EXPLORING THE USE OF FRICTION TO INTRODUCE DUCTILITY IN COMPOSITES

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Keywords: Ductility, friction

ABSTRACT

The use of friction mechanisms for introducing pseudo-ductility in brittle materials has been investigated. These mechanisms are inspired by nature, specifically by nacre. When nacre is loaded in tension, the aragonite tablets, making around 95 % of nacre, slide relatively to each other. The wedge shape of these tablets in combination with internal constraints, provided by the remaining 5 % of the organic interfaces, induces interlocking by frictional forces. This work investigates how this mechanism can be transferred to composite materials in order to increase their ductility in tension. Modelling is used to predict the tensile behaviour of interlocking configurations that exploit friction with either internal or external constraint. Two different design approaches of internally constrained specimens with various geometries are investigated using 3D printed materials. Externally constrained specimens, with different wedge angles are then investigated and finally this approach used with carbon composite structures.

1 INTRODUCTION

High performance composites are very attractive due to their high strength, high modulus, good fatigue properties and ease of manufacture. However, structures made of composites tend to fail in a sudden, catastrophic manner with little or no warning. Thus, the introduction pseudo-ductile behaviour into these brittle materials is highly desirable.

Friction mechanisms have been used for increasing the toughness and deformations of several materials. Dyskin et al. [1] used osteomorphic (bone-like shape) blocks, assembled onto a plate, to arrest crack growth and considerably increase the maximum deflection of the indentor during an indentation test when compared to using a solid plate made of the same material. Mirkhalaf et al. [2] have demonstrated that the friction generated at the contact surfaces in a jigsaw-like interface can make glass up to 200 times tougher. More recently Valashani and Barthelat [3] used a laser engraving technique to produce nacre-like glass increasing the toughness up to 700 times and showing failure strains as high as 20%. Bacarreza et al [4] showed that friction in an interlocking configuration can be used to produce pseudo-ductile behaviour in brittle materials. Moreover, careful design of the interlocking structure can lead to pseudo-ductility with hardening behaviours.

This paper will describe an investigation to introduce ductility in composites by exploiting mechanisms which resist extension by friction. In the investigation, analytical and finite element models have been used to study the behaviour of configurations consisting of "bow-tie" and "dog-bone" shaped platelets. Various geometries have been manufactured and tested in a 3D printed polymer as well as an initial study of interlocking composite structures.

2 MANUFACTURING AND PREPARATION OF SAMPLES

The manufacturing of the specimens for the tension tests is described in the following section. The 3D printing of the polymer parts and the production of the clamps which provide the lateral external constraint is explained. Finally, the manufacturing technique developed for producing composite bow ties is presented.

