HIERARCHICAL BRICK–AND–MORTAR COMPOSITES FOR DAMAGE TOLERANCE AND PROGRESSIVE FAILURE

Soraia Pimenta, Joël Henry

meComposites, Mechanical Engineering Department, Imperial College London,
South Kensington Campus, London, SW7 2AZ, UK
Email: soraia.pimenta@imperial.ac.uk, joel.henry13@imperial.ac.uk

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Abstract

This work proposes bio–inspired hierarchical brick–and–mortar microstructures — where each "brick" is itself composed of smaller platelets regularly staggered in a matrix — to add damage tolerance to conventionally brittle composites. Finite element simulations of different geometries are performed, using cohesive elements to model damage in the matrix; models with multiple repetitions of unit–cells are also used to evaluate damage dispersion at a macroscopic scale. It is shown that optimised hierarchical brick–and–mortar architectures create a markedly non-linear material response, with extensive energy dissipation before failure, and also delay damage localisation in larger structures.

1. Introduction

Composite materials are remarkably stiff and strong, but their conventional architecture — with continuous fibres — makes them inherently difficult to manufacture and prone to brittle failure. Discontinuous composites can overcome these two problems, as the discontinuities in the reinforcement allow the fibres to slip, making the material mouldable [1, 2] and less brittle [3, 4].

Two complementary mechanisms can contribute towards a more ductile and damage–tolerant behaviour in discontinuous composites. Before ultimate failure, the matrix is sheared between overlapping inclusions, thus dissipating energy through plasticity or fracture, and leading to a non-linear macroscopic response of the material [5]. During the failure process, the discontinuous architecture promotes crack deflection, thus increasing the fracture surface area and dissipating energy through friction [6].

While these mechanisms have been successful in creating remarkably tough and damage–tolerant natural structural composites — such as nacre, wood and bone [7] — man–made discontinuous composites are often susceptible to damage localisation. It has been shown that, in a brick–and–mortar architecture under tension, strain localisation may occur in large structures even when the material has a (pseudo–) ductile response at the micro–scale [5].

In addition to discontinuous architectures, Nature also uses hierarchies (up to three in nacre and seven in bone) to create damage tolerant materials [8]. This paper therefore combines these two bio-inspired motifs — discontinuous reinforcement and a hierarchical microstructure — in *hierarchical brick–and–mortar composites* (see Figure 1a), to promote diffuse damage and energy dissipation during a progressive failure process.

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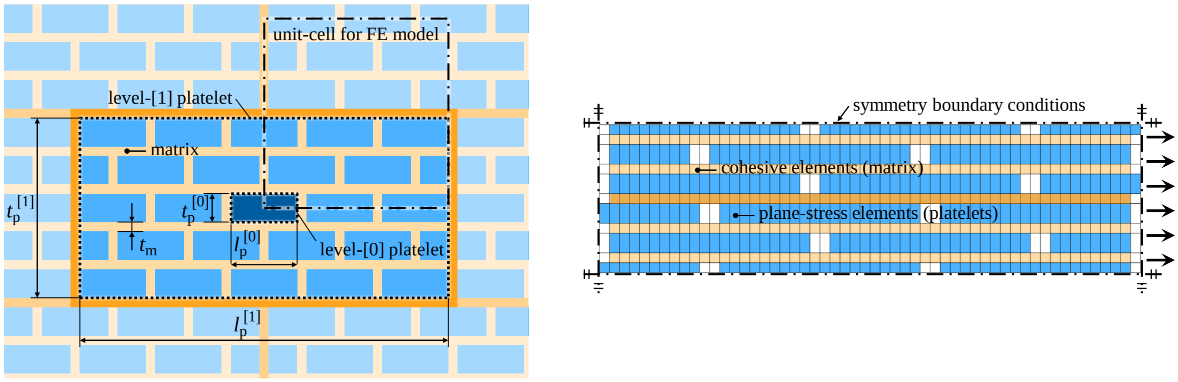

(a) Hierarchical levels and geometric parameters. (b) FE model of a hierarchical B&M unit–cell.

