results in an overall decrease in the volume of the wall, leading to noticeable thinning and increased roughness of the treated fibers at a macroscopic level. The increased surface roughness of the treated jute fibers alters their interaction with the resin matrix. It promotes better adhesion between the fiber/resin, thus improving stress transmission and the efficiency of the composite [35].



**Fig. 3** Microscopic observations on the effect of heat treatment on surface characteristics of jute fibers

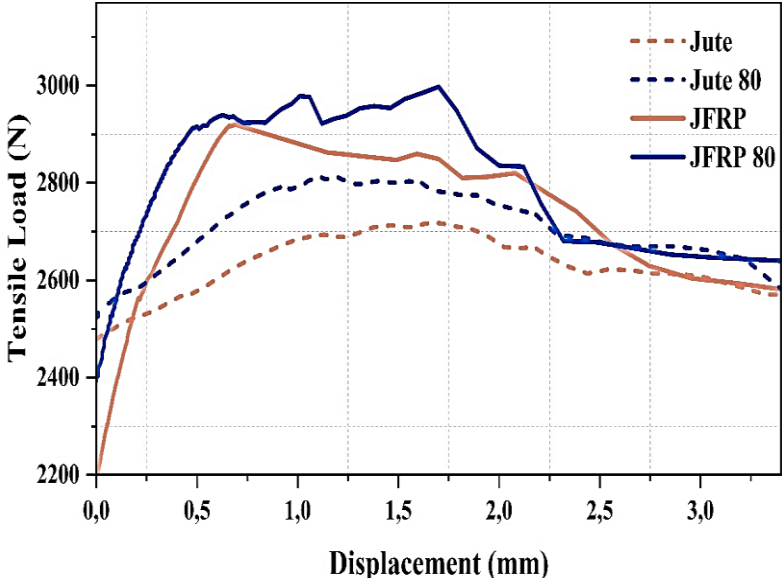
**Fig. 4** depicts the experimental setup of the tensile strength test conducted on jute fibers and JFRP. The test, performed in accordance with ASTM standards [36], shows the mechanical behavior of the fibers and the composites under tension.



**Fig. 4** Experimental setup of tensile strength test of jute fibers and JFRP

The graph (**Fig. 5**) illustrates the mechanical behavior of treated and untreated jute fibers and JFRP under a tensile test. Initially, all configurations demonstrate a linear relationship between the load and displacement, indicating an elastic behavior consistent with Hooke's law. The tensile strengths obtained for treated jute fiber and treated JFRP are respectively 2.8 kN and 2.99 kN, approximately 3% higher than those of untreated jute fiber and untreated JFRP (2.7 kN and 2.92 kN). This is attributed to the

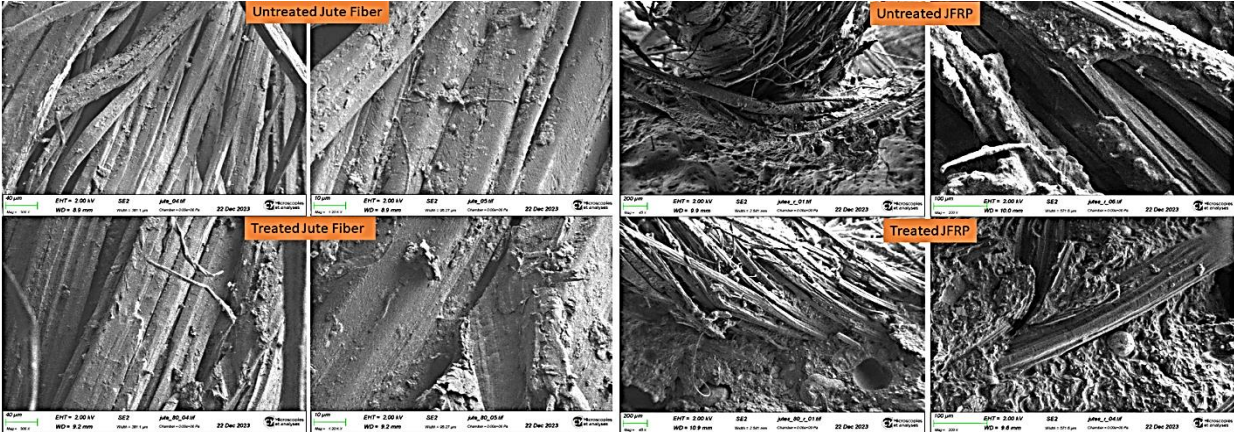
synergistic interaction between the polymer matrix and the plant fibers, as well as the enhanced crystallinity of the cellulose. This observation aligns with the findings from optical microscopy, which show increased roughness, facilitating resin anchorage and load transmission.



**Fig. 5** Mechanical behavior comparison of treated and untreated jute fibers and JFRP in tensile testing

Scanning electron microscopy (SEM) analysis within **Fig. 6** showcased the untreated jute fibers displaying smooth surfaces covered in wax, exhibiting minimal debris and impurities. These fibers demonstrated clean, organized cylindrical structures aligned along the fiber direction. Contrarily, the SEM images of heat-treated jute fibers illustrated notably rougher and more textured surfaces, suggesting the removal of surface wax components. The heating process induced increased micro-porosity and deformations along the fiber length due to wax melting and vaporization.

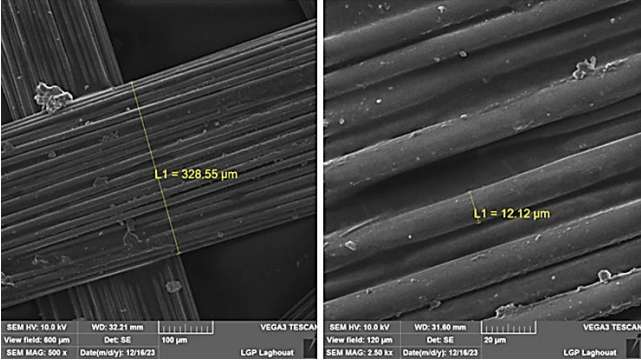
Regarding the untreated JFRP, the SEM analysis revealed evident gaps and limited interfacial bonding between the smooth jute fibers and the surrounding polymer matrix. A clear separation was observed at the interface, indicating insufficient integration of the jute fibers with the polymer phase. Conversely, the SEM image of the heat-treated JFRP composite displayed significantly improved fiber-matrix interfacial adhesion. The treated jute fibers exhibited a roughened, porous surface facilitating robust mechanical interlocking with the polymer matrix, resulting in a unified composite structure with no observable separation or gaps at the interface.



