OPTIMISATION OF DUCTILE INTERLOCKING COMPOSITE STRUCTURES

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Keywords: Pseudo-ductile, friction, optimisation

Abstract
An investigation on how interlocking composite structures can be designed using a multiobjective optimisation algorithm is described and the trade-off between the ultimate stress and the associated strain of pseudo-ductile composite interlocking structures is illustrated. Parameters changing the geometry of the interlocking structure and the friction coefficient were varied during the optimisation. Finite element models have been used to study the behaviour of these configurations. Different behaviours can be observed ranging from models with ultimate stress and associated strain in the optimal solutions from 333 MPa and 4.5% to 146 MPa and 20.2%.

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, introducing ductile or 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) blocks, assembled onto a plate, to arrest crack growth and considerably increase the maximum deflection of an indentor during an indentation test. Mirkhalaf et al. [2] have demonstrated that friction in a jigsaw-like interface can make glass up to 200 times tougher. Valashani and Barthelat [3] used a laser engraving technique to produce nacre-like glass increasing the toughness and failure strains. Bacarreza et al [4] showed that friction in an interlocking configuration can be used to produce pseudo-ductile behaviour in brittle materials and later Bacarreza et al [5] demonstrated that interlocking structures with internal and external constraints can be used to produce ductile composites.

FE analysis and Genetic Algorithms have been employed in the optimisation of composite structures [6-9], taking advantage of the increase in computational power and making use of metamodels to approximate the response of the composite structures to reduce the computational resources needed for the task. Bacarreza et al [10] used a similar approach for the Robust Design Optimisation of composite stiffened panels.

In this paper a design of experiments using optimal latin hypercube sampling was used to build a metamodel based on Radial Basis Function Networks. Once this Artificial Neural Network (ANN) is built, the multiobjective optimization is performed using the Non-dominated Sorting Genetic Algorithm (NSGA-II) [1]. The FE analyses include progressive failure based on continuum damage mechanics.

2. FE Modelling and validation

The type of interlocking structure explored is this paper is shown in Figure 1. It is made of a continuous laminate with bow-tie-shaped wedges machined into each side. The overall thickness of the laminate is 6 mm and the layup is $[[+45/-45/+3/-3]_{2S}]_3$. The interlocking structure was made of T300/914 CFRP.

The structure was initially laid up as a single plate, then cured and finally machined to form the interlocking wedges. Due to the machining tolerance the interlocking structure was loose when initially assembled.

The model was meshed with continuum shells, and composite layup sections were applied. Orthotropic material was defined with Hashin damage. Periodic boundary conditions were applied to mimic a Representative Volume Element (RVE). Displacement was applied in the longitudinal direction and all other directions were left free. General contact with a coefficient of friction of 0.2 was also used.

