

# Bioinspired curved brick-mortar architectures for enhanced mechanical performance: Insights from cuscutea reflexa stem morphology

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## ABSTRACT

We investigated the epidermal morphology, microstructure, and mechanical properties of the stem of *Cuscuta reflexa* (dodder) to uncover the mechanisms underlying its high mechanical strength. Natural stems and experimentally fabricated bio-inspired models were examined using microscopy, numerical simulations, and mechanical testing. The results show that the stem's distinctive curved brick-and-mortar architecture plays a critical role in enhancing mechanical performance, providing superior strength compared to conventional stem structures (e.g., those with straight interfaces). This bio-inspired curved configuration produces tensile stress-strain curves shifted to higher stress levels relative to simple (uncurved) brick-and-mortar designs, enabling the structure to withstand greater tensile loads before failure. Furthermore, flexural tests on the bio-inspired models demonstrated a 20% increase in flexural strength for the modified curved brick-and-mortar structure compared to the basic uncurved configuration. Crack propagation in the modified composite is influenced by elevated shear stress at the interfaces, promoting preferential crack growth perpendicular to the loading direction (horizontal) within the hard mortar phase. This behavior enhances fracture toughness through longer crack propagation paths and increased energy dissipation. Additionally, the larger interfacial area and higher mortar volume fraction in the modified structure contribute to more efficient load transfer and improved crack resistance.

## 1. Introduction

The development of next-generation lightweight, high-strength, and tough structural materials continues to pose a major challenge in materials science, where conventional designs often encounter fundamental trade-offs between strength and fracture toughness. Nature provides exceptional models through hierarchical, multiscale architectures that optimize mechanical performance using modest constituent materials arranged in sophisticated configurations. Biomimetic approaches, by replicating these strategies, offer a promising pathway to engineer advanced composites that surpass traditional limitations [1].

Nacre (mother-of-pearl) serves as a prominent exemplar, renowned for its characteristic "brick-and-mortar" microstructure

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featuring stiff aragonite platelets (bricks) separated by compliant organic interlayers (mortar). This design facilitates crack deflection, bridging, and progressive interfacial sliding with locking, yielding fracture toughness dramatically higher than that of its brittle mineral phase while preserving substantial stiffness and strength. Critical geometric factors, including brick aspect ratio and the relative thickness of vertical to horizontal mortar interfaces, govern these enhancements [2–5]. At the nanoscale, such materials exhibit reduced flaw sensitivity, as demonstrated by Gao et al. [5], where structural dimensions approaching the nanometer scale render toughness largely insensitive to defects in composites like nacre, bone, and teeth.

Plant stems, particularly bamboo, offer complementary insights through their extraordinary mechanical versatility. These materials span vast ranges in Young's modulus ( $\sim 0.3$  MPa in soft parenchyma to  $\sim 30$  GPa in dense palm tissues) and tensile strength ( $<1$  MPa in parenchyma to  $>100$  MPa in hardwoods, with crystalline cellulose nearing  $\sim 1$  GPa), arising from hierarchical organization of four primary polymers: cellulose, hemicellulose, lignin, and pectin. At the nanoscale, cellulose forms crystalline microfibrils within a matrix, with lignification and oriented cell wall layers enhancing strength and stiffness. At cellular and tissue scales, architectures vary widely—from honeycomb-like wood and closed-cell foams in parenchyma to vascular bundle-reinforced composites in palm and bamboo—producing lightweight yet mechanically robust structures [6].

Bamboo exemplifies functional grading in its culm, characterized by a radial density gradient: vascular bundles (composed of unidirectional stiff sclerenchyma fiber bundles,  $\sim 21$ – $40\%$  gross volume fraction, including  $5$ – $8\%$  conductive vessels) are densely packed in the outer region ( $\sim 60\%$  volume fraction) compared to the inner region ( $\sim 10$ – $15\%$ ), embedded in a spongy parenchyma matrix [7,8]. This nonuniform fiber distribution induces locally varying properties along the thickness, with stiffness increasing toward the outer surface for enhanced flexural rigidity [9].

Combined with a hollow tubular cross-section, interconnected porous channels, and gradient parenchyma distribution [10], this architecture imparts high flexural stiffness, bending resistance (e.g., under wind-induced loads), and anisotropic fracture behavior while maintaining low density [11]. Nanoindentation mapping of Young's modulus variations, integrated into computational models, reveals orientation-dependent fracture toughness: inward-propagating cracks encounter maximal resistance through dense cellulose bridging and crack-tip shielding; outward cracks exhibit minimal bridging and lowest resistance; side cracks show intermediate toughening via ligament bridging. This gradient explains bamboo's characteristic inside-out splitting under overload [12].

Additional natural systems reinforce these principles, including mantis shrimp [13,14], pearl mussels [15], bone [16,17], Bamboo [11,18], Honeycomb [19,20] and glass sponge [21,22] featuring complex porous and gradient designs. Key mechanical attributes include:

- Hollow/porous architectures enabling lightweight construction and high energy absorption.
- Fine-to-coarse gradients conferring resistance to crack propagation and overall structural hardening.
- Nano-to-macro complex mechanisms delivering synergistic toughening and strengthening.

For instance, bamboo's integration of porous architecture with axially oriented parallel fibers and radial density gradient achieves exceptional flexural stiffness and strength at low weight [23,24].

