

BIO-INSPIRED NON-SELF-SIMILAR HIERARCHICAL COMPOSITES

Joël Henry, Soraia Pimenta

meComposites, Mechanical Engineering Department, Imperial College London, South Kensington
Campus, London, SW7 2AZ, UK

Email: joel.henry13@imperial.ac.uk, soraia.pimenta@imperial.ac.uk

Keywords: Hierarchical Composites, Discontinuous Composites, Non-self-similarity, Damage tolerance

Abstract

The use of hierarchies in naturally occurring composites motivated several studies in the literature, which demonstrated that hierarchical features could be integrated in composites to achieve damage tolerance. However, while most natural composites exhibit non-self-similarity in their hierarchical microstructure, most synthetic hierarchical designs in the literature use self-similar features. The aim of this work is therefore to investigate whether non-self-similar composites could be more damage tolerant than their self-similar equivalent. Hierarchical composites were designed, manufactured and tested, and results show that releasing the self-similar constraint could increase the design space and achieve better damage tolerance and warning before failure, and provide a more stable failure mechanism.

1. Introduction

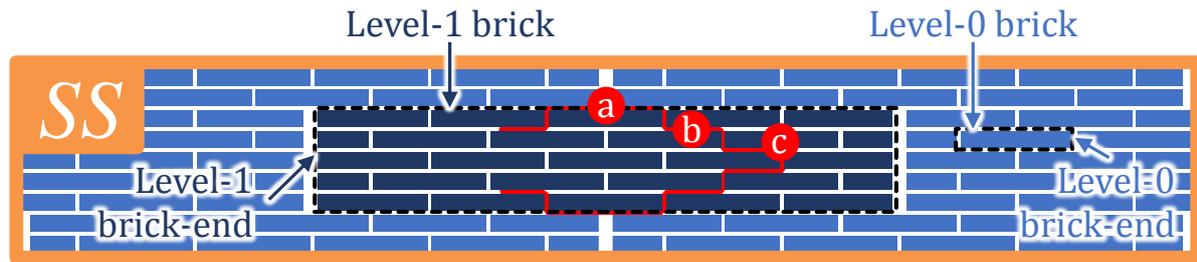
Naturally occurring composites, made of brittle constituents, achieve damage tolerance [1] by combining discontinuities [2] and hierarchies [3] in their microstructures. As a result, various works in the literature studied the effect of discontinuities and hierarchies on composites, and demonstrated that they could increase damage tolerance when microstructures are carefully designed [4, 5].

However, despite successful results in combining hierarchies and discontinuities, most research on hierarchical composites was carried out using a self-similar (*SS*) constrain when designing new microstructures [5, 6]. Although this assumption seems attractive for its simplicity, natural composites exhibit non-self-similar (*NSS*) microstructures [3]. Nacre for example displays different structures at each hierarchical level [7], and bone exhibits different arrangements at different hierarchical levels [3]. Interestingly, this non-self-similarity was found to increase further the damage tolerance of these materials [8].

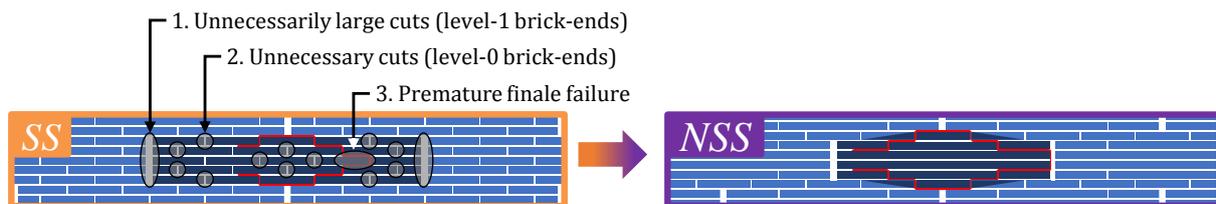
The aim of this work is therefore to explore new non-self-similar hierarchical designs and investigate how much damage tolerance can be increased when compared to a self-similar equivalent design. Sec. 2 describes the design of the hierarchical microstructures (self-similar and non-self-similar), Sec. 3 present and discusses the mains results, and Sec. 4 draws the main conclusions of the work.

2. Design of non-self-similar microstructures

A first design was developed considering a *SS* microstructure [5]. The microstructure consists of rectangular bricks used to form a simple (i.e. non hierarchical) brick-and-mortar (BaM) structure at a smaller level (hereafter identified as level-0), which is itself used to form rectangular bricks at a larger level (hereafter identified as level-1) (see Fig. 1a).



(a) The hierarchical *SS* microstructure with damage initiating at the end of neighbouring level-1 bricks (Point (a)), and propagating between the level-0 bricks (Point (b)) within the level-1 brick, until final failure of the brick (Point (c)).