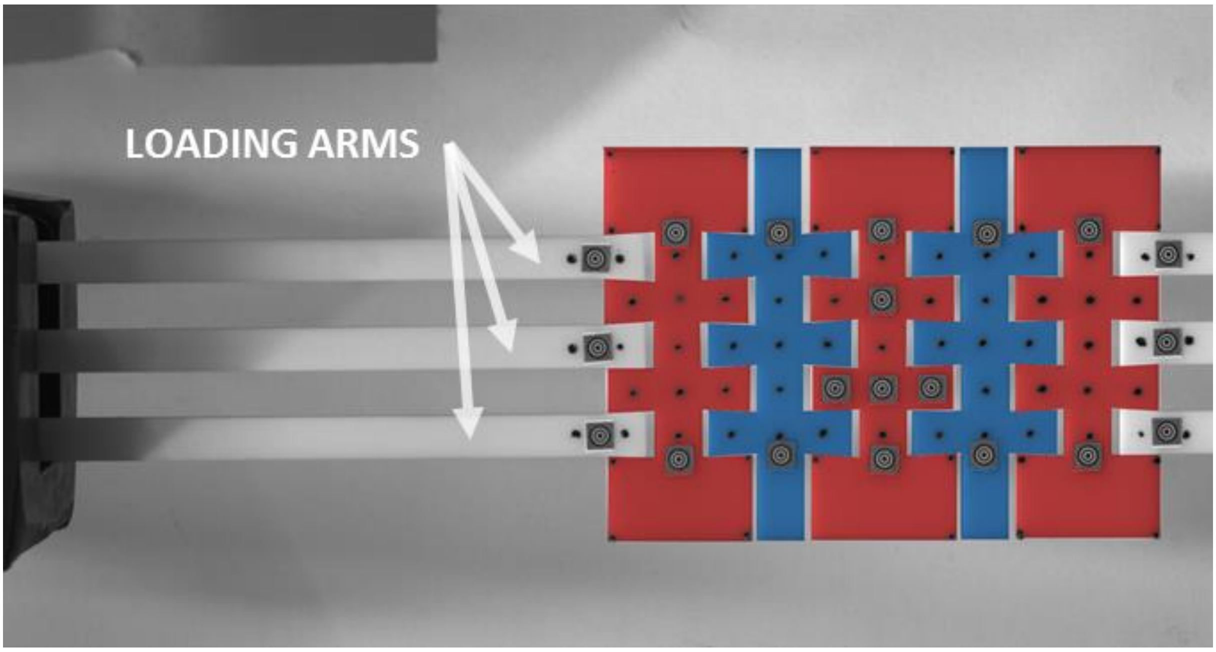

Figure 1: 3D printed specimen with internal constraint (“dog-bone” structure)

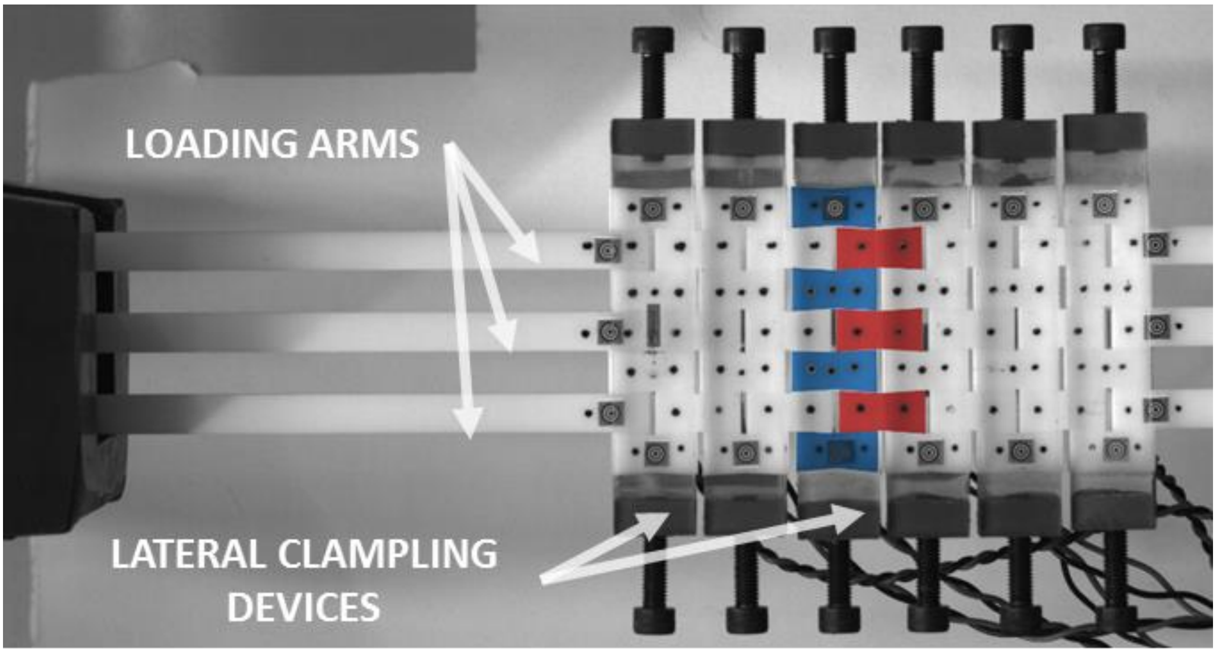

Figure 2: 3D printed specimen with external constraints (“bow-tie” structure)

