

Cross-configuration assessment of functionally graded adhesives in single-lap joints via an elastoplastic ductile-damage framework

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ABSTRACT

Functionally Graded Adhesives (FGAs) are established as means to mitigate edge-peaked stresses in Single-Lap Joints (SLJs). However, their effectiveness has not been systematically compared across different adherend configurations. This work presents a Finite Element (FE) framework with an elastoplastic adhesive model coupled to a ductile-damage formulation, validated against Aluminum–Glass Fiber Reinforced Polymer (Al–GFRP) SLJ experiments and reproducing ultimate loads within 3–15 %. The framework is applied to four representative adherend configurations: Al–Al, Al–GFRP, GFRP–GFRP, and Steel–GFRP, under both single and bi-adhesive layouts. Introducing a moderately ductile adhesive at the overlap ends increases ultimate load by approximately 67 % (Al–Al), 153 % (Al–GFRP), 265 % (GFRP–GFRP), and 103 % (Steel–GFRP) relative to a uniform single-adhesive baseline. Stress analyses indicate delayed edge yielding, 2–4 mm inward shifts of transfer zones, and 40–80 % higher mid-span shear plateaus. Overall, the attainable benefit is governed not by adhesive layout alone but by the stress-redistribution capacity of the adherends, being greatest for compliant–compliant pairs, least for rigid–rigid, and intermediate for asymmetric systems. This cross-configuration perspective links grading choices to adherend properties and may inform the design of multi-material bonded structures.

1. Introduction

Adhesive bonding has become central to the design of lightweight multi-material structures in aerospace, automotive, and civil engineering, where strict mass requirements and the integration of dissimilar materials must be balanced [1]. Its importance is now recognized not only at the design stage but also within certification and regulatory frameworks in aerospace and transport applications [2]. Compared with mechanical fastening using bolts or rivets, which requires through-thickness holes and produces local stress concentrations, bonded joints preserve the integrity of laminates and provide a continuous path for load transfer [3], enabling the efficient joining of thin sheets and large-area components that would otherwise be vulnerable to early failure. Despite these advantages, single-lap and related joints often exhibit steep stress gradients near the overlap ends, which

promote premature debonding and limit capacity well before the adhesive itself reaches its intrinsic strength [4].

Several approaches have been proposed to mitigate these end stresses in single lap joint. On the adherend side, geometric tailoring such as tapering, spew fillets, or stepped profiles redistributes stresses away from the edges and encourages smoother load transfer [5,6]. On the adhesive side, modification and toughening strategies, for example, adding thermoplastics, graphene, rubber particles, or nanofillers, increase fracture energy and hinder crack growth [7–9]. In addition, functionally graded adhesives (FGAs), proposed more than a decade ago, vary local stiffness along the bond-line to deliberately adjust the stress-transfer process [10]. Beyond smooth gradation, discrete stiffness segmentation, such as bi-adhesive layouts, has been investigated as a practical alternative owing to its manufacturability and the ability to tailor stiffness distribution in a piecewise fashion [11]. Dual-adhesive

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systems have been experimentally shown to increase capacity over wide temperature ranges when joining similar and dissimilar adherends [12]. More recent studies extend this principle toward triple-adhesive lap joints, demonstrating staged failure and enhanced deformation capacity under tensile loading [13], confirming that combining regions of different stiffness can modify load redistribution and damage evolution beyond the binary bi-adhesive concept.

Both numerical and experimental studies lend support to these strategies. Finite-element simulations consistently show that placing a more compliant adhesive at the overlap ends lowers peel and shear stress peaks and postpones debonding relative to uniform baselines [11]. Through-thickness grading has also been reported to homogenize stress distributions [14], while extensions to stepped and double-lap joints suggest that the principle can be generalized beyond single-lap geometries [15,16]. Experimental observations corroborate numerical predictions. Graded joints generally achieve higher ultimate loads than their single-adhesive counterparts [17,18], while bi-adhesive layouts have been shown to improve residual strength after impact in carbon fiber reinforced polymer (CFRP)–metal hybrids [19]. Parametric analyses further indicate that gradual stiffness reductions toward the overlap ends maximize both ultimate load and energy absorption [20]. Recent reviews consolidate these findings, portraying FGAs as a practical and versatile approach for enhancing joint strength and durability [21–23]. Non-contact full-field methods, particularly digital image correlation (DIC), have recently been adopted in these studies to characterize local strain evolution within the overlap and validate FE-predicted stress transfer [24]. Similar concepts have also been extended to the adherends themselves, where functionally graded adherends have been proposed to further homogenize stress transfer and improve load capacity [25]. Collectively, these studies establish graded and hybrid adhesives as effective strategies for mitigating edge stresses and extending bonded-joint performance.

Beyond adhesive-side optimization, adherend configuration has been recognized as a key factor controlling stress evolution in single-lap joints. For composite adherends, ply orientation and lay-up sequence are critical design parameters that strongly govern stress transfer mechanisms. Cross-ply and quasi-isotropic laminates distribute stresses more evenly than unidirectional plies, shifting the location of damage initiation [26]. Studies on CFRP–aluminum joints reveal that stiffness mismatch concentrates peel stresses near the compliant adherend, generating asymmetric fields and premature debonding [27]. Reviews of multi-material lap joints further emphasize that adherend stiffness mismatch and free-edge effects are recurrent drivers of failure, underscoring the central role of adherend configuration in bonded-joint design [28]. Recent surveys of bonded-joint innovations likewise highlight adherend tailoring strategies, including graded-stiffness adherends, as a promising frontier [29]. Complementary surveys echo this conclusion, pointing to free-edge discontinuities and stiffness asymmetry as persistent triggers of failure [30]. More recent developments include hybrid lay-ups combining thin-ply reinforcements or deliberately graded stiffness within the adherends, which have been shown to further enhance load-bearing capacity [31,32]. Beyond strength, such adherend-side tailoring, including thin-ply reinforcement and profiling concepts, has been shown to delay damage onset, divert crack paths, and improve durability under cyclic or environmental conditions [33–35]. Collectively, these findings confirm that adherend stiffness and symmetry govern stress evolution and failure, framing adherend configuration as a primary determinant of bonded-joint behavior.

Nevertheless, adhesive grading and adherend configuration are still often studied in isolation. Most analyses of FGAs and bi-adhesives use fixed adherends, while adherend-related studies typically assume a uniform adhesive. As a result, the coupled influence of adhesive gradation and adherend properties remains poorly mapped. This gap is not only of academic concern but also directly relevant to engineering practice: modern aircraft fuselages and wind-turbine blades often rely on multi-material joints, where optimization of both the adhesive layer

and the adherend configuration proceeds in parallel [36]. Without a cross-configuration perspective, it is difficult to translate isolated findings into design-oriented guidance for such applications.

To address this, the present work develops a finite-element framework that combines an elastoplastic adhesive constitutive law with a ductile-damage formulation. Four representative adherend systems: Al–Al, Al–GFRP (glass fiber reinforced polymer), GFRP–GFRP, and Steel–GFRP are examined, covering symmetric, compliant, rigid, and mismatched cases. Model predictions are benchmarked against experiments and then extended to systematic assessments of FGAs, with bi-adhesive layouts included for comparison. The results reveal a clear trend: compliant–compliant systems achieve the largest gains, rigid–rigid the smallest, and asymmetric cases fall in between. By linking FGA effectiveness directly to the redistribution capacity of the adherends, the study establishes a cross-configuration view and offers design-oriented insights for multi-material bonded structures.

2. Methodology

2.1. Geometrical model and boundary conditions

The single-lap joint (SLJ) geometry was based on the fixture layout of ASTM D5868-01, but with a deliberately extended bonded overlap of 50 mm, a width of 25 mm, and an adhesive thickness of 0.5 mm (Fig. 1a). These dimensions follow the experimental configuration of Dadian and Rahnama [20], from which the present adhesive dataset is taken, and therefore deviate from the short-overlap coupon recommended by ASTM D5868-01, which is primarily intended for material-property shear strength measurements. In the context of functionally graded adhesives, a longer overlap is required so that variations in local adhesive properties (single-, bi- and graded layouts) can develop distinct stress-redistribution patterns along the bond-line and be meaningfully compared on a structural scale.

The main deviations from ASTM D5868-01 are as follows: (i) the bonded overlap was extended to 50 mm, rather than the shorter gauge length specified in the standard, to allow the stress-redistribution effects of grading to fully develop; (ii) the adherend thicknesses were taken directly from the laminate lay-up and plate stock used in the reference Al–GFRP experiments [20] (2.88 mm for GFRP and 3.00 mm for the metallic adherends), instead of the plate-type coupon thicknesses prescribed by the standard; and (iii) the adhesive thickness was controlled by calibrated spacers to remain at 0.5 mm across all configurations, again matching the reference experiment. Except for these intentional deviations in specimen geometry, the overall SLJ layout and loading followed the ASTM D5868-01 fixture concept.

To reduce computational cost while preserving the essential load-transfer mechanism, the finite element (FE) model omitted the griped sections used in the experiments. As shown in Fig. 1b, the left end of the upper adherend was fully constrained in all translational and rotational degrees of freedom. Loading was applied at the right end of the lower adherend along the overlap direction to induce shear in the adhesive layer. Rigid-body motion was prevented by fixing the vertical displacement U_y of the corner nodes at the loaded end to zero, while in-plane motion along the overlap direction remained free. A displacement-controlled boundary condition was imposed at the loaded end for all analyses, including ultimate-strength prediction, experimental benchmarking, and stress-field evaluation. This setup provides a consistent basis for the subsequent parametric studies. Fig. 1c provides a schematic key to the single-adhesive and functionally graded (bi-adhesive) adhesive sets used in this work.

2.2. Materials and configuration

2.2.1. Adhesive systems and configurations

To ensure reproducibility and direct comparability with the reference experiments, the adhesive systems analyzed in this study are

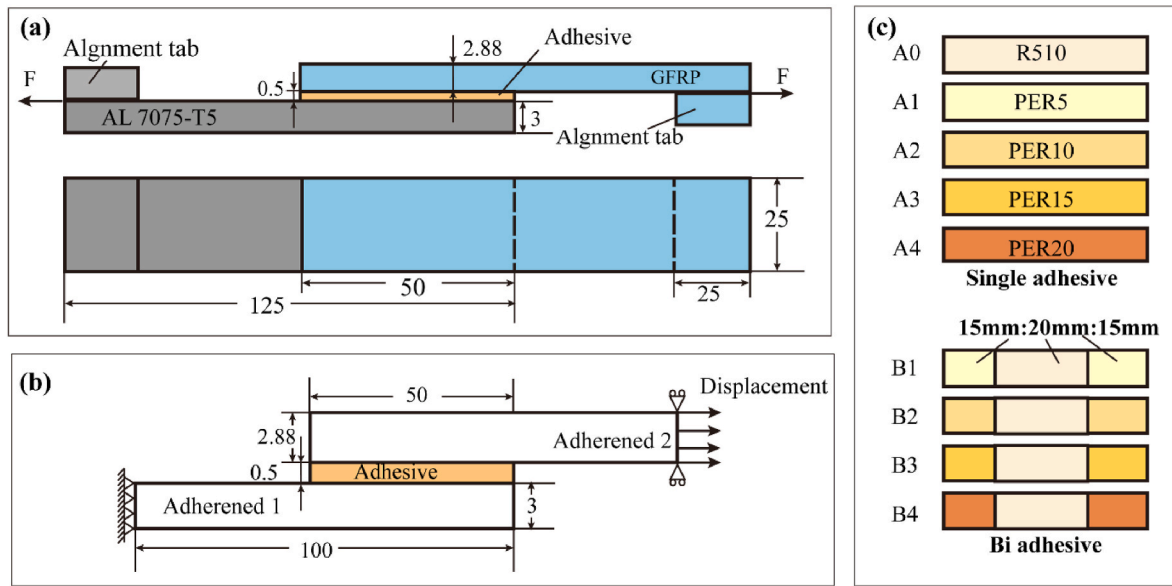


Fig. 1. SLJ geometry and FE models: (a) ASTM-based reference configuration consistent with the Al–GFRP experiments in Ref. [20], (b) simplified FE model with the gripped sections omitted, a fully fixed left end and displacement loading at the right end, and (c) schematic of the adhesive layouts used in this study: single-adhesive A0–A4 and bi-adhesive B1–B4.

aligned with the Al–GFRP tests on functionally graded epoxy/Carboxyl-terminated butadiene–nitrile (CTBN) joints reported by Dadian and Rahnama [20]. A neat epoxy resin (R510; Iran Mandegar Baspar) serves as the baseline formulation, and CTBN was incorporated at 5, 10, 15, and 20 phr (parts per hundred of resin) to obtain four modified adhesives, denoted as PER5, PER10, PER15, and PER20. Here, PER x refers to R510 modified with x phr CTBN.

