DESIGN OF PIN REINFORCEMENTS IN METAL-COMPOSITE HYBRID JOINTS TO MAXIMISE ENERGY ABSORBANCE DURING FRACTURE

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ABSTRACT

Hybrid metal-to-carbon fibre composite joints are of special interest for the aerospace industry. Interface pins present a highly effective solution for delaying catastrophic joint failure and tracking the failure process by absorbing significant amounts of energy during the pin pull-out process. Here, a validated design approach is presented to design pin geometry, pin angle and density in accordance with joint parameters (adherend thickness, adherend strength, bond line stresses) to achieve maximum energy absorbance during joint fracture.

1 INTRODUCTION

Hybrid joints are generated a result of a push for lightweight designs combining several types of materials, most notably structural composites and metallic alloys for modern aircraft. Adhesive joining is a relatively low cost solution in this case, alleviating galvanic corrosion problems and potential stiffness/thermal property mismatch. However, an adhesive interface bond can suffer catastrophic failure; effectively eliminating adhesive joints from use in primary structures which require regular safety inspections and tracking of progressive damage events [1,2].

In recent years, a wide range of methods for through-thickness reinforcement for hybrid joints have been investigated, including using additive manufacturing [3], electron beam surface texturing [4], cold-metal transfer [5], laser-cut metal sheets [6] and laser riveting [7]. All studies show that metallic through-thickness reinforcements can increase the fracture toughness and crack growth resistance significantly. However, the studies do not attempt to create the basic understanding necessary to optimize the design process for hybrid joints with reinforcements. As the studies are generally undertaken on different types of joints with different stress states at the interface, it is difficult to determine general design guide lines based on published work.

In this paper we present a coherent methodology correlating the behaviour of single pin and multi-pin joints. Based on these outcomes, we outline an optimization methodology to determine the optimum pin geometry, density and angles for the hybrid multi-pin interface based on the local stress state. We discuss our findings for the case studies of a double cantilever beam joint (mode I dominated) and a single lap joint (mixed mode). These joints have significantly different stress characteristics and hence result in significantly different optimum pin arrangements.

2 METHODOLOGY

2.1 Hybrid joint optimization

The authors [8-10] previously developed and validated a multi-scale finite element modelling approach to (1) numerically predict the bridging law of the pin pull-out process with a high fidelity finite element unit cell model and (2) embed the resulting bridging law into a structural level model through the use of simple representative spring elements. This approach is outlined in detail in Figure 1. Input data is presented in form of load-displacement curves for the nonlinear spring elements, an element type which later represents the discrete arrangement of pins within the multi-pin joint. This approach has the advantage that various pin arrangements and angle distributions may be validated and optimized for the joint design. The cohesive zone elements on the other hand represent relatively uniform damage mechanism events in form of fibre bridging and resin fracture.

