Structural behaviour of adhesive bonds in 3D printed adherends

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Abstract This work studies the tensile performance of adhesively-bonded single-lap joints (SLJ) between additive manufactured (AM) adherends of Polylactic Acid (PLA), Polyethylene Terephthalate Glycol-modified (PETG), and Acrylonitrile Butadiene Styrene (ABS), bonded with the adhesives Araldite® 2015 and Sikaforce® 7752. The adherends' mechanical elastic, plastic and fracture properties are determined prior to the assessment of the adhesive performance in SLJ. Failure modes, joint strength, assembly stiffness, and failure energy are obtained experimentally and compared to CZM predictions, aiming to provide the best material/adhesive combination that maximizes the joint performance. In terms of strength and stiffness, PLA joints bonded with the Araldite® 2015 provided the best results, although the behavior was different for the dissipated energy. The CZM approach showed to be a reliable design approach for bonded AM joints.

Objectives

✓Manufacture and characterization of thermoplastic adherends (PLA, ABS and PET
✓Experimental and numerical study of single lap joints under tensile loads;
✓Compare experimental and CZM numerical data;

✓ Evaluate:

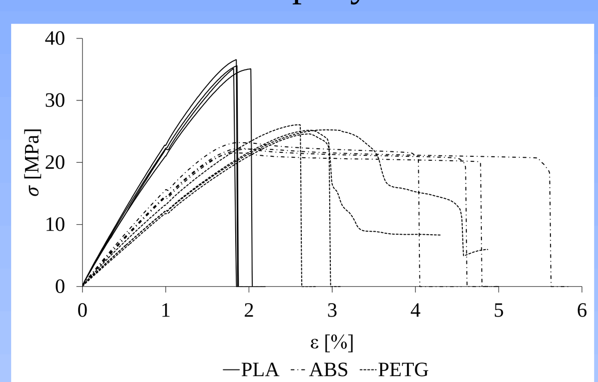
- Failure modes;
- Joint strength (P_m)
- Assembly stiffness (K_m)
- Failure energy (E_m)

Outcomes:

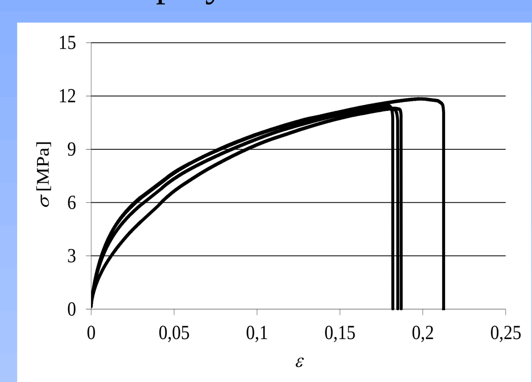
✓Guidelines for strong and energy absorbing SLJ;
✓Validation of CZM model for AM SLJ..

Selected materials

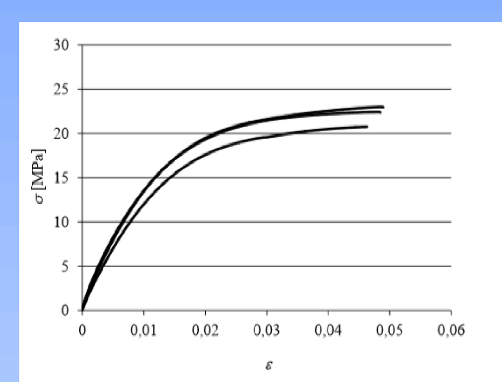
- **Adherends** – PLA, ABS and PETG
-**Adhesive** – Epoxy Araldite® 2015 and ductile polyurethane adhesive Sikaforce® 7752.