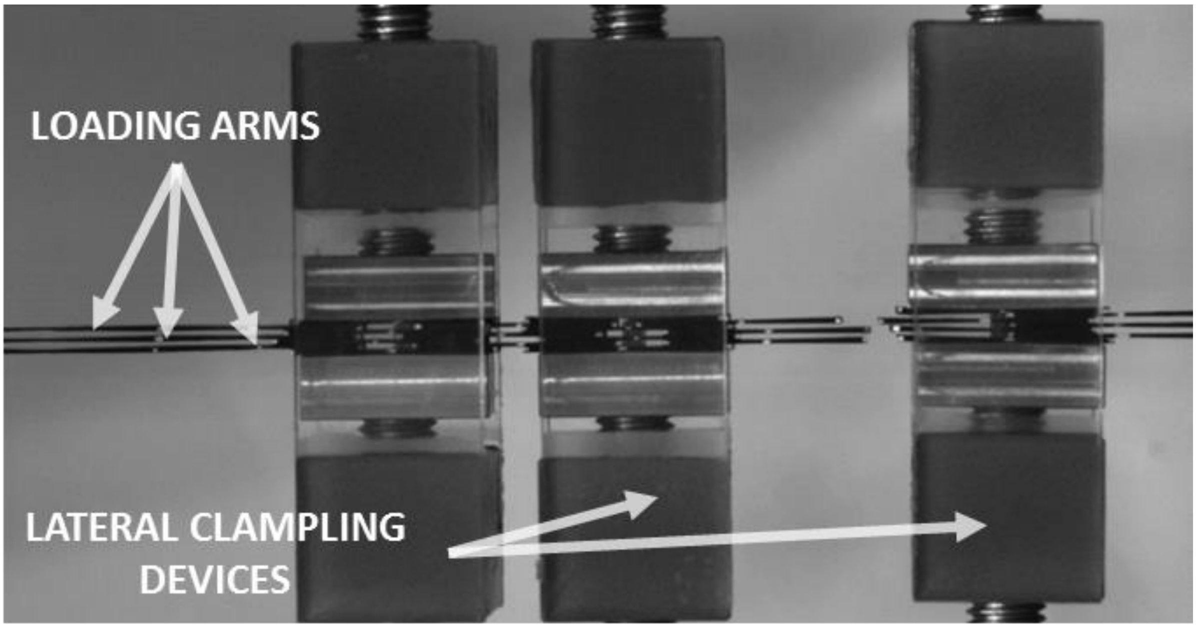

Figure 3: Composite specimen with external constraints

2.1 Production of 3D printed parts

All parts of the internally constrained specimens as well as the polymer parts of the specimens with external constraints (loading arms and bow ties) are 3D printed on a Connex350 printer. Rigur and FullCure 750 from Stratasys Ltd. are used as the 3D printable polymer and support material, respectively. To achieve the same surface finish on all the printed parts, the printing quality is set to 'high', the surface finish is selected to be 'matt' and the support of the part is defined to be 'lite'. Furthermore, the orientation of the parts during printing is set so that the printing direction is always parallel to the longitudinal central axis of the bow ties or dog bones. In this way, the same printer step width is achieved on the frictional surfaces and therefore uniform frictional properties of all the inclined surfaces are ensured. Having removed the parts from the printer, the support material is washed off in a high-pressure water cleaning cabinet. Afterwards, the parts are dried over night at ambient conditions. At this stage, the parts of the internally constrained specimens require no further treatment and are ready to be assembled.

2.2 Production of external constraints

For the externally constrained specimens, the lateral clamping devices need to be manufactured. The clamping devices for the 3D printed specimens and composite ones are similar except for their dimensions.

Each clamping device consists of two threaded metal blocks adhesively bonded to two transparent PMMA plates. The assembled specimen made of bow ties passes between the PMMA plates. Bolts screwed through the upper and low metal blocks drive the clamping plates (shaped to match the bow tie geometry) to laterally compress the bow tie assembly.

After sandblasting and cleaning the bonding areas, Loctite 770 Primer is applied onto the PMMA plates and the PMMA plates and metal blocks are glued together with Loctite 406 adhesive. Strain gauges from Tokyo Sokki Kenkyujo Co., Ltd. are then glued centrally onto the PMMA plates of the clamps to permit measurement of the strains in these plates during a test.