Figure 1: Geometry of a brick–and–mortar composite with two hierarchical levels.

This paper is organised as follows: Finite Elements (FE) simulations (described in Section 2) are used to analyse the local response of hierarchical Brick–and–Mortar (B&M) composites and understand the effect of the microstructure (in Section 3). Section 4 shows how hierarchical B&M microstructures can be used to promote diffuse damage and energy dissipation in the material, and the main conclusions are summarised in Section 5.

2. Finite Element modelling

Figure 1a shows the two–levels hierarchical B&M composite considered in this study. The material is composed of stiff *level–[0] platelets* (with thickness $t_\mathrm{p}^{[0]}$ and length $l_\mathrm{p}^{[0]}$) embedded in a soft *matrix* (with thickness t_m); the B&M arrangement of level–[0] platelets and matrix creates *level–[1] platelets* (with thickness $t_\mathrm{p}^{[1]}$ and length $l_\mathrm{p}^{[1]}$), which are themselves also structured in a B&M arrangement. Hierarchical B&M unit–cells (as exemplified in Figure 1b) are modelled through FE simulations [9], based on variation of the nominal geometry described in Table 1.

Table 1: Geometry of the nominal B&M hierarchical configuration considered in this study.

Level–[0] platelets		Level–[1] platelets		Cohesive layer
thickness $t_\mathrm{p}^{[0]}$	length $l_\mathrm{p}^{[0]}$	thickness $t_\mathrm{p}^{[1]}$	length $l_\mathrm{p}^{[1]}$	thickness t_m
20 μm	500 μm	$5 \times (t_\mathrm{p}^{[0]} + t_\mathrm{m})$	$5 \times (l_\mathrm{p}^{[0]} + t_\mathrm{m})$	10 μm

Table 2: Mechanical properties of the carbon–epoxy thin–ply used as platelets [4].

Longitudinal modulus, $E_{11,\mathrm{p}}$ (GPa)	Transverse modulus, $E_{22,\mathrm{p}}$ (GPa)	Shear modulus, $G_{12,\mathrm{p}}$ (GPa)	In-plane Poisson's ratio, $\nu_{12,\mathrm{p}}$	Longitudinal tensile stength, $X_{\mathrm{T1,p}}$ (MPa)
125.3	8.4	5.1	0.28	2500

Table 3: Mechanical properties of the cohesive elements used in the FE model to represent the matrix [4].

Mode–II stiffness, $G_{\mathrm{II,m}}$ (GPa)	Mode–II strength, $S_{\mathrm{II,m}}$ (MPa)	Mode–II fracture toughness, $\mathcal{G}_{\mathrm{II,m}}$ (kJ/m^2)
1.5	88.5	1.0

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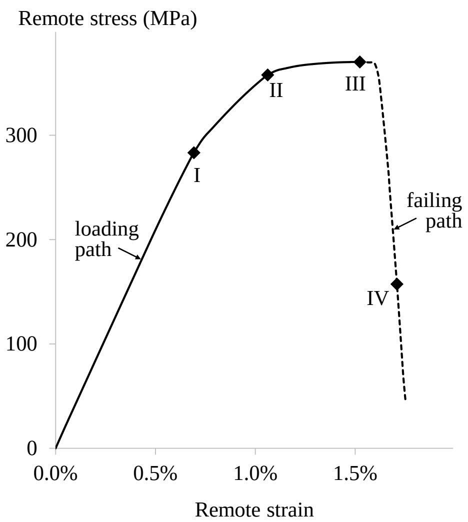
Individual level–[0] platelets are modelled with an orthotropic linear–elastic material with Hashin's criteria, with properties representative of a carbon–epoxy thin ply [4] (shown in Table 2). The matrix is modelled with cohesive elements representing a resin–rich zone between the individual plies, with mode–II properties shown in Table 3.

