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Design optimisation procedure for fibre metal laminates based on fatigue crack initiation

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ABSTRACT

A design optimisation procedure for fibre metal laminates based on fatigue crack initiation is presented. The state-of-the-art design method is a solution-oriented analysis, where only selected lay-ups are assessed for satisfying the design criteria. This study aims to develop a reversed design procedure where the lay-ups are obtained as design solutions. Therefore, a genetic algorithm procedure is developed to find the optimal lay-up satisfying the required fatigue life. The accuracy of the prediction method for crack initiation depends on the selected S–N curve of the constituent metal, which is observed to influence the obtained design solutions. Additionally, it was observed that the settings of genetic algorithm need to be tuned to obtain a robust optimisation methodology. In conclusion, with the presented methodology appropriate design solutions were obtained that satisfy the minimum fatigue life.

1. Introduction

The race of designing aircraft as light as possible while maximising the performance led to the application of Fibre Metal Laminates (FMLs) in fatigue sensitive structures, such as the fuselage and lower wing. FMLs can be customised specific to the design requirements by changing properties like the stacking sequence, the number of metal and fibre layers, the thickness of metal and fibre layer, and the fibre ply orientation. These variables create an immense design space of lay-ups that can be explored.

The performance of each FML lay-up is different. As a consequence, prediction methods are required to determine the performance to check whether the selected lay-ups satisfy the design requirements. The current design procedure for FMLs is limited in the sense that only selected lay-ups (design solutions) are assessed for satisfying the design criteria. In other words, the design procedure is a solution-oriented analysis, where only a limited amount of configurations are analysed while a large amount of configurations are ignored, which might include a better solution. For this solution-oriented analysis, prediction methods were developed to predict and assess the fatigue performance, like fatigue crack initiation (FCI) [1,2] and fatigue crack propagation (FCP) [3]. The current work focuses on the FCI phase.

The above-mentioned prediction methods work only in one direction. For two reasons it is not possible to revert mathematically the analysis process and to obtain lay-ups as output for given design criteria as input. Firstly, the method is not invertible due to the complex structure (e.g. the iterative process wherein the growth is calculated incrementally) of the prediction methods. Secondly, FMLs are characterised by a number of parameters which is usually smaller than the number of design variables, thus different sets of design variables can produce similar results [4]. In other words, various lay-ups have similar fatigue behaviour. As a result, a reversed mathematical function cannot result in a unique answer. Thus, a search procedure (optimisation algorithm) is needed which allows to explore a design domain and find the optimal or near-optimal solution based on constraints set on the required fatigue behaviour.

In FMLs, manufacturing constraints often limit the choice of fibre orientations to 0°, ±45° and 90°, and fix the metal sheet thickness and basic ply thickness, making the minimum weight design of a laminate a discrete optimisation problem [4]. It is possible to find continuous solutions and to round to the closest constraint, but this will have the risk that this solution is not optimal [5]. The need is for an algorithm that can cope with discrete variables. Genetic algorithm (GA) is in this case the best available algorithm; it copes with continuous and discrete problems [4]. GA is a search technique based on a survival of the fittest concept and uses natural selection and genetics to create a design population in which it finds the optimal solution by performing random probability

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searches [4]. GA is extensively used in composite structural design, such as in lay-up optimisation of composite laminates for maximum strength and buckling criteria [4–7].

The purpose of the current study is to develop a design optimisation procedure for FMLs by formulating an optimum (minimum weight) design satisfying the required FCI life implemented in the GA search method. While addressing this purpose, the following questions had to be addressed:

(a) How should the procedure be implemented without adapting the prediction method?
(b) What parameters do influence the design solutions?
(c) How to select an appropriate design solution?

2. Problem formulation

2.1. Optimisation problem

The design optimisation problem is formulated as a minimum weight design of an FML panel subject to fatigue life constraints. This problem can be expressed as:

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

Subject to

$$N_i \geqslant N_{i,\mathrm{req}} \quad \text{(fatigue life requirement)} \tag{2}$$

where W is the laminate weight, $\bar{x}$ is design vector representing the lay-up of the laminate, N_i is the fatigue life of the laminate and $N_{i,\mathrm{req}}$ is the required laminate life. 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), the thickness of metal layers (x_m) and the thickness of fibre ply (x_f). These design variables and the laminate definition are discussed in Section 3.1.

The main constraint for the optimisation procedure is set by the fatigue life ($N_{i,\mathrm{req}}$). The design solutions, represented by vector $\bar{x}$, should satisfy the required life when a constant amplitude loading is applied in the longitudinal direction. The FCI prediction method [2] is used to evaluate the fatigue life (N_i) for generated FML solutions.

