EXPERIMENTAL STUDY ON THE PERFORMANCE OF HYBRID METAL-COMPOSITE JOINTS AT QUASI-STATIC AND INTERMEDIATE STRAIN RATES

Karthik Ramaswamy, Ronan M. O'Higgins, Michael C. Corbett, Conor T. McCarthy, Michael A. McCarthy

CONFIRM Centre, Bernal Institute, University of Limerick, Limerick, Ireland

karthik.ramaswamy@ul.ie; ronan.ohiggins@ul.ie; michael.corbett@ul.ie
conor.mccarthy@ul.ie; michael.mccarthy@ul.ie

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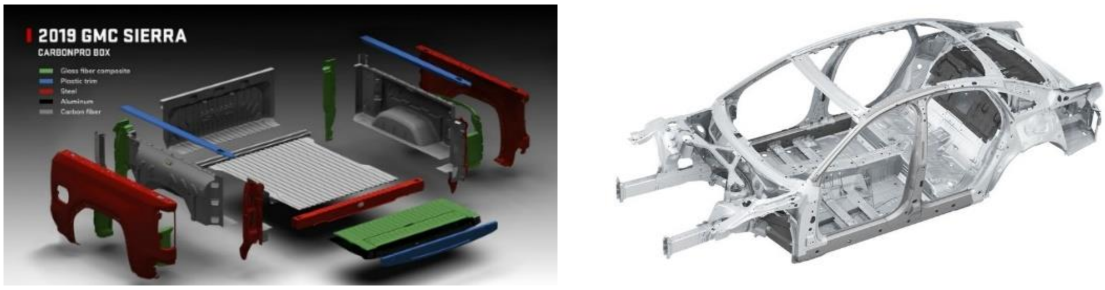
ABSTRACT

Carbon Fibre Reinforced Plastics (CFRP) offer excellent specific mechanical properties, making them ideal for lightweight structural applications. However, in practice it is difficult to produce a viable design concept from just one material system, so a variety of different materials are required to produce an optimum design. Joining of dissimilar materials efficiently poses a significant challenge to the implementation of multi-material design concepts. Hybrid joining processes possess the advantages of both the mechanical fastening and adhesive bonding methods. This research considers a novel, interlocked/bonded technique for joining metals to CFRPs. The technique presented herein employs interlocking bond-surface morphology formed on the faying surfaces of male (metal) and female (composite) adherends that mechanically interlock in shear when coupled with a layer of adhesive.

In this study, a single-lap joint (SLJ) configuration is employed to examine the effect of the interlocking features on lap shear strength and work-to-failure. The results are compared to data obtained from standard bonded SLJs. Two adhesives were studied for bonding of the standard SLJ adherends: (i) a two-part acrylic-based adhesive and (ii) a one-part crash-toughened epoxy adhesive. The toughened epoxy exhibited preferable performance characteristics, so was chosen to bond the interlocking adhesive joints (IAJs). The baseline SLJ and IAJ were tested at two test velocities – 1 mm/min (quasi-static) and 0.5 m/s (intermediate). The quasi-static and intermediate loading rate tests were performed on an electromechanical universal test machine (UTM) and high-speed servo-hydraulic UTM, respectively. The IAJs displayed an increased performance at intermediate loading rate compared to the standard SLJs but showed a reduced performance at quasi-static loading rates.

1 INTRODUCTION

There is increasing demand for lightweight automotive structures due to statutory requirements on emissions and fuel efficiency, as well as the need for improved crashworthiness. Composite materials, such as Carbon Fibre Reinforced Plastics (CFRP), offer excellent specific strength and stiffness properties, making them highly attractive for lightweight structural applications. However, all-composite structures are currently considered too slow to produce and costly for general automotive applications. Multi-material designs currently offer the most viable option. For instance, the General Motors Corporation (GMC) Sierra pick-up truck (Figure 1a), employs glass and carbon fibre composites along with aluminium, steel, and plastics in the construction of the truck bed, resulting in a mass saving of 28 kg. Figure 1b presents the Audi (A8) space frame, which employs CFRP with metals like steel, aluminium and magnesium.



