A NOVEL PROFILING CONCEPT LEADING TO A SIGNIFICANT INCREASE IN THE MECHANICAL PERFORMANCE OF METAL TO COMPOSITE JOINTS

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Abstract: *In this work, we designed metal-CFRP joints with a profiled adherend termination to improve the mechanical performance. We have applied several profiles to the edge of titanium adherends which were adhesively bonded to CFRP substrates. We conducted finite element modelling and experimental 4PB (4-Point-Bend) testing to investigate how the geometry of the adherend edge profile effects the mechanical performance of the joint. This work shows that profiling of the metal adherend can result in increases of at least 27% in the peak load, and of at least 272% in the energy dissipated up to critical failure normalised by the mechanical energy.*

Keywords: Adhesive-Bonded Joints; CFRP; Joint Design; Stress Concentration; Erosion Shields

1. Introduction

Industry has increasingly made use of composite laminates [1] and consequently, designs include more interfaces between metal and composite components. Adhesive bonding provides a high joining strength and improved stress distributions relative to traditional mechanical joining methods [2]; however the discontinuity in stiffness at the joint edge means a stress concentration is still present, with higher stresses found along the edge of the joint [3].

Solutions to improve the performance of adhesive joints with composite adherends have been investigated in the literature [4]. The focus is predominantly on axial loading of the joints; however bonded joints may also be subjected to transverse loading. Bird strikes to laminate blades with adhesively bonded metallic erosion shields are one critical example.

In this work, we aim to improve the resistance to translaminar fracture of CFRP substrates with adhesively bonded metal adherends subjected to transverse loading as shown in Figure 1. To achieve this goal, we have taken the novel approach of systematically profiling the edge of the

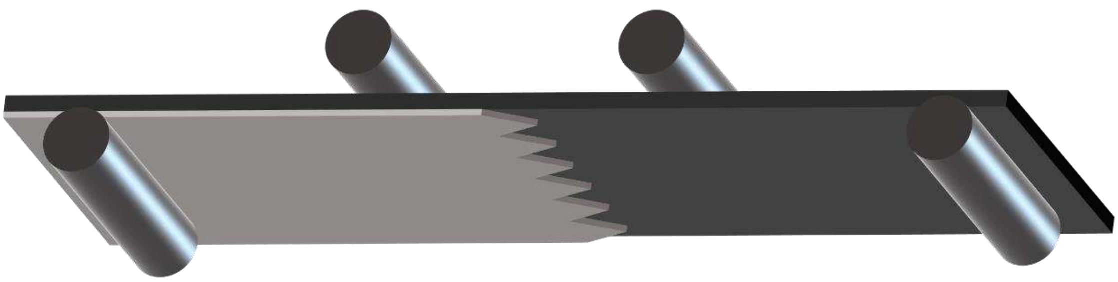

Figure 1. An example metal-CFRP 4PB test specimen with a profiled metal adherend.

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metal adherend, in order to:

1. replace the discontinuous change in stiffness with a progressive change;
2. increase the effective length of the joint edge, hence increasing the load transfer area and reducing the stress concentration; and
3. deflect the straight translaminar fracture induced by a straight edge, thus increasing the energy dissipated during failure.

2. Finite Element Model

We developed a Finite Element (FE) model to guide the experimental study, as detailed further by Whitehouse et al. [5]. The model uses LaRC05 failure criteria [6, 7] to assess the propensity to failure of the laminate. We used the model to design a 4PB test coupon which would yield the failure mode of interest: laminate failure local to the bond edge for a straight edged specimen. We then modified the model to investigate the effect of the different adherend profiles. Figure 2 shows that profiling of the metal adherend effects the morphology of the failure indices within the laminate, resulting in isolation of the critically stressed areas.

