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Damage tolerance optimization of composite stringer run-out under tensile load

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ABSTRACT

Stringer run-outs are a common solution to achieve the necessary strength, stiffness and geometric requirements of some structural solutions. The mechanical behavior and complexity of such design details requires careful and thorough studies to ensure the structural integrity of the structure. The influence of some geometric variables of the run-out in the interface of the set stringer-panel is crucial to avoid the onset and growth of delamination cracks. In this study, a damage tolerant design of a stringer run-out is achieved by a process of design optimization and surrogate modeling techniques. A parametric finite element model created with *python* was used to generate a number of different geometrical designs of the stringer run-out. The relevant information of these models was adjusted using Radial Basis Functions (RBF). Finally, the optimization problem was solved using Quasi-Newton method and Genetic Algorithms. In the solution process, the RBF were used to compute the objective function: ratio between the energy release rate and the critical energy release rate according to the Benzeggagh–Kenane mixed mode criterion. Some design guidelines to obtain a damage tolerant stringer-panel interface have been derived from the results.

1. Introduction

The benefits of composite materials in aircraft/aerospace structures have been demonstrated in the last years. Stiffened panels are a common design strategy to obtain high stiffness in shell structures, keeping the lightness of the component and ensure the required buckling strength of the shell structure. As many others commonly used structural subcomponents these structures are frequently analyzed [1–4] using the so-called virtual tests, which aims to reduce the design cost by reducing the number of test on real components.

One method to increase stiffness and buckling strength of shells is the use of stringers which are efficient but requires careful analysis and design of the panel-stringer interface [5–7]. Additionally, the geometric specification of the design sometimes requires a special termination of the stringer named run-out, which is a cut-out showing a certain angle at the tip. This termination can be classified to different types and geometries. Run-outs have been analyzed by different authors [8–12] to define the behaviors and the best design. Hence, virtual tests, sometimes accompanied by experimental tests, have been deeply used to design and help to manufacture composite stringer run-outs [13–17].

However, the use of virtual tests needs large computation time for complex models. This prevents the use of optimization methods due to the necessity of generating a large number of different design cases (geometric, load states, boundary conditions, etc.) and their high computational cost. Metamodeling (or surrogate modeling) methods [18] are approximation techniques which can be used to substitute partially the solution of a complete finite element model. The use of surrogate models for design optimization or control of nonlinear systems has increased significantly in the last decade. The idea of surrogate models is to alleviate the burden of performing many computationally expensive analyses on a detailed model by constructing an approximation model (the surrogate model), that mimics the behavior of the detailed simulation model as closely as possible while being computationally inexpensive to evaluate. Metamodeling may thus enable the use of design optimization techniques of complex and numerically expensive systems [19,20].

In the present study, an optimization process with the aim of obtaining a damage tolerant design of run-out has been established and conducted. A parametric virtual test has been developed

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(Section 2) and Virtual Crack Closure Technique (VCCT) in the interface panel-stringer has been implemented. The structural influence of the different geometric variables of a run-out have been studied to choose the most significative ones (Section 3.1). The creation and verification of a Radial Basis Function (RBF) to reduce the computational time has been achieved (Section 3.4). Finally, optimizations of the RBF with Quasi-Newton method and Genetic Algorithms (GA) with different variable intervals have been performed and compared (Section 4).

2. Virtual test

2.1. Specimen and test

The study carried out by Greenhalgh and Garcia [11] has been used to design the specimen and virtual test. The specimen is a panel with an attached stringer run-out. This specimen was also used in a previous work [21] by the authors of the present paper to analyze the mechanical response of the different geometries and achieve a better understanding of the component and the test. A displacement boundary condition δ is applied at the tip of the specimen (Fig. 1(a)). The stringer run-out of this model is defined by four variables: the stringer rib angle α, the stringer base angle β, the distance between the rib tip and the stringer base tip d, and the distance between the stringer base and the point where the stringer rib angle starts L_{ro} (Fig. 1(b)). In this study, *python* code together with ABAQUS™ 6.12-1 Standard [22] have been used to create a parametric model that automatically can be generated.