**Fig. 6** SEM analysis of untreated and heat-Treated jute fibers and their corresponding JFRP composites



1 The SEM imaging within **Fig. 7** facilitated detailed observations of the glass fiber cross-sections,  
2 providing precise measurements and characterization of their diameters. Furthermore, Energy  
3 Dispersive X-ray Analysis (EDX) was employed to determine the elemental composition of the glass  
4 fibers, revealing the presence of oxygen (O) at 48.9%, silicon (Si) at 29.3%, calcium (Ca) at 15.7%, and  
5 aluminum (Al) at 6.1% as the major chemical elements detected within the fibers.  
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18 **Fig. 7** SEM characterization of glass fibers.  
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22 **2.2. Reinforcement procedure**

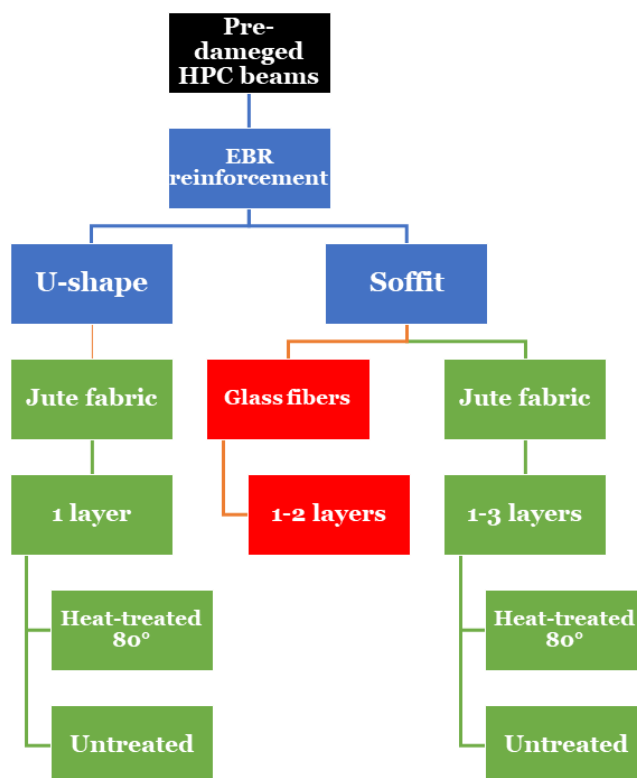
23 The concrete surface was prepared by wire brushing to create a roughened surface for improved bonding.  
24 Any dust was removed using compressed air [37]. For the EBR strengthening [38], the fabric sheets  
25 were cut to the required size and bonded to the beam soffit using the hand layup process with epoxy  
26 resin (**Fig 8**). For the U-shape, the fabric was wrapped around the three sides of the beam before resin  
27 application. A total of 30 HPC beam specimens were tested in 5 series, the number of layers, fiber type,  
28 and thermal treatment were assigned to each beam specimen as specified in **Table 2**. All strengthened  
29 beams were left to cure at room temperature for 20 days prior to testing. **Fig. 9** displays the summary of  
30 experimental procedure.  
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47 **Fig. 8** Fiber saturation of resin: full impregnation.  
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**Table 2** Overview of beam specimens.

Series	Designation	Fiber	Number of layers	Heat-Treatment	Configuration
Serie 0	CB	-	-	-	-
Serie 1	J-1L	Jute	1	-	soffit
	J-2L	Jute	2	-	soffit
	J-3L	Jute	3	-	soffit
Serie 2	J-1L80	Jute	1	80°C	soffit
	J-2L80	Jute	2	80°C	soffit
	J-3L80	Jute	3	80°C	soffit
Serie 3	G-1L	Glass	1	-	soffit
	G-2L	Glass	2	-	soffit
Serie 4	J-U	Jute	1	-	U-shaped
	J-U80	Jute	1	80°C	U-shaped



**Fig. 9** Summary of experimental procedure flowchart

### 2.3. Test procedure

The three-point bend test setup is illustrated in **Fig. 10**. This setup conforms to the ASTM standard [39] for determining the flexural strength of concrete. A 400 kN capacity hydraulic actuator was used to apply the load on the test specimens. The actuator was mounted to a stiff steel loading frame designed to resist flexure and deflection during testing. The HPC beams were placed on two steel rollers spaced 200 mm apart to provide simple support conditions. The rollers had a diameter of 25 mm and were of

sufficient length to prevent localized crushing of the concrete. A third steel roller of identical dimensions was attached to the actuator for the application of a concentrated load at the midspan of the test beams.

Vertical deflection was measured using a linear variable differential transformer (LVDT) with a repeatability of 0.01 mm. The LVDT had a 50 mm measurement range and was securely fastened above the beam at midspan using a magnetic holder. To measure applied load, a 400 kN load cell was attached between the actuator and the top roller. The LVDT and load cell were connected to a data acquisition system to record the signals. During testing, vertical load and midspan deflection were recorded. The acquired data was processed to generate the load-deflection curves for each beam specimen. Prior to testing, all instrumentation was calibrated according to manufacturer specifications to ensure accuracy of the measured data.

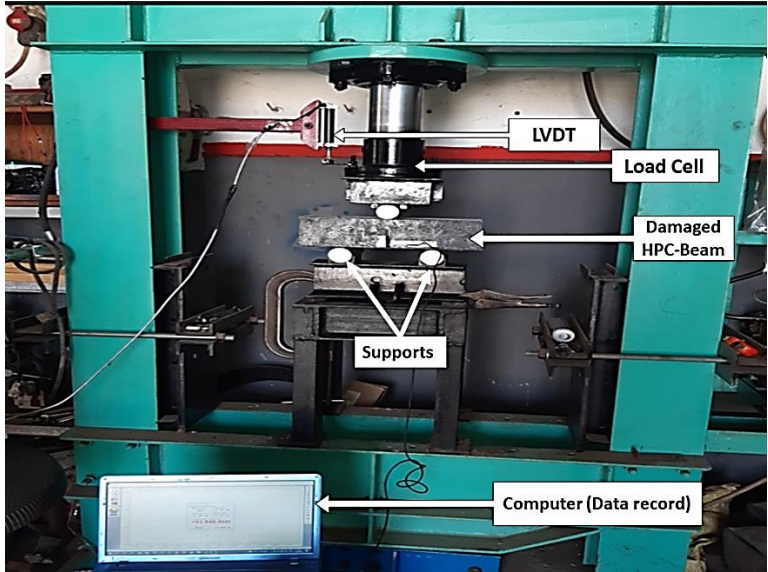


Fig. 10 Experimental setup

### 3. Results and discussion

#### 3.1. Load-deflection analysis

##### 3.1.1. The effect of JFRP in soffit configuration

Fig. 11 provides a summary of the load-bearing capacity and mid-span deflection results for both control beams and JFRP-reinforced beams in the soffit configuration. These curves initially exhibit an elastic behavior phase, demonstrating the ability of the specimens to absorb a certain amount of stress while returning to their original shape. However, this progressive deformation is followed by a sudden rupture, marking the point at which the beams reach their ultimate strength.

