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Comparison on damage tolerance of scarf and stepped-lap bonded composite joints under quasi-static loading

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ABSTRACT

Scarf or stepped-lap repairs are desirable for composite structures in aerospace, especially where a flush finish is required. Damage tolerance is a critical issue in the repair design. This paper investigates and compares the damage tolerance of scarf and stepped-lap joints (repairs) under quasi-static loading using finite element analysis (FEA). The damage was represented by a flaw embedded in the bondline between composite adherents. 3D FE models were built for both scarf and stepped-lap joints. Both linear and nonlinear adhesive properties were simulated under room temperature (RT) and hot-wet (HW) conditions. The flaws with varying length and width were imbedded in the bondline, so that the sensitivity of damage tolerance to the flaw size can be analysed and compared between scarf and stepped-lap joints. Other parameters, which may affect the damage tolerance of both joints, include flaw location, number of steps of stepped-lap joint, stacking sequence of laminate adherend, out-of-plane boundary conditions and the presence of an external doubler. The results showed that the stepped-lap joint exhibited better damage tolerance than the scarf joint with linear elastic adhesive. The damage tolerance of both joints became similar when the adhesive became nonlinear under RT or HW conditions. The damage tolerance of both joints can be improved by attaching composite doubler reinforcement or constraining the out-of-plane movement.

1. Introduction

Fibre reinforced polymer (FRP) composites have been adopted as construction materials for automotive, aerospace, civil and marine structures [1–4]. Suitable methods are required when connecting FRP components [5] to form larger structural systems or repairing damaged FRP parts [6] to restore their designed capacities. Two methods are currently widely adopted in composite structures, namely mechanical fastening and adhesive bonding. It has been widely reported that adhesive bonding had benefits such as lighter weight, better load transferring mechanism through larger bonded area and better fatigue performance [1,5,7–10]. On the other hand, mechanical fastening methods using bolts or rivets were always criticised due to stress concentration resulting from fibre cutting at bolt holes, and increasing the self-weight of structure [1,9,11]. The weight saving is especially more important in modern airplane structures where FRP composites become more extensively used (e.g. Boeing 787 with about 50% FRP by weight [12]), which makes the adhesive bonding methods more desirable [9].

There are several types of adhesive joint configurations, like single-lap joint, double-lap joint, scarf joint and stepped-lap joint [13,14]. Scarf joint and stepped-lap joint were mostly adopted when connecting composites to carry higher loads [9,15] or higher strength recovery for damage repair is required or when a flush surface is necessary to satisfy the aerodynamic requirements [14]. Analytical solutions in literature [16–18] seemed proposing scarf joint as more efficient than stepped-lap joint because the shear stress was almost constant along the bondline and stress concentration was minimised at the end of adherends. However, these observations were made on joints with isotropic adherends. Things may become different when anisotropic composite adherends (like FRP) were considered. For example, the adhesive shear stress and peel stress were found varying significantly along the bondline of the composite scarf joint [14,19]. This was mainly because of the stiffness variation due to the change of fibre orientation of each ply in the laminated adherends, with the stress concentrations mainly occurred around 0° plies [11]. This particular stress distribution may largely reduce the scarf joint efficiency when allowable shear stress was considered [19]. Furthermore, several studies argued that composite stepped-lap joints could be more desirable than corresponding scarf

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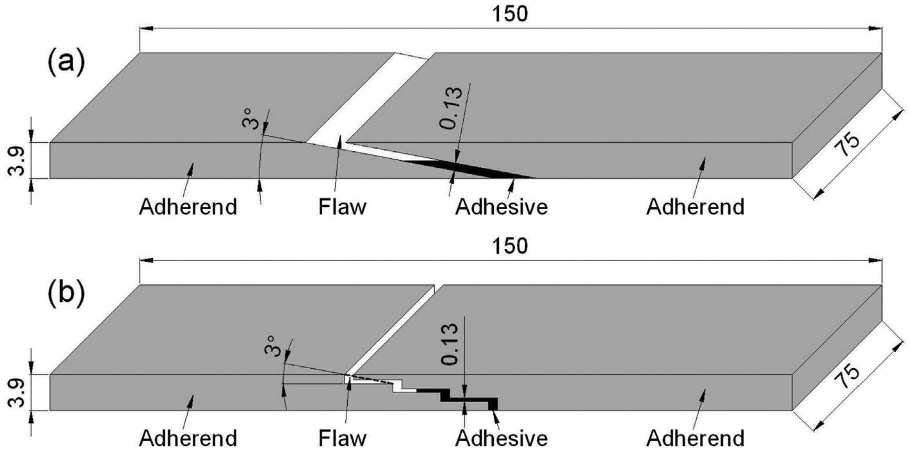

Fig. 1. Dimensions of (a) scarf joint and (b) stepped-lap joint (not to scale, unit in mm).

joints when considering the manufacturing cost [1,5,7,10]. However, there has been very limited direct comparison between the composite scarf and stepped-lap joints [20].