The mechanical and fracture properties adopted in the FE analysis are summarized in Table 1. These parameters (elastic modulus, Poisson's ratio, yield and failure strengths, failure strain, shear modulus, and fracture energies G_{IC} and G_{IIC}) were taken from the experimental characterization reported in Dadian and Rahnama [37] and also tabulated in Ref. [20]. Representative engineering stress–strain curves redrawn from Ref. [37] are shown in Fig. 2. As the CTBN content increases, the adhesive stiffness and strength decrease, whereas ductility and fracture energy increase. This trade-off underpins the end-modified adhesive layouts investigated in this work.

In the single-adhesive configurations (A-series), each formulation (A0–A4) was applied over the entire overlap to examine the influence of adhesive ductility on joint performance. In the bi-adhesive configurations (B-series), a symmetric end-modified layout was adopted, with the compliant adhesive PER x (PER x = R510 + x phr CTBN, x = 5, 10, 15, 20) placed at the overlap ends and the stiff R510 located in the central region. These configurations are denoted B1–B4, corresponding to PER5–R510–PER5 through PER20–R510–PER20. The definitions of all adhesive configurations are summarized in Table 2 and illustrated in Fig. 1c.

Table 1

Mechanical and fracture properties of the neat epoxy (R510) and CTBN-modified adhesives (PER5–PER20) used in Finite Element Analysis (FEA) [37].

Property	R510	PER5	PER10	PER15	PER20
Young's modulus, E (GPa)	1.89	1.58	1.42	1.26	1.01
Poisson's ratio, ν	0.34	0.38	0.40	0.41	0.42
Tensile yield stress, σ_y (MPa)	41.93	36.70	34.17	30.88	24.15
Tensile failure strength, σ_f (MPa)	78.18	76.15	71.13	57.59	38.91
Tensile failure strain, ϵ_f (%)	5.30	6.60	7.80	8.30	8.50
Shear modulus, G (GPa)	0.70	0.57	0.50	0.44	0.35
G_{IC} (N/mm)	0.44	0.96	1.49	2.04	2.29
G_{IIC} (N/mm)	4.27	5.21	5.70	6.32	6.52

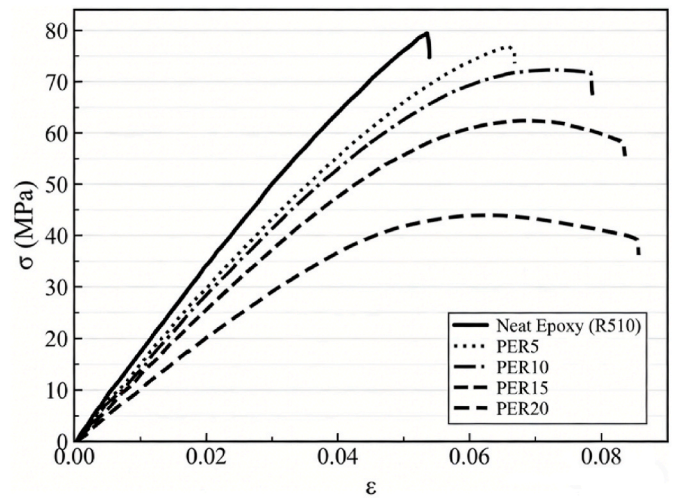


Fig. 2. Engineering stress–strain curves of the neat epoxy (R510) and CTBN-modified adhesives (PER5–PER20), redrawn from Ref. [37] - σ in MPa and ϵ is engineering strain.

Table 2

Adhesive configurations considered in this study (A-series: single-adhesive, B-series: bi-adhesive).

Series	Label	Center region (phr CTBN)	End region (phr CTBN)	Definition
Single adhesive	A0	0	–	R510
	A1	5	–	PER5
	A2	10	–	PER10
	A3	15	–	PER15
	A4	20	–	PER20
Bi adhesive	B1	0	5	PER5–R510–PER5
	B2	0	10	PER10–R510–PER10
	B3	0	15	PER15–R510–PER15
	B4	0	20	PER20–R510–PER20

Notes: PER x = R510 + x phr CTBN; phr = parts per hundred of resin.

2.2.2. Adherend materials

Three adherend materials were selected to represent both identical and dissimilar-material joints, covering a broad range of stiffness and deformation characteristics. An aluminum alloy AA 7075-T6 and GFRP laminate were adopted to reproduce the Al–GFRP experimental configuration reported in Ref. [20] and to establish a validation baseline. In addition, a structural carbon steel (Q235/ASTM A36) was included to extend the analysis to stiffer adherend combinations commonly encountered in engineering practice.

The aluminium adherends were modelled as elastoplastic, while steel and GFRP were treated as linear-elastic within the load range of bonded-joint failure. The elastoplastic behavior of AA 7075-T6 was defined using a tabulated stress–strain input in Abaqus. The stress–strain evolution used for this tabulation was redrawn and adapted from tensile data reported in Dou et al. [38], shown in Fig. 3. Only the post-yield region was introduced into the plastic portion of the tabular law, and the elastic slope was assigned using literature-reported modulus values ($E = 71.7$ GPa, $\nu = 0.33$). For consistency with the adhesive material definition in Section 2.2.1, the aluminum elastoplastic input curve used in Abaqus was obtained following the same conversion procedure, where the reported true stress–true plastic strain data were converted into an elastoplastic tabular form.

The structural steel adherends (Q235/ASTM A36) were treated as a linear-elastic material ($E = 210$ GPa, $\nu = 0.30$), because the stress levels achieved prior to adhesive failure remain below the yield strength of steel (≈ 250 MPa). Therefore, no plastic deformation is expected within the deformation range relevant to the present single-lap joints.

The GFRP adherends consisted of a laminate composed of nine plies of unidirectional E-glass fibers embedded in an epoxy matrix system (Epon 828 resin with Epikure 205 hardener), as reported in the reference experimental study [20]. The laminate was described as a unidirectional layup, with all plies oriented along the longitudinal loading direction (0° orientation). According to the reference study, the Young's modulus of the E-glass fibers was reported as $E_f = 80$ GPa, while the epoxy matrix exhibited a Young's modulus of $E_m = 2.75$ GPa. Poisson's ratios of the fiber and matrix were reported as $\nu_f = 0.22$ and $\nu_m = 0.35$, respectively.

The laminate was characterized under longitudinal tension in accordance with ASTM D3039/D3039M, also in the reference study [20], yielding an equivalent longitudinal elastic modulus of 19.18 GPa, which corresponds to the longitudinal modulus E_1 used in the orthotropic material representation.

Given the relatively small laminate thickness (2.88 mm) compared to the overlap length (50 mm), the GFRP adherends were represented as a

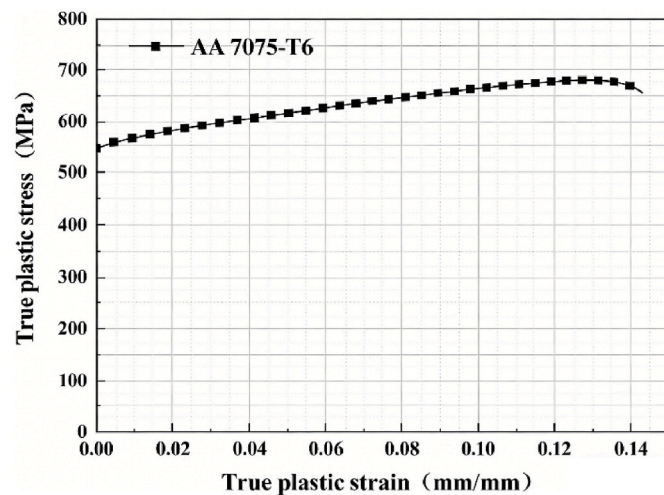


Fig. 3. True plastic stress–strain curve of AA 7075-T6, redrawn and adapted from Dou et al. [38]. (Only the plastic portion of the curve was used to construct the elastoplastic tabular input in Abaqus.

homogenized orthotropic elastic solid in the numerical simulations, rather than explicitly resolving individual plies. Since the reference experimental study reports only an equivalent longitudinal elastic modulus for the GFRP laminate, the remaining transverse and shear properties required for finite element modeling were estimated using micromechanical relations based on the constituent properties. The complete set of orthotropic elastic constants adopted for the GFRP material is reported in Table 3. Consistent with its brittle fracture behavior and lack of measurable post-yield deformation, GFRP was also treated as linear elastic in the present simulations.

To assess the influence of these estimated parameters on the structural response, a material sensitivity study was conducted by comparing the orthotropic GFRP representation with a simplified isotropic model using the same longitudinal modulus (19.18 GPa). The difference in the predicted ultimate failure load was found to be less than 1 %, indicating that the global load-bearing capacity of the joint is predominantly governed by the longitudinal stiffness of the GFRP adherends within the scope of this study. Accordingly, the conclusions are insensitive to the specific values of the estimated transverse elastic constants.

2.2.3. Adherend configurations

The adherend configurations considered in this study are shown in Fig. 4: (a) Al–GFRP (validation baseline), (b) Al–Al, (c) GFRP–GFRP, and (d) Steel–GFRP. Model credibility is first established against the published Al–GFRP data [20] Fig. 4a. The same modeling framework is then applied, without further modification, to the remaining three systems Fig. 4(b–d), to assess configuration-dependent responses under identical geometry, boundary conditions, and adhesive layouts. This sequence allows a systematic examination of how adherend arrangement governs the performance of functionally graded (bi-adhesive) joints.

For all numerical models, only the adherend material was varied to form the Al–Al, GFRP–GFRP, and Steel–GFRP configurations, while the joint geometry, adherend thicknesses, adhesive thickness, overlap length, boundary conditions, and loading protocol were kept identical. This strategy ensures that the observed differences in structural response arise solely from adherend material effects, rather than from geometric variations.

2.3. Finite element modeling framework

Finite Element Method (FEM) has long been established as a primary tool for analyzing adhesive joints, providing detailed resolution of stress transfer and progressive failure beyond the reach of closed-form solutions [39,40]. In Abaqus, adhesive layers can be represented either by cohesive interfaces or as continua with elastoplasticity and damage; for ductile epoxies [41], the latter effectively captures bulk yielding and subsequent degradation without prespecifying a crack path [42]. Recent reviews also identify elastoplastic, Continuum Damage Mechanics (CDM) formulations as a robust approach across various loading modes and material systems [43]. Accordingly, the adhesive in this study was modelled as an elastoplastic solid coupled with a CDM law to examine how grading and adherend configuration govern stress redistribution and strength.

Table 3

Mechanical properties of the adherend materials used in FEA.

Material	Type	Young's Modulus, E (GPa)	Shear Modulus, G (GPa)	Poisson's Ratio, ν
AA 7075-T6	Isotropic	71.70	27.00	0.33
Steel (Q235)	Isotropic	210.00	80.80	0.30
GFRP	Orthotropic	$E_1 = 19.18$ $E_2 = E_3 = 3.5$	$G_{12} = G_{13} = 1.3$ $G_{23} = 1.3$	$\nu_{12} = \nu_{13} = 0.32$ $\nu_{23} = 0.35$

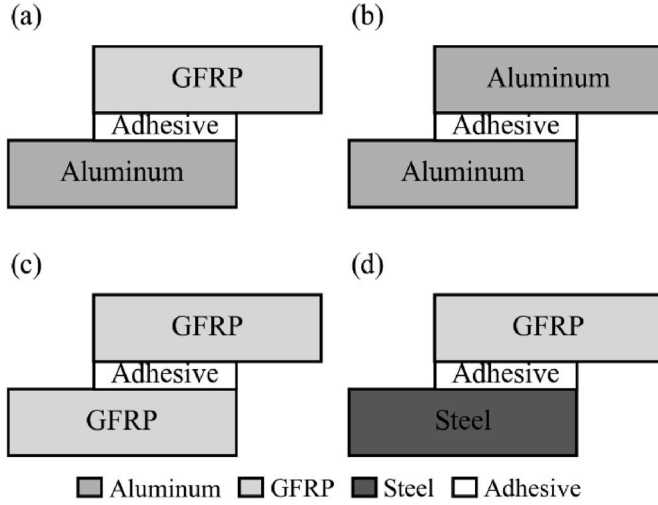


Fig. 4. Adherend configurations considered: (a) Al-GFRP (validation baseline), (b) Al-Al, (c) GFRP-GFRP, and (d) Steel-GFRP. All joints share the geometry and boundary conditions of Fig. 1.

2.3.1. Constitutive and damage modelling

The adherends (aluminum, steel, and GFRP) were modelled as linear elastic solid definitions in Abaqus, characterized by their respective Young's modulus and Poisson's ratio (Table 2), since their deformation remained essentially elastic within the applied load range.

The adhesive was described by an elastoplastic solid model coupled with a Continuum Damage Mechanics (CDM) law. The elastic response of the adhesive was characterized by the Young's modulus E and Poisson's ratio ν (Table 1).

