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Finite Element Study on Strength Optimization of Functionally Graded Adhesives

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GHENT UNIVERSITY

Yanan Zhang, Magd Abdel Wahab
Soete Laboratory, Ghent University, Belgium

Introduction

Adhesive bonding is widely employed in lightweight structures due to its ability to join dissimilar materials and distribute stress over large areas. However, conventional adhesives with uniform properties often face challenges such as high stress concentrations at the overlap ends, leading to premature failure. To address this, Functionally Graded Adhesives (FGAs) have been introduced as a novel concept, where mechanical properties such as stiffness and ductility vary gradually along the bond line. This gradation enables stress redistribution and delays damage initiation, offering enhanced joint performance without compromising strength or flexibility. In this study, a series of epoxy-based adhesives were used to construct graded adhesive layers.

The primary objective is to understand how adhesive gradation influences the stress distribution, damage evolution, and load-bearing capacity in single-lap joints (SLJs), through a combination of high-resolution finite element modeling and experimental validation.

Methods

- A series of 2D finite element (FE) models were developed in Abaqus to evaluate the mechanical performance of single-lap joints (SLJs) with different adhesive gradation strategies.
- A high-resolution mesh (minimum element size: 0.1 μm) was used to resolve local stress concentrations and damage evolution along the overlap.
- Three adhesive layout strategies were investigated:
  1. Single-adhesive joints, employing either the brittle base epoxy (R510) or ductile rubber-modified epoxies (PER5–PER20),
  2. Dual-graded joints, featuring a stiffer R510 core and more compliant outer layers,
  3. Multi-graded joints, with smooth modulus transitions (e.g., PER20–PER5–R510–PER5–PER20) to mitigate stress peaks at the edges.
- The adhesive behavior was modeled using a ductile damage formulation based on equivalent plastic strain and fracture energy degradation. Damage initiation and evolution were governed by strain-based criteria, and energy dissipation was captured using the Benzeggagh–Kenane (BK) law to account for mixed-mode fracture behavior.
- The scalar damage variable SDEG (0–1) was used to visualize progressive degradation in the adhesive layer, from crack onset to full failure.
- Simulated force–displacement responses and damage patterns were compared across adhesive types and configurations to assess the effect of gradation on structural performance.

