Enhancing Joint Performance with Residual Stresses: An Optimization Study on Adhesively Bonded Joints using Dissimilar Joints

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1 Introduction

Adhesive bonding has emerged as a promising technique in the aeronautical industry due to its design versatility, vibration damping capabilities, and capacity to join dissimilar materials. Composite materials, such as carbon-fibre-reinforced polymers (CFRPs), are commonly employed for their high strength and stiffness-to-density ratios; however, delamination remains a prevalent failure mode in CFRP single lap joints (SLJ) [1]. This study aims to prevent delamination in CFRP single lap joints by employing curved substrates and non-uniform adhesive layer thicknesses. Substrate curvature is achieved either by varying the composite layer orientation or by incorporating an aluminium layer, which induces curvature due to thermal expansion mismatch during curing. The resultant curvature yields non-uniform adhesive layers with thicker edges, generating higher compressive thermal stresses, which are anticipated to prevent delamination. The combined effects of geometry and thermal stresses are expected to reduce peel stresses, enhance joint ductility, and ultimately improve joint strength. The curved concept has shown promising results in metal SLJ, while curved CFRP joints are still under investigation, with manufacturing challenges yet to be resolved.

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.

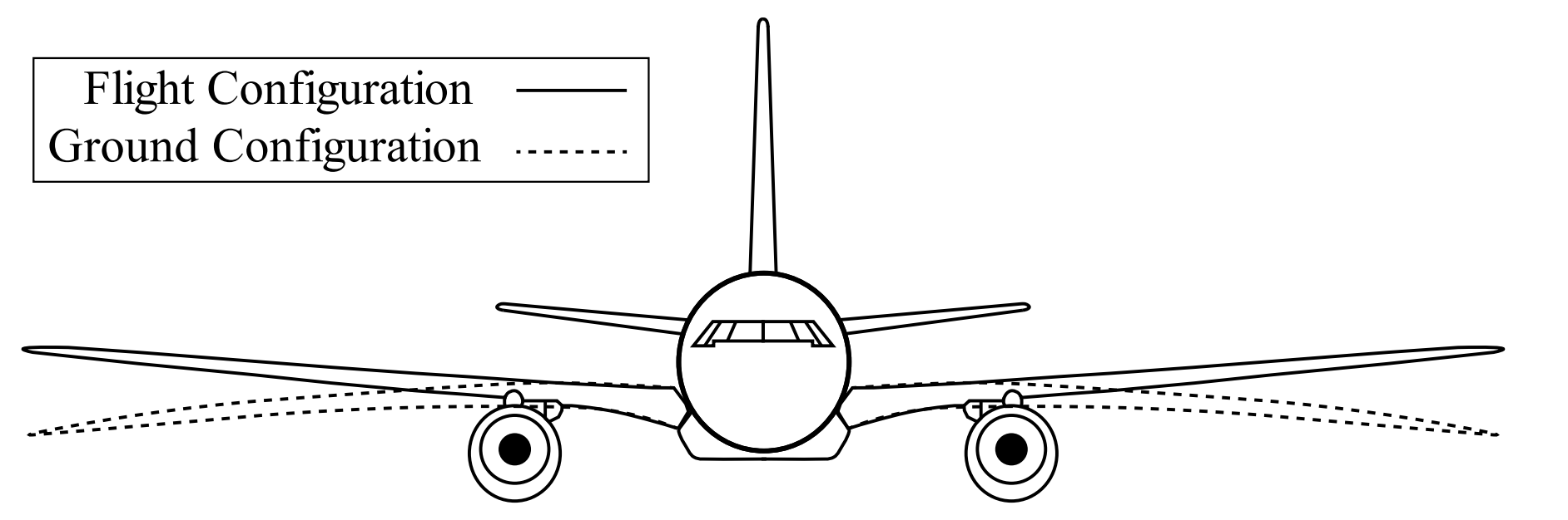


Figure 1 - Schematic of an airplane where wing deflection for ground and flight configuration is displayed. The depiction of the ground configuration serves as a representation of pre-bending in the design of aircraft wings for example.