2.3 Production of Composite Specimens

Composite bow ties are made from M21/T800S prepreg material and are cured in a mould in an autoclave. As illustrated in the cross section in Figure 4, the mould consists of suitably shaped upper (a) and lower (b) mould parts. The skin layers (c) consist of a single layer of prepreg material laid up on the mould halves with the fibres in the longitudinal direction of the figure. The diamond-shaped filler (d) consists of strips of prepreg material with the fibre orientation perpendicular to the figure plane.

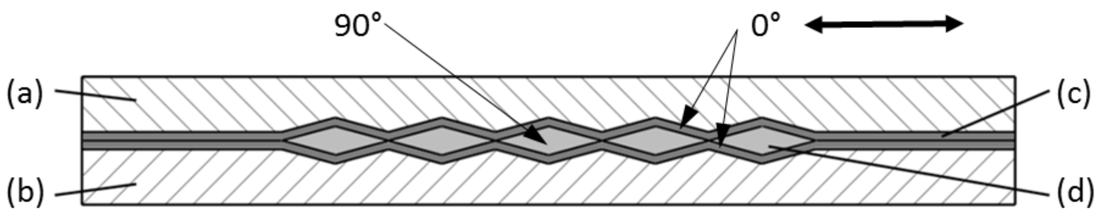

Figure 4: Layup and tooling for production of composite bow-ties

The layup is cured at 200 °C for two hours in an autoclave. The cured plate was then cut into bow tie shapes using a wire saw. Figure 5a shows a longitudinal section of a composite bow tie platelet. Higher magnification images in Figure 5b and c confirm that the diamond-shaped zones between the skins are well filled with no signs of voids. Figure 5d, e and f show transverse sections of the bow tie at the locations indicated in Figure 5a.

