Quasi-static and dynamic performance of novel interlocked hybrid metal-composite joints

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A B S T R A C T
This study presents a novel hybrid technique for joining composites to metal, employing an array of macro-scale interlocking features on the faying surfaces of adhesively bonded adherends. Single-lap, interlocking adhesive joints (IAJs) and baseline adhesive joints (BAJs), are tested at quasi-static and transient dynamic (0.5 m/s and 3 m/s) loading rates. The joint deformation mechanisms are examined and fractography analysis is performed at the macro and micro scales. Results indicate a 10% increase in lap-shear strength, and 75–120% increase in work to failure for the IAJs compared to the BAJs, at all loading rates. In addition, IAJs exhibit improved damage tolerance compared to adhesive joints, due to reduced joint rotation, more stable adhesive fracture growth, and the ability to sustain load even after cracks have propagated through the adhesive at the ends of the overlap region. The high energy absorption capacity (23–38 J) of IAJs indicates they could be used to significantly improve the crashworthiness performance of multi-material transportation structures.

1. Introduction

The European Union has a roadmap to realise a competitive, resource-efficient, and safe transportation system, that will reduce greenhouse gas emissions by 20% (based on that observed in 2008) and halve the number of road causalities (based on that observed in 2018) by 2030 [1,2]. This highlights the importance of lightweight, but also crashworthy transportation structures. Carbon fibre-reinforced polymer (CFRP) composites are ideal candidates for such applications due to their excellent specific mechanical properties. While more than 75% of CFRPs are manufactured using a thermoset matrix, the transportation industry is increasingly adopting thermoplastic composites due to their short processing cycles, high fracture toughness, unlimited shelf-life, good solvent resistance, and inherent recyclability. However, fully composite automobile structures are considered too costly and slow to produce, so multi-material designs currently offer the most viable solution to lightweighting and crashworthiness. Reliably joining composites, particularly low surface energy thermoplastic matrix composites, to metals though, presents a considerable challenge.

Mechanical fastening, i.e. bolting or riveting, and adhesive bonding are widely used to join dissimilar materials. Mechanical fastening requires drilling, introduces stress concentrations and potential galvanic corrosion, and suffers from low sealing capability as well as a weight penalty. Adhesive bonding presents a different set of challenges, such as consistency of surface preparation, brittle failure, complexity in the choice of chemically compatible adhesives, and environmental ageing. The abrupt failure behaviour of bonded structures has led to consideration of hybrid bonded/bolted joints [3–5], but these retain the shortcomings of mechanical fastening. Welding is another option for joining metals with thermoplastic composites. However, laser or friction-based welding can result in issues like porosity and degradation of the polymer which affect joint strength, and welded joints often have lower stiffness than equivalent adhesively bonded joints [6].

Through-thickness reinforced joining, is a novel technique in which an array of protrusions and cavities are created on the faying surfaces of adherends through surface structuring techniques such as laser or electron beam machining [7–9], additive manufacturing (AM) [10–12], cold-metal transfer (CMT) [10,13], stud welding [10] or chemical etching [14]. Detailed reviews of various through-thickness reinforced metal-composite joints are presented in [15–17]. Studies typically report higher load carrying capacity and energy absorption, and a more progressive failure mode, relative to bonded/co-cured “control” joints. However, most studies employ either titanium or steel as the metal adherend. From weight considerations, it desirable to

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increase the use of aluminium and composites in cars, which calls for research on joining aluminium with composites. Relatively few studies have been undertaken on through-thickness reinforced aluminium to composite joints [10,18,19]. Graham et al. [10] reported that the CMT-welded pins in aluminium-CFRP joints had a propensity to shear at the base, limiting joint performance, while references [10,11] suggested that optimisation of pin geometry can improve performance. Corbett et al. [20] studied interlocking adhesive joints (IAJs) which are the focus of the current study, and optimised the design using three-dimensional finite element models incorporating state-of-the-art material models to represent the aluminium and thermoset composite adherends, and the epoxy adhesive. O’Brien et al. [21] tested miniature metal-metal IAJs, which were optimised via modelling in [22], and reported improvements of up to 27% and 542% in failure load and energy absorption, respectively.

None of the above studies addressed through-thickness reinforced joints between aluminium and thermoplastic composites, despite the obvious advantages for the automotive industry of such a material combination. The current study employs an array of macro-scale interlocking features on the faying surfaces of aluminium and carbon-fibre-reinforced polyamide thermoplastic composite adherends that are bonded using a crash-durable epoxy adhesive, as shown in Fig. 1. The joints are tested at dynamic as well as quasi-static rates, since automotive structures demand joints engineered for dynamic crash loading rates, as well as normal, in-service loading rates. Lap-shear strength and energy absorption are used as performance metrics, and deformation mechanisms and post-failure surfaces are analysed at macro and micro scales. The IAJs are compared to baseline adhesive joints (BAJs) which have no interlocking features.

2. Materials and methods

2.1. Materials

A structural Al-Mg alloy, AA5754-H111 (Aalcob Metals Ltd., 2018), often employed in the automotive industry [23] for its moderate strength and good corrosion resistance, formability and weldability, is selected as the metallic adherend. A stretch-broken textile composite, details of which are shown in Table 1, is selected for the composite adherend, as realigning of the fabric yarns around the interlocking features during manufacturing demands high drapability. A polyamide 12 (PA12) matrix is chosen for its superior properties over polypropylene (PP) and polyethylene (PE) in terms of strength and stiffness, as well as adequate ductility, flexibility, and high-temperature performance. The carbon fibres are co-wrapped with a thin polyamide film and a 2 × 2 twill weaving pattern is used. Commingled/co-wrapped yarns offer the potential for low-cost manufacturing of complex-shaped composite parts and this particular composite material system was successfully investigated for a non-isothermal stamp forming process [24] and compression moulding [25]. The properties of the selected composite material make it attractive for use in the automotive industry. Table 2 summarises the mechanical properties of the adherend materials. A one-component structural epoxy adhesive, Betamate 1496 V (Dow Automotive, USA, 2017), employed in the automotive industry to bond body panels, is used here due to its high stiffness and crash performance.