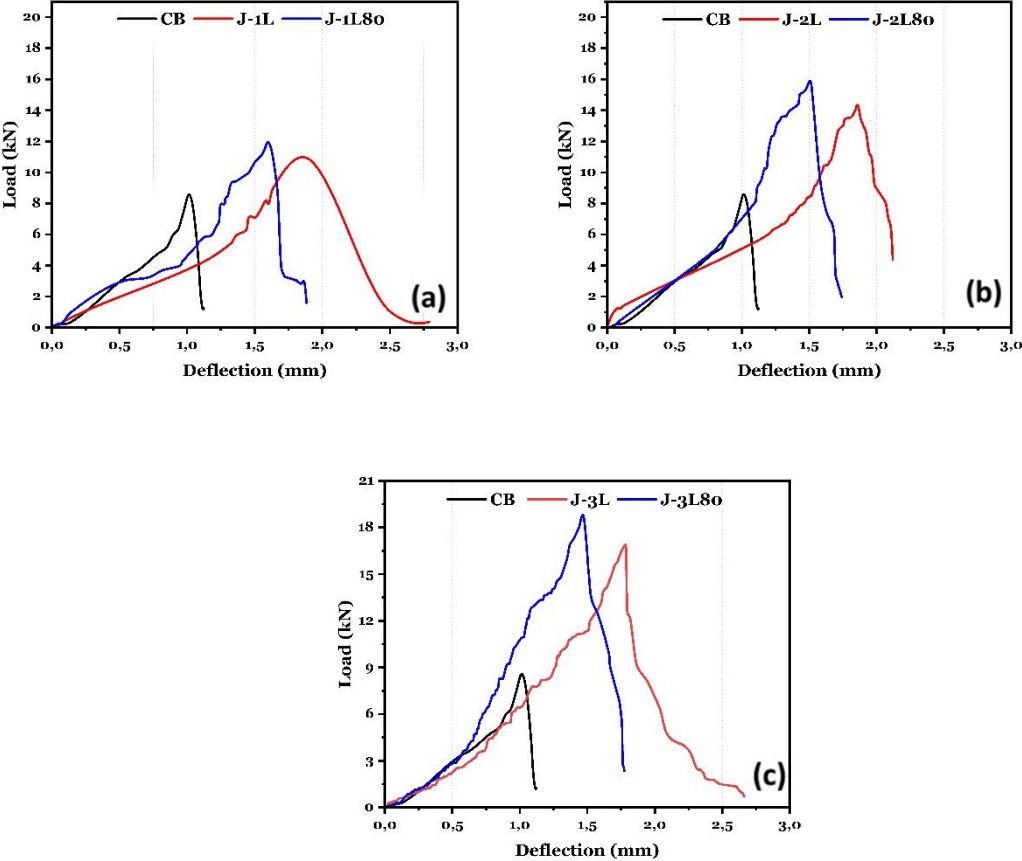
For the control beam (CB), a peak load of 8.57 kN and a corresponding midspan deflection of 1.012 mm were observed. In series 1, additional layers of fabric led to increased load capacities. J-1L showed a 24% higher load capacity (10.68 kN) compared to CB, while J-2L and J-3L exhibited increases of 69% (14.51 kN) and 97% (16.91 kN), respectively. However, the midspan deflection decreased with more layers, reaching 1.93 mm, 1.85 mm, and 1.78 mm for J-1L, J-2L, and J-3L, respectively.

In series 2, the heat-treated jute EBR beams displayed improved performance over the untreated jute. Higher load capacities were attained by the specimens J-1L80 (11.80 kN), J-2L80 (15.85 kN), and J-3L80 (18.81 kN), representing improvements of 58%, 85%, and 120% over the control beam.

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Meanwhile, the midspan deflections were lower than those of the untreated jute counterparts, measuring 1.56 mm, 1.51 mm, and 1.46 mm for J-1L80, J-2L80, and J-3L80, respectively.

These results reveal a gradual increase in ultimate flexural load as the number of layers goes from 1 to 3. This rise can be ascribed to the constraining influence imposed by the JFRP layers on the concrete, thereby restricting its cracking under the load. Moreover, a homogeneous stress distribution is achieved with the addition of extra layers, enhancing the overall load-bearing capacity of the beam. The outcomes are consistent with previous studies. Yaseen A. et al. [40] also observed an improvement in ultimate flexural load when incorporating JFRP layers. Additionally, A. Abdulla et al. [17] noted substantial strength increases with the addition of JFRP laminate layers, reporting enhancements of 45%, 62%, and 71% for beams reinforced with 2, 4, and 6 layers of JFRP laminates, respectively. However, the reduction in deflection observed with the increase in reinforcement layers can be attributed to the confinement effect induced by the layering. This confinement phenomenon is not just a simple increase in mechanical strength; it also alters the dynamics of stress distribution within the structure, leading to a significant improvement in overall structural integrity [16].



**Fig. 11** Load and mid-span deflection results of CB and JFRP beams in soffit configuration (a) one layer (b) two layers (c) three layers.

In the other hand, shifting focus from the impact of the number of layers to the influence of heat treatment. It's evident that the heat treatment also plays a crucial role in enhancing the performance of JFRP-reinforced beams. In series 2, where heat-treated jute EBR beams were employed, improved performance over the untreated jute is noticeable. J1-L80 exhibit a significant 10% increase in their ultimate load-bearing capacity compared to J1-L. Comparable increases of 9% and 11% are also

observed for J2-L80 and J3-L80, respectively. The beneficial effect of heat treatment can be attributed to the microstructural changes induced in the jute fibers. This beneficial influence of the heat treatment corroborates the increase in surface roughness observed under the optical microscope and SEM, which promotes mechanical anchorage with the polymer matrix and improved load transfer from the fibers to the matrix.

The analysis of the results regarding mid-span deflection in beams reinforced with treated jute composites (J-1L80, J-2L80, J-3L80) shows a higher rigidity compared to those reinforced with untreated fibers. This increase in rigidity could be related to an improved modulus of elasticity of the treated fibers. Therefore, the treatment of jute fibers appears to play a role in enhancing the structural performance of the beams.

T. Jirawattanasomkul et al. [28] emphasize that JFRP reinforcement with heat treatment at 80°C for 1-hour results in a significant increase in ultimate compressive load capacity, reaching approximately 15% more than untreated reference specimens. This improvement is largely attributed to the weight loss of the jute fabric, resulting from the evaporation of water content within the fibers. These combined findings underscore the substantial enhancement in load-bearing capacity achieved through heat treatment and its associated mechanisms in JFRP-reinforced beams.

### 3.1.2. The effect of JFRP in U-shape configuration

The load-deflection curves for the JFRP-reinforced beams in the U-shaped configuration, as shown in Fig. 12, whether treated or not, exhibit a pronounced similarity. In both cases, these curves initially demonstrate an elastic behavior phase followed by a sudden rupture of the beams at the maximum load.

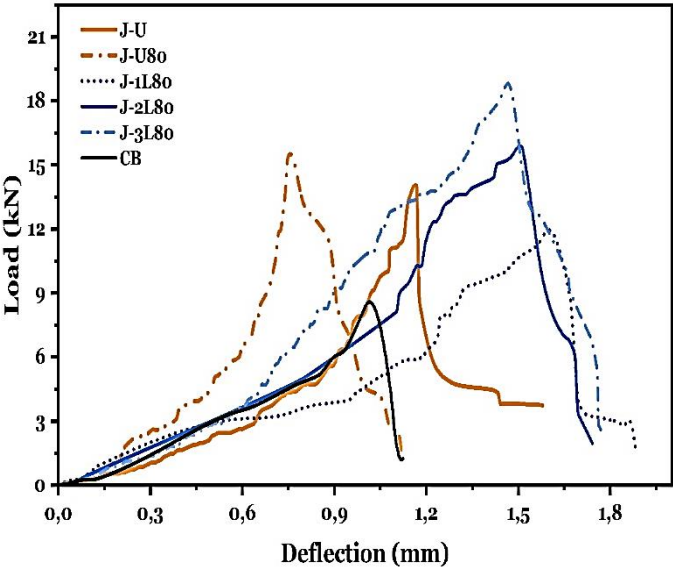


Fig. 12 Load and mid-span deflection results of JFRP beams in U-shape and soffit configuration.