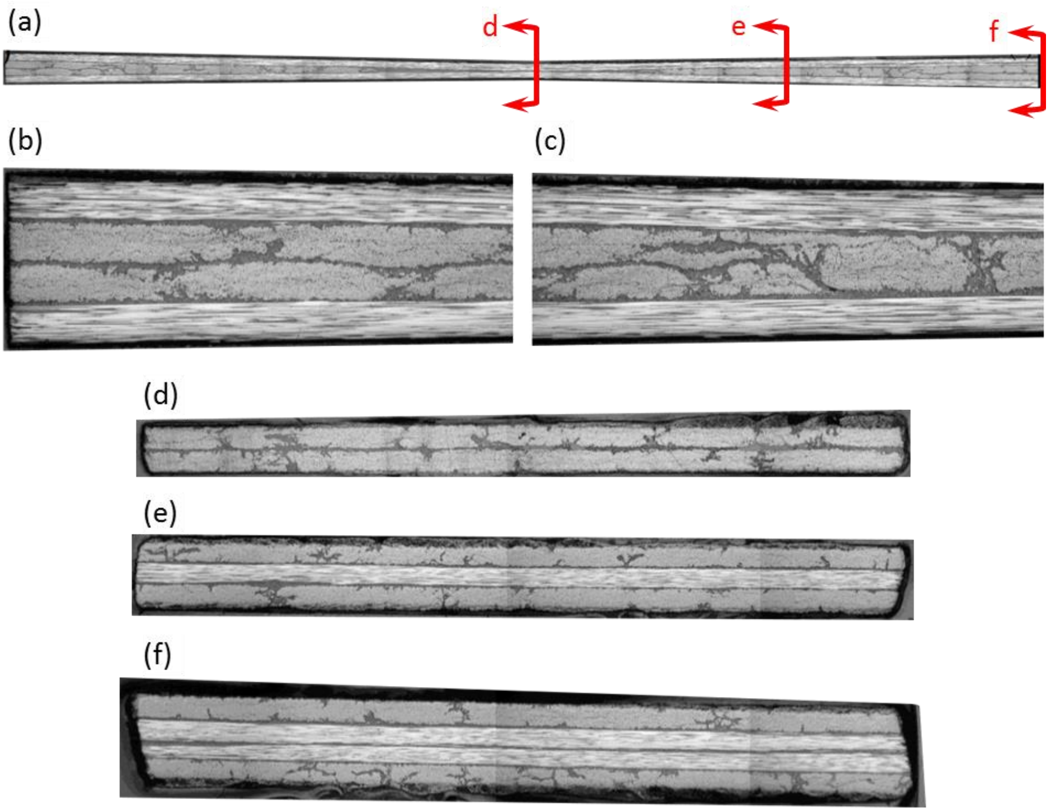

Figure 5: Microsections of composite bow ties

3. EXPERIMENTAL SETUP AND PROCEDURE

The specimens are tested to ultimate failure using an Instron 5969 testing machine fitted with a 50kN load cell. The strains of the specimen during testing are determined using a video extensometer by Imetrum Ltd. The strains of the clamping devices, used for externally constrained specimens, are obtained from strain gauges.

4. EXPERIMENTAL RESULTS AND DISCUSSION

Stress-strain plots for the configurations made of 3D printed materials are shown in Figure 6. It can be observed the specimens show an initial response which is approximately linear. The stiffness of the externally constrained specimen is higher because, for a given stress, the extension of the central part of the dog bone shape is small compared to the extension due to sliding of the inclined surfaces.

The tangent stiffness for both curves starts to reduce (at a stress between 0.75 -0.9 MPa) and finally levels out at a maximum stress of around 0.95 MPa.

At this point the sliding has started to localize at one position and beyond this, the stress drops gradually until complete separation of the interlocking shapes occurs at that position.

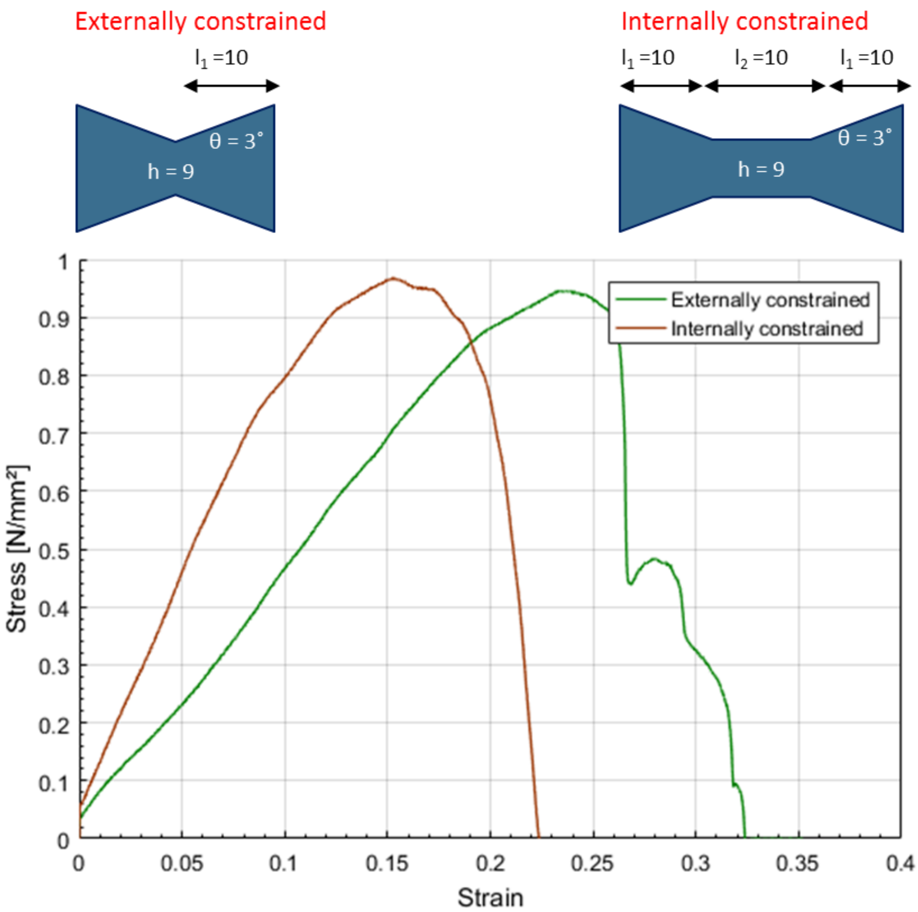

Figure 6: Mechanical response of 3D printed bow-tie structures

The mechanical responses of the composite specimens and their analytical predictions are displayed in Figure 7. Here, the overall strain in the diagram is determined from the crosshead displacement of the test machine. Both composite samples display a high initial stiffness before sliding starts and then show a similar response to the 3D printed specimens.