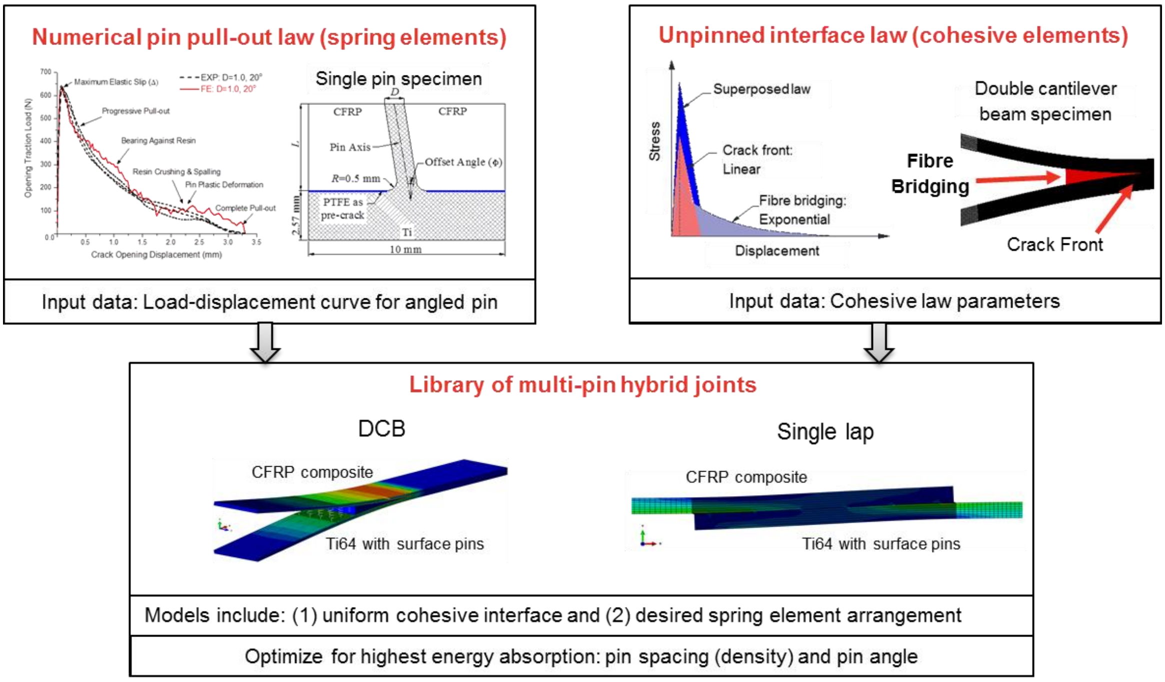


Figure 1: Design framework for hybrid joints with maximum energy absorbance

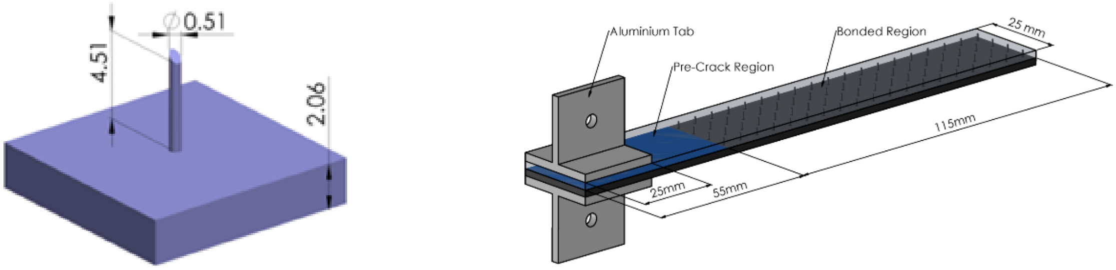
Load-displacement curves differ in shape depending on the pin angle and stress state experienced by the pin during pull-out. The numerical model can also predict metallic pin fracture, hence the optimum pin geometry in terms of length and diameter for a given stress state can be established. As a result, pin design maps can be created for given set of material properties.

For the optimization of the multi-pin hybrid joint, the stress state in the bond line needs to be established first. In Figure 1, we highlight double cantilever beam (DCB) and single lap joints as potential target joints for optimization. These two joints have significantly different stress states in the bond line. For the DCB joint, the stress state is a dominant mode I close to the crack tip as the crack progresses along the interface. Hence the pull-out mechanism is mode I dominated. For the single lap joint, on the other hand, the stress state is known to vary throughout the joint length, with the centre section under high shear stresses and the regions close to the overlapping ends experiencing higher peel stresses. The appropriate optimization approach is then outlined in Figure 2. Based on the known stress state distribution in the bond line, we can firstly optimize the pin angle according to the local stress state to minimize the shear force acting on the pin. It should be noted that additive manufacturing easily allows for the variation in pin angle along the bonded surface area. Based on the material properties of the pin and bond strength, the *L/D* ratio of the pin can now be optimized to be close to the transition region. Joint considerations apply in this step, ie the maximum pin length L is restricted by the composite thickness and the diameter D should be small enough as to not disturb the fibre network unnecessarily. In the last step, we optimize the pin density. Pin density should now be chosen in such a way that the resulting fracture toughness is maximized for the respective adherend strength.

Figure 2: Design steps for hybrid joints with maximum energy absorbance

2.2 Specimen design, manufacturing and testing

For single pin and multi-pin joint manufacture, metallic adherends and their integrated surface pins with various geometric details (length, diameter, surface angle) were additively manufactured in Titanium-6Al-4V via selective laser melting (SLM 250HL, SLM Solutions). Single pins were manufactured on the centre of a square base, while double cantilever beam specimens were manufactured and tested according to ASTM D5528-13. The respective specimen designs are shown in Figure 3.



(a) (b)

Figure 3: (a) Single pin specimen and (b) DCB specimen

A PTFE insert of 0.1mm thickness was used as a starting crack for the DCB specimens and as a separator at the interface of the titanium and composite single pin geometry. In the latter case, this allowed to exclusively study the pull-out response of the pin without needing to consider the adhesion properties of the flat surface. The T700 carbon/epoxy composite prepreg material was carefully pushed ply-by-ply onto the pinned surfaces, and the resulting hybrid joints were co-cured in the autoclave at 120°C and 620kPA for 1 hour according to the manufacturer's recommendations.