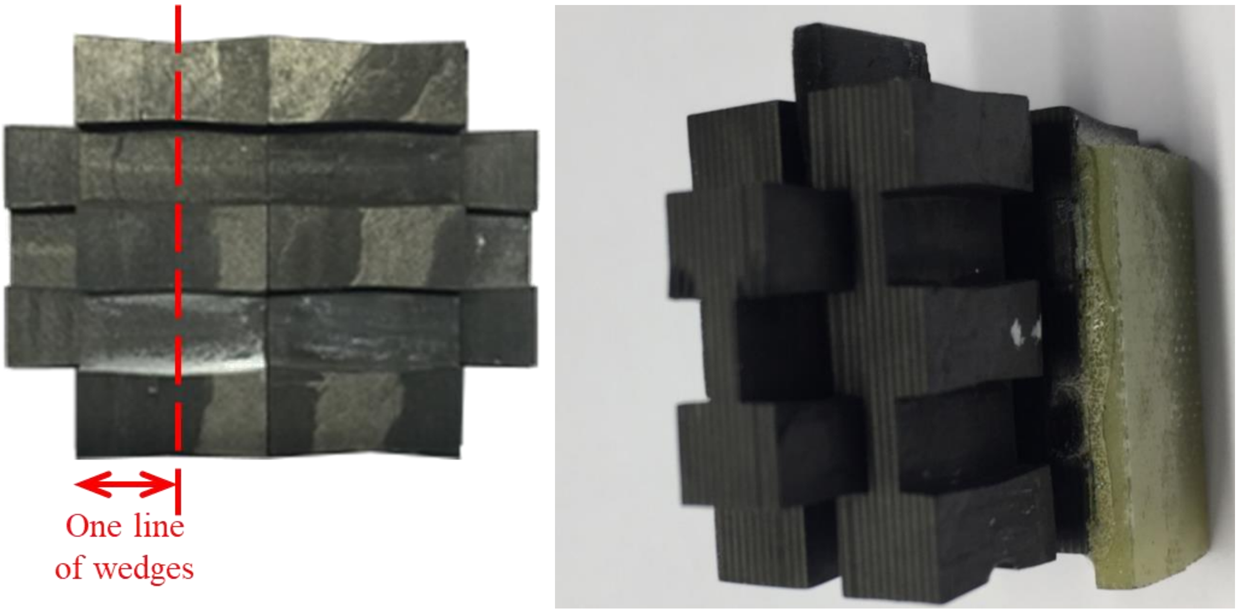

Figure 1. Interlocking structure

Figure 2 shows the results obtained from the FE model and experimental results. It can be seen the behaviour is nonlinear almost from the beginning of the loading. The experimental result begins with a flat region where the initially loose structures slides and then starts to interlock leading to an increase on the stress. Subsequently the structure shows a yielding-like behaviour as the wedge surfaces slide throughout the structure until the maximum stress is reached. The sliding then localises at single line of wedges leading to final failure.

The discrepancy between the FE model and the experimental results can be attributed to many factors including: difference between the coefficient of friction of the model and the experiment; use of a perfect (infinite) unit cell in the model while the geometry of the experimental sample was imperfect due to machining tolerances.

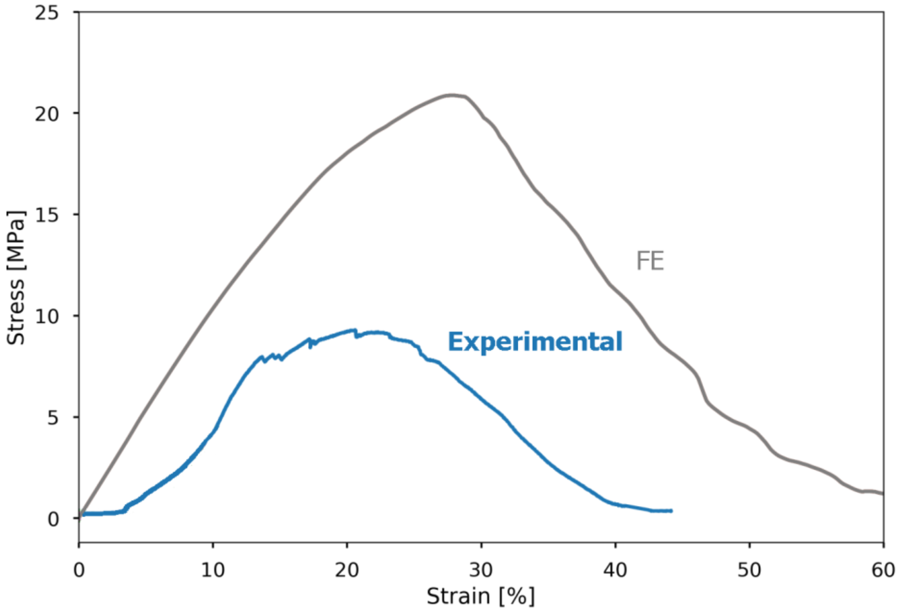

Figure 2. Validation of the FE model

3. Design Optimisation

In order to perform the design optimisation of the pseudo-ductile composite interlocking structure, latin hypercube sampling was used to build a metamodel. The parameters that were studied are those in Table 1a, and they are depicted in Figure 3.

The metamodel used is a type of ANN that is a Radial Basis Function (RBF) Network, which uses radial basis functions as activation functions. An advantage of using RBFs is that the interpolation problem becomes insensitive to dimensions of the space where multivariable functions are approximated by linear combination of single variable functions.

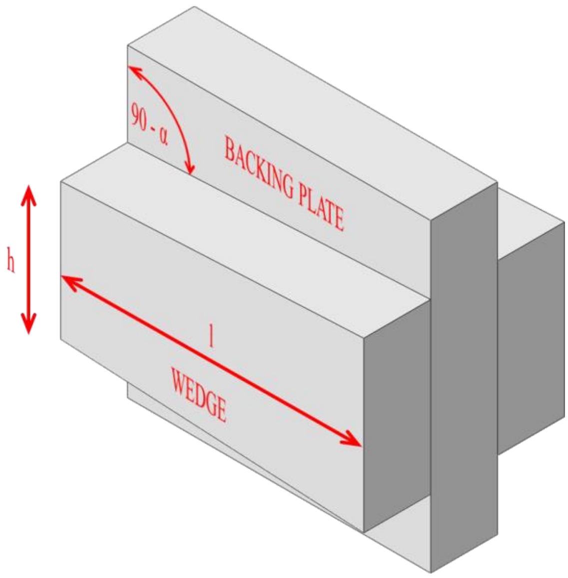

Figure 3. Parameters defining geometry

3.1. Problem definition

The design space is defined in Table 1a. It considers all the parameters that define the geometry of the interlocking structure shown in Figure 3. Notice that all the layups are quasi-isotropic. Table 1b shows the defined objectives for this problem since designs with a high strength and strain at maximum stress are desirable.