(b) The *NSS* microstructure is obtained (i) by removing the unnecessary level-0 brick-ends, (ii) by reducing the length of the level-1 brick-ends, and (iii) by increasing the size of the central level-0 brick and modifying the dimensions of each level-0 brick individually.

Figure 1. The new *NSS* hierarchical microstructures (not to scale) obtained by relaxing the self-similarity constraint (highlighted in grey in Fig. 1b) imposed on the initial *SS* design. For the sake of clarity, for each microstructure, the central level-1 brick is highlighted in a darker colour, and damage in the matrix is represented in red in that central level-1 brick only.

In this *SS* hierarchical microstructure, the presence of hierarchies leads to additional large level-1 brick-ends (see Fig. 1a) when compared to the non-hierarchical BaM microstructure. These level-1 brick-ends are responsible for triggering damage initiation (Point (a) in Fig. 1a) in the matrix of neighbouring level-1 bricks [5]; once initiated, this damage in the matrix then propagates within the level-0 bricks (e.g. Point (b) in Fig. 1a). This hierarchical design ensures that damage is initiated and propagated in all level-1 bricks of the microstructure, before final failure occurs in some of the level-1 bricks. As a result, a significant amount of energy is dissipated stably via diffusion of damage throughout the microstructure, before failure.

However, although the size of the bricks in the microstructure was optimised at each hierarchical level [5], the microstructure was constrained by self-similarity. In particular, the shape (rectangular) and size of all bricks in a given hierarchical level are the same, which limits the efficiency of the microstructure. These limitations are addressed below to create the *NSS* microstructure (see Fig. 1b):

1. The level-1 brick-ends, although necessary to initiate damage in all level-1 bricks, are needlessly large, which unnecessarily reduces the strength of the composite. The level-1 end-brick size was therefore reduced to achieve a better brick-packing in the *NSS* microstructure;
2. Some of the level-0 brick-ends are of no use for the damage to propagate within each level-1 brick of the *SS* microstructure. Such level-0 brick-ends were identified and removed in the *NSS* microstructure, to increase the stiffness of the composite;
3. Finally, premature failure of the *SS* composite occurs when the path of damage in the matrix is completed in some of the level-1 bricks only, while that path is not fully propagated yet in most other level-1 bricks. To delay final failure, the dimensions of the central level-0 brick of each *NSS* level-1 brick were increased, making it more difficult for matrix damage to localise within a few level-1 bricks.

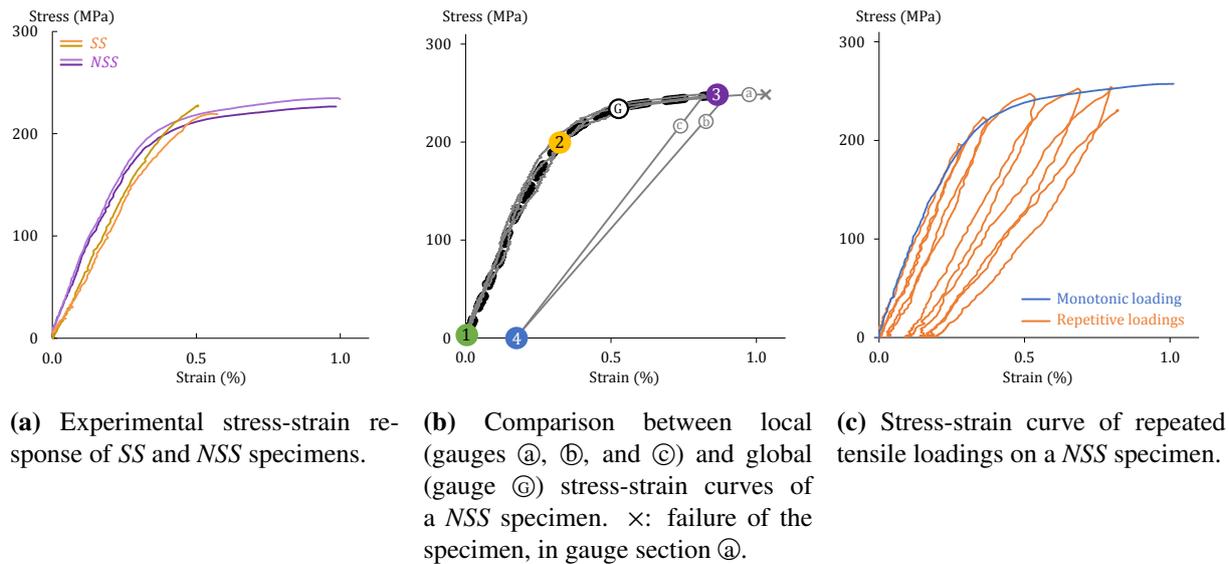


Figure 2. Demonstration of stable failure mechanism in NSS hierarchical composites, during loading in tension.

