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Cross-Configuration Assessment of Functionally Graded Adhesives in Single-Lap Joints via an Elastoplastic Ductile-Damage Framework

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Introduction

Adhesively bonded single-lap joints are widely used in lightweight and multi-material structures, but severe peel and shear stress concentrations often develop near the overlap ends, leading to premature damage initiation.

Functionally graded adhesives and bi-adhesive layouts can mitigate these edge-dominated stresses by combining ductile adhesive regions at the overlap ends with a stiffer adhesive in the central region.

However, most studies evaluate adhesive grading under a fixed adherend configuration. This work compares Al–Al, Al–GFRP, GFRP–GFRP, and Steel–GFRP joints to clarify how adherend configuration affects stress redistribution, damage evolution, and joint strength.

Methods

- A two-dimensional finite element framework was established for single-lap joints, using consistent geometry and loading conditions across all cases.

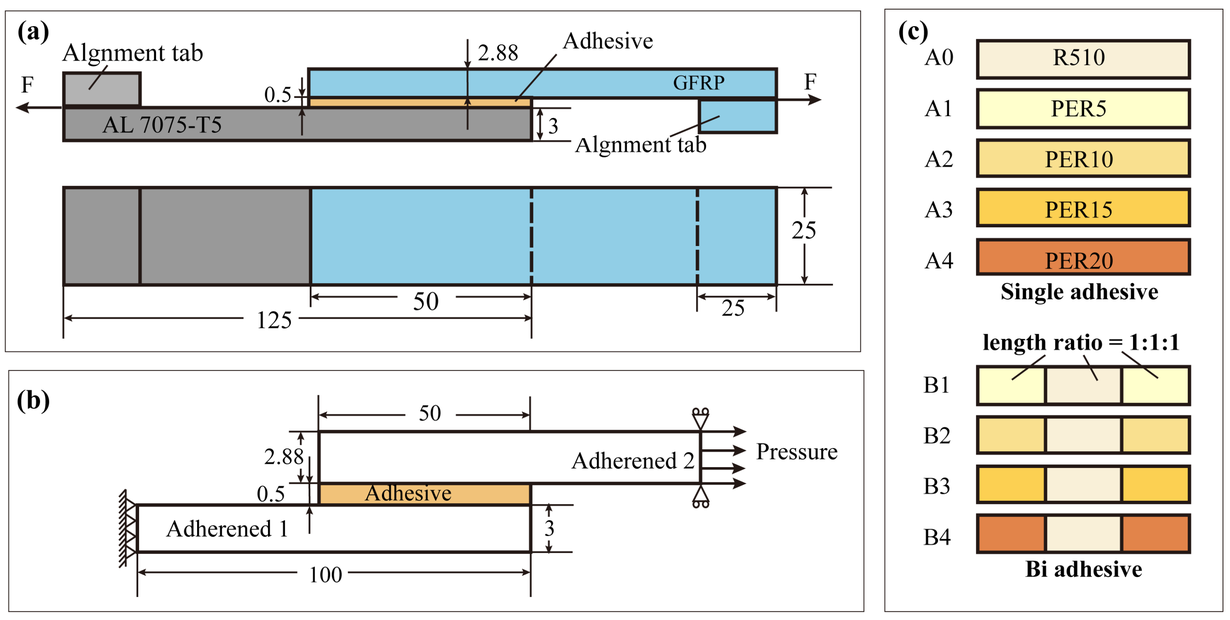

Figure 1. Single-lap joint geometry, FE model, and adhesive layout definitions.

- The adhesive was described by an elastoplastic ductile-damage model, allowing joint strength, stress redistribution, and damage evolution to be evaluated.

- Four adherend configurations were compared under single-adhesive and bi-adhesive layouts, with the model first validated against Al–GFRP experimental data.

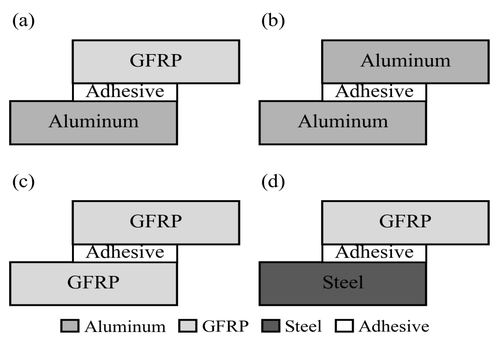

Figure 2. Adherend configurations considered in the cross-configuration assessment.