Table 1: Preliminary design - Problem definition

(a) Design variables

Description	***Value***
Wedge angle	$2^\circ \leq \alpha \leq 5^\circ$
Height of the neck of the wedge	$2 \leq h \leq 5$
Length of the wedge	$10 \leq l \leq 40$
Coefficient of friction	$0.1 \leq \mu \leq 0.3$
Layups of wedges and backing plate	$[60/-60/0]_S$
	$[45/-45/0/90]_S$
	$[72/36/0/-36/-72]_S$
	$[60/-60/0]_{2S}$
	$[45/-45/0/90]_{2S}$

(b) Objectives

Description	**Operation**
Maximum stress	maximise
Strain at maximum stress	maximise

3.2. Optimisation

The optimisation is done using the Non-dominated Sorting Genetic Algorithm (NSGA-II) [1] which is a multiobjective technique that deals with the high computational complexity of non-dominated sorting, lack of elitism and need of a sharing parameter specification by using a fast non-dominated sorting, an elitist Pareto dominance selection and a crowding distance method. This algorithm can deal with the complex optimization of composite structures.

3.3. Results

The part of the objective space that was explored is shown Figure 4 and the Pareto front was built using non-dominating sorting. All the points which are not dominated by any other member of the set are called the non-dominated points or Pareto Optimal Set in the design variable space or Pareto front in the objective space and are shown in Figure 4 highlighted in red. Table 2 shows the values of the design variables for some of the solutions in the Pareto front. Each objective component of any point along this front can only be improved by degrading at least another objective component.

A trade-off between the ultimate stress and its associated strain can be observed. The behaviour of the interlocking structures varies and the strength and corresponding strain ranges from 333 MPa and 4.5% to 146 MPa and 20.2%.

For comparison, the unidirectional laminate made of this material (T300/914) has a strength of 1650 MPa with a failure strain of 1.22% in the fibre direction when tested in tension.

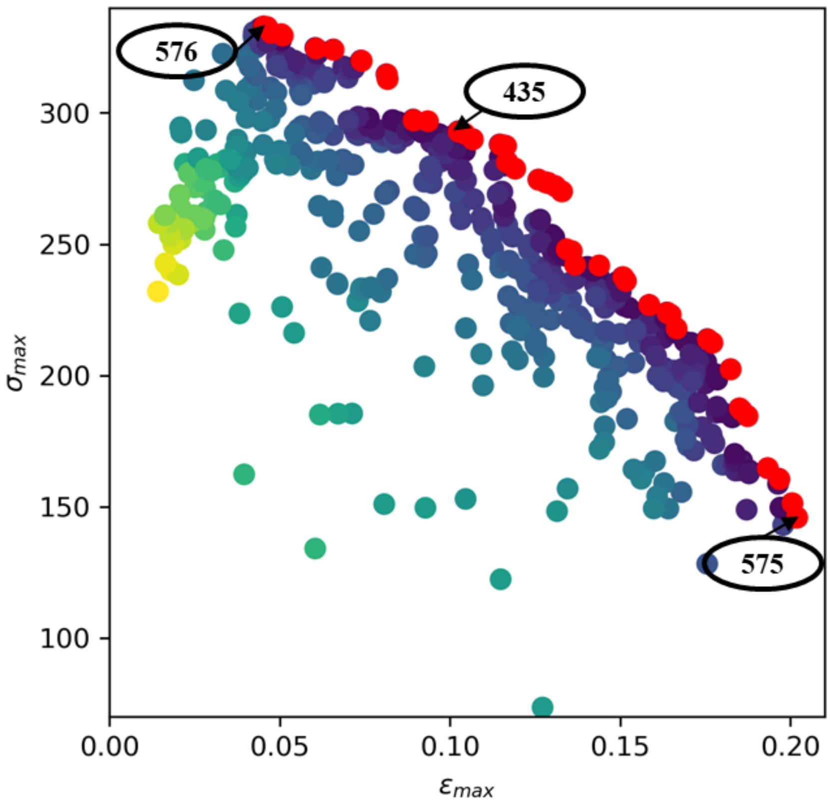

Figure 4. Pareto frontier

Table 2: Selected solutions

Model #	*α*	*h*	*l*	*Wedge layup*	*Backing plate layup*	*μ*
576	2.004	4.099	38.830	$[45/-45/0/90]_{2S}$	$[72/36/0/-36/-72]_S$	0.147
435	2.059	2.006	12.121	$[45/-45/0/90]_S$	$[45/-45/0/90]_{2S}$	0.117
575	2.025	4.920	10.926	$[45/-45/0/90]_S$	$[45/-45/0/90]_{2S}$	0.102

3. Conclusions

This paper has shown that friction in an interlocking configuration can be used to produce pseudo-ductile behaviour in UD CFRP materials. The design optimisation of this interlocking structures can be performed using a genetic algorithm that uses a previously built metamodel using latin hypercube sampling to generate the finite element models of the interlocking structures. A trade-off between the strength and its corresponding strain can be observed.

Acknowledgments

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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