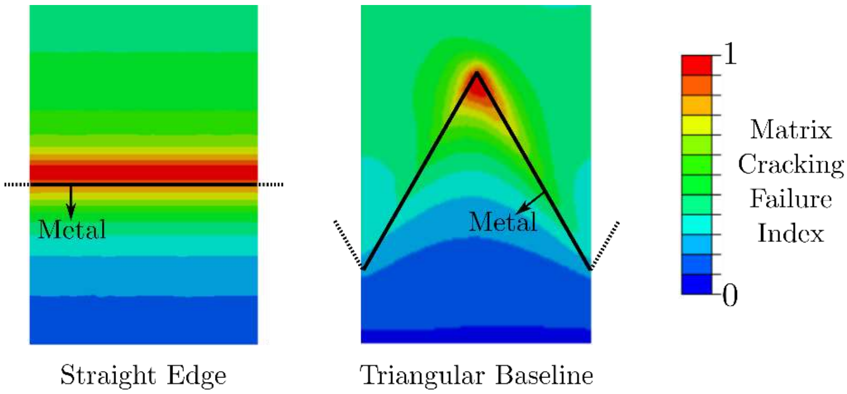


Figure 2. Matrix cracking failure index in a sub-surface ply, directly below the metal termination, at the onset of damage.

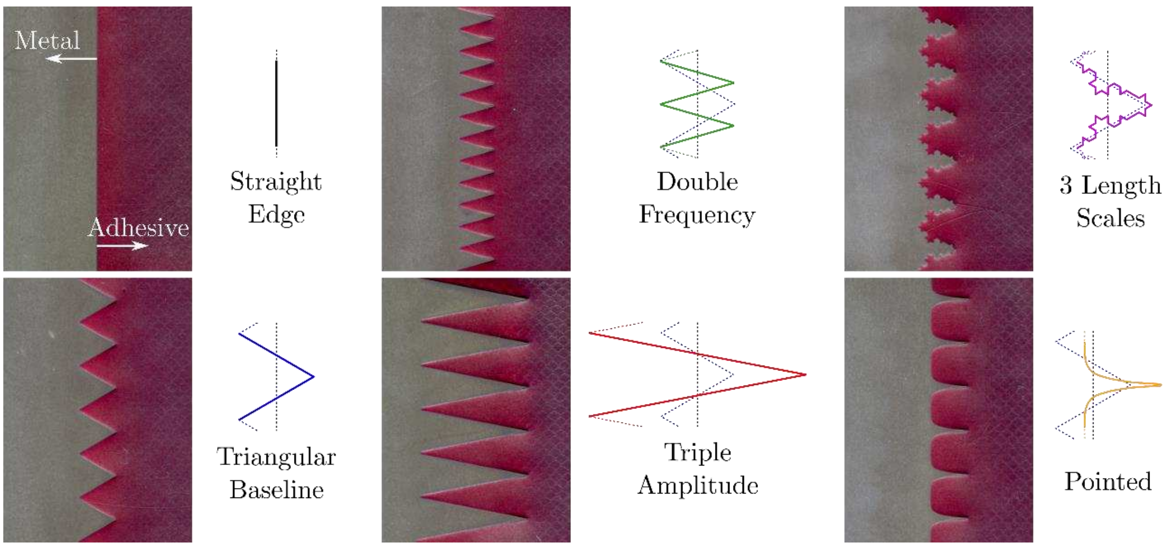


Figure 3. The profile patterns to be tested with their repeat units compared to the triangular baseline profile. The red film adhesive was extended beyond the edge of the metalwork such that a natural adhesive fillet formed at the profile edge.

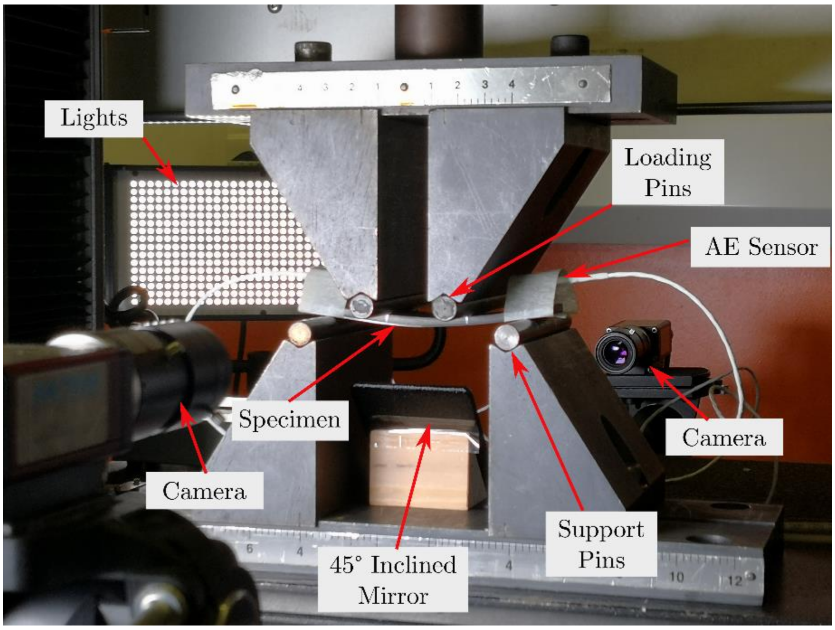


Figure 4. The experimental 4PB test set up.