Graphics / Images

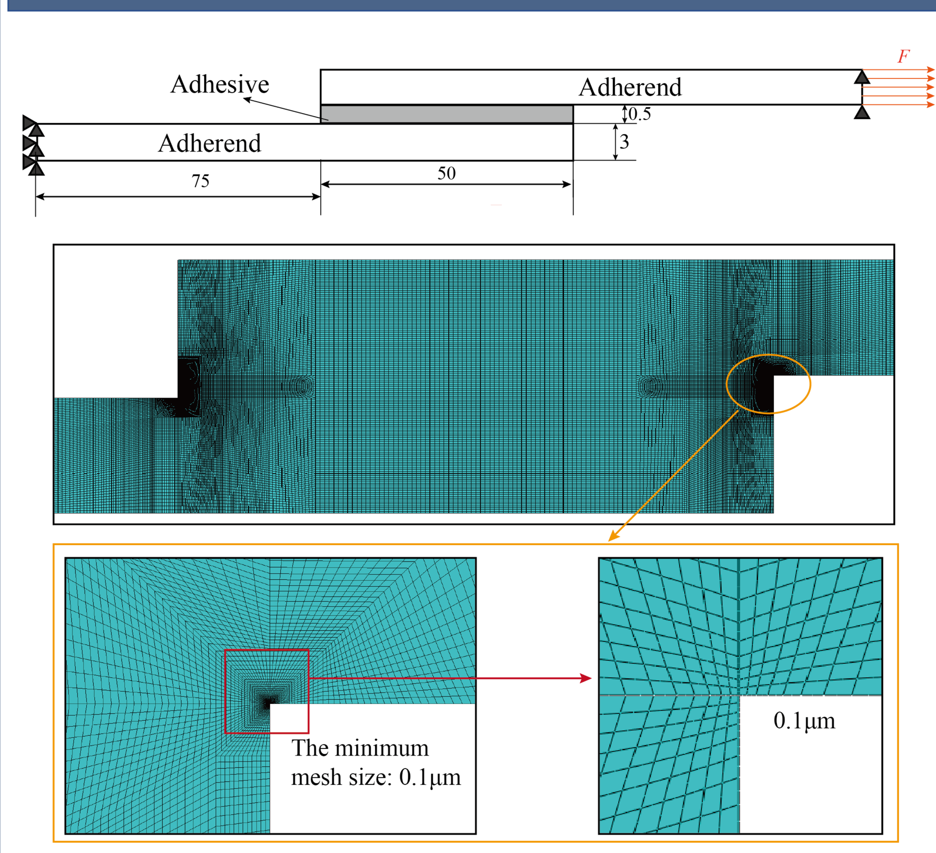


Fig. 1. FE model of SLJ with high-resolution mesh (min size: 0.1 μm)

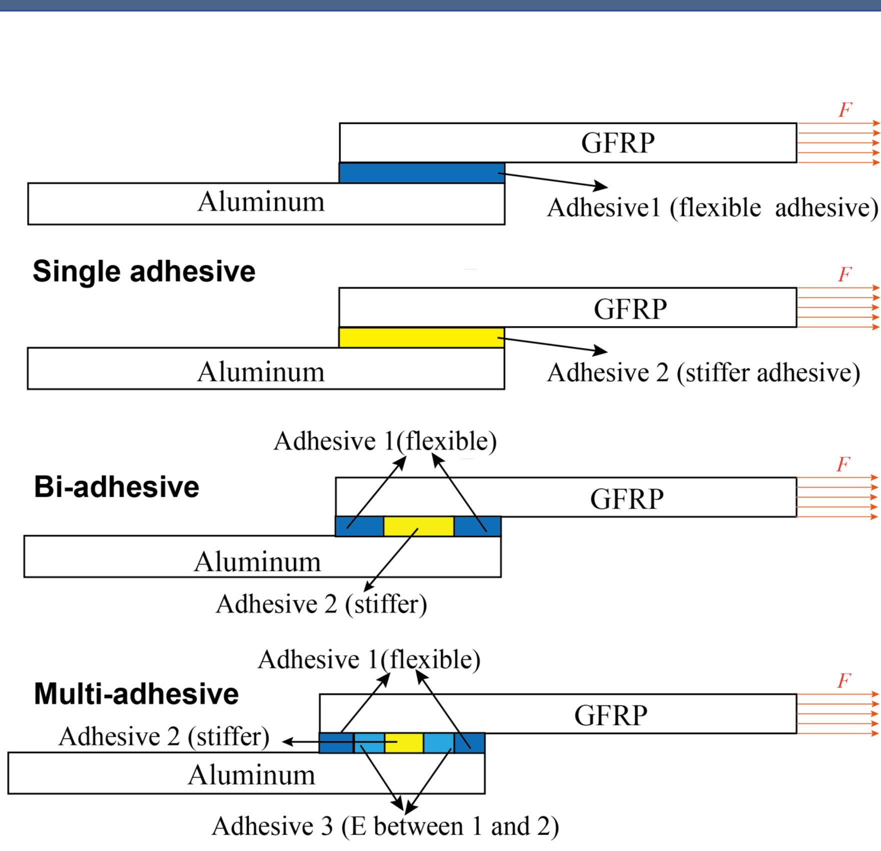
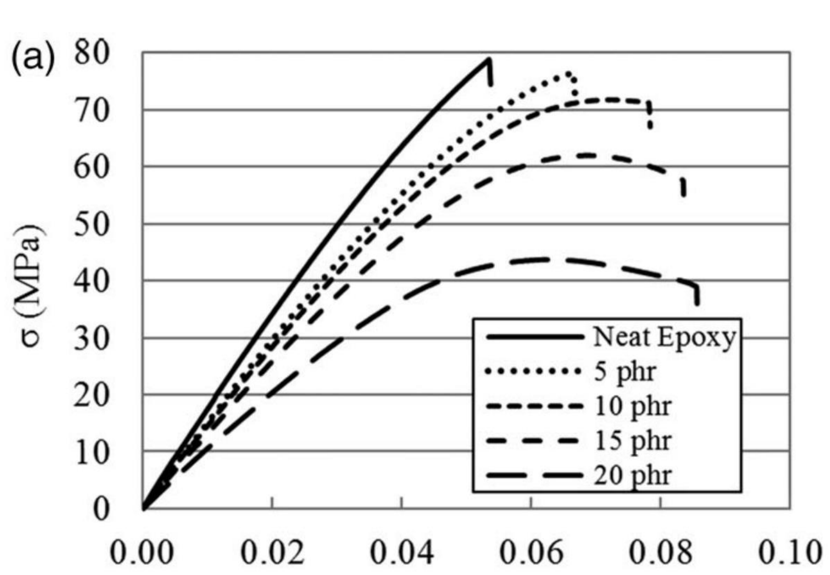