Graphics

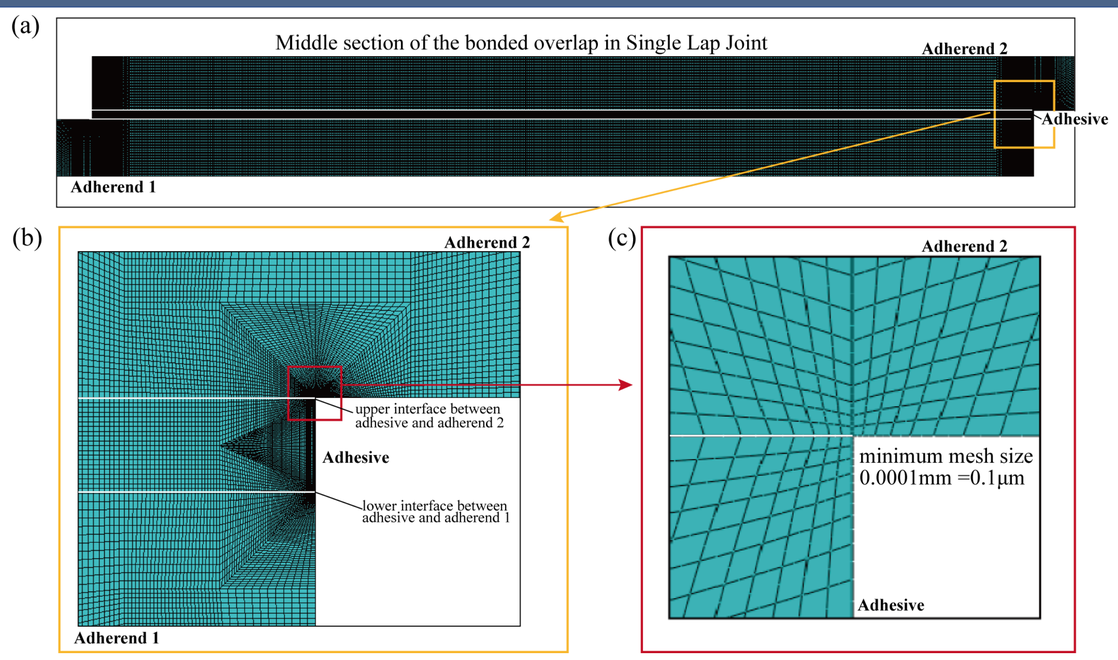

Figure.3 Finite element mesh of the single-lap joint model with local refinement near the adhesive end region.

