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# Simulation of pin-reinforced single-lap composite joints

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**Abstract**

A simple and efficient computational approach is presented for analyzing the benefits of through-thickness pins for restricting debond failure in joints. Experiments have shown that increases in debond resistance and ultimate strength depend on the material, size, density, location, and angle of deployment of the pins and the mechanisms of pin deformation, which are complex and strongly affected by the mode ratio of the debond crack. Here the mechanics problem is simplified by representing the effects of the pins by tractions acting on the fracture surfaces of the debond crack. The tractions are prescribed as functions of the crack displacement, which are available in simple forms that summarize the complex deformations to a reasonable accuracy. The resulting model can be used to track the evolution of competing failure mechanisms, including tensile or compressive failure of the adherends, joint debonding (creating leak, for example, if the joint is in a pipeline), and ultimate failure associated with pin rupture or pullout. Calculations illustrating complex mode ratio variations are presented for a lap joint specimen comprising curved laminate segments cut from pipes.


*Keywords:* Adhesively bonded lap joint; Through-thickness reinforcement; Bridging law; Debond; Delamination; Pipes

## 1. Introduction

Adhesive bonding is the most popular method for joining polymeric matrix composite parts together, for many reasons. For example, compared to mechanical fastening techniques, such as bolting, it offers improved fatigue resistance, greater design flexibility, and much reduced manufacturing cost. It is also capable of joining thin sheets efficiently. Thin-walled structures are very common in aerospace and civil pipeline structures. However, even with excellent adhesion, the joint does represent a discontinuity in the material resulting in high stresses that often initiate joint failure. The most challenging problem faced by a design engineer is the potential weakness of the adhesive bond and the poor through-thickness strength of the adherends. In addition, secondary bending in a single lap joint creates a non-uniform stress distribution and mixed failure mode. Bond weakness in a complex stress field can result in debond failure and much lower design strength. Manufacturing defects and service-induced damage will make the matter worse.

One promising approach is to apply through-thickness reinforcement using small diameter metallic or fibrous pins. This technique was first motivated by the quest for damage tolerance in airframe structures [1–5], but a preliminary study has recently investigated their suitability for joining pipelines [6]. By an attractive and inexpensive technique, in which pins were inserted into holes drilled through a bonded joint section, significant gains were demonstrated in ultimate strength and resistance to debond growth.

The optimal design of a pin-reinforced joint is a complex problem. The experiments in [6] showed that ultimate strength tends to rise with pin density and the size of the pins, but the benefit varies with the pin material (pins can be made of metal alloys or carbon or glass fiber composite). Furthermore, the efficacy of the pins in deterring debond-

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**Nomenclature**

| | |
|---|---|
| $B$ | joint width |
| $F(u,w)$ | load–displacement vector for a pin |
| $F_1$, $F_3$ | traction component against Mode II and Mode I failure, respectively |
| $G_{\mathrm{I}}$, $G_{\mathrm{II}}$ | strain energy release rates in modes I and II |
| $G_{\mathrm{IC}}$, $G_{\mathrm{IIC}}$ | critical strain energy release rates in modes I and II |
| $L$ | joint length |
| $L_2$ | joint overlap length |
| $L_{\mathrm{s}}$ | pin slip length |
| $P$ | external applied load |
| $a_1$, $a_2$ | debond length at side 1 and side 2, respectively |
| $d_s$ | pin pullout length |
| $n_i$ | number of iteration step |
| $r$ | pin radius |
| $t$ | adherend thickness |
| $t_{\mathrm{a}}$ | adhesive thickness |
| $\delta$ | applied total displacement |
| $\theta_y$ | maximum angle of bending for the joint |
| $\sigma_0$ | axial stress in the bridging pin |
| $\tau_0$ | shear flow stress in the bridging pin |
| $\theta_0$ | tow angle of deflection at the fracture plane |
| $\phi$ | pin insertion angle |
| CSLJ | curved single-lap joint |

ing depends on where in the joint area the pins are inserted; pins are more useful if inserted near the ends of the joint. Experiments on materials more relevant to airframes, i.e., using small carbon fibre pins in carbon/epoxy laminate joints, show that the angle at which the pins are inserted has a strong effect on the mechanics of delamination resistance [7,8]. Optimal angling of the pins is expected to be especially important in cases of mixed mode delamination. To fully use the advantages of adhesive bonding and pin reinforcement, the engineer needs to understand various design parameters that influence the strength and damage tolerance of composite structural joints. Accurate simulations of debonding and the ultimate failure of pinned joints can streamline the design task, avoiding unnecessary and expensive fabricate-and-test cycles. This is the motivation of this paper.

Adhesively bonded lap joints have been studied for many years, with most analytical and theoretical work being focussed on predicting the stress within the thin adhesive layer [9–12]. For a single lap joint debond, mixed mode failure criteria have been implemented for fracture failure prediction [13–15]. However, no study has been reported on pin-reinforced joints. With pin reinforcement, a model should incorporate the crack-closing tractions generated by those pins, by a formula that reflects the large deformation the pins experience en route to ultimate failure. The simulations must deal with the true geometry of the joint, since geometry determines the mode ratio of the debond crack.

The finite element method has proved a robust and flexible tool to perform complex analyses for composite structures, e.g. [16,17]. Some work has been done for through-thickness reinforced laminates at coupon levels [18,19].

This article presents a simplified and efficient formulation of the pinned joint problem and demonstrates some of the unusual characteristics of fracture in a complex joint caused by the presence of pins. The case used for illustration is motivated by recent tests on pipe joints [6]. The model combines the finite element method and a previously developed analytical model for the pins, which can account for pins of arbitrary initial orientation, subject to large mixed-mode deformations [20–23]. The model is incorporated here as prescribed bridging tractions, which act on the surfaces of the adherends when a debond crack exists. Once a joint geometry has been meshed, the simulations allow consideration of arbitrarily varied pin parameters with great ease simply by varying the incorporated bridging tractions. If the pin locations are varied, it is only necessary that a single pair of nodes is available in the adherend meshes at each pin location – a nonlinear spring element between the pair of nodes will represent the action of the pin completely.

## 2. Problem statement

### 2.1. Single lap-joint analysis with large scale bridging

The illustrative problem is a single lap-shear joint connecting two composite laminates, bonded with an adhesive and reinforced by pins in the joint region. The study problem is a curved single lap shear test specimen (CSLJ), which was used in [6] to study joints representative of pipes (Fig. 1).

In a joint between whole pipe segments (i.e., a complete axisymmetric joint), the mode I displacement in the wake of a debond crack within the joint would be limited. In the CSLJ geometry, in contrast, the opening displacement in the crack wake can be large and might even dominate over the sliding displacement in some cases. Because of this, the CSLJ should not be the sole test for qualifying the behaviour of pin-reinforced pipe joints. Nevertheless, the presence of pins tends to suppress the opening mode even in the CSLJ specimen, so the conditions seen by a pin in the crack wake in the CSLJ specimen may not be too different to those expected in an axisymmetric joint. The CSLJ also allows insight into the behaviour for other joints, such as those in sheet structures (airframes, truck