(a) **(b)**

Figure 1. Automotive structures employing multi-material construction: a) GMC Sierra – the truck bed, b) Audi A8 – space frame [1]

However, multi-material assemblies pose a significant challenge for joining technologies. Conventional mechanical fastening, such as bolting or riveting, is widely used to join dissimilar materials. Mechanical fastening requires hole machining, which introduces stress concentrations in the assembly, leading to increased weight. For composites in particular, the drilling process is detrimental to structural integrity, leading to overdesign of the composite part. Adhesive joining is the second preferred method for joining dissimilar materials. Although this technique addresses the key shortcoming of bolted joints, it presents a new set of challenges, such as: brittle failure, complexity in the choice of chemically-compatible adhesives, property degradation with time etc. Moreover, the central bond region of an adhesive bonded joint is widely recognised as being relatively inactive during load transfer and joint failure. Recessed adhesive joints [2], show that removing adhesive from the central overlap region has minimal effect on adhesive stress state. This has led to the evolution of a hybrid joining process that takes the advantages of both mechanical fastening and adhesive bonding methods. References [3,4] present improved strength and energy absorption using bolting or riveting in addition to adhesive bonding. However, these approach retains the shortcomings of mechanical fastening.

This research considers a novel, interlocked/bonded technique for joining metals to CFRP. The technique employs interlocking bond-surface morphology formed on the faying surfaces of male (metal) and female (composite) adherends that mechanically interlock in shear when coupled with a layer of adhesive. In this study, a single-lap joint (SLJ) configuration is employed to examine the effect of interlocking features on the lap shear strength and work-to-failure. The results are compared to data obtained from standard bonded SLJs.

2 MATERIALS AND METHODS

2.1 Materials

The aluminium alloy AA5574-H111 was selected for the manufacture of the metallic adherends. It has good corrosion resistance, moderate strength and weldability, favourable surface quality and is suitable for structural sheet applications. These properties make it an attractive material for use in the automotive industry.

Thermoplastic composites offer several advantages such as high fracture toughness, high elongation to failure, easy storage (unlimited shelf-life and no requirement for refrigeration), good solvent resistance and inherent recyclability. Processing cycles for thermoplastic composites offer faster through-put time compared to conventional thermoset material systems, which is of significant interest to high volume production industries, such as the automotive industry. In this study, a woven fabric, in which carbon fibre cores, co-wrapped with PolyAmide12 (PA12), are stretch-broken and woven in a 2/2 twill weave is selected for the manufacture of the composite adherend. The thermoplastic filaments are homogenously blended together with the reinforcing fibre in commingled yarns and offer an efficient manufacturing option.

Epoxies are widely used in automotive applications to bond body panels and automotive interior components [5]. A literature survey has been conducted to identify adhesive systems suitable for the present application [6–11] . Based on this, the following adhesives were selected:

• 3M™ Scotchweld™ structural plastic adhesive, DP 8005 – a two-part acrylic-based adhesive, suitable for many low surface energy plastics, including many grades of PP, PE, and TPO [12].

• Dow Betamate™ 1496 V – a one-component epoxy-based adhesive [13].

2.2 Specimen geometry and preparation

The geometry of the test specimens must consider the specifics of the dynamic testing machine. Typically, high-speed servo-hydraulic test systems use a slack cylinder or a lost motion cage that allows the actuator to accelerate to the desired test velocity before loading the specimen. The Zwick HTM 5020 employs a lost motion unit as shown in Figure 2a. The lost motion unit is accelerated by the actuator end to the desired test velocity (Figure 2b). Therefore, the test specimen needs to be long enough to allow for the acceleration of the lost motion cage to the desired test velocity, before the specimen is engaged. A grip to grip distance of 150 mm allows a maximum velocity of approximately 3 m/s to be achieved, hence the length of the lap joint specimen was set to 150mm.

