Optimization of dissimilar single-lap joints bonding different adherends in quasi-static conditions with thermal residual stresses

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Introduction

Adhesive bonding has emerged as a promising technique in the transportation industry due to its design versatility, vibration damping capabilities, and ability to join dissimilar materials. However, when using carbon-fibre-reinforced polymers (CFRPs) in single lap joints (SLJ), delamination caused by high peel stresses remains a common issue [1].

This study aims to address delamination issues in CFRP SLJs through numerical optimization of various aspects, including materials, geometries, and residual thermal stresses. One approach introduced in this study involves the use of curved substrates and varying adhesive layer thicknesses. The desired curvature is achieved by adjusting the orientation of composite layers, utilizing the thermal expansion mismatch between the longitudinal and transverse directions during the curing process. Additionally, the use of hybrid joints, specifically CFRP and aluminium, is explored as well and is compared with the curved configuration. The concept of curved joints holds potential for direct implementation within the aeronautical industry, particularly in applications such as aircraft wings, which typically exhibit bending while on the ground and subsequently straighten during flight, as seen in Figure 1.

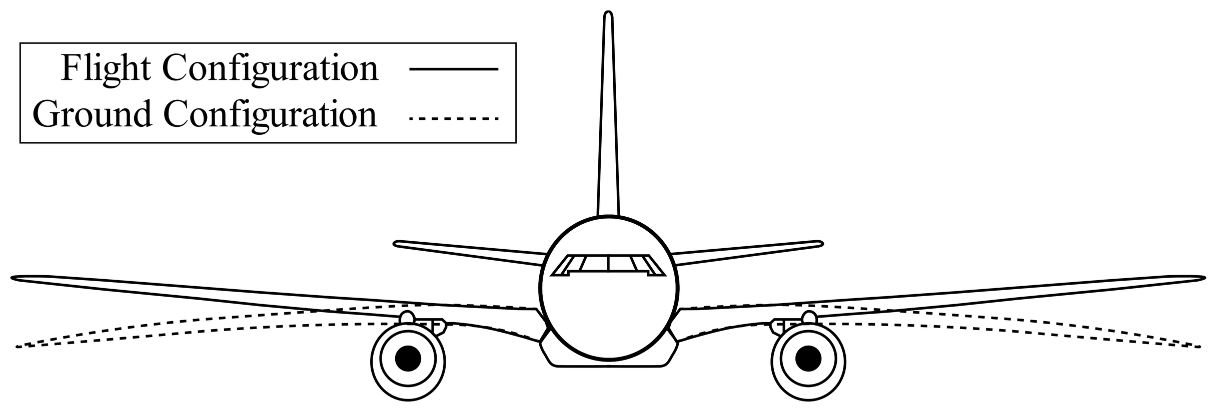

Figure 1 – Schematic of an airplane where wing deflection for ground and flight configuration is displayed. The depiction of the ground configuration serves as a representation of pre-bending in the design of aircraft wings for example.

Numerical details

In order to investigate the various configurations, several numerical models were developed. The stress distributions were analysed using an elastic modelling approach, while the failure mode and failure load were predicted using cohesive zone modelling (CZM). Additionally, thermal residual stresses were incorporated into the models using a thermal step. All of these numerical models were constructed using ABAQUS CAE software.

Adhesive and Adhrends

The adhesive chosen for this study was the Scotch Weld AF 163-2k, manufactured by 3M Company. This adhesive is a film-form modified epoxy that is widely recognized for its excellent fracture toughness, peel strength, and extensive use in the aerospace industry [2]. The CFRP material used in all tested configurations was Texipreg HS 160 T700, a unidirectional prepreg. Additionally, an aluminium alloy from the 2024-T3 Alclad series, supplied by AMI Metals, was used for the hybrid SLJs.

Joint Geometry

Figure 2 illustrates the geometry of the specimens and the material distribution in the adherends that were utilized for the tests. The geometry parameters adopted were : L_T = 215 mm, L_0 = 25 mm, t_s = 3.20 mm, $t_{a,min}$ = 0.2 mm, $t_{a,max}$ = 1.0 mm and h = 1.4 mm (for the curved cases using a layup of of $[0^{\circ}_{10}/90^{\circ}_{11}]$). The hybrid joints featured the same geometry however, an 0.8 aluminium layer is used.

