Biomaterials as an Alternative to Steel Reinforcement in Concrete: A Comparative Analysis of Stiffness and Strength

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ABSTRACT

Objective: To assess whether any biomaterial can match both the tensile strength and the elastic modulus of reinforcing steel, and to quantify the reinforcement area required when it cannot. **Methodology:** Eleven bio-based materials were compared with CA-50 steel and GFRP bars using published data, a strength–modulus selection chart and equivalent-area calculations for a 20 × 50 cm C30 beam reinforced with four 16 mm bars. **Results:** Stiffness governed design in every case. The stiffest macroscopic candidates (cellulose nanofibril filament, flax fibre and densified wood) required 2.4–5.3 times the steel area, raw bamboo 10.5 times, and strength-based sizing delivered only 3–33% of the cracked stiffness of the steel-reinforced beam. **Limitations:** Representative literature values, a single beam geometry, perfect bond and no long-term effects were assumed. **Originality:** A simple stiffness-based screening criterion separates promising biomaterials from those that excel only in strength. **Conclusions:** Biomaterial reinforcement should follow the design path established for GFRP, governed by deflection, and is currently suited only to members in which deflection is not critical.

Keywords: biomaterials; non-metallic reinforcement; bamboo; nanocellulose; material selection; reinforced concrete.

1 INTRODUCTION

Reinforced concrete relies on steel to carry tension, and that steel brings two well-known problems: corrosion and the energy needed to produce it. The cement matrix protects the bar with a pore solution at pH 12 to 13, which forms a passive film on the steel, but chlorides and carbonation break down this protection over the service life (Javadian et al., 2020). The result is loss of bar cross-section, cracking of the cover and maintenance costs that grow with the age of the structure.

The industry's answer has been non-metallic reinforcement. Glass fibre-reinforced polymer (GFRP) bars do not corrode and have higher tensile strength than steel, but an elastic modulus of only 35 to 51 GPa (Saleh et al., 2019). Despite this low stiffness, GFRP reached the building codes: in 2022 the American Concrete Institute published ACI CODE-440.11-22, the first comprehensive code for concrete structures reinforced with GFRP bars, modelled on ACI 318-19 (ACI Committee 440, 2022). A low modulus, therefore, does not rule out structural use; it changes the criterion that governs design.

Biomaterials enter this debate for a different reason: their renewable origin. Bamboo has been studied as reinforcement since the early twentieth century, and in Brazil the group led by Ghavami at PUC-Rio has worked on the subject since 1979 (Ghavami, 2005). In recent years, cellulose-based materials with properties far above those of natural wood and bamboo have appeared. Partially delignified, densified wood reached a tensile strength of 548.8 MPa (Song et al., 2018). Filaments of aligned cellulose nanofibrils reached 1.57 GPa in strength and 86 GPa in modulus (Mittal et al., 2018). Among unprocessed biological materials, the teeth of the limpet, a marine mollusc, showed tensile strengths between 3.0 and 6.5 GPa (Barber et al., 2015).

These figures feed the idea of a "bio-steel" able to replace the metal bar without loss. The question behind this work is narrower: is there a biomaterial whose tensile strength and elastic modulus both equal or exceed those of steel? And if not, how much material would be needed to make up the difference in a real member?

The aim of this paper is to answer that question in a quantitative and reproducible way, without laboratory testing. To this end, (i) a property database for eleven biomaterials is compiled from the literature; (ii) these materials are placed on a strength × modulus selection chart alongside steel and GFRP; and (iii) for a reference beam, the reinforcement area each material would need to match the

strength and the stiffness of steel is computed. The contribution is a simple screening criterion that separates promising materials from those that impress only in strength.

2 THEORETICAL BACKGROUND

2.1 Requirements for a reinforcing bar

A reinforcing bar has to meet five requirements at once, and tensile strength is only one of them.

1. *Tensile strength*: sets the maximum force the reinforcement can carry at the ultimate limit state. Brazilian CA-50 steel has a minimum characteristic yield strength of 500 MPa (ABNT, 2024).
2. *Elastic modulus*: sets how much the bar elongates under service loads and, therefore, crack widths and deflections. NBR 6118 adopts 210 GPa for reinforcing steel (ABNT, 2023).
3. *Bond*: the bar only works if force passes from the concrete into it. Hygroscopic materials swell with water from fresh concrete and shrink when they dry, opening a gap at the interface.
4. *Ductility*: steel yields before it fails, so the beam gives warning through wide cracks and large deflections. A material that stays elastic up to rupture gives no such warning.
5. *Durability in alkaline media*: the bar must keep its properties for decades inside a medium with a pH close to 13.

