



Influence of low-velocity impact damage on the mechanical performance of adhesively bonded thermoplastic composite single-lap joints

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ABSTRACT

Adhesively bonded single-lap joints (SLJ) are widely used in composite structures. They are known to be sensitive to low-velocity impact damage, which may significantly reduce residual strength. While this behavior has been investigated for thermoset-based composite joints, corresponding studies on carbon fiber reinforced high-performance thermoplastic (CF-TP) adhesive joints remain scarce. In particular, the influence of different impact-induced damage characteristics on joint strength is not yet fully understood.

In this study, adhesively bonded SLJ with CF-TP adherends were subjected to low-velocity impact, followed by non-destructive damage characterization. Six categories of impact damage were identified, ranging from localized to widespread delamination. The residual strength, deformation behavior and fracture pattern characteristics were systematically analyzed and complemented by finite element simulations. Furthermore, a generic numerical damage study was conducted to isolate effects of delamination size and through-thickness position.

Results indicate a clear distinction between damage-tolerant and damage-critical states. Localized delamination does not lead to significant reduction in residual strength. However, widespread delamination causes a pronounced reduction. Numerical results indicate that delamination-induced stress redistribution in the adhesive layer governs joint failure. The numerical study further demonstrates that the position of delamination relative to the adhesive layer is more critical than the size of the delamination.

1. Introduction

The ongoing quest for weight reduction, structural efficiency, and damage tolerance has rendered advanced composite materials indispensable in contemporary aerospace structures. In recent years, there has been an increasing interest in carbon fiber-reinforced high-performance thermoplastic composites (CF-TP) as a potential alternative to conventional thermoset-based composites for lightweight structural applications. This interest is driven by their enhanced fracture toughness, intrinsic damage tolerance, weldability, recyclability, processing versatility, and suitability for automated and high-rate manufacturing processes. Recent reviews have emphasized the increasing relevance of thermoplastic composites due to their recyclability, damage tolerance, and advanced processing routes, including automated tape placement, in-situ consolidation, thermoforming, and compression molding. These advancements substantiate their utilization in scalable structural applications within sectors such as aerospace, automotive, marine, and construction. In the aerospace context, recent studies have examined the potential of carbon fiber-reinforced low-melt poly-aryl-ether-ketone (CF/LM-PAEK) for laser-assisted automated fiber placement and in-

situ consolidation. These studies have underscored the significance of this material for future aircraft production, particularly due to its ability to achieve short cycle times, out-of-autoclave processing, weldability, recyclability, and reduced manufacturing waste [1–3]. Concurrent with the increasing use of advanced composites, adhesive bonding has emerged as a pivotal joining technology in the domain of aerospace engineering. Compared with mechanical fastening, adhesive bonding offers several advantages for composite structures. Since the load is transferred over the bonded overlap rather than through discrete fastener holes, adhesive joints can reduce local stress concentrations and avoid drilling-induced fiber damage in the adherends. In addition, adhesive bonding can reduce fastener-related weight penalties, provide sealing functionality, and enable the joining of dissimilar material systems, which is particularly relevant for lightweight aerospace structures. For these reasons, adhesively bonded joints are widely used in composite and composite to metal structures, including applications where continuous load transfer, low structural weight, and minimal laminate disruption are required [4,5]. Consequently, adhesively bonded joints have become a prevalent component in primary and secondary aerospace structures, encompassing fuselage panels, stringer-skin

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connections, and stiffened composite assemblies. The single-lap joint (SLJ) remains one of the most commonly employed geometries due to its simplicity and manufacturability [6]. However, SLJs are inherently prone to secondary bending and peel stresses, especially when subjected to out-of-plane or transverse loading. These stress components are widely recognized as critical drivers for damage initiation in the adhesive layer and adjacent composite plies [4]. In the context of aerospace service environments, bonded joints are frequently subjected to low-velocity impact (LVI) events. Such events may include tool drops during assembly and maintenance, impacts from runway debris, or accidental contact during ground handling. Although such impacts often do not cause overt surface damage, numerous studies have demonstrated that they can induce barely visible impact damage (BVID) accompanied by severe internal degradation, including delamination, matrix cracking, cohesive cracking within the adhesive, and interfacial debonding. This hidden damage poses a major challenge for structural integrity assessment, inspection, and certification in aerospace applications [7].

The influence of LVI on SLJs has been the subject of extensive research in the context of thermoset-based composite systems. This research has revealed that joint geometry, material combination, and damage mechanisms significantly influence post-impact load-carrying capacity. Preliminary experimental findings by Farrow et al. revealed that the application of transverse impact loading can substantially diminish the effective strength of composite SLJs, even in cases where the adhesive interface remains predominantly undamaged. In the case of carbon/epoxy joints, impact damage resulted in significant laminate delamination and shear cracking in the adhesive, leading to a residual strength reduction of approximately 50%. Failure was primarily governed by laminate damage rather than adhesive debonding [8]. Subsequent studies have underscored the pivotal function of overlap geometry. Ma et al. reported a consistent 30–35% reduction in load-carrying capacity for CFRP/Al SLJs after impact, while demonstrating that shorter overlap lengths are markedly more sensitive due to a larger proportion of damaged bonding area [9]. This trend was confirmed by Çallioğlu and Ergun, who observed early perforation and extensive debonding in SLJs with a 20 mm overlap length, leading to a drastic reduction in adhesive strength. Conversely, longer overlaps limited crack propagation and preserved higher residual capacity [10]. A mechanistic interpretation of these observations was provided by Choudhry et al., who identified characteristic overlap dimensions governing the dominant damage mode. In the case of lower characteristic overlap widths, adhesive debonding dominated and was identified as the load-limiting mechanism. Conversely, larger overlaps shifted damage towards laminate-dominated mechanisms, such as delamination and tow splitting. Although the measurement of residual strength was not a direct objective of the study, bondline damage was explicitly identified as a critical factor for structural integrity [11]. A thorough investigation into the nature of damage was conducted by Kim et al., who demonstrated that low-velocity impacts result in delamination, adhesive-adjacent debonding, and fiber fracture, with these effects being most pronounced in the regions where overlap edges exhibit the highest levels of peel stress. Although the post-impact strength of the samples was not the focus of the experimental study, the authors underscored the notion that these damage modes inherently impose limitations on strength [12]. The impact of material combination and impact location was emphasized in the context of hybrid joints. Liu et al. demonstrated that, in the case of CFRP/Al SLJs, the impact on the aluminum adherend resulted in severe plastic indentation and extensive adhesive damage, leading to residual strength reductions of up to 42%. Conversely, the impact on the CFRP adherend caused predominantly laminate damage and limited strength loss [13]. These findings were further corroborated by Hu et al., who reported extreme reductions in tensile-after-impact strength of up to 88% for impacts on the aluminum side, while impacts on the CFRP side caused only minor reductions [14]. A comparative assessment by Wei et al. demonstrated that Al–Al SLJs

exhibited the most significant reductions in adhesive strength, while CFRP–CFRP joints demonstrated superior impact tolerance and hybrid CFRP–Al joints exhibited the best overall damage tolerance of the tested configurations. A study of micro-computed tomography results indicated that adhesive failure mechanisms vary depending on the stiffness and plasticity of the adherends [15]. More recently, impact-induced damage in adhesively bonded thermoplastic composite joints has also attracted attention. In Al/CFRTP adhesive joints subjected to transverse impact, damage morphology, residual strength, strain evolution, and cross-sectional failure mechanisms were shown to depend strongly on both impact energy and impacted surface. The study demonstrated that using the CFRTP adherend as the impact surface can reduce damage severity and help maintain residual tensile strength, highlighting the relevance of adherend material, impact location, and internal damage evolution for the post-impact assessment of bonded thermoplastic composite joints [16]. Although Wu et al. did not quantify post-impact residual strength, their investigation into the transverse crashworthiness of CFRP SLJs demonstrated a strong increase in crack length and adhesive damage with increasing impact energy, indicating an inevitable degradation of joint strength [17]. Complementary studies by Huang et al. further demonstrated that joints exhibiting pronounced stiffness mismatch, such as composite/steel configurations, demonstrated the most severe reductions in residual strength and exhibited heightened vulnerability to post-impact fatigue loading [18,19]. Finally, several authors addressed the numerical prediction of impact-induced strength degradation. As demonstrated by Oliveira et al., the load-bearing capacity of SLJs is directly limited by impact damage, as measured using a combination of continuum damage mechanics and cohesive zone modelling [20]. In a similar vein, Hu, Athinaios, and Yang et al. have shown that advanced finite-element models can accurately predict impact response and tensile-after-impact strength [21–23]. Specifically, the restart-based approach validated by Yang et al. demonstrated a maximum deviation of 3% between numerical predictions and experimental results, thereby establishing a robust correlation between impact damage evolution and reduced adhesive strength.