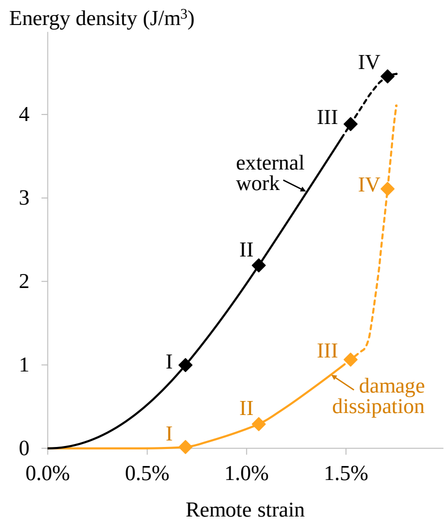
3. Effect of geometry on the failure mechanisms of hierarchical brick–and–mortar composites

Figure 2 shows the results obtained with the unit–cell FE simulation of a hierarchical B&M composite with the nominal geometry defined in Table 1. The response of this material can be decomposed into the following stages:

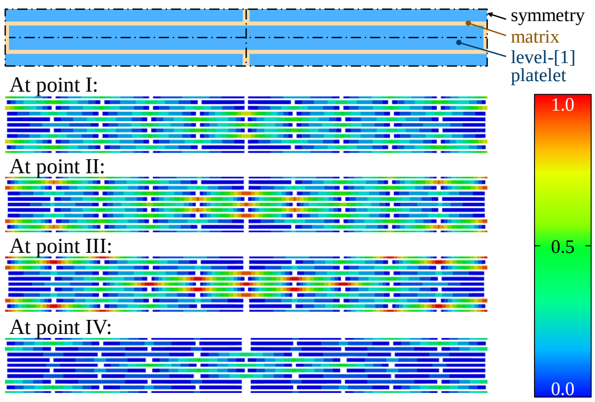
i. *Linear–elastic stage* (up to point I in Figure 2). This stage ends with damage initiation in the matrix, occurring at the edges of the overlaps between level–[1] platelets (as shown in Figure 2d, point I);



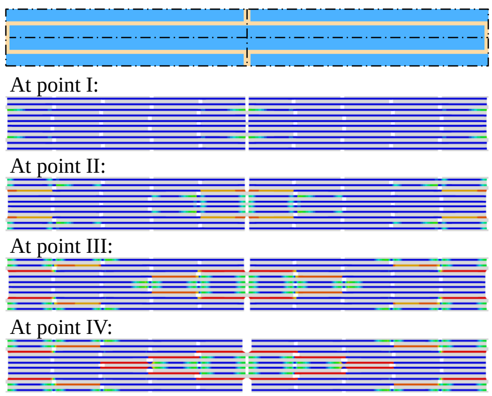
(a) Remove stress vs. strain curve.



(b) External work and energy dissipated by the cohesive matrix.



(c) Longitudinal tensile stresses in the level–[0] platelets (normalised by the maximum value of 2046 MPa observed).



(d) Stiffness degradation in the matrix.

Figure 2: Mechanical response of a hierarchical B&M with nominal geometry (Table 1).

