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Predicting self-healing strength recovery using a multi-objective genetic algorithm

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ABSTRACT

This study aims to identify the optimum location and distribution of a healing agent within the delamination of a fibre reinforced plastic to ensure effective self-healing by utilising a multi-objective Genetic Algorithm (GA). Two optimisation problems were formulated and addressed with a different set of objectives. A simple finite element (FE) model is used to evaluate the mechanical performance of the healing component. The FE model consists of an idealised delamination region, which allows the direct discretisation of the problem used for the optimisation algorithm. Effective healing locations are found for a specific load case with a healing efficiency of up to 95% for the best performing solution.

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1. Introduction

The quest for lighter, more efficient and multi-functional structures has led to the increased utilisation of fibre reinforced polymer (FRP) composite materials within the aerospace industry. The arguments for using this material are their superior specific strength and stiffness, as well as a significantly lower density than their metallic counterparts. However, unlike metallic materials, FRPs do not have the ductility required to absorb high levels of impact energy and dissipate this energy through elastic deformation and damage formation [1]. The resultant damage, which can occur in service or even during the manufacturing process, can cause significant reductions in mechanical performance whilst leaving little visual evidence of the impact event; a situation termed Barely Visible Impact Damage (BVID) [2–4].

As a part of ongoing work into multi-functional materials, embedded healing capabilities for composites are under investigation with the aim of reducing system and maintenance costs. Autonomous self-healing capabilities are envisaged to address the pernicious problem of Barely Visible Impact Damage (BVID) allowing a movement away from conservative component design philosophies leading to more efficient end products. The precise healing strategy employed varies with the intended application. For example, microcapsules [5–7] distributed appropriately may be sufficient to stop slow propagating cracks while embedded liquid filled hollow glass fibres [8–10] or vascular networks [11–17] allow for healing by facilitating a bleeding of healing agent into larger damage regions. For microcapsules and hollow glass fibres, the volume of healing agent corresponds to the number of reservoirs incorporated within the composite structure. After the occurrence of damage the reservoirs are consumed and unable to heal subsequent damage events [15].

Experimental investigations assessing the complete [8] and partial filling [9,18,19] of a damage region with healing agent suggest that, depending on the extent of damage monitored within the laminate [20], strategic restoration using a limited volume of self-healing agent may be sufficient to ensure a restoration of load bearing capabilities [18]. In particular, pinning of delaminations or localised reattachment of the interfaces can be effective in restabilising the laminate and counter-acting localised buckling when subjected to compressive loading. This leads to the immediate challenge of defining the necessary healing strategy with respect to the required self-healing agent volume and design of an efficient healing delivery system.

Genetic Algorithms (GA) are widely used to address optimisation tasks and inverse problems. In particular for composite materials GAs are successfully applied to optimise stacking sequences [21–23] or woven composite draping strategies [24,25]. Furthermore inverse parameter estimation for elastic mechanical properties [26–28], resin infusion and curing [29–33] are often addressed with this family of algorithms. In this study, a multi-objective GA is used with the aim of identifying effective healing locations along a unit crack length. Thereby, the problem is constrained by minimising the volume of self-healing agent. The metric addressed in this study is the recovery of uniaxial compressive strength in a thin laminate. To assess both counter intuitive objectives, maximal compressive strength vs. minimal self-healing agent, a simple finite element

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(FE) model is used to obtain the compressive strength for the different configurations generated by the GA.

This paper provides a detailed description of the optimisation problem and the discretisation using an FE model. The operations performed in the implemented GA are explained and outlined. In addition, the objective functions are defined and explained in detail and the configurations for the GA run are presented. Subsequently, the results obtained are shown and discussed whilst the optimum solutions are identified and visualised. Finally, concluding remarks and suggested routes for optimisation of self-healing capable laminates are provided.

2. Optimisation problem

The problem to be addressed using a Genetic Algorithm (GA) is the apparent contradiction in restoring maximum compressive load-bearing ability while employing only a minimum amount of self-healing, i.e. identifying the laminate's tolerance to delamination within a unit length before catastrophic failure occurs. Thereby, a finite element (FE) model is used to assess the compressive strength of a specimen for a given delamination pattern as generated by the GA.

2.1. Finite element modelling methodology

The explicit FE solver LS-DYNA® [34] has been utilised to obtain the compressive strength for a candidate configuration of delaminations as proposed by the optimisation algorithm. The overall dimensions of the compression specimen, shown in Fig. 1a, are 120 mm × 10 mm × 4 mm. Here two sub-laminates of carbon fibre reinforced plastic (CFRP) are associated with a composite damage material model (*MAT_022) (see also Table A1) linked via a single layer of cohesive elements (see Fig. 1b).