2.2. Single-lap configuration and adherend manufacture

The single lap joint (SLJ) specimen, illustrated in Fig. 2(a), has an overlap length of 25 mm, in accordance with ASTM D 5868 [26]. A grip-to-grip length of 150 mm was chosen to account for the slack mechanism in the high-speed testing machine [27]. In this study, two SLJ configurations were investigated, namely: (i) the baseline or control adhesive joint (BAJ), with flat faying surfaces, and (ii) the IAJ. The design of the IAJ, shown in Fig. 2(b), was adapted from [20], and has an array of truncated rectangular pyramid-shaped depressions on the faying surface of the composite (‘female’) adherend and corresponding projections on the aluminium (‘male’) adherend. To reduce the asymmetric stress distribution across the overlap caused by the dissimilar adherend materials, as recommended in [28], the adherend thicknesses were selected to balance the longitudinal and bending stiffnesses of the adherends relative to one another, as much as possible. The overlap region of the SLJs does not bend until the damage initiates in the adhesive layer, as the bending stiffness of the overlap is much higher than either adherends. Therefore, the interlocking features in the overlap region of IAJs, are not expected to alter the balance of the adherends’ longitudinal and bending stiffnesses, until the damage initiation. A constant bond line thickness of 0.25 mm was accounted for in the dimensions of the aluminium adherend. To minimise secondary bending due to loading eccentricity, 2 mm thick aluminium spacers were bonded to the adherends (Fig. 2(a)). In addition, to improve specimen gripping in the high-speed test machine, 0.25 mm thick aluminium tabs were also bonded to the adherends (Fig. 2(a)).

Table 3 summarises the cure cycle employed to consolidate the composite panels, containing eight plies, with dimensions of 600 mm × 600 mm × 2.16 mm. For the BAJs, 25 mm wide and 132.5 mm long composite adherends were cut from the panels, using a water-lubricated diamond bladed cutter to ensure defect-free edges, as recommended by ASTM D3039 [28]. Similar-sized flat metal adherends were milled from a 2 mm thick aluminium sheet. Aluminium male adherends for the IAJs were machined from a 4 mm thick aluminium sheet, with a tolerance of ±0.025 mm for all dimensions.

Panels for the composite (‘female’) IAJ adherends were manufactured using a mould-in-manufacturing technique, a method investigated as an alternative to the drilling in [29,30]. A mould-tool with male interlocking features, capable of accommodating five composite adherends, was manufactured through precision milling. Seven layers of the commingled woven fabric (thickness 1.89 mm which is the same as the depth of the features) were preformed around the structures of the mould-tool, and the eighth, non-preformed ply was placed on the top of the preformed plies. The optimised consolidation cycle for the mould-in-manufacturing method (Table 3) was obtained through trial and error, as when the consolidation cycle for flat panels was used for the mould-in panels, significant dry spots were observed in the vicinity.

(a) Interlocking features
(b) Metal
(c) Composite
(d) Adhesive

Fig. 1. Interlocking adhesive joint: (a) composite and metal adherends with interlocking profiles, (b) joint assembly and bonding, (c) assembled joint (metal adherend cutaway to show adhesive).
of depressions. The IAJ composite adherends were water-jet cut from the composite panels.

2.3. Surface pre-treatment and joint specimen preparation

The alkaline etching process recommended in [31] was used for pre-treatment of the metal adherends. For the composite adherends, an optimised alumina grit-blasting procedure described in [32] was employed. The adherends were then bonded in a mould to minimise joint misalignment and to ensure accuracy of the overlapping area. The bondline thickness was controlled by adding 250-µm glass microbeads. Bonding was performed in an oven at 180 °C for 60 min, following the manufacturer’s recommendation [33]. The bondline thickness was found to vary by less than ±10% from the desired value. As illustrated in Fig. 2(a), the adhesive spew was allowed to take an unconstrained “oval” shape at the metal free end, while a flat adhesive spew was enforced by the use of a shim at the composite free end during the bonding process. A trial study of spew shapes on BAJs showed that this configuration yielded best repeatability and joint performance.

2.4. Mechanical testing

Quasi-static (QS) tests were conducted at 1 mm/min on a tensile test machine (Tinius Olsen) with a 25 kN load-cell. Transient dynamic tests were performed at 0.5 m/s (DY0.5) and 3 m/s (DY3.0) on a Zwick HTM5020 high-speed servo-hydraulic test machine. In the dynamic tests, the load was recorded using a 50 kN piezo-electric load washer (Kistler9051a), at a sampling frequency of 0.95 MHz, with no inbuilt filter employed. As shown in Fig. 2(a), one side of the specimen was speckled for full-field strain measurements using two-dimensional digital image correlation (2D-DIC) with LAVision Strain master software, and identifiable black dots were placed 45 mm apart for joint deformation measurements. For the QS tests, a LAVision camera at 14 fps was employed. For the dynamic tests, a Photron SA1.1 high-speed camera recorded the tests at 100,000 frames per second (fps), with a resolution of 512 × 92 pixels. Five BAJ test repeats and three IAJ test repeats were performed at each test speed to gauge the repeatability of results.