Despite extensive research on the impact behavior and residual strength of adhesively bonded composite single-lap joints, most available studies have focused on thermoset-based composite adherends or hybrid composite-metal configurations. Systematic investigations of adhesively bonded joints with carbon fiber-reinforced high-performance thermoplastic (CF-TP) adherends are scarce, even though these materials are becoming increasingly relevant for damage-tolerant aerospace structures. Furthermore, previous studies often correlate residual strength with global descriptors, such as impact energy or projected damage area. However, these descriptors alone do not determine whether joint strength degradation is caused by damage size, damage morphology, through-thickness delamination position, interaction with the overlap edge, or direct adhesive-layer degradation. This lack of damage-state-specific data creates uncertainty in the damage tolerance assessment of bonded CF-TP aerospace structures, since allowable damage limits, inspection criteria, and certification-relevant design margins require a clear correlation between impact-induced damage morphology and residual joint strength.

The present study establishes a correlation between low-velocity impact damage and the residual mechanical performance of adhesively bonded CF-TP single-lap joints based on damage morphology. This study uses ultrasonic inspection, residual strength testing, digital image correlation (DIC)-based deformation analysis, fracture surface observation, and finite element modelling to determine which impact-induced damage characteristics are critical to load-carrying capacity. Specifically, the work aims to: 1) classify distinct impact-induced damage states in bonded CF-TP single-lap joints, 2) quantify their effect on residual joint strength and deformation behavior, and 3) separate the effects of delamination size and through-thickness position on adhesive stress redistribution and joint failure.

2. Materials and methods

2.1. Experimental testing

The specimens were designed as adhesively bonded SLJs. The overall geometry was based on dimensions commonly used in compression-after-impact (CAI) testing. The dimensions of each specimen were 150 mm in length by 100 mm in width. The bonded adherends, measuring 90 mm $\times$ 100 mm, were joined with an overlap length of 30 mm, resulting in a symmetric overlap configuration. The CAI-inspired specimen width was selected to provide a sufficiently large unsupported region for controlled transverse impact loading in the overlap area. Standard narrow single-lap joint geometries would be less suitable for this purpose, because the resulting impact damage field could be dominated by specimen edges, grips, or fixture constraints. The selected configuration is therefore not intended to represent a standard single-lap shear test geometry, but to combine a controlled impact-damage configuration with the characteristic load-transfer features of an adhesively bonded single-lap joint, including eccentric loading, secondary bending, and combined shear and peel stresses in the adhesive layer. Consequently, the reported strengths are geometry-specific, whereas the relative comparison between damage categories remains valid because all specimens shared the same geometry and loading configuration. The adherends were fabricated from unidirectional carbon fiber-reinforced low-melting polyaryletherketone (CF-LMPAEK) prepreg material (Toray TC1225). The laminates were consolidated by hot-press processing, resulting in a quasi-isotropic stacking sequence of [45/0/90/−45]_{2S} with a total of 16 plies with a ply thickness of 0.136 mm, which leads to a total thickness of 2.176 mm. The adherends were bonded using a structural paste-type epoxy adhesive (3M™ 9323 B/A). Glass beads were incorporated into the adhesive composition to ensure a controlled and uniform bondline thickness of 0.1 mm. The adhesive was cured for 2 h at 65°C under a surface pressure of 0.35 N/mm², according to the manufacturer's guidelines. In order to ensure a high and reproducible adhesive bond strength, the bonding surfaces of the composite adherends were treated using oxygen low-pressure plasma activation prior to bonding.

Low-velocity impact tests were performed using an instrumented drop-weight impact testing system (CEAST 9350, Instron, USA). The specimens were fixed on a rigid support plate, which provided a support

width of 12.5 mm along each edge. Four mechanical clamps were used to prevent out-of-plane movement. The impactor was composed of a hemispherical steel tup with a diameter of 16 mm and a total mass of 5.048 kg. Impact energies ranged from 15 J to 22.8 J, corresponding to dropping heights of 303 mm to 460 mm, respectively. During each impact event, the reaction force–time histories were recorded by the integrated force sensor. The impact configuration was selected to generate representative transverse damage states while circumventing complete perforation of the specimens. The upper impact energy of 22.8 J was selected because it produced the most severe non-perforating damage state observed in this study. Higher impact energies were not considered because they would increase the risk of complete perforation, extensive crushing, or global specimen failure, thereby preventing a meaningful correlation between internal delamination morphology and residual joint strength. The selected energy range therefore covers the transition from localized to severe widespread delamination while preserving sufficient residual load-carrying capacity for subsequent tensile testing. The geometry of the specimen and the configuration of the experimental apparatus for the low-velocity impact tests are illustrated in Fig. 1.

After the impact testing, the characterization of damage was executed through the implementation of ultrasonic immersion testing (USPC 3060-UHF, Hilger NDT GmbH, Germany). The experiment utilized a 20 MHz immersion transducer operating in pulse-echo mode, with the probe performing a raster scan over the specimen surface. The scan step size was set at 0.2 mm in both the x- and y-directions. Scanning was conducted from the impacted side and the rear side of each specimen. The damage assessment process involved capturing C-scans and B-scans, which facilitated the determination of the projected delamination area and the assessment of the internal damage morphology based on time-of-flight (ToF) information.

The residual load-carrying capacity of the impacted joints was assessed through the implementation of quasi-static tensile tests, which were conducted using a universal testing machine (ZwickRoell GmbH & Co. KG, Germany). The experimental tests were conducted under displacement control conditions, with a constant speed of 2 mm per second and at ambient temperature. For a select group of specimens, full-field strain measurements were conducted using a 3D digital image correlation (DIC) system (ARAMIS, Carl Zeiss IQS Deutschland GmbH, Germany) to monitor strain localization and damage progression during

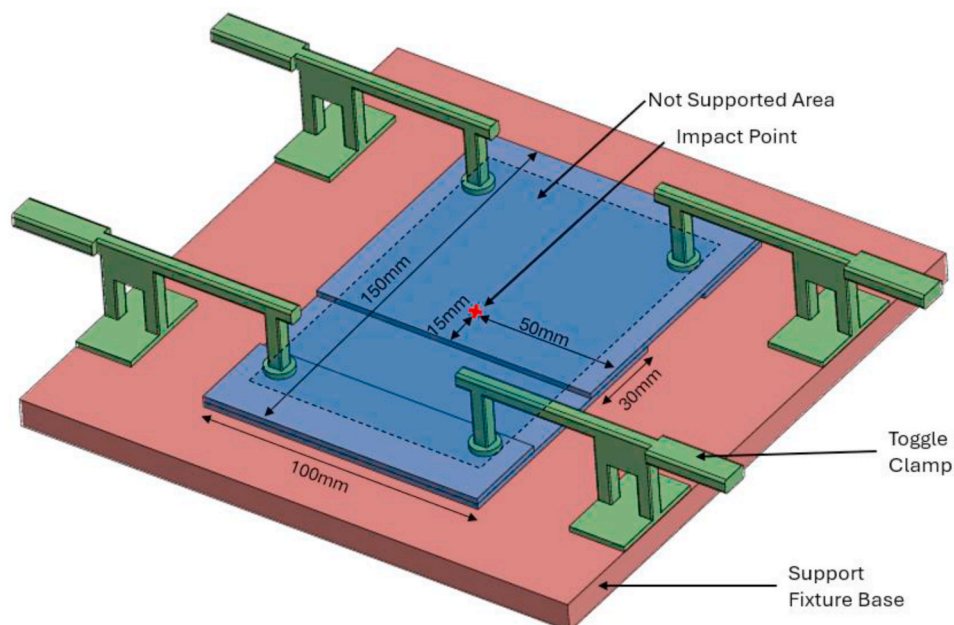


Fig. 1. Low-velocity impact setup and geometry of the single-lap joint specimen.

loading. After completion of the tensile tests, an examination of the fracture surfaces was conducted using optical microscopy. The predominant failure modes were identified and classified as cohesive failure within the adhesive, adhesive failure or substrate-related failure within the composite adherends.

2.2. Numerical modelling

The objective of the numerical modelling was to provide a supporting simulation of the quasi-static tensile test in order to investigate the influence of different impact-induced damage types on the fracture behavior of adhesively bonded single-lap joints. All finite element simulations were performed using the commercial software Abaqus (Dassault Systèmes Simulia Corp., Providence, RI, USA) employing the implicit solver. Instead of employing an explicit simulation of the impact event, the experimentally observed damage states were reconstructed within the finite element model based on the results of non-destructive testing. This methodological framework enables a systematic investigation of the effect of individual and combined damage characteristics on the residual joint strength. To reduce computational effort while preserving the relevant load transfer mechanisms, the numerical model was limited to the free joint length, excluding the clamped regions of the experimental setup. Consequently, the total model length was reduced to 90 mm, corresponding to the effective load-bearing region of the joint. The overlap length and relative positioning of the adherends were maintained, while the boundary conditions were selected to replicate the quasi-static tensile test.