2.2. Fatigue crack initiation

Fatigue life can be split in two phases [8]: (1) the number of loading cycles required to initiate a crack (N_i) and (2) the number of cycles it takes that crack to propagate to failure (N_p). While there is no clear transition from one phase to other, a crack length of 1 (mm) has proven to be an appropriate limit of the initiation phase [9]. The FCI method described in [2] predicts, therefore, the cycles to initiation N_i, which is thus defined as the number of cycles from crack nucleation till a crack length of 1 (mm). In FMLs, the FCI process is regarded as a fatigue process in the metal layers only, because the fibres show no sensitivity to cyclic loading. For this reason, the prediction is based on actual stresses and stress concentration factors in the metal layers [1,2]. Experiments have shown that this methodology is valid for Glare and other aluminium-based FMLs [1,2,10]. The methodology as used in this study is summarised in Fig. 1.

2.2.1. Prediction procedure

The crack initiation analysis assumes an FML panel with a notch, with known stress concentration factor (SCF) based on monolithic material ($K_{t,\mathrm{metal}}$), subjected to constant amplitude loading in longitudinal direction. This loading causes a crack to initiate at the notch root.

The method calculates the internal far-field layer stresses (S_{ff}) using Classical Laminate Theory (CLT) [11] by considering both the applied stress (S^{mech}) and the thermal stress (S^{th}). The nominal stress (S_{nom}) is then calculated by considering the reduced cross-section due to the notch.

$$S_{\mathrm{nom}}^{\mathrm{mech}} = (S_{ff} - S^{\mathrm{th}})\left(\frac{W}{W-D}\right) \tag{3}$$

$$S_{\mathrm{nom}} = S_{\mathrm{nom}}^{\mathrm{mech}} + S^{\mathrm{th}} \tag{4}$$

where, W is the width of the laminate and D is the diameter of the notch. In Fig. 2, the specimen and the stress distributions are illustrated.

By using the SCF calculation for anisotropic plate with a circular hole [12], the SCF of the notch for infinite wide FML plate ($K_{t,\mathrm{FML},\infty}$) is calculated. The SCF for infinitely large isotropic aluminium plates is $K_{t,\mathrm{metal},\infty} = 3$. The SCF of finite width FML panel ($K_{t,\mathrm{FML}}$) is then calculated based on a fixed ratio of SCF of infinite and finite wide plate:

$$\frac{K_{t,\mathrm{FML}}}{K_{t,\mathrm{metal}}} = \frac{K_{t,\mathrm{FML},\infty}}{K_{t,\mathrm{metal},\infty}} \tag{5}$$

The peak stress at the notch is then calculated by:

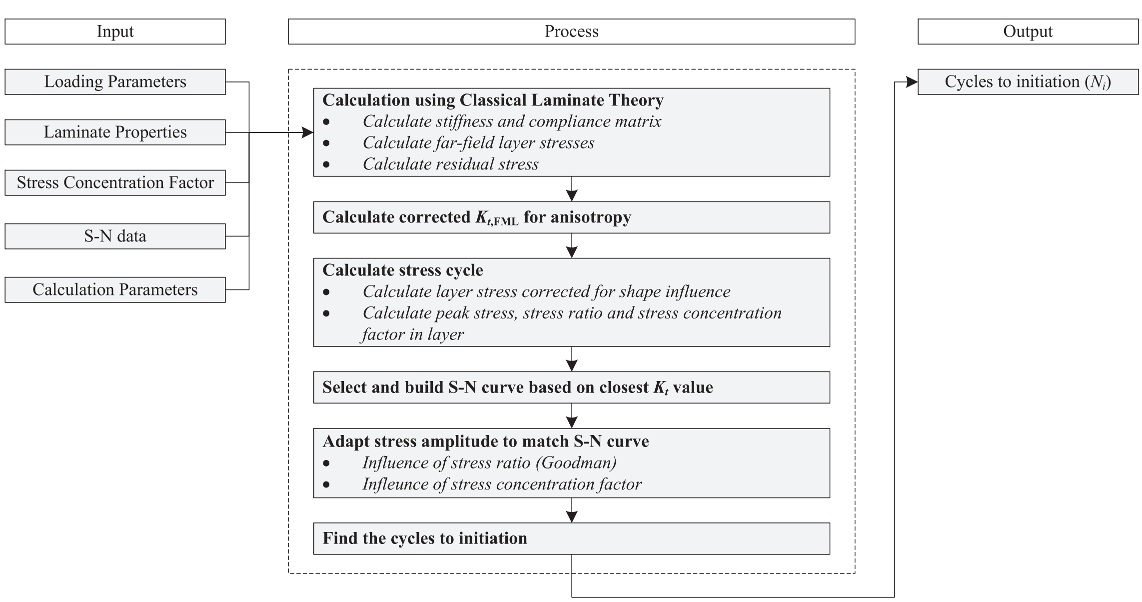

Fig. 1. Flowchart describing the crack initiation methodology.