Plastic behavior was calibrated from true stress-strain curves converted from the experimental engineering data of R510 and the CTBN-modified systems (Fig. 2), so that the FE model reproduces the gradual yielding observed in tests. The conversion was performed using standard continuum mechanics relations,

$$\sigma_{\text{true}} = \sigma_{\text{eng}} (1 + \varepsilon_{\text{eng}}) \quad (1)$$

$$\varepsilon_{\text{true}} = \ln(1 + \varepsilon_{\text{eng}}) \quad (2)$$

where σ_{eng} and ε_{eng} denote the engineering stress and engineering strain, respectively; σ_{true} and $\varepsilon_{\text{true}}$ are the true stress and true strain, respectively. The corresponding true plastic strain was obtained as:

$$\varepsilon_{\text{pl}} = \varepsilon_{\text{true}} - \frac{\sigma_{\text{true}}}{E} \quad (3)$$

where ε_{pl} is the true plastic strain and E is the elastic modulus adopted in the finite element model (Table 1). Eqs. (1)–(3) define the conversion from engineering stress-strain data to the true stress-true plastic strain representation adopted for the elastoplastic material definition in Abaqus, in accordance with the Abaqus Analysis User's Guide [44].

Damage initiation was described using the three-parameter ductile damage criterion as implemented in Abaqus [43]. Within this framework, damage initiation is governed by the accumulation of the equivalent plastic strain $\bar{\varepsilon}^p$, and occurs when the following condition is satisfied:

$$\int_0^{\bar{\varepsilon}^p} \frac{d\bar{\varepsilon}^p}{\bar{\varepsilon}_f^p(\eta, \dot{\varepsilon}^p/\dot{\varepsilon}_0^p)} = 1 \quad (4)$$

where $\bar{\varepsilon}_f^p$ denotes the critical failure strain defined in the Abaqus ductile damage initiation model [43] as a function of the stress triaxiality η and the plastic strain-rate ratio $\dot{\varepsilon}^p/\dot{\varepsilon}_0^p$. Accordingly, during plastic deformation, damage initiation is assessed by continuously monitoring the

accumulation of $\bar{\varepsilon}^p$ relative to the corresponding failure strain, which depends on the stress triaxiality and the plastic strain-rate ratio.

In the present work, the evaluation of the ductile damage initiation parameters followed the loading conditions relevant to the single-lap joint configuration. Although the stress state within a single-lap joint is generally multiaxial due to the combined effects of tension, shear, and bending, the global loading condition is dominated by tensile deformation along the loading direction. Accordingly, for the purpose of evaluating the ductile damage initiation parameters, a uniaxial stress state was adopted as a representative approximation. Under uniaxial tension, the stress triaxiality takes the value $\eta = 1/3$ by definition. The strain-rate dependence was evaluated at $\dot{\varepsilon}^p/\dot{\varepsilon}_0^p = 1$, corresponding to the reference strain rate adopted in the quasi-static analysis. The values of $\bar{\varepsilon}_f^p$ were taken from Table 1; for example, the neat epoxy R510 was calibrated using $\bar{\varepsilon}_f^p = 0.053$.

Once the initiation condition is met, a scalar damage variable D is introduced to govern progressive stiffness degradation. The variable ranges from 0 (undamaged) to 1 (fully damaged), reducing the nominal stress σ to the effective stress $\bar{\sigma}$ according to Eq. (5), where σ is the stress carried by the undamaged material and $\bar{\sigma}$ is the effective stress accounting for stiffness. Across the four adherend configurations, Fig. 10 reveals a distinct hierarchy gradation:

$$\bar{\sigma} = (1 - D) \sigma, 0 \leq D \leq 1 \quad (5)$$

Damage evolution was governed by an energy-based formulation, where the critical fracture energy followed the Benzeggagh-Kenane (BK) mixed-mode criterion [45]:

$$G_c = G_{Ic} + (G_{IIc} - G_{Ic}) \left(\frac{G_{II}}{G_I + G_{II}} \right)^{\eta_{BK}} \quad (6)$$

Here, G_{Ic} and G_{IIc} are the critical Mode I and Mode II fracture energies, respectively, and η is the mode-mixity exponent. Values of G_{Ic} and G_{IIc} were taken from Table 1.

Regarding the mode-mixity parameter η_{BK} , it is noted that η_{BK} is a semi-empirical material parameter that defines the fracture envelope and reflects the sensitivity of an adhesive to mixed-mode loading, i.e., the interaction between Mode-I and Mode-II fracture energies. In principle, η_{BK} should be calibrated through dedicated mixed-mode fracture tests (such as mixed-mode bending). Reported values for structural thermoset epoxies typically fall within a broad range of approximately $\eta_{BK} = 1.0 - 2.5$, depending on the degree of ductility and polymer morphology. Because dedicated mixed-mode fracture tests were not conducted for the present CTBN-modified epoxy systems, a representative value $\eta_{BK} = 1.5$ within this commonly applied range was adopted. In this work, this fixed value is used consistently for all adhesive formulations as part of the modelling strategy, such that the comparative structural-scale results are governed primarily by the experimentally defined elastic properties and fracture-energy contrasts listed in Table 1, rather than influenced by variations in an uncalibrated mixed-mode parameter. To mitigate convergence issues associated with excessive damage accumulation and to improve the physical consistency of crack propagation, element deletion was enabled [46].

In this study, a CDM formulation with solid elements was adopted instead of a Cohesive Zone Model (CZM). Although CZM is widely used for simulating interfacial debonding through predefined traction-separation laws, it requires specification of a crack path in advance [47]. CDM, by contrast, captures bulk plasticity and progressive degradation within the adhesive layer, thereby enabling direct evaluation of stress redistribution and damage evolution under graded material properties [48]. This feature is particularly relevant to the objectives of the present work, which examines how adherend configuration and adhesive gradation govern joint strength and stress transfer.

2.3.2. Numerical framework

The numerical framework was implemented in Abaqus/Standard

using a "Static, General" implicit procedure. A two-dimensional plane-stress solid continuum model was adopted. This choice is justified by the joint's geometric proportions and material characteristics. Specifically, the adhesive thickness (0.5 mm) is significantly smaller than the overlap length (50 mm) and width (25 mm), and the joint is subjected to predominantly in-plane tensile loading along the overlap direction. The adherends considered in this study include an isotropic metals (Al and Steel) and a GFRP composite reinforced with unidirectional fibers aligned with the loading direction. Under these conditions, the stress and strain variations along the joint width are minimal, and the out-of-plane stress σ_z is negligible. Therefore, the layer thickness was assigned as a section property, and the out-of-plane stress σ_z was set to 0. This assumption, widely applied in analyses of thin adhesive joints [49], provides a physically appropriate representation of the stress state relevant to failure, while also enabling the numerical resolution required for the present CDM-based modelling. Adopting a 2D formulation therefore prioritizes spatial accuracy at critical regions of the bondline without introducing the computational cost associated with a full 3D model.

Following the CDM formulation described in Section 2.3.1, both the adherends and the adhesive were discretized using eight-node quadratic plane-stress elements from the solid (continuum) element family (CPS8, full integration). This solid-element formulation enables continuous representation of graded material properties and access to stress and damage variables within the bondline.

The bi-adhesive configuration was represented in the finite element model as a single continuous adhesive layer. Geometric partitions were introduced along the overlap length to distinguish regions with different adhesive formulations, and each region was assigned its corresponding elastoplastic properties and CDM parameters. No additional contact definition, tie constraint or cohesive interface element was introduced at the junction between adjacent adhesive regions. Instead, the interface was treated as an internal material transition inside a solid continuum. Under this formulation, displacement continuity and stress transfer across the junction are maintained through the shared CPS8 continuum elements. This approach is consistent with the continuum-based modelling strategy adopted in this work and allows the analysis to

focus on how material property differences influence stress redistribution and damage progression.

2.3.3. Mesh refinement and convergence

A graded mesh was used to balance numerical accuracy and computational efficiency. The full model consisted of 1.30×10^5 elements, including approximately 1.10×10^5 elements in the adherend and 2.02×10^4 elements in the adhesive layer. Along the overlap, elements were coarsened in the central region and progressively refined toward the ends to resolve stress concentrations, with in-plane element sizes decreasing from 0.1 mm to a minimum of 0.1 μm (Fig. 5). Across the adhesive thickness, 22 element layers were applied in the mid-span and up to 94 layers near the overlap ends, resulting in on the order of 10^4 solid elements within the adhesive. This discretization was sufficient for predicting the ultimate load and tracking stress redistribution and damage evolution, while enabling consistent extraction of stress metrics along the mid-layer, near-interface paths, and end regions.

A mesh-sensitivity analysis was carried out to assess the numerical stability of the adopted discretization strategy. Three models were analyzed with minimum in-plane element sizes of 0.001 mm, 0.0005 mm and 0.0001 mm along the overlap length. The corresponding predicted ultimate loads were 6.198 kN, 6.044 kN and 5.902 kN, respectively. Refining the mesh from 0.001 mm to 0.0005 mm resulted in a moderate variation of approximately 2.5 %, indicating that the overall structural response is largely converged at this resolution. Further refinement to 0.0001 mm yielded a slightly lower ultimate load (approximately 4.8 % relative to the 0.001 mm mesh), which can be attributed to the greater localization of softening behavior in the ductile-damage formulation.

Fig. 6 compares the near-tip peel-stress distributions for minimum element sizes ($E_{\min}$) of 0.001 mm, 0.0005 mm and 0.0001 mm. All three curves exhibit a similar decay pattern within the first 0.002–0.003 mm from the adherend corner, followed by a gradual flattening along the adhesive. Although small deviations occur within the peak region because of the strong sensitivity of this singular-type gradient to element size, the profiles rapidly converge beyond the immediate vicinity of the

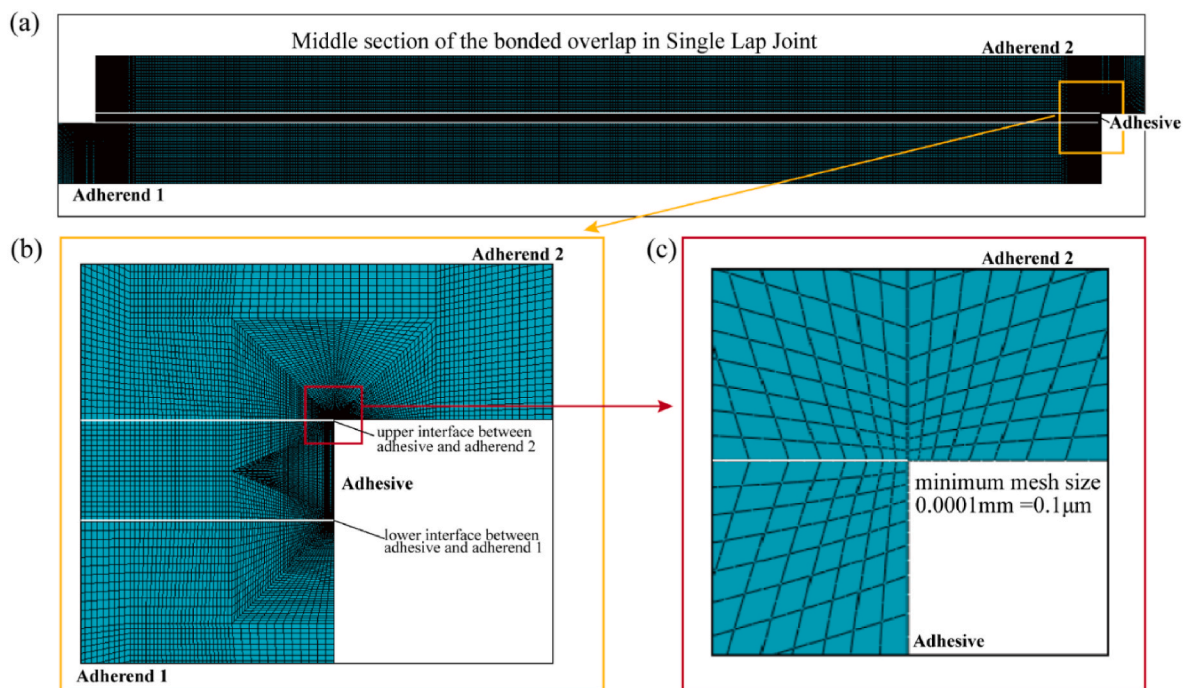


Fig. 5. Finite element mesh of the single-lap joint model and local detail of the end zone with the minimum element size of 0.1 μm across the adhesive layer: (a) Middle section of the bonded overlap, (b) right-end region of the bonded overlap and (c) upper adherend and adhesive interface corner at the right end.

