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# Adhesively bonded lap joints with extreme interface geometry

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ABSTRACT

The role of adhesive–adherend interface morphology (through intentional deviation from a flat joint plane) on the mechanical behavior of adhesively bonded lap joints is studied. Two mirror-image types of joints with a zigzag interface containing 'positive and negative' interlocking teeth were fabricated and their tensile behavior was measured and compared to the response of a standard flat joint. Numerical simulations were used to explore the role of tooth height and width on the stress distribution in the adhesive, and on crack propagation and arrest after initial fracture. The data suggest that stress distribution along the bond line – and thus, the initial fracture load of the joint – is altered considerably by the positive and negative interlocking teeth. The tendency of a crack to either propagate along the bond or to arrest also depends strongly on morphological details. When crack arrests, the bonded joint can sustain a higher load and thus benefits from some of the intrinsic properties of the adherends (e.g. the plasticity of metal adherends) to enhance energy absorption and toughness. Our findings provide insight for the development of robust multi-material and multi-component structural systems with tailorable properties, and for understanding the role of interface morphology in some biological systems.


## 1. Introduction

Where structural materials join together, geometrical or elastic discontinuities generally lead to a complex state of deformation and concentrated stresses, which may encourage cracks and defects to initiate and propagate along the bonded joint. The challenge of joint design is especially pronounced for non-metallic structures, since traditional ductile attachment techniques (e.g., welding or brazing) cannot generally be employed. Adhesive properties have been shown to be the limiting factor in many bonded systems [1–4]. This has stimulated the development of better adhesives [5–9] and surface treatments which modify the micro-topography of the adherend surfaces [1,2,10,11]. Another promising avenue for enhancing bond properties is to tailor the joint geometry (by adherend scarfing or tapering, adhesive fillets, etc.) [5,12,13]. For example, bonded wavy lap joints exhibit higher strength than a counterpart flat lap joint [14–17]. Here, we extend these studies by introducing extreme morphological changes close to the edges of bonded lap joints, where peel and shear stresses are known to be intensified [18–23]. It was hypothesized that strength and ductility could both be enhanced by changing the bonded region topography.

The challenge of creating joints with elevated strength and ductility has been well addressed in nature, where the connections between organic and inorganic materials generally occur at multiple length scales. An example is nacre (mother-of-pearl), a natural nano-composite of ceramic and biopolymer with surprising mechanical properties [24–26]. The toughness of nacre [24] is partly attributed to interlocking 'wave shape' polygon tablets, which delay localization by propagating deformation through the entire structure [25–29]. The roles of geometrical organization and topology on improving the behavior of materials and structures have also been demonstrated in other biological systems. For example, the heterogeneous structural organization of bone is shown to be critical for its superb energy dissipation and toughness [30,31].

Geometrical and structural organizations have been also exploited recently to develop high-performance *multifunctional* materials and structural systems. Hierarchical honeycombs [32–34] and functionally graded cellular structures [35,36] are examples of such developments, which can be tuned to exhibit enhanced properties. Another unique example is the recent demonstration of *Buckliballs*, a class of patterned shells that undergo large buckling-induced deformations under pressure, of a type not observed in continuum shells [37].

Our study includes fabricating and testing bonded lap joints with different interface morphologies, along with detailed finite element modeling. For our experiments (Section 2), we fabricated standard flat joints as well as joints with two mirror-image zigzag surface morphologies, and measured the tensile behavior up to failure. The experiments themselves were not intended to explore extensive parameter variations, but rather to benchmark and

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validate the associated finite element (FE) modeling. It was observed that each kind of non-flat interface morphology displays a characteristic and explainable load–displacement curve, with an initial cracking or debonding event, followed by rapid crack propagation or arrest depending on the interface morphology. A particular geometry was identified as offering twofold to threefold reduction in maximum peel stress over the experimentally evaluated non-flat geometries, and thus by implication, greater initial failure strength than the standard flat lap joint. In Section 3, linear-elastic FE analysis using ABAQUS is employed to evaluate distributions of stress and strain in all the experimental geometries. Also FE simulations are used to obtain the optimized geometrical parameters resulting in the largest strength and load capacity. In Section 4, we carried out further simulations to study elastic stresses in joints with partially debonded lengths. The results can provide insight into bonded-joint crack propagation, thus revealing the behavior after initial cracking. Conclusions are presented in Section 5.