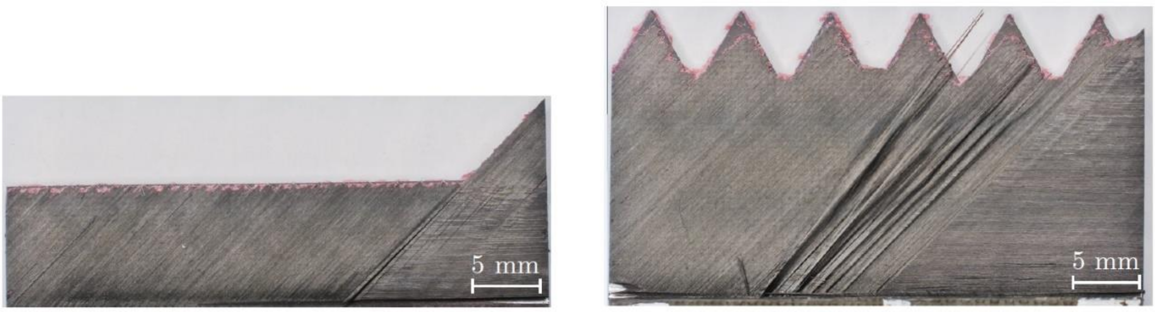
3. Experimental Testing

3.1 Experimental Setting

In this work we vary the profile amplitude, profile frequency, number of length-scales, and profile geometry type, to investigate the effect of each on the mechanical performance of the adhesive joint. Figure 3 shows the different profiles considered. The test specimens are composed of a Titanium (TiAl6V4) adherend which has undergone a sodium hydroxide anodising surface treatment, and a IM7/8552 CFRP laminate substrate. They are adhesively bonded together using a AF163-2K film adhesive. We conducted quasi-static 4PB tests and used acoustic emission (AE) monitoring during the tests to assist with characterisation of failure modes via characteristic peak frequencies, as determined by Gutkin et al. [8]. The test set-up is displayed in Figure 4.

3.2 Results

A representative fracture surface for a straight edged specimen is shown in Figure 5a, whilst that of a triangular baseline profile specimen is shown in Figure 5b. Characteristic force versus displacement traces are shown in Figure 6 for each sample. Figure 7 displays the AE data



(a) Straight edged specimen (b) Triangular baseline specimen

Figure 5. Fracture surfaces on the underside of the titanium adherend.