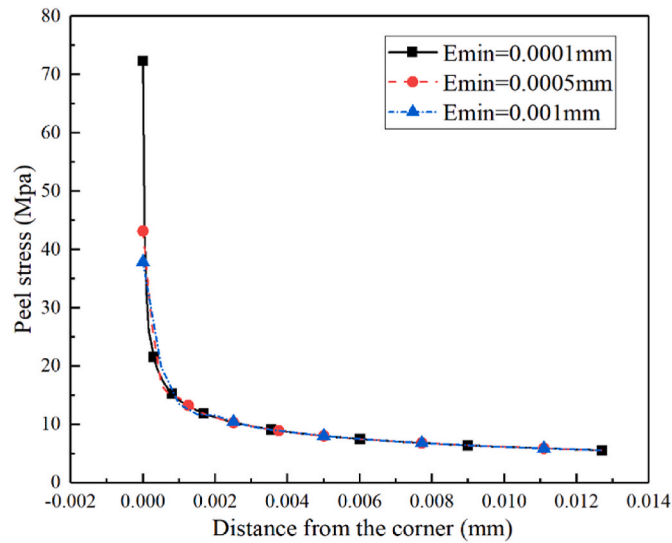


Fig. 6. Peel stress distributions near the corner of the adhesive-adherend interface for three mesh configurations, corresponding to minimum in-plane element sizes of 0.001 mm, 0.0005 mm and 0.0001 mm.

corner, indicating that the stress fields governing structural-scale damage evolution are only weakly sensitive to further mesh refinement. The 0.0001 mm mesh produces a smoother curve in the peak region and reflects the near-tip stress gradient with greater numerical detail, which forms the basis for its selection in this study.

3. Results and discussion

3.1. Model validation (Al-GFRP)

The FE model was validated against the experimental results for the Al-GFRP configuration, which is the only adherend combination with both single- and bi-adhesive data available in the literature [20]. Validation was carried out in two steps: first by comparing the predicted ultimate loads with the experimental values, and then by examining whether the model could reproduce the experimentally observed failure mechanisms.

3.1.1. Comparison of ultimate loads (experiment vs simulation)

The ultimate load was consistently defined at the inflection point of the load-displacement response, corresponding to the onset of the plateau region where the slope significantly decreases. This criterion provided a robust and consistent measure of the structural capacity across both numerical and experimental results. The relative error (RE) was calculated as:

$$RE(\%) = \frac{(F_{FEA} - F_{EXP})}{F_{EXP}} \times 100\% \quad (7)$$

where F_{FEA} and F_{EXP} denote the predicted and experimental failure loads, respectively.

As shown in Fig. 7, the FE model reproduced the experimentally observed non-monotonic variation of joint strength in the single-adhesive series (A0–A4), with capacity increasing up to A2 before decreasing at higher CTBN contents. Differences between FEA and test values (3.1 %–14.7 %) remain. These deviations mainly reflect the sensitivity of the calibrated ductile-damage formulation to the local stress state as the adhesive behavior transitions from brittle (A0) to increasingly ductile (A2–A4). Under a single CDM parameter set calibrated from uniaxial tension, damage initiation and evolution in the model require plastic-strain accumulation to reach a critical threshold, leading to slightly earlier degradation for the brittle formulation and a delayed onset of degradation for the tougher systems. Within the range represented by the experimental scatter, these deviations do not affect the interpretation of strength trends prior to discussing failure mechanisms.

For the bi-adhesive joints (B1 and B2), modelled using a near-equal 1:1:1 partition (16.67–16.66–16.67 mm), the FE predictions were within 3 % of the experimental values, showing that the model can also reproduce the strength of graded configurations with a similar level of consistency.

3.1.2. Failure initiation and propagation

Beyond global strength prediction, the failure patterns of Al-GFRP joints were examined by combining experimental [20] observations with FE-based damage evolution. The experimental fracture surfaces (Fig. 8) show that for the neat-epoxy joint, debonding initiates at the overlap ends along the adhesive-GFRP boundary and residual adhesive remains mainly on the aluminum side. In the bi-adhesive layout (PER10–R510–PER10), failure still concentrates at the GFRP ends, the crack path is confined within the compliant PER10 segments, and propagation advances toward the overlap interior. These observations

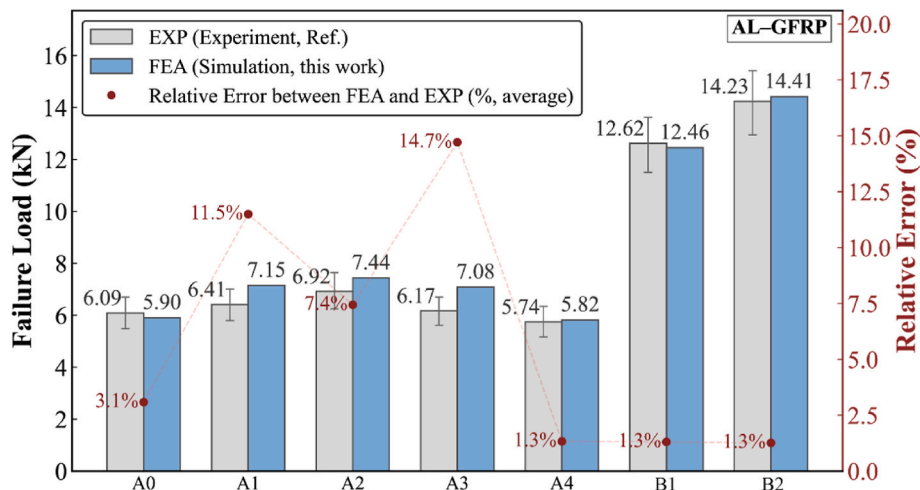


Fig. 7. Failure load (kN) of Al-GFRP single-lap joints for different adhesive configurations. Gray bars: experimental results [20] (EXP: mean values with error bars). Blue bars: finite element predictions (FEA). Red markers: relative error (%) between FEA and EXP. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

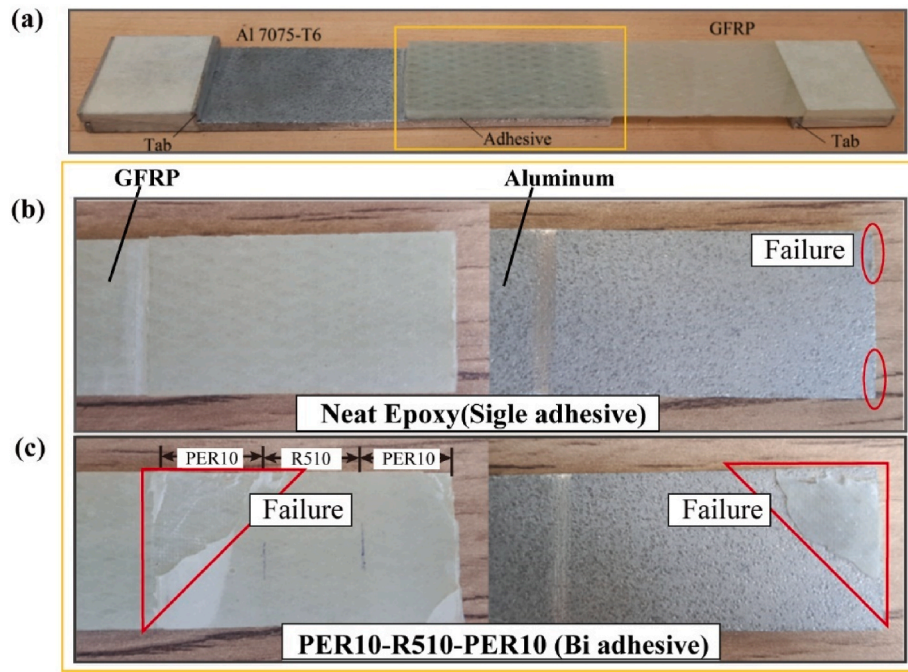


Fig. 8. Experimental fracture morphologies of Al-GFRP single-lap joints [20]:

(a) Overall view showing Al, GFRP, and adhesive regions, (b) Neat-epoxy joint: end-initiated deboned along the adhesive-GFRP boundary with adhesive residues mainly on the Al side, and (c) PER10-R510-PER10 joint: failure localized at GFRP ends within PER10 segments and propagation toward the overlap interior.

indicate that the adhesive-GFRP boundary governs failure under combined peel and shear.

The FE simulations (Fig. 9) capture the experimentally observed failure morphology through the evolution of the ductile damage variable, SDEG. Damage initiates at both overlap corners, occurring on the adhesive-Al boundary on the metallic side and on the adhesive-GFRP boundary on the composite side. The right end is identified as the dominant initiation site and exhibits a substantially longer propagation length, in agreement with the broader fracture zone observed in Fig. 8. The dashed lengths in Fig. 9c indicate the intentionally truncated adherend regions, included only to focus on the overlap. The enlarged fields in Fig. 9d further clarify the sequence of degradation, where

damage first emerges at the GFRP-side corner and subsequently progresses inward.

From a mechanistic perspective, the preferential initiation along the adhesive-GFRP boundary arises because the compliant GFRP undergoes larger local deformation than aluminum, thereby imposing higher shear and peel stresses within the adjacent adhesive. The singular stress state at the free edge amplifies this effect and promotes the early activation of ductile damage. Both the experimental fracture morphology and the numerical fields consistently identify the adhesive-GFRP interface as the governing weak zone, which also justifies its use as the primary focus in the subsequent adherend-configuration analyses.

Because global loss of equilibrium occurs prior to local SDEG

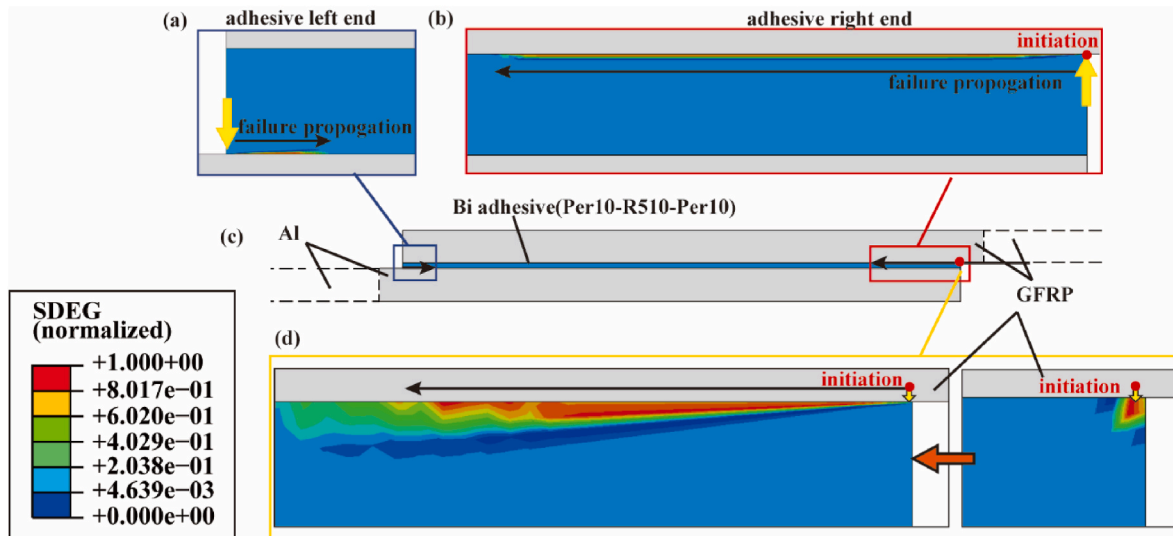


Fig. 9. FE predictions of damage initiation and propagation (normalized SDEG) for PER10-R510-PER10. (a) Left end – initiation at the adhesive-Al corner, (b) right end – dominant initiation at the adhesive-GFRP corner with longer propagation, (c) joint schematic indicating Al, GFRP, and bi-adhesive layout (dashed lengths truncated for clarity), and (d) enlarged views of the right end. The SDEG field is normalized (0–1).

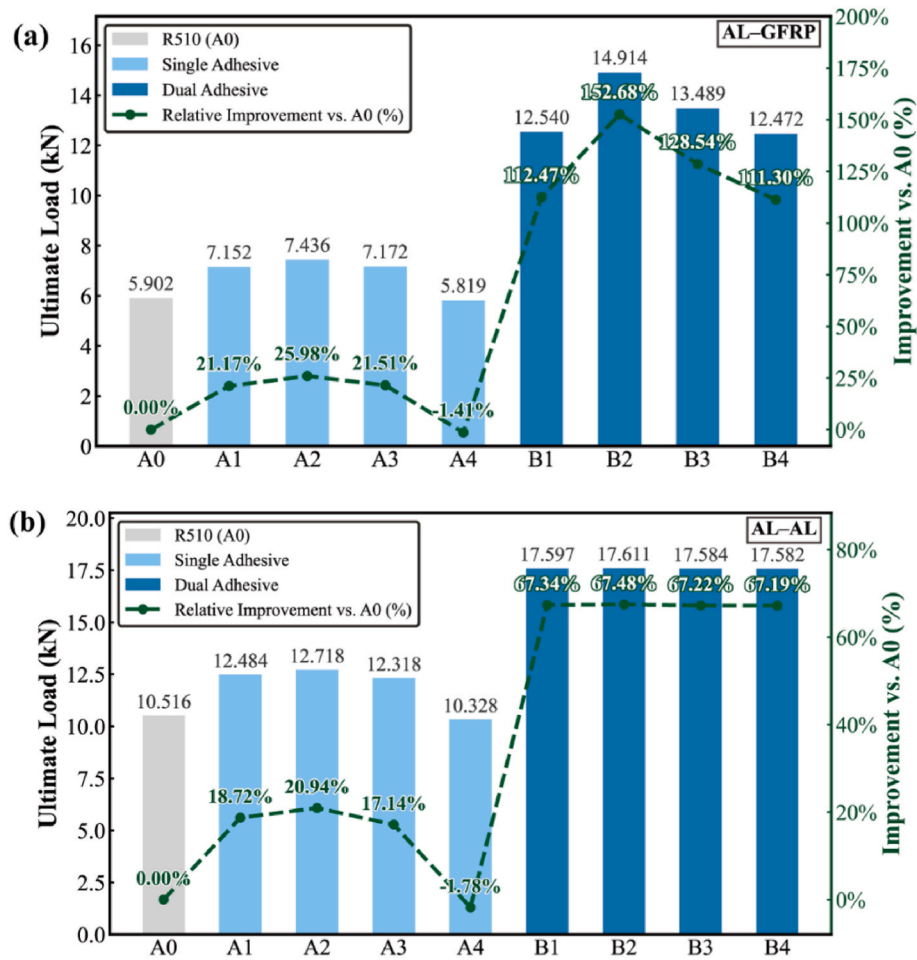


Fig. 10. Ultimate load and relative improvement of adhesive joints in four adherend configurations: (a) Al-GFRP, (b) Al-Al, (c) GFRP-GFRP, and (d) STEEL-GFRP. Light blue: single-adhesive joints (A-series); dark blue: dual-adhesive joints (B-series). All loads are given in kN and A0 (R510) is the baseline. **Improvement (%)** = $100 \times (F_{\max} - F_{A0}) / F_{A0}$, where $F_{\max}$ denotes the ultimate load of the joint and F_{A0} is the ultimate load of baseline A0. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

reaching unity, the contour field is presented using a normalized scale (0–1), highlighting relative degradation rather than absolute magnitude.

