21st International Conference on Composite Materials
Xi'an, 20-25th August 2017

INVESTIGATING THE POTENTIAL OF HIERARCHICAL NON-SELF-SIMILAR DISCONTINUOUS COMPOSITES

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Keywords: Discontinuous composites, Hierarchical composites, Modelling, Experiments

ABSTRACT

This work investigates the potential and the applicability of combining hierarchical and discontinuous microstructures to overcome the brittleness of man-made composites. Finite Element simulations were developed to model hierarchical "brick-and-mortar" composites, in which each brick of the structure is itself made of an arrangement of bricks at a smaller scale. Then, optimal brick geometries were identified, manufactured and tested. The experimental results confirmed the potential of such microstructures to dissipate energy stably through damage dispersion in the whole material, hence delaying damage localisation, and providing warning before failure. Finally, non-self-similar microstructures were identified and optimised to improve further the tensile response of composites. It was found that relaxing the constraints of self-similarity could delay damage localisation even more, and increase both the strength and the damage tolerance of hierarchical discontinuous composites.

1 INTRODUCTION

Despite their high stiffness, high strength and their lightweight, conventional continuous-fibre composites are brittle, tend to localise damage, and as a result cannot absorb a significant amount of energy stably. This lack of damage tolerance not only limits the design efficiency of composite-based structures, but also limits their applications.

A first solution to tackle this issue is the use of discontinuous reinforcements, which makes the material more mouldable [1,2] and less brittle [3,4]. Nacre, for instance, is composed of 95% of stiff mineral platelets embedded in 5% of a soft organic phase, and has a 3000-fold increase in toughness compared to the platelets, while maintaining reasonable stiffness and strength [5]. However, man-made composites are often susceptible to damage localisation, and it has been shown that, in a brick–and–mortar (BaM) discontinuous architecture under tension, strain localisation may still occur in large structures even when the material has a (pseudo–) ductile response at the micro–scale [6]. In addition to discontinuities, Nature produces a range of hierarchical microstructures (up to three in nacre and seven in bone) to overcome the brittleness introduced by stiff inclusions (fibres or platelets) [7].

The concept of combining hierarchies and discontinuities in composites has been verified numerically and experimentally by studying hierarchical brick-and-mortar composites [8,9], but only self-similar microstructures (with the same shape of reinforcement at all hierarchical levels) were considered. The aim of this work is to improve further the damage tolerance of hierarchical discontinuous composites by exploring new *non-self-similar* hierarchical microstructures.

This paper is organised as follows: Section 2 explains the concept of hierarchical BaM composites, and quickly summarises the previous work of the authors on such microstructures [8,9]. Section 3 improves further the concept and presents two new non-self-similar microstructures, their failure mechanisms, and how they can be optimised to maximise their damage tolerance. Finally, the last section summarises the main conclusions.

2 THE USE OF HIERARCHIES TO AVOID DAMAGE LOCALISATION

2.1 Finite element modelling

Consider the conventional BaM microstructure shown as ❶ in Table 1; this microstructure is composed of staggered small stiff bricks (or platelets), embedded in a soft mortar (or matrix). This section focuses on a self-similar hierarchical version of BaM composites (shown as ❷ in Table 1), which is composed of small level-0 rectangular bricks which form larger level-1 rectangular bricks [8,9]. Unit-cells as well as whole specimens have been modelled through Finite Element (FE) simulations [10], based on the nominal geometry and properties described in Table 2.

It was found that hierarchical BaM microstructures promote damage dispersion and energy dissipation by damaging the matrix in all level-1 bricks of the material, forming diamond patterns (Figure 1 and 2) [8,9]. Figure 1 shows that matrix degradation is predicted not only at the failure site (shown by the black line), but also away from the failure site. Moreover, Figure 2 shows more non-linearity and more energy dissipation for the hierarchical (❷) than for the conventional BaM (❶) composite. This hierarchical BaM architecture is therefore successful in delaying damage localisation.