It can be seen that the specimen with no preload reaches a strength of 24 MPa at a strain of 18 %. However, the geometrically identical but preloaded specimen achieves 27 MPa at 15 % strain. Between approximately 3% strain and the curve peak, the curve of the preloaded specimen is shifted to higher stresses than the curve of the specimen without preload by a relatively constant value of about 5 MPa. The composite assembly fails prematurely due to localization of the deformations, but prior to failure the behaviour shows good agreement with the prediction. The localisation problem can be reduced by using an internally constrained configuration and if this can be achieved, an optimised configuration could achieve much higher strengths and failure strains.

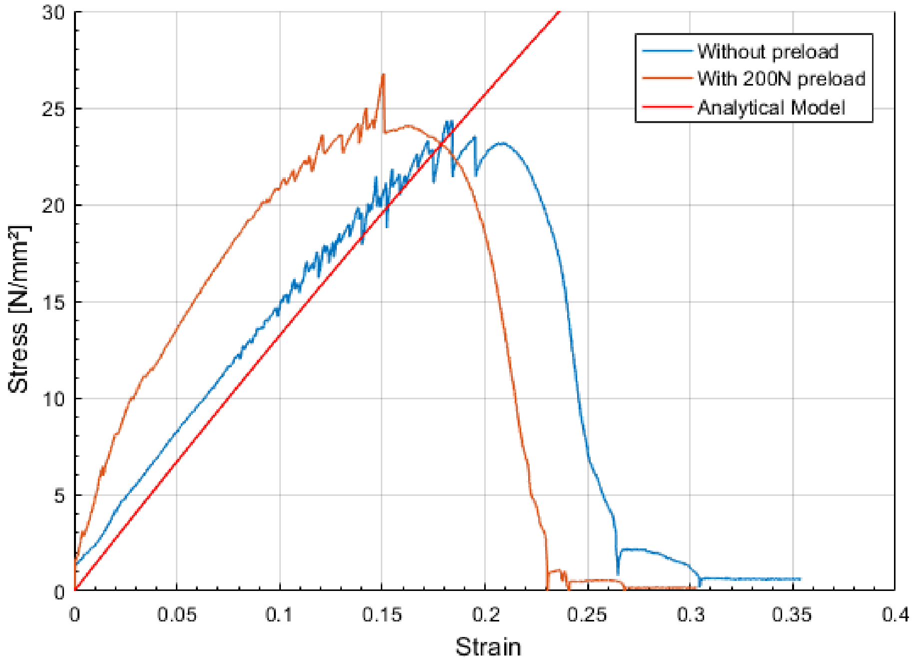

Figure 7: Mechanical response of composite bow-tie structure

5 CONCLUSIONS

Internally and externally constrained interlocking specimens made of a 3D printed polymer were investigated to show that significant tensile strains can be achieved by exploiting friction. Composite specimens were also tested to show that it is possible to transform a brittle material, into a ductile one by harnessing friction. All specimens were found to exhibit a non-linear behaviour with large strains prior to failure.

The composite specimens showed strains at the maximum stress of between $15 - 20$ %, which is about ten times the usual failure strain of carbon composites. However, the strength of approximately 25 MPa is only about 1% of the strength in the fibre direction of the parent composite material used in the manufacture. The composite configuration is now being studied to determine the improvement in mechanical properties that can be achieved by optimisation of the interlocking structure.

ACKNOWLEDGEMENTS

This work was funded under the UK Engineering and Physical Sciences Research Council (EPSRC) Programme Grant EP/I02946X/1 on High Performance Ductile Composite Technology in collaboration with the University of Bristol. Supporting data can be requested from the corresponding author, but may be subject to confidentiality obligations.

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