3.2. Ultimate-load and load-displacement results

The effect of adherend configuration on joint-scale performance was evaluated through four representative systems, Al-GFRP, Al-Al, GFRP-GFRP, and Steel-GFRP, each modelled using five single-adhesive (A0–A4) and four dual-adhesive (B1–B4) designs. The ultimate load was defined at the inflection point of the load-displacement curve. A unified soft-end ratio of $f = L_{\text{soft}}/L = 0.30$ (15:20:15) was used throughout, verified against the validated $f = 0.333$ (1:1:1) case, which yielded near-identical results. Fig. 10 summarizes the resulting capacities and relative improvements, with A0 (R510) taken as baseline across all systems.

Across the four adherend configurations, Fig. 8 reveals a distinct hierarchy in terms of grading effectiveness. GFRP-GFRP exhibits the largest improvement (+264.71 % at B2) and Al-GFRP follows (+152.68 %). Steel-GFRP shows intermediate enhancement (+103.04 %), while Al-Al records the smallest relative gain (+67.48 %) despite achieving the highest absolute forces. These trends already indicate that the effectiveness of functional grading is closely linked to how much deformation is permitted within the adhesive layer itself: compliant or moderately dissimilar adherends provide greater improvement potential, whereas stiff symmetric systems inherently limit enhancement.

To contextualize these scalar trends, representative load-displacement curves were extracted for A0, A2, and B2. Because GFRP-GFRP and Steel-GFRP exhibit curve shapes closely mirroring those of Al-GFRP, only the representative Al-GFRP and the contrasting Al-Al cases are presented in Figs. 11 and 12 to avoid excessive repetition.

In Al-GFRP (Fig. 11), the elastic ranges of A0, A2, and B2 nearly coincide, indicating that initial stiffness is governed by the adherend pair and overlap geometry. The enlarged views, however, expose the first signs of differentiation: A0, containing a rigid adhesive, exhibits the highest tangent slope in the near-elastic region, whereas A2 shows a slightly reduced slope due to its ductile nature, and B2 lies between. Distinct separation occurs at the terminal stage: A0 terminates abruptly over a short segment, reflecting quasi-brittle failure; A2 develops a visibly longer softening region; and B2 sustains load transfer over the widest displacement range, suggesting delayed onset of damage and extended deformation capacity.

In Al-Al (Fig. 12), the initial slope is steeper than in Al-GFRP, and the curve gradually bends towards a plateau, marking the development of plastic deformation in the aluminum adherends. Differences among adhesives still emerge near the final stage—A0 shows the shortest terminal degradation span, A2 exhibits moderate extension, and B2 maintains the longest range—but the separation between curves is noticeably reduced relative to Al-GFRP. This aligns with the reduced relative strength gains observed in Fig. 8 and reflects that, once adherend plasticity becomes dominant, variations in adhesive deformation

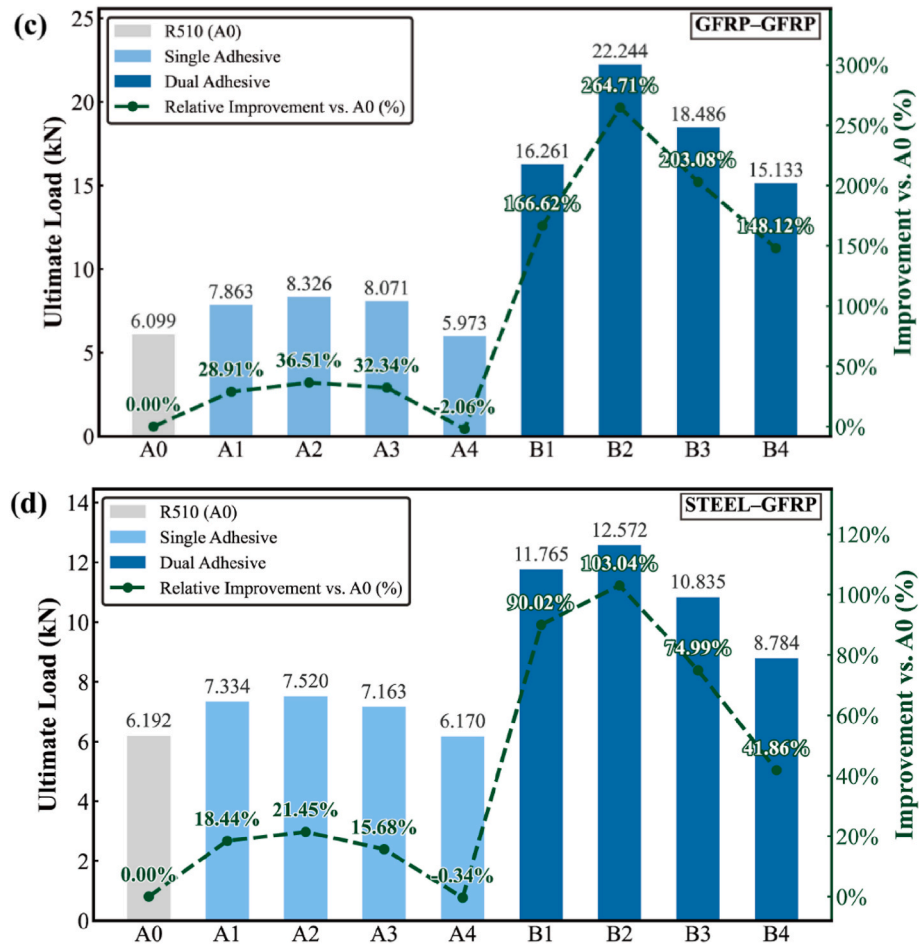


Fig. 10. (continued).

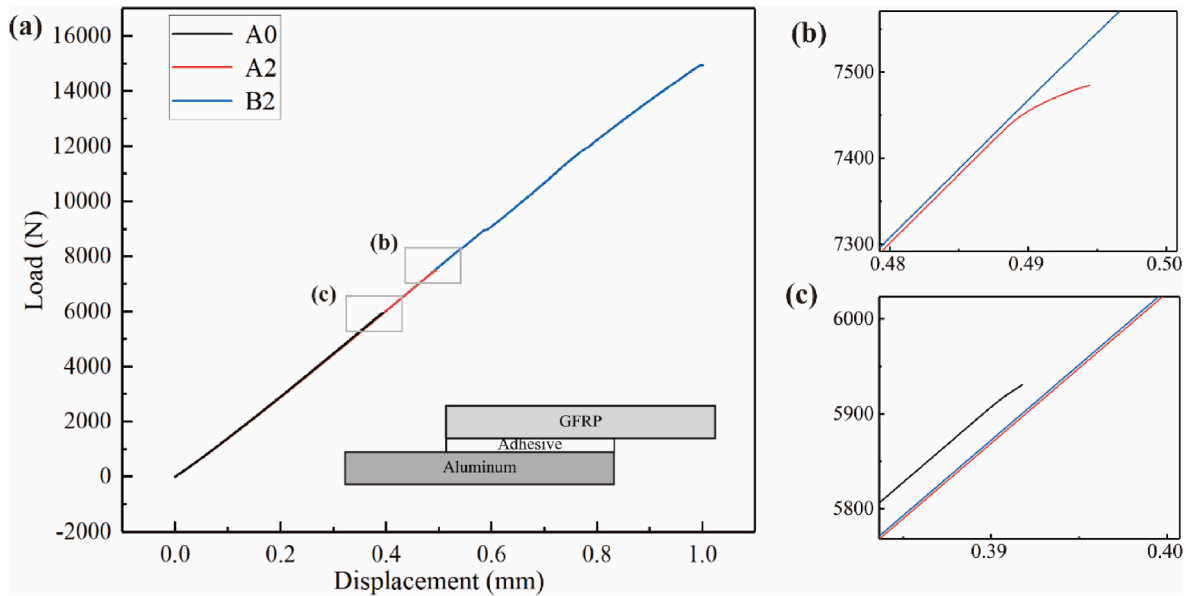


Fig. 11. Load-displacement curves of Al-GFRP joints with A0, A2, and B2 adhesives: (a) Overall curves, (b) zoomed view near the ultimate region of A2, and (c) zoomed view near the ultimate region of A0. The schematic illustrates the Al-adhesive-GFRP configuration.

characteristics contribute less to the global failure response.

Overall, the load-displacement responses and ultimate-load results together indicate that the degree to which functional grading enhances

performance depends strongly on how global deformation is accommodated within the joint. Systems such as Al-GFRP and GFRP-GFRP, where the adhesive layer contributes substantially to the overall

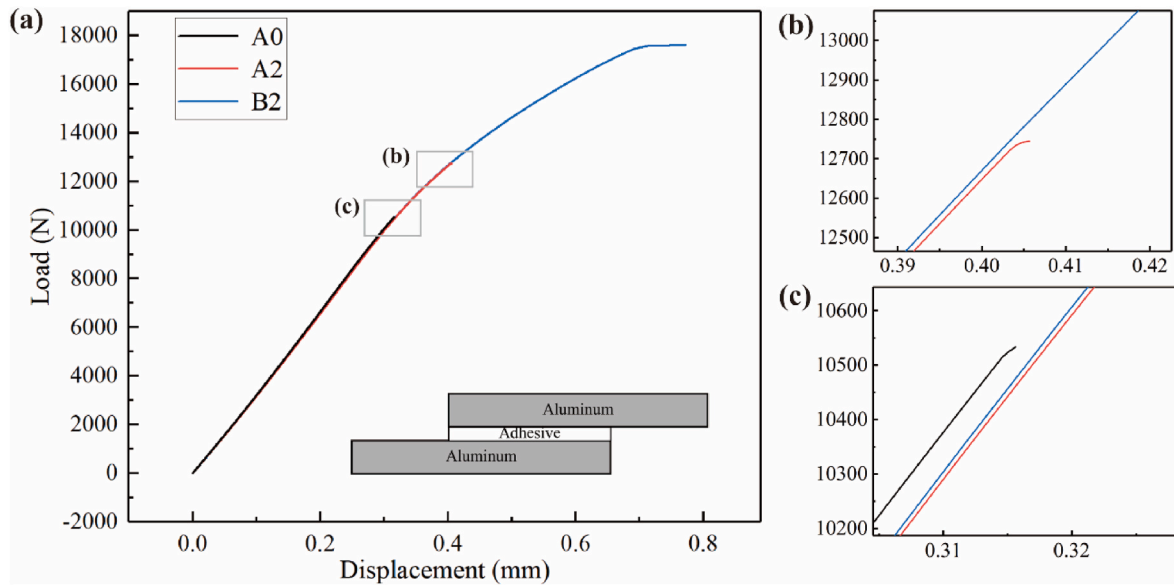


Fig. 12. Load-displacement curves of Al-Al joints with A0, A2, and B2 adhesives: (a) Overall curves, (b) zoomed view near the ultimate region of A2, and (c) zoomed view near the ultimate region of A0. The schematic shows the Al-adhesive-Al configuration.

deformation, display markedly extended terminal ranges and the largest relative gains, whereas Al-Al, governed increasingly by adherend plasticity, exhibits less distinction among adhesive types and consequently smaller improvement margins.