The size of the bricks has been optimised at each level to maximise the energy dissipated stably in the material, by promoting interfacial damage. Shorter level-0 bricks cause the matrix/interface to fail at low stress (Figure 3a). On the other hand, longer level-0 bricks trigger brick failure with only little damage in the matrix (Figure 3c). Therefore, the optimum can be found so as to reach high stresses and still fail by matrix shearing rather than brick fracture (Figure 3b). The dimensions of the optimal level-0 bricks are l^{b}=450 µm and t^{b}=18 µm, and level-1 bricks are made of 5×5 level-0 bricks [8,9].

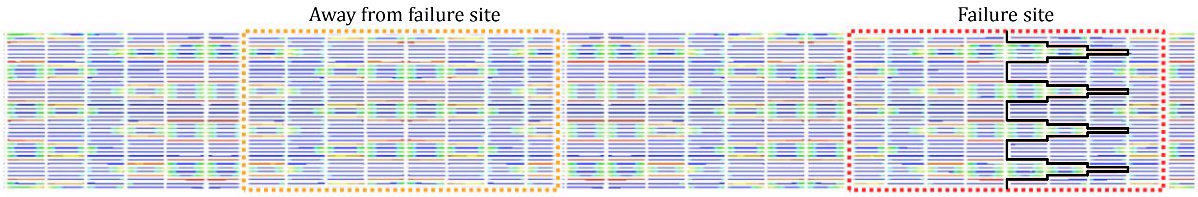


Figure 1: Stiffness degradation in the matrix throughout the whole specimen. Damage can be observed in the matrix both at the failure site and away from the failure site.

2.2 Experimental validation

The FE study [8,9] showed the importance of using thin bricks in hierarchical composites, and therefore thin carbon/epoxy prepreg (23µm thick) was used to achieve a small thickness of the level-0 bricks. A micro-milling laser was used to cut the hierarchical patterns in thin prepreg plies (Figure 4a) which were then laid-up using an alignment fixture (Figure 4b) [4,8]. Specimens were then cut from the cured plate (Figure 4c), end tabbed (Figure 4d), and polished.

Two sets of tests were performed, aiming to validate the model both quantitatively (in terms of stress-strain response) and qualitatively (in terms of damage dispersion). A first set of specimens was tested using optical strain gauges in order to measure the stress-strain response of hierarchical BaM composites. A second set of specimens was tested under a Scanning Electron Microscope (SEM) in order to observe the damage mechanism in the composite.

The results from the tests with optical strain gauges have been compared to the predictions of the model, and similar stress-strain curves were observed (Figure 3). Moreover, the results from the tests in the SEM showed damage dispersion throughout the material, as expected, with several damage mechanisms (Figure 5). The final failure predicted by the model (closure of one half of the diamond pattern, in black in Figure 1) is also verified experimentally [8]. All these results confirm the potential of hierarchical discontinuous composites to delay damage localisation, give damage warning before failure, and dissipate energy stably through damage diffusion in the microstructure.

