Composite Structures 130 (2015) 1–8

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Optimisation study of tapered scarf and stepped-lap joints in composite repair patches

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ARTICLE INFO

Article history:
Available online 24 April 2015

Keywords:
Composite repair
Scarf
Stepped-lap
Adhesive joints
Stress concentration
Finite element analysis

ABSTRACT

Stepped-lap repairs of composite structures can offer an alternative that is easier to perform and less time-consuming to produce than the widely used tapered scarf repair. However, the design of stepped-lap joints must be carefully investigated in order to avoid generating stress concentration regions. This study investigates the influence of joint parameters on peak stresses in the adhesive bondline in tapered scarf and stepped-lap joints. Linear finite element analysis was performed to conduct a parametric study with focus on six joint design parameters: ply thickness, adhesive thickness, taper angle, stacking sequence, overply layup, and overply lap length. Results showed that tapered scarf and stepped-lap joints have a strong sensitivity to ply thickness, taper angle, and stacking sequence. The introduction of overplies provided protection and stiffness at joint tips, and a critical overply lap length was identified. The location of 0° plies in the composite laminates was highlighted as an important factor. The analysis was then extended to three-dimensional FE models for verification. In conclusion, results showed that high stress concentration in stepped-lap joints can be mitigated with the introduction of overplies and appropriate changes in joint design parameters to reduce stress peaks at joint tips and step corners.

1. Introduction

The increased use of composite materials in aircraft structural parts has led to further interest in efficient composite repair methods. Adhesively bonded repair patches are considered to be mechanically efficient and can be quickly applied depending on the size of the repair, and the proficiency of the repair technician. Several bonding joints can be used: tapered scarf, stepped-lap, and overlap. In aerospace, where there often is a need for a flush surface to meet aerodynamic requirements, a tapered scarf or stepped-lap repair is applied.

In recent years, adhesively bonded repair patches have been extensively studied [1–3]. However, the use of fibre-reinforced composite materials adds to the complexity of designing and validating repair designs due to their anisotropic nature. The mechanical integrity of a repair patch is dependent on the stress distribution and stress peaks in the adhesive bondline between the patch and the parent structure. The stress distribution along an adhesive joint between two homogeneous adherends with identical material properties can be considered to be uniform [4]. However, the use of composite laminates featuring different fibre orientations through the thickness results in a varying stress distribution and stress concentration in the adhesive bondline [5]. In particular, shear stress and peel (i.e. normal) stress can significantly vary through the thickness of the laminate [6,7].

The design of tapered repairs has typically been based on a two dimensional (2D) approach with the results being implemented in real-world three dimensional (3D) repair scenarios. Although tapered scarf joint failure predictions based on 2D models can be consistent with 3D applications, the application of 2D design methodology can result in overly conservative design guidelines and lead to excessive material removal [8,9], particularly when investigating compressive loading cases. Analysis methods used by engineers to assess joint design can be analytical [10–12] or based on a finite element (FE) modelling approach [13–15]. Several certification frameworks for composite repairs have also been proposed [16–18].

Flush bonded repairs, such as tapered scarf and stepped-lap joints, are typically preferred for repairs of primary composite structures as they are more structurally efficient than external or bolted repair patches. However, tapered scarf repairs can be difficult to apply depending on the repair configuration. Stepped-lap

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http://dx.doi.org/10.1016/j.compstruct.2015.04.016
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joints offer an alternative that is easier to perform and less time-consuming to produce [19]. However, the design of stepped-lap joints must be carefully investigated in order to avoid generating stress concentration at step corners.

Hart-Smith [20] provided early analytical models for analysis of tapered scarf and stepped-lap joints which considered potential adherend stiffness- and thermal-mismatch effects. Gunnion and Herszberg [21] performed a parametric study where they investigated the influence of tapered scarf joint parameters on the stress distribution in the adhesive bondline. Their investigation mainly focused on stress distribution and average stresses along the centreline of the adhesive layer. However, local peak stresses may also contribute to failure if stress limits are exceeded before the average stress reaches allowable stress levels. As was noted by Gunnion and Herszberg, further investigation in local peak stresses is needed, particularly as local yielding of the adhesive may affect the fatigue and creep performance of the bonded joint.

The aim of this paper is to present an investigation of the influence of joint parameters on peak stresses in the adhesive bondline in tapered scarf and stepped-lap repairs. FE models of tapered scarf and stepped-lap joints were built, and peak peel and shear stresses for several joint configurations were compared. A parametric study was performed with focus on six joint design parameters: ply thickness, adhesive thickness, taper angle, stacking sequence, overply layup, and overply lap length. The analysis was then extended to three-dimensional FE models to further investigate stress concentration regions across the adhesive bondline.