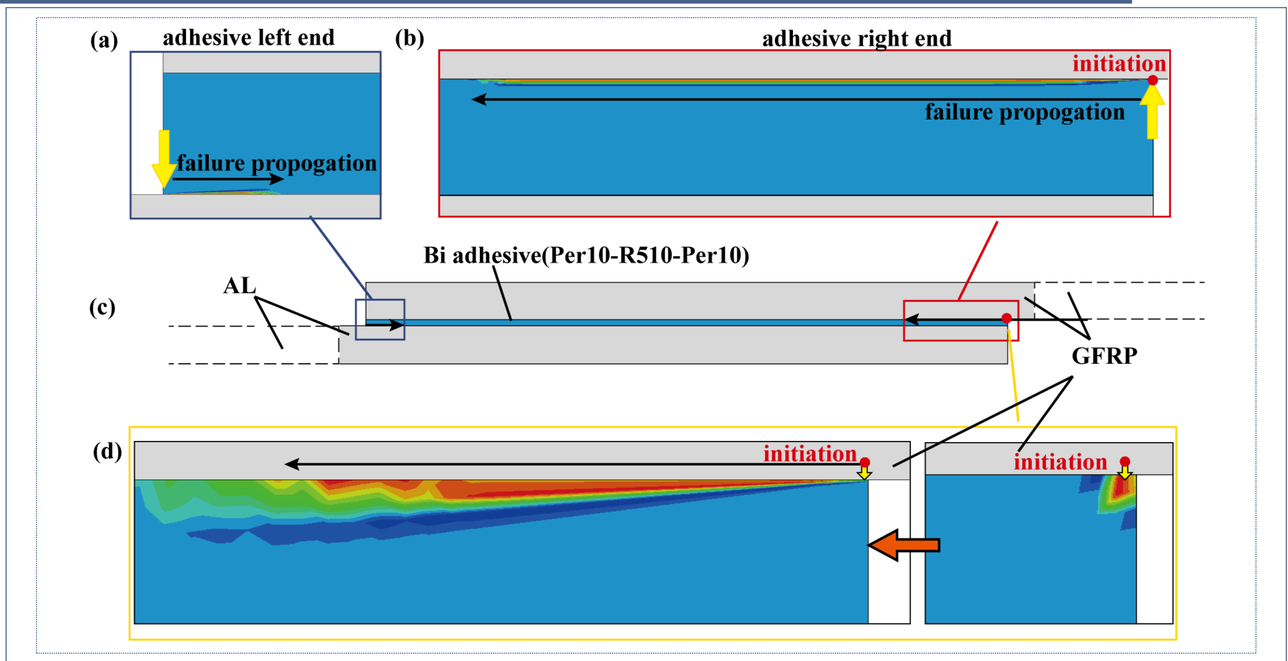

Figure.4 Predicted damage initiation and propagation in the Al–GFRP bi-adhesive joint.

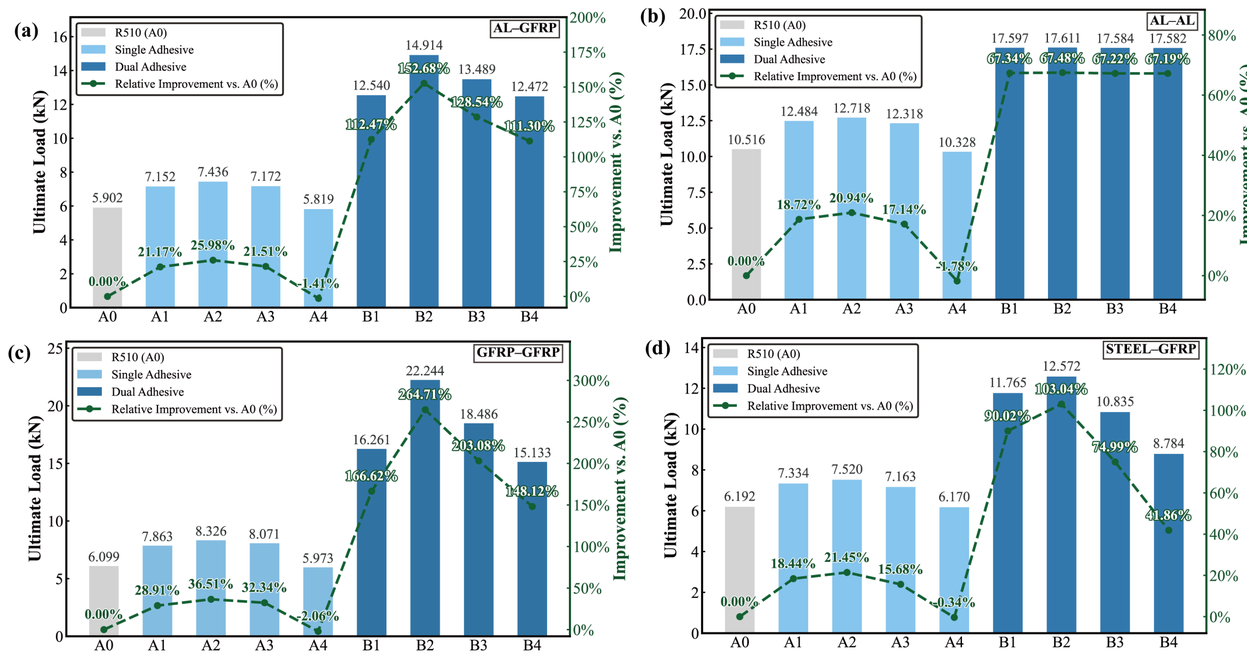

Figure 5. Ultimate load and relative improvement across different adherend configurations.