Other issues with adhesive joints include the lack of inspection method and analytical solution as well as damage tolerance information for ensuring the bondline integrity [6,21]. In other words, in order to promote the application of adhesive joints or repairs in composite structures, it is necessary to assess the joint efficiency when bondline damages exist [6,21]. A recent work on the damage tolerance of composite scarf joints was reported in Ref. [21]. A bondline flaw was embedded at the interface between adhesive and composite adherend. Scarf joint specimens were prepared with flaw lengths of 3 mm, 6 mm and 12 mm. It was found that the load-carrying capacity of scarf joints was dependent on the size of flaw as well as the ply orientation close to the tip of the flaw. Numerical modelling was conducted with cohesive zone model (CZM), virtual crack closure technique (VCCT) and linear elastic fracture mechanics (LEFM). It was proposed that the CZM could be used for damage tolerance analysis of composite scarf joints. The impact damage tolerance of adhesively bonded composite scarf joints was reported in Refs. [22–24]. Impact loading was applied to the scarf joint when it was loaded either in tension or compression. The tensile strength and compression strength after impact of the joint were measured. It was found that low energy impact could cause 35% reduction in tensile strength of the scarf joint. However, there have been no reports on the damage tolerance behaviour of composite stepped-lap joints considering bondline flaw effects on the joint strength, which makes it impossible to select a suitable joint method for a robust design of composite repair.

Another issue with the damage tolerance of adhesively bonded composite joints is associated with the working environment, like temperature and humidity, which have shown extensive effects on the bondline behaviour. The combined moisture and temperature effects on the bonded composite joints were reviewed by Budhe et al. in Ref. [25], and it was mentioned that the moisture absorption sensitivity was increased at high temperature, which lead to more damaged structure. Knox and Cowling [26] found that the epoxy adhesive, AV119, showed approximately 20% reduction in strength and a correspondingly 10% reduction in Young's modulus as a result of accelerated ageing at 30 °C and 100% humidity. The weakened adhesive bondline of electro-galvanized steel (EGS) single lap joint were also observed by Zhang et al. [27]. They found that after 20 days exposure at 80 °C and 95% humidity, the EGS joint would undergo significant loss of bond strength due to the zinc coating corrosion on the adhesive-zinc interface. Similar observations were also reported by other researchers in Refs. [28–30]. Therefore, it is necessary to investigate the effect of the adhesive with changing properties due to hydrothermal effect on the damage tolerance of scarf and stepped-lap joints.

This paper presents a direct comparative study on the damage tolerance between composite scarf and stepped-lap joints through three-dimensional non-linear finite element analysis (FEA). Composite scarf and stepped-lap joints under quasi-static loading were modelled with a flaw of various lengths and widths in the bondline. The location of the flaw was also changed from the tip to the middle of the bondline. Each ply of the composite adherends was individually modelled so that the ply orientation effects were considered. Non-linear adhesive properties under both room temperature (RT) condition and hot-wet (HW) condition (or hydrothermal condition) were input in FE models. Comprehensive parametric studies were conducted on parameters which may affect the damage tolerance of scarf and stepped-lap joints. These parameters included stacking sequence of composite adherend, out-of-plane boundary conditions, the presence of an external doubler and the number of steps of stepped-lap joint. For joints of isotropic materials such as aluminium, it is generally believed that a scarf joint has better static mechanical behaviour than a stepped-lap joint. However, it may not be the case for joints of composite materials, especially when the damage tolerance behaviour is of particular interest. This paper reports a comprehensive comparison on the damage tolerance behaviour of composite scarf and stepped-lap joints, and contributes to the preliminary understanding on how to make a selection of a proper composite joint when the damage tolerance becomes a required criterion in a composite repair design.

2. Finite element model

The finite element analysis software, Abaqus, was adopted for the simulations. Three-dimensional FE models were built for composite scarf and stepped-lap joints. The dimensions of both joints are presented in Fig. 1. It should be noted that the number of steps of stepped-lap joint in Fig. 1b is only for illustration purpose, which varied in the following FE simulations. Also, the width of the flaw in Fig. 1 is the same as the width of the joints (full width flaw). In the following analysis, the flaw width also varied to investigate its effect on the damage tolerance behaviour of both joints.

As can be seen in Fig. 1, the total length of both joints is 150 mm, and the width is 75 mm. The thickness of the joints depends on the number of plies of the adherends and the thickness of each ply. In the current study, a ply thickness of 0.13 mm was used and the adherends consisted of 30 plies. Therefore, the thickness of the joints is 3.9 mm. The adhesive thickness is the same as the thickness of the ply (0.13 mm). In this paper, a scarf angle of 3° was used and the stepped-lap joints has the same angle as defined in Fig. 1b.