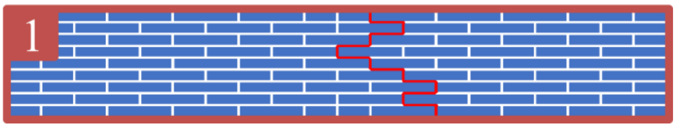
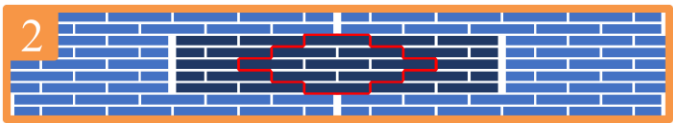
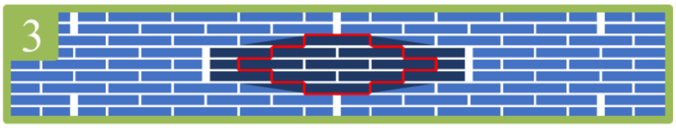
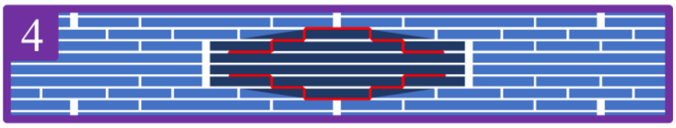
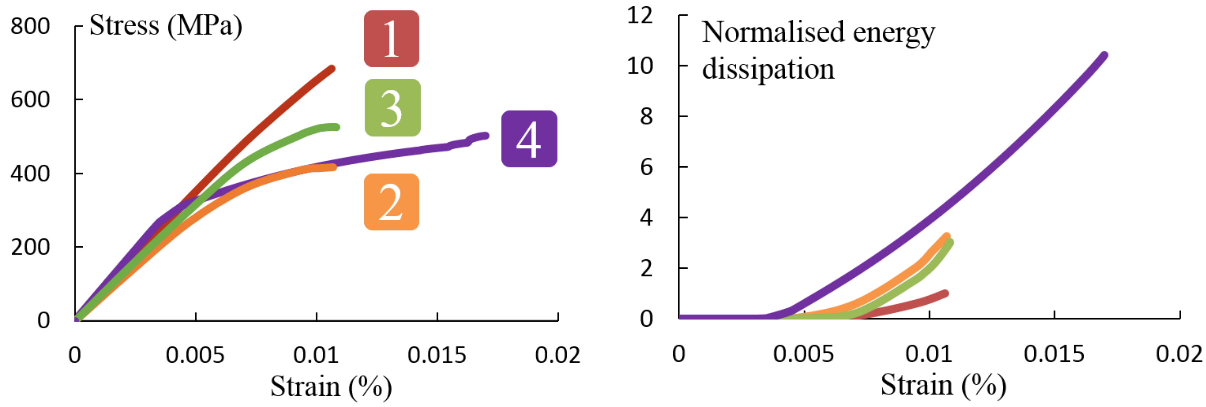
Microstructure	Key features of the microstructure
Brick-and-mortar: 	—
Self-similar hierarchical brick-and-mortar: 	- Delay damage localisation; - Spread damage throughout the structure; - Dissipate energy stably before failure.
Diamond hierarchical brick-and-mortar: 	- Keep the same energy dissipation mechanism as in ❷; - Increase the strength and the stiffness of the composite compared to microstructure ❷.
Strong-core hierarchical brick-and-mortar: 	- Improve the damage dissipation by delaying the damage localisation further; - Achieve a failure strain similar to that of the brick material in bulk.

Table 1: Overview of the BaM microstructures and their key features (failure path is shown in red, and central level-1 brick in dark blue).

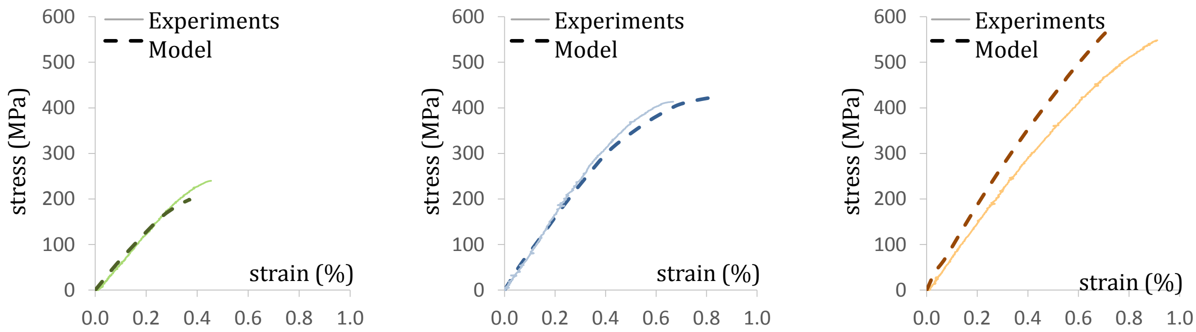


a. Stress-strain curves. b. Normalised energy dissipated versus strain.

Figure 2: Model predictions for the four microstructures presented in Table 1.

