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Optimization of crenellation patterns for fatigue crack retardation via genetic algorithm and the reduction in computational cost

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ABSTRACT

Crenellation is a promising technique to effectively improve the fatigue life of metallic airframe structures. It systematically varies the thickness of the fuselage skin at constant structural weight. In order to optimize the geometric designs of crenellation patterns for the maximum fatigue crack retardation, we apply an approach coupling genetic algorithm with FEM simulations to examine the vast candidate designs. Additionally, a progressively refined searching strategy and an old-individual-filtering technique were also used to minimize the computational cost. It was found that the crenellation patterns with nonlinear monotonous increase and decrease of skin thickness showed the best fatigue performance, which is expected to extend the fatigue life by 10% compared to the existing design based on experience. The applied strategies for reducing computational cost not only shortened the solving time but also improved the solution quality.

1. Introduction

Laser-beam welding is a very promising technique to be widely applied in future fuselage construction. It not only enhances the production efficiency significantly (over 15 times faster than the traditional riveting technique [1]) but also helps to reduce the structural weight by getting rid of the redundant materials at the riveted joints. However, the damage tolerance of the welded structure is inferior compared to the riveted structure [2]. Therefore, its application region nowadays is confined to parts of the fuselage, where damage tolerance is not a critical design criterion. To further extend the application of LBW in fuselage construction, the concept of crenellation [3–6] was proposed in recent years, which can improve the fatigue resistance of the welded structure without increasing the structural weight.

The idea of crenellation is to introduce a systematic thickness variation in the fuselage skin (Fig. 1), where the local variation of mass among the thickened and thinned areas counterbalances each other. The fatigue life gain due to the local thickening of fuselage skin will far outweigh the fatigue life loss in the locally thinned region, which results in an overall fatigue life improvement. The effectiveness of crenellations depends on its geometry, which can be well estimated from the stress intensity factor profile along the crack path by using the finite element analysis (FEM) [3,7]. Therefore it is very promising to perform a geometric optimization of crenellation patterns based on the FEM simulations. This paper presents an approach of automatic optimization of crenellation pattern by coupling the FEM simulation with a genetic algorithm (GA).

GA is an optimization technique inspired by the evolution process of nature as characterized by Darwin's theory of survival-of-the-fittest [8]. It works on a group of candidate solutions called population, which are ordinarily stochastically generated in the beginning. Each individual, like an organism in nature, has its own genotype and the corresponding phenotype. The genotype is usually a series of binary code, which is also called the chromosome of the individual (Fig. 2a). Each digit of the binary code

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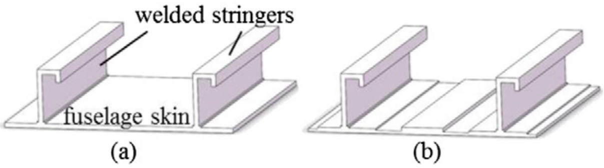

Fig. 1. (a) Flat and (b) crenelated integral structures with the same weight.

can be considered as one allele of the chromosome. Several alleles together can form a gene, which corresponds to one factor of the solution that the chromosome represents (Fig. 2b) — that is the phenotype. As shown in Fig. 2c, the optimization process runs in loops. Firstly the fitness of each individual in the population is evaluated based on the success of its represented solution. Then, the more fit individuals representing the more successful solutions will be selected. Their genotypes will be used for the subsequent crossover and mutation operations, during which the next generation will be produced. Through the repeated cycles of selection and reproduction, better and better solutions will be evolved.

Genetic algorithm is very robust in finding the global optimum in large and complex searching space (e.g. high-dimensional, discontinuous space with many local optima) [11,12]. In addition, it requires no prior information about the problem itself and can work purely based on the feedback from the evaluation process. These characteristics make GA very suitable for solving the present optimization problem, which involves a large number of design variables and can be considered as a "black-box" optimization process due to its full dependency on the evaluation results from the FEM simulations [13,14]. The first results obtained by using this approach have been published in a previous work [15]. In this work, efforts were continuingly devoted to the reduction of the computational cost, which can be crucial for solving the optimization problems with complex FEM models. To this end, a strategy of progressively refined searching similar to the method of Kim and Weck [16] combined with an old-individual filtering technique [17] was proposed in this study. Their influences on the computational cost as well as the solution quality were examined.

2. Proposed GA-FEM methodology

2.1. Description of the optimization problem

The optimization is based on the assumption that the crack starts at the root of the stringers, where favorable conditions for fatigue crack initiation have been developed during the welding process, such as high defect content and tensile residual stresses. The aim of the optimization is to maximize the number of cycles needed for growing an initiated crack from a detectable length to the final allowable length (from $a_0 = 5$ mm to $a_f = 145$ mm, Fig. 3). The thickness of fuselage skin between those two stringers can vary freely within the following three constrains:

1. inequality constraint — the variation of thickness t is confined in the following range: $1.9\text{ mm} < t < 4.15\text{ mm}$.
2. Equality constraint — the crenelated panel should be equivalent in weight to a flat panel with a thickness $t_{flat} = 2.9$ mm.
3. Symmetrical constraint — the crenellation pattern should be symmetrical to the center line of each bay between two stringers since fatigue crack can initiate from either welding site.

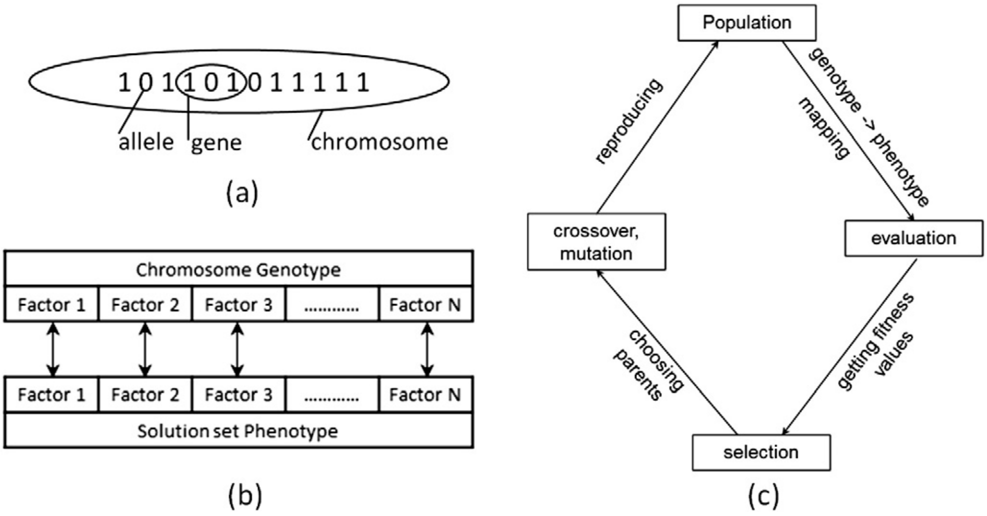

Fig. 2. (a) Schematic sketch of the genotype of an individual (after [9]) (b) mapping from genotype to phenotype (after [10]) (c) the loop of the optimization process based on genetic algorithm.