VCCT is used to determine the energy release rate of the existing initial crack (explained in Section 2.2). Previous work [21] shows that the formation of a crack always appears in the tip of the stringer base. For this reason, the initial crack is modeled in all the different cases at this location, in the longitudinal midplane between the stringer and the panel.

The material for both the stringer and the panel is AS4/8552 and they are bonded using FM-300K adhesive. All the material properties are described in Table 1.

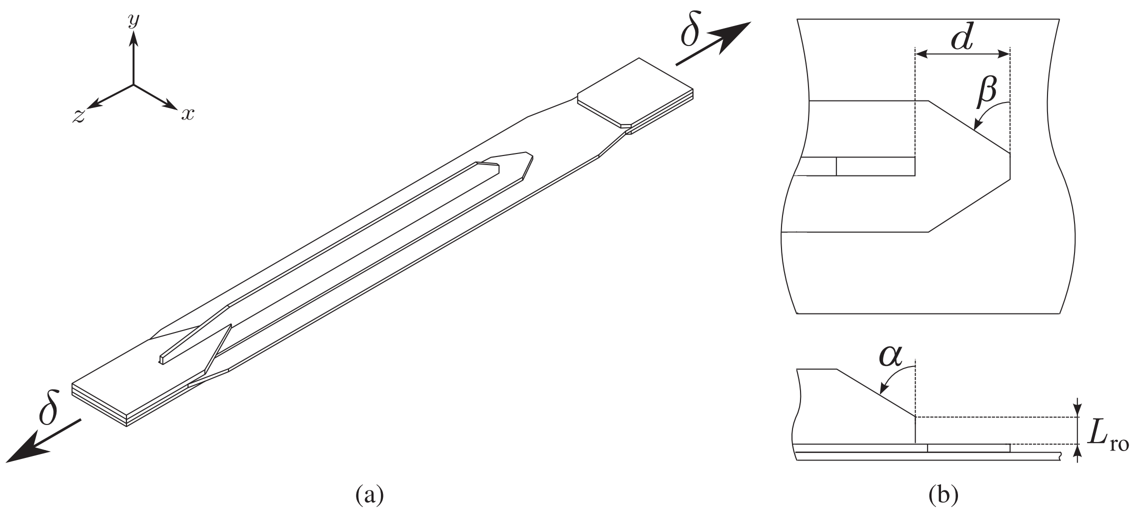

Fig. 1. Schematic representation of the test and the initial design variables.

Table 1
AS4/8552 and FM-300K properties.

Material	Property	Value	Units	Description
AS4/8552[a]	E_{xx}	135	GPa	Young's modulus in fiber direction
	E_{yy}	9.6	GPa	Young's modulus in transversal fiber direction
		9.6	GPa	Estimated $E_{yy} = E_{zz}$ (transversally isotropic material)
	ν_{xy}	0.32	–	Poisson's modulus in XY plane
	ν_{xz}	0.32	–	Estimated $\nu_{xy} = \nu_{xz}$ (transversally isotropic material)
	ν_{yz}	0.487	–	Poisson's modulus in YZ plane
	G_{xy}	5.3	GPa	Shear modulus in XY plane
	G_{xz}	5.3	GPa	Estimated $G_{xy} = G_{xz}$ (transversally isotropic material)
	G_{yz}	3.228	GPa	Shear modulus in YZ plane
	X_T	2207	MPa	Longitudinal tensile strength
	X_C	1531	MPa	Longitudinal compressive strength
	Y_T	80.7	MPa	Transverse tensile strength
	Y_C	199.8	MPa	Transverse compressive strength
	$S_{L_{UD}}$	114.5	MPa	In-plane shear strength
	$\mathcal{G}_{I_c}$ [b]	0.2839	N/mm	Critical fracture energy in mode I
	$\mathcal{G}_{II_c}$ [c]	1.0985	N/mm	Critical fracture energy in mode II
	ρ	$1.59 \cdot 10^{-9}$	T/mm^3	Density
FM-300K	$\mathcal{G}_{I_c}$	1.084	N/mm	Critical fracture energy in mode I
	$\mathcal{G}_{II_c}$	4.931	N/mm	Critical fracture energy in mode II
	η	6.5687	–	Benzeggagh–Kenane interaction parameter between modes

[a] Source: [36].
[b] Source: [37].
[c] Source: [38].