2 Aim

- Determine the potential of the curved geometry by the use of curved aluminium single lap joints;
- Evaluate the benefits of curved substrates with a gradually increasing adhesive thickness towards the overlap region in CFRP joints where the curvature is obtained due to residual stresses in asymmetric laminates or due to the addition of an aluminium layer to the composite;
- Analyse the effects of geometry, thickness, and material selection on joint performance through numerical simulations, finite element analysis, and experimental validation;

3 Numerical Modeling

Curved Aluminium Single Lap Joints

This study employed several numerical models, using ABAQUS/CAE, with non-uniform adhesive layer thicknesses under quasi-static conditions, seen in Figure 2, to investigate the curved substrate concept, considering the linear-elastic behaviour of aerospace industry-standard aluminium alloy 2024-T3. Two adhesives, ARALDITE® 2015-1 (HUNTSMAN) and Scotch Weld AF 163-2k (3M Company), were selected based on their distinct curing properties. To examine the impact of thermal stresses, a thermal step simulating the adhesive cure cycle and a mechanical step with a 1mm displacement applied to all models were incorporated into the analysis.

Nomenclature: $\Delta h\ X$, refers to the model with Xmm of extra maximum thickness relative to the reference

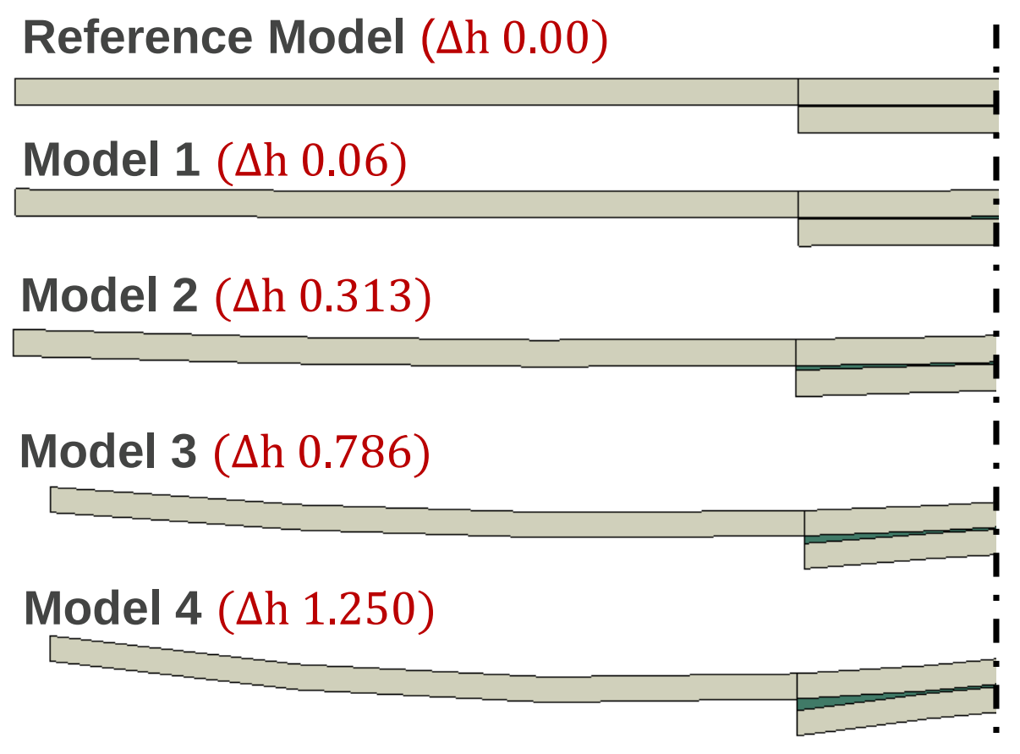
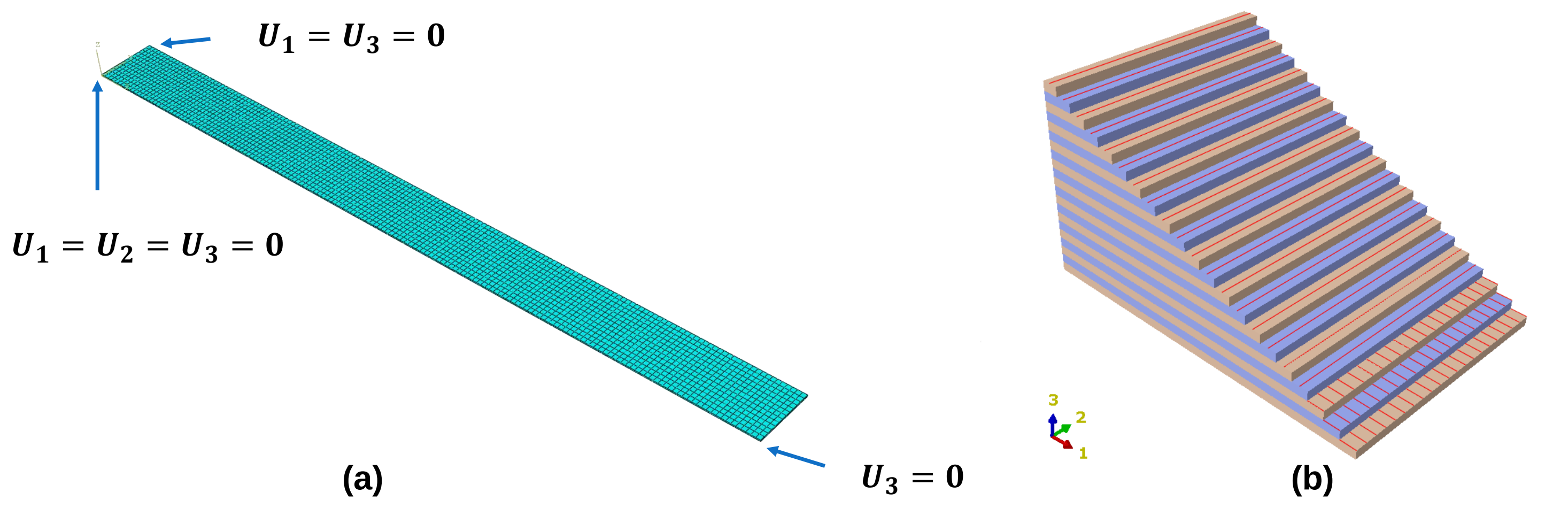