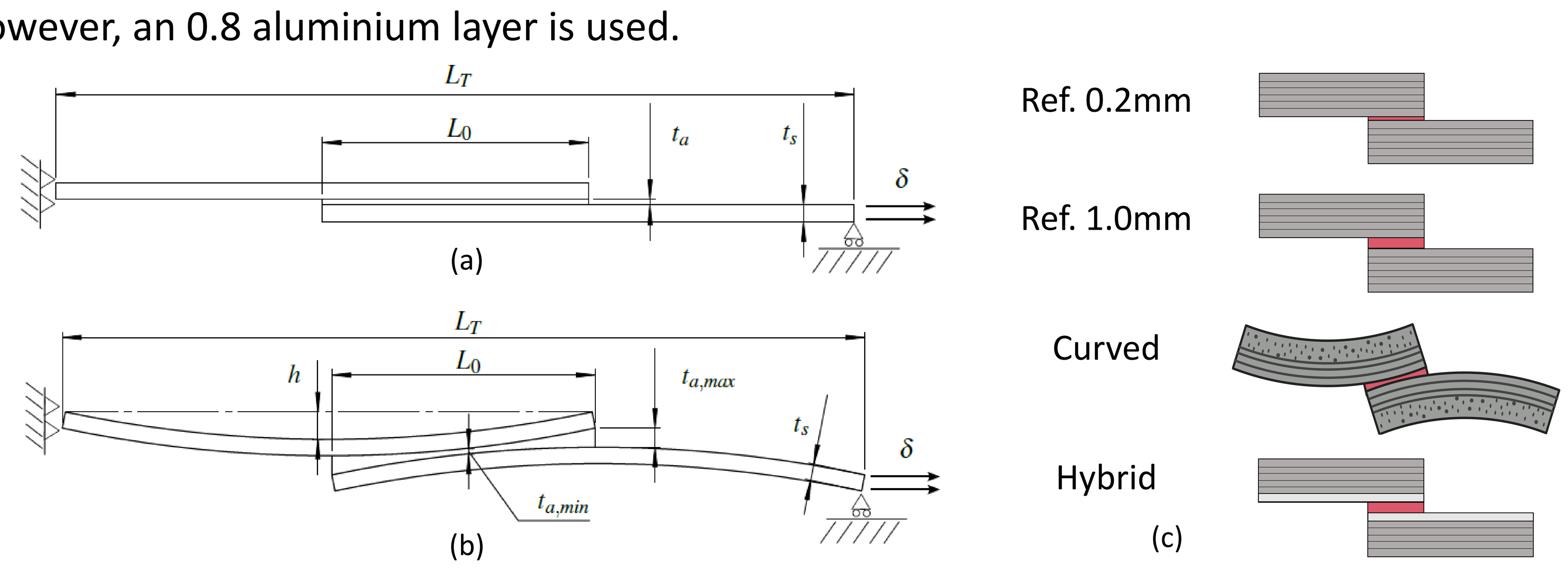

Figure 2 – SLJ specimen geometry: (a) planar SLJ and (b) curved SLJ. (c) SLJs configurations.

Stress distributions

The stress distributions, as depicted in Figure 3, exhibit notable differences among the reference cases, curved SLJ, and hybrid configurations. In the reference cases, stress concentrations are observed at the overlap ends, whereas the curved SLJ demonstrates a significant reduction in stress concentration at these regions. This reduction is attributed to the suppression of bending caused by the curved geometry and the additional compressive thermal stresses. In the case of the hybrid configuration, it is believed that stress homogenization occurs due to the plasticization of the aluminium and the presence of compressive stresses, as highlighted by Simões et al. [2]. Thus, distinct stress alleviation mechanisms are evident in these two configurations.