Fig. 2. Single lap joint, (a) dimensions in mm and speckled surface for analysis of strain and deformation, and (b) geometry of interlocking features in IAJ.

Table 1
Specifications of the carbon fibre reinforced thermoplastic composite.

| Material supplier     | Matrix polymer       | Fibre type                | Weaving pattern                  | Fibre volume fraction | Density  | Nominal consolidated ply thickness |
|-----------------------|----------------------|---------------------------|----------------------------------|-----------------------|----------|------------------------------------|
| Schappe Techniques, France | Polyamide12 (PA12) | Stretch-broken carbon fibre | Co-wrapped 2 × 2 twill weave | 52 ± 3%               | 1550 kg/m³ | 0.27 mm  |

Table 2
Mechanical properties of the adherend materials.

| Material Type | Tensile modulus (GPa) | Tensile yield strength (MPa) | Modulus (GPa) | Tensile strength (MPa) | Strength coefficient (MPa) |
|--------------|-----------------------|------------------------------|---------------|------------------------|---------------------------|
| AA5754-H111  | 68                    | 115                          | 469.4         | 56                     | 55                        |
| GF/PA12      | 299.6                 | 115                          | 56            | 688                    | 55                        |
|              |                       | 469.4                        | 113           | 655                    | 49.5                      |

Table 3
Autoclave cure cycle.

| Autoclave cure cycle | Flat panel | Mould-in manufacturing |
|----------------------|------------|------------------------|
| Pressure Ramp Rate   | 50 kPa/min | 50 kPa/min             |
| Pressure             | 600 kPa    | 600 kPa                |
| Temperature Ramp Rate| 3.5 °C/min | 3.5 °C/min             |
| Temperature          | 220 °C     | 250 °C                 |
| Dwell time           | 40 min     | 50 min                 |

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3. Results and discussion

3.1. “Apparent” lap shear strength and work to failure

Fig. 3(a) presents representative force-deformation curves for quasi-static and dynamic tests on BAJs and IAJs. At all loading rates the BAJs achieve a higher peak force, \( F_{\text{max}} \) and a larger deformation at failure, \( \delta_{\text{max}} \), than the BAJs. The difference in \( \delta_{\text{max}} \) is larger than that of \( F_{\text{max}} \) due to the ductility of the aluminium adherend. It has a yield stress of 115 MPa, and consequently yields at a joint load of about 5.5 kN (Fig. 3(a)). It then undergoes extensive plastic deformation and strain localisation prior to failure. Before the aluminium yields, the deformation of the aluminium and composite adherends is almost the same, since their tensile modulus is well matched (Table 2), but afterwards, the plastic deformation of the aluminium adherend dominates the joint response. The final deformation of the composite adherend is negligible (<0.1 mm) compared to the overall joint deformation (1.5 to 4.25 mm). \( F_{\text{max}} \) shows a negligible increase under dynamic loading compared to the quasi-static loading, for both joint configurations. Maximum deformation, \( \delta_{\text{max}} \) is similar for QS and DY3.0 loading but significantly larger for DY0.5 loading for both BAJs and especially IAJs.

The following joint performance parameters are used to compare the different configurations. The “apparent” lap shear strength (LSS), is given by, ASTM D 5868 [26]:

\[
\text{LSS} = \frac{F_{\text{max}}}{A_{\text{nom}}}
\]

where \( F_{\text{max}} \) is the peak force and \( A_{\text{nom}} \) is the nominal overlap area.

The work-to-failure, WF, or energy absorbed is:

\[
\text{WF} = \int_0^{\delta_{\text{max}}} F(\delta)\,d\delta
\]

where \( F(\delta) \) is the force and \( \delta \) is the deformation of the gauge length.

Fig. 3(b) and (c) present the mean LSS and WF values respectively, with the error bars indicating one standard deviation. The LSS is seen to be relatively unaffected over this strain rate range, for both joint configurations. Even though the adhesive is significantly strain-rate dependent [34], the LSS of the joint is not, because the plastic deformation of the aluminium dominates the response, and the yield strength and hardening rate of this aluminium are not significantly strain-rate dependent [35]. In contrast, the WF shows a significant dependence on strain rate, with highest values seen at the intermediate rate (DY0.5 or 2000/s). For BAJs, the WF increases by 41% and decreases by 12% from its quasi-static values, respectively for DY0.5 and DY3.0 loading rates. Similarly, for IAJs, the WF increases by 65% at DY0.5 and decreases by 1% at DY3.0 loading rate. The reasons for the relative decrease in WF at the highest loading rate, for both joint configurations, are discussed when examining the deformation mechanisms (Section 3.2.3.2) and failure surfaces (Section 3.3).

3.2. Joint deformation and damage mechanisms

3.2.1. Crack-growth restraint mechanism in IAJs

To reveal the fundamental mechanism in the IAJs, the strain-state in the IAJ’s adhesive layer was examined by creating a test specimen was created with one of its sides abraded using 240-grit sandpaper to expose the first column of interlocking profiles, as shown in Fig. 4(a). The exposed surface was speckled for DIC analysis, and the joint was tested under QS loading. Fig. 4(b) and (c), show the axial (loading direction) strain and shear strain, respectively. Based on the areas of high tensile/compressive strain in Fig. 4(b), and high shear strain in Fig. 4(c), four distinct zones can be identified, as illustrated in Fig. 4(d). At the overlap ends, zone A, the adhesive experiences a combination of peel and shear strains, typically of an adhesively bonded SLJ. In the region sloping to the right, zone B, the adhesive is in tension, while in the region inclined to the left, zone D, the adhesive is in compression. Finally, the adhesive in the flat region at the top of the feature, zone C, is loaded in shear.