The second requirement is the one most often overlooked when materials are compared. In a cracked beam the tensioned concrete no longer contributes, and the flexural stiffness depends almost entirely on the product $E \cdot A$ of the reinforcement. A bar with half the modulus of steel, at the same area, roughly doubles the reinforcement strain for the same force.

2.2 The GFRP precedent

GFRP is the most useful precedent for this study. Its bars have tensile strengths of 483 to 1,600 MPa but moduli of 35 to 51 GPa, against 200 GPa for steel (Saleh et al., 2019). They are linear elastic up to rupture, with no yield plateau. Even so, the material has been codified: ACI CODE-440.11-22 allows almost any member covered by ACI 318-19 to be designed with GFRP instead of steel (ACI Committee 440, 2022).

The code handles the low modulus through three measures: stricter serviceability checks, larger safety margins to account for brittle rupture, and reductions of the design strength according to the exposure environment. In practice, the design of GFRP-reinforced beams is usually governed by deflection and crack width, not by strength. A biomaterial would have to follow the same path.

2.3 Why biomaterials are compliant

Almost all structural biomaterials follow the same logic: stiff fibres embedded in a softer matrix. In plants, the fibres are microfibrils of crystalline cellulose, and the matrix consists of hemicellulose and lignin. Bamboo, for example, is described as a natural composite in which cellulose fibres reinforce a lignin matrix, much like a fibre-reinforced polymer (Javadian et al., 2019).

The cellulose crystal itself is very stiff. For perfect crystals, the axial modulus has been estimated at 124 to 173 GPa and the strength at about 7.5 GPa (Moon et al., 2011). The problem is scale: going from crystal to fibre, from fibre to yarn and from yarn to member introduces matrix, voids, misalignment and defects. Natural and man-made cellulose composites are 3 to 15 times weaker than the nanofibrils they are made of (Mittal et al., 2018). This is why the modulus of wood and bamboo lies between 10 and 30 GPa, far below that of the crystal.

In animal tissues, the role of the stiff fibre is played by proteins or minerals. Tendon collagen has a modulus of about 1.2 GPa and a strength of 0.12 GPa. Spider dragline silk reaches 1.1 GPa in strength, but with a modulus of only 10 GPa (Gosline et al., 1999; Gosline et al., 2002). The exception is the limpet

tooth, a composite of nanofibres of the mineral goethite in a chitin and protein matrix, which combines high strength with a modulus of 90 to 140 GPa (Barber et al., 2015; Lu et al., 2012). Structural proteins are therefore strong and tough but compliant; high stiffness in nature comes from crystals, whether of cellulose or of minerals.

2.4 Durability of plant fibres in concrete

The alkaline environment of cement is hostile to plant fibres. Sisal and coconut fibres kept in a calcium hydroxide solution at pH 12 completely lost their flexibility and strength after 300 days (Tolêdo Filho et al., 2000). In the composites, the main mechanism was mineralisation: hydration products, mainly calcium hydroxide, migrate into the fibre lumen and walls and make the fibre brittle.

There are known ways to reduce this attack. Pre-soaking the fibres in silica fume slurry, early curing in a CO_2-rich environment and partial replacement of cement by silica fume reduced the embrittlement of the composites (Tolêdo Filho et al., 2003). For bamboo, coatings also improve bond: epoxy-coated splints showed a bond strength of 2.75 MPa, against 0.52 MPa without coating (Ghavami, 2005). Even so, the long-term behaviour of bamboo inside concrete remains an open problem, and cycles of swelling and shrinkage have caused almost complete loss of bond in beams (Javadian et al., 2020).

3 METHODOLOGY

The study is entirely computational and has three steps: property compilation, a selection chart and calculations on a reference beam. All calculations were carried out in a Python script, with the input data listed in Table 2.

3.1 Property database

Eleven biomaterials were selected in three groups, plus two references (CA-50 steel and GFRP): (a) available at scale: bamboo culm, bamboo-fibre composite, sisal fibre, flax fibre and unidirectional flax/epoxy composite; (b) laboratory-processed: densified wood and cellulose nanofibril filament; and (c) high-performance biological materials without large-scale production: spider silk, tendon collagen, cellulose crystal and limpet tooth.