3 RESULTS AND DISCUSSION

3.1 Failure modes in hybrid joints with pin reinforcement

The multi-scale modelling approach was validated through single pin pull-out experiments for selected mode mixity loading ratios as well as structural double-cantilever beam tests. The interface damage mode plays a crucial role in the joint's resistance to interface fracture. Figure 4 shows the fracture mechanisms occurring in a pin-reinforced hybrid metal-composite joint. Along with fibre bridging and resin fracture, two main failure modes are observed for the pins: (1) pin fracture and/or (2) pin pull-out.

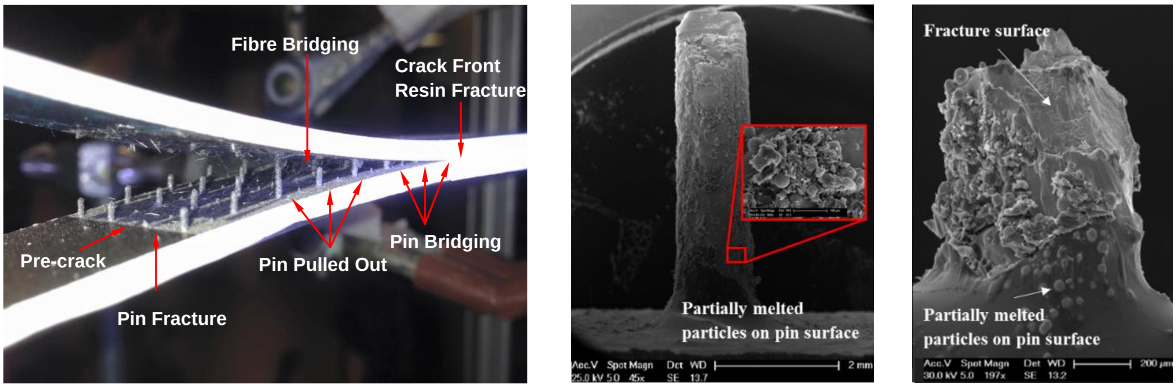


Figure 4: Fracture mechanisms for pin-reinforced hybrid joints (adapted from [8])

It is well-known that the pin pull-out mechanism is much more effective at absorbing energy (due to the friction force to be overcome during pull-out) than a broken pin. The transition point between both failure modes depends on the pin's geometry (length L to diameter D), the pin's material strength, σ_{max}, the pin's interface strength, τ_{max}, to the surrounding matrix system, and the external loading condition (mode mixity ratio of normal versus shear loading). For straight mode I pull-out of a pin out of the surrounding material, a relatively simple expression may be established for the critical transition aspect ratio L/D based on the values of σ_{max} and τ_{max} [8]:

$$\frac{L}{D} = \frac{\sigma_{max}}{4\tau_{max}} \tag{1}$$

As the shear loading on the pin increases during pull-out, the critical transition aspect ratio L/D for complete pin pull-out is reduced further. This is highlighted in Figure 5. It is shown that the deformation becomes increasingly non-symmetric and pin stresses increase as we increase the pin angle. This then results in ductile fracture progressing from the region of highest tensile stress due to pin bending. Failure is predicted to occur close to the pin root, which is generally also observed experimentally.