Translational biomimetic research has advanced these concepts into synthetic materials. Pioneering macroscopic models replicated nacre's sliding and locking using millimeter-scale PMMA tablets connected by transverse fasteners, achieving significant strain hardening and enhanced ductility ( $9$ – $12\%$  strain capacity) while uncovering novel deformation modes such as free-surface effects and "unzipping" relevant to biological composites [25]. More recently, additive manufacturing has facilitated precise fabrication of bio-inspired microstructures—including brick-and-mortar (nacre), cross-lamellar (conch shell), concentric hexagonal (bone osteon), and rotating plywood (stomatopod dactyl club)—with fracture tests demonstrating superior crack resistance curves. Notably, the rotating plywood configuration exhibited the highest work of fracture [26].

These developments highlight the transformative potential of hierarchical, functionally graded, and multiscale designs in creating lightweight composites that harmonize strength, toughness, and damage tolerance beyond conventional capabilities. However, our



Fig. 1. Images of the dodder plant wrapped another plant.

understanding of nature is still in its early stages, and nature's immense potential for inspiring design solutions should be more fully recognized and utilized. This underscores the need for further exploration in this captivating field. In this context, the authors identified a remarkable structure belonging to the dodder plant (genus *Cuscuta*, Fig. 1). Dodder is a parasitic annual plant that infests various crops and native plants. Over 150 species exist worldwide, with the highest prevalence in the Americas. As dodder grows, it repeatedly attaches to host plants and can spread horizontally from one host to another, extending stems more than 50 times their thickness — as measured by the authors. Additionally, dodder stems can adhere to host plants with substantial force. These behaviors motivated the authors to investigate the plant's mechanical properties. While the signaling and agricultural impact of dodder have been examined in several studies [27,28], to the best of the authors' knowledge, its mechanical properties have not yet been systematically characterized. Therefore, the aim of this research is to uncover the underlying role of microstructure in the mechanical properties of the dodder plant (*Cuscuta reflexa*) through bio-inspiration and numerical analysis. Experimental and numerical methods were used to evaluate the tensile strength and bending behavior of the bio-inspired structure. The results emphasize the importance of epidermal geometry and the inherent microstructure for the stability of these plant stems.

## 2. Materials and methods

Dodder specimens were collected from various local regions in Isfahan, Iran. According to ASTM D3822, the samples prepared from the dodder stem were subjected to a tensile mechanical examination by the MTS tensile testing machine.

The macro and microstructure of the dried samples were examined using SEM analysis. By detail evaluation of the microstructure inspired and designed geometrical models were prepared.

The bio-inspired microstructures were fabricated as mechanical bending specimens using the following methodology:

Specimens were produced via a two-stage prototyping process: a) CNC Machining of Wooden preform employing precision-machined using a CNC router with a ball-nose end mill to machine the negative sinusoidal profile into the wood brick preforms to replicate the desired brick-mortar geometries, and b) Epoxy Resin Casting in which a two-part epoxy resin was injected into the cured wooden molds and allowed to cure at 25°C for 24 h to achieve optimal polymerization. To clarify the overall inspiration process—from initial observation in nature to the final inspired model and specimen—an informative diagram is presented in Fig. 2. Subsequently bending tests were conducted on these specimens according to ISO 178 standard with a span of 160 mm, to evaluate the flexural properties of these structures. The total length of the samples was 200 mm.

Given the importance of the effect of the designed structures on the mechanical properties, numerical micromechanical analysis was applied to these structures. The results were presented as maps of stress and strain distributions within the microstructure as well as stress-strain curves.

## 3. Results and discussion

The results of tensile tests on the dodder stem are shown in Fig. 3. The measured mechanical properties indicate an elastic modulus of approximately 0.43 MPa and a tensile strength of approximately 2.5 MPa. Scanning electron microscopy of the stem surface and cross-section revealed a distinct pavement cell structure consisting of lobes and necks, forming a brick-and-mortar-like arrangement (Fig. 4).

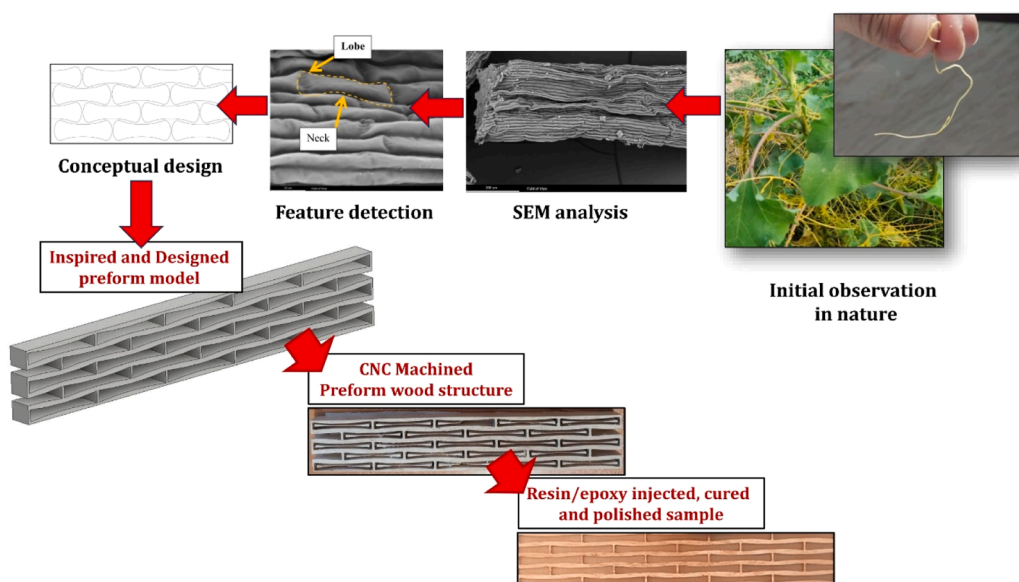


Fig. 2. An informative diagram of overall inspiration process.