The reinforced beams in series 3, J-U and J-U80, demonstrate an impressive ultimate load-bearing capacity of 14.02 kN and 15.21 kN, respectively. These values represent a substantial increase, approximately 63% and 77% higher than that of CB. Moreover, when considering mid-span deflection, a notable difference emerges. J-U80 exhibits a deflection of 0.75 mm, which is approximately 1.56 times greater than the deflection observed in J-U, measuring at 1.17 mm. These findings strongly support the notion that utilizing jute fibers as reinforcement in the U-shaped configuration significantly enhances

1 the structure's flexural load-carrying capacity. These outcomes align seamlessly with the research of T.  
2 Sen . [41] and H. N. J. Reddy [42], who reported an approximate 67% increase in the ultimate load-  
3 bearing capacity for JFRP-reinforced U-shaped beams in comparison to CB.

4 When comparing the performance of J-U beams with J-1L and J-1L80, a significant improvement in  
5 their flexural load-carrying capacity is observed, with an average increase of about 30% compared to J-  
6 1L and 18% compared to J-1L80. These results align with the observations of Attari et al. [43], Chen et  
7 al. [44], and Yuvaraj et al. [45], who reported that U-shaped reinforcement beams exhibited increased  
8 strength compared to soffit-reinforced beams.  
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11 Specimens reinforced with two layers, J-2L and J-2L80, show an average increase of about 3.5%  
12 compared to J-U and J-U80. This demonstrates that U-shaped reinforcement is an effective means to  
13 improve the flexural performance of concrete beams. Similarly, the same positive effect is noted in terms  
14 of stiffness. J-U exhibits an average stiffness about 1.3 times higher than that of beams in series 1 and  
15 2, which are reinforced with one and two layers of laminate.  
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18 Conversely, J-3L and J-3L80 exhibit better performance in terms of ultimate flexural capacity, showing  
19 respective improvements of 11% and 24% compared to J-U80. However, it's important to note that this  
20 improvement in the ultimate flexural capacity is accompanied by an inverse trend regarding deflection.  
21 Indeed, J-U80 exhibits an average stiffness about 2 times higher than that observed for beams J3-L and  
22 J3-L80. These results emphasize that beams J-3L and J-3L80 are more resistant in terms of the maximum  
23 load they can support, but they also experience greater deformation compared to J-U80.  
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### 29 **3.1.3. JFRP beams versus GFRP beams**

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31 **Fig. 13** presents the load-deflection curves for the GFRP-reinforced beams in the soffit configuration.  
32 The addition of a single layer of GFRP (G-1L) resulted in a substantial increase in peak load, reaching  
33 14.67 kN, which was 71% higher than CB. This improvement in load-carrying capacity was  
34 accompanied by stiffness enhancement, as reflected by a midspan deflection of 1.0108 mm, which  
35 remained comparable to that of the CB.  
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38 With the introduction of two layers of GFRP (G-2L), the peak load experienced a further significant  
39 increase, reaching 19.33 kN, representing a remarkable 125% improvement over the CB. The additional  
40 GFRP reinforcement layer enabled greater load resistance prior to failure, agreeing with Hong et al.  
41 [46]. However, this also led to a more flexible response, with the midspan deflection increasing  
42 significantly compared to both the CB and G-1L (2.393 mm). The larger deflection suggests that the 2-  
43 layer GFRP reinforcement may have been less effective at controlling crack propagation and  
44 deformations, as also indicated in research by Smith and Teng [47].  
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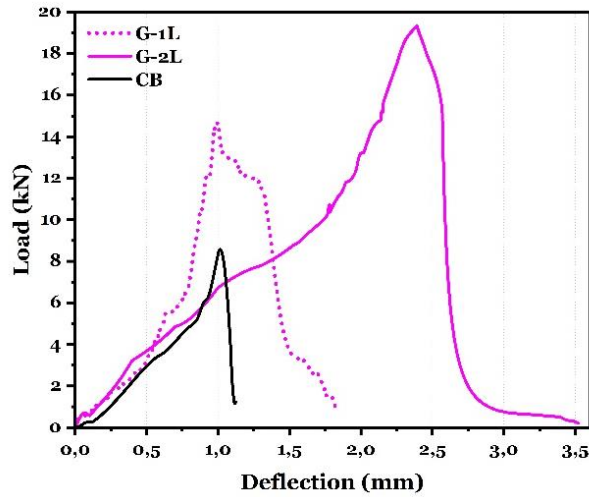


Fig. 13 Load and mid-span deflection results of GFRP beams

The load-deformation values for the beams, illustrated in Fig. 14 reveal that suitably designed JFRP composites can provide flexural strengthening on par with GFRP materials. In fact, the 3-layer heat-treated JFRP nearly matched the 2-layer GFRP performance with only a 2% difference in maximum loads. This demonstrates the potential for optimized JFRP reinforcement schemes to attain equivalent or marginally better strength improvements versus GFRP alternatives.

These findings align with the results of M.H. Amirhafizan et al. [48], who conducted an experimental study and demonstrated that reinforcement with 4 layers of thermosetting JFRP significantly improved mechanical properties and increased ultimate shear capacity by about 73% compared to thermosetting GFRP composites. However, it is important to note that despite these advantages in terms of load-carrying capacity, the midspan deflections varied noticeably. The GFRP beams showed significantly lower deflections, suggesting enhanced stiffness despite the high loads attained by the JFRP strengthening.

While the peak load capacities were comparable between the heat-treated JFRP and GFRP strengthening systems, the midspan deflection response varied noticeably between the two fiber types. With a single ply reinforcement layer, the GFRP beam exhibited a lower deflection of 1.0108 mm compared to 1.5864 mm for the equivalent heat-treated JFRP beam, despite both achieving similar ultimate loads. This indicates that the GFRP reinforcement provided enhanced stiffness and deformation control with just one layer of fibers. The lower deflection suggests more effective crack propagation resistance by the glass fibers compared to the jute. However, with two reinforcement layers, the trend reversed - the GFRP beam showed a significantly higher midspan deflection of 2.393 mm versus 1.4651 mm for the heat-treated 3-ply JFRP system. Although both fiber composites attained comparable peak loads, the jute fabric layers were able to provide greater stiffness with the same number of plies. The additional jute reinforcement likely enabled better distributed cracking control compared to the more localized fracturing in the GFRP beam.