For each material, the published ranges of tensile strength and elastic modulus were recorded, and a representative value within the range was adopted for the calculations. Where the source gives a single value, it was used directly. Single-fibre values (flax, sisal) are upper bounds, because a bar made from these fibres needs a matrix and loses part of the properties; the flax/epoxy composite was therefore included as a realistic case. The cellulose crystal and the limpet tooth exist only at the nanometre or micrometre scale and are included as a theoretical bound on what biology achieves.

3.2 Selection chart

The materials were plotted on a tensile strength $\times$ elastic modulus chart on logarithmic axes, in the format of material selection maps. The steel point divides the plane into quadrants. A direct substitute for steel would have to fall in the upper-right quadrant, with a strength of at least 500 MPa and a modulus of at least 210 GPa.

3.3 Reference beam and equivalent areas

A rectangular beam of $b \times h = 200 \times 500$ mm was adopted, with effective depth $d = 450$ mm, C30 concrete and tension reinforcement of four 16 mm CA-50 bars, giving $A_s = 804$ mm^2. The secant modulus of the concrete was taken from NBR 6118, $E_{cs} = 26.8$ GPa. The maximum longitudinal reinforcement area, 4% of the concrete section, is 4,000 mm^2. Table 1 summarises these parameters.

For each biomaterial i, two areas were computed. The first matches the tensile capacity of the steel

Table 1. Reference beam

Parameter	Symbol	Value	Unit
Width	b	200	mm
Total depth	h	500	mm
Effective depth	d	450	mm
Concrete secant modulus (C30)	E_{cs}	26.8	GPa
Steel area (4 bars of 16 mm)	A_s	804	mm^2
Steel yield strength	f_{yk}	500	MPa
Steel modulus	E_s	210	GPa
Maximum reinforcement area (4%)	$A_{s,max}$	4,000	mm^2

reinforcement:

$$A_{f,i} = A_s \, \frac{f_{yk}}{f_i} \tag{1}$$

The second matches the axial stiffness $E \cdot A$, which controls the reinforcement strain under service loads:

$$A_{E,i} = A_s \, \frac{E_s}{E_i} \tag{2}$$

The required area is the larger of the two, and the criterion that produces it is called the governing criterion. The ratio between the required area and A_s measures how much more material the biomaterial demands.

A third analysis shows what happens if the designer sizes the reinforcement by strength alone, as would be done with steel. In this case, the flexural stiffness of the cracked section (stage II) was computed with area $A_{f,i}$. The neutral-axis depth x and the cracked moment of inertia I_{II} follow from the classical expressions, with modular ratio $n_i = E_i/E_{cs}$:

$$\frac{b\,x^2}{2} = n_i \, A_{f,i} \, (d - x) \tag{3}$$

$$I_{II} = \frac{b\,x^3}{3} + n_i \, A_{f,i} \, (d - x)^2 \tag{4}$$

The result was expressed as a percentage of the stiffness $E_{cs} I_{II}$ of the steel-reinforced beam. Since deflection is inversely proportional to this stiffness, a stiffness of 25% means a service deflection about four times larger.

3.4 Simplifying assumptions

The analysis uses characteristic values with no partial safety factors, so that all materials are compared on equal terms. It assumes perfect bond, linear elastic behaviour and properties that remain stable over time. All of these assumptions favour the biomaterials, so the results represent an optimistic scenario. The effect of an additional factor for brittle rupture and degradation is discussed in Section 5.

4 RESULTS

4.1 Compiled properties

Table 2 lists the published ranges and the values adopted in the calculations. Seven of the eleven biomaterials have a representative strength equal to or greater than 500 MPa, but none comes close to a modulus of 210 GPa outside the nanoscale.

Table 2. Tensile properties compiled from the literature

Material	Group	f (MPa)	E (GPa)	Adopted f / E	Source
CA-50 steel	Reference	$\geq$ 500 (yield)	210	500 / 210	ABNT (2023, 2024)
GFRP	Reference	483–1,600	35–51	1,000 / 45	Saleh et al. (2019)
Bamboo culm	At scale	140–363	11–22.6	250 / 20	Faruk et al. (2012); Javadian et al. (n.d.)
Bamboo-fibre composite	At scale	270 (mean); $>$ 400 in prototype	30 (mean); $\sim$50 in prototype	270 / 30	Javadian (2022); Javadian et al. (n.d.)
Sisal fibre	At scale	511–635	9.4–22	570 / 16	Faruk et al. (2012)
Flax fibre	At scale	345–1,830	27–80	800 / 50	Dong (2018)
Flax/epoxy composite (48% fibre)	At scale	387	35	387 / 35	EcoTechnilin (n.d.)
Densified wood	Laboratory	300–549	up to 40	549 / 40	Song et al. (2018); Jakob et al. (2022)
Cellulose nanofibril filament	Laboratory	1,570	86	1,570 / 86	Mittal et al. (2018)
Spider dragline silk	Natural	1,100	10	1,100 / 10	Gosline et al. (1999)
Tendon collagen	Natural	120	1.2	120 / 1.2	Gosline et al. (2002)
Cellulose crystal	Natural (nano)	$\sim$7,500	124–173	7,500 / 150	Moon et al. (2011)
Limpet tooth	Natural (micro)	3,000–6,500	90–140	4,750 / 120	Barber et al. (2015); Lu et al. (2012)