σ-ε curves of all adherends



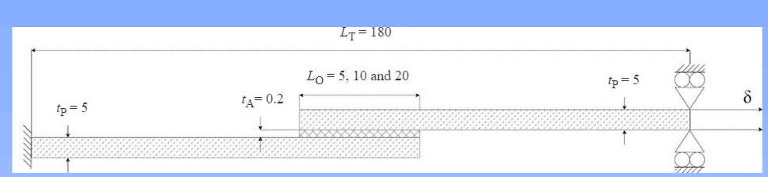
σ-ε curves of the Araldite® 2015



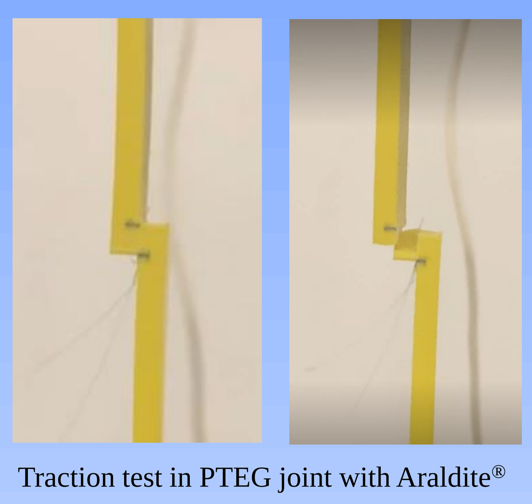
σ-ε curves of the Sikaforce® 7752

Single-lap joints configuration and testing

Geometry



Testing



Traction test in PTEG joint with Araldite® 2015 before failure; after failure

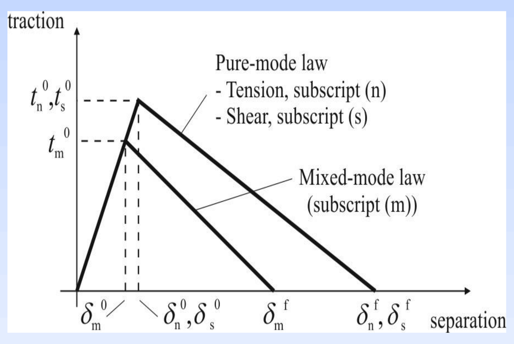
Traction test in ABS joint with Araldite® 2015

Numerical analysis conditions

Numerical simulation– 2D Abaqus®:

- Abaqus® elements:
  - CPE4R;
  - COH2D4.
- Mesh size– 0,2x0,2 mm^2:
  - Single bias – 0,2 – 2 mm.

Triangular traction–separation law



Triangular model:

$$\mathbf{t}=\begin{Bmatrix} t_n \\ t_s \end{Bmatrix}=\begin{bmatrix} K_{nn} & K_{ns} \\ K_{ns} & K_{ss} \end{bmatrix}\cdot\begin{Bmatrix} \varepsilon_n \\ \varepsilon_s \end{Bmatrix}=\mathbf{K}\boldsymbol{\varepsilon}.$$

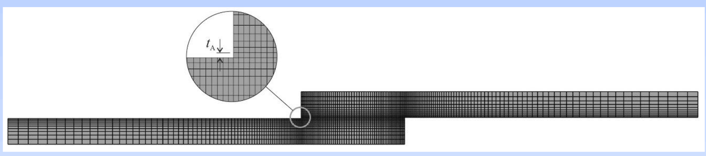
QUADS damage

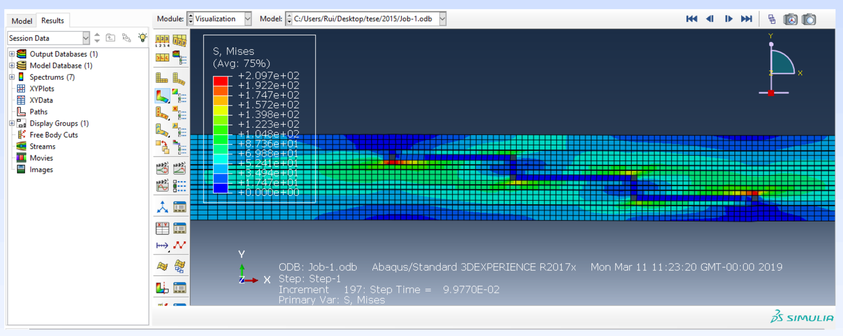
$$\left\{\frac{\langle t_n \rangle}{t_n^0}\right\}^2+\left\{\frac{t_s}{t_s^0}\right\}^2=1.$$