Video analysis of the abraded joint test showed that the primary crack initiated in the adhesive spew at the composite free end and slowly propagated into the overlap region until it reached the interlocking feature, where it stopped. A secondary crack initiated in the adhesive spew at the aluminium free end and propagated rapidly into the overlap region, through zones A, B and C of the first interlocking feature, stopping at zone D. This difference in crack propagation at the composite and aluminium free ends is due to the adhesive strain state described previously. The first zone in the interlock region that the primary crack encounters is of type D, where the adhesive is loaded in compression. This limits further crack growth and relative displacement of the adherends. In contrast, the secondary crack propagates relatively easily through zones A through C, where the adhesive is in tension and/or shear, before being arrested at zone D. This simple experiment demonstrates how the interlocking features impede crack propagation.
propagation in the adhesive and reduce the relative displacement between the adherends, allowing the joint to sustain load even after the damage has initiated. These experimental observations reinforce conclusions drawn from finite element investigations of IAJ mechanics conducted by Corbett [20].

3.2.2. Progression of deformation and damage in quasi-static tests

3.2.2.1. Joint rotation analysis. Fig. 5(a) shows a schematic of a tensile-loaded SLJ. Due to the eccentric load path, the adherends experience shear force (V), and moment (M) in addition to the applied tensile force (T). This causes the adherends to stretch and bend, which leads to joint rotation. At the overlap ends, the adhesive experiences high shear stress due to differential shear of the adherends [36], and high peel stress due to the joint rotation [37]. Peel stresses are critical to joint strength, as adheres are usually weak in tension. In this section, the progression of joint rotation is tracked, and is shown to correlate well with strain measurements from DIC.

As shown in Fig. 5(b), two points in the overlap region, on the outer surface of the composite, were used to compute joint rotation. The aluminium adherend was not used because its rotation angle is affected by plastic hinge formation and in-plane extension. Fig. 5(c) shows representative rotation curves for a BAJ and an IAJ tested under quasi-static loading. Through analysis of test videos, a series of five significant events were identified. By correlating with joint deformation, these events are marked as events 1–5 in Fig. 5(c) (note that events 4 and 5 occur in a different order for the BAJ and the IAJ). The five events are:

Event 1: Yielding of the aluminium adherend
Event 2: Initiation of primary crack in the adhesive spew at the composite free end
Event 3: Beginning of stable primary crack growth through the overlap region
Event 4: Beginning of unstable primary crack growth
Event 5: Initiation of a secondary crack at the aluminium free end

Fig. 5(d)–(h) (on the left) present the transverse normal DIC strain contours ($\varepsilon_{yy}$) at the joint deformations corresponding to events 1–5 for the BAJ. For the adhesive, $\varepsilon_{yy}$ corresponds to peel strains. Fig. 5(i)–(m) (on the right) present the corresponding contours for the IAJ. For the best comparison of both joint types, the strain contour range was manually scaled to the value in their respective legend. Moreover, a maximum value of 3%, for the contour range, was chosen, as the tensile butt-joint tests presented in Ref. [34] for the adhesive used here, shows almost a perfectly-plastic behaviour after 3% strains. The percentage value in brackets is the load level at the event, expressed as a percentage of the relevant $F_{\text{max}}$.

Initially, Fig. 5(c), joint rotation increases linearly, in a virtually identical fashion for both joint configurations, until event 1, the onset of plasticity in the aluminium adherend. In the DIC images, Fig. 5(d) and (i) for the BAJ and IAJ respectively, the onset of plasticity can be identified by the appearance of compressive values of $\varepsilon_{yy}$ in the aluminium adherend which indicates that it is starting to reduce in thickness.

Following event 1, the slope of the joint rotation versus deformation curve reduces, Fig. 5(c), for both joint configurations. From Fig. 5(e) and (j), the plasticity is seen to spread through the thickness of the aluminium adherend, ultimately reaching the outer surface. Adherend yielding has been reported to increase the adhesive peel and shear stresses due to increased differential shearing [38], and reductions in width and thickness of the yielding adherend [39–41]. In addition, in the current situation, involving dissimilar materials, different degrees of adherend flexure occurs at the overlap edges. Higher degree of flexure as a result of the more complaint aluminium adherend, as can be seen in Fig. 5(e) and (j), a plastic hinge forms in the metal adherend for both joint types. This, combined with the width and thickness contractions of the yielding metal in the vicinity of the composite free end, lead to higher adhesive peel stresses at the composite free end than at the metal free end, which can be clearly seen for the BAJ in Fig. 5(e). The reasons for the absence of high peel strains for the IAJ in Fig. 5(f) will be discussed when analysing the strain fields (Section 3.2.2.2). Further, the high peel stresses result in the primary crack initiation at the adhesive spew near the composite free end. It cannot be seen in Fig. 5(e) or (j), because it initiates in the adhesive spew at the mid-width of the joint, before spreading out to fillet edges. The reasons for this will be discussed when the dynamic tests are examined (Section 3.2.3.1). In Fig. 5(c), primary crack initiation, event 2, is seen to be accompanied by a sharp increase in joint rotation angle.

Once the primary crack appears, the rate of joint rotation increases (see the higher slope after event 2, than before event 2, in Fig. 5(c)). The crack travels through the spew and reaches the overlap region (event 3), as illustrated in Fig. 6. At this point, the crack is visible in the DIC image for the BAJ, Fig. 5(f), indicating it has progressed from the mid-width to the edge. But it is still not visible in the DIC image of the IAJ, Fig. 5(k). Fig. 5(k) though, does show high values of peel stress at the composite free end of the IAJ.