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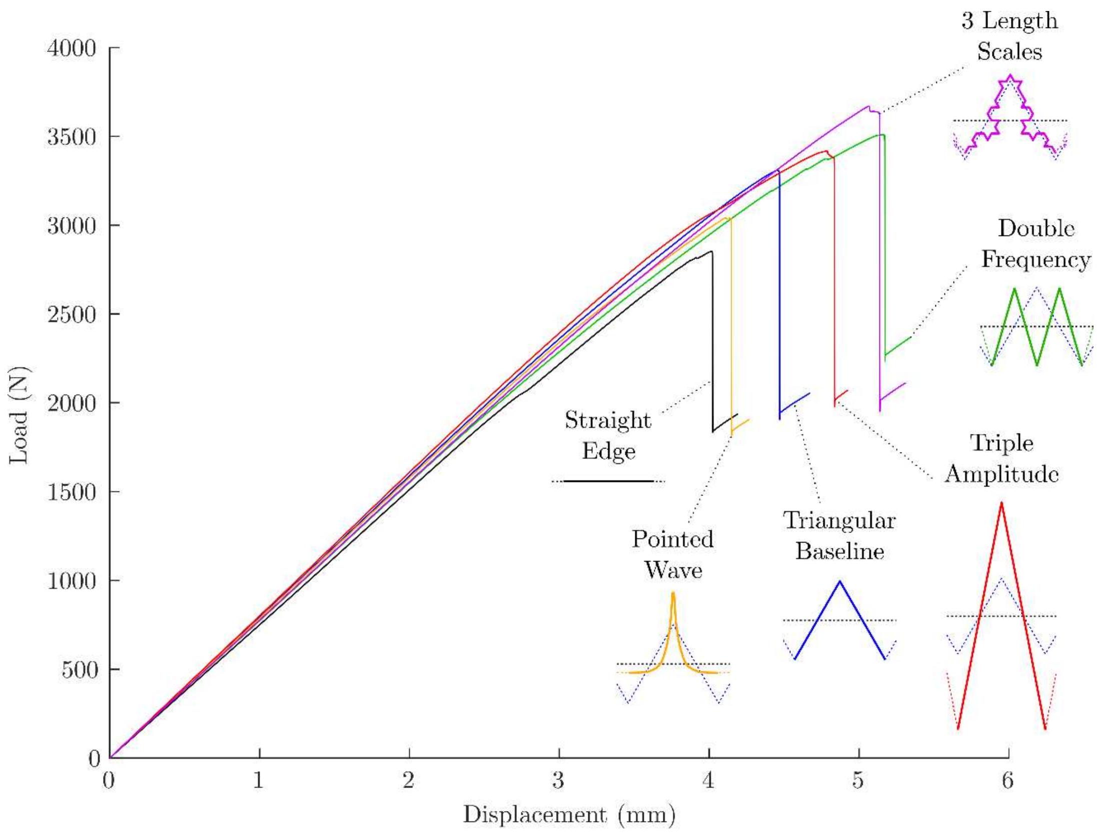

Figure 6. Representative load vs displacement traces for each sample.

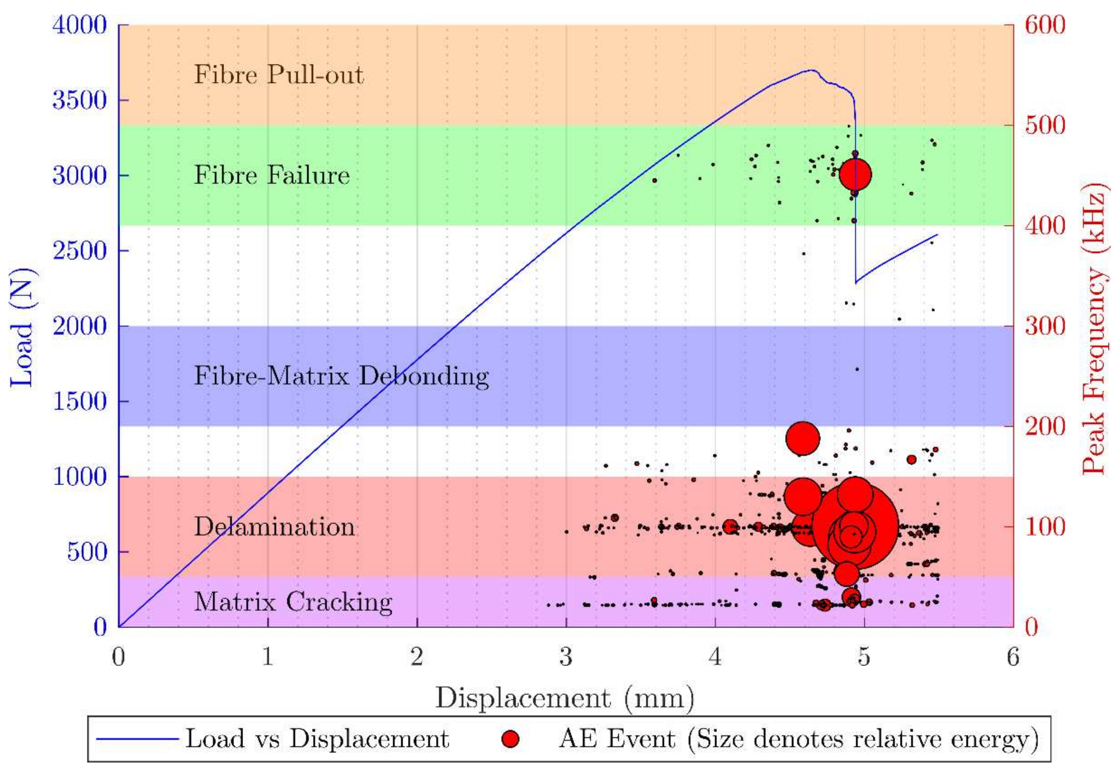

Figure 7. Force vs displacement and AE results of a double frequency specimen.