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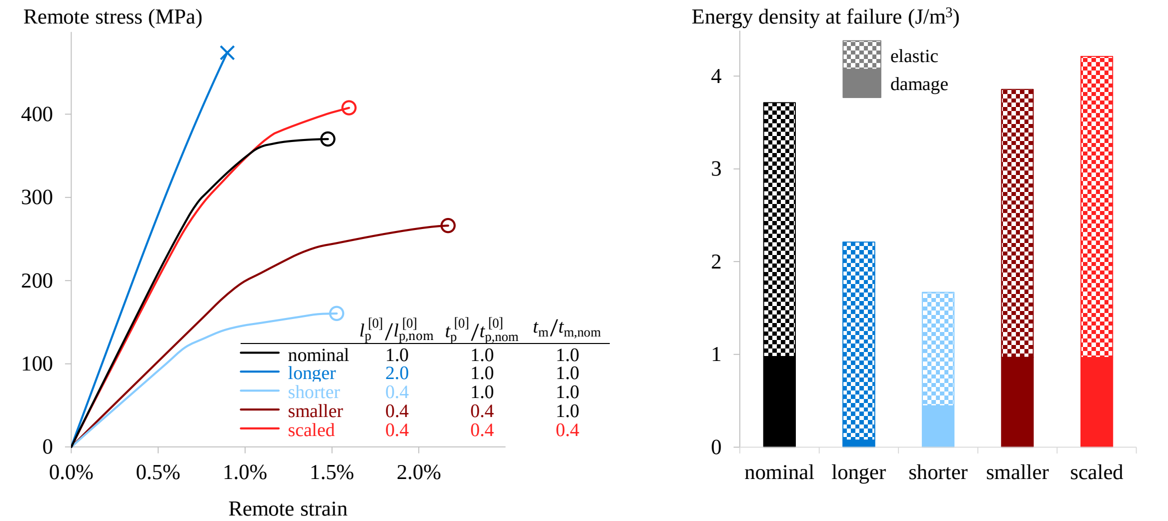
ii. *Damage accumulation stage* (between points I and III in Figure 2). The stresses in the platelets increase further (as shown in Figure 2c, points II and III), but damage in the matrix propagates from the edges of level–[1] overlaps towards the centre of level–[1] platelets, following the overlaps between level–[0] platelets in a staircase pattern (as shown in Figure 2d, points II and III). Consequently, the material loses tangent stiffness in an almost discrete way (see different slopes up to point I, between points I and II, and between points II and III in Figure 2a), corresponding to damage propagation in each individual step of this staircase pattern;

iii. *Post–failure stage* (after point III in Figure 2). The maximum load–bearing capacity of the material (at point III) is defined when a crack tip is fully developed, at which time matrix damage within a level–[1] platelet creates a full rhombus shape. Subsequently, damage localises in one of the two level–[1] platelets in the unit–cell (as shown in Figure 2d, point IV), and the level–[0] platelets unload elastically (as shown in Figure 2c, point IV).

The effect of modifying the geometry of level–[0] platelets on the stress–strain curve and energy dissipation of a hierarchical B&M material is shown in Figure 3, and can be summarised as follows:

a. Decreasing the level–[0] platelet length (compare *nominal* vs. *shorter* configurations) leads to a decrease in the stiffness of the material, as the shear–lag stress transfer becomes less effective. However, increasing the level–[0] platelet length (compare *nominal* vs. *longer* configurations) can lead to fracture of the platelets and, consequently, premature and brittle failure of the hierarchical B&M composite;

b. Decreasing the scale of the level–[0] platelets while keeping the same platelet aspect–ratio and volume fraction (compare *nominal* vs. *scaled* configurations) slightly increases the strength and failure strain of the material, as this is equivalent to increasing the fracture toughness of the matrix [5]. Decreasing the size of the level–[0] platelets while keeping the matrix thickness constant (compare *nominal* vs.



(a) Remote stress vs. strain curves. Only the loading path is shown, and the failure point is identified with a circle (○) for matrix shear failure, and with a cross (×) for platelet tensile failure.

(b) Elastic energy stored and damage energy dissipated at the failure point.