Events 4 and 5 occur differently in the BAJ and the IAJ. In the BAJ, once the primary crack reaches the overlap region, it progresses in a stable fashion. The joint rotation continues to increase gradually, Fig. 5(c), and the crack travels part-way through the overlap region, Fig. 5(g). As the primary crack advances, the plastic hinge position moves with it, staying close to the crack tip location, as seen in Fig. 5(g). Then at event 4, the slope of the rotation-deformation curve...
Fig. 5. Joint deformation, strains and damage mechanisms, (a), (b), (c) show forces and moments in tensile-loaded single-lap joint, and joint rotation, (d) – (h) show BAJ transverse normal (peel) strains from DIC analysis at events 1–5, (i) – (m) show IAJ peel strains at events 1–5. Percentages are of the peak load.
in Fig. 5(c) increases sharply. Note that event 4 occurs just after the occurrence of peak load, where the load has dropped to 95% of its peak value. From that point on, rapid, unstable growth of the primary crack occurs until event 5, Fig. 5(b), when the secondary crack initiates at the metal free end, which is followed almost immediately by abrupt joint failure. In the IAJ, once the primary crack reaches the overlap region, event 3, propagation into the overlap region is initially limited by the compressive strains in the adhesive, caused by the first interlocking features (zone D, Fig. 4(d)). Consequently, the applied load redistributes between the interlocking features, closest to the composite free end, and the adhesive. Meanwhile, similarly to the BAJ, the rotation continues to increase gradually, Fig. 5(c). Then, in contrast to the BAJ, initiation of the secondary crack (event 5) precedes unstable propagation of the primary crack (event 4). This is a consequence of temporarily restricting the primary crack propagation and interlocking features sharing the load. Secondary crack initiation leads to a sharp increase in rotation-deformation slope, see points 5a to 5c in Fig. 5(c), but then the slope drops again, as its further propagation is inhibited by the compressive strains in the adhesive, caused by the interlocking features closest to the aluminium free end (Fig. 4(d)). Consequently, the load redistributes again, across the overlap, between the mechanical interlock and adhesive; however, the interlocking features closer to the overlap edges remain highly loaded. The peel strain contours at points 5a, 5b, and 5c, are presented in Fig. 5(f). As can be seen, high peel strain at the metal free end (point 5a), quickly leads to secondary crack initiation and propagation into the overlap region, by point 5c. Meanwhile the primary crack has travelled very little, as it is inhibited from growing by the compressive strains. Consequently, significant further deformation with gradually increasing rotation is possible, after point 5c, see Fig. 5(c). As the rotation increases, the compressive strains restricting the crack growth, at Zone D, becomes dominated by shear, eventually, reinitiating the crack (primary/secondary) propagation and resulting in a rapid joint rotation (event 4) until complete failure.

3.2.2.2. Strain field analysis. To gain further insights into the mechanisms for the IAJ’s improvements in performance, the evolution of strain distribution in the adhesive layer, from DIC, is compared for both joint types. Fig. 7(a) presents, the evolution of shear strain $\gamma_{xy}$ in the adhesive layer, along the overlap length ($0 \text{ mm} < x < 25 \text{ mm}$) for the BAJ, at various joint deformation points, corresponding to significant damage propagation events. Fig. 7(b) presents a corresponding plot for IAJ. The strain measurements were obtained from ‘virtual gauges’ positioned at a nominal interval of 2 mm, in the adhesive layer, starting from the composite free end. Initially, for both joint types, as can be seen in the curves corresponding to event 1, $\gamma_{xy}$ increases progressively, with concentration at the overlap ends. On further loading, for BAJ, the curves corresponding to event 2 in Fig. 7(b), clearly show higher $\gamma_{xy}$ values at the composite free end than at the metal free end, due to the increased differential straining, resulting from plastically deforming aluminium. Typically in SLJs, more load is transferred through the plastically deforming end [41,42]. Consequently, for both joint types, the curves corresponding to event 3, clearly show increasing asymmetry in the $\gamma_{xy}$ distribution along the overlap, with a maximum value closer to the composite free end. Interestingly, up to event 3, as can be seen in Fig. 7(a) and (b), the $\gamma_{xy}$ for the IAJ is considerably lower than the values for BAJ, particularly near the overlap ends. This stress relief in IAJs, even while the bondline is intact, can be attributed to the load redistribution between the mechanical interlock and adhesive. This can be expected as the interlocking features are located at the highly stressed overlap ends. Moreover, this load redistribution is also believed to result in low peel strains at the composite free end, shown in Fig. 5(e). Similarly to the observations here, Parkes et al. [11] reported that the pins carry some load while the bondline is intact, for through-thickness reinforced metal-composite joints.

On further loading, damage initiates due to high local strains. However, progressive adhesive failure ensues as, in modern toughened adhesives like that used in this study, fracture occurs by the development and propagation of damage zones [43], rather than a single sharp crack. As the BAJ deforms, the primary crack propagates with an asymmetric $\gamma_{xy}$ distribution along the overlap, until final joint failure. For the IAJs, after the secondary crack initiates and propagates, the curve corresponding to 1.5 mm deformation in Fig. 7(b), clearly shows a considerable increase in $\gamma_{xy}$ at the centre of the overlap, resulting in a more uniform $\gamma_{xy}$ distribution along the overlap length. As the primary and secondary crack propagates, the adhesive at the centre of the overlap continues to contribute to the load transfer in the joints. Therefore, relative to BAJs, the IAJs show a higher $\gamma_{xy}$ and a more uniform $\gamma_{xy}$ distribution across the overlap, indicating that the interlocking features enhance shear deformation in SLJ.