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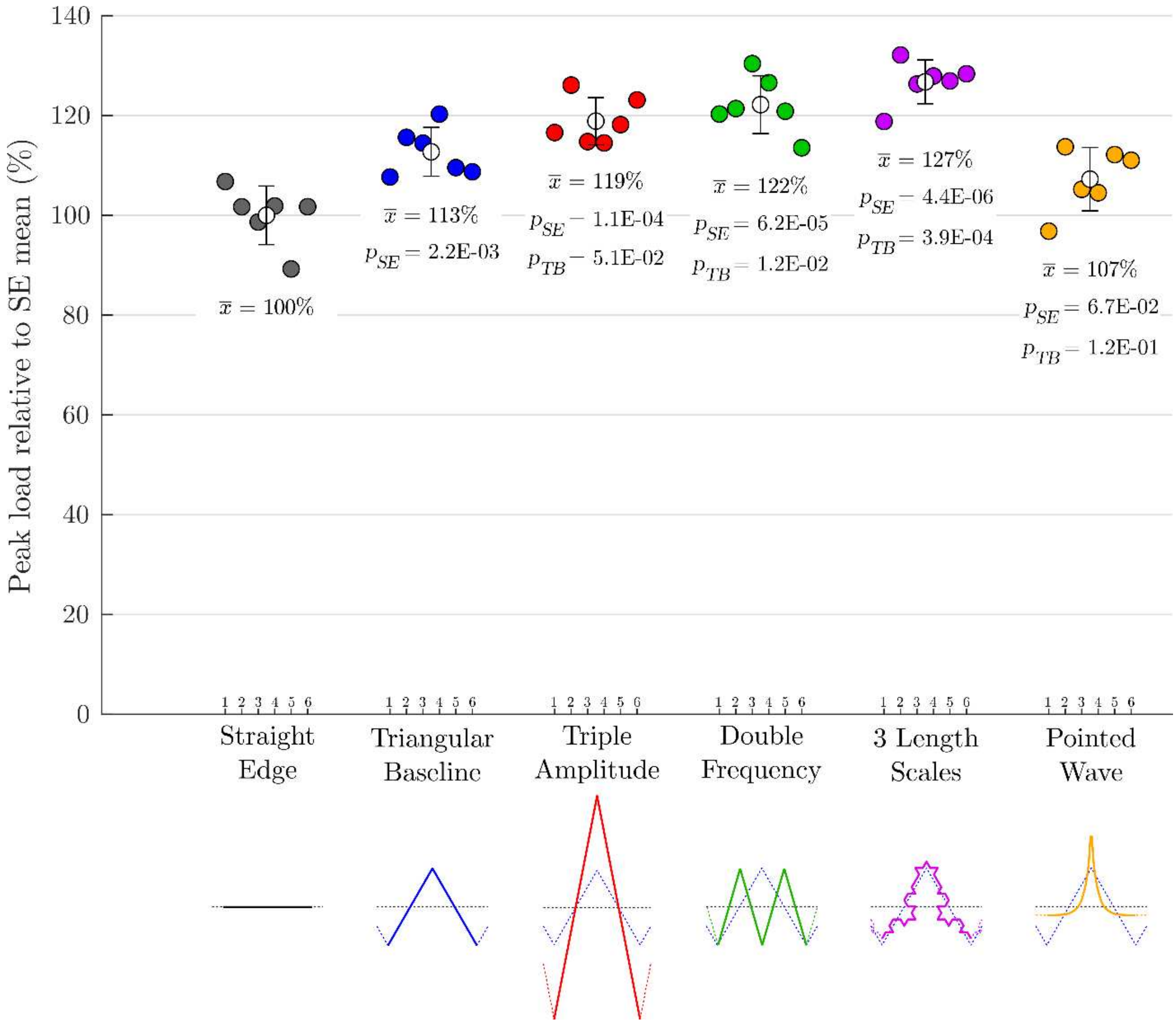

Figure 8. Peak load relative to a straight edged adherend. $\bar{x}$ indicates the sample mean, and p_{SE} & p_{TB} indicate the p-values compared to the straight edged and triangular baseline samples respectively.

overlaid on the loading trace for a double frequency profile specimen. The results for peak load, and dissipated energy normalised by the mechanical energy up to critical failure, are displayed in Figures 8 and 9 respectively. In order to judge the statistical significance of the results, the p-values have been calculated for each measure, relative to both the straight edge and triangular baseline samples, and are reported in Figures 8 and 9. A typical interpretation of p-values in the literature is that $p \leq 0.05$ indicates statistically significant results.