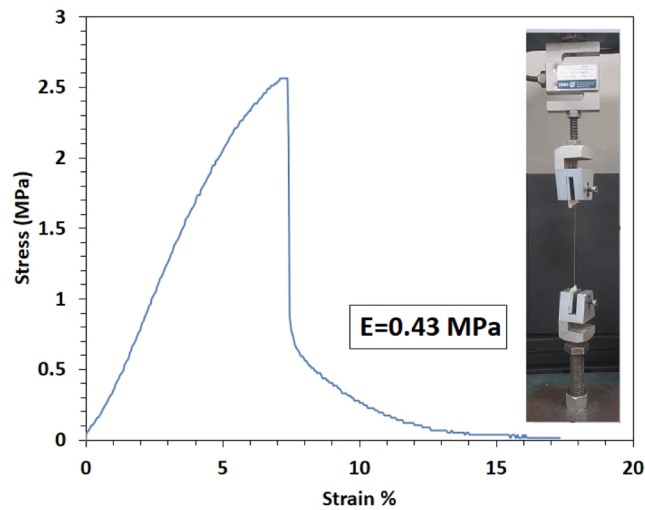


Fig. 3. Stress-strain curve of the tensile test on the specimens.

This distinctive morphology may have significant mechanical implications. We propose the following potential functions for further investigation:

1. Distributing strain concentration regions within the structure during loading to prevent localized strain concentration.
2. Distributing buckling initiation sites during loading to delay single-point or major buckling.
3. Increasing the moment of inertia of the entire structure.
4. Enhancing the trade-off between strength and ductility through the composite brick-and-mortar-like architecture.
5. Inducing compressive stresses around the lobes near the neck regions, which may enhance ductility and fracture resistance.
6. Serving as hard phases (lobes) that reinforce the overall structure.

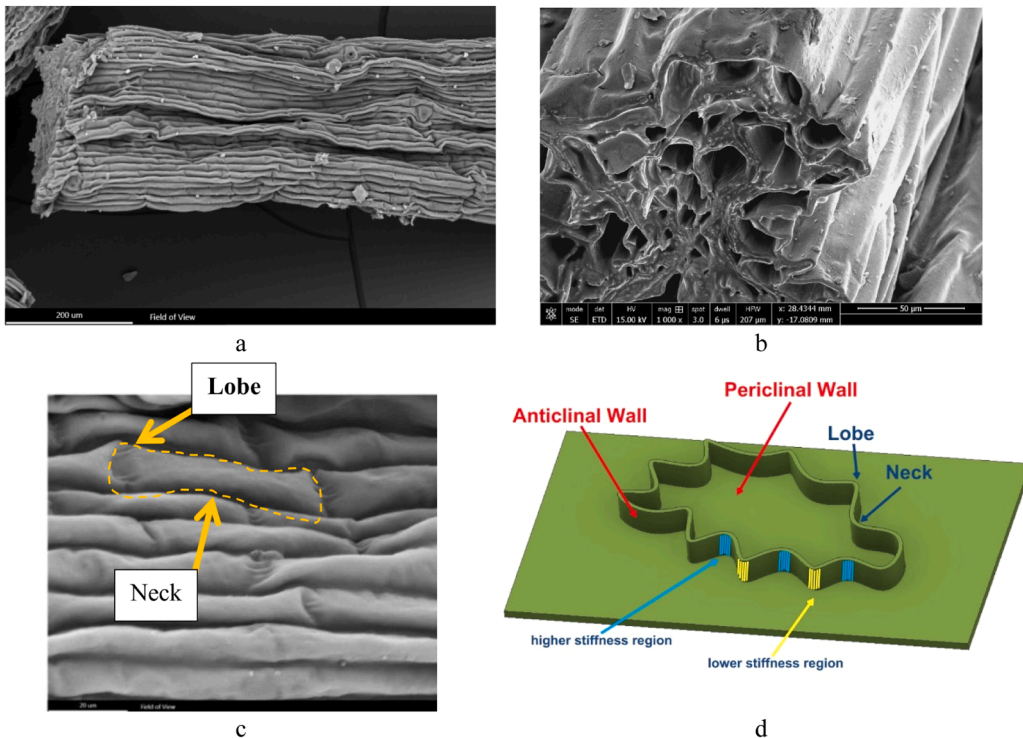


Fig. 4. a, b) SEM micrographs of the dodder plant stem. c) Schematic representation of anticlinal and periclinal cell walls Alternating stiff and soft regions along the wall and across the wall thickness. d) indication of Lobe and Neck within the dodder epidermis.

Based on these hypotheses, we have initiated a comprehensive study of this pavement cell architecture to gain a detailed understanding of its mechanical nature and potential benefits.

### 3.1. Pavement cell structure feature

Cell division is the process by which a parent cell splits into two or more daughter cells. There are two different ways of cell division: anticlinal and periclinal. In periclinal cell division, the cell splits parallel to the tissue or organ surface, resulting in stacked rows of cells, creating a pavement cell structure. On the other hand, anticlinal cell division occurs perpendicular to the adjacent layer of cells, creating columns of cells adjacent to each other. In simple terms, the anticlinal division adds more thickness to the tissue, while the periclinal division adds length.

