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Review article

Fiber-oriented repair geometries for composite materials

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In this paper, the idea of fiber-oriented repair geometries for carbon fiber reinforced plastics (CFRP) is investigated. It considers the differing mechanical properties of unidirectional fiber reinforced material by excluding overlapping regions perpendicular to the fiber direction of the particular layer.

A mechanical and numerical comparison of tensile strength of stepped joints with continuous step lengths per ply and stepped joints with reduced step lengths in plies with fiber orientation differing from load direction is performed.

Finite element simulations show similar shear stresses. Mechanical tests of CFRP laminates with stepped joints show no significant deviation in tensile strength, in spite of a joint length reduction of nearly 40%. This leads to the possibility of a significant reduction of repair area.

Contents

1. Introduction

In both civil and military aircraft, CFRP are used to lower weight, gain performance and to reduce lifetime costs. Several aircrafts consisting of more than 50% fiber reinforced structures were introduced into service, e.g. the Boeing 787 and the Airbus A350XWB. Compared to metallic structures, fiber reinforced parts are often designed integrally to reduce the overall amount of parts. Along with high weight-specific material strength, favorable fatigue behavior and good corrosion resistance comes a very specific damage behavior of the CFRP parts. In case of damage, structural replacements often cannot be readily performed because of huge dimensions and inseparable connections. Repair of the damaged

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part is left as the only option to re-establish the strength of the structures.

1.1. Scarf repairs and automation

Once damage is identified, a proper selection of repair strategy has to be made [1]. Repair processes for less severe damages in non-primary structures are often described in the aircraft's structural repair manual (SRM). Repairs of severe damage occurring in load-bearing structures have to be designed and approved according to the OEM directives [2]. Bonded or bolted repairs are used to re-establish structural integrity of the part by reinforcing or replacing the damaged material. Adhesively bonded flush repairs can fulfill both aerodynamical requirements and uniform load transfer between structure and reinforcement [3]. The repair procedure can be generally divided into damage identification, material removal, adhesive bonding of intact CFRP plies, curing, non-destructive evaluation of the repaired area, and final surface treatment.

Until now, most repair process steps are carried out by hand. Especially the manual sanding of the laminate surface (e.g. via air-powered grinders) is very time-consuming and sensitive to mistakes. Material around the damage is abrasively removed ply by ply in a defined pattern. By extending the chosen pattern in surface direction, a void with a defined scarf angle is created for adhesive bonding of repair material. Scarfing the structure is necessary to supply enough area for load transmission between structure and repair plies by adhesives. Due to tolerances in manual processes and no available technology to correlate the quality of adhesive bonds with resulting bonding strength, high safety factors lead to low scarfing angles and enlarge small damages in thick structures to extensive repair areas.

By automation of repair processes, improvements for bonded repairs can be reached. Repeatable machining of laminates guarantees a defined geometry and more uniform surface quality necessary for reliable bonding processes. Several machining technologies were investigated to determine optimal parameters and approaches for a fast repair. Material removal by laser, waterjet, grit blasting or milling show specific advantages and disadvantages towards treatment of heterogeneous composite structures [4–9]. Besides fast repairs, realization of complex and optimized repair geometries is another positive side effect of automated machining [10]. Currently used scarf repair patterns are of simple circular, rectangular or elliptical shapes with increasing dimensions towards the structure surface. With recently developed automated milling systems, it became possible to machine ply-wise stepped repairs with individual shapes into laminates.

1.2. Repair design and optimization

To sufficiently design adhesively bonded joints in repair geometries, two-dimensional models have been found to be adequate. Scarfed and stepped repairs (Fig. 1) are therefore simplified into scarfed and stepped joints in analytical and numerical models [11–16]. Structure and repair materials are discretized as adherents connected by an adhesive layer. Strength or strain criteria applied to those models can be used to determine maximal bearable loads. Considering the necessary safety margins, the geometrical parameters, e.g. scarfing ratios or angles, of the repair can be defined.

Stress peaks at the end of every step limit the strength of a stepped lap joint. Scarf joints tend to equalize stresses in the adhesive due to the continuous angle. Due to this, higher joint

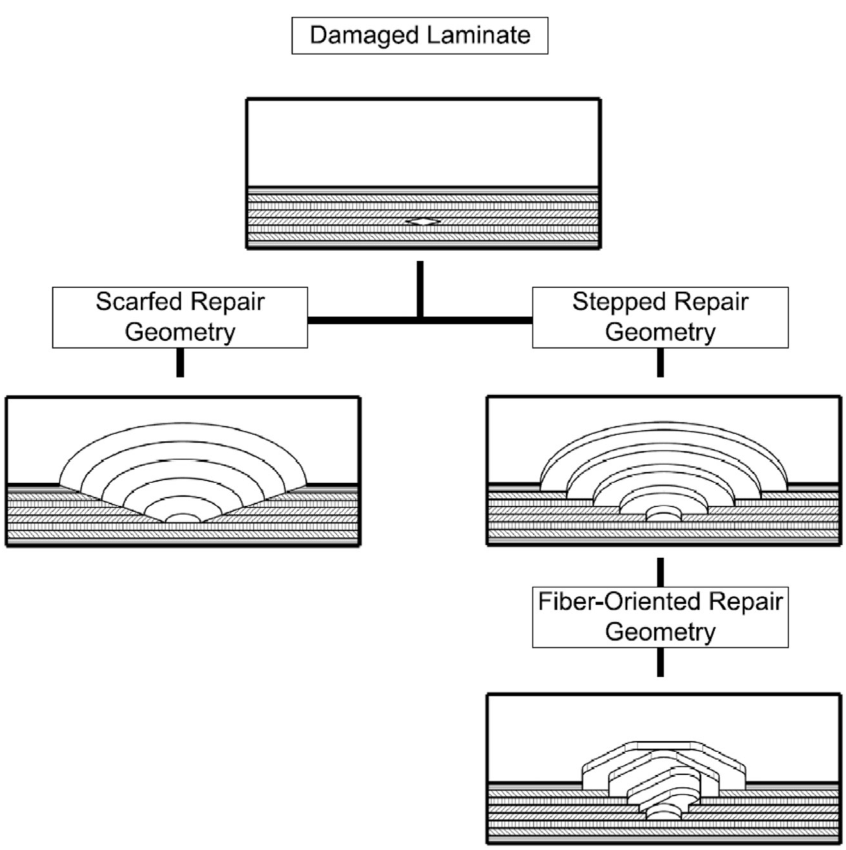

Fig. 1. Schematic visualization of possible repair geometries.