Figure 3: Effect of varying the level–[0] geometric parameters on the mechanical response of hierarchical B&M composites. The nominal configuration is defined in Table 1.

smaller configurations) leads to a decrease in stiffness and strength, and to a small increase in failure strain (due to the higher matrix content);

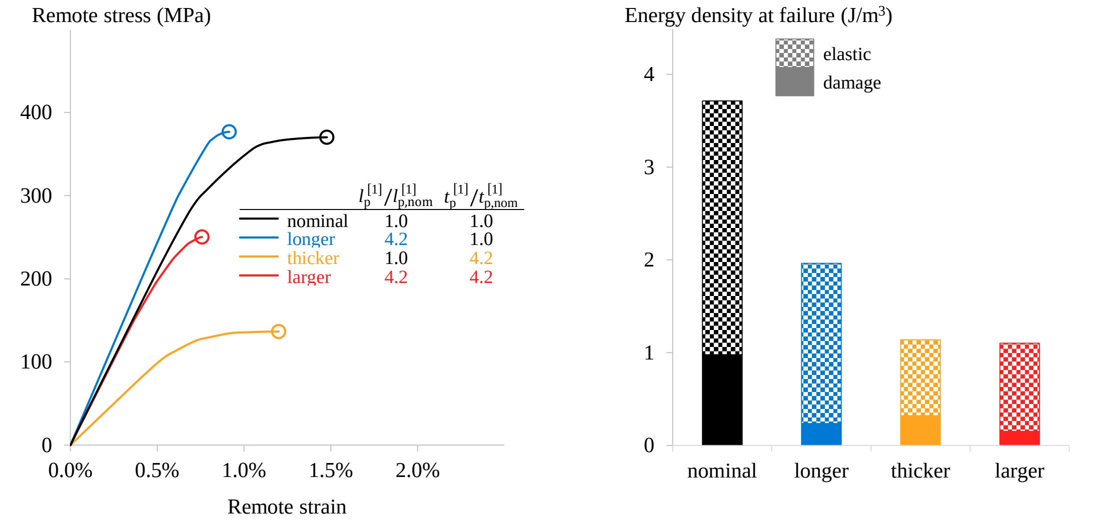
c. Decreasing the level–[0] platelet thickness while keeping the same platelet length and volume fraction (compare *shorter* vs. *scaled* configurations) has a similar effect to increasing the level–[0] platelet length (see point a. above).

The effect of modifying the geometry of level–[1] platelets on the stress–strain curve and energy dissipation of a hierarchical B&M material is shown in Figure 4, and can be summarised as follows:

a. Increasing the level–[1] platelet size while keeping its aspect ratio (compare *nominal* vs. *larger* configurations) leads to a decrease in strength and failure strain. This is due to the finite fracture toughness of the matrix, which limits the shear–lag process zone that can be created before developing a full crack tip, and also limits the size of the rhombus pattern where matrix shear–stresses are effectively transferred (as shown in Figure 2d);

b. Increasing the level–[1] platelet length — or increasing the aspect ratio (compare *nominal* vs. *longer* configurations) — leads to an increase of stiffness and a decrease of failure strain, with no further increase in strength; this is due to the fact that the critical rhombus pattern of matrix damage (shown in Figure 2d) is governed by the level–[1] platelet thickness, and the additional length experiences nearly no damage (and, consequently, nearly no loss of stiffness nor extra deformation);

c. Increasing the level–[1] platelet thickness — or decreasing the aspect ratio (compare *nominal* vs. *thicker* configurations) — leads to loss of stiffness and strength due to a less efficient shear–lag stress transfer, in addition to the same effects observed when increasing the level–[1] platelet size (see point a. above).



(a) Remote stress vs. strain curves. Only the loading path is shown, and the failure point is identified with a circle (○) for matrix shear failure.

(b) Elastic energy stored and damage energy dissipated at the failure point.

Figure 4: Effect of varying the level–[1] geometric parameters on the mechanical response of hierarchical B&M composites. The nominal configuration is defined in Table 1.