Figure 2 - Schematic of the curved SLJ numerical models in aluminium.

Curved CFRP Single Lap Joints

The curved substrate concept was also applied to composite materials, where curvature was achieved through thermal stresses resulting from asymmetric layer layup, causing composite bending and a non-uniform adhesive layer. For composite plates, warpage arises from the orthotropic behaviour of the coefficient of thermal expansion (CTE) [2].

The desired curvature was predicted numerically, using shell elements with a composite layup section, shown in Figure 3.



(a) (b)

Figure 3 – Thermo-mechanical model of the composite layup. (a) Geometry and boundary conditions of the 3D shell model. (b) Composite layup.

4 Experimental Details

The desired curvature was achieved by mechanically bending the aluminium adherends. 3D printed spacers were utilized to control the non-uniform adhesive layer thickness, as shown in Figure 4. Adherends underwent surface treatment, specifically sandblasting followed by acetone cleaning, before bonding. The joints were fabricated using the paste adhesive ARALDITE® 2015-1, which cured at ambient temperature.

Composite manufacturing involved a manual layup, followed by placement in a hot press for a 2-hour cure cycle and subsequent cooling to ambient temperature at 5 bar.

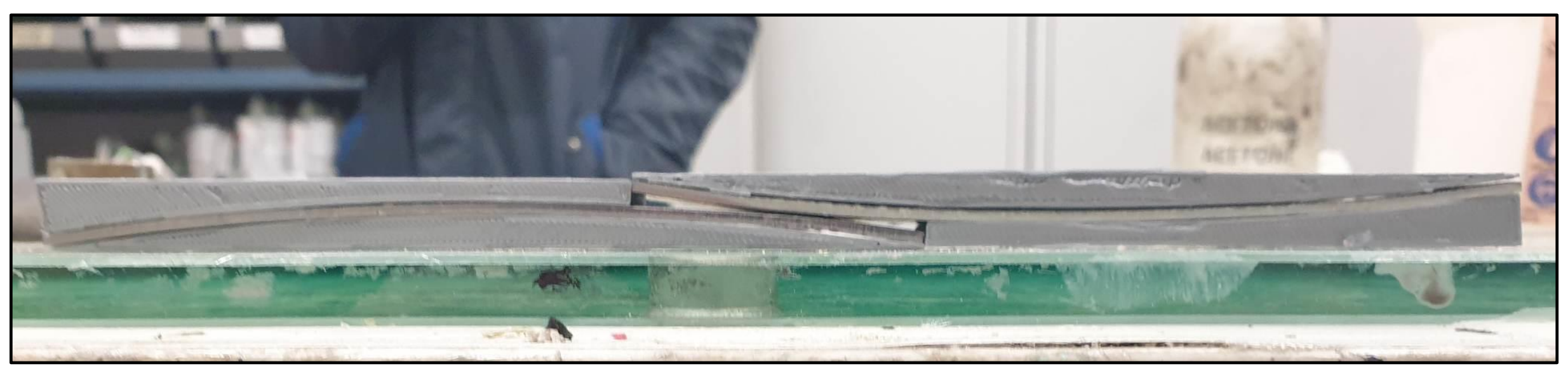
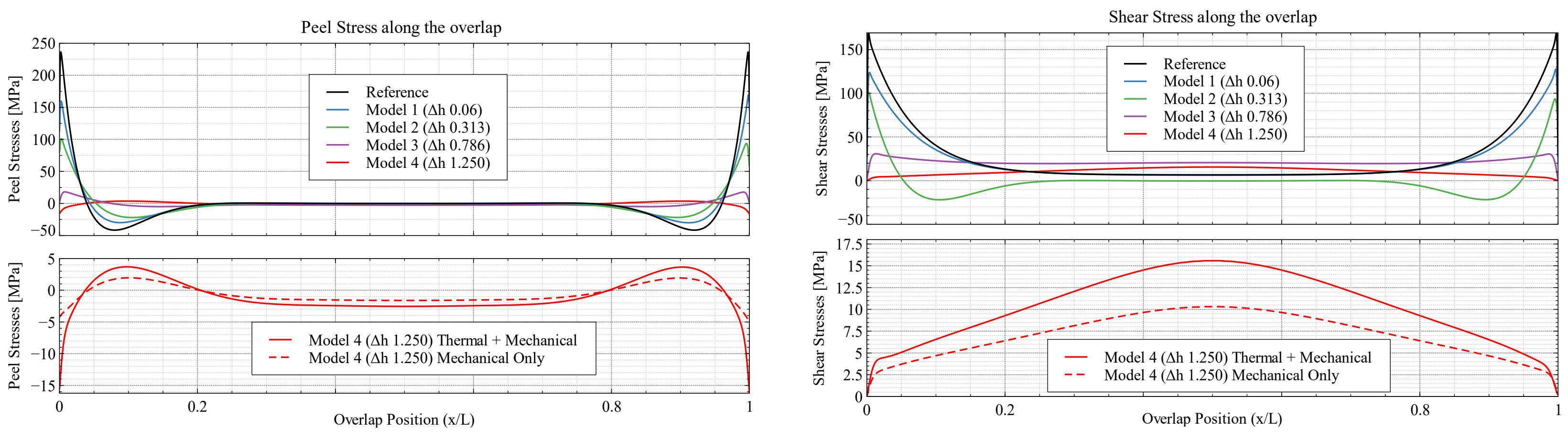


Figure 4 – Curved aluminium SLJ assembly prior to adhesive application.