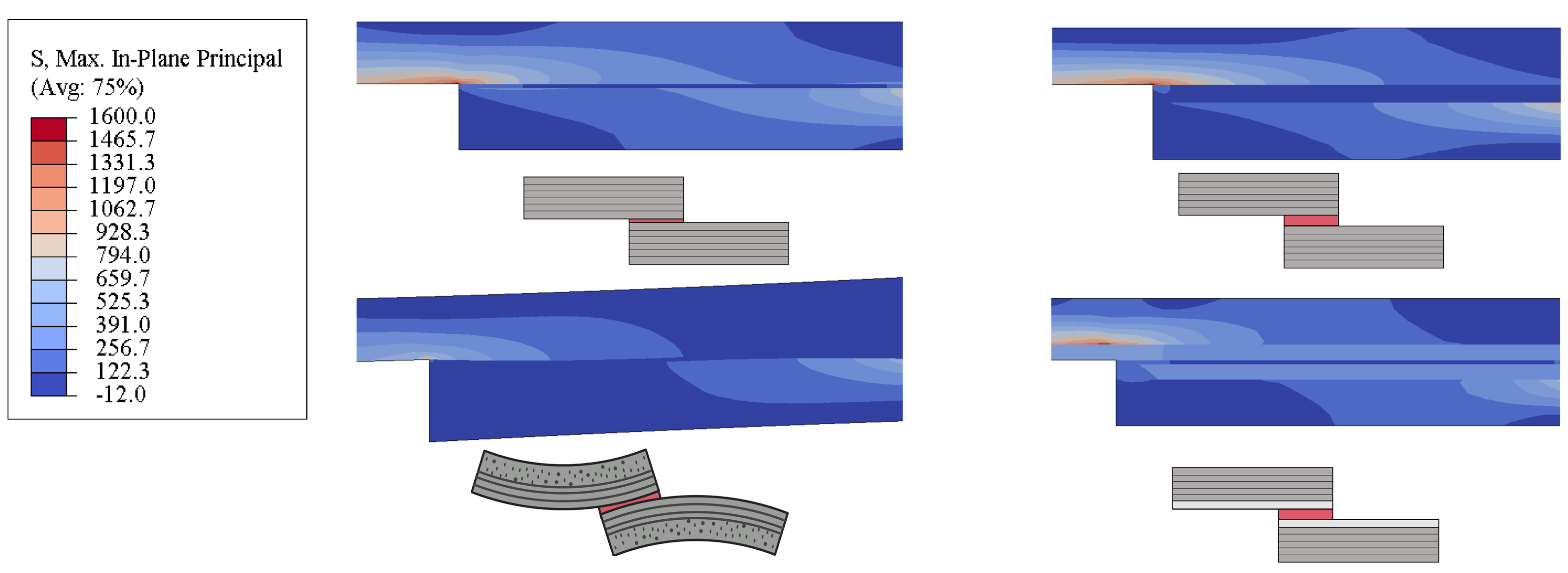

Figure 3 – Maximum principal stress distribution of each configuration.

SLJ performance

Quasi-static testing was conducted on the joints to assess their failure load and failure mode. The results, depicted in Figure 4, revealed that the conventional CFRP SLJ exhibited delamination as the failure mode. In contrast, cohesive failure was observed in all other configurations tested.

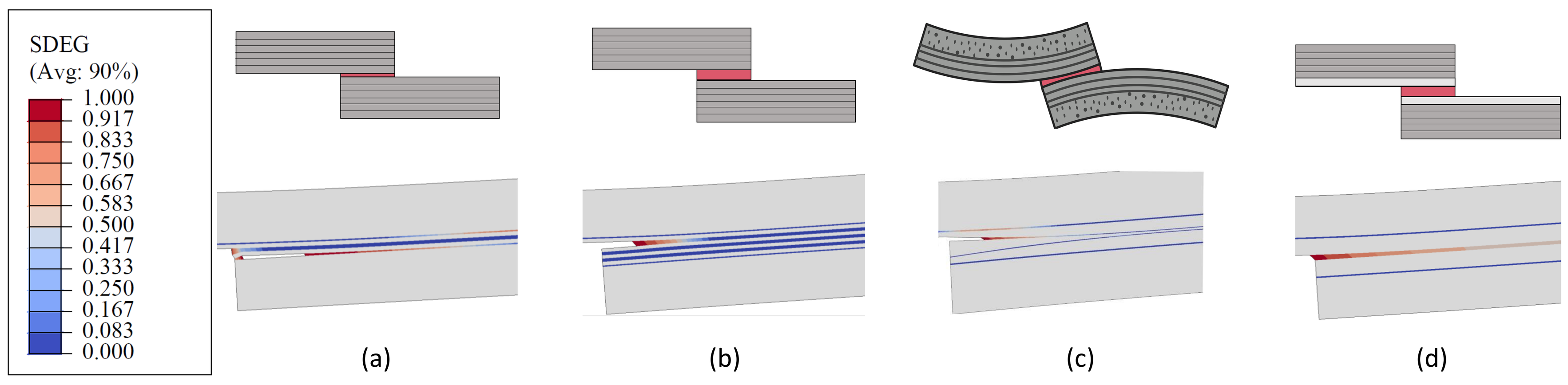

Figure 4 – Failure modes obtained for all configurations.

When comparing the $P-\delta$ curves, it is evident that the curved SLJ exhibits a failure load that is comparable to the reference 0.2 mm configuration, while significantly surpassing the 1.0 mm configuration in terms of failure load. However, this configuration is clearly surpassed by the hybrid joint. Not only that, but also in this configuration a much more ductile joint is obtained.