For the purpose of using the FE model in the context of an optimisation study, the model was reduced to a slice with a thickness of 0.5 mm, as shown in Fig. 2a. Hence, the model used is discretised by 3504 elements and 7504 nodes. This arrangement results in a model runtime of 2 min (4 core CPU 2.6 GHz, RAM 8 GB).

Within the gauge length of the specimen, a predefined delamination zone is created as shown in Fig. 2b. The 60 cohesive elements located in this region are used for the encoding of the delamination information as evaluated by the GA. For this study an in-house developed cohesive element formulation is used [35,36] which allows the user to *activate* and *deactivate* the element. In an *active* state the formulation follows a cohesive behaviour defined by the peak stress, interface stiffness and fracture toughness for mode I and II respectively (see Table A2). However, in a deactivated state the element functions as a contact definition which disallows the penetration of the top and bottom surface of the element. Thus, the delamination region can be manipulated to represent delaminated and healed zones within the predefined region while elements outside this predefined region remain in the *active* state throughout the duration of the simulation. The information of *active* and *deactive* element can be encoded into a binary string (chromosome) of 60 Boolean values used by the GA for the optimisation process, e.g. 0011 corresponds to a condition where the first two elements act as contact definitions while the third and fourth element follows a cohesive formulation.

Furthermore, as the exact form of failure may vary for compression experiments (e.g. Euler buckling modes), the mesh of the finite element model was modified to ensure the same form of failure for all simulations (see Fig. 3). Therefore, the nodes located in the gauge length are shifted in the thickness direction following a half-period sine function. The shift was applied in the counter direction for the nodes belonging to the respective sub-laminate, and the thickness of the cohesive element layer increases from 5 μm to 25 μm at the centreline.

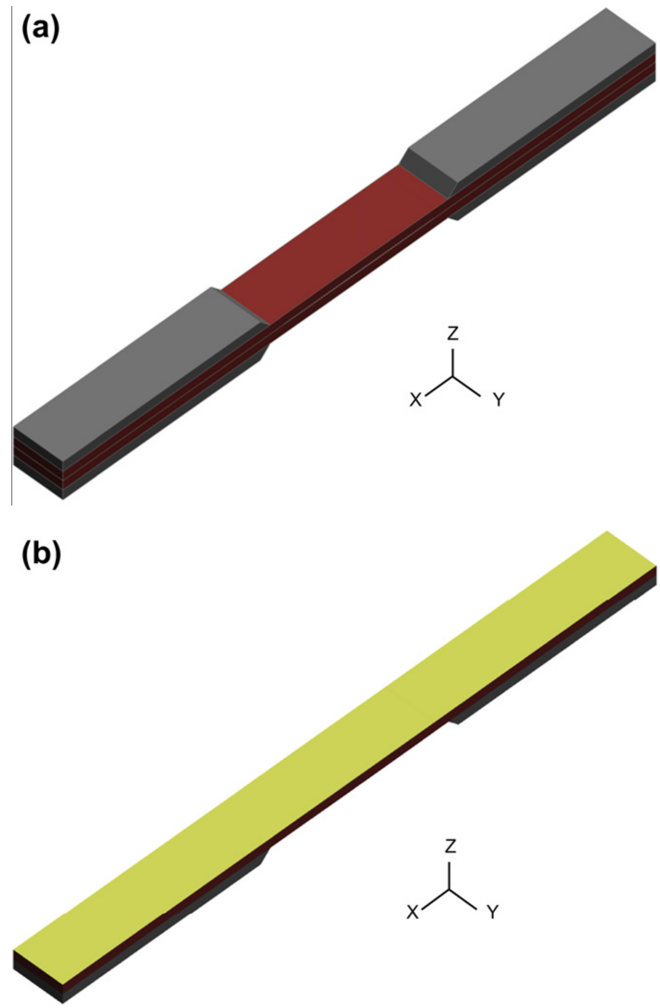

Fig. 1. FE model for compression test, (a) full model and (b) interface layer with cohesive elements and predefined delamination zone.

2.2. Genetic algorithm

A Genetic Algorithm (GA) developed by Skordos et al. [25,30], based on the principles of nPGA [37] and NSGA [38], was implemented in C++ and is outlined below. The GA addresses the optimisation problem in an iterative manner where the information to optimise is encoded as a binary string (chromosome or individual) that undergoes *genetic* operations.

For the first generation, multiple individuals (population) are initialised. Each individual has a partial fitness value corresponding to each objective. In order to evaluate and rank the population with respect to the total fitness, a tournament modus is introduced as follows. For the tournament modus, each individual competes with the other members of the population by comparing the partial fitness values of each objective. The individual with the lower partial fitness value is penalised by decreasing its dominance metric. In addition, each individual is compared with the other members of the population within the objective space. If another individual is found within a predefined range the individual's sharing metric is reduced. The total fitness of the individual is determined as a combination of the dominance and sharing metric.

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