4. Discussion

The specimens exhibited the failure mode of interest, translaminar fracture in the laminate local to the adherend termination, as shown in Figure 5. The acoustic emission results, such as that seen in Figure 7, suggest matrix cracking and delamination are the initial modes of failure, whilst fibre failure begins to occur later. The fracture surfaces in Figure 5 show, in support of the AE data, that failure occurred in the laminate with interlaminar, intralaminar and translaminar failure modes all present. The fracture surface in Figure 5b shows that the translaminar fracture of the 45° ply is seen to be deflected away from being a straight fracture in the profiled specimen.

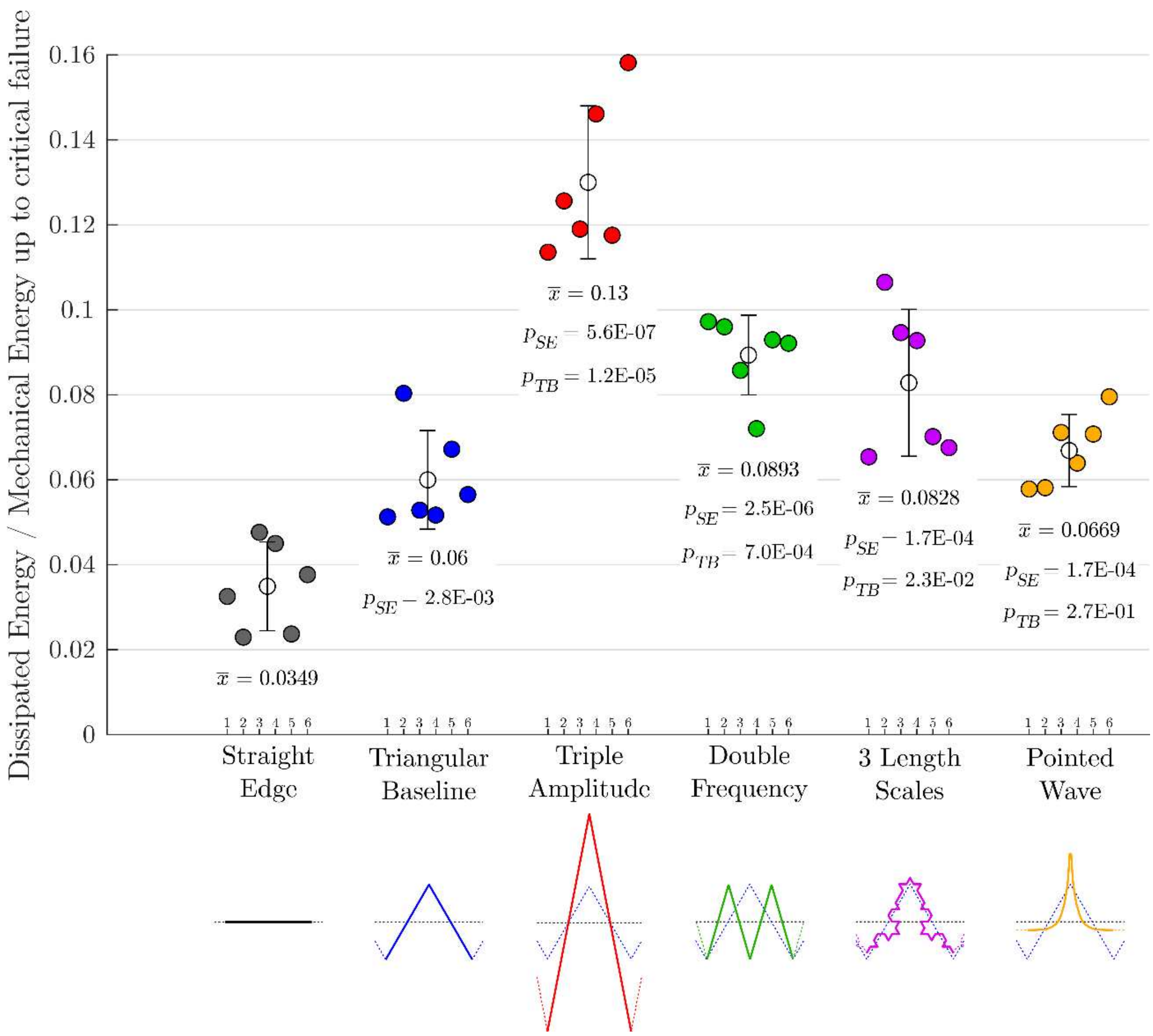

Figure 9. The ratio of dissipated energy to mechanical energy up to the critical failure. $\overline{x}$ indicates the sample mean, and p_{SE} & p_{TB} indicate the p-values compared to the straight edged and triangular baseline samples respectively.

Profiling of the adherend led to significant increases in mechanical performance. In the current work, the best improvements achieved relative to the straight edged sample were: a 27.0% increase in peak load ($p = 4.4 \times 10^{-6}$) achieved using a 3-length-scale profile; and a 272% increase in the ratio of dissipated to mechanical energy up to the critical failure ($p = 5.6 \times 10^{-7}$) achieved using a triple amplitude profile.

Further improvements could in principle be obtained using this profiling technique. The triangular baseline sample gave increases relative to the straight edge sample of 12.7% ($p = 2.2 \times 10^{-3}$) in peak load and 71.8% ($p = 2.8 \times 10^{-3}$) in the ratio of dissipated to mechanical energy up to the critical failure. Increasing the amplitude, frequency, and number of length scales in the pattern were all shown to further improve the performance as shown in Figures 8 and 9. Relative to the triangular baseline sample: increasing the number of length-scales from 1 to 3 led to an increase in peak load of 12.4% ($p = 3.9 \times 10^{-4}$), and an increase in the ratio of dissipated to mechanical energy up to the critical failure of 38.1% ($p = 2.3 \times 10^{-2}$); doubling the frequency of the profile led to an increase in peak load of 8.38% ($p = 1.2 \times 10^{-2}$), and an increase