3.3. Mechanistic analysis based on stress redistribution

Before examining each adherend configuration individually, two sets of stress profiles are presented to establish the general redistribution features associated with functional grading. Fig. 13 focuses on the

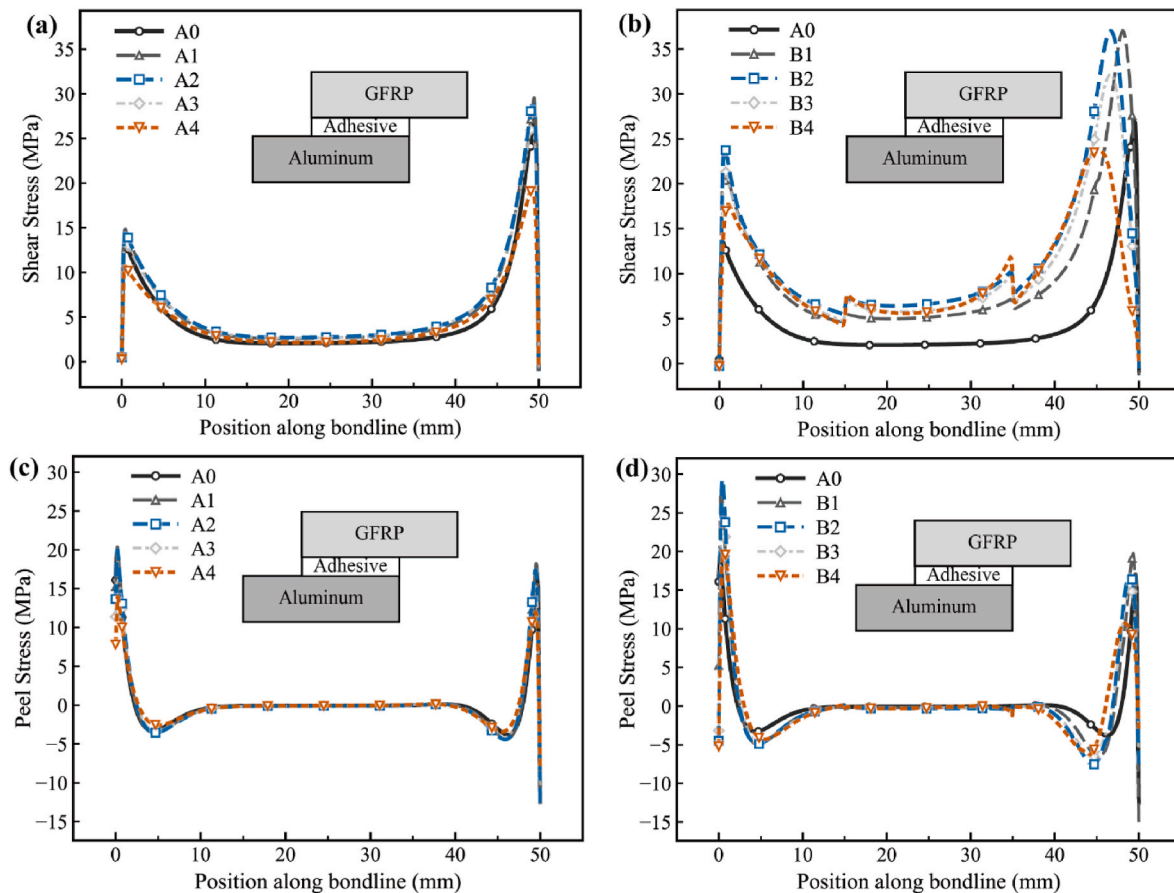


Fig. 13. Shear and peel stress distributions along the adhesive midline before failure load of Al-GFRP configuration: (a) and (c) single adhesive; (b) and (d) bi-adhesives.

Al-GFRP configuration and illustrates how modifying the adhesive layout from the single-adhesive series (A0–A4) to the bi-adhesive series (B1–B4) alters shear and peel stresses along the adhesive midline. Al-GFRP is selected as the reference case because the adherends remain predominantly elastic, allowing any modification within the bond-line to be reflected directly in stress transfer and ultimately in load-carrying capacity. Stresses were extracted along the adhesive midline, a commonly adopted path in analytical and numerical studies because it approximates the thickness-averaged stress state of the adhesive layer while avoiding singularities at the adherend–adhesive interfaces. The curves correspond to the last converged increment prior to failure, representing the fully activated load-transfer state, where accumulated ductile damage approaches the structural capacity.

Fig. 14 then compares the same midline stress profiles across the four adherend systems, using the single-adhesive baseline A0 and the representative graded layout B2. This cross-configuration view highlights how the redistribution mechanism identified in Al-GFRP strengthens or weakens depending on adherend stiffness and mismatch. In systems where adherends are stiff and symmetric (Al–Al), the mechanism becomes moderated because the overlap already engages more uniformly; in compliant or stiffness-mismatched pairs such as GFRP–GFRP or Steel–GFRP, the mechanism becomes amplified because bond-line deformation governs the structural response. An additional Steel–Steel case is discussed separately as a benchmark in Section 3.3.5,

as it lies outside the intended functional-grading design space.

With this framework established, the following subsection begins with Al-GFRP as the reference system, using Fig. 13 to elucidate the detailed mechanism by which grading alters stress transfer, before Fig. 14 is revisited to explain how the same mechanism manifests differently across the remaining adherend configurations.

3.3.1. Al-GFRP joints

The Al-GFRP configuration is first examined because the adherends remain predominantly elastic, allowing the effect of adhesive architecture to manifest directly in both stress transfer and global capacity. As shown in Fig. 10 (a), the single-adhesive series displays a non-monotonic trend: A0 reaches 5.90 kN and A2 attains the highest capacity at 7.44 kN (+26 %). In the dual-adhesive layouts, the representative graded system B2 more than doubles the capacity to 14.91 kN (+153 %), confirming that the strengthening mechanism arises not from ductility alone, but from the spatial allocation of compliant and stiff regions. Because this spatial sensitivity depends on the end partition, the standardized soft-end ratio $f = 0.30$ (15:20:15) was adopted following validation against a near-equal 1:1:1 split, where the capacity variation remained <3.5 %.

Since the mechanical function of an FGA lies not in global stiffness alteration but in modifying the singular end stress state, it is essential to examine the stress field directly at the joint ends. Fig. 15 therefore

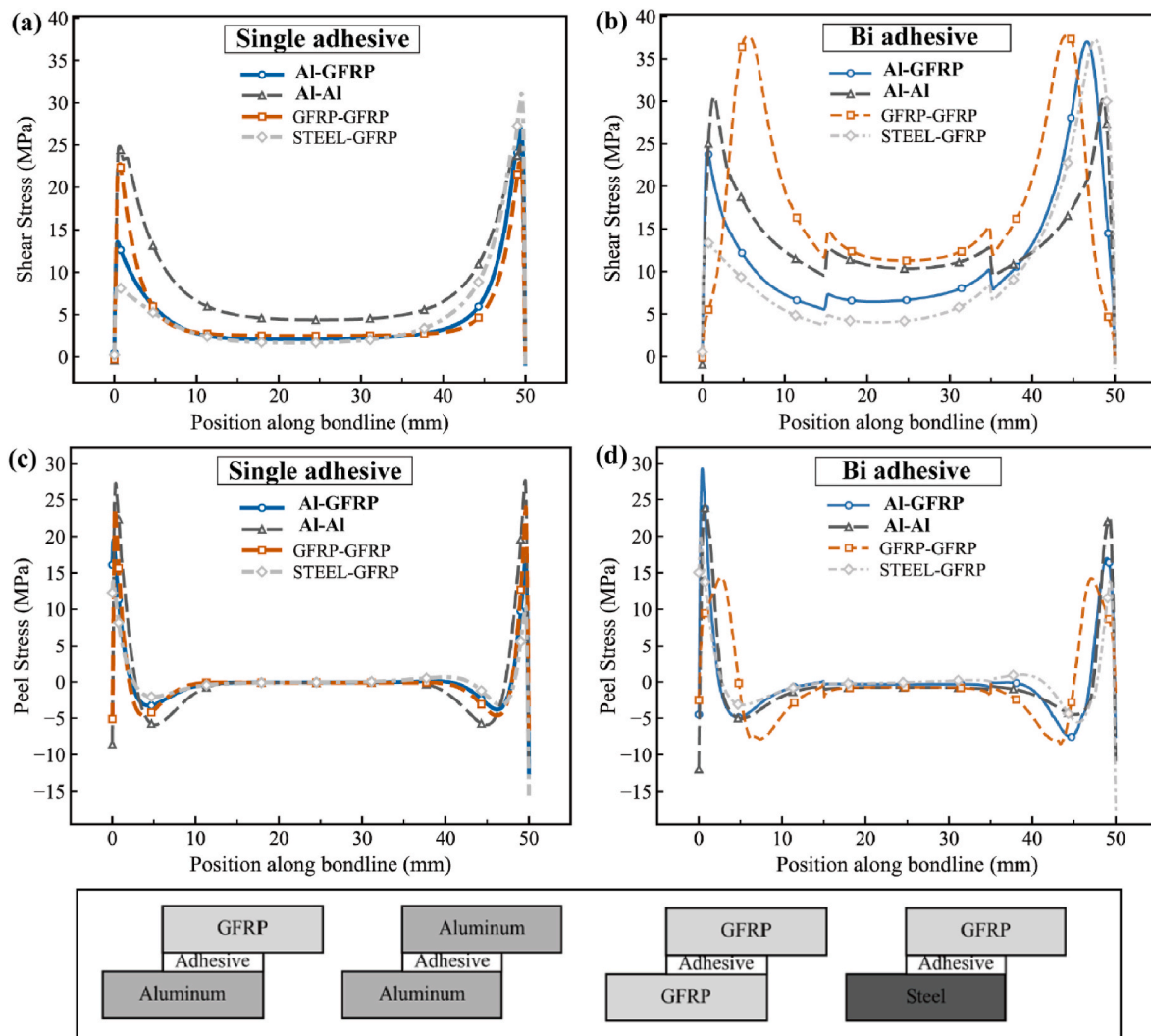


Fig. 14. Shear and Peel stress distributions along the adhesive midline before failure load in different adherend configurations: (a) and (c) single adhesive A0; (b) and (d) bi-adhesives B2.

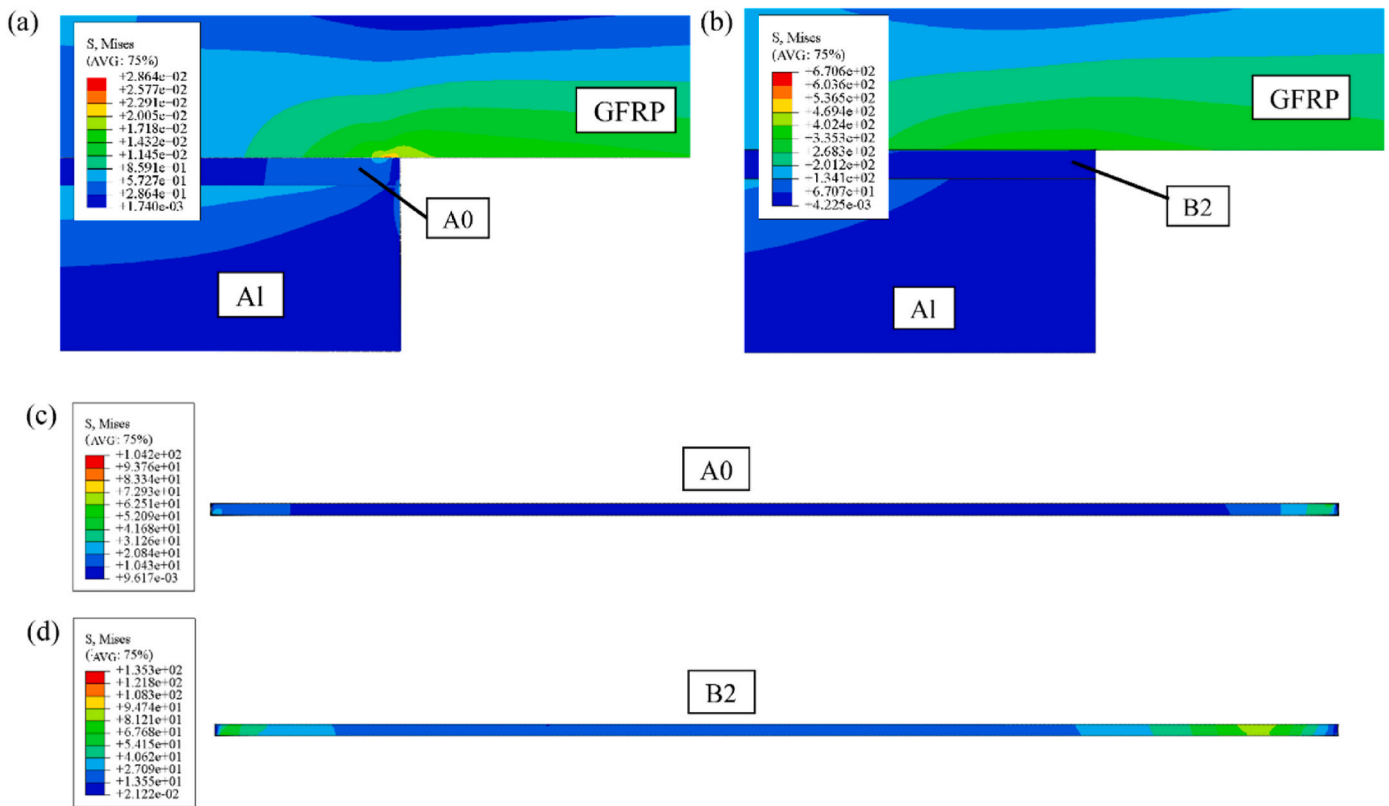


Fig. 15. von Mises stress contours for the Al-GFRP joints: (a) A0 – local von Mises stress at the right overlap end (full joint), (b) B2 – local von Mises stress at the right overlap end (full joint), (c) A0 – von Mises stress extracted in the adhesive layer, and (d) B2 – von Mises stress extracted in the adhesive layer.

provides von Mises fields extracted at the right overlap end, comparing A0 with B2. The full-joint plots capture adherend deformation contrast, while the adhesive-only extraction isolates the load transfer within the bond-line. The longer inward stress penetration observed in B2 already signals the redistribution behavior that Fig. 13 quantifies.