5 Results

Curved Aluminium Single Lap Joints

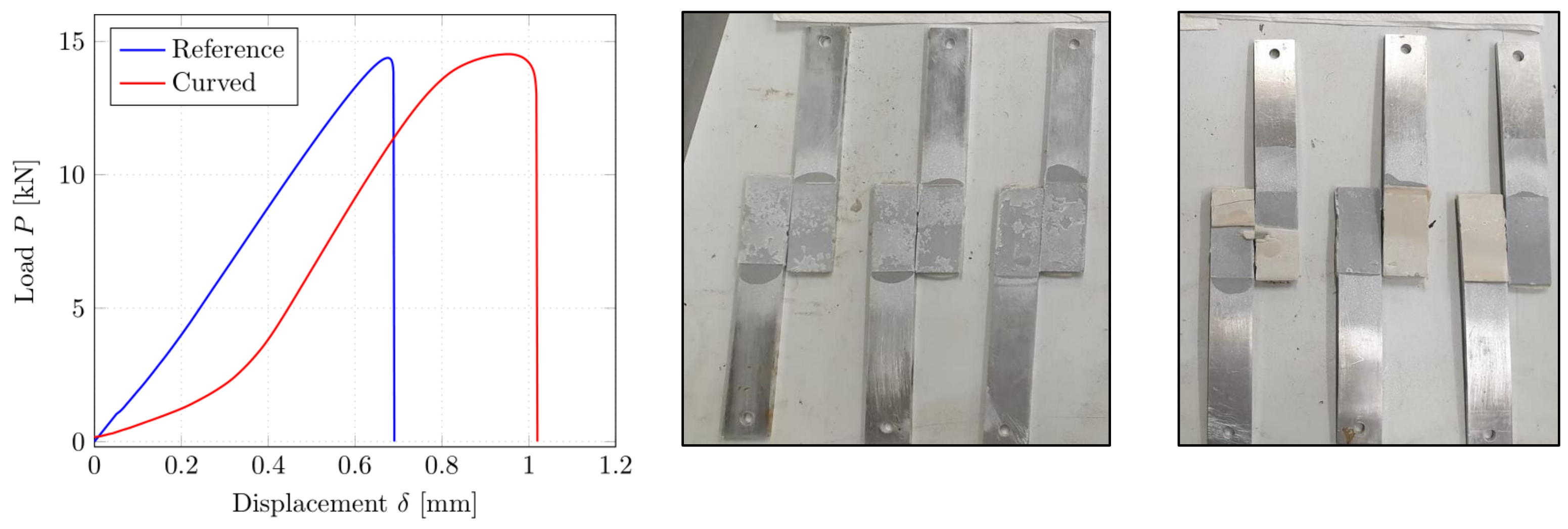
Stress evaluation was conducted for all curved aluminium SLJ models in the elastic-static simulation along the overlap length, examining both peel and shear stresses, as depicted in Figure 5. The results indicate that the most curved model exhibited the lowest peel and shear stresses after the mechanical step of 1mm displacement. Furthermore, it was observed that thermal stresses did not significantly impact the results for this joints.



(a) (b)

Figure 5 – Numerical results, the upper plot corresponds to the full simulation, including thermal and mechanical steps, while for the bottom plots, a comparison between the effect of the thermal stresses can be seen. (a) Peel stress distribution. (b) Shear stress distribution.

Experimentally, the manufactured curved joints exhibited higher ductility compared to reference joints, as shown in Figure 5(a). In terms of failure mode, mixed failure was observed for reference joints, while adhesive failure occurred in curved joints, illustrated in Figure 5(b) and (c).



(a) (b) (c)

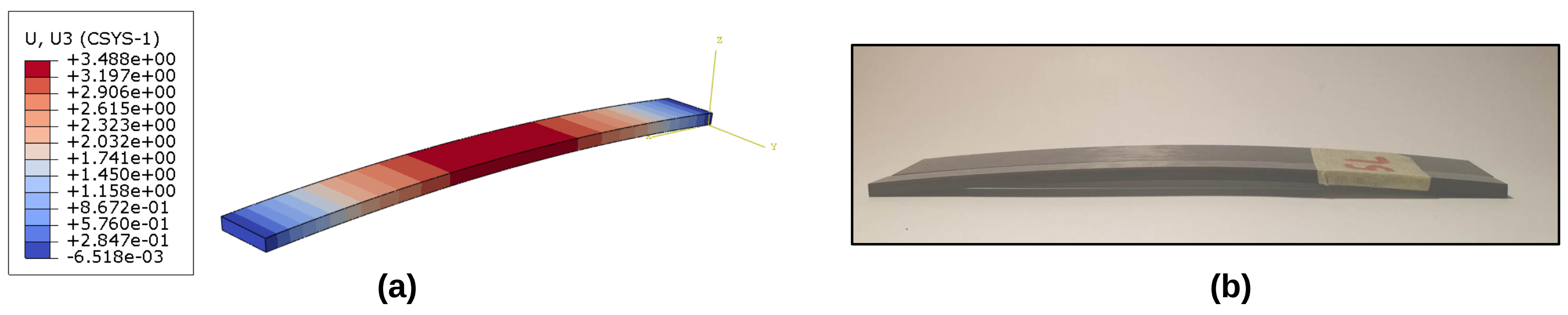
Figure 6 – Experimental results obtained for the aluminium SLJ. (a) Force – Displacement curve. (b) Failure mode of the reference joints. (c) Failure mode of the curved SLJ.

Curved CFRP Single Lap Joints

Relatively, to the CFRP adherends, the curvature obtained matched with the experimental results, as seen in Table 1 and on Figure 7.