4.2 Selection chart

Figure 1 shows that the zone where a material would match steel in both properties is empty for macroscopic materials. Only the cellulose crystal and the limpet tooth, which exist only at the nanometre or micrometre scale, approach it.

The points spread along a diagonal band below and to the left of steel. The processed materials (densified wood and nanocellulose) shift upwards and to the right relative to bamboo and sisal, showing the gain obtained by aligning and densifying cellulose. Spider silk and collagen sit on the left: they are strong or tough, but compliant.

4.3 Equivalent areas in the reference beam

Table 3 gives the areas computed for the reference beam ($A_s = 804$ mm^2). For every biomaterial, the area required by stiffness (A_E) exceeds the area required by strength (A_f); stiffness is always the governing criterion.

Three results stand out. First, only three macroscopic materials fit in the section with the same stiffness as steel: the cellulose nanofibril filament, flax fibre and GFRP. Second, densified wood sits at the limit (4,222 mm^2 against 4,000 mm^2 allowed). Third, when the area is set by strength alone, the biomaterial-reinforced beam loses 67% to 97% of its cracked stiffness.

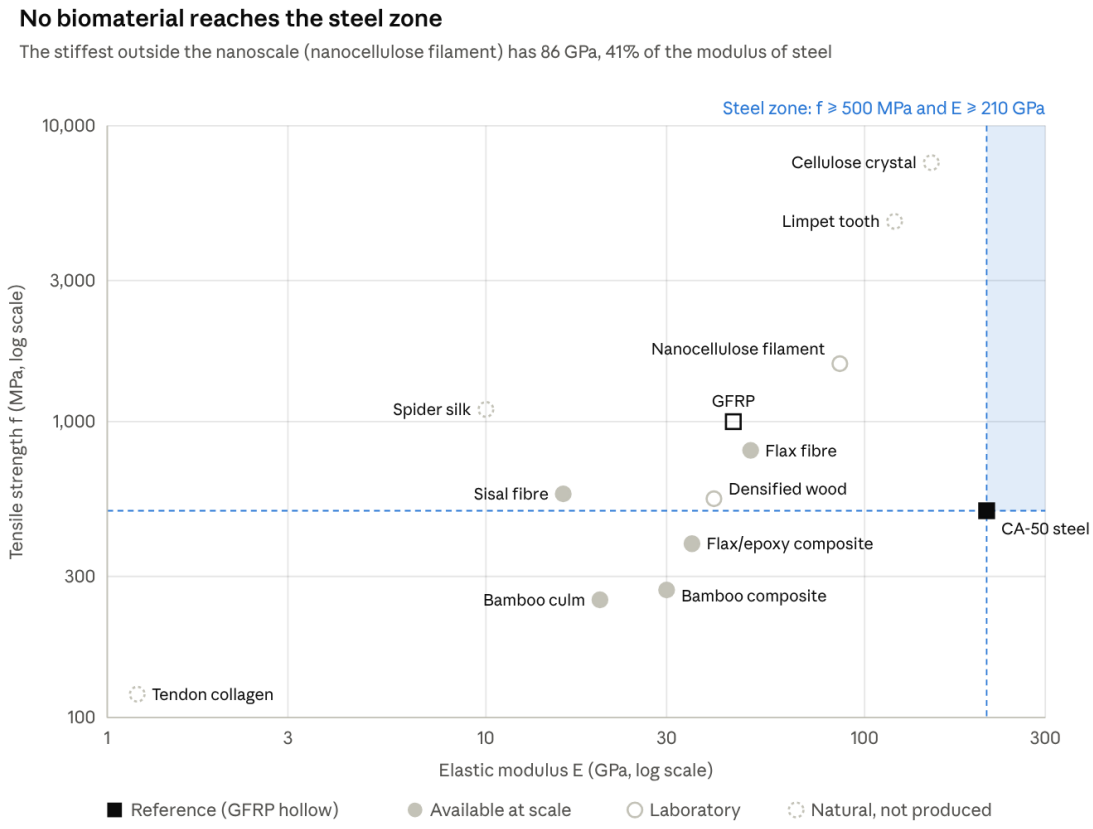


Figure 1. Strength × modulus selection chart. Adopted values from Table 2

5 DISCUSSION

5.1 Strength is not the problem; stiffness is

The central result is that stiffness governs the design for all eleven biomaterials. Seven of them have a representative strength equal to or greater than the 500 MPa of steel and, by that criterion alone, would need less area than steel. When the same axial stiffness is required, the picture reverses: none of them falls below 1.4 times the steel area, and even that value applies only to the cellulose crystal, which does not exist at bar size.

Comparison with GFRP helps put these numbers in context. A GFRP bar needs 4.7 times the steel area for the same stiffness and is nevertheless codified and used in practice. By this criterion, the cellulose nanofibril filament (2.4 times) and flax fibre (4.2 times) would be as good as or better than GFRP. Densified wood (5.3 times) and the flax/epoxy composite (6.0 times) are slightly worse and already exceed, by a small margin, the 4% reinforcement limit of the section. The bamboo composite (7.0 times), the bamboo culm (10.5 times) and sisal fibre (13.1 times) exceed that limit by a wide margin: in this beam there is simply no physical room for the required material.

Structural proteins are out of the running. Spider silk, often described as “stronger than steel”, would need 21 times the steel area for the same stiffness, and collagen 175 times. Proteins have remarkable strength and toughness, but the stiffness needed to reinforce concrete comes, in nature, from crystals of cellulose or minerals.