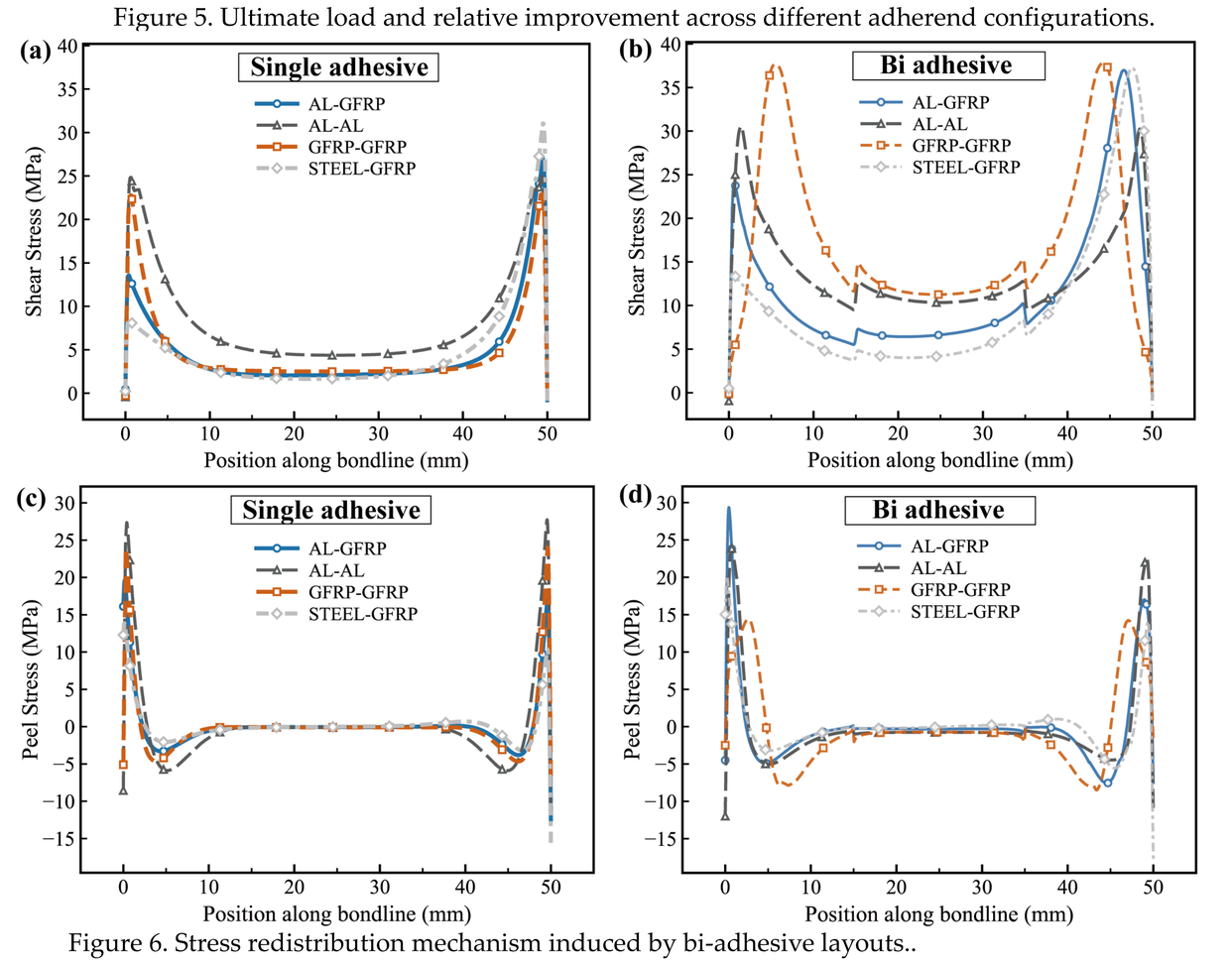

Figure 6. Stress redistribution mechanism induced by bi-adhesive layouts..

Conclusions

1. Bi-adhesive layouts improved the ultimate load in all investigated adherend configurations, but the magnitude of improvement depended strongly on the adherend system.
2. The largest relative improvement was obtained in compliant–compliant GFRP–GFRP joints, while rigid–rigid Al–Al joints showed more limited gains. Al–GFRP and Steel–GFRP exhibited intermediate gains due to adherend stiffness mismatch.
3. Stress analysis indicates that functional grading enhances joint performance by delaying edge-dominated damage, shifting load-transfer zones inward, and increasing mid-span shear transfer.
4. Overall, the effectiveness of functionally graded adhesives is governed not by adhesive layout alone, but by the stress-redistribution capacity permitted by the adherends.