Table 1 – Numerical and experimental results of the observed curvature of the asymmetric composite plates.

Layup	Numerical (mm)	Experimental (mm)	Error (%)
$[0°_5/90°_{16}]$	3.49	3.72	6.2



(a) (b)

Figure 7 – Curvature of the CFRP adherends. (a) Numerical simulation results. (b) Manufactured adherend.

Simões et al. [3] previously observed that adding a planar aluminium layer to a planar SLJ resulted in a 35% increase in strength and prevented delamination compared to the conventional reference CFRP SLJ.

Curved CFRP joints are expected to surpass conventional ones in failure load, with optimization procedures determining the optimal curvature and composite layup. Additionally, incorporating an aluminium layer could further enhance the joint concept's potential.

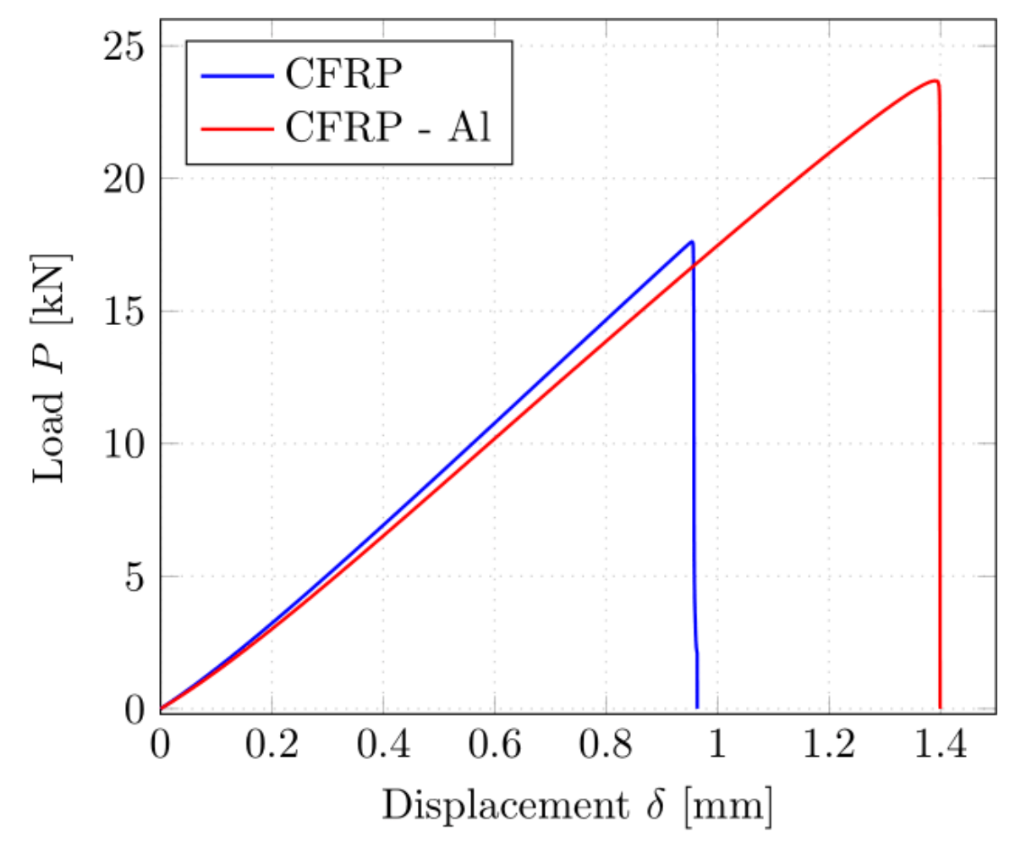


Figure 8 – Load-displacement curves of the conventional CFRP joints and planar CFRP-Al tested by Simões et al. [3] .

6 Conclusions

- The results from curved metal SLJ experiments, aimed at validating the curved joint concept, demonstrated promising outcomes, yielding a more ductile joint. Moreover, numerical findings revealed significantly lower peel stresses in this geometry compared to the traditional planar configuration, an essential factor in the failure of composite CFRP SLJs.
- Curved CFRP adherends were successfully manufactured through modifications in the composite layup and accurately predicted using the ABAQUS software package.
- The curved joint concept is expected to yield higher failure loads than conventional CFRP joints, and when combined with the CFRP-Al approach, it is expected to further improve joint performance.

References

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