5.2 The trap of sizing by strength alone

If the designer replaces steel with a biomaterial and sizes it by force alone, as would be done with steel, the resulting beam has 3% to 33% of the cracked stiffness of the original beam. Since deflection is inversely proportional to this stiffness, service deflections would be 3 to 30 times larger.

Table 3. Equivalent reinforcement areas and cracked stiffness, sorted by area ratio

Material	A_f (mm^2)	A_E (mm^2)	A_{req}/A_s	$\leq 4\%$ limit?	EI_{II} with A_f (%)
CA-50 steel	804	804	1.0	yes	100
Cellulose crystal	54	1,126	1.4	yes	7
Limpet tooth	85	1,407	1.8	yes	9
Cellulose nanofibril filament	256	1,964	2.4	yes	18
Flax fibre	503	3,378	4.2	yes	20
GFRP	402	3,753	4.7	yes	15
Densified wood	732	4,222	5.3	no	23
Flax/epoxy composite	1,039	4,825	6.0	no	28
Bamboo-fibre composite	1,489	5,630	7.0	no	33
Bamboo culm	1,608	8,445	10.5	no	25
Sisal fibre	705	10,556	13.1	no	10
Spider silk	366	16,889	21.0	no	3
Tendon collagen	3,351	140,743	175	no	4

This result has a counter-intuitive side: the stronger the material, the worse the beam sized by strength. Spider silk, being very strong, receives little area and delivers only 3% of the stiffness. The bamboo composite, being weaker, receives more area and reaches 33%. High strength on its own is a trap: it reduces the area precisely in the material that most needs it.

The same conclusion follows from the rupture strain, $\varepsilon_u = f/E$. CA-50 steel yields at a strain of about 0.24%. The biomaterials reach their strength only at much larger strains: about 1.1% for the flax/epoxy composite, 1.3% for bamboo, 1.4% for densified wood, 1.6% for flax fibre, 1.8% for the nanocellulose filament and 11% for spider silk. To use the strength of these materials, the reinforcement would have to elongate 5 to 46 times more than steel, which means very wide cracks in the surrounding concrete.

5.3 Effect of a factor for brittle rupture and degradation

The analysis used characteristic values without reduction. In practice, a brittle material prone to degradation would receive an additional strength reduction, as is already the case for GFRP. Applying an illustrative factor of 0.5 to the strength of the biomaterials doubles the area required by the strength criterion. Even so, it remains smaller than the area required by stiffness in every case. For the bamboo culm, for example, the strength-based area rises from 1,608 to 3,217 mm^2, still well below the 8,445 mm^2 required by stiffness. The conclusion that stiffness governs is therefore robust: it does not depend on the safety factor chosen.