Redistribution characteristics are first illustrated in Fig. 13. Stresses were extracted along the adhesive mid-thickness to represent thickness-averaged shear and peel behavior while avoiding interface singularities. In the single-adhesive baseline A0, shear stress shows pronounced end concentrations, and the overlap interior carries only a small fraction of the load; peel stress follows a similar pattern. Although A1–A3 achieve capacity gains of 21–26 % over A0, their elevated shear profiles scale proportionally with capacity and do not alter peak locations or enlarge the transfer region; A4 performs slightly below A0 and likewise does not relieve end-dominated transfer. A consistent asymmetry is also observed, with the GFRP-side peak approximately 10–15 % higher than the aluminum side, reflecting the inherent mismatch of this adherend pair.

Once grading is introduced, the stress field changes in character (Fig. 13b–d). In B2, the mid-span shear plateau increases by approximately 40–50 % relative to A0, and the effective transfer region shifts inward by ~ 2 –3 mm, meaning a larger fraction of the bond-line becomes engaged prior to failure. The overall shear magnitude approaches roughly $2.5 \times A0$, consistent with the capacity increase. Other layouts exhibit similar tendencies but do not sustain the corresponding structural benefit: B1 increases mid-span shear but does not significantly expand the active region, whereas B4 forms a more uniform field but experiences premature soft-end damage and loses capacity accordingly. Peel stresses evolve in parallel; only B2 simultaneously stabilizes the ends while enhancing the interior. These midline observations identify the core mechanism: the effectiveness of grading depends on whether the bond-line deformation is sufficient to shift stress inward and enlarge the active load-bearing zone.

To examine how this redistribution develops through the adhesive thickness, Fig. 16 presents stress extracted along the upper, middle, and lower adhesive lines at the last converged increment prior to failure. Unlike the midline-only curves in Fig. 13, these profiles directly reflect how deformation engages the adhesive interior.

In the baseline A0 (Fig. 16a–c), all three curves show a sharply end-dominated response: shear peaks at both edges and drops to nearly zero across most of the overlap, while peel stresses remain confined to the ends and exceed 80 MPa at the aluminum interface. The three curves nearly collapse along the interior, indicating insufficient deformation to activate thickness-wise stress sharing.

In contrast, the graded B2 (Fig. 16b–d) exhibits markedly different behavior. The mid-span shear level increases by approximately 40–50 % relative to A0, and the shear-transfer zone shifts inward by ~ 2 –3 mm. More importantly, the separation between the upper, middle, and lower curves becomes distinct, demonstrating that load is no longer carried predominately through the GFRP-side interface but is progressively transferred through the adhesive thickness toward the aluminum side. Peel stresses also reorganize although edge tension increases, the aluminum-side peel response remains comparatively stable, indicating delayed damage initiation near the more compliant adherend.

This thickness-wise activation explains the capacity gain: grading does not merely suppress peak stress but enlarges the effective load-bearing zone, mobilizes the adhesive interior, and stabilizes both interfaces long enough for the joint to sustain greater global deformation. Excessively soft architectures (e.g., PER20-ended layouts) may yield more uniform distributions, but premature end damage limits capacity, whereas B2 balances redistribution with edge stability.

It should also be noted that the sharp stress jumps at the very last nodes near the upper and bottom adhesive interfaces are associated with the theoretical stress singularity at the free overlap edges, combined with numerical noise introduced by nodal sampling in the finite element post-processing. Although the mesh was strongly refined in these

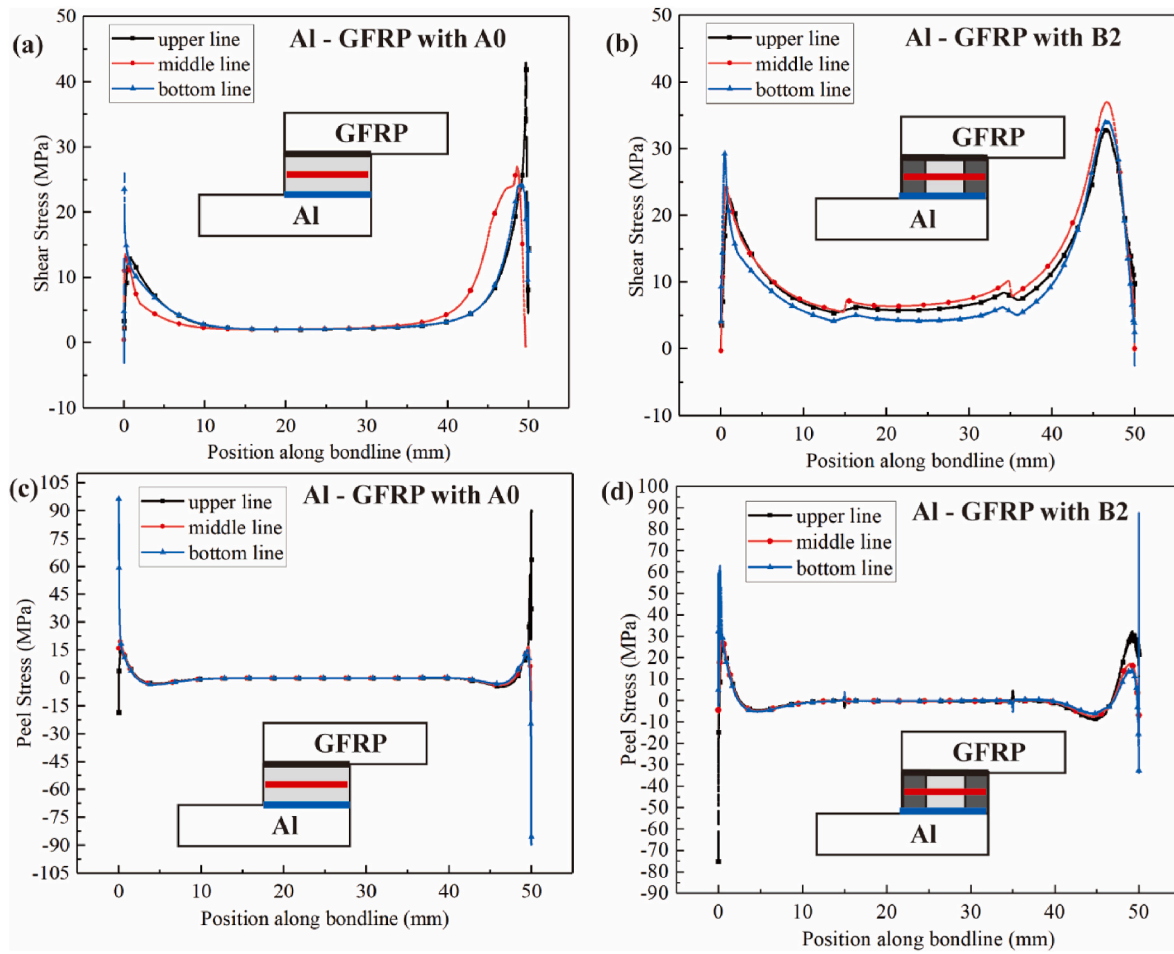


Fig. 16. Three-line shear and peel stress distributions along the adhesive before failure in Al-GFRP: (a, c) single-adhesive A0, and (b, d) graded bi-adhesive B2. Upper line: adhesive surface bonded to GFRP; Middle line: adhesive mid-thickness; Bottom line: adhesive surface bonded to Al.

regions, such localized peaks are not interpreted as physically meaningful interface stresses but as artefacts of the discretized representation. The discussion therefore focuses on the near-edge trends and the evolution of the stress field over the main part of the overlap, rather than on the last data points immediately adjacent to the singular corner.

Taken together, these observations indicate that the Al-GFRP configuration displays a clear grading-induced transition—from an end-dominated and interface-focused stress field (A0) to a more distributed load-bearing region (B2). Because this system features an elastic adherend pair, the modification of the bond-line alone is sufficient to reshape the load-transfer mechanism. In the subsequent subsections, this reference mechanism is used to interpret where redistribution becomes moderated (Al-Al), amplified (GFRP-GFRP), or asymmetric (Steel-GFRP).

3.3.2. Al-Al joints

For the Al-Al configuration, the variation in capacity among different adhesive layouts is comparatively subdued, and the bi-adhesive designs tend to approach a similar upper bound (Fig. 10b). In contrast to other adherend systems, where adhesive architecture induces pronounced differentiation, the Al-Al joints exhibit a noticeably smaller spread between single- and dual-adhesive performance. This comparatively narrow response range implies that adhesive modification plays a more limited role in governing the structural outcome, pointing toward the adherends' stiffness and deformation mode as primary factors. To understand why this configuration reacts less sensitively to grading, the following discussion turns to the stress-transfer features that shape its mechanical behavior.

Stress-transfer tendencies corroborate these macroscopic outcomes. The baseline Al-Al joint (A0) already displays a relatively efficient and symmetric distribution (Fig. 14a-c): shear stresses peaked at ~ 28 – 30 MPa at both ends, while the mid-span plateau reached ~ 10 MPa, the highest among all A0 systems, indicating that a substantial portion of the overlap was already engaged. Peel stresses were confined to the edges, with tensile levels of ~ 8 MPa and negligible interior contribution. Introducing grading (B2) produced the expected signature, slight inward displacement of the end peaks (≤ 1 mm) and a modest elevation of the shear plateau to ~ 11 – 12 MPa, corresponding to a 10–15 % rise relative to A0. Peel stresses increased only slightly to ~ 9 – 10 MPa and remained localized at the overlap ends, with limited extension into the interior (Fig. 14b-d).

These quantitative features explain why Al-Al records the smallest relative improvement despite high absolute capacities for the baseline configuration. In a stiff, symmetric system where the single-adhesive baseline already transfers load efficiently through the overlap, the activation of the redistribution mechanism by end grading is necessarily constrained, resulting in incremental gains that are outpaced by those in compliant or highly mismatched configurations.

3.3.3. GFRP-GFRP joints

Among all configurations, the GFRP-GFRP joints exhibit the most pronounced redistribution effect when adhesive grading is introduced. Because both adherends are compliant, shear transfer in the baseline single-adhesive joint (A0) is highly localized at the overlap ends. As seen in Fig. 14 (c), shear stresses exceed 35 MPa within a narrow zone of ≈ 2 mm at both edges, whereas the mid-span remains < 5 MPa, indicating

that only a small fraction of the overlap is effectively engaged prior to failure. Peel stresses show a similar pattern, with tensile peaks of $\approx 12\text{--}14$ MPa confined to the outermost region.

With dual-adhesive grading (B2), the transfer zone expanded markedly. The mid-span shear plateau increased to $\sim 12\text{--}14$ MPa, representing a 70–80 % rise relative to A0, and the effective transfer region shifted inward by approximately 3–4 mm from each end. End peak dominance was simultaneously alleviated, with the maximum shear at the edges reduced in relative proportion to the interior. Peel stresses displayed a similar redistribution: tensile concentrations moved inward from the outermost edges, and the central zone carried ~ 40 % higher peel stresses compared with A0.

Taken together, these distributions explain the large capacity gains of the B2 layout. In compliant GFRP adherends, baseline joints suffer from pronounced end singularities and limited central engagement, but functional grading mitigates these effects by enlarging the effective load-bearing zone. By delaying edge damage and mobilizing the mid-span adhesive, B2 produces the most pronounced redistribution effect and the greatest ultimate capacity among all configurations.

3.3.4. Steel–GFRP joints

In contrast, the Steel–GFRP system shows only partial redistribution when grading is applied. Owing to the pronounced stiffness contrast, shear transfer in the baseline A0 configuration remains asymmetric: the GFRP-side peak reaches $\approx 32\text{--}34$ MPa, whereas the steel-side peak remains $\approx 25\text{--}26$ MPa (Fig. 14 a), and the mid-span shear level (< 6 MPa) indicates that less than 20 % of the overlap contributes prior to failure. Peel stresses are unevenly distributed in the opposite direction, with $\approx 11\text{--}12$ MPa on the steel side and $\approx 7\text{--}8$ MPa on the GFRP side.