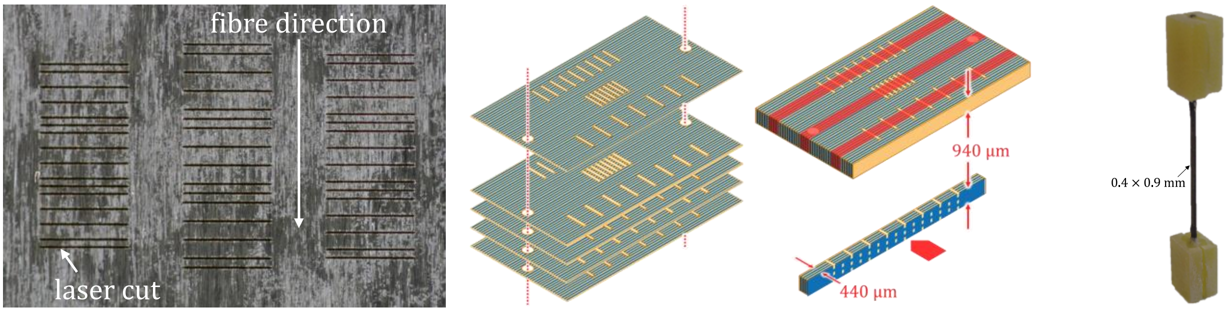
Bricks			Matrix		
Variable	Unit	Value	Variable	Unit	Value
E_1	[GPa]	153.3	G_{II}	[GPa]	1.5
E_2	[GPa]	7.67			
G_{12}	[GPa]	6.52			
X^b	[MPa]	2417.6	S_{II}	[MPa]	88.5
ν_{12}	–	0.28	$\mathcal{G}_{IIc}$	[kJ/m^2]	1.0
t^b	[µm]	18	t^m	[µm]	5

Table 2: Mechanical properties of the level-0 bricks and the matrix in the FE model (derived from [4]).



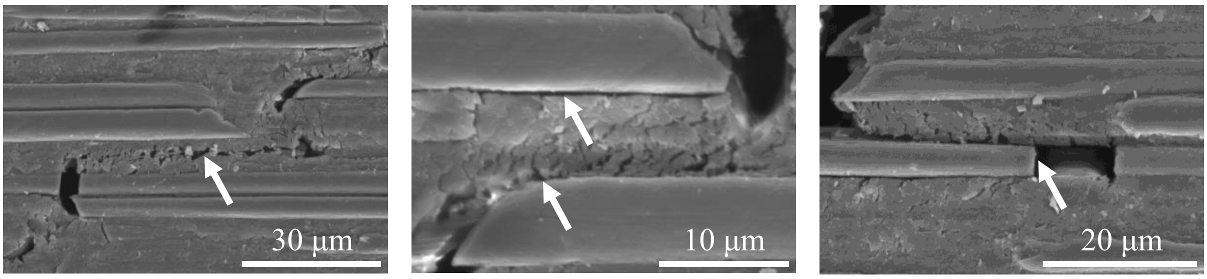
a. Short level-0 bricks. b. Medium-length level-0 bricks. c. Long level-0 bricks.

Figure 3: Stress-strain curves predicted by the model and measured in the experiments for self-similar hierarchical BaM composites.



a. Hierarchical pattern cut in the thin prepreg using the micro-milling laser. b. Alignment of the different plies. c. Cutting of the specimens from the cured plate. d. Specimen.

Figure 4: Manufacturing process used for hierarchical BaM composites.



a. Matrix failure. b. Fibre-matrix interface debonding. c. Fibre pull out.

Figure 5: Different damage mechanisms contributing to the increase of stable energy dissipation before failure in hierarchical brick-and-mortar composites.

3 THE BENEFITS OF NON-SELF-SIMILAR ARCHITECTURES

3.1 Diamond hierarchical BaM

The main drawback of self-similar hierarchical BaM microstructures is the significant decrease in strength and stiffness due to the presence and the alignment of discontinuities at the end of the level-1 bricks (see ❷ in Table 1). Indeed, in a BaM composite, the weakest cross-section is half formed by cuts and, therefore, is only half as strong as the brick material; with two self-similar levels of hierarchy, the hierarchical BaM composite can only be a quarter as strong as the brick material.