The adherends were discretized using oriented single plies, with each ply representing one lamina of the quasi-isotropic laminate. In order to isolate the influence of adhesive-layer and interlaminar delamination on the residual tensile response, the individual adherend plies were modeled as orthotropic linear-elastic. Intralaminar damage mechanisms, such as matrix cracking, fiber fracture, and fiber–matrix debonding, were not explicitly included. This simplification is justified by the objective of the numerical model, which was not to simulate impact damage initiation and growth, but to analyze the quasi-static residual strength of experimentally observed and NDT-reconstructed delamination states. The ultrasonic B-scan and cross-sectional observations indicated that the dominant impact-induced damage modes considered in this study were interlaminar delaminations within the adherends. Therefore, the model focuses on the resulting disturbance of bending stiffness and adhesive-layer stress redistribution caused by these delaminations. Nevertheless, for severely impacted specimens, additional intralaminar damage may contribute to the absolute residual strength and is therefore considered a limitation of the present modeling approach. The element type C3D8R was used to represent this behavior. Interlaminar damage was modeled by introducing five discrete interlaminar damage planes. The selected interlaminar damage planes were chosen based on the experimentally observed delamination

locations obtained from ultrasonic B-scans, time-of-flight information, and complementary cross-sectional/CT observations. Cohesive elements (element type COH3D8) with zero thickness were inserted only at these through-thickness positions required to reconstruct the recurring damage morphologies, including delaminations close to the outer plies and adhesive-adjacent laminate regions. This reduced computational effort and avoided introducing artificial damage paths not supported by the inspection results. Since the simulations were intended to analyze the residual tensile response of experimentally reconstructed damage states rather than to predict impact-induced delamination initiation, the use of selected interfaces was considered appropriate.

The adhesive layer was explicitly modeled using cohesive zone elements with a thickness of 0.1 mm, corresponding to the bondline thickness that was experimentally controlled. A schematic representation of the finite element model, including the laminate plies, interlaminar cohesive layers, and adhesive layer, is shown in Fig. 2. The mesh was refined in the overlap region, the adhesive layer, and along the interlaminar cohesive interfaces, where damage initiation, delamination representation, and adhesive stress redistribution occur. During model setup, several mesh refinements were tested to ensure a stable global force-displacement response and a reasonable representation of the reconstructed delamination boundaries. These preliminary mesh variations affected the absolute predicted peak loads to some extent, as expected for cohesive-zone models, but did not change the relative ranking of the damage categories or the distinction between localized and widespread delamination. Therefore, the numerical results are interpreted primarily in terms of relative trends and stress redistribution mechanisms rather than exact pointwise stress values. A full systematic mesh-convergence study was not performed and is considered a limitation of the present model.

The initiation and propagation of damage within both the adhesive

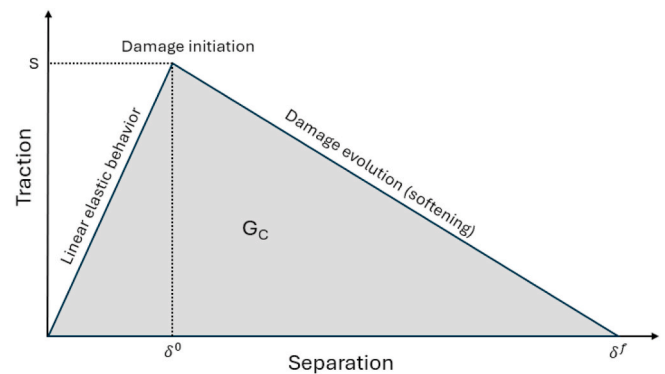


Fig. 3. Bilinear traction–separation law used for the cohesive zone model, illustrating the linear-elastic response, damage initiation, progressive softening, and complete failure governed by the critical strain energy release rate.

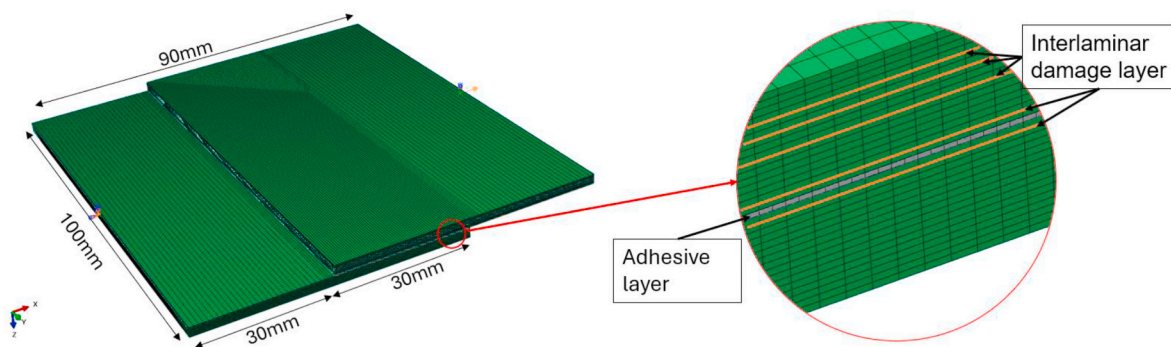


Fig. 2. Schematic representation of the finite element model of the single-lap joint, illustrating the reduced free length, oriented laminate plies, interlaminar cohesive interfaces, and the adhesive layer modeled using cohesive zone elements.

layer and the interlaminar interfaces were modeled using a cohesive zone model (CZM) with a bilinear traction–separation law (TSL), as illustrated in Fig. 3. The TSL comprises an initial linear-elastic response, which signifies the undamaged interface ($D = 0$), succeeded by a softening regime once damage initiation occurs. In this regime, stiffness undergoes a progressive degradation ($0 < D < 1$), while the element persists in transferring load at a diminished level. A complete failure is achieved when the area under the traction–separation curve is equivalent to the critical strain energy release rate. At this juncture, the damage variable reaches $D = 1$, and the cohesive element is no longer capable of load-bearing [24].

The initiation of damage was governed by the quadratic nominal stress criterion, which accounts for the interaction of normal and shear stresses at the interface. The initiation of damage is contingent upon the fulfillment of the following condition:

$$\left(\frac{\langle \sigma_n \rangle}{S_n}\right)^2 + \left(\frac{\sigma_s}{S_s}\right)^2 + \left(\frac{\sigma_t}{S_t}\right)^2 = 1$$

In this formulation σ_n , σ_s , and σ_t denote the current nominal stresses in the normal and the two shear directions, respectively. S_n , S_s , and S_t represent the peak nominal stress values under pure normal or pure shear loading. The Macaulay bracket $\langle \rangle$ ensures that compressive normal stresses do not contribute to damage initiation, i.e., damage does not initiate under pure compression [25].

For mixed-mode loading conditions, the evolution of damage was controlled using the Benzeggagh–Kenane (BK) criterion, which defines the effective critical strain energy release rate as a function of the mode mixity:

$$G_{Tc} = G_{Ic} + (G_{IIc} - G_{Ic}) \left(\frac{G_{II}}{G_T}\right)^\eta$$

with

$$G_T = G_I + G_{II}$$

G_{Ic} and G_{IIc} denote the critical strain energy release rates for Mode I and Mode II loading, respectively. G_{Tc} represents the total critical strain energy release rate under mixed-mode conditions, η is an experimentally determined exponent that controls the relative contribution of shear-dominated failure modes [26].

Pre-existing damage observed in experimental settings was incorporated into the model through the selective removal of cohesive zone elements within the affected regions of the adhesive layer and the interlaminar interfaces. The delaminated areas identified by ultrasonic inspection were represented by fully deleted cohesive elements, ensuring that no load transfer could occur across these damaged regions at the start of the simulation. This approach allows the influence of individual damage characteristics—such as delamination extent, adhesive cracking, and their spatial distribution—to be assessed independently and in combination.

The elastic properties of the unidirectional T700/LMPAEEK lamina were obtained from the NCAMP test report [27] and are summarized in Table 1. The values for strength [27] and critical strain energy release rates [28] for interlaminar failure and adhesive failure are enumerated in Table 2. The interfacial strength values for the adhesive bond are assumed values based on preliminary simulations and literature ranges. Strength parameters of the adhesive cohesive law were not determined independently and therefore represent assumed model parameters. During model calibration, additional trial simulations with varied adhesive strength values were performed. These variations showed that

Table 2

Strength parameters and critical strain energy release rates used for cohesive zone modelling of interlaminar and adhesive failure; with * marked values are assumed values based on preliminary simulations and literature ranges.

	S_n [MPa]	S_s [MPa]	S_t [MPa]	G_{Ic}	G_{IIc}
interlaminar failure [27,28]	61	96.5	96.5	2.1	2.6
adhesive failure	70*	48*	48*	3.23	3.99

the assumed cohesive strengths influence the absolute predicted fracture strength, as expected for a cohesive-zone formulation. However, the relative ranking of the investigated damage configurations and the distinction between localized and widespread delamination remained unchanged. The numerical results are therefore interpreted primarily with respect to relative trends and damage-mechanism identification rather than as an exact prediction of absolute joint strength. The critical energy release rates for the adhesive layer were determined through experimental methods in accordance with the standards established by ASTM D5528 for Mode I and ASTM D7905 for Mode II loading.

3. Results and discussion

3.1. Experimental results

3.1.1. Low-velocity impact damage characteristics

Low-velocity impact testing revealed distinct impact-induced damage characteristics that can be classified into two main categories: localized delamination dominated damage, and widespread delamination dominated damage. Within these main categories, six damage categories were identified, each representing a progressive stage of damage with increasing impact energy. The classification was based on ultrasonic C-scan and B-scan information rather than on impact energy alone. The projected delamination area was determined from the C-scan images, whereas the affected adherend, the through-thickness position of delamination, and the interaction with the overlap edge were assessed from B-scan and time-of-flight information. Six recurring damage morphologies were identified. The six resulting categories and the classification criteria are summarized in Table 3. Fig. 4 summarizes representative ultrasonic C-scan images and projected delamination areas for all damage categories.