It has been discovered that the growth of cells in a specific direction leads to the formation of jigsaw-shaped cells in the outer layer of the plant. These cells have alternating neck and lobe regions. The neck region is an indentation while the lobe region protrudes outwards. The neck and lobe regions have different stiffness and strength values, with the lobe being stiffer and stronger [29,30]. Milani et al. [31] have shown that the difference in stiffness between the two regions is about 20 %. Fig. 4(d) shows a representation of the anticlinal and periclinal cell walls with alternating stiff and soft regions along and across the wall thickness. Additionally, Fig. 4(c) shows the presence of Lobes and Necks within the dodder epidermis. Simplified, a pavement cell structure or brick-mortar structure was inspired by the structure of dodder.

### 3.2. Numerical examinations

In general, using a brick-mortar-like structure has been found to be effective in improving the strength and ductility of materials. However, different patterns of brick and mortar as well as height-to-width ratio (aspect ratio) of the bricks and the horizontal mortar thickness [32] could alter the outcome.

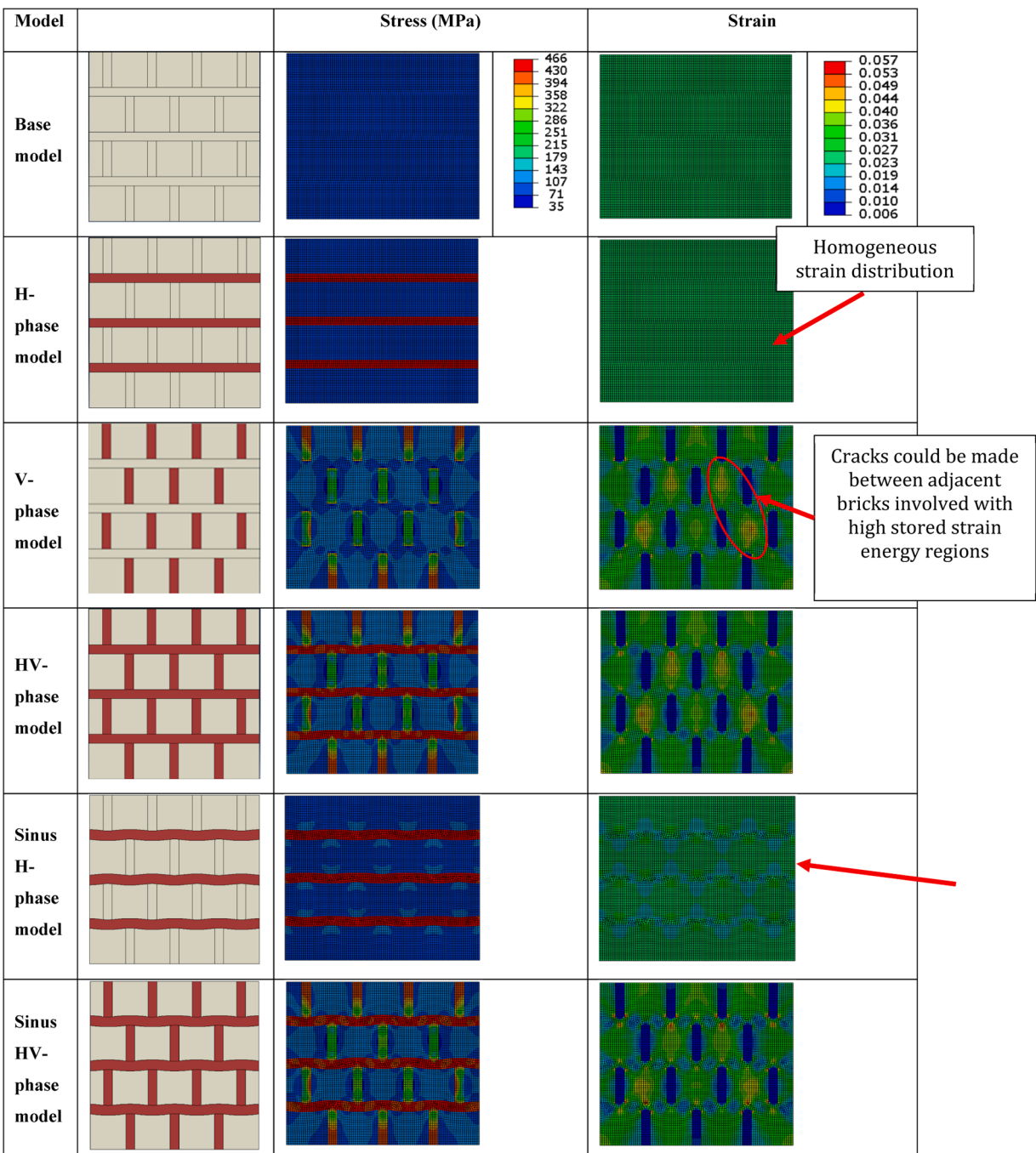
In this study, the brick-mortar appearance of the dodder structure has been considered, and four construction patterns/models have been hypothetically proposed, as shown in Fig. 5. Then, the finite element method is used to study the brick-and-mortar structures inspired from the dodder structure on the mechanical behavior of material. The models are titled base model, V-phase model, H-phase model and HV-phase model. The red areas in the models show the hard phase, while the gray areas depict the soft phase. There is no hard phase in the base model. In the H-phase model, only horizontal boundaries are considered as hard phases, while in the V-phase model, only vertical boundaries are considered as hard phases. In the HV-phase model, the hard phase is chosen for vertical and horizontal boundaries. Among these models, HV-phase model seems to be the most appropriate. This model appears to be more consistent with reality, but in order to gain a good understanding of the deformation within these structures, the four models were loaded and stress-analyzed in their entirety. The wood material is assigned for the hard mortar and the epoxy-resin is considered for the soft brick. The raw wood and employed epoxy-resin tensile properties are measured experimentally. Because the fact the both wood and epoxy resin are nearly brittle materials, the elastic property is only considered for them. The boundary conditions and material parameters for the hard and soft phases are listed in Fig. 6(a) and Table 1. Simple tensile tests are applied to all models. As can be seen in Fig. 6(a), for implementing the boundary loading which approximates the uniaxial tension, symmetry conditions are applied on planes  $x = 0$  and  $y = 0$ . There is no traction on plane  $y = b$ ; and all nodes on the surface have the same displacement in the direction normal to the surface. The model is subjected to a uniaxial tension by displacing the plane at  $y = a$ . Fig. 6(b) depicts the model together with the mesh used for it. The linear quadrilateral elements of type CPS4R are used for simulation. The mesh dependency analysis was carried out for all models. The stress-strain curves obtained from simulation for these models are presented in Fig. 7.

