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Lay-up optimisation of fibre metal laminates based on fatigue crack propagation and residual strength

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ABSTRACT

A methodology to design and optimise fibre metal laminates for improved fatigue and damage tolerance properties is presented. The lay-ups are defined in a systematic manner where the number and thickness of metal layers are varied and the lay-ups are divided into grades in which the amount and orientation of the fibre plies in the fibre layers are defined. The optimisation procedure is implemented with genetic algorithms and the lay-ups are designed such that the fatigue crack propagation or residual strength criteria is satisfied. The design criteria are evaluated using prediction methods and fitness approximations of these prediction methods. The latter evaluation aims to speed up the optimisation procedure. The functions of the fitness approximation are verified against the prediction methods and the design solutions of both evaluation methods are in compliance with each other. In conclusion, the procedure managed to find the optimal solutions within the design space while an improvement in computation time is achieved with the use of fitness approximation.

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1. Introduction

Fibre metal laminates (FML), which consist of thin metal layers bonded with layers of fibre composite [1], are well known for their improved fatigue and damage tolerance (F&DT) properties compared to monolithic aluminium. After successful exploitation of the FML technology in fuselage design (Airbus A380), there is a serious interest in application in other aircraft structures, such as wings. This interest led to research in characterisation and understanding of the F&DT behaviour of FMLs. In the literature, many studies have been presented to predict properties, like fatigue crack initiation [2–4], fatigue crack propagation [5–8], blunt-notch strength [9] and residual strength [10,11]. As a results, prediction methods were developed to predict the corresponding behaviour for FMLs.

FMLs have an increased design freedom, since their lay-ups can be specifically designed to the requirements by simply changing the number, thickness or orientation of the fibre and metal layers. In the past, FMLs were only designed and certified based largely on single material models, and therefore, all other potential solutions were automatically excluded in the design process. In this so-called solution-based analysis, the prediction methods were used to determine the performance and properties, while the limited lay-up options were manually evaluated. This strong focus on single material models restricted the actual search for a more advanced and better solution in the design space. The need is for a design procedure in which all possible lay-ups are obtained based on the design requirements and ranked according to their performance and weight. This way a fast overview of the potential solutions are obtained which could be used to correlate the design requirement to the lay-ups parameters and to identify different lay-ups that might have better performance or weight ratio.

Reviewing the literature, there is a lack of a design optimisation method for FMLs. The closest to the current problem are only optimisation procedures for composite structures in which laminates are designed for buckling or maximum strength [12–16]. These procedures focus mainly on stacking sequence or ply orientation optimisation, which could not be applied to FMLs due to its different build up with the additional metal layers. Designing FML structures requires the assessment of F&DT criteria due to its application in fatigue sensitive aircraft structures. This means the buckling or maximum strength assessments in the literature are not sufficient. Criteria like fatigue crack initiation (FCI), fatigue crack propagation (FCP) and residual strength (RS) are required for an F&DT design.

Furthermore, the build-up of FMLs are different from composites, and therefore, a different lay-up definition and stacking procedure is required. With the certification of Glare FMLs [17], certain lay-ups were standardised and defined as a grade. This approach is

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useful for defining the lay-ups in the optimisation procedure for FMLs. Instead of setting all variables free, it is organised by defining the grades as variable and fixing the compositions of the fibre layers, while the metal layers are varied to create a large design space. This method has the benefit that the obtained optimal lay-ups are not completely random and thus easier to manufacture.

Cooper [18] proposed a design approach for FMLs in which an FML sizing module based on the ultimate tensile strength failure criteria is integrated together with a manufacturability module into a wing design framework. This approach has the potential to be extended to incorporate the F&DT criteria, but the optimisation is rather limited to the required minimum number of metal layers in FML for a user-specified grade and material thickness, then giving the possibility to explore a large design space for other potential solutions.

In previous work [19], a design optimisation method for FMLs based on fatigue crack initiation using genetic algorithms was presented. The study concluded that the accuracy of the crack initiation prediction method influences the output of the design solutions, meaning that the user needs to be aware of this complication during design. Nonetheless, the use of the fatigue crack initiation prediction method as evaluation method proved to be working and resulted in optimal solutions. This paper proceeds on this work in the context of F&DT design and discusses the methodology for fatigue crack propagation and residual strength criteria with the difference that next to the prediction methods also its fitness approximations is considered as evaluation method.