At lower impact energies between 15 J and 18.9 J, the dominant damage morphology was localized central delamination (LCD). These damage states were characterized by small projected delamination areas ranging from 48 mm² to 81 mm² and were confined strictly to the upper adherend on the impact side. The delaminations were confined to the

Table 3

Quantitative and morphological criteria used for classification of impact damage categories.

Category	Projected delamination area [mm ²]	Affected adherend	Lateral position
LCD	48–81	upper	central
LOCD	185–253	upper	overlap-confined
LOCDI	287–330	upper	overlap-confined + interface-near
OSWD	1398–1442	both	widespread
OSWD + LOCD	1370–1675	both	widespread + local overlap-confined
DSWD + LOCD	2118–2159	both	widespread both sides + LOCD

Table 1

Elastic properties of the unidirectional T700/LMPAEEK composite lamina [27].

E_{11} [GPa]	E_{22} [GPa]	E_{33} [GPa]	ν_{12}	ν_{13}	ν_{23}	G_{12} [GPa]	G_{13} [GPa]	G_{23} [GPa]
130	9.1	9.1	0.337	0.337	0.487	4.65	4.65	3.06

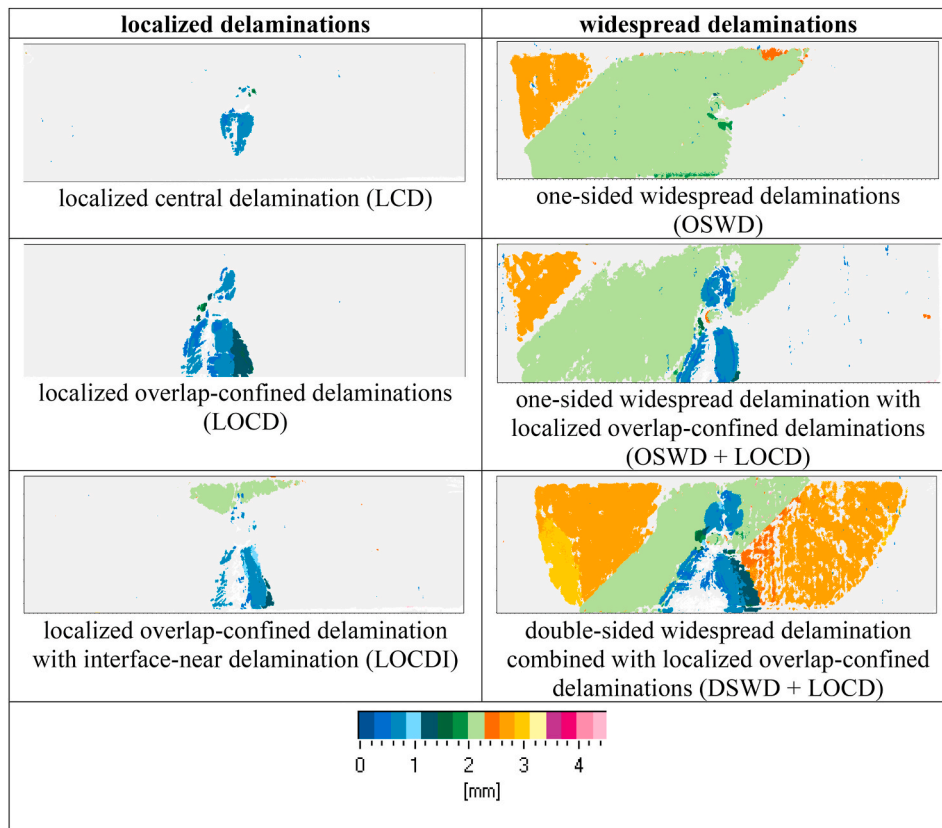


Fig. 4. Representative ultrasonic C-scan images of the overlap area for the six damage categories defined according to the classification criteria in [Table 3](#).

upper half of the laminate thickness and were fully detached from the overlap edges. This indicates a purely impact-centered damage mechanism, independent of joint geometry. No damage was detected near the overlap boundaries, and the adhesive layer remained intact.

The second category of damage, caused by impact energies of 15 J to 21 J, are localized overlap-confined delaminations (LOCD). In this category, the projected delamination area increased significantly, reaching values between 185 mm² and 253 mm². While the delamination remained restricted to the upper adherend on the impact side, its lateral extent was now clearly constrained by the adherend termination at the overlap end. This transition indicates an increasing influence of joint geometry on damage development because the overlap boundary limits further delamination growth toward the joint interior.

At impact energies between 18.5 and 21 J, a more complex localized damage configuration referred to as localized overlap-confined

delamination with interface-near delamination (LOCIDI) was observed. These damage states exhibited projected delamination areas between 287 and 330 mm² and combined the characteristics of LOCD with an additional independent delamination zone near the overlap end. In addition to overlap-confined delamination in the upper adherend, a second delamination formed between the last (45°) and penultimate (0°) plies of the upper adherend, close to the adhesive interface. Importantly, this delamination occurred entirely within the laminate, and no adhesive failure was observed. The presence of two distinct delamination zones above the adhesive layer is clearly visible in the longitudinal B-scan shown in [Fig. 5](#). The through-thickness positions of these delaminations were independently confirmed by complementary CT scans.

The first type of damage in the second main category is referred to as one-sided widespread delaminations (OSWD). These are caused by impact energies in the range of 18.7 J to 23 J. These damage states were

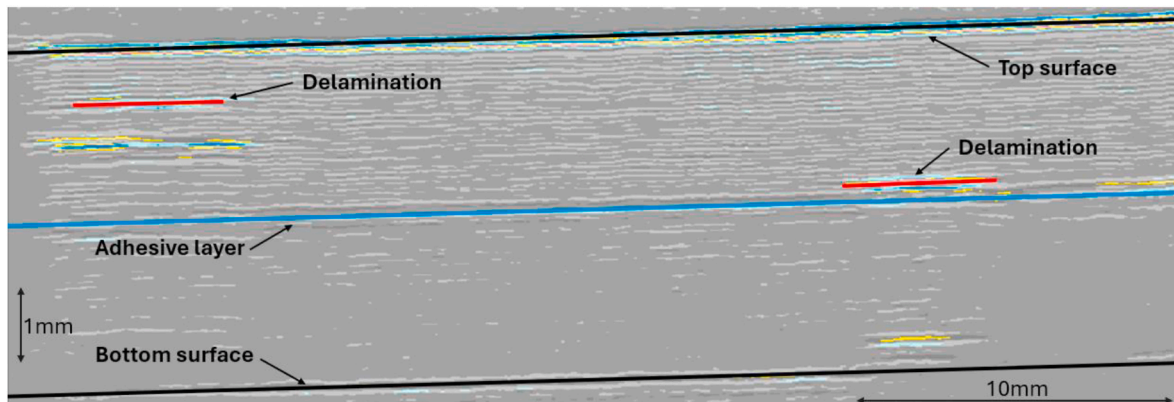


Fig. 5. Ultrasonic B-scan through the overlap region showing two distinct interlaminar delamination zones above the adhesive layer for the LOCIDI damage category.

characterized by large projected delamination areas ranging from 1398 mm² to 1442 mm². Unlike the localized damage regimes, the delaminations extended over a large portion of the overlap region and occurred in both adherends. However, delamination was confined to specific interlaminar interfaces: between plies 15 and 16 in the upper adherend and between plies one and two in the lower adherend. Despite the extensive interlaminar damage, the adhesive layer remained intact.

In an intermediate impact energy range of 19 J to 21 J, a combined damage morphology consisting of one-sided widespread delamination combined with localized overlap-confined delaminations (OSWD + LOCD) was identified. This damage state exhibited a projected delamination area between 1370 mm² and 1675 mm² and was characterized by widespread interlaminar delamination in both adherends accompanied by additional localized delamination near the overlap end. The localized component closely resembled the LOCD morphology observed at lower impact energies, indicating a superposition of localized and global damage mechanisms.

At the highest impact energies investigated, between 21 J and 22.8 J, the most severe damage configuration was observed. It was classified as double-sided widespread delamination combined with localized overlap-confined delaminations (DSWD + LOCD). These damage states exhibited the largest projected delamination areas, ranging from 2118 mm² to 2159 mm². Extensive interlaminar delamination developed in both the upper and lower adherends, predominantly between plies 15 and 16 in the upper adherend and between plies one and two in the lower adherend. Simultaneously, localized overlap-confined delaminations were present near the overlap end. Even under these severe impact conditions, no failure of the adhesive layer was detected.

Across all the damage categories investigated, no adhesive-layer detachment or interfacial debonding between adhesive and adherend was detected. This observation is supported by the representative cross-section shown in Fig. 6, where the adhesive layer remains continuous at the investigated section. However, small, isolated cracks within the adhesive layer were visible in the cross-section. Therefore, the impact-induced damage was classified as predominantly laminate-dominated interlaminar delamination rather than bondline detachment.