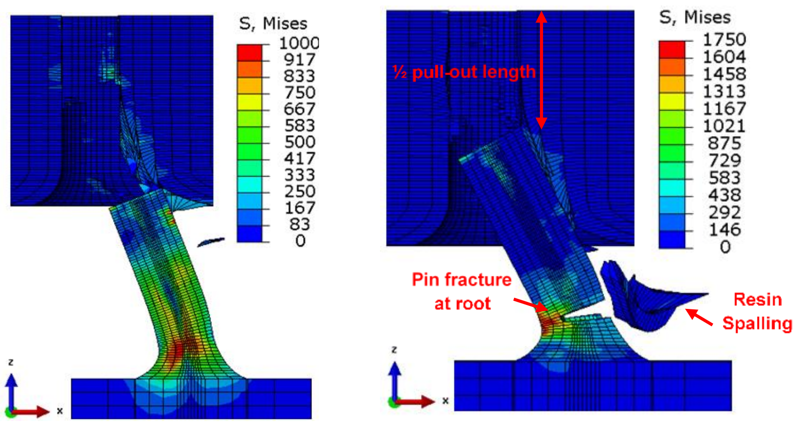
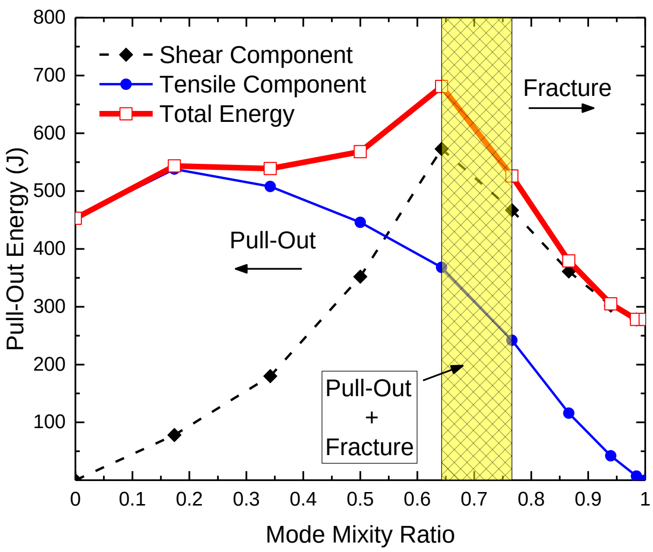


Figure 5: Pin deformation and fracture during pin pull-out for (a) 30° and (b) 50° loading angle

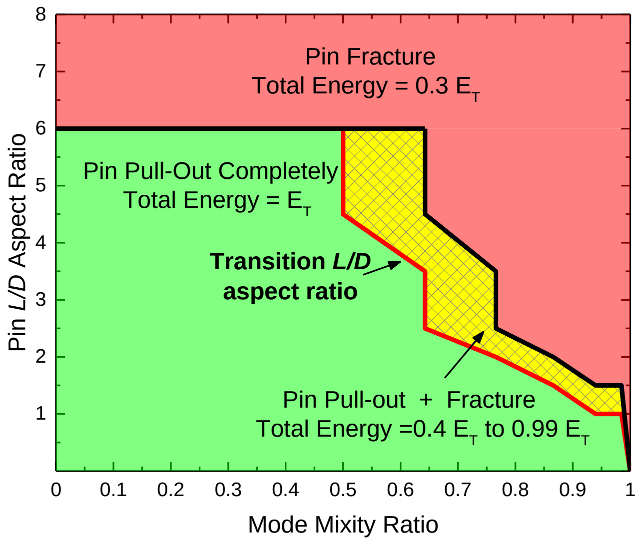
3.2 Failure maps for pin reinforcement as a function of mode mixity

Figure 6(a) shows the simulated absorbed energy for a single pin pull-out test (L/D=3.5) as a function of mode mixity ratio. Under tension-dominant loading (mode mixity ratio < 0.5), this pin geometry will pull out from the surrounding composite material. As mode II contributions increase (mode mixity ratio > 0.65), the pin will undergo a transition point where partial pull-out and fracture co-exist, followed by pin fracture without any signs of pull-out (mode mixity ratio > 0.8). The pull-out energy increases with increasing mode mixity ratio as long as the joint fails via pin pull-out. This is due to additional damage process occurring in form of resin crushing and spalling as well as metallic strain-hardening of the titanium pin. It is important to note that the absorbed energy reduces drastically once pin fracture occurs.

Figure 6(b) shows the complete design map of the selected Ti64/CFRP system. We display the absorbed energy as a function of the critical pin aspect ratio and the mode mixity ratio. We establish that for low mode mixity ratios (< 0.5) the transition point only depends on the ratio of the pin length to diameter. For shear-dominated loading on the pin, the maximum *L/D* ratio for pin pull-out reduces and becomes a function of the mode mixity ratio. Increasing the shear loading component for the same pin dimensions will therefore lead to pin breakage and hence reduced energy absorbance. A pin exposed to shear conditions while absorbing maximum energy during pull-out therefore needs to have a much lower aspect ratio *L/D* compared to a pin in a mode I loading state.