Fig. 2. Different adhesive layout strategies for SLJ: single, bilayer, and Multi gradients.



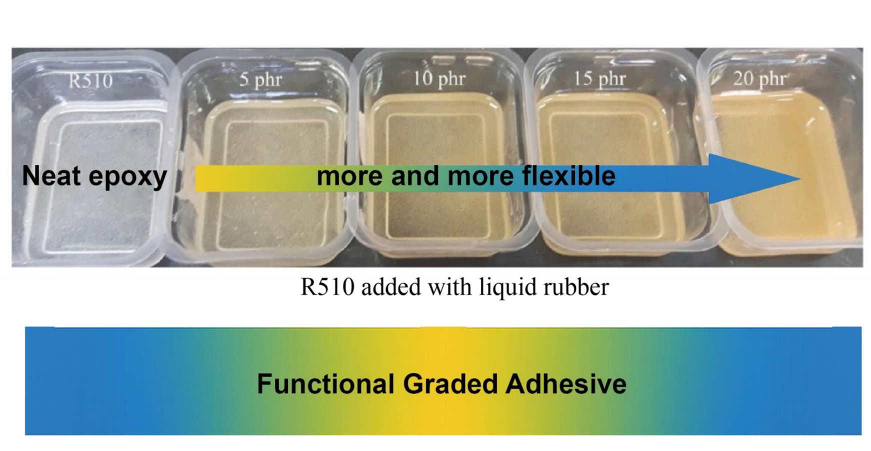


Fig. 3. Mechanical behavior and visual appearance of the five epoxy adhesives used for functional gradation.

Note: The adhesives include a neat epoxy resin (R510) and four modified epoxies containing 5, 10, 15, and 20 phr of CTBN liquid rubber. The stress–strain curves show that increasing CTBN content leads to a reduction in stiffness and an increase in ductility. Visually, the adhesives transition from transparent to yellowish as flexibility increases, forming the basis for constructing a functionally graded adhesive (FGA) with a gradual stiffness distribution.