4. Energy dissipation and damage localisation in brick–and–mortar composites

While unit–cell FE models (as shown in Figure 1b) are useful to understand the response of periodic microstructures (as described in Section 3), they intrinsically impose periodicity of damage in the post–failure unloading path (seen in Figure 2a), thus artificially avoiding damage localisation. Consequently, FE models with multiple level–[1] unit–cells (i.e. with $n \times n$ unit–cell repetitions along the length and thickness of the model) were also run, with no imposed internal symmetry conditions. The results are shown in Figure 5, comparing two types of B&M configurations: (i) a *hierarchical* architecture with two levels (as previously analysed in Section 3), and (ii) a *single–level* (non-hierarchical) architecture (both configurations correspond to the nominal level–[0] geometry defined in Table 1, and to the same overall model size for the same n).

Figures 5a–5b show that, while the single–level B&M is stronger, the hierarchical B&M material has a much more non-linear stress–strain curve, producing a small plateau (at nearly constant remote stresses) before failure, even when multiple unit–cells are modelled. This results in a twice–as–large energy dissipation through damage of the matrix in the hierarchical configuration compared to the single–level geometry, as shown in Figures 5c–5d.

Figure 5f highlights that, for the single–level B&M architecture, the damage patterns in the matrix are highly dependent on the size of the model, and become very localised for $n = 5$. On the contrary, the hierarchical B&M architecture successfully avoids damage localisation and results in widespread matrix damage (shown in Figure 5e), creating diffuse damage patterns which are fairly independent of the scale of the model.

It must be emphasised that the material properties assumed in the FE models presented in this paper are representative of standard carbon–epoxy composites, which are recognisably brittle. Consequently, the non-linear and energy–dissipative behaviour predicted for hierarchical B&M composites relies not on ductile constituents, but rather on an optimised microstructural design.

5. Conclusions

This work shows that bio-inspired hierarchical brick–and–mortar composites can be designed to fail in a gradual manner, promoting diffuse damage and energy dissipation. The FE results analysed in this paper lead to the following conclusions:

- The optimal geometry of a hierarchical brick–and–mortar composite promotes failure through matrix shearing rather than tensile fracture of the smaller–scale platelets, as well as the formation of rhombus–shaped damage process zones in the matrix within each larger–scale platelet;
- Compared to a single–level brick–and–mortar microstructure, hierarchical brick–and–mortar composites with brittle constituents can show a more pronounced stiffness degradation and dissipate more energy before failure, while maintaining a similar stiffness;
- These characteristics of hierarchical brick–and–mortar composites can provide a warning before catastrophic failure, and reduce stress–concentrations in structures with geometric discontinuities.

Further work will focus on further optimisation of hierarchical brick–and–mortar architectures and experimental validation of the concept.

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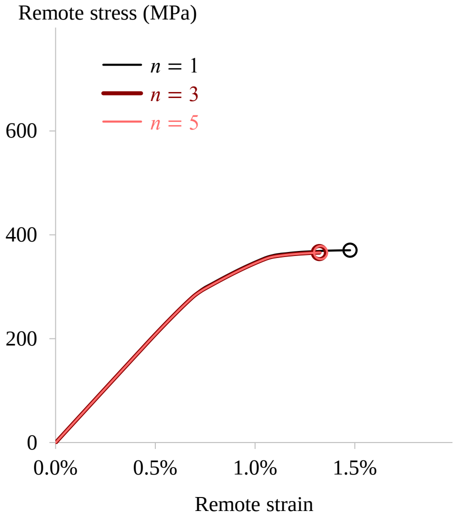
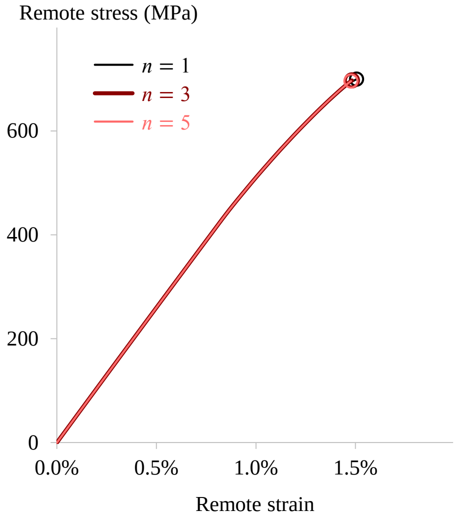
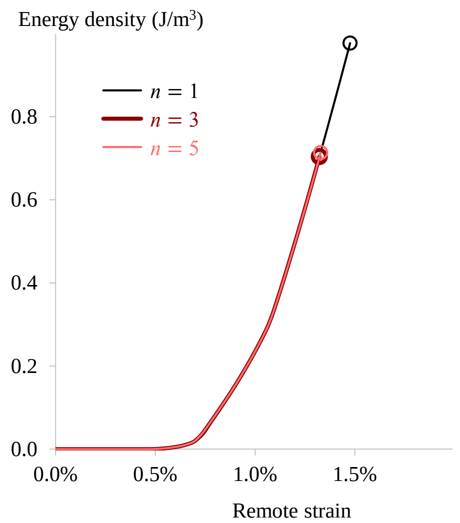