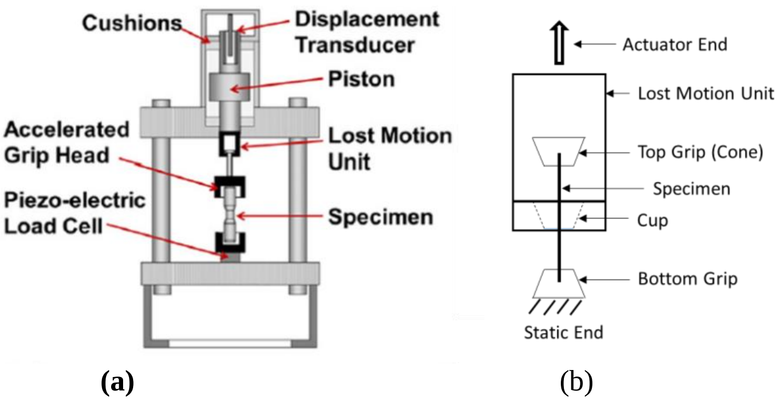
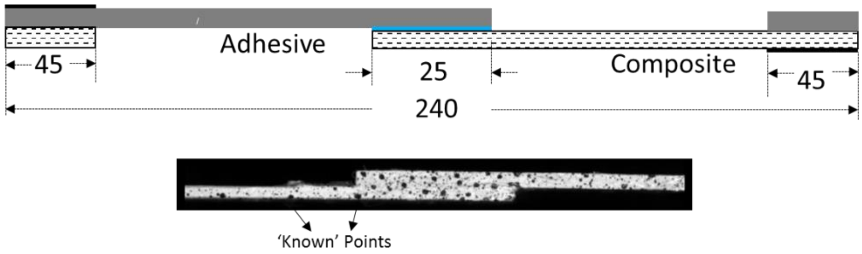
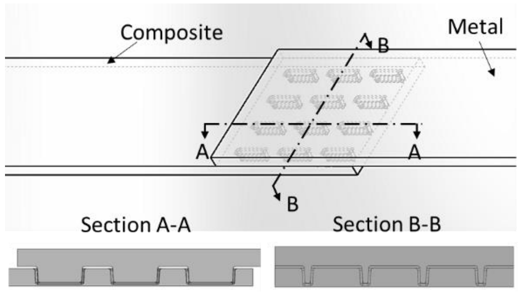


Figure 2. High-speed servo-hydraulic test system: a) schematic of Zwick Amsler HTM 5020 [10] b) lost motion cage

The composite adherends for single lap joints (SLJ) were prepared from an 8-ply thick, 600 x 600 mm composite laminate. The laminate was manufactured by stacking 8 fabric plies, followed by vacuum bagging and consolidation in an autoclave, at a temperature of 240°C, for 40 minutes, at 6 Bar pressure. A hot press system can process this laminate more quickly, but an autoclave was used to ensure that the laminate produced was consolidated to a very high quality, so that laminate quality would not be a variable in the testing series. Adherends 132.5mm long by 25mm wide were harvested from the consolidated laminate using a diamond blade cutting saw. Aluminium adherends of 2 mm thickness were machined from a 2mm thick AA5754 sheets to the equivalent dimensions of the composite adherend. The composite and metal adherends were bonded with a 2 mm thick aluminium spacer, to minimise secondary bending due to eccentric loading in the single-lap tests. Tabs of 0.5 mm thickness were bonded on the other face of the adherend, to improve specimen gripping in the test machine (as shown in Figure 3a). A3M-DP8005 was used for bonding spacers and tabs.



(a)



(b)

Figure 3: Single lap joint and Interlocking adhesive joint specimens (a) specimen geometry and 'speckled' surface for image analyses (b) schematic of interlocking adhesive joint

The design of interlocked adhesive joint (IAJ) was adopted from [14]; three-dimensional finite element models with state-of-the-art material models to represent the metal, composite, and adhesive were employed. Adaptive surrogate-based design optimisation was employed to optimise the design of the IAJ, with an objective function defined to maximise the peak load. This study used a laminated CFRP system with quasi-static properties of HTA/6376 for the composite adherend and AA5754 for the metallic adherend. The mechanics governing the optimal IAJ design are expected to yield comparable performance improvement, although a different material system was employed in the optimisation study. Figure 3b shows a schematic of the optimised IAJ design. The aluminium adherends were laser machined with a tolerance of ± 0.025mm from a 4mm thick AA5754-H111 sheet. Un-machined ends of the AA5754 sheets act as the spacers for the metallic adherend. A metallic tool plate/mould was fabricated to manufacture the composite female adherend. The composite adherend for IAJs was manufactured by stacking 8 fabric plies on the tool plate. The tool plate with the fabric plies was vacuum bagged and consolidated in the autoclave. The cure cycle for manufacturing flat panels when used for manufacturing complex profiles of the IAJ resulted in significant dry spots and uneven consolidation around the interlocking features. The cure cycle was optimised through trial and error. The optimised cure cycle had a dwell at 120°C, for 20 minutes and a dwell at 250°C, for 60 minutes, at 6 Bar pressure.