Our findings highlight the unique characteristics of the HV-phase model. Fig. 7 shows that adding a vertical hard phase (V-phase) to the base material leads to a slight increase in tensile strength. Similarly, incorporating a horizontal hard phase (H-phase) increases the stress to a level comparable to that of the base material. However, the H-phase model exhibits a remarkable increase in stress compared to the V-phase model. The HV-phase model, which combines both V- and H-phases, shows a further increase in strength relative to the H-phase model. Consequently, both the H-phase and HV-phase models exhibit superior strength, making them more effective for higher energy absorption capacity.

To better elucidate the deformation behavior in the supposed models, stress and strain distribution within the microstructure of these materials are calculated and presented in Fig. 5, columns 2 and 3, respectively. As shown in Fig. 5, the stress magnitude within the vertical phases of the V-phase model is low, because all deformation is accommodated by the soft phase. Consequently, the vertical phase does not function as a load-bearing skeleton, and strain concentrates in the soft phase located between the vertical phases. This interphase region therefore serves as an energy-storage zone. Regions of high strain concentration are likely sites for crack initiation. The adjacent zones formed between the vertical phases may coalesce, leading to either initial microcracks or microcrack bridging. While microcrack bridging can retard crack propagation, its occurrence alongside microcrack coalescence may still contribute to early microstructural damage. Similar bridging and cracking between adjacent bricks in a brick-and-mortar structure were also observed in a previous study [1].

On the other hand, in the H-phase model, the hard horizontal phase acts as a load-carrying phase, which leads to an increase in the ultimate tensile strength of the material. In the H-phase model, the hard and soft phases are layered on top of each other and both endure the same amount of deformation. The behavior of the hard phase is brittle as long as it does not fail; it only shifts the stress-strain diagram.

The coexistence of vertical and horizontal phases could promise an increase in strength. The effect of regular microstructure morphology or uniform distribution of reinforcing phases on increasing the uniformity of strain distribution as well as preventing the



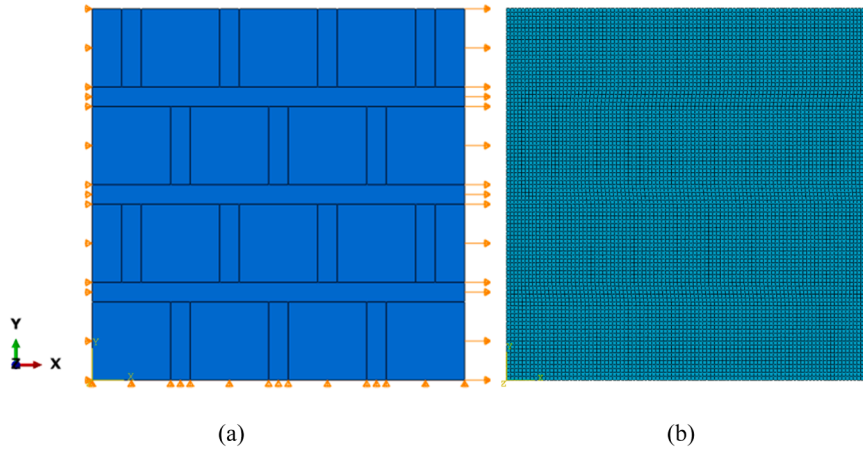


Fig. 6. (a) Loading and boundary conditions of the model, (b) Mesh generation of the model.

Table 1

Material parameters for the hard and soft phases.

| Parameter                            | Value |
|--------------------------------------|-------|
| Elastic modulus for soft phase (GPa) | 1.95  |
| Elastic modulus for hard phase (GPa) | 12.4  |
| Poisson ratio for soft phase         | 0.25  |
| Poisson ratio for hard phase         | 0.29  |