Considering the asymmetric load distribution and damage propagation in BAJs, as well as progressive failure of toughened epoxy adhesives, it is worth comparing the evolution of adhesive strains, near the composite free end, for both joint types. Fig. 7(c) presents the evolution of $\gamma_{xy}$ and $\gamma_{yy}$, with increasing deformation for BAJ, at points P1, P2, and P3, respectively located at approximately 1.5 mm, 2.5 mm, and 6.5 mm from the composite free end. Fig. 7(d) presents a corresponding plot for the IAJ. The choice of these points is due to their location relative to the interlocking features near the composite free end, as shown in the inset of Fig. 7(d).

Typically in SLJs, $\gamma_{yy}$ is lower than $\gamma_{xy}$ except at the overlap edges, where highly concentrated peaks appear due to joint rotations. As the damage initiates and propagates, both $\gamma_{xy}$ and $\gamma_{yy}$ develop ahead of the crack tip. For BAJ, Fig. 7(c), the $\gamma_{xy}$ increases linearly with increasing slopes as the joint deforms, while $\gamma_{yy}$ increases exponentially. For P1, in BAJ, $\gamma_{yy}$ starts to increase exponentially, after primary crack reaches the overlap edge (event 3). Relative to P1 and P2, at P3, the $\gamma_{yy}$ increases abruptly, due to rapid joint rotation and unstable crack propagation (event 4). For IAJ, at P1, Fig. 7(d), $\gamma_{xy}$ starts to increase after event 3, and increases exponentially after the secondary crack initiation (event 5a), as would be expected from the joint rotation curves. Interestingly, at P1 and P2, $\gamma_{xy}$ reaches a plateau, almost immediately after the secondary crack initiation (event 5a), indicating that the interlocking features transfer a considerable portion of the applied load. At P2 and P3, $\gamma_{xy}$ increases very gradually, due to interlocking features sharing the load, restricting further crack propagations, and reducing joint rotations.

For both joint types, Fig. 7(e) compares the evolution of mode-mixity $\beta$, defined as the ratio of $\gamma_{yy}$ to $\gamma_{xy}$, for increasing joint deformations beyond event 3 (as $\gamma_{yy}$ increases after event 3). As the damage initiates and propagates in the overlap (event 3), $\beta$ increases for both joint types. Typically, high values of $\beta$ are associated with low fracture energy, as the fracture toughness values for the adhesives in peel (Mode I) are significantly lower than in shear mode (Mode II). For the adhesive used here, the fracture toughness in Mode I and Mode II, at quasi-static loading rate, are 4.5 N/mm and 20 N/mm, respectively [44]. For BAJs, increasing rotations result in exponential increases in $\gamma_{xy}$, consequently increasing $\beta$, and also resulting in a rapid transition to low fracture energy modes. In the IAJ, very gradual
increases in $\varepsilon_{yy}$ relative to $\gamma_{xy}$, results in a slow transition to a low $\beta$, hence, the damage evolution in IAJs is more progressive and involves higher energy dissipation relative to the BAJs.

In summary, under quasi-static loading, the interlocking features act to inhibit the growth of the primary crack and allow the secondary crack to grow in a stable fashion, reducing the joint rotation after damage onset, increasing shear deformation and reducing peel deformation, ultimately resulting in a significant increase in energy absorption.

3.2.3. Progression of deformation and damage in dynamic tests.

3.2.3.1. Dynamic loading rate – 0.5 m/s (DY0.5). The failure mechanisms for 0.5 m/s loading rate, DY0.5, are similar to those for quasi-static loading. Fig. 8(a) shows representative force and rotation curves for the BAJ and IAJ, tested at 0.5 m/s. From the test videos, major events were identified, and correlated with joint deformation. Three of these are considered here and marked in Fig. 8(a):

Event 1: Initiation of primary crack in the adhesive spew at the composite free end. Event 2: Beginning of stable primary crack growth through the overlap region. Event 3: Final failure in the bondline for the BAJ, and in the metal adherend for the IAJ.

Fig. 8(c)–(e) (on the left) show the DIC strain contours at events 1–3 for the BAJ, and Fig. 8(f)–(h) show them for the IAJ. Note that at event 1, Fig. 8(c) and (f), axial strain $\varepsilon_{xx}$ is shown, whereas at events 2 and 3, transverse normal strain $\varepsilon_{yy}$ is shown.

From Fig. 8(a), it can be seen that both joint configurations exhibit a linear increase in joint rotation until about 0.1 mm joint deformation, which corresponds to the onset of plasticity in the aluminium adherend. In the BAJ, this is quickly followed at just 0.12 mm deformation (~5.4 kN load), by primary crack initiation, event 1 in Fig. 8(a), which, as for quasi-static loading, occurs at the composite free end. In contrast for the IAJ, primary crack initiation is delayed until 0.43 mm (~7 kN load). For both joint types, primary crack initiation is accompanied by a sharp drop and oscillation in the load, Fig. 8(a). Moreover, at the instant of this load drop, careful observation of the test video shows a cloud of dust, Fig. 8(b), erupting from the composite free end. This observation is attributed to the primary crack initiating in the adhesive spew, at the mid-width of the joint, and rapidly spreading out to edges, as shown in the schematic in Fig. 8(b). The crack ini-
iates at the mid-width due to anticlastic bending, as has been reported in the literature [41,45]. The presence of anticlastic bending in the IAJs will be discussed when the optical micrographs are examined (Section 3.3). The absence of a load drop in the curve for quasi-static loading is due to a lower recording frequency relative to the duration of the event. The DIC results at event 1, Fig. 8(c) and (f), show high axial (i.e. loading direction) strains in the aluminium adherend due to plastic deformation, and high strains in the adhesive spew which is also transferring some load from the yielding metal adherend to the non-yielding composite adherend.