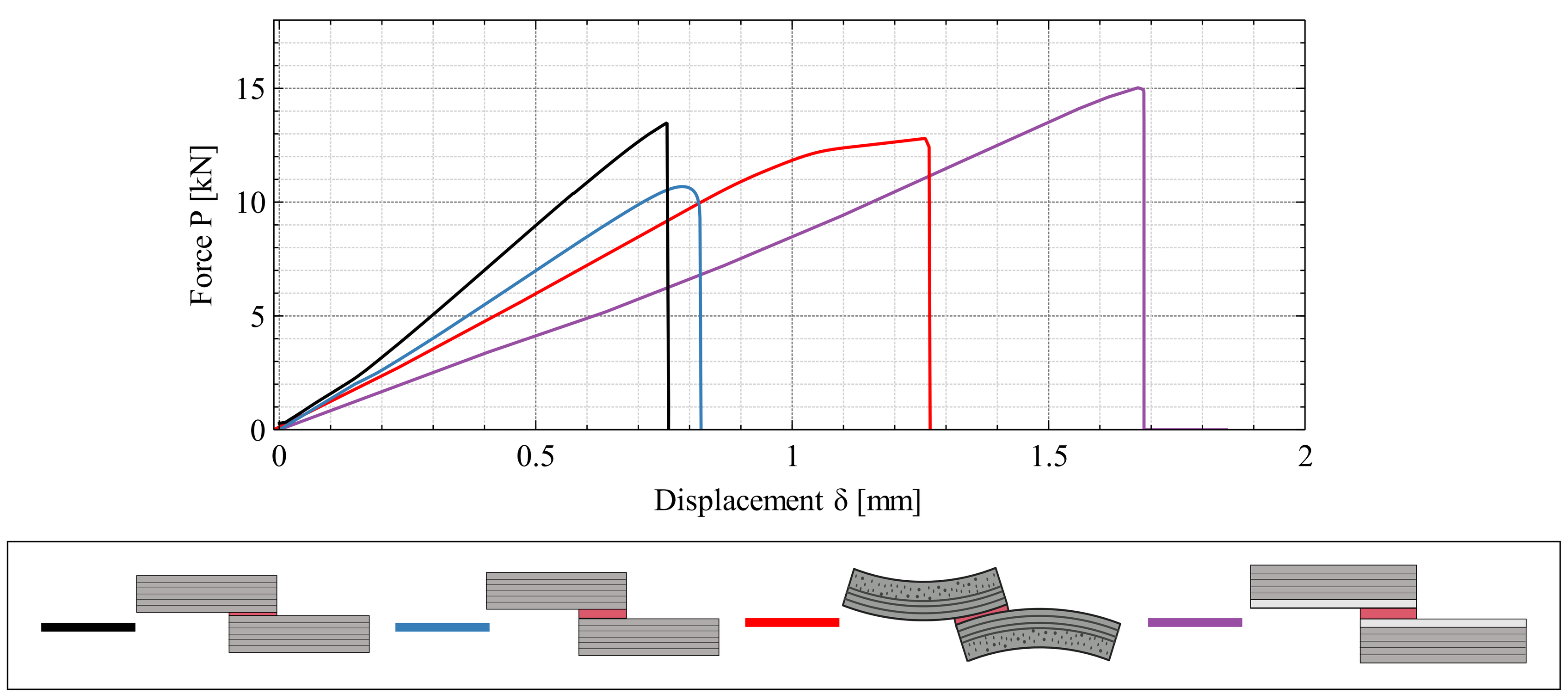

Figure 5 – $P-\delta$ curves obtained numerically for all the considered configurations.

Conclusions

- Numerical testing of various configurations revealed promising results in preventing delamination. The reference case with a 1.0 mm adhesive thickness demonstrated cohesive failure, effectively avoiding delamination but at the cost of a significant decrease in failure load.

- The curved configuration exhibited a remarkable reduction in stress concentration, resulting in lower peel stresses and preventing delamination. Similarly, the hybrid configuration showed stress homogenization due to the presence of the aluminium layer, leading to a substantial increase in failure load and joint ductility, while still preventing delamination. It is worth noting that the hybrid configuration requires special surface treatments, such as Sol-Gel + Primer, for optimal bonding between the aluminium and CFRP. On the other hand, the curved configuration necessitates different stacking sequences and the incorporation of adhesive to achieve its desired effect, requiring additional manufacturing steps when compared with the reference CFRP SLJ.

References

[1] da Silva, L. F. M., Öchsner, A., & Adams, R. D. (2018). Handbook of Adhesion Technology (2nd ed.). Springer Berlin Heidelberg.

[2] Simões, B. D., Nunes, P. D. P., Ramezani, F., Carbas, R. J. C., Marques, E. A. S., & da Silva, L. F. M. (2022). Experimental and Numerical Study of Thermal Residual Stresses on Multimaterial Adherends in Single-Lap Joints. Materials, 15(23).

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