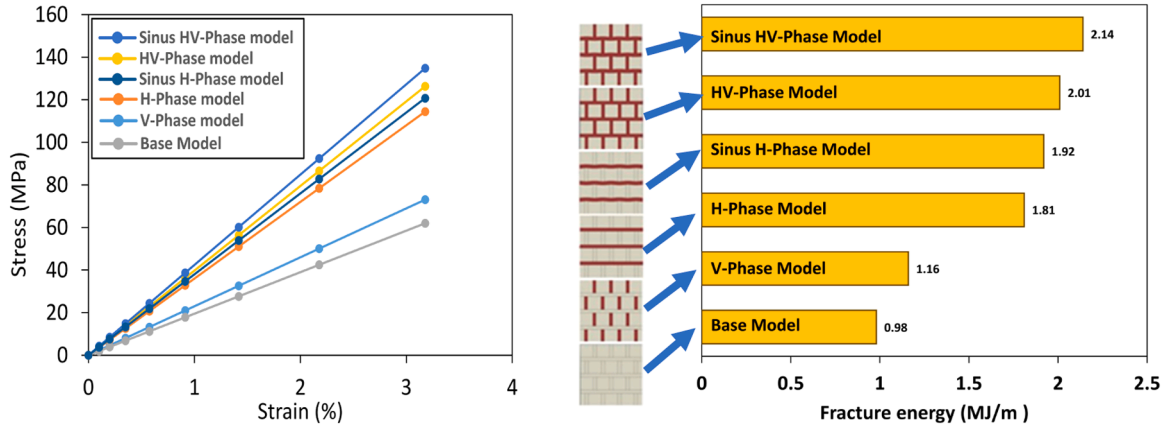


Fig. 7. Structural patterns/models supposed for micromechanical analysis as well as their numerical calculated stress-strain diagrams and fracture energy calculated by the area under the stress-strain curve.

strain localization regions and growing and interacting of these regions with each other is well discussed in the authors' previous paper [33]. The higher stored energy capacity of the HV-phase structure could also be elucidated from the strain-stress curve. Overall, the higher the area under the stress-strain curve, the higher the stored energy capacity or fracture energy of the material. It would also lead to the higher damage resistance of the material. Comparison of the area under the stress-strain curve or the fracture energy of different structural models studied are presented in Fig. 7.

More detailed observation of the dodder structure reveals a curved morphology along the brick-mortar-like structure as depicted in Fig. 8. The models mentioned above are thus modified as presented in the Sinus H-phase model and Sinus HV-phase model in Figs. 5 and 7. Surprisingly, as can be seen in Fig. 7, the curved structures shift up the stress-strain curves of the previous models, as seen in the H-phase and Sinus H-phase models and also in the HV-phase and Sinus HV-phase models. Less homogenous strain distribution is obvious in the Sinus H-phase model compared with that in the H-phase model as shown in Fig. 5. Based on the preceding discussions, it was concluded that the presence of heterogeneous strain distribution would result in strain accumulation within the microstructure. This, in turn, leads to the higher strain hardening compared to that observed in the homogeneous microstructure. The same conclusion can also be drawn for the Sinus HV-phase model. Overall, it is observed that the brick-mortar microstructure with the curved interfaces

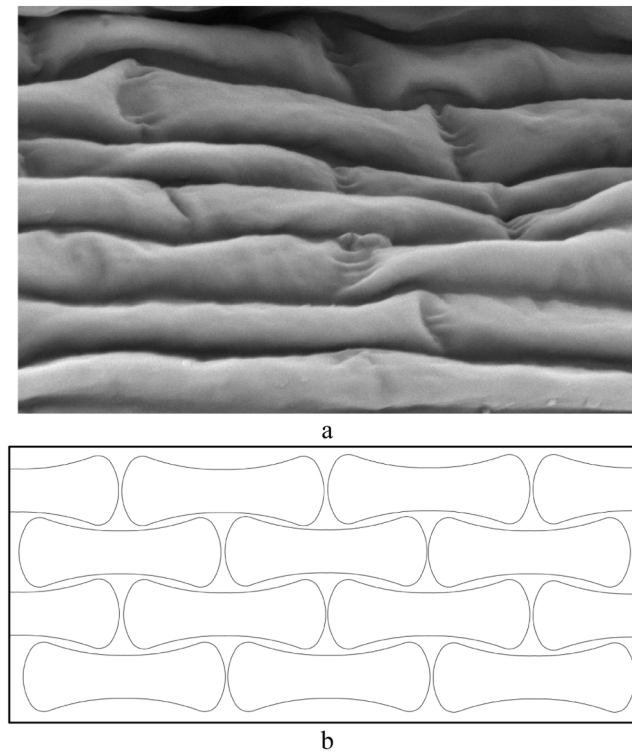


Fig. 8. a) SEM image representing the real epidermal morphology of the dodder, b) Adapted brick-mortar structure with curved interfaces.

leads to the most superior mechanical properties within the structures inspired by the dodder stem plant. To more precisely investigate the effect of curved interfaces on the behavior of the brick-and-mortar structure, experimental tests were conducted.

### 3.3. Experimental examinations

To better elucidate the brick-mortar morphology, experimental validation was conducted on CNC-machined specimens composed of wood and epoxy-resin. The specimens were designed to replicate two distinct structural configurations:

- Sinus HV-phase model, representing a curved brick-mortar morphology.
- HV-phase model, featuring a simple, non-curved brick-mortar interface.