On the other hand, J-U80 achieved a peak load of 15.21 kN, surpassing the 1-layer GFRP beam G-1L (14.67 kN) by 3.5%. This result underscores the remarkable flexural strengthening potential of heat-treated jute in a U-shape configuration, even in the face of potential debonding issues. The thermal enhancement of jute fiber strength and fiber-matrix adhesion allowed for efficient stress transfer, enabling J-U80 to outperform the 1-ply GFRP. However, when compared to G-2L, J-U80 exhibited a

19% lower peak load capacity. The enhanced performance of the 2-layer GFRP, in this case, highlights the limitations of the jute U-shape system, particularly concerning debonding.

Regarding midspan deflections, J-U80 demonstrated significantly lower deflection (0.747 mm) than both 1 and 2-layer GFRP beams. This lower deflection indicates superior stiffness and crack control achieved by the J-U80 configuration, even with its lower load capacity. The ability to maintain reduced deflections while withstanding considerable loads suggests that J-U80's crack control and deformation resistance mechanisms were effective in enhancing the beam's overall performance compared to its GFRP counterparts.

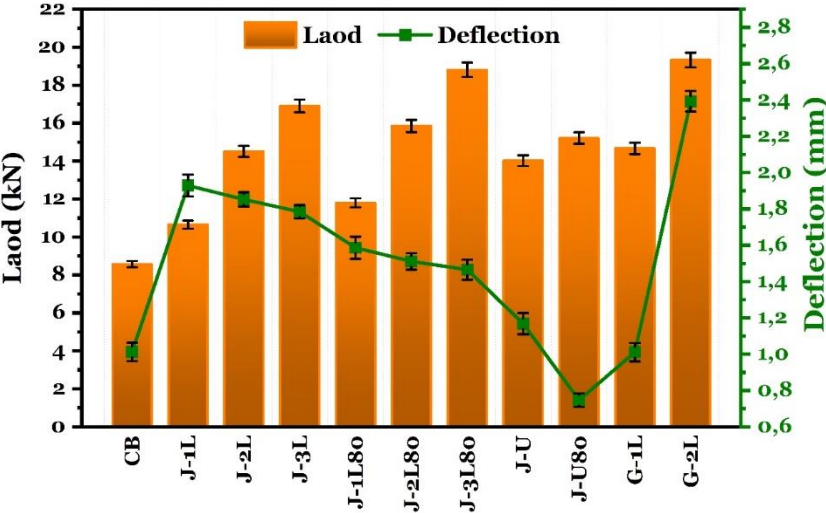
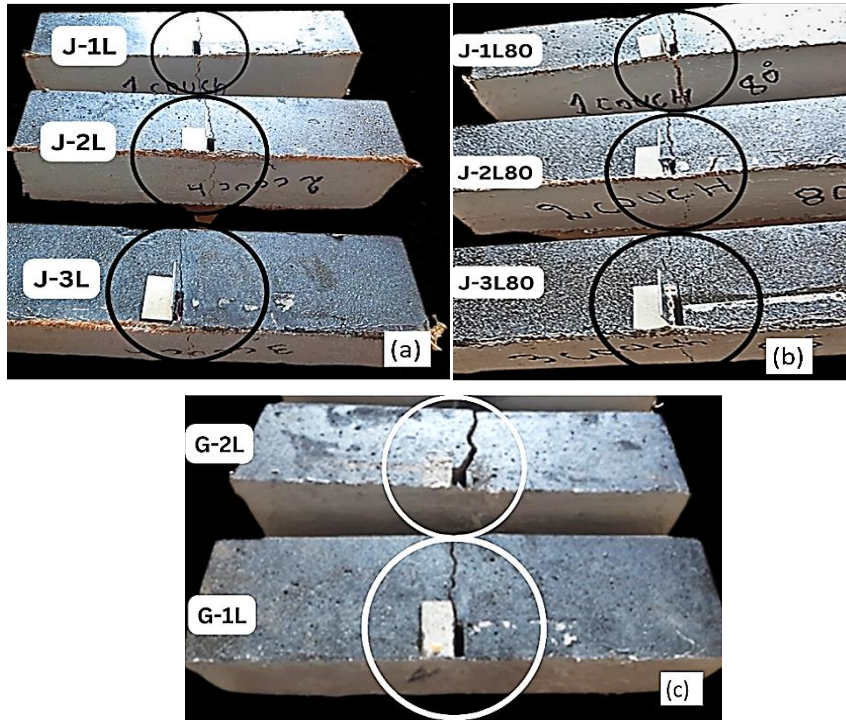


Fig. 14 Loads and mid-span deflections of all strengthened beams

### 3.2. Failure modes

A thorough comparison of the failure mode between untreated JFRP and treated JFRP reveals a significant difference, primarily in terms of crack width. The results presented in Fig. 13 indicate that the cracks observed in the jute fiber fabric gradually decrease in width from one layer to two layers and then to three layers of reinforcement. More precisely, the cracks in the three-layer configuration are notably finer than those in the two-layer configuration, which, in turn, are finer than those in the one-layer configuration. This observation suggests that the application of additional layers of jute fiber fabric allows for better crack control, and more efficient distribution of fracture in the localized region around the initial defect. Furthermore, the increased number of finely spaced microcracks along the beam's length corroborates this finding. As the overall load-carrying capacity increases with the addition of these extra layers, the jute fabric manages to contain crack openings more effectively.





**Fig. 13** Reinforced beams in soffit configuration after failure (a) untreated JFRP beams (b) Heat-treated JFRP beams (c) GFRP beams

However, it is essential to note that the effect of heat treatment is also evident in this comparison. Heat-treated JFRP beams exhibit finer cracks than their untreated counterparts. This difference can be attributed to the beneficial effect of heat treatment on the properties of jute fibers. It promotes cross-linking of the fibers' cellulose structure, thereby increasing their strength and enhancing their adhesion with the composite material. The increase in surface roughness of thermally treated jute fibers, as observed under the microscope and through SEM, enhances mechanical anchoring and load transfer to the matrix. This microstructural improvement leads to finer cracks in treated JFRP beams compared to untreated ones, indicating more effective control over crack propagation. Furthermore, the increased strength of the treated fibers, as observed in tensile tests, endows them with enhanced reinforcing properties and the ability to limit crack opening in the composite.

In comparison, the glass fibers in the GFRP beams displayed remarkable crack control. Unlike JFRP, no cracks propagated along the GFRP length, indicating it maintained adhesion to the concrete matrix across cracks. The high stiffness of glass fibers enabled continuity between the concrete and glass mat, allowing effective transfer of stress without debonding at the interface. This demonstrates a key difference between the mechanical interactions of jute and glass with concrete matrices. While jute excels in crack bridging and controlling localized fracture, glass provides superior interface bonding.

All major cracks originated from the initial saw cut notch in the center of the beams. Both jute and glass reinforcements prevented the formation of new cracks away from this high-stress region. This mechanism allowed the materials to enhance ductility through the controlled distribution of microcracks emanating from the defect location, rather than the formation of new early cracks that lead to abrupt brittle failure.

The study emphasizes the vital role of fiber-concrete interaction in material behavior. Jute fibers effectively control crack propagation and localized fractures, seen in reduced crack width with increased jute layers. However, high-stress conditions revealed potential debonding issues, this slight debonding may be attributed to the organic nature and flexibility of jute fibers. In contrast, glass fibers displayed outstanding bonding strength, maintaining an unbroken interface with concrete, and preventing crack

propagation. These findings underscore the robust bonding of glass fibers compared to jute, highlighting their distinct behaviors and implications for reinforced material performance.