5.4 Feasibility of each candidate

The figures above measure mechanical performance only. To reach the construction site, each material must still overcome barriers of scale and durability.

The cellulose nanofibril filament is the stiffest macroscopic candidate, but it has been produced only as threads 5 to 20 μm in diameter, and its authors point to sensitivity to humidity as a limitation (Mittal et al., 2018). A concrete reinforcing bar would require millions of aligned threads in a matrix, which would lower the modulus.

Flax fibre and the flax/epoxy composite are the closest to market. The composite with 48% fibre content is already sold as a prepreg (EcoTechnilin, n.d.). The resin protects the fibres from the alkaline medium, following a technological path similar to that of GFRP. Durability inside concrete, however, still needs to be studied.

Densified wood has good strength, but it swells substantially after 24 hours of water immersion, which its authors flag as an important drawback (Jakob et al., 2022). Inside fresh concrete, this swelling

would repeat the bond problem seen with bamboo.

Bamboo, as culm or composite, is cheap and abundant. The Brazilian standard NBR 16828-1 covers structures made of bamboo culms (ABNT, 2020), but it does not apply to glued laminated bamboo or to composites and does not address bamboo as concrete reinforcement. The bamboo-fibre composite has been tested in beams, and its authors concluded that the ACI guidelines for FRP are suitable for members where deflection does not govern, such as low-cost, low-rise housing (Javadian et al., 2020).

Silk, collagen, the cellulose crystal and the limpet tooth are not practical candidates. The first two have a very low modulus; the last two exist only at the nanometre or micrometre scale. They serve as a reference for what biology can achieve and as inspiration for biomimetic materials.

5.5 Working around the low stiffness

Since stiffness is the bottleneck, the strategies that make sense are those that increase the stiffness of the member rather than the strength of the material. Increasing the section depth is the simplest, because the cracked stiffness grows roughly with the square of the effective depth. Prestressing, already studied with basalt-fibre bars, reduces deflections by keeping the reinforcement in a favourable state under service loads. Hybrid reinforcement, with a minimum amount of steel to provide stiffness and ductility and the biomaterial supplying the remaining strength, is another option. All of these strategies are natural subjects for future numerical studies.

5.6 Limitations

The study uses representative values from wide ranges, and natural materials vary greatly between species, batches and parts of the plant. The analysis considers a single beam geometry, perfect bond and elastic behaviour, with no creep or degradation over time. These assumptions favour the biomaterials, so real performance is likely to be worse than calculated. The qualitative conclusion, that stiffness governs, does not depend on them.

6 CONCLUSIONS

This work compared eleven biomaterials with CA-50 steel and GFRP bars as potential concrete reinforcement, using only published data and section calculations. Within the domain investigated, the following conclusions were drawn:

1. No biomaterial available at scale matches steel in both strength and modulus. Several exceed 500 MPa in strength, but the stiffest outside the nanoscale, the cellulose nanofibril filament, has 86 GPa, or 41% of the modulus of steel. Stiffness equal to or greater than that of steel appears only in nanoscale structures, such as the cellulose crystal and the limpet tooth.

2. Stiffness governs the design in every case, even when a factor of 0.5 is applied to strength to account for brittle rupture and degradation.

3. The most promising candidates are cellulose-based. The nanocellulose filament (2.4 times the steel area) and flax fibre (4.2 times) match or outperform GFRP (4.7 times), which is already codified. Densified wood (5.3 times) and the flax/epoxy composite (6.0 times) come close, but already at the limit of the section.

4. Densified wood, the flax/epoxy composite, bamboo and sisal cannot match the stiffness of steel in the beam studied, because the required area exceeds the 4% limit of the section. Their use makes sense in members where deflection does not govern.

5. Structural proteins are not suitable as reinforcement. Silk and collagen would require 21 to 175 times the steel area.

6. Sizing a biomaterial by strength alone produces beams with 3% to 33% of the original stiffness. Design must start from deflection and crack-width checks, as is already done with GFRP.

The answer to the initial question is therefore negative for modulus and positive for strength. The realistic path for biomaterials is not to copy steel but to follow the GFRP model: accept the lower modulus, design for stiffness and, at first, restrict use to members where deflection is not critical. Future work should extend the analysis to several beam and slab geometries, model beams reinforced with flax/epoxy and bamboo composite by the finite element method including bond, assess hybrid steel and biomaterial reinforcement, and estimate the environmental benefit through life cycle assessment, taking into account the larger reinforcement area required.

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