Following event 1, both joint configurations continue to exhibit a linear increase in rotation in Fig. 8(a), until the primary crack reaches the overlap region, event 2, at which high peel strains and plastic hinges exist at the composite free end, as seen in Fig. 8(d) and (g). After event 2, the BAJ rotation increases gradually at first with stable primary crack propagation, but then accelerates, indicating unstable crack growth. This is followed by secondary crack initiation at event 3, Fig. 8(e), followed quickly by catastrophic failure. For the IAJ, after event 2, joint rotation almost plateaus, Fig. 8(a), and the crack grows very slowly, as can been seen in Fig. 8(g) and (h). Load transfer due to the mechanically interlocking profiles limits further rotation, and hence peel stresses. Instead the joint stretches through plastic deformation in the aluminium adherend, which ultimately fails near the composite free end.

### 3.2.3.2. Dynamic loading rate – 3 m/s (DY3.0)

Fig. 9(a) shows representative rotation and force responses for both joint configurations. Detailed analysis of joint rotation is not performed due to significant oscillations in the data. For the BAJ, similarly to the QS and DY0.5, the primary crack initiated in the adhesive spew at the composite free end and propagated into overlap region. This was followed by secondary crack initiation and large rotations prior to joint failure. In IAJs the primary crack also initiated at the composite free end and propagated into the overlap region. But unlike the lower speed tests, the composite then underwent damage, forming a hinge at the metal free end, as seen in Fig. 9(b). As the secondary crack advanced into the overlap region, the position of the hinge moved just ahead of the crack. Once the hinge reached the first interlocking feature, abrupt failure of the composite adherend occurred due to the reduced cross-sectional area in this region. This catastrophic net-section failure, through bending of the composite adherend, involves a lower energy absorption relative to the gradual failure process, observed in IAJs under DY0.5 loading. However, it is reasonable to presume that, avoid
ing the bending failure can significantly improve the energy absorption, for the highest loading rate. Two of the three IAJs tested at 3.0 m/s, failed in the composite adherend, while the other one failed in the aluminium adherend, resulting in the high standard deviation for WF (7.31 J).

3.2.4. Effect of loading rate and stable crack length. Table 4 presents the total (primary plus secondary) crack length just before catastrophic joint failure, expressed as a percentage of the overlap length, and the final failure mode for both joint configurations at each loading velocity. Also shown is the average work to failure (WF), shown previously in Fig. 3(c). For the BAJs, the crack length shown is entirely due to the primary crack, as the secondary crack growth was negligible before catastrophic failure. It can be seen that, for the BAJs, there is a proportional relationship between primary crack length and WF, i.e. the longest primary crack is for the 0.5 m/s test speed, and this also gave the highest work to failure. For the IAJs, under quasi-static loading, the crack-inhibiting effect of zone D of the interlocking features on the primary crack allowed considerable secondary crack propagation before the primary crack started to grow again. Overall the total crack length before failure was 72%, which is considerably higher than for the corresponding BAJ, and consequently the WF is higher also. On the other hand, IAJs under dynamic loading displayed significantly shorter crack propagation as the interlocking features impeded the crack-growth more effectively, resulting in a net-section tensile failure in the aluminium adherend for DY0.5 and a net-section bending failure for DY3.0. Overall, the IAJs exhibit either a longer stable crack propagation or significantly shorter crack propagation than BAJs, resulting in significantly improved joint performance.

3.3. Fractography analysis

Fig. 10 presents images of failure surfaces as well as joint deformation just prior to final failure. Fig. 10(a) defines the colours used to identify different regions. In accordance with ASTM D5573-99 [46], three failure modes are identified:

(i) thin-layer cohesive (blue boundary),
(ii) dissipative adhesive with light fibre-tearing (red boundary), and
(iii) dense fibre-tearing (yellow boundary)

As described earlier (Section 3.2.2.2), toughened epoxy adhesives generate crack tip deformation zones of significant size before fracture. These zones are identified by adhesive discolouration due to substantial plastic flow, in a similar fashion to ‘stress whitening’ seen in clear plastics. Initially, the epoxy adhesive appears as a bright shade of blue, as shown in the box ‘0’ in Fig. 10(a). The colour gradually lightens as it undergoes plastic deformation. The change in the colour, as shown in boxes ‘0’ to ‘4’ in Fig. 10(a), are used to estimate the degree of plastic deformation in the adhesive. For failure modes (i) and (ii) (blue and red boundaries), the adhesive colour lightens considerably, indicating substantial plastic flow and energy absorption by the adhesive. Modes (ii) and (iii) are characterised by the appearance of carbon fibres on a thick layer of adhesive left on the aluminium adherend. In mode (iii), there are regions such as those labelled A, B, C and D in Fig. 10(a) which are densely populated with strands of carbon fibre that have been removed from the composite surface. Because the fibres in this material are stretch-broken, this requires relatively little energy, and there is also little evidence of adhesive plastic deformation in these regions, so mode (iii) is believed to be a lower energy mode than modes (i) and (ii).