However, it is possible to tackle this strength reduction by modifying the shape of the level-1 bricks. When looking at hierarchical BaM composites (Figure 1, and ❷ in Table 1), it can be seen that the damage pattern in the matrix forms a diamond shape. Therefore, by changing the shape of level-1 bricks from a (*self-similar*) rectangular to a *diamond* shape, it is possible to keep exactly the same failure mechanism as in the *self-similar* hierarchical BaM – and therefore the same energy dissipated – but increasing the strength of the *diamond* hierarchical composite (see ❸ in Table 1 and Figure 2).

This increase in strength happens because the diamond shape is generated by reducing the size of the cuts at the ends of level-1 bricks (compare the ends of level-1 bricks for ❷ and ❸ in Table 1). As a result, the stress concentration due to the ends of the neighbouring *diamond* level-1 bricks will be smaller than for the *self-similar* architecture. This brings three improvements to the tensile response of the diamond-shaped composite compared to the self-similar version: (i) an increase of the stiffness as less cuts are made into the material, (ii) a more pronounced non-linearity in the stress-strain curve just before failure, with an increase of the stress at the onset of non-linearity, and (iii) an increase the final strength of the material (compare ❷ and ❸ in Figure 2a).

3.2 Strong-core hierarchical BaM

Although the *diamond* hierarchical BaM architecture increases the composite strength compared to *self-similar* hierarchical BaM composites (Figure 2a), both microstructures still share some similarities: the level-0 bricks all have the same size, and not all level-1 bricks will reach the last step of damage propagation (which corresponds to debonding the last brick at the corner of the diamond-shaped failure pattern). This means that the localisation of damage has simply been shifted from the level-0 scale in conventional BaM composites to the level-1 in hierarchical BaM composites. Although this shift of damage localisation to a second hierarchical level already allows a significant increase of damage dissipation and reduces the dependence of damage dissipation on specimen size, it is still possible to improve it further.

To do so, we propose a new architecture (❹ in Table 1): knowing the "damage path" within the matrix from the previous design versions, brick-ends have been added only when necessary, and all the existing cuts not needed for creating the diamond damage pattern in the matrix are removed. Consequently, the level-0 bricks are not all of the same shape, but the geometry of each level-0 brick is optimised separately. In particular, the main difference with the previous hierarchical microstructures (❷ and ❸) is that the level-0 bricks within the central layer of level-1 bricks are now longer and twice as thick, in order to delay the closure of the diamond pattern of matrix damage and, consequently, delay damage localisation and final failure of the specimen.

The reduction of cuts in the material recovers the stiffness loss introduced by the hierarchies, and even allows the microstructure to reach a stiffness which is higher than that of the BaM composite (compare ❶ and ❹ in Figure 2a). Moreover, the damage pattern will initiate and propagate in all level-1 bricks of the composite (as in designs ❷ and ❸), but this creates a strain-hardening response which delays damage. Therefore, optimising the geometry of the level-0 bricks separately results in a significant increase of energy dissipation, as well as in a higher failure strain of the composite, similar to that of the bulk brick material (compare ❸ and ❹ in Figure 2a).

4 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 and experimental results analysed in this paper lead to the following conclusions:

- Hierarchical brick–and–mortar composites promote failure through matrix shearing rather than tensile fracture of the smaller–scale bricks, as well as the formation of diamond–shaped damage process zones in the matrix within each larger–scale bricks. As a result, hierarchical brick–and–mortar composites exhibit in a more pronounced stiffness degradation and dissipate more energy before failure compared to conventional brick–and–mortar composites;
- Hierarchical composites were manufactured and tested, and experimental results showed good agreement with the response and the failure modes predicted by the FE model;
- Non-self-similar architectures were developed in order to increase further the damage tolerance of composites. The results suggest that relaxing the constraints of self-similarity by changing the shape and the size of the bricks at each hierarchical level could significantly increase the energy dissipated before failure as well as the failure strain, compared to self-similar microstructures.

ACKNOWLEDGEMENTS

S. Pimenta acknowledges the support from the Royal Academy of Engineering in the scope of her Research Fellowship on `Multiscale discontinuous composites for large scale and sustainable structural applications' (2015-2019).

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