With dual-adhesive grading (B2), the stress distribution was modified but not fully balanced. The mid-span shear plateau increased to $\sim 9\text{--}10$ MPa, a $\sim 40\text{--}50$ % rise compared with A0, and the effective shear transfer zone shifted inward by ~ 2 mm on the GFRP side. The peak asymmetry was moderated but not eliminated: the GFRP side still exceeded ~ 30 MPa while the steel side remained $\sim 25\text{--}26$ MPa. Peel stresses also moved slightly inward, and the GFRP side increased to ~ 9 MPa, narrowing the steel–GFRP difference but leaving the edge dominance intact.

These quantitative features explain why Steel–GFRP achieves only an intermediate improvement despite its low baseline. Functional grading raises the interior plateau and shifts part of the transfer inward, but the severe stiffness contrast maintains residual asymmetry, limiting the ability to mobilize the full overlap width. Consequently, Steel–GFRP joints exhibit only an intermediate capacity increase. Grading enhances the load-bearing region but cannot overcome the limitation imposed by adherend modulus disparity, leading to improvements smaller than those of GFRP–GFRP or Al–GFRP, yet larger than in the fully stiff Al–Al configuration.

3.3.5. Steel–Steel benchmark configuration

To evaluate whether the adhesive-dependent strength behavior identified in the previous configurations is transferable to systems with substantially higher adherend stiffness, an additional Steel–Steel bonded joint was analyzed as a benchmarking case. This configuration is not part of the functional-grading design scope of the present work. Only the representative adhesive types used throughout the paper were included (A0, A2, A4, B2, B4), keeping the benchmark concise while still enabling comparison against the key trends identified in the main configurations. The finite element settings, including geometry, mesh discretization, material laws, and loading and step controls, were kept fully consistent with those of the primary analyzing.

The benchmarking results are summarized separately in Table 4. In absolute terms, Steel–Steel develops the highest load-bearing capacity owing to its substantially larger elastic modulus. When normalized relative to A0 (R510), however, the ordering among adhesive types remains unchanged: A2 (+19.0 %) outperforms A0, A4 (–8.0 %) decreases

Table 4

Ultimate loads of the Steel–Steel bonded-joint benchmark configuration.

Joint type	Steel–Steel	
	Load(kN)	Improvement (%)
A0 (R510)	16.216	0.00
A2	19.302	+19.0
A4	14.922	–8.0
B2	21.497	+32.6
B4	19.543	+20.5

capacity, and the bi-adhesive B2 layout yields the largest enhancement (+32.6 %), followed by B4 (+20.5 %). These observations indicate that the strengthening mechanism associated with functional grading is transferable across adherend systems.

However, the magnitude of achievable enhancement becomes increasingly limited as the adherend system stiffens. The attainable improvement is strongly constrained by the stiffness of the adherends, and the structural benefit of functional grading decreases as the adherend pair becomes stiffer. This behavior is consistent with the overall conclusion of this study that the benefit of functional grading is reduced when the stiffness of the adherends limits the extent to which the bond-line can deform.

3.4. Cross-configuration comparison and discussion

Fig. 14 compares the shear and peel stress distributions of the four adherend systems, contrasting the baseline single-adhesive joints (A0; Fig. 14a–c) with the optimal dual-adhesive design (B2; Fig. 14b–d). Both sets of curves were extracted at the last converged increment prior to failure and plotted with unified axis ranges to facilitate direct comparison. This cross-configuration analysis consolidates the results of Sections 3.3.1–3.3.4 and highlights how adherend stiffness and symmetry govern the redistribution mechanisms activated by functional grading. Baseline throughout this study refers to the single-adhesive reference A0 (R510).

Across all systems, the single-adhesive joints exhibited a consistent non-monotonic trend: A2 (PER10) improved capacity by 20–36 % over A0 (R510), whereas A4 (PER20) reduced it slightly below baseline (–0.3 to –2.1 %). In the dual-adhesive designs, B2—incorporating PER10 at the overlap ends with a stiff R510 core—produced the largest gains, ranked as GFRP–GFRP (+264.7 %) > Al–GFRP (+152.7 %) > Steel–GFRP (+103.0 %) > Al–Al (+67.5 %). B4, with PER20 placed at the ends, also exceeded A0 in every case but at uniformly lower levels, from +41.9 % (Steel–GFRP) to +148.1 % (GFRP–GFRP).

The stress distributions clarify these outcomes. PER10, with moderate ductility, delays peak intensification at the overlap edges and, in graded layouts, raises the mid-span plateau by 40–80 % while shifting the effective transfer region inward by 2–4 mm, thereby enlarging the active bond-line. In contrast, PER20, with much lower modulus, yields and accumulates damage prematurely: in single adhesive (A4), this depresses capacity below baseline, and in graded form (B4) it produces smoother profiles but sacrifices edge stability, capping the attainable improvement despite remaining above A0.

These results establish a configuration-independent principle: functional grading is most effective when a moderately ductile adhesive (PER10) is placed at the overlap ends, as in B2, which maximizes redistribution and strength; by contrast, overly compliant ends (PER20, B4) smooth the profile but compromise edge stability, constraining the attainable gain. These results show that moderate end-softening enhances load capacity by redistributing stresses, whereas excessive softening reduces efficiency. Mechanistically, an optimal soft-end ratio alleviates end-region stress concentrations while preserving load transfer through the central adhesive. When the soft-end length exceeds the characteristic length of the fracture process zone, further increases yield diminishing or plateaued gains in strength—a behavior confirmed by

recent fracture analyses linking process zone dimensions with strength limits [50]. Moreover, dual-adhesive joints consistently outperformed single-adhesive ones, confirming the advantage of combining stiff and compliant regions.

In symmetric adherend systems, the effectiveness of functional grading depends strongly on adherend compliance. In Al–Al, the baseline already mobilizes a substantial portion of the overlap, so placing PER10 at the ends (B2) produces only limited redistribution: the mid-span plateau rises modestly (≈ 10 – 15 %) and the end peaks shift inward by less than 1 mm, yielding a moderate gain of +67.48 %. By contrast, in GFRP–GFRP, the baseline of single adhesive is dominated by sharp end concentrations with little interior engagement; with the same B2 layout, the mid-span plateau increases by 70–80 % and the transfer zones move inward by 3–4 mm, leading to the largest improvement of +264.71 %. Thus, for symmetric systems, adherend stiffness governs the available redistribution space: stiff–stiff joints leave little scope for further enhancement, whereas compliant–compliant joints permit extensive redistribution and deliver the greatest benefits from grading.

In asymmetric adherend systems, the baseline single-adhesive joint is inherently unbalanced: the compliant side attracts higher shear, whereas the stiffer side carries higher peel. In Al–GFRP, the lower stiffness of GFRP concentrates shear at the composite end, while the Al side sustains higher peel, producing asymmetric edge singularities. Introducing PER10 at the ends (B2) mitigates both effects: the GFRP-side shear peak is moderated and displaced inward, the Al-side peel is reduced, and the mid-span shear plateau rises by ≈ 40 – 50 % with transfer zones shifting ~ 2 – 3 mm inward, yielding a +152.68 % capacity gain. In Steel–GFRP, the modulus mismatch is more severe, with shear overwhelmingly concentrated on the GFRP side and peel on the steel side. Grading with PER10 increases the mid-span shear by ≈ 40 % and shifts the dominant GFRP-side peak ~ 2 mm inward, but a pronounced left–right imbalance remains because the stiffness contrast keeps transfer edge-dominated; consequently, the gain is limited to +103.04 %, smaller than in Al–GFRP despite a similar A0 baseline.

Mechanistically, the benefit of grading in asymmetric pairs depends on the extent to which the stiffness mismatch can be alleviated. When the contrast is moderate (Al–GFRP), redistribution into the overlap interior can be more effectively activated and a larger fraction of the core is engaged; when the contrast is severe (Steel–GFRP), end yielding remains biased and only partial relief is achieved, limiting—though not eliminating—the attainable improvement.

Beyond symmetry, adherend stiffness also influences the extent of redistribution that grading can activate. In the rigid Al–Al system, the baseline already carries relatively high loads, with moderate end peaks and the highest mid-span stress among the A0 cases (≈ 10 MPa). Adding PER10 at the ends (B2) induces only limited changes—the plateau rises by ~ 10 – 15 % and end peaks shift inward by < 1 mm—corresponding to a gain of +67.5 %. In contrast, the compliant GFRP–GFRP system starts from the lowest baseline (6.099 kN), dominated by steep end singularities and little interior sharing; here B2 elevates the mid-span plateau by 70–80 %, shifts transfer zones 3–4 mm inward, and increases capacity by +264.7 %.

This contrast reflects the different redistribution space available in the overlap. In rigid–rigid joints, the adhesive layer is already substantially engaged, so grading can only incrementally smooth edge stresses without altering the governing transfer mode. In compliant–compliant joints, however, the baseline is strongly end-dominated, and moderately ductile ends delay local yielding and redirect load into the adhesive core. The higher the adherend compliance, the greater the redistributive potential, and consequently, the more pronounced strength gain achievable by functional grading.

Overall, the cross-configuration analysis highlights that the extent of improvement from functional grading varies systematically with adherend properties: rigid–rigid joints provide limited stress redistribution and modest gains, compliant–compliant joints enable broader load sharing and deliver the largest increases, while asymmetric joints

fall in between, with the outcome governed by mismatch severity. In general, the effectiveness of functional grading in improving joint strength depends not only on the grading layout but also on the load-redistribution capacity allowed by the adherends.

4. Conclusion

Finite element simulations using an elastic–plastic material model with a ductile damage formulation were conducted to investigate functionally graded adhesive joints. The model was validated against published Al–GFRP data, predicting ultimate loads with deviations of 3–15 %. This level of agreement supports its use for strength assessment and, importantly, enables analysis of midline stress redistribution of adhesive that cannot be directly measured.

For single-lap joints, graded (bi-adhesive) layouts increased strength relative to the single-adhesive baseline. Comparative analysis of bi-adhesive configurations indicates that an appropriate level of end-adhesive ductility is critical—the effectiveness of grading depends on achieving sufficient, but not excessive, ductility at the overlap ends, a principle that carries across different adherend configurations. In graded joints with an R510 core, B2 (PER10 at the overlap ends) consistently outperformed B4 (PER20 at the overlap ends). In Al–GFRP, for example, B2 increased strength by 152.7 % over the R510 baseline, whereas B4 achieved 111.3 %, indicating that excessive end softening promotes earlier yielding and limits the benefit. The same qualitative trend persisted across all four configurations.

Across adherend systems, the attainable gain varied with adherend stiffness and symmetry. In rigid–rigid joints (Al–Al), redistribution was limited and the relative gain remained modest (+67.5 %). In compliant–compliant joints (GFRP–GFRP), grading enlarged the effective transfer region and produced the largest improvement (+264.7 %). Asymmetric pairs exhibited intermediate gains: Al–GFRP, with moderate mismatch, reached +152.7 %, whereas the more severely mismatched Steel–GFRP was limited to +103.0 %. These comparisons indicate that the effectiveness of grading depends not only on adhesive layout but also on adherend stiffness, symmetry, and the severity of mechanical mismatch.

Mechanistically, the observed capacity trends are consistent with stress redistribution along the bondline. With graded adhesives, local yielding at the ends is delayed, edge-peak dominance is reduced, the mid-span shear plateau rises, and peak stresses shift inward from the overlap edges toward the joint interior. This redistribution is strongly conditioned by adherend properties: in rigid–rigid joints, the baseline already transfers load efficiently, so the inward shift is limited; in compliant–compliant joints, pronounced edge concentrations allow substantial peak relief and a wider transfer zone; in asymmetric systems, grading moderates side-to-side imbalance, yet stiffness mismatch limits the extent of redistribution.

In conclusion, the effectiveness of functional grading is shaped not by adhesive layout in isolation but by the joint action of end-adhesive ductility and the scope for stress redistribution permitted by the adherends. Through a systematic comparison of Al–GFRP, Al–Al, GFRP–GFRP, and Steel–GFRP joints, this study links adhesive grading schemes, adherend properties, redistribution mechanisms, and macroscopic strength within a single analytic frame. The results indicate that compliant adherends provide the greatest latitude for load reallocation and thus the largest attainable gains, rigid–rigid pairs offer only limited improvement, and asymmetric systems fall in between, with benefits bounded by mismatch severity. Compared with the existing literature, where adhesive grading and adherend effects have largely been examined separately. This work provides a cross-configuration framework that demonstrates their combined influence and offers design-oriented guidance for multi-material joints in which functional grading is to be applied.

CRediT authorship contribution statement

Yanan Zhang: Investigation, Methodology, Software, Writing – original draft. **Dong Chen:** Supervision, Writing – review & editing. **Yuxuan Wu:** Software. **Lihua Wang:** Supervision, Writing – review & editing. **Magd Abdel Wahab:** Writing – review & editing, Supervision, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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