All localized delaminations were confined to the upper adherend on the impact side, with no localized damage detected in the lower adherend. Widespread delamination always occurred at well-defined interlaminar interfaces: between plies 15 (0°) and 16 (45°) in the upper adherend, and between plies one (45°) and two (0°) in the lower adherend, as shown in Fig. 7. No delamination was observed at deeper

interfaces within the lower adherend, regardless of impact energy. These consistent features suggest that laminate architecture and joint geometry strongly influence damage manifestation.

Fig. 8 shows the projected delamination area as a function of impact energy for all impacted specimens. The data show a general increase in delamination area with increasing impact energy, but the relationship is not strictly linear. It is important to note that the impact energy ranges of the damage categories exhibit partial overlap. This discrepancy can be attributed to the utilization of nominal impact energy as the loading input, while the classification was based on the damage morphology observed through ultrasonic inspection. The same nominal impact energy does not necessarily lead to the same internal damage state, since the damage evolution is affected by local variations in laminate consolidation, adhesive thickness, support and clamping conditions, and the exact interaction of the impact-induced bending field with the overlap edge. Additionally, the nominal impact energy is not equivalent to the energy dissipated by damage formation; different portions of the input energy may be stored elastically, dissipated by contact and friction, or returned during rebound. Consequently, analogous impact energies can stimulate disparate interlaminar interfaces, culminating in varied delamination morphologies. This observation lends further support to the utilization of NDT-based damage morphology as a foundation for residual strength assessment, superseding the conventional reliance on impact energy alone.

3.1.2. Residual strength and failure behavior of SLJs

The findings from the quasi-static single-lap shear tests demonstrated a discernible correlation between residual joint strength, the extent of impact-induced delamination, and the concomitant strain and deformation fields. When the measured fracture strengths were plotted as a function of the projected delamination area, as shown in Fig. 9, the results could be distinctly divided into two non-overlapping strength levels.

The first level includes all reference specimens without prior impact damage, along with all specimens manifesting localized damage states, including localized LCD, LOCD and LOCDI. All specimens within this group exhibited fracture strengths exceeding 30 MPa, and no significant reduction in strength was observed compared to the undamaged reference joints. This finding suggests that localized delamination, even when occurring near the overlap region, does not adversely affect the global load-carrying capacity of the joint.

In contrast, the second level consisted exclusively of specimens with

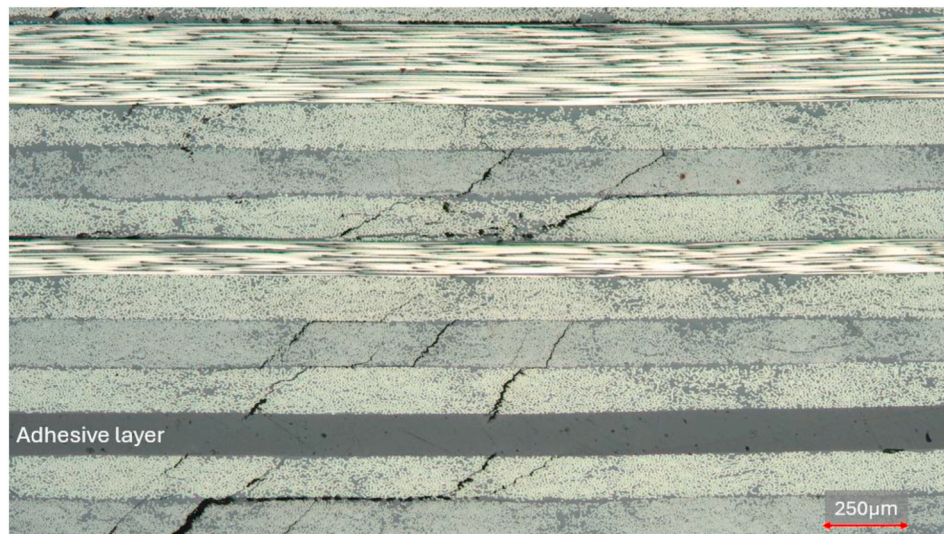


Fig. 6. Representative cross-section of a severely impacted single-lap joint after low-velocity impact. Interlaminar delamination is visible within the composite adherend. The adhesive layer remains continuous at the investigated section, with no interfacial debonding, although small, isolated cracks within the adhesive layer are visible.

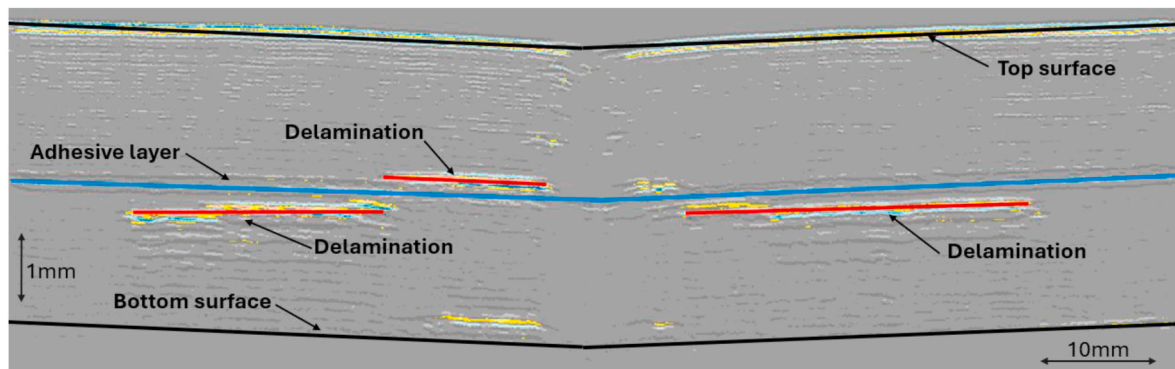


Fig. 7. Ultrasonic B-scan across the overlap region showing distinct interlaminar delamination areas for the DSWD + LOCDI damage category.

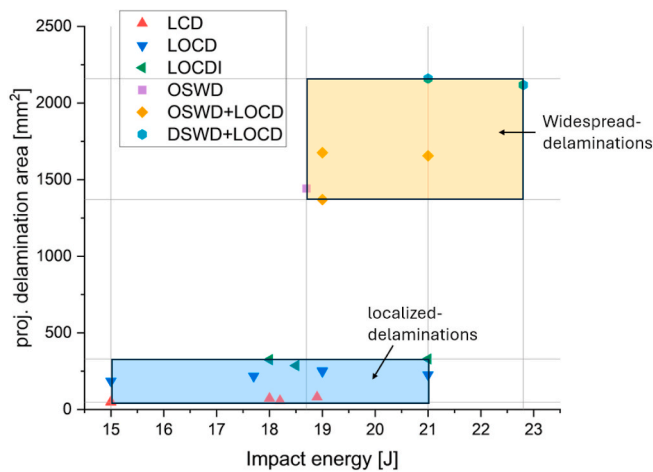


Fig. 8. Projected delamination area as a function of impact energy for all impacted specimens. Symbols indicate the assigned damage categories.

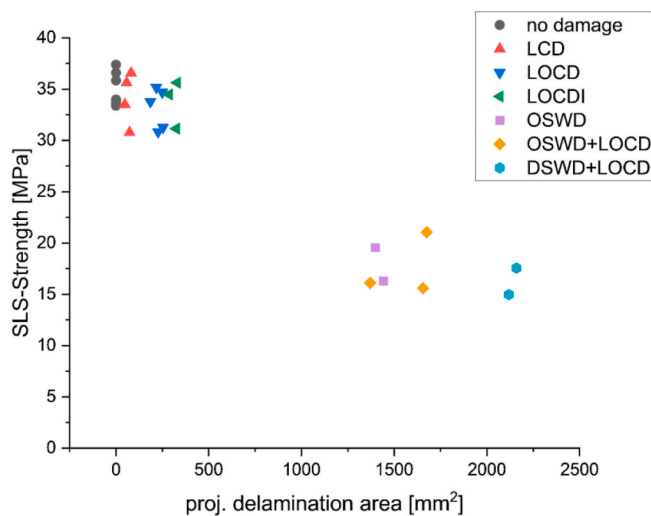


Fig. 9. Residual single-lap shear strength as a function of the projected delamination area for all investigated damage categories.

widespread delamination, namely OSDW, OSDW combined with LOCD, and DSWD combined with LOCD. All specimens within this group exhibited fracture strengths below 21 MPa, representing a significant reduction compared to both the reference specimens and the locally damaged joints. It is noteworthy that no fracture strength values were documented within the intermediate range of 21 to 30 MPa. According

to the experimental separation, the transition between damage-tolerant and damage-critical states was defined quantitatively for the configuration that was investigated. Damage-tolerant states are defined as those that retain residual shear strengths above 30 MPa, which corresponds to the strength range of undamaged and locally damaged specimens. Damage-critical states are defined as those with residual shear strengths below 21 MPa, which corresponds to widespread delamination and a strength reduction of approximately 49–54% relative to the undamaged reference configuration. The range between 21 and 30 MPa thus signifies the experimentally observed transition interval, wherein no specimens were identified.

This clear separation into two strength levels was further reflected in the full-field strain measurements obtained by DIC. Representative longitudinal strain distributions and out-of-plane displacement fields for selected specimens from both groups, as well as a reference specimen, are shown in Fig. 10. For the reference specimen, both the longitudinal strain and the out-of-plane displacement exhibited uniform distribution across the entire specimen width. This finding suggests that stable and symmetric load transfer occurred through the overlap region.