in the ratio of dissipated to mechanical energy up to the critical failure of 49.0% ($p = 7.0 \times 10^{-4}$); and tripling the amplitude of the profile led to an increase in peak load of 5.46% ($p = 5.1 \times 10^{-2}$) which was only of marginal statistical significance, but it led to a highly significant increase in the ratio of dissipated to mechanical energy up to the critical failure of 117% ($p = 1.2 \times 10^{-5}$).

The alternative geometry profile, the 'pointed wave', was less successful than the other profiles tested. It showed an increase of 7.25% ($p = 6.7 \times 10^{-2}$) in peak load relative to the straight edged sample which was only marginally statistically significant, and an increase lower than for the triangular baseline profile sample. The pointed wave profile showed an increase in the ratio of dissipated to mechanical energy up to the critical failure of 91.6% ($p = 1.7 \times 10^{-4}$) relative to the straight edged sample, but when compared to the triangular baseline sample the increase of 11.5% ($p = 2.7 \times 10^{-1}$) was statistically insignificant.

5. Conclusions

This paper shows the effects of applying a profiled termination to the metal adherend of a metal-CFRP adhesive joint. Our results show that using a suitably defined pattern:

- the peak load can increase by at least 27.0%; and
- the energy dissipated up to critical failure normalised by the mechanical energy can increase by at least 272%.

The work also shows that this technique may be utilised to obtain further improvements by:

- increasing the profile amplitude (in our tests, tripling the amplitude resulted in a peak load increase of 5.46% and an increase of the energy dissipated up to critical failure normalised by the mechanical energy of 117%);
- increasing the profile frequency (in our tests, doubling the frequency resulted in a peak load increase of 8.38% and an increase of the energy dissipated up to critical failure normalised by the mechanical energy of 49.0%); and
- increasing the number of length scales (in our tests, incorporating 3 length-scales into the profile, rather than 1, resulted in a peak load increase of 12.4% and an increase of the energy dissipated up to critical failure normalised by the mechanical energy of 38.1%).

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