## 2. Experimental investigation

### *2.1. Specimen preparation and test methods*

Adherends with three different profiles were machined from 1018 CR steel bar with the following assumed properties: Young's modulus, $E_s = 200$ GPa, Poisson ratio 0.3, and tensile yield strength 386 MPa. The adherends' length $d$, width $w$, and mean height $h$ were 120 mm, 3 mm, and 10 mm, respectively. Standard flat lap joints, as well as two non-flat types with a v-shaped tooth and the matching v-shaped notch (or negative tooth) on each adherend were fabricated and tested. The two non-flat types of adherends are as follows:

- "Positive then negative tooth" adherend defined by each adherend becoming thicker (i.e., a tooth) as it enters the joint region from its grip. This morphology is frequently denoted by '/\' or 'first point upward' in the paper.
- "Negative then positive tooth" adherend defined by each adherend becoming thinner (i.e. a notch) as it enters the joint region from its grip. This morphology is frequently denoted by '\/' or 'first point downward' in the paper.

Fig. 1A provides a generic description of joint geometry. Interface morphology is defined by an overlap distance $L$ (the projected bond length), first-tooth slope angle $\theta$, and tooth height $A$ (from which is derivable total tooth width $B = 4A/\tan(\theta)$). Then flat, /\, and \/ joints correspond to $\theta$ & $A = 0$; $\theta$ & $A > 0$; and $\theta$ & $A < 0$, respectively. Each tooth is in the form of an isosceles triangle. We define the geometry in non-dimensional terms through the tooth height to adherend height ratio ($A/h$), the total tooth width to

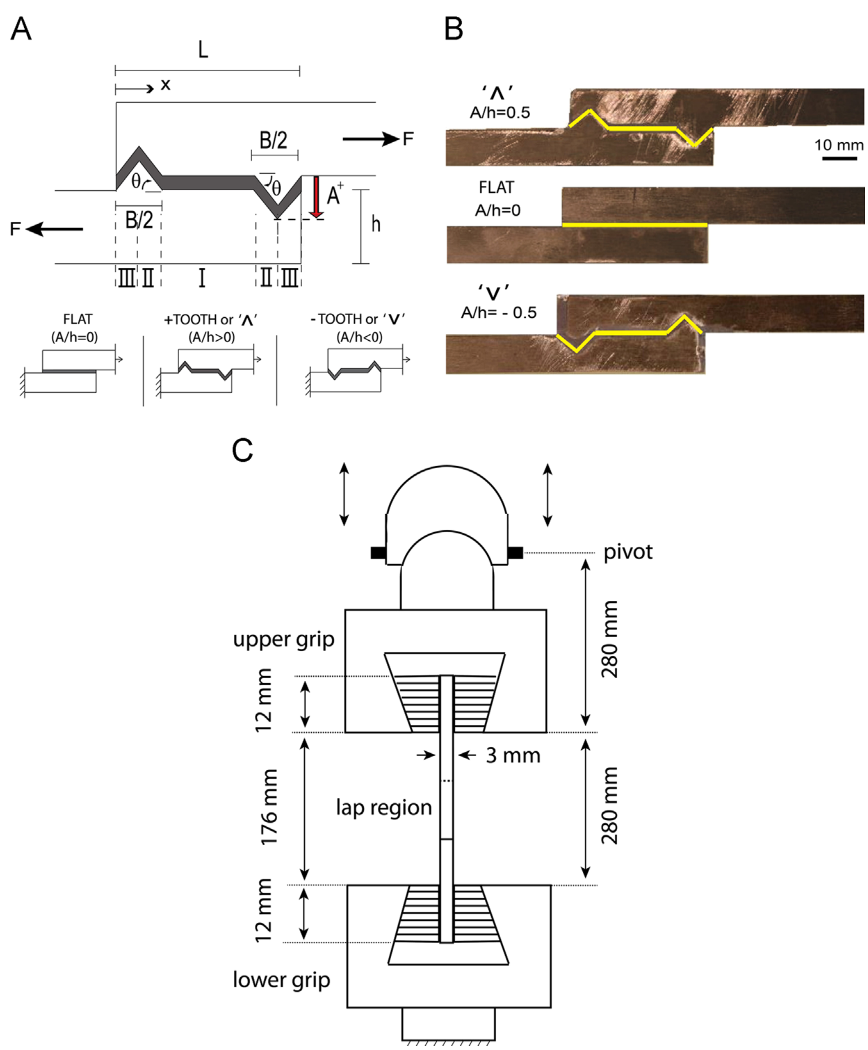


**Fig. 1.** (A) Schematic of the bonded joint. (B) Bonded joint with three different interface profiles of $A/h = 0.5$, 0 and $-0.5$. The adherends are made of steel and the adhesive layer is highlighted by lines to better show the interface morphology. (C) Schematic of the experimental setup.