2. Geometry and material properties

Two-dimensional CAD models for the tapered scarf and stepped-lap joints were built as shown in Fig. 1. The models consisted of eight-layered composite laminates for the parent structure and the repair patch bonded by an adhesive placed along a taper. Individual plies were discretely modelled, and a ply-by-ply match was assumed between the parent structure and the repair patch. The radius for the top layer of the repair patch was set at 150 mm and the length of the top layer in the parent structure was set at 50 mm. In the stepped-lap joint, for comparison purposes, the taper angle (α) was defined as the angle between the top surface of the joint and the centreline of the adhesive bondline, while adhesive thickness (t_a) was defined as the distance between the patch and the parent structure, as shown in Fig. 1. The material for the parent structure and the repair patch was carbon/epoxy AS4 3501–6, and the adhesive material was FM300. Material properties for AS4 3501–6 and FM300 are shown in Table 1 [21].

3. Methodology

3.1. Parametric model

A parametric study was undertaken to investigate the influence and sensitivity of joint parameters on stresses in the adhesive in tapered scarf and stepped-lap joints. Peak shear and peak peel stresses in the adhesive bondline were evaluated with respect to changes in six design parameters: ply thickness (t_p), adhesive thickness (t_a), taper angle (α), stacking sequence, overply layup, and overply lap length. Design parameters were defined for the tapered scarf and stepped-lap joints as shown in Fig. 1, with baseline values as listed in Table 2. A parametric study was then performed, as listed in Table 3. Except when under investigation, the baseline parameters listed in Table 2 were used.

3.2. Finite element model

FE models for the tapered scarf and stepped-lap joints were built in ANSYS. The models featured three main sections: the parent structure, the adhesive layer, and the repair patch. Shell elements were used which featured four-node elements with six degrees of freedom at each node (translations in the *x*, *y*, and *z* directions, and rotations about the *x*, *y*, and *z* axes). The model also included contact elements between the adhesive and the composite plies. Each composite ply and the adhesive layer had four elements through the thickness. Face meshing was applied across the composite plies and the adhesive layer to enhance aspect ratio and mesh uniformity. Local coordinate systems were created for each fibre orientation present in the laminate (i.e. 0°, +45°, −45°,

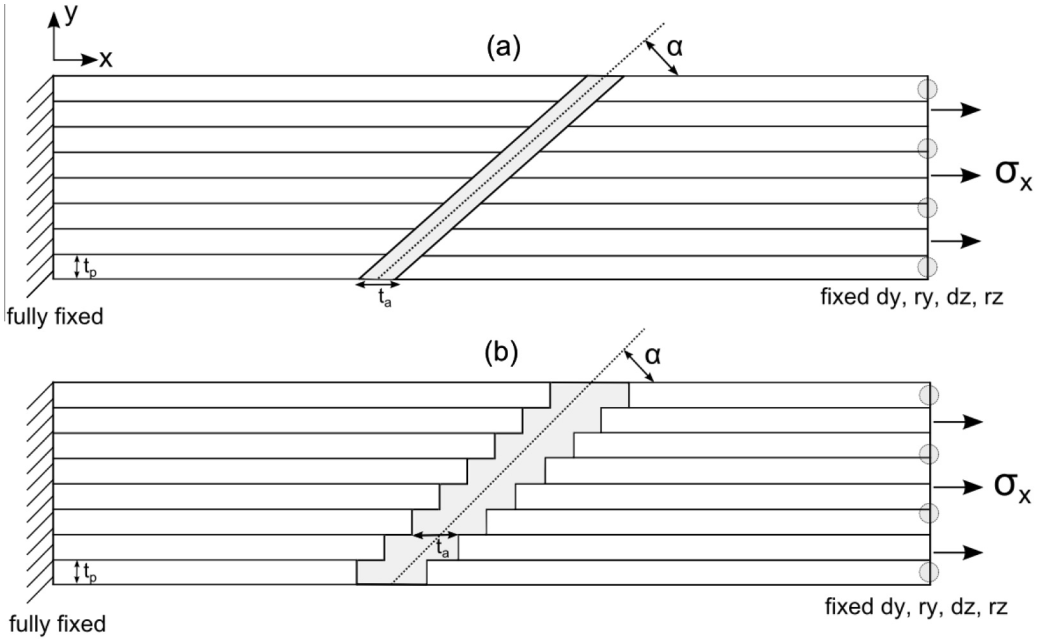

Fig. 1. Design parameters for (a) tapered scarf joint, and (b) stepped-lap joint.