Power law criterion

$$\frac{G_n}{G_n^c}+\frac{G_s}{G_s^c}=1.$$

Mesh details for a SLJ with L_O=20 mm





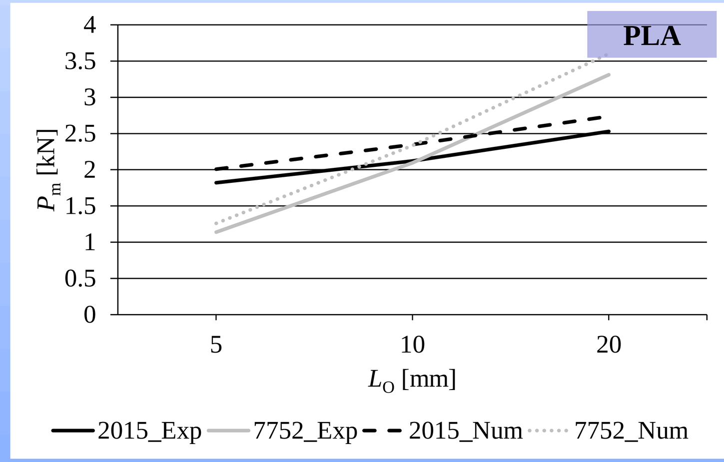
Experimental and numerical results

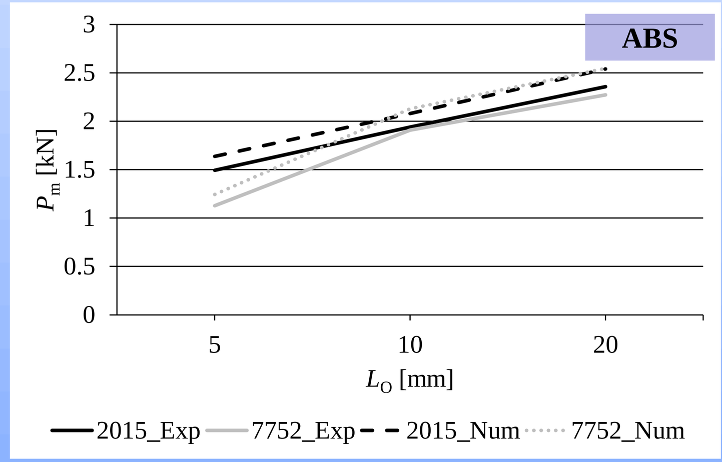
Failure modes: a) Cohesive in the adhesive (PLA with Sikaforce® 7752) and b) adherend (ABS with Araldite®2015).

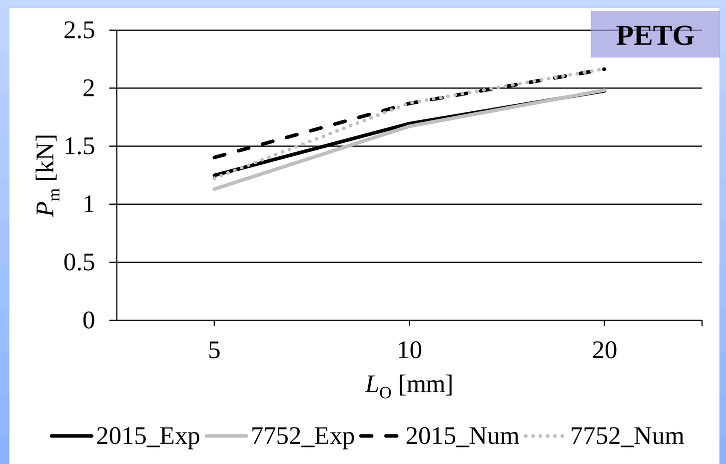
Adhesive	L_O [mm]	PLA		ABS		PETG	
	Analysis	EXP	NUM	EXP	NUM	EXP	NUM
Araldite® 2015	5	Adh	Coh	Adh	Adh	Adh	Adh
	10	Adh	Coh	Adh	Adh	Adh	Adh
	20	Adh	Coh	Adh	Adh	Adh	Adh
Sikaforce® 7752	5	Coh	Coh	Adh	Coh	Adh	Coh
	10	Coh	Coh	Adh	Adh	Adh	Adh
	20	Coh	Coh	Adh	Adh	Adh	Adh