(a)



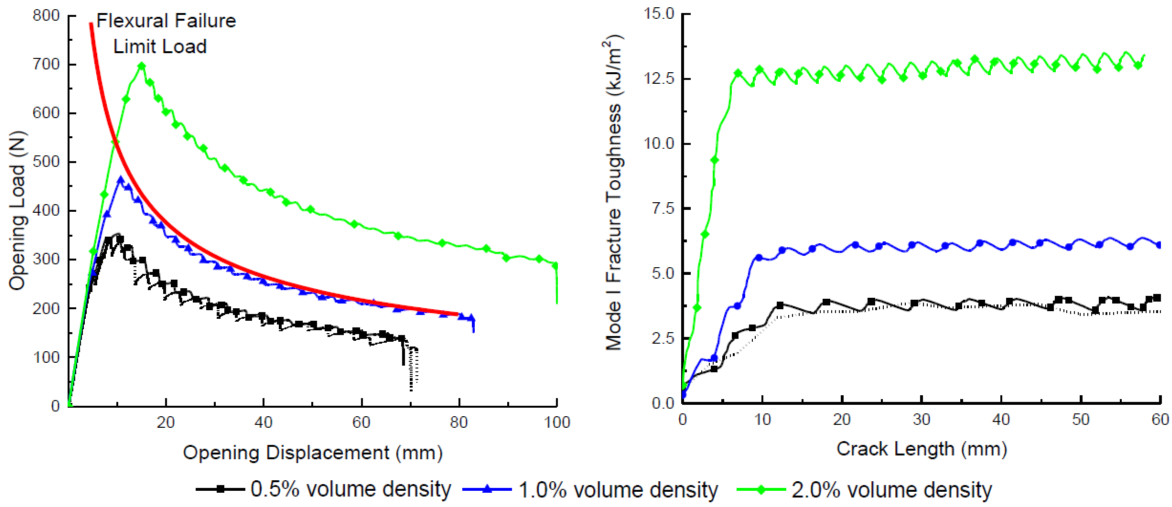
(b)

Figure 6: (a) Single Ti64 pin energy uptake in CFRP as a function of mode mixity for *L/D*=3.5 and (b) energy map as function of mode mixity and pin aspect ratios, both assuming σ_{max}=1200MPa as per bulk material strength of SLM-manufactured Ti64 and τ_{max}=50MPa [11].

3.3 Design strategies for optimal multi-pin DCB joints

For this case study we focussed on a pin geometry of 0.5mm diameter and 2mm length. As previously discussed, the stress state for DCB joins is mode I dominated within the pin pull-out zone. Hence all pins should be designed with regard to Eq. (1) close to the critical transition ratio, where the maximum length *L* is constrained by the adherend thickness (2.6mm thickness in this case, hence resulting in 2mm effective maximum pin length due to chamfer and manufacturing considerations). The diameter *D* was chosen as 0.5mm in this work, which results in a value of L/D=4. This is below the critical transition ratio of L/D=6 highlighted in Figure 6(b) for mode I loading. However, pins with higher aspect ratios were found to fail prematurely for diameters of 0.5mm and smaller. For these smaller pin diameters close to manufacturing limits of the SLM printing equipment, some manufacturing defects may occur close to pin roots, effectively raising the stresses concentrations and hence reducing the transition ratio to a value closer to 4. For larger diameters of 1mm, the critical aspect ratio of 6 may be reached. However, validation testing then requires much thicker adherends up to 6mm thickness, hence limiting the amount of testing to be completed due to material cost.