Examining the failure surfaces of the BAJ QS specimen, Fig. 10(b), high-energy mode (i) is evident at the composite free end, high-energy mode (ii) is apparent in the central overlap region, and low-energy mode (iii) appears at the metal free end. For the BAJ DY0.5 specimen, Fig. 10(c), the central area of mode (ii) failure is larger than for QS loading, and the areas showing mode (i) and (iii) are reduced. Thus,
the BAJ DY0.5 joints undergo greater deformation than the BAJ QS joints, which results in a higher WF. For the BAJ DY3.0 specimen, equal areas of mode (ii) and (iii) can be seen in Fig. 10(d) and the primary crack extension (side view) is similar to that for the BAJ QS specimen. Finally, the mode (ii) and (iii) zones become darker with increasing loading rate, indicating increased fibre-tearing. As expected from May et al. [34], the adhesive strength is increasing with loading rate and exceeds the fibre-matrix interface strength, which is typically not strain-rate-dependent, and by a large extent at the highest loading rate. Therefore, the extensive fibre-tearing observed for BAJ DY3.0 specimen result in a reduced in WF.

For the IAJs, bondline failure occurred in the quasi-static tests, Fig. 10(e), while adherend failure occurred in the dynamic tests, Fig. 10(f) and (g). For the IAJ QS specimen, Fig. 10(e), the rows of interlocking features closest to the overlap ends, show significant deformation, indicating substantial work done by the features. This is added to by mode (i) and (ii) failure, at the composite and aluminium free ends, respectively. For the IAJ DY0.5 specimen, Fig. 10(f), metallic adherend failure occurred in the vicinity of gauge length considered for deformation analysis (Fig. 2(a)), leading to a high value of WF. On the other hand, the IAJ DY3.0 specimen, Fig. 10(g), shows a composite adherend failure at the location of interlocking features.

Fig. 11 presents the post-test optical micrographs of IAJs. For the QS specimen, the micrograph along longitudinal section A-A, Fig. 11(a), shows adhesive crushing due to compressive strain (zone D, Fig. 4(d)), caused by the interlocking features. The transverse section B-B, Fig. 11(a), display resin-rich regions in between the interlocking features, suggesting a potential opportunity for improving the method for the manufacture of composite adherends with macro-scale interlocking features. Finally, the composite adherends do not show any evidence of microstructural damage after the joint failure.
For the IAJ DY0.5 specimens, as shown in the inset of Fig. 11(b), the micrographs were obtained at longitudinal and transverse sections. For both longitudinal sections, as can be seen in Fig. 11(b), the interlocking projections (metal), near the composite free end, are substantially deformed, as the load redistributes to these interlocking features after the primary crack reaches the overlap edge. However, interlocking projection in section A-A is more deformed relative to section C-C. In contrast to section C-C, the enlarged micrograph of section A-A shows bondline failure at zone B (tensile strain) and zone C (shear strain). These perceptible differences between section A-A and C-C indicate an uneven load redistribution across the overlap. Moreover, the longitudinal sections illustrate the effectiveness of compressive strains at zone D in restricting the primary crack propagation.

Transverse section D-D, Fig. 11(b), shows a curvature across the adherend width, indicating the presence of anticlastic (concave transverse) bending in IAJs. Anticlastic bending SLJs is due to the interaction between the lateral (width) and thickness contractions (Poisson’s ratio effect), and local secondary bending due to load eccentricity [38,45]. The outward bending of the outermost interlocking projections and a wider bondline crack at the overlap edges (green arrow) in section D-D are a result of anticlastic bending in IAJs.

Fig. 11. (a) Optical micrographs of longitudinal (A-A) and transverse (B-B) sections of IAJ QS specimen, (b) longitudinal (A-A and C-C) and transverse (D-D) sections of IAJ DY0.5 specimen, and (c) 3D-µCT scans of IAJ DY0.5 specimen.
4. Conclusions

In this study, a novel interlocked hybrid joining technology was investigated experimentally using carbon-fibre thermoplastic composite and aluminium adherends, loaded at quasi-static and transient dynamic loading rates. The mechanical response and damage progression were compared to baseline adhesive joints to quantify performance improvements. Table 5 summarises the performance and failure analysis of the BAJs and IAJs, tested at different loading rates, considering the BAJs tested under quasi-static loading as a reference.

This novel joining technique considerably reduces the joint rotation after damage onset, a crucial aspect affecting the performance of eccentrically loaded single-lap joint configurations, resulting in enhanced shear deformation and reduced peel deformation. Consequently, positioning this novel joining technology as a promising alternative to the intricate double-lap joint configuration that is preferred for its non-eccentric load path. Dynamic IAJ tests displayed adherend failure indicating that this novel joining technology can result in joints stronger than the substrate materials, thus allowing for tailoring joint performance, particularly with respect to failure modes. The high energy absorption capacity, 38 J for tests at 0.5 m/s and 23 J for quasi-static and 3 m/s tests, shows the potential use of this joining technology for crashworthiness applications. Importantly, this novel joining technique exhibits excellent capability to sustain load even as the crack grows into the overlap region. This allows minor cracks or damage to grow to a visually detectable extent before failure occurs, allowing a potential reduction in maintenance time and cost. Hence, this technology addresses the key drawback – catastrophic failure behaviour of bonded joints – which restricts the application of bonded joints in load-critical structures. The current work has shown potential for attractive performance improvements, however further experimental work is still required to obtain a detailed understanding of this technique for various loading scenarios, such as out-of-plane impact, fatigue, etc.

CRediT authorship contribution statement

Karthik Ramaswamy: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Validation, Writing - original draft, Writing - review & editing, Visualization. Ronan M. O’Higgins: Conceptualization, Supervision, Project administration, Resources, Writing - review & editing. Michael C. Corbett: Methodology, Visualization, Writing - review & editing. Michael A. McCarthy: Supervision, Writing - review & editing, Project administration, Resources, Funding acquisition. Conor T. McCarthy: Conceptualization, Supervision, Writing - review & editing. Data curation, Formal analysis, Validation, Writing - original draft, Writing - review & editing. Michael C. Corbett: Conceptualization, Supervision, Resources, Funding acquisition.

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 statement

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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