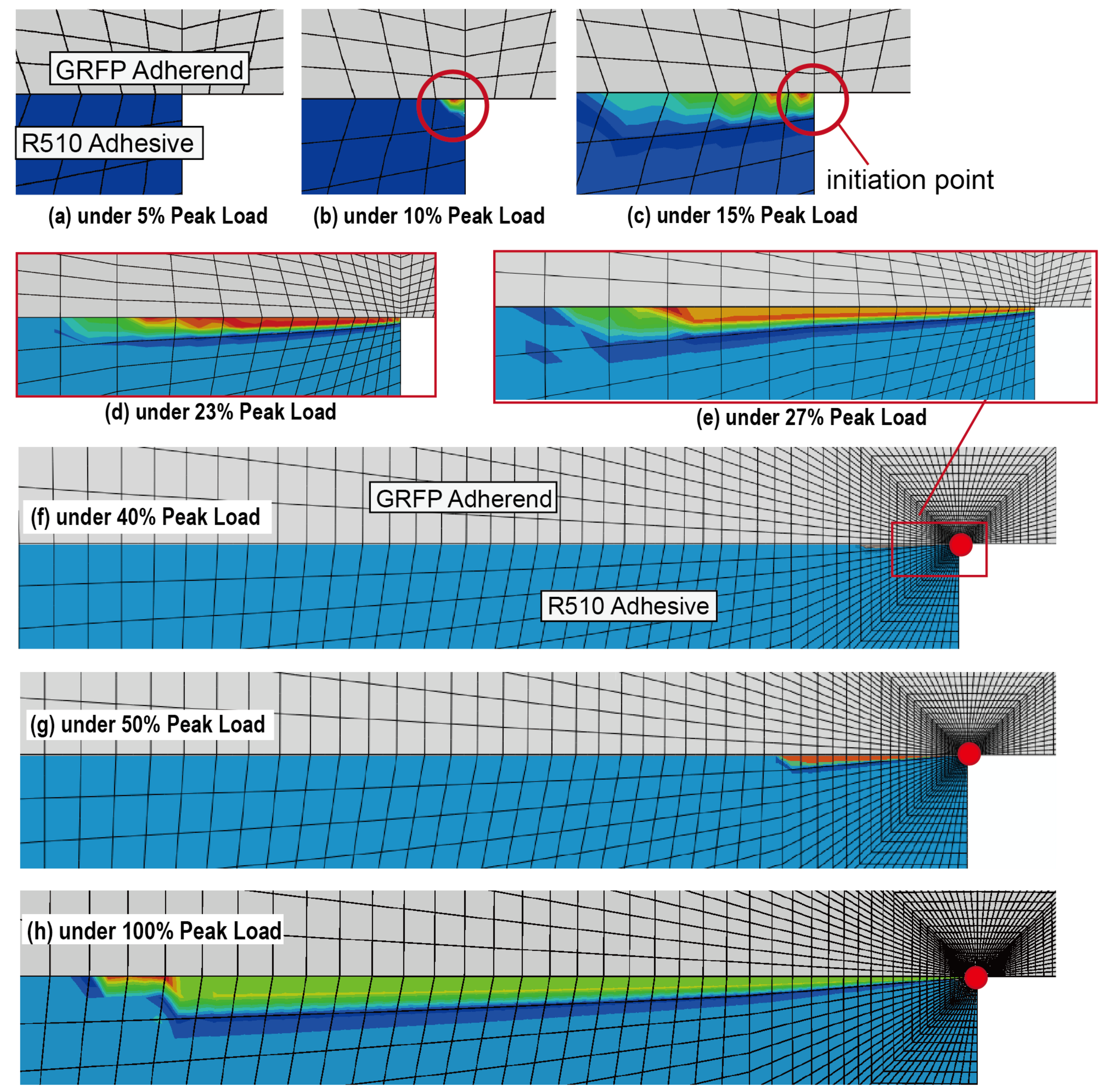


Fig. 4 Damage evolution in R510 adhesive layer under increasing load levels (GRFP–R510–AL joint). Progressive damage accumulation is illustrated by the SDEG parameter (0–1). (a–e) Close-up views near the overlap end show damage initiation and growth. (f–h) Full-length damage contours under 40%, 50%, and 100% peak load. Crack initiates at the edge and propagates along the interface.