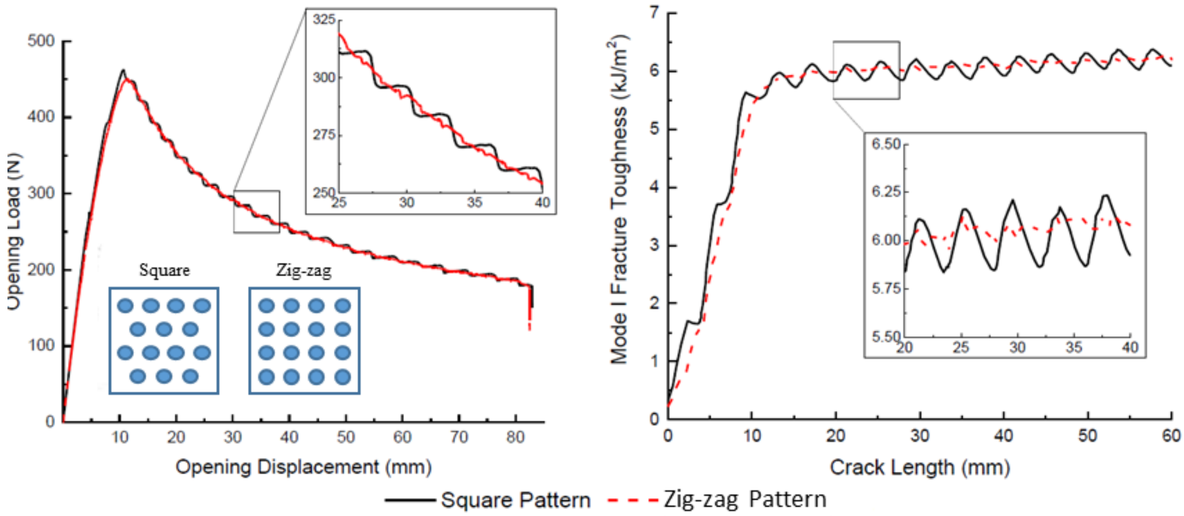
Figure 7 shows the corresponding load-displacement curves and resulting mode I fracture toughness as a function of crack length for the same pin geometry (close to optimum) and varying pin volume density. For 0.5% volume density, the agreement with the experimental test results is also shown and is very good. For 1% and 2% volume density, the predicted maximum load and mode I fracture toughness increase approximately linearly, similar to results obtained with carbon fibre z-pins. For a cantilever beam, the flexural failure limit load may be derived via Timoshenko beam theory. The CFRP flexural strength is reduced by 10% due to the presence of fibre misalingment in the presence of pins [12]. This limiting flexural failure load is indicated with the red line and hence results in an upper limit of 1% for the pin density to ensure that progressive fracture without adherend fracture occurs. The same design process may be followed for other adherend thickness values.



(a) (b)

Figure 7: Optimization of pin density for maximum energy absorbance for DCB joint with 2.6mm composite adherend layer thickness

Lastly, we would like to highlight that further optimization of the pin pattern may be achieved. This is shown in Figure 8 for two different forms of pin arrangement, namely square and zig-zag patterns. It can be seen that the steady-state mode I fracture toughness achieved is the same for both configurations as the same pin geometry and pin density is used. However, the stick-slip behaviour of the square pattern is stabilized significantly by offsetting the pinned rows relatively to each other. Additionally, using zig-zag patterns also avoids the formation of resin-rich channels in the composite adherend due to fibre misalignment during pin insertion, a well-known side-effect of pin reinforcement which can knock down composite in-plane properties significantly [12].



(a) (b)

Figure 8: Influence of pin arrangement on crack propagation (D=0.5mm, L=2mm, volume density =1%, adherend thickness=2.6mm).

3.4 Design strategies for optimal pin-reinforced single lap joint

Figure 9 shows the resulting design schematic for a small-scale single lap joint for optimum fracture energy with pin pull-out. The pin aspect ratio L/D is reduced toward the bondline centre to allow for continued pin pull-out. The pin angles are also optimized locally. This optimization accounts for the differences in mode mixity along the bond line.

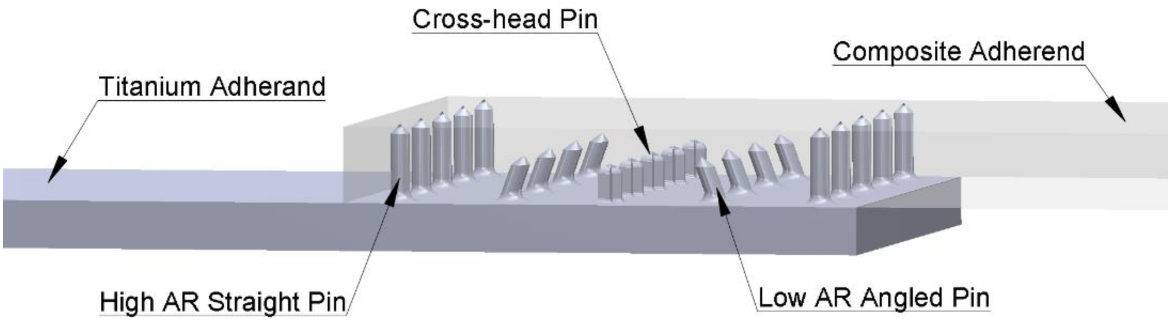


Figure 9: Design philosophy for single lap joint

4 CONCLUSIONS

The work presented demonstrates the potential design process to achieve the desired maximum energy absorbance for hybrid metal-composite joints. We show that it is possible to optimize pin details in terms of geometry, angle and density locally with respect to the stress state of the bond line. In this context, additive manufacture allows for an effective solution to print metallic components with bespoke and optimized surface features for subsequent bonding to composite parts.

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