### 3.3. Cost analysis

Economic sustainability is critical for practical adoption of natural fiber reinforcements. The market price analysis revealed that the cost of jute fibers is estimated to be between \$30 and \$40 per ton [49]. In contrast, glass fibers exhibit a significantly higher cost, with prices varying considerably, ranging from \$2,518 to \$18,445 per ton [50]. The lower price of jute can be attributed to the higher labor costs associated with glass fiber production involving energy-intensive high temperature processes.

The outcomes indicate that jute reinforcement can provide direct economic benefits in addition to the environmental advantages highlighted in the carbon footprint assessment. With suitable supply chain management, jute and other natural bast fibers are attractive low-cost alternatives to traditional glass fiber. This demonstrates the potential for biobased reinforcements to improve both the environmental and economic sustainability of composites.

## 4. Conclusion

The experimental study presented in this article reported the flexural response of pre-damaged HPC beams reinforced with heat-treated JFRP laminates in two distinct configurations. A comparison with GFRP-reinforced beams is also conducted. The main findings are as follows:

- The use of heat-treated JFRP in the soffit reinforcement of pre-damaged beams with 1, 2, and 3 layers revealed an increase in load-carrying capacity ranging from 38% to 119% compared to CB. The comparison between J1-L, J1-L80, and J3-L, J3-L80 showed an additional strength gain of approximately 59% with the addition of just two layers.
- U-shaped reinforcement proved to be more effective, enhancing the stiffness and load-carrying capacity of the beams. These improvements resulted in a 63% and 77% increase in load-carrying capacity for untreated and heat-treated JFRP compared to CB. Although slightly less efficient flexural strength was observed compared to soffit reinforcement with 3 layers. J3-L and J3-L80 displayed better performance of approximately 11% and 24% compared to J-U80.
- Comparison with GFRP laminates showed nearly identical load-carrying capacities. With 3 layers of heat-treated JFRP, the jute composites exhibited only a 2% difference compared to beams reinforced with 2 layers of glass fibers.
- The comparison of failure modes between untreated and treated JFRP reveals that the number of layers significantly affects crack width, with finer cracks observed in configurations with more layers. Additionally, heat treatment enhances crack control by narrowing crack widths.
- Jute reinforcement offers economic and environmental benefits, offering low-cost alternatives to traditional glass fiber, demonstrating the potential for biobased reinforcements to enhance composite sustainability.

These experimental results highlight that external reinforcement of HPC beams using the EBR technique with heat-treated natural fiber composites, particularly at 80°C, holds strong potential as a promising alternative to GFRP. Their adoption could reduce CO<sub>2</sub> emissions and costs while providing adequate mechanical properties. These findings open up new perspectives of the use of natural fibers in structural reinforcement, offering advantages, both technically and environmentally.

1  
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3

4 **Availability of Data** The data underpinning this research is accessible upon reasonable request  
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6

7 **Declaration of Conflicts of Interest** The author affirms the absence of any conflicts of  
8 interest.  
9

10 **Ethical Approval** This article does not involve experiments with human participants or animals  
11 conducted by any of the authors.  
12  
13

## 14 15 16 17 **References**

- 18  
19 [1] I. Shakir Abbood, S. aldeen Odaa, K. F. Hasan, et M. A. Jasim, « Properties evaluation of fiber  
20 reinforced polymers and their constituent materials used in structures – A review », *Mater. Today*  
21 *Proc.*, vol. 43, p. 1003- 1008, janv. 2021, doi: 10.1016/j.matpr.2020.07.636.
- 22 [2] C. O. Nwankwo, J. Mahachi, D. O. Olukanni, et I. Musonda, « Natural fibres and biopolymers in  
23 FRP composites for strengthening concrete structures: A mixed review », *Constr. Build. Mater.*,  
24 vol. 363, p. 129661, janv. 2023, doi: 10.1016/j.conbuildmat.2022.129661.
- 25 [3] D. U. Shah, P. J. Schubel, P. Licence, et M. J. Clifford, « Hydroxyethylcellulose surface treatment  
26 of natural fibres: the new ‘twist’ in yarn preparation and optimization for composites  
27 applicability », *J. Mater. Sci.*, vol. 47, n° 6, p. 2700- 2711, mars 2012, doi: 10.1007/s10853-011-  
28 6096-1.
- 29 [4] S. Das, A. La Rosa, S. Goutianos, et S. Grammatikos, « Flax fibers, their composites and  
30 application », 2022, p. 209- 232. doi: 10.1016/B978-0-12-824528-6.00017-5.
- 31 [5] Institute of Radiation and Polymer Technology, Bangladesh Atomic Energy Commission, Dhaka  
32 1349, Bangladesh *et al.*, « A brief review on natural fiber used as a replacement of synthetic fiber  
33 in polymer composites », *Mater. Eng. Res.*, vol. 1, n° 2, p. 88- 99, 2019, doi:  
34 10.25082/MER.2019.02.007.
- 35 [6] S. Navaratnam, K. Selvaranjan, D. Jayasooriya, P. Rajeev, et J. Sanjayan, « Applications of natural  
36 and synthetic fiber reinforced polymer in infrastructure: A suitability assessment », *J. Build. Eng.*,  
37 vol. 66, p. 105835, mai 2023, doi: 10.1016/j.job.2023.105835.
- 38 [7] R. Chlela, D. Bigaud, H. Riahi, M. Quiertant, L. Curtil, et K. Benzarti, « Durability and Lifetime  
39 Prediction of Flax Fiber Reinforced Polymer Composites », in *10th International Conference on*  
40 *FRP Composites in Civil Engineering*, vol. 198, A. Ilki, M. Ispir, et P. Inci, Éd., in *Lecture Notes*  
41 *in Civil Engineering*, vol. 198. , Cham: Springer International Publishing, 2022, p. 695- 705. doi:  
42 10.1007/978-3-030-88166-5\_60.
- 43 [8] F. Duc, P. E. Bourban, C. J. G. Plummer, et J.-A. E. Månson, « Damping of thermoset and  
44 thermoplastic flax fibre composites », *Compos. Part Appl. Sci. Manuf.*, vol. 64, p. 115- 123, sept.  
45 2014, doi: 10.1016/j.compositesa.2014.04.016.
- 46 [9] M. Ben Ameer, A. El Mahi, J. L. Rebiere, M. Beyaoui, M. Abdennadher, et M. Haddar, « Bending  
47 Fatigue Behavior of Flax and Carbon Fiber Reinforced Epoxy Resin », in *Design and Modeling*  
48 *of Mechanical Systems - IV*, N. Aifaoui, Z. Affi, M. S. Abbas, L. Walha, M. Haddar, L. Romdhane,  
49 A. Benamara, M. Chouchane, et F. Chaari, Éd., in *Lecture Notes in Mechanical Engineering*.  
50 Cham: Springer International Publishing, 2020, p. 567- 575. doi: 10.1007/978-3-030-27146-6\_61.
- 51 [10] G. Di Luccio, L. Michel, E. Ferrier, et E. Martinelli, « Seismic retrofitting of RC walls externally  
52 strengthened by flax-FRP strips », *Compos. Part B Eng.*, vol. 127, p. 133- 149, oct. 2017, doi:  
53 10.1016/j.compositesb.2017.06.017.
- 54 [11] W. Wang, Z. Mo, Y. Zhang, et N. Chouw, « Dynamic Splitting Tensile Behaviour of Concrete  
55 Confined by Natural Flax and Glass FRP », *Polymers*, vol. 14, n° 20, p. 4424, oct. 2022, doi:  
56 10.3390/polym14204424.  
57  
58  
59  
60  
61  
62  
63  
64  
65