Specimens exhibiting localized delamination demonstrated local deviations in the longitudinal strain field around the damage area, while the overall strain distribution across the specimen width remained largely homogeneous. Specifically, the out-of-plane displacement field demonstrated a distribution analogous to that observed in the reference specimens, indicating that localized delamination did not substantially affect the global deformation behavior of the joint.

Specimens containing widespread delamination exhibited a divergent deformation response. These specimens exhibited pronounced heterogeneity in both the longitudinal strain distribution and the out-of-plane displacement across the specimen width. The non-uniform through-thickness displacement indicates a redistribution of bending and shear deformation within the overlap region, which can lead to local stress concentrations and promote premature failure.

The distinction between the two strength levels was also reflected in the fracture surface characteristics, as illustrated in Fig. 11. Reference specimens and specimens with localized damage predominantly exhibited cohesive failure within the adhesive layer at the overlap ends, often accompanied by mixed-mode failure and limited substrate-related failure near the adhesive-substrate interface in the remaining overlap region. In contrast, specimens with widespread delamination exhibited failure that was predominantly characterized by substrate fracture within the composite adherends, primarily at locations coinciding with pre-existing delamination planes, with only minor contributions from cohesive or mixed adhesive failure. These fracture patterns further corroborate the hypothesis that widespread interlaminar delamination fundamentally alters the load transfer mechanism and governs the residual strength of the joint.

The collective analysis of fracture strength, full-field deformation behavior, and fracture surface morphology demonstrates that localized

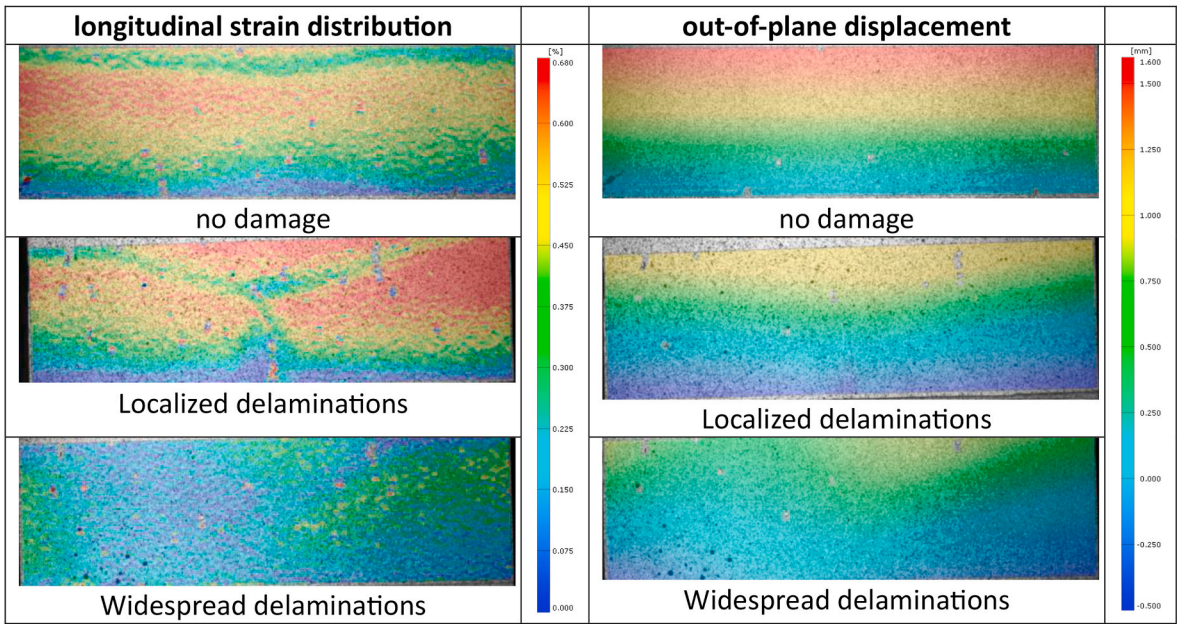


Fig. 10. Longitudinal strain fields and out-of-plane displacement distributions obtained by DIC for selected specimens, illustrating the fundamentally different deformation behavior of locally damaged and widespread-delaminated joints.

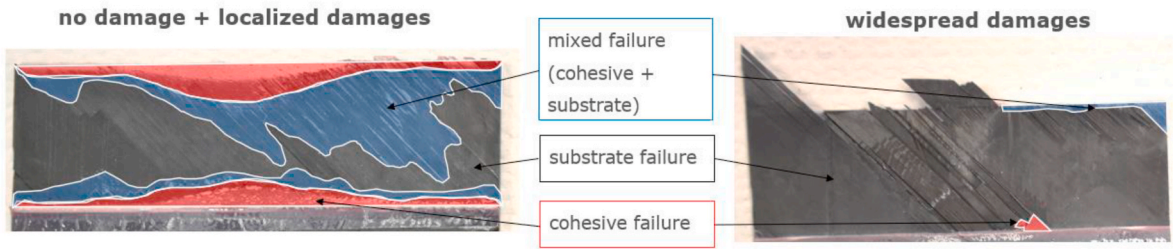


Fig. 11. Comparison of fracture surface characteristics for locally damaged and widely delaminated single-lap joints after shear loading.

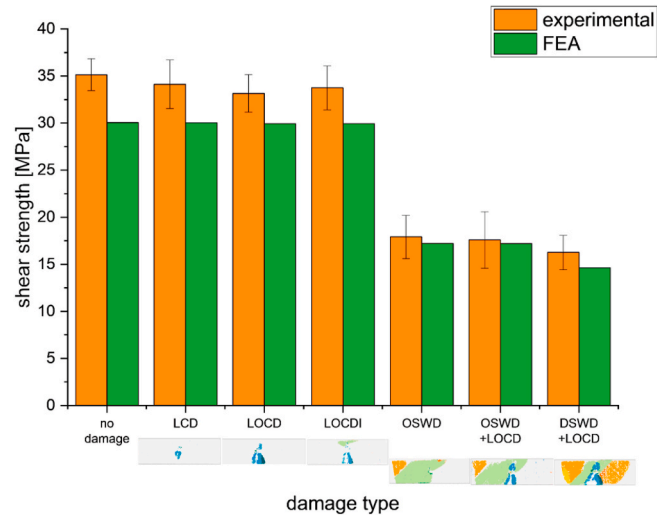


Fig. 12. Comparison of experimental and numerical fracture strengths for all investigated damage categories.

impact-induced delamination does not significantly reduce the bond strength. Whereas widespread interlaminar delamination represents a critical damage state that leads to a drastic reduction in load-carrying capacity.

3.2. Numerical results

The numerical simulations reproduced the main trends observed in the experimental single-lap shear tests and provided additional insight into the influence of different impact-induced damage states on the residual joint strength and global stiffness. In general, the finite element analysis (FEA) yielded slightly lower fracture strengths compared to the experimentally measured values. This deviation was consistently observed for all damage categories as well as for the undamaged reference configuration, indicating a systematic but conservative prediction of joint strength rather than damage-specific discrepancies. A direct

Table 4
Summary of experimentally measured and numerically predicted fracture strength reductions relative to the undamaged reference configuration for all investigated damage categories.

Damage category	Experimental mean value	FEA
Localized Central Delamination (LCD)	-2,90%	-0,09%
Localized Overlap-confined Delamination (LOCD)	-5,64%	-0,37%
Localized Overlap-confined Delamination + Interface near (LOCDI)	-3,96%	-0,36%
One-sided Widespread Delamination (OSWD)	-49,02%	-42,68%
One-sided Widespread Delamination + LOCD	-49,96%	-42,75%
Double-sided Widespread Delamination + LOCD (DSWD + LOCD)	-53,73%	-51,29%

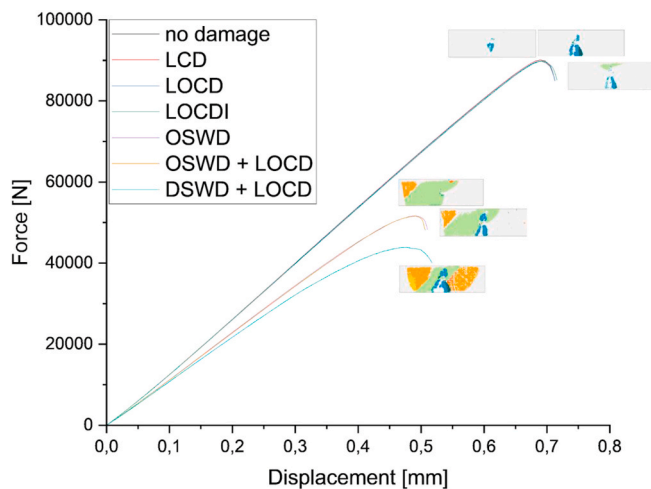


Fig. 13. Representative force–displacement curves obtained from FEA for all configurations, highlighting the influence of damage extent on global joint stiffness.

comparison of the fracture strengths obtained from experiments and simulations for all the damage categories investigated is presented in Fig. 12. Notwithstanding the systematic underestimation, the numerical results accurately reflected the relative ranking of the damage categories and the distinct separation between damage-tolerant and damage-critical states. Specifically, the simulations indicated that there would be no substantial decrease in fracture strength for joints exhibiting localized delamination, which is consistent with the experimental observations.