Adh – adherend failure; Coh – cohesive failure in the adhesive

Experimental and numerical P_m comparison for SLJ

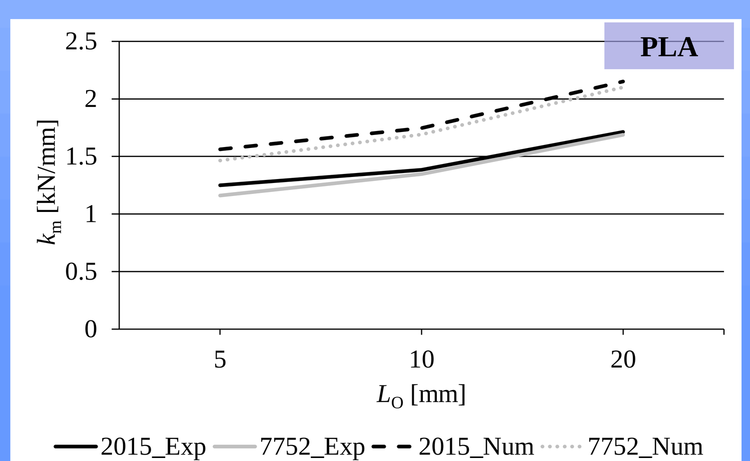


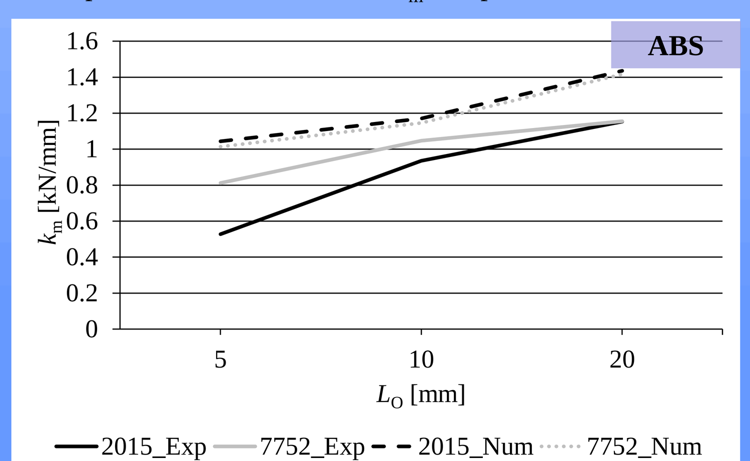


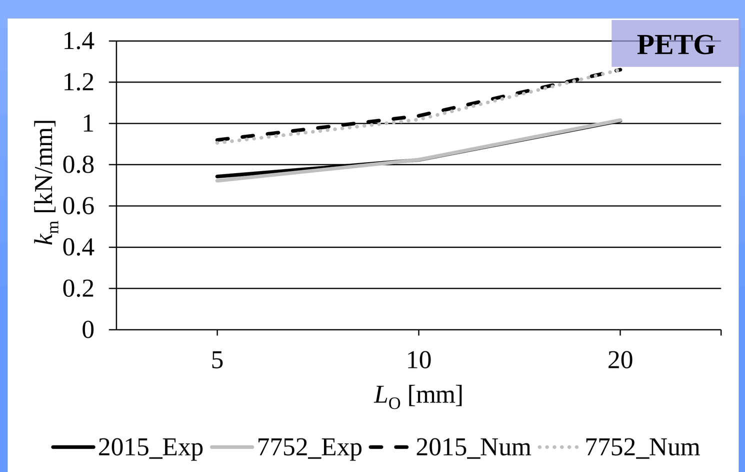


- P_m found for PLA with Sikaforce® 7752 (3.3 kN) and L_O=20 mm
- Exp vs numerical maximum deviations
  - PLA 2015 = 9.8 ± 1.3%
  - PLA 7752 = 9.8 ± 1.0%
  - ABS 2015 = 8.2 ± 1.5%
  - ABS 7752 = 11.3 ± 0.7%
  - PETG 2025 = 10.7 ± 1.2%
  - PETG 7752 = 9.8 ± 1.5%