- 1 [12] W. Wang, X. Zhang, Z. Mo, N. Chouw, Z. Li, et Z.-D. Xu, « A comparative study of impact  
2 behaviour between natural flax and glass FRP confined concrete composites », *Constr. Build.  
3 Mater.*, vol. 241, p. 117997, avr. 2020, doi: 10.1016/j.conbuildmat.2020.117997.
- 4 [13] W. Wang, X. Zhang, Z. Mo, N. Chouw, Z. Li, et Z.-D. Xu, « A comparative study of impact  
5 behaviour between natural flax and glass FRP confined concrete composites », *Constr. Build.  
6 Mater.*, vol. 241, p. 117997, avr. 2020, doi: 10.1016/j.conbuildmat.2020.117997.
- 7 [14] E. Ferrier, L. Michel, et M. D. Ngo, « Experimental study on the shear behavior of RC beams  
8 reinforced by natural composite materials (flax fibers) », *Structures*, vol. 33, p. 637- 654, oct.  
9 2021, doi: 10.1016/j.istruc.2021.03.027.
- 10 [15] E. Yooprasertchai, P. Wiwatrojanagul, et A. Pimanmas, « A use of natural sisal and jute fiber  
11 composites for seismic retrofitting of nonductile rectangular reinforced concrete columns », *J.  
12 Build. Eng.*, vol. 52, p. 104521, juill. 2022, doi: 10.1016/j.jobe.2022.104521.
- 13 [16] C. Chen *et al.*, « Eco-friendly and mechanically reliable alternative to synthetic FRP in externally  
14 bonded strengthening of RC beams: Natural FRP », *Compos. Struct.*, vol. 241, p. 112081, juin  
15 2020, doi: 10.1016/j.compstruct.2020.112081.
- 16 [17] A. Abdulla, R. Thaker, et A. Khazaal, « Toughness of Timber Beams Strengthened with Jute  
17 Fibers », *Tikrit J. Eng. Sci.*, vol. 27, p. 94- 112, déc. 2020, doi: 10.25130/tjes.27.3.11.
- 18 [18] T. Lu, M. Jiang, Z. Jiang, D. Hui, Z. Wang, et Z. Zhou, « Effect of surface modification of bamboo  
19 cellulose fibers on mechanical properties of cellulose/epoxy composites », *Compos. Part B Eng.*,  
20 vol. 51, p. 28- 34, août 2013, doi: 10.1016/j.compositesb.2013.02.031.
- 21 [19] A. Langhorst, M. Ravandi, D. Mielewski, et M. Banu, « Technical agave fiber tensile  
22 performance: The effects of fiber heat-treatment », *Ind. Crops Prod.*, vol. 171, p. 113832, nov.  
23 2021, doi: 10.1016/j.indcrop.2021.113832.
- 24 [20] J. S. S. Neto, R. A. A. Lima, D. K. K. Cavalcanti, J. P. B. Souza, R. A. A. Aguiar, et M. D. Banea,  
25 « Effect of chemical treatment on the thermal properties of hybrid natural fiber-reinforced  
26 composites », *J. Appl. Polym. Sci.*, vol. 136, n° 10, p. 47154, mars 2019, doi: 10.1002/app.47154.
- 27 [21] « Bamboo heat treatments and their effects on bamboo properties », *Constr. Build. Mater.*, vol.  
28 331, p. 127320, mai 2022, doi: 10.1016/j.conbuildmat.2022.127320.
- 29 [22] Y. Cao, F. Chan, Y.-H. Chui, et H. Xiao, « CHARACTERIZATION OF FLAX FIBRES  
30 MODIFIED BY ALKALINE, ENZYME, AND STEAM-HEAT TREATMENTS », 2012.
- 31 [23] B. P. Chang, W. H. Chan, M. H. Zamri, H. Md Akil, et H. G. Chuah, « Investigating the Effects  
32 of Operational Factors on Wear Properties of Heat-Treated Pultruded Kenaf Fiber-Reinforced  
33 Polyester Composites using Taguchi Method », *J. Nat. Fibers*, vol. 16, n° 5, p. 702- 717, juill.  
34 2019, doi: 10.1080/15440478.2018.1432001.
- 35 [24] S. Mishra et V. Parashar, « Experimental analysis of duo-fiber interaction on the tensile strength  
36 of surface-modified flax–kenaf-reinforced epoxy composite », *Polym. Bull.*, janv. 2023, doi:  
37 10.1007/s00289-023-04708-6.
- 38 [25] A. Azadeh, K. Ghavami, et J. J. García, « The influence of heat on mechanical properties of  
39 *Dendrocalamus giganteus* bamboo », *J. Build. Eng.*, vol. 43, p. 102613, nov. 2021, doi:  
40 10.1016/j.jobe.2021.102613.
- 41 [26] J. Cui *et al.*, « Effects of Thermal Treatment on the Mechanical Properties of Bamboo Fiber  
42 Bundles », *Materials*, vol. 16, n° 3, p. 1239, janv. 2023, doi: 10.3390/ma16031239.
- 43 [27] T. Voravutvityaruk, T. Jirawattanasomkul, T. Ueda, N. Wuttiwannasak, et T. Poonsawat, *Behavior  
44 of Concrete Confined by Jute Natural Fiber Reinforced Polymer with Heat Treatment*. 2017.
- 45 [28] T. Jirawattanasomkul, S. Likitlersuang, N. Wuttiwannasak, T. Ueda, D. Zhang, et T.  
46 Voravutvityaruk, « Effects of Heat Treatment on Mechanical Properties of Jute Fiber–Reinforced  
47 Polymer Composites for Concrete Confinement », *J. Mater. Civ. Eng.*, vol. 32, p. 04020363, déc.  
48 2020, doi: 10.1061/(ASCE)MT.1943-5533.0003456.
- 49 [29] C. Campana, R. Leger, R. Sonnier, L. Ferry, et P. Jenny, « Effect of post curing temperature on  
50 mechanical properties of a flax fiber reinforced epoxy composite », *Compos. Part Appl. Sci.  
51 Manuf.*, vol. 107, p. 171- 179, avr. 2018, doi: 10.1016/j.compositesa.2017.12.029.
- 52 [30] Michael Carus, Niels de Beus, et Martha Barth, « Carbon Footprint and Sustainability of Different  
53 Natural Fibres for Biocomposites and Insulation Material ». *Comprehensively*, 2019. [En ligne].  
54 Disponible sur: [https://growinghempassociation.org/wp-content/uploads/2022/11/19-08-06-  
56 Study-Natural-Fibre-Sustainability-Carbon-Footprint-1.pdf](https://growinghempassociation.org/wp-content/uploads/2022/11/19-08-06-<br/>55 Study-Natural-Fibre-Sustainability-Carbon-Footprint-1.pdf)  
57  
58  
59  
60  
61  
62  
63  
64  
65