Conversely, the numerical outcomes exhibited a significant reduction in fracture strength for joints exhibiting extensive interlaminar delamination, consistent with the experimental observations. In comparison with the reference configuration, all damage categories exhibiting large-area delamination demonstrated a significant reduction in load-bearing capacity. The magnitude of the strength reduction predicted by the simulations closely followed the experimental trend, thereby supporting the validity of the damage representation strategy employed in the finite element model. A quantitative summary of the fracture strength reductions for the individual damage categories is provided in Table 4.

Further insight into the mechanical response of the joints was obtained from the force–displacement curves, as shown in Fig. 13. For the reference configuration and joints with localized delamination, the numerical results indicated nearly identical initial stiffness and overall force–displacement behavior. This demonstrates that localized damage does not significantly affect the global stiffness of the joint. In such instances, the load transfer mechanism within the overlap region exhibited minimal alterations.

Conversely, joints exhibiting widespread delamination demonstrated a marked decrease in global stiffness, which became apparent at the initial stages of loading. The simulations further revealed that the stiffness degradation was more pronounced for double-sided widespread delamination than for one-sided delamination, indicating a stronger disruption of load transfer.

At the maximum applied load, the FEA provides detailed insight into the shear and peel stress distributions within the adhesive layer for the reference configuration and all investigated impact damage categories. Fig. 14 compares the shear and peel stress distributions in the adhesive layer at maximum load.

The undamaged reference joint exhibits the characteristic SLJ stress state, with elevated shear and peel stress near the overlap ends and lower peel stress in the overlap center.

A comparable overall stress distribution is observed for specimens

exhibiting localized delamination. In such instances, the global shear stress pattern remains predominantly unaltered in comparison to the reference configuration, with peak shear stresses persisting in proximity to the overlap ends. Local irregularities in the shear stress field can be identified around the delaminated regions. However, these remain spatially confined and do not significantly affect the overall stress distribution across the adhesive layer. In a similar manner, the peel stress distributions for these damage categories remain comparable to the reference case, exhibiting only minor local deviations near the delamination area.

In contrast, specimens exhibiting widespread interlaminar delamination exhibit a fundamentally altered stress state within the adhesive layer. For these damage configurations, the shear stress distribution becomes highly non-uniform, with extensive regions of reduced shear stress interspersed with localized zones of elevated stress. This phenomenon results in a considerable reduction in the effective load transfer through the adhesive layer. The peel stress distributions for the widespread damage categories reveal an even more pronounced change in behavior. In contrast to the uniform and symmetrical peel stress profile exhibited by the reference and localized damage cases, the adhesive layer shows significant spatial variations in peel stress, containing localized tensile and compressive regions distributed across the overlap width. These variations are indicative of altered bending kinematics and asymmetric deformation of the adherends caused by extensive delamination. The resulting peel stress concentrations provide a plausible explanation for the premature failure observed experimentally for these damage categories.

To further investigate the influence of delamination characteristics on the residual strength of adhesively bonded single-lap joints, a generic numerical damage study was performed. In this study, delaminations of controlled size were introduced at selected through-thickness positions within the upper adherend. The damage configuration was based on the experimentally observed widespread delamination morphology and systematically varied in terms of both delamination size and damage plane location.

Four different delamination sizes were considered, corresponding to projected areas of 304 mm², 598 mm², 897 mm² and 1197 mm². These delaminations were introduced at three distinct interlaminar interfaces, namely between plies 4-5, 9-10, and 15-16 of the upper adherend, representing increasing proximity to the adhesive layer.

The resulting fracture strengths obtained from the finite element simulations are presented in Fig. 15. For delaminations located between the 4th and 5th ply, the predicted fracture strength remained essentially unchanged for all investigated delamination sizes, with strength reductions below 1%. When the delamination was shifted towards the laminate mid-plane, between the 9th and 10th ply, the influence increased slightly but remained limited. For increasing projected delamination areas, the predicted strength reductions were 0.24%, 1.36%, 2.42%, and 3.75%, respectively. In contrast, delaminations located close to the adhesive layer, between the 15th and 16th ply, caused a pronounced reduction in residual strength. For the same sequence of increasing delamination areas, the predicted reductions were 6.26%, 18.82%, 29.76%, and 39.24%, respectively.

These results show that the effect of a delamination is governed not only by its projected area but also by its through-thickness position relative to the adhesive layer. Delaminations far from the adhesive layer remain weakly coupled to the adhesive load-transfer region and therefore have only a minor effect on the residual joint strength, even when their projected area is increased. In contrast, delaminations close to the adhesive layer directly affect the local bending stiffness of the adherend and promote adhesive stress redistribution, particularly increased peel stress concentrations. Consequently, smaller delaminations near the adhesive layer can be more critical than larger delaminations located farther away from the load-transfer region.

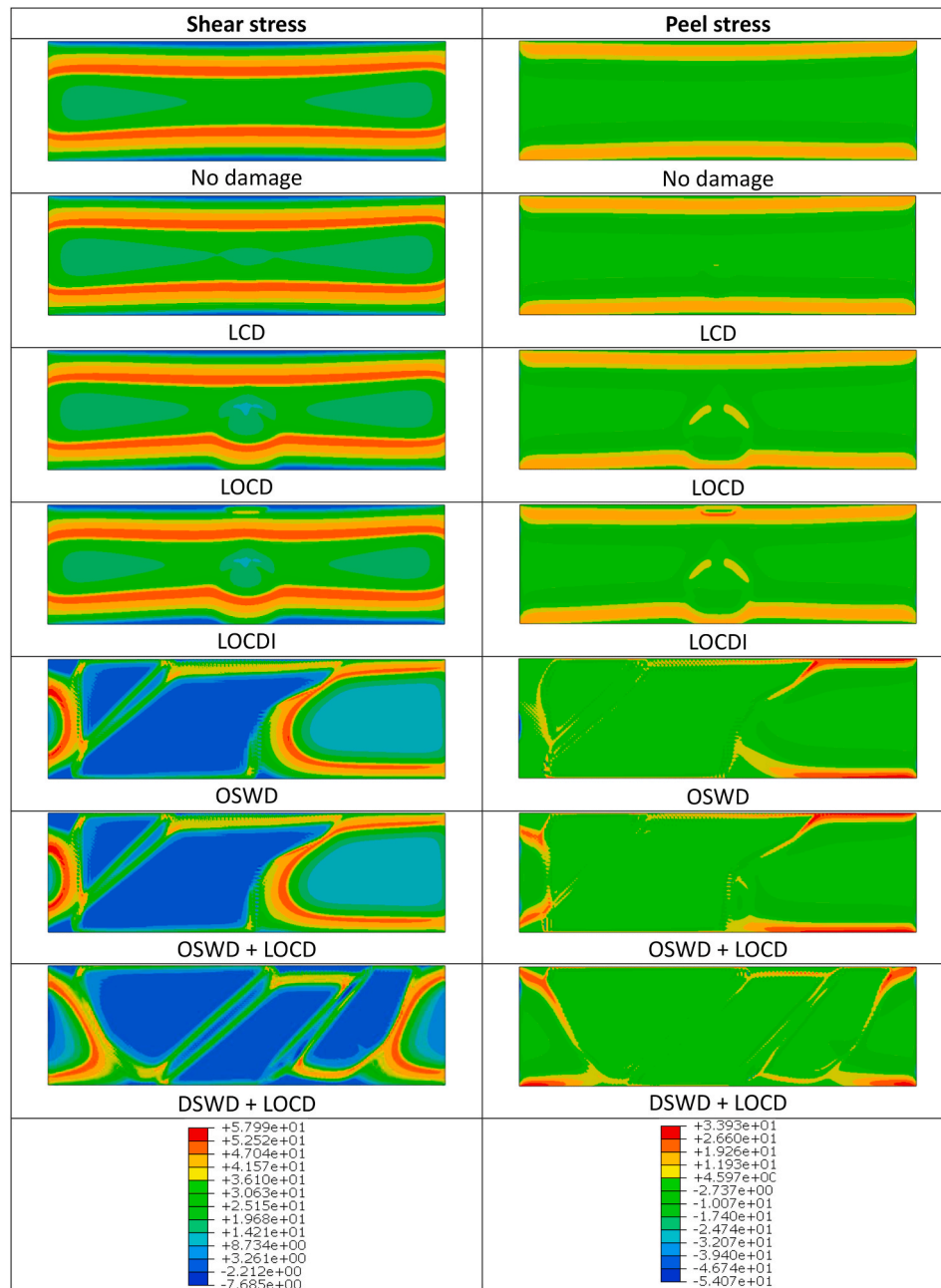


Fig. 14. Finite element results showing the distribution of shear stress (left column) and peel stress (right column) within the adhesive layer at maximum applied load for the reference configuration and all investigated impact damage categories; units in MPa.

3.3. Discussion

The present study provides a comprehensive assessment of the influence of low-velocity impact-induced damage on the residual strength of adhesively bonded single-lap joints with carbon fiber-reinforced high-performance thermoplastic adherends. A clear distinction between damage-tolerant and damage-critical impact scenarios is achieved by combining detailed experimental characterization with validated numerical modelling.