Initially, the metallic adherends were cleaned with acetone to remove the dirt from the manufacturing process. This was followed by three rounds of ultrasonic treatment, first in a 0.5M sodium-hydroxide bath for 30 minutes, then two rounds in a de-ionized water bath for 5 minutes each. The bond area of the composite adherend was grit-blasted with 220 grit aluminium oxide to remove any surface contaminants, such as the release agent used for de-moulding during the autoclave consolidation process. The grit-blasting process used a 4 mm nozzle at a pressure of 1.72 Bar, held approximately 300 mm from the surface. The grit-blasted area was cleaned with acetone and ultrasonically treated in a de-ionized water bath for 5 minutes. The grit blasting procedure was optimised in a separate study [15] to obtain the best surface for adhesive bonding. Both the treated composite and metallic adherends were dried in an oven at 80°C for 16 hours. The surface-prepared adherends were bonded on a mould to minimise joint misalignment [15]. The crash-durable epoxy (Betamate 1496V) has a supplier recommended cure temperature of 180°C for 30 minutes; the bonding process was carried out in an oven and the mould was allowed to cool before extracting the bonded specimens. In the case of ductile acrylic adhesive (DP8005), the bonded specimens were cured in the mould for 16 hours at room temperature, according to a rate of strength build-up chart provided by the manufacturer. Bondline thickness for both adhesives was controlled by adding 250-micron glass microbeads. Sufficient measures were exercised to ensure a uniform loading on the bonded adherends during the curing process. The bondline thickness was measured post-cure for each specimen and was found to vary less than ±10%. The adhesive spew along the sides of the specimen has been carefully filed down, without damaging the adherends. The adhesive spews were "unconstrained" at the metal free-end and forced an "L" shape at the composite free end, based on an unpublished study [16].

2.2 Test method

Table 1 presents the test matrix identified for testing the standard bonded SLJs (referred to as BSL henceforth) and IAJs. Quasi-static tests were conducted at a test velocity of 1mm/min on an electro-mechanical universal test machine (Tinius – Olsen), with a 25kN load cell. Tests at 0.5m/s were conducted on a high-speed servo-hydraulic UTM, Zwick HTM 5020, with a 50kN piezoelectric load washer. The images of the tests at quasi-static and intermediate rates were recorded using a LA Vision Digital Image Correlation (DIC) system and Photron SA1.1 high-speed camera, respectively. The displacement measurements were obtained through an image processing technique using a MATLAB script. At least 3 repetitions of each specimen configuration were conducted to verify the test repeatability.

Test Code	Loading Velocity
SLJ_QS_Spec# IAJ_QS_Spec#	Quasi-static (QS) (1mm/min)
SLJ_IR_Spec# IAJ_IR_Spec#	0.5 m/s (IR)

Table 1: Test matrix

The performance characteristics of BSLs and IAJs were compared based on the following parameters:

(a) "Apparent" lap shear strength (LSS) – LSS is calculated following the equation recommended in ASTM D 5868 [17]

"Apparent" lap shear strength (LSS) = Peak force / Nominal overlap area (1)

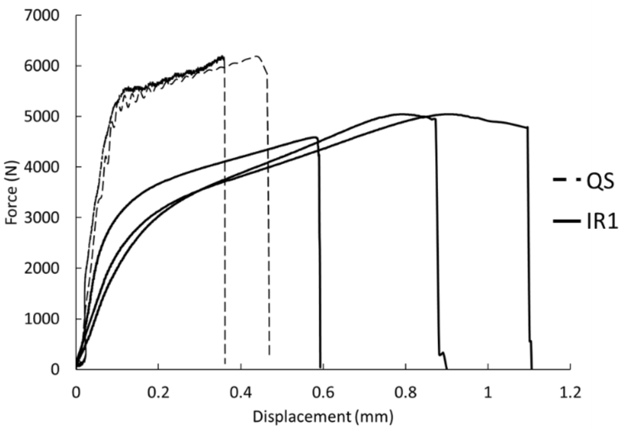
(b) Work to failure (WF) – WF is obtained by computing the area enclosed by the force-deformation curves through a trapezoidal integration scheme.