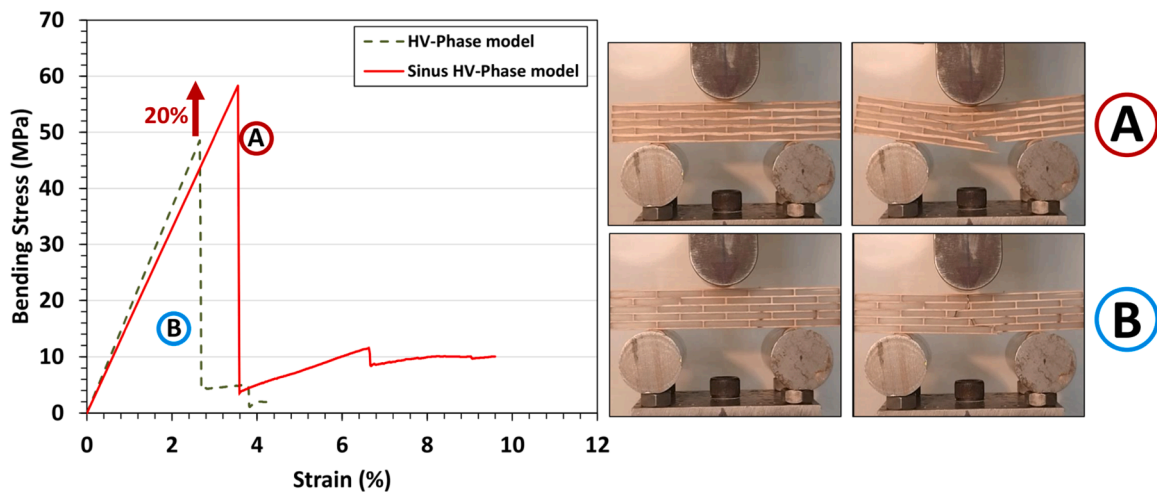


Fig. 9. The experimental flexural bending test on simple basic and cured brick-mortar morphology.

Each model was fabricated using a hard mortar (wood) and a soft brick (epoxy resin). The tensile properties of the raw wood and the epoxy resin were measured experimentally, and the results are presented in Table 1. As illustrated in Fig. 9, the highest performance was achieved by combining the hard mortar with a sinusoidal morphology. These findings align closely with the simulation results shown in Fig. 5, confirming the superior load-bearing capacity of curved interfaces within stiff mortar matrices.

Experimental bending observations comparing a standard rectangular-brick specimen (HV-Phase model) and a specimen incorporating bricks with sinusoidal interfaces (Sinus-HV) revealed significant improvements in the mechanical behavior of the Sinus-HV configuration. Specifically, superior load-bearing capacity and increased fracture energy absorption are evident. These enhancements can be quantitatively attributed to fundamental micromechanical mechanisms related to interfacial load transfer and crack propagation.

#### 1. Geometrical factors contribution:

The sinusoidal geometry of the bricks in the Sinus-HV phase model intrinsically increases the brick/mortar interfacial area ( $A_i^{\text{Sinus-HV}}$ ), compared to the planar interfaces in the HV Model ( $A_i^{\text{HV}}$ ), such that:  $A_i^{\text{Sinus-HV}} > A_i^{\text{HV}}$ . This increased interfacial area facilitates significantly enhanced load transfer efficiency ( $\eta$ ) from the relatively soft brick phase to the hard mortar phase. It could be said that the effective stress borne by the mortar phase ( $\sigma_{m,\text{eff}}$ ) under an applied global stress ( $\sigma_{\text{applied}}$ ) is governed not only by its volume fraction ( $V_m$ ) but critically by  $\eta$ :

$$\sigma_{m,\text{eff}} \propto \eta \cdot \frac{\sigma_{\text{applied}}}{V_m}, \quad (1)$$

where the load transfer efficiency factor ( $0 \leq \eta \leq 1$ ) depends on interfacial properties and geometry. A second geometrical factor—increased mortar volume fraction ( $V_m$ )—further enhances load-bearing capacity and energy dissipation during crack propagation. This effect is captured by a modified rule of mixtures incorporating  $\eta$ , which describes the global compressive strength ( $\sigma_c$ ) of the composite:

$$\sigma_c = \sigma_b V_b + \eta \sigma_{m,\text{ult}} V_m \quad (2)$$

#### 2. Increased Fracture Energy Absorption:

The observed greater final crack length in the Sinus-HV phase model is a direct indicator of enhanced fracture energy absorption ( $G_f$ ), defined as the energy dissipated per unit area of new crack surface formed ( $J/m^2$ ).

A longer crack path ( $af$ ) necessitates the dissipation of more energy to create the additional crack surface area and to drive crack propagation through the microstructure. This increased energy dissipation arises from mechanisms such as crack deflection, bridging by aggregate or brick fragments, and frictional pull-out within the tortuous crack path promoted by the sinusoidal geometry and higher mortar volume.

As observed (Fig. 10), in the curved brick-mortar specimen, it is observed that the crack propagation path follows a stair pattern, guided by shear stresses along the mortar joints. However, in the simple brick-mortar specimen, the applied stresses are transmitted to the bricks, and crack growth occurs either through the bricks themselves or along the vertical brick-mortar interfaces.

In brick-and-mortar architectures featuring curved (or wavy) bricks, the mechanisms of brick sliding and progressive locking facilitate heterogeneous stress distribution, thereby mitigating rapid strain localization [25]. In the present study, within the region indicated in Fig. 11, a locking compressive stress is introduced as the curved bricks slide against each other under applied stress. According to the Mohr-Coulomb failure criterion (Eq. 3) [34], this additional locking compressive stress reduces the critical shear stress in the overlap regions (Fig. 11), thereby directing the crack propagation path along the shear stress direction.

Consequently, in a nacre-like brick-and-mortar composite subjected to bending deformation, cracks are preferentially deflected and channeled to propagate nearly horizontally within the mortar phase. This horizontal crack trajectory significantly reduces the incidence of crack paths oriented perpendicular to the loading direction. As a result, the crack must extend further along the mortar before the local crack driving force (e.g., stress intensity factor) reaches the critical value required for final fracture. This extended crack path, combined with associated energy dissipation mechanisms (such as friction and interfacial sliding), ultimately contributes to higher overall fracture toughness.

$$\tau_{\text{MC}} = \tau_c + \mu_{\text{MC}} \sigma_n \quad (3)$$

where  $\tau_{\text{MC}}$  is the critical shear stress under a normal stress,  $\tau_c$  is the critical shear stress in the absence of normal stress,  $\mu_{\text{MC}}$  is the



Fig. 10. crack growth morphology in the studied Sinus-HV phase and HV phase models' structure.