A central outcome of the experimental investigation is the separation of all specimens into two non-overlapping strength levels. Joints exhibiting localized delamination damage (LCD, LOCD, and LOCDI) retain fracture strengths comparable to undamaged reference specimens, whereas joints affected by widespread interlaminar delamination (OSWD, OSWD + LOCD, and DSWD + LOCD) show a pronounced and

abrupt reduction in load-carrying capacity. The absence of intermediate strength values indicates a threshold-type behavior rather than a gradual degradation with increasing damage extent. The quantitative strength threshold corresponds to a morphological transition from localized delamination to widespread interlaminar delamination. In the present configuration, localized delamination with projected areas up to 330 mm² remained damage-tolerant, whereas widespread delamination with projected areas of approximately 1370 mm² and above led to damage-critical behavior. However, a generic numerical study indicates that the delamination area alone is not sufficient to define criticality. The through-thickness position relative to the adhesive layer and the associated disturbance of the load path are decisive. This behavior is explained by the full-field DIC measurements. For reference specimens and joints with localized damage, the longitudinal strain and out-of-plane displacement fields remain largely homogeneous, indicating

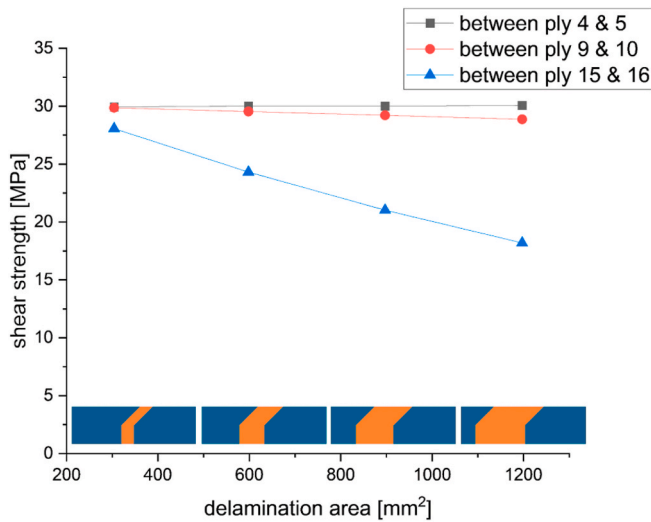


Fig. 15. Effect of generic delamination size and location on the numerically predicted residual shear strength of the single-lap joint.

preserved global load transfer. In contrast, widespread delamination results in heterogeneous strain distributions and pronounced out-of-plane displacement gradients, reflecting altered bending kinematics and local stress concentrations that promote premature failure.

The numerical simulations corroborate these findings by linking the experimentally observed strength reduction to adhesive stress redistribution. For localized damage states, the shear and peel stress distributions remain close to the reference configuration, preserving the characteristic shear-dominated load transfer with localized peel stresses at the overlap ends. In contrast, widespread delamination produces a highly non-uniform shear stress distribution and a strongly asymmetric peel stress field. This indicates a loss of effective load transfer and a transition towards bending- and peel-dominated loading caused by reduced bending stiffness and asymmetric deformation of the delaminated adherends. These numerically predicted stress concentrations are consistent with the experimentally observed early failure of widespread damage states and the pronounced reduction in residual strength. They indicate that the pre-existing delaminations did not need to involve direct adhesive-layer damage during impact to become critical; instead, they promoted local adhesive stress amplification during subsequent tensile loading. The resulting peel- and shear-stress concentrations therefore provide the mechanical link between the impact-induced laminate delaminations and the final experimental failure under quasi-static loading.

The model reproduced the experimental ranking of the damage categories and the clear separation between localized and widespread delamination but systematically underestimated the absolute fracture strengths. This discrepancy is attributed to modelling idealizations, including assumed adhesive cohesive strengths, idealized delamination representation by deleted cohesive elements, neglected contact or friction between closed delamination surfaces, possible mesh sensitivity of local cohesive stress peaks near delamination boundaries, and linearly elastic adherend plies. Accordingly, local stress maxima are discussed qualitatively with respect to stress redistribution, whereas the main numerical conclusions are based on global trends and relative differences between damage configurations. The assumed adhesive strengths directly affect cohesive damage initiation and therefore the absolute peak load; however, parameter variations during model calibration changed the predicted peak loads without altering the relative separation between damage categories. Since the same modelling assumptions were applied consistently to all configurations, the simulations are interpreted primarily in terms of relative trends, stress redistribution, and damage-mechanism identification rather than exact absolute

strength prediction.

Across all damage categories investigated, no failure of the adhesive joint occurred during impact. The reduction in joint strength is therefore not governed by bondline failure, but by delamination-induced changes in global load transfer and bending behavior, which impose unfavorable peel-dominated stress states on an otherwise intact adhesive layer.

The combined experimental and numerical results show that projected delamination area alone is insufficient to assess damage criticality. For the investigated joints, the structural relevance of impact damage is governed by the combined effect of lateral extent, through-thickness position, affected adherend, local bending stiffness loss, and interaction with the overlap edge. Delaminations located far from the adhesive layer remain weakly coupled to the critical load-transfer region and mainly affect local laminate stiffness. In contrast, delaminations close to the adhesive layer or extending into both adherends reduce bending stiffness, promote asymmetric out-of-plane deformation, and amplify peel and shear stresses in the adhesive layer. From a design perspective, damage evaluation should therefore consider both the spatial extent and through-thickness position of delamination relative to the adhesive load path, rather than relying on projected C-scan area or impact energy alone.

4. Conclusions

The present study examined the effect of low-velocity impact-induced damage on the residual performance of adhesively bonded single-lap joints with carbon fiber-reinforced high-performance thermoplastic adherends. A comprehensive approach encompassing experimental testing, damage characterization, finite element modelling, and a complementary generic numerical damage study was employed to establish a clear distinction between damage-tolerant and damage-critical impact scenarios.

The experimental findings demonstrate that impact damage does not result in a gradual degradation of joint strength. In contrast, the joints manifest two distinct strength levels that do not overlap. Localized delamination damage, including localized central delaminations, localized overlap-confined delaminations, and localized overlap-confined delaminations with interface-near delamination, does not lead to a measurable reduction in residual single-lap shear strength compared to undamaged reference specimens. Conversely, damage conditions characterized by widespread delamination lead to a significant and rapid decline in load-bearing capacity without any identifiable intermediate strength levels.

DIC measurements confirmed this distinction: localized delamination caused only local strain perturbations, whereas widespread delamination produced heterogeneous strain fields and pronounced out-of-plane displacement gradients, indicating disturbed load transfer and premature failure.

Across all categories of damage that were the focus of the investigation, the adhesive layer did not fail during impact. The adhesive integrity was maintained even under conditions of severe impact. Consequently, the reduction in residual joint strength is not governed by adhesive failure but by delamination-induced changes in global load transfer and bending behavior. These changes impose unfavorable peel-dominated stress states on an otherwise intact adhesive layer.

The numerical simulations reproduced the experimental ranking of damage categories and captured the transition from damage-tolerant to damage-critical states. Although absolute strengths were slightly underestimated, the simulations showed that widespread delamination causes substantial shear and peel stress redistribution in the adhesive layer.

The generic finite element investigation further demonstrates that delamination size alone is not a reliable indicator of residual joint strength. Delaminations located in structurally less relevant laminate regions have only a minor influence on load-carrying capacity, even at large projected areas. Conversely, delaminations occurring in proximity

to the adhesive layer, particularly at interlaminar interfaces adjacent to the outer plies, result in substantial strength reductions, even in cases of moderate damage sizes. This identifies the through-thickness position of delamination relative to the adhesive layer as the dominant parameter controlling joint failure.

In essence, the present study offers a systematic damage–strength correlation for adhesively bonded single-lap joints with carbon fiber-reinforced high-performance thermoplastic adherends under low-velocity impact. The findings expand the scope of established concepts from thermoset-based composite joints to thermoplastic systems. They demonstrate that CF-TP joints exhibit tolerance to localized impact damage but sensitivity to widespread interlaminar delamination intersecting structurally relevant load paths. These findings lend support to damage-tolerant design and assessment approaches that prioritize delamination extent and location over impact energy or visible surface damage.

Future work should focus on extending the present findings towards a comprehensive assessment of structural integrity and damage tolerance of adhesively bonded CF-TP joints. In particular, the interaction of impact-induced damage with fatigue loading, temperature effects, and environmental influences should be investigated, as these factors are expected to significantly affect the evolution of delamination and the long-term load-carrying capacity. Furthermore, the identified damage–strength relationships should be expanded towards a damage tolerance framework, enabling the definition of allowable damage limits and inspection criteria for structural applications.

From a numerical perspective, future developments should include the incorporation of intralaminar damage mechanisms in addition to interlaminar failure, to capture the full spectrum of damage evolution and failure processes in CF-TP laminates. Such extensions will enable a more comprehensive prediction of damage progression and its impact on residual strength. Overall, these efforts will contribute to a more complete understanding of the structural integrity of impact-damaged thermoplastic composite joints and support the development of reliable design and certification approaches.

Declaration of competing interests

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.

Data availability

Data will be made available on request.

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