- 1 [31] Yu. I. Kolesov, M. Yu. Kudryavtsev, et N. Yu. Mikhailenko, « Types and Compositions of Glass  
2 for Production of Continuous Glass Fiber (Review) », *Glass Ceram.*, vol. 58, n° 5, p. 197- 202,  
3 mai 2001, doi: 10.1023/A:1012386814248.
- 4 [32] D.-Y. Yoo et N. Banthia, « Size-dependent impact resistance of ultra-high-performance fiber-  
5 reinforced concrete beams », *Constr. Build. Mater.*, vol. 142, p. 363- 375, juill. 2017, doi:  
6 10.1016/j.conbuildmat.2017.03.080.
- 7 [33] Z. Zhang, M. Shakoorioskooie, M. Griffa, P. Lura, et U. Angst, « A laboratory investigation of  
8 cutting damage to the steel-concrete interface », *Cem. Concr. Res.*, vol. 138, p. 106229, déc. 2020,  
9 doi: 10.1016/j.cemconres.2020.106229.
- 10 [34] T. Sen et A. Paul, « Confining concrete with sisal and jute FRP as alternatives for CFRP and  
11 GFRP », *Int. J. Sustain. Built Environ.*, vol. 4, n° 2, p. 248- 264, déc. 2015, doi:  
12 10.1016/j.ijse.2015.04.001.
- 13 [35] P. A. Sreekumar, S. P. Thomas, J. marc Saiter, K. Joseph, G. Unnikrishnan, et S. Thomas, « Effect  
14 of fiber surface modification on the mechanical and water absorption characteristics of  
15 sisal/polyester composites fabricated by resin transfer molding », *Compos. Part Appl. Sci. Manuf.*,  
16 vol. 40, n° 11, p. 1777- 1784, nov. 2009, doi: 10.1016/j.compositesa.2009.08.013.
- 17 [36] « ASTM D 3039: Standard Test Method for Tensile Properties of Polymer Matrix Composite  
18 Materials ».
- 19 [37] C. Chen *et al.*, « Effect of transverse groove on bond behavior of FRP-concrete interface:  
20 Experimental study, image analysis and design », *Compos. Part B Eng.*, vol. 161, p. 205- 219,  
21 mars 2019, doi: 10.1016/j.compositesb.2018.10.072.
- 22 [38] L. D. Lorenzis, B. Miller, et A. Nanni, « BOND OF FRP LAMINATES TO CONCRETE », *ACI  
23 Mater. J.*, vol. 98, n° 3, 2001.
- 24 [39] « ASTM C78/C78M-18; Standard Test Method for Flexural Strength of Concrete (Using Simple  
25 Beam with Third-Point Loading). ASTM International: West Conshohocken, PA, USA, 2018; pp.  
26 1-5. »
- 27 [40] Y. A. Salih, N. N. Sabeeh, M. F. Yass, A. S. Ahmed, et E. S. Khudhurr, « Concrete Beams  
28 Strengthened with Jute Fibers », *Civ. Eng. J.*, vol. 5, n° 4, p. 767- 776, avr. 2019, doi:  
29 10.28991/cej-2019-03091286.
- 30 [41] T. Sen et A. Paul, « Confining concrete with sisal and jute FRP as alternatives for CFRP and  
31 GFRP », *Int. J. Sustain. Built Environ.*, vol. 4, n° 2, p. 248- 264, déc. 2015, doi:  
32 10.1016/j.ijse.2015.04.001.
- 33 [42] T. Sen et H. N. J. Reddy, « Pretreatment of Woven Jute FRP Composite and Its Use in  
34 Strengthening of Reinforced Concrete Beams in Flexure », *Adv. Mater. Sci. Eng.*, vol. 2013, p.  
35 e128158, oct. 2013, doi: 10.1155/2013/128158.
- 36 [43] N. Attari, S. Amziane, et M. Chemrouk, « Flexural strengthening of concrete beams using CFRP,  
37 GFRP and hybrid FRP sheets », *Constr. Build. Mater.*, vol. 37, p. 746- 757, déc. 2012, doi:  
38 10.1016/j.conbuildmat.2012.07.052.
- 39 [44] W. Chen, T. M. Pham, H. Sichembe, L. Chen, et H. Hao, « Experimental study of flexural  
40 behaviour of RC beams strengthened by longitudinal and U-shaped basalt FRP sheet », *Compos.  
41 Part B Eng.*, vol. 134, p. 114- 126, févr. 2018, doi: 10.1016/j.compositesb.2017.09.053.
- 42 [45] S. Yuvaraj, K. Chithra, K. Nirmalkumar, et B. Jeyanth, « Performance evaluation of hybrid fibers  
43 strengthened reinforced concrete », *Mater. Today Proc.*, avr. 2023, doi:  
44 10.1016/j.matpr.2023.03.667.
- 45 [46] K.-N. Hong, C.-G. Cho, S.-H. Lee, et Y. Park, « Flexural Behavior of RC Members Using  
46 Externally Bonded Aluminum-Glass Fiber Composite Beams », *Polymers*, vol. 6, n° 3, Art. n° 3,  
47 mars 2014, doi: 10.3390/polym6030667.
- 48 [47] S. T. Smith et J. G. Teng, « FRP-strengthened RC beams. II: assessment of debonding strength  
49 models », *Eng. Struct.*, vol. 24, n° 4, p. 397- 417, avr. 2002, doi: 10.1016/S0141-0296(01)00106-  
50 7.
- 51 [48] M. H. Amirhafizan, M. Y. Yuhazri, H. M. Umarfaruq, S. T. W. Lau, A. M. Kamarul, et A. J.  
52 Zulfikar, « Laminated Jute and Glass Fibre Reinforced Composite for Repairing Concrete Through  
53 Wrapping Technique », *Int. J. Integr. Eng.*, vol. 15, n° 1, Art. n° 1, avr. 2023.
- 54  
55  
56  
57  
58  
59  
60  
61  
62  
63  
64  
65

[49] WILHEM et G. clasen, « Rapport du Marché de Jute pour janvier 2023 ». Natural fiber worldwid, 2023. [En ligne]. Disponible sur: [https://www.wgc.de/media/pages/produkte/jute/b5792261d3-1675415945/fr\\_jute-marketreport\\_01.2023.pdf](https://www.wgc.de/media/pages/produkte/jute/b5792261d3-1675415945/fr_jute-marketreport_01.2023.pdf)

[50] « Glass Fiber Price in the United States - 2023 - Charts and Tables - IndexBox ». Consulté le: 6 octobre 2023. [En ligne]. Disponible sur: <https://www.indexbox.io/search/glass-fiber-price-the-united-states/>

1  
2  
3  
4  
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6  
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