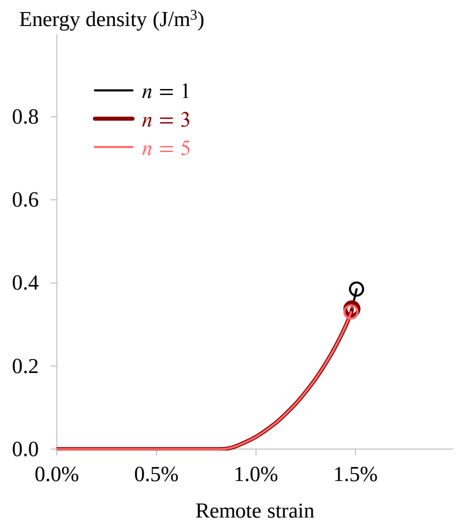
(a) Remote stress vs. strain curves for *hierarchical* B&M composites.



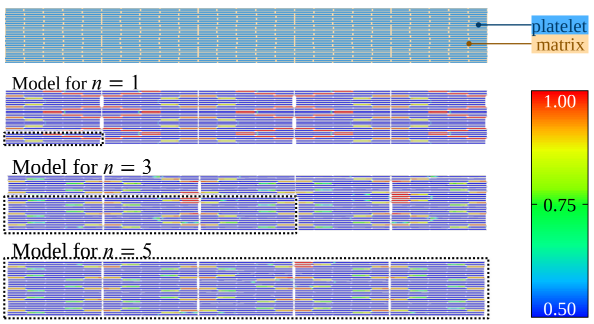
(b) Remote stress vs. strain curves for *single–level* B&M composites.



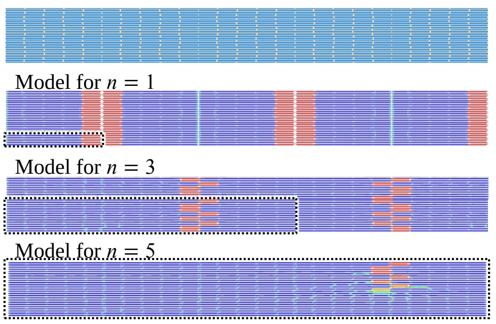
(c) Energy dissipated by damage in *hierarchical* B&M composites.



(d) Energy dissipated by damage in *single–level* B&M composites.



(e) Critical stiffness degradation in *hierarchical* B&M composites.



(f) Critical stiffness degradation in *single–level* B&M composites.

Figure 5: Stress–strain curves and damage localisation for B&M FE models with different numbers of unit–cells ($n \times n$). The fields in subfigures 5e and 5f represent the stiffness degradation of the matrix at the development of a full crack tip; the $n \times n$ domains actually modelled with FE are highlighted by a dashed line, but (for clarity) the results are tiled in a 5×5 domain.

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