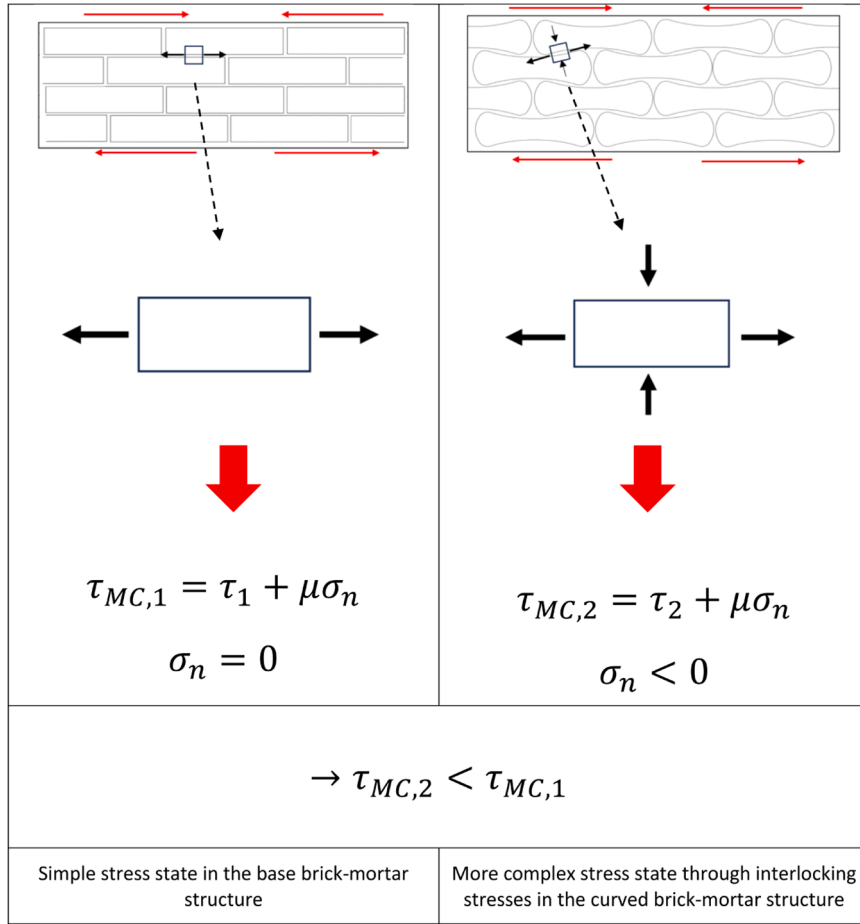


Fig. 11. evaluation of the shear stress in the mortar phase, in studied brick-mortar structures.

coefficient of friction, and  $\sigma_n$  is the normal stress (negative for compression).

Overall, the Sinus-HV phase model demonstrates enhanced mechanical performance, characterized by higher load-bearing capacity ( $\sigma_c$ ) and fracture energy absorption ( $G_f$ ), compared to the base simple rectangular brick-mortar configuration. In this context, the geometric factors contribute in micromechanical mechanisms explanation by two items: (1) A significantly increased brick/mortar interfacial area ( $A_i$ ) which enhances load transfer efficiency ( $\eta$ ) to the strong mortar phase, and (2) elevated volume fraction of the mortar phase which amplifies its load-bearing contribution and energy dissipation during crack propagation. These observations are consistent with the findings of reference [25] in their PMMA-based model material, where brick waviness and transverse reinforcement (via fasteners that emulate mineral bridges) promoted progressive locking and strain hardening while influencing failure patterns through free-surface effects and unzipping. However, our focus on crack dynamics under bending in the Sinus-HV geometry reveals additional aspects of crack channeling and deflection that were not fully addressed in previous millimeter-scale tensile models, underscoring the role of curvature-induced shear in governing fracture resistance.

#### 4. Conclusions

To improve the trade-off between strength and ductility, the microstructure of a unique plant, dodder (*Cuscuta* sp.), was investigated. Examination of the microstructural details inspired various bio-inspired models, which were then experimentally investigated using wood–epoxy composites. The results demonstrated the significant influence of microstructural and epidermal morphology on the mechanical properties of this plant. The key findings are presented below:

- The plant stem was found to consist of a pavement cell structure comprising lobes and necks, forming a brick-and-mortar-like architecture.
- Simulations of the brick-and-mortar microstructure incorporating curved interfaces, inspired by the plant stem structure, yielded superior mechanical properties compared to a simple brick-and-mortar configuration.

- The experimental wood–epoxy model, inspired by the epidermal morphology of *Cuscuta reflexa*, exhibited enhanced bending performance, with flexural strength increased by up to 20%.
- The improved crack resistance in the modified structure is attributed to geometry-induced shear stress concentration at the hard mortar interfaces, which directs crack growth parallel to the loading direction. This orientation promotes greater energy dissipation during crack propagation, ultimately resulting in higher fracture toughness.

### CRedit authorship contribution statement

**saeidi navid:** Writing – original draft, Investigation, Formal analysis, Conceptualization. **Mohammad Jafari:** Writing – review & editing, Visualization, Validation, Software, Investigation. **Parastoo Ebrahimi:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Parsa Salehi:** Investigation, Formal analysis.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Data Availability

Data will be made available on request.

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