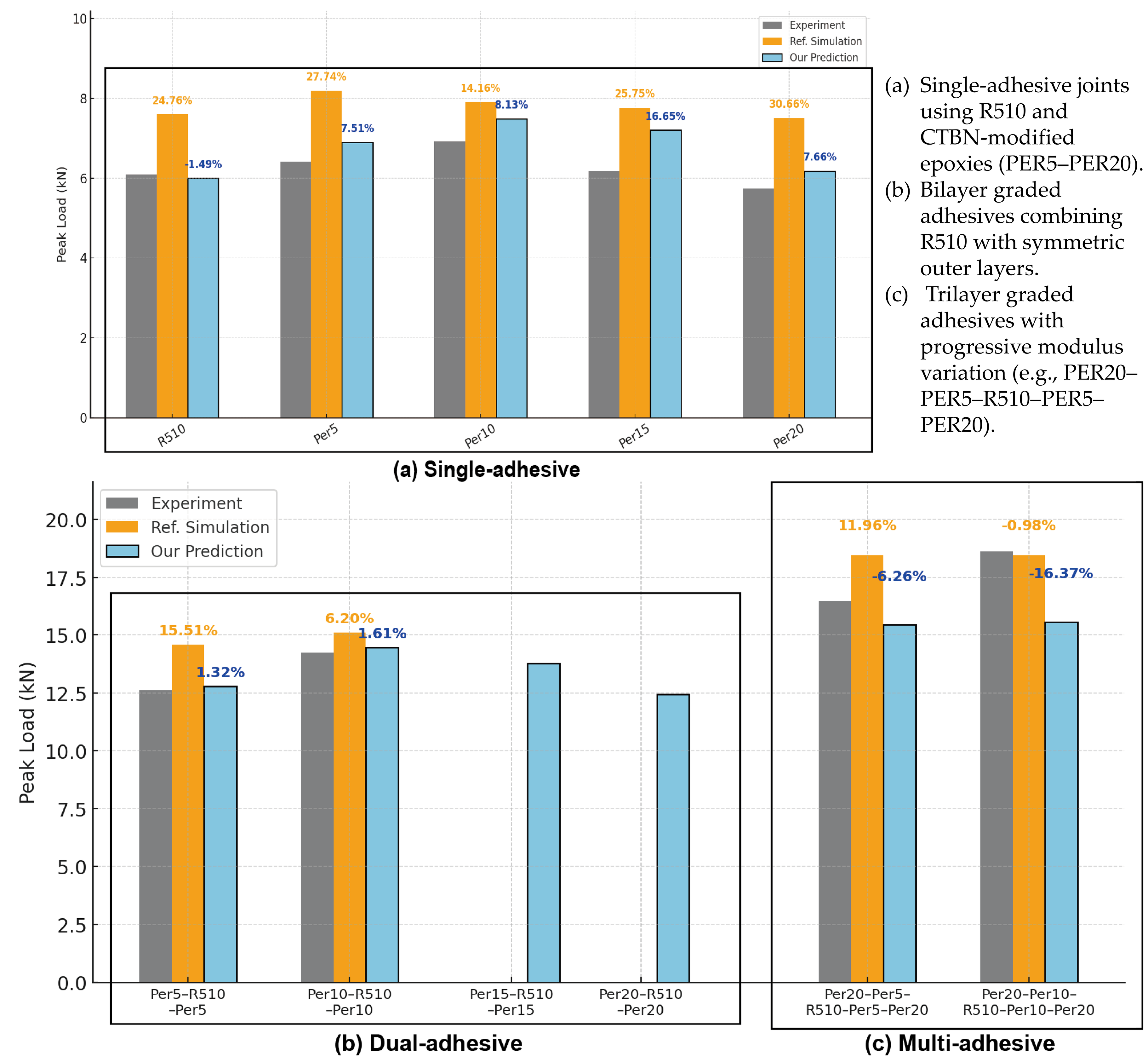


Fig. 5. Experimental, reference simulation, and our predicted peak loads for different adhesive configurations.

Conclusions

- Adhesive property gradation significantly influences stress distribution and failure in bonded joints.
- Compared to single-adhesive designs, graded adhesives redistribute stress and enable more uniform load transfer.
- Trilayer graded joints (e.g., PER20–PER5–R510–PER5–PER20) showed delayed damage initiation and improved load-bearing capacity.
- The ductile damage model with BK law effectively captured failure evolution, as reflected in the SDEG contours at different load stages.
- Numerical results matched experimental trends in peak load, confirming the accuracy of the modeling approach.
- This study confirms the potential of functionally graded adhesives to enhance joint strength and provides a validated simulation framework for future design.