3 RESULTS & DISCUSSION

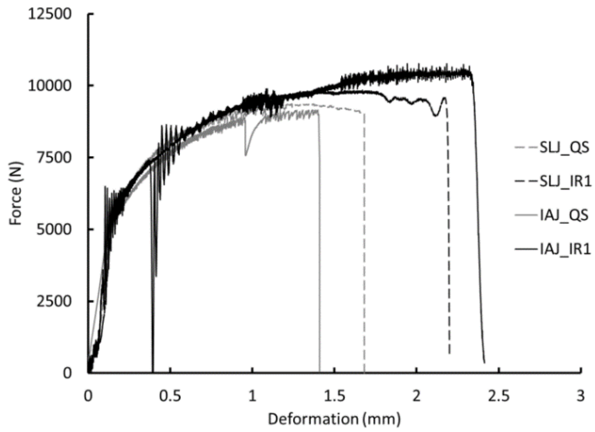
3.1 Quasi-static and intermediate rate responses

Figure 4a presents the force-deformation response of BSLs, bonded using the ductile-acrylic adhesive, and tested at QS and IR test velocities. The QS responses displayed an average peak force of 4.72kN with a standard deviation (SD) of 559N and an average deformation at the failure of 0.87mm (SD: 0.26 mm). The acrylic adhesive showed a dependency on the loading rate. The average peak force increased by 31%, whereas the deformation at failure decreased by 54%. It was decided not to use the acrylic adhesive for the IAJ tests, as acrylic bonded SLJs exhibited low magnitudes of deformation at failure, as well as significant scatter in the results. Figure 4b compares the representative curves for SLJs and IAJs bonded using the crash-durable epoxy adhesive, at both QS and IR test velocities. SLJs bonded using crash-durable epoxy showed a 99.7% and 53.4% higher peak forces than the ductile-acrylic SLJs at QS and IR loading rates, respectively. Moreover, the crash-durable epoxy SLJs recorded 1.9 and 5.4 time higher deformation at failure than the acrylic SLJs. Therefore, the crash-durable epoxy was considered a suitable adhesive for this application.

The epoxy bonded SLJs showed a marginal increase in peak force and a considerable increase in deformation at failure. This can be attributed to the plastic deformation of the aluminium adherend, initiating at approximately 5500N, which limits a further increase in peak force. The representative curve of the QS IAJs demonstrates less peak force and deformation at failure. It should be noted that there is an apparent drop in load, at approximately 8300N, for all repeats of IAJ test at the QS rate. Otherwise, the BSLs and IAJs show similar force-deformation response, although the IAJ demonstrate earlier failure. However, the IAJs attested at IR loading rates display a considerable increase in peak force and displacement at failure for the IR test velocity when compared to the BSL.



(a)



(b)

Figure 4: Force-deformation characteristics (a) SLJs bonded with ductile acrylic adhesive (b) Representative curves for SLJs and IAJs bonded with epoxy adhesive tested at QS and IR loading rates

3.2 "Apparent" lap shear strength and Work to failure

As described earlier, the "apparent" lap shear strength (LSS) was estimated following equation (1) and work to failure (WF) was computed from the area under the force-deformation curve. Figure 5 compares the performance parameters from testing the baseline SLJs and IAJs at QS and IR loading velocities. The error bars represent the standard deviation computed from three repetitions of each test. For the QS test velocity, the IAJs displayed 4% lower LSS and 19% lower WF compared to the BSLs, whereas at the IR test velocity, the IAJs demonstrates a 7% increase in LSS and a 27% increase in WF than the SLJs. The IAJs show a higher improvement in both performance parameters with increasing loading rate than the BSLs. The WF increased by 105% for IR tests compared to QS tests, whereas WF increased by 32% with increasing loading rate for the BSLs.

The trend in the performance characteristics of the IAJ can be explained by understanding the impact of manufacturing of the 'female' composite adherends, the influence of adhesive spew, and the joint deformation mechanisms. The reduction in performance of IAJs tested at the QS test speed indicated a loss of interlocking due to premature damage in the adhesive layer or composite adherend. The significant difference between the deformation mechanisms of IAJs and SLJs, tested at QS and IR loading rates, is the initiation of adhesive damage. The damage initiated in the adhesive layer at the metal-free end for IAJs at the QS loading rate, while at the IR loading rate, the damage initiated at the composite free-end. At the IR loading rate, higher effectiveness of the interlocking features resulted in better performance compared to the baseline SLJs. The LSS increased by 7% and the WF by 31% as a result of restricted crack growth, due to the interlocking profiles, before ultimate joint failure.