Experimental and numerical K_m comparison for SLJ

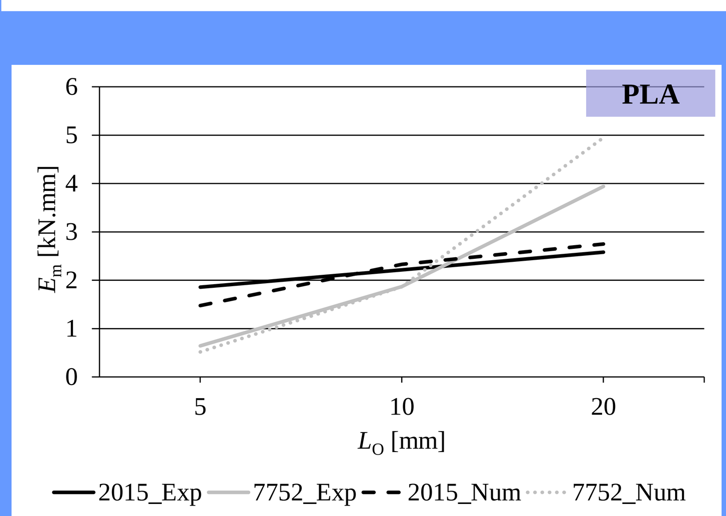


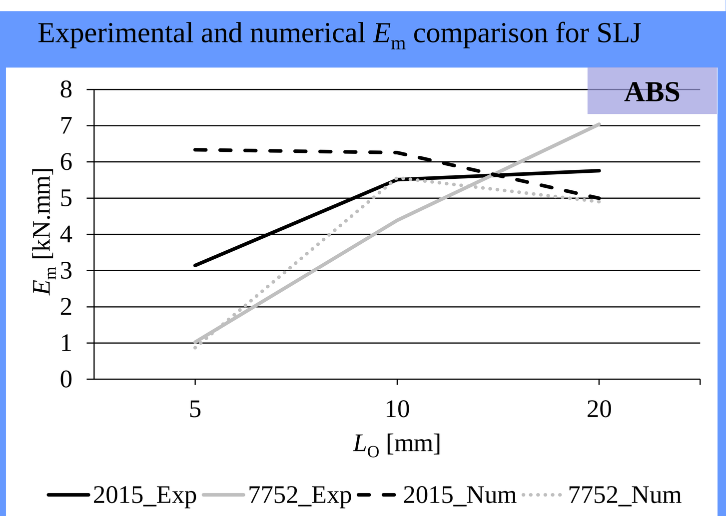


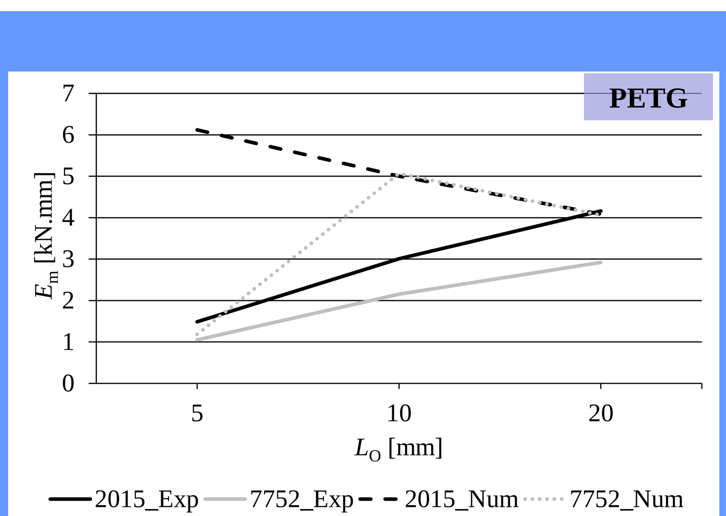


- K_m found for PLA with Araldite® 2015 (1.7 N/mm) and L_O=20 mm
- Exp vs numerical maximum deviations
  - PLA 2015 = 25.6 ± 0.6%
  - PLA 7752 = 25.4 ± 0.76%
  - ABS 2015 = 49.1 ± 34.4%
  - ABS 7752 = 19.0 ± 6.8%
  - PETG 2025 = 24.7 ± 0.9%
  - PETG 7752 = 24.3 ± 0.7%

Experimental and numerical E_m comparison for SLJ







- E_m found for ABS with Sikaforce® 7752 (7.0 J) and L_O=20 mm
- Exp vs numerical maximum deviations
  - PLA 2015 = 10.7 ± 7.0%
  - PLA 7752 = 15.1 ± 10.9%
  - ABS 2015 = 42.8 ± 41.7%
  - ABS 7752 = 29.3.7 ± 10.8%
  - PETG 2025 = 126.8 ± 133.6%
  - PETG 7752 = 62.4 ± 52.9%

Conclusions

- The PLA material showed the highest P_m and E, although the smallest ε_{max}.
- ABS was the least strong material, but showed a marked plastic behaviour prior to failure and second highest E.
- The SLJ analysis that followed revealed two failure types: cohesive in the adherend, mostly with PLA adherends, and in the adherends, for the other adherend materials.
- A good correspondence was found between the experimental and numerical failure modes, despite few discrepancies.
- The P_m analysis showed best results for the PLA joints, and typically best results for the Araldite® 2015, despite being less ductile than the Sikaforce® 7752.
- The highest numerical deviation to the experiments between all conditions was 12.3%.
- The final E_m analysis was not conclusive in the way that the results depended on L_O. Nonetheless, the Sikaforce® 7752 could absorb more energy for higher L_O.
- The highest E_m overall was attained with ABS joints and the Sikaforce® 7752.
- Due to the difficulties in reproducing the joints' plasticity, significant deviations were obtained in some joint configurations.
- In view of the obtained results, guidelines were suggested to provide strong and energy absorbing joints, which can be further used in the design of AM component joints.

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