Fitness approximation is considered for two reasons: first, the prediction method for fatigue crack propagation used in the design procedure encounters procedural errors when the laminate stress exceeds the yield strength with the application of high loads on thin laminates in the optimisation procedure [20]. Second, the iterative structure of the prediction methods for fatigue crack propagation and residual strength impacts the computation time. Therefore, a fitness approximation is considered to eliminate the procedural errors and to speed up the optimisation procedure.

This paper presents a design and optimisation methodology for lay-ups of FMLs based on fatigue crack propagation and residual strength. The optimal lay-ups are obtained with the optimisation procedure which evaluates the laminates for fatigue crack propagation or the residual strength criteria. The optimisation procedure is implemented with the use of genetic algorithms (GA) and the prediction methods (or its fitness approximation) as evaluation criteria. The crack propagation and residual strength criteria are separately discussed and the optimal solutions per criteria are presented.

2. Optimisation problem

The optimisation problem aims to achieve a lay-up with minimised weight while satisfying the fatigue crack propagation or residual strength criteria. The optimisation problem can be formulated as:

$$\min[W(x)] \quad \text{with} \quad \bar{x} = [x_h \quad x_n \quad x_m] \tag{1}$$

subject to

$$N_{fcp} \geqslant N_{req} \quad (\text{FCP requirement}) \tag{2}$$

or

$$S_{lam} \leqslant S_{rs} \quad (\text{RS requirement}) \tag{3}$$

where W is the laminate weight, $\bar{x}$ is design vector representing the lay-up of the laminate, N_{fcp} is the fatigue crack propagation life of the laminate, N_{req} is the required laminate life, S_{lam} is the laminate stress and S_{rs} is the residual strength of the laminate.

The optimisation procedure is implemented using genetic algorithms (GA) as the optimisation algorithm. This algorithm requires a solution domain where the solutions are coded as a vector with integers. Therefore, the design vector $(\bar{x})$ consists of integers referring to design values representing the grade of the laminate (x_h), the number of metal layers (x_n) and the thickness of metal layers (x_m). The algorithm requires also a fitness function with constrained functions to evaluate the domain. Therefore, the design solutions are evaluated using the design requirements. The fatigue crack propagation criteria requires that the lay-up will have at least a fatigue life (number of cycles) (N_{fcp}), that is needed to propagate the crack from its initial crack length until a critical crack length, equal or larger to the required fatigue life (N_{req}). For the residual strength criteria, the laminate stress (S_{lam}) caused by the external load and the internal residual (thermal) stress, should not exceed the residual strength (S_{rs}) of the laminate at a defined critical crack length.

3. Lay-up variables

The lay-ups are defined by three parameters: the grade (h), the thickness of the metal layer (n) and the number of metal layers (or the number of repetitions) (m). The metal layers have the same thickness in all layers and the two outer layers are metal while the layers in-between are an alternation of the metal layers with the fibre layers. The fibre layers consist of fibre plies with the amount, orientation and stacking order of these plies defined by the grade. The composition of the fibre layers are fixed and only change when the grade is changed.

For the genetic algorithm procedure, it is required to have a genetic representation of the laminate. Each individual in the solution space is represented by a vector L that describes the appearance of a laminate.

$$L = [h \quad n \quad m] \tag{4}$$

This vector includes the three design variables mentioned above to build up the laminate. However, in the coding space the laminate is represented by vector x that describes the coded laminate using integer coding.

$$\bar{x} = [x_h \quad x_n \quad x_m] \tag{5}$$

The parameters x_h, x_n and x_m have fixed position in the design vector and are integers referring to the position of the design value in the corresponding design vector h, n and m (alleles). An example design space is given below.

The grade is defined as:

$$h = [(0/0) \quad (0/90/0) \quad (90/0/90)] \tag{6}$$

The number of metal layers possible are:

$$n = [2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \quad 9 \quad \dots \quad 20] \tag{7}$$

The thickness of metal layers are:

$$m = [0.3 \quad 0.4 \quad 0.5 \quad 0.6 \quad 0.7 \quad 0.8 \quad 0.9 \quad 1.0] \tag{8}$$

4. Fitness evaluation

The fitness evaluation of an individual requires the calculation of the laminate weight using the fitness function and the evaluation of the fatigue crack propagation life or the residual strength using the constraint function (prediction methods). Every individual in the population is assigned a fitness value based on the overall performance, which is measured by the total weight of the laminate and the value of the constraints [15]. The fatigue life of the laminate is checked with the required fatigue life and the

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