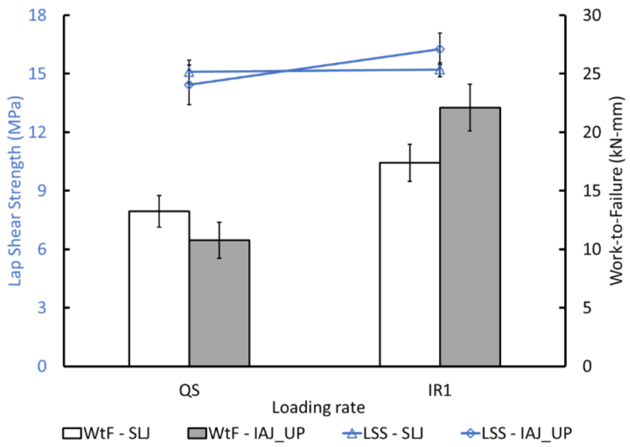


Figure 5: SLJ and IAJ performance characteristics at quasi-static and 0.5m/s loading velocities.

3.3 Failure surfaces

Figure 6 shows the typical failure modes observed in an IAJ tested at the IR loading rate. The failure surfaces show a dominant dense fibre pull-out without adhesive discolouration at the free-end of the male adherend. Whereas, a light fibre pull-out with adhesive discolouration is observed at the free-end of the composite adherend. Adhesive discolouration indicates the extent of adhesive deformation and consequent energy dissipation. Composite damage such as fibre breakage, matrix cracking, and through-thickness composite cracking were observed in the vicinity of the interlocking features close to the metal free-end. Extensive composite damage along the wider faces of the interlocking features can be attributed to the resin rich regions. These resin rich regions are a result of issues associated with casting in the complex interlocking profile shapes into the laminate. Adhesive failure was observed in the vicinity of the middle row of interlocking features. As a result, the central bond region contributes less to the total work-to-failure. The interlocking features on the metallic adherend exhibit plastic-ductile deformation at their roots. The severity of plastic deformation is greatest for the interlocking features at the free-end of the composite adherend and progressively decreases towards the free-end of the aluminium adherend. Metallic adherend yielding next to the overlap area shows the extent of plastic deformation in the metallic adherend.

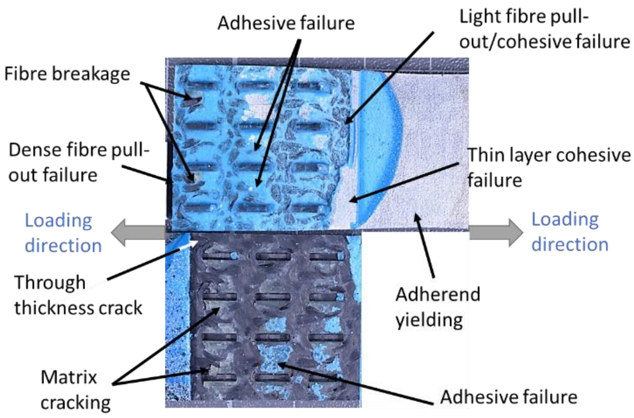


Figure 6: Typical failure surface of IAJ tested at 0.5m/s test velocity

4 CONCLUSIONS

The preliminary results of a study investigating a shear-interlocking mechanism on the faying surfaces of a hybrid metal-composite joint are presented. The lap shear strength (LSS) and work-to-failure (WF) performance of interlocking adhesive joints (IAJ) are compared to standard bonded single-lap joints (SLJ) for two loading rates. Baseline SLJ tests were performed with a ductile acrylic adhesive and a crash-durable toughened epoxy adhesive. The toughened epoxy adhesive exhibited superior performance and was chosen for use in the IAJ tests. At quasi-static loading rate, the IAJ demonstrated 4% lower LSS and 19% lower WF than the SLJs. However, at the intermediate rate (IR) loading (0.5m/s), the IAJ displayed a 7% increase in LSS and a 27% increase in WF compared to the baseline. The IAJ performance was found to be influenced by the effect of 'female' adherend manufacturing, adhesive spews and deformation mechanism. The failure surfaces display significant composite damage in the vicinity of the interlocking profiles. A comprehensive study to assess the effect of 'female' adherend manufacturing technique, adhesive spew, and deformation mechanisms will be performed as a part of future work.

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