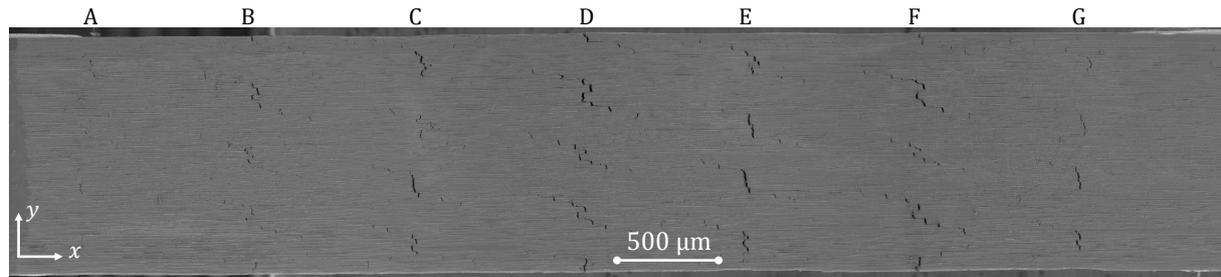
The improvements listed above were implemented in the NSS microstructure, which was then optimised using numerical simulations [9]. Both SS and NSS optimal microstructures were manufactured using thin-ply prepreg [5], and tested in tension (i) using optical strain gauge and a speckle pattern to measure the stress-strain response, and (ii) in a Scanning Electron Microscope (SEM) to observe the specimens during loading.

3. Results

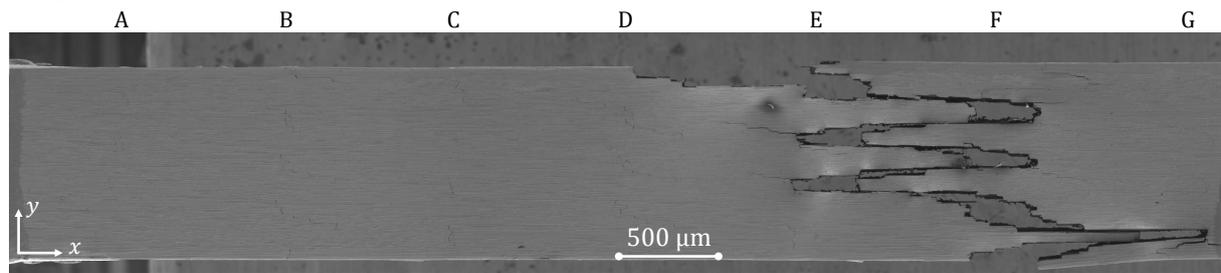
Results suggest not only that self-similarity is not needed for hierarchical failure mechanisms (level-1 brick-opening during loading in Fig. 3a) to occur, but Fig. 2a also demonstrates that the NSS microstructure achieves higher failure strain, higher stiffness, and more non-linearity than the SS equivalent. In particular, the stress-strain response of NSS specimens features a very distinct stress-plateau (Fig. 2a), which cannot be found in the SS specimens, and which does not exist either in non-hierarchical BaM composites.

Fig. 2b shows that the stress-plateau found in the stress-strain curve of NSS specimens (see gauge ③) is observed not only at the failure site (see gauge ①), but also throughout the microstructure (see gauges ② and ③). This result suggests a spread of damage in the specimen during loading, which was also observed when loading the specimen in the SEM (see Fig. 3a). The permanent deformation after failure, measured away from the failure site (see Step 4 in gauges ② and ③) was also observed in the SEM (see Fig. 3b), suggesting that energy has been dissipated stably.

Finally, repetitive loading tests were performed on NSS specimens [9], and Fig. 2c shows that the stress-plateau occurs in a stable manner: the NSS specimens can be loaded and unloaded safely, even at strains within the plateau region.



(a) Before failure (86% of maximal load): brick-ends open throughout the specimen and matrix damage propagates along the desired pattern.



(b) After failure: permanent brick-end opening can be observed at the brick-ends A-G throughout the specimen.

Figure 3. Diffuse damage during loading, and permanent deformation after failure, in NSS specimens. Letters A to G represent the level-1 brick-end longitudinal locations.

4. Conclusion

Self-similar and non-self-similar hierarchical microstructures have been designed, manufactured and tested, and the following conclusions have been reached:

- Self-similarity is not a necessary feature for hierarchical failure mechanisms to occur in hierarchical discontinuous composites.
- The non-self-similar microstructure achieved better mechanical properties (non-linearity, strain at failure, damage diffusion) than the self-similar equivalent.
- Damage tolerance of the non-self-similar microstructure was demonstrated via damage diffusion during loading, permanent deformation after failure, and a stable stress-plateau under repetitive loading in the stress-strain curve.

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). The authors are also grateful to Steve Harrison from Triple-H Composites for supplying the prepreg material used in this work.

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