Delamination Behaviour of Composite Materials Repaired with Structural Adhesives

P. Vigón[1], **A. Argüelles**[1], JA. Viña[2], M. Lozano[1], R. García[1]

[1] Department of Construction and Manufacturing Engineering, University of Oviedo, West Departmental Building No. 7, Viesques Campus, 33203 Gijón
[2] Department of Materials and Metallurgical Engineering, University of Oviedo, 13 Independencia St., s/n, 33004 Oviedo Spain

EPI Gijón Universidad de Oviedo
Research group IEMES

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Introduction

- Delamination is one of the main failure mechanisms in laminated composite materials, significantly reducing their reliability and service life.
- The relationship between matrix properties and fracture toughness plays a key role in predicting delamination behaviour.
- Structural adhesives are widely used for repair, with epoxy and acrylic adhesives being the most common in aerospace and industrial applications.
- Recycling and reusing composite materials is challenging due to their heterogeneous nature, making repair strategies increasingly relevant.
- This study investigates the repair applicability of carbon fibre–reinforced epoxy composites using three commercial structural adhesives: Loctite® EA 9461 (epoxy), Araldite® 2015 (epoxy), and Scotch-Weld™ DP8810NS (acrylic).

Property	Epoxy Adhesives	Acrylic Adhesives
Impact resistance	Low	Good
Service temperature	–55 to 120 °C	–70 to 120 °C
Curing process	Heat or two component mix	Room temperature (fast)
Handling/Recycling	Difficult	Easier

Methodology

MATERIALS AND SPECIMENS

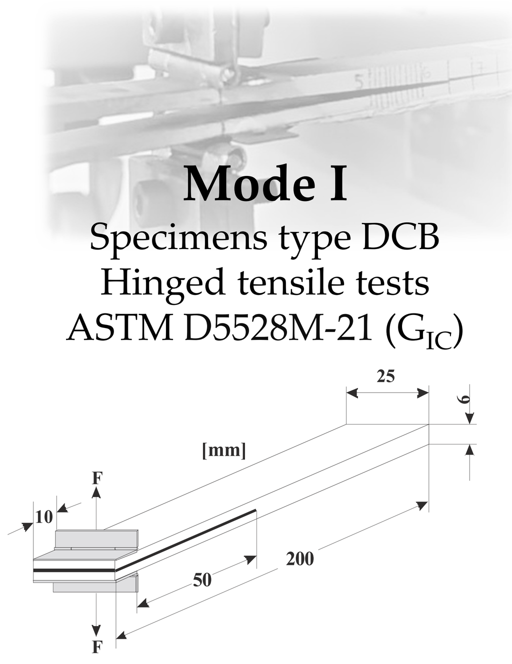
	Elastic modulus [GPa]		Tensile strength [MPa]		Shear modulus [GPa]	Shear strength [MPa]
Material	E_{11}	E_{22}	σ_{11}	σ_{22}	G_{12}	τ_{max}
8552	144	10.6	1703	30.8	5.36	67.7
3501-6	131	8.9	1954	24	5.09	79.3

11 - Fiber's direction; 22 - Fibers perpendicular direction

ADHESIVES

	Base	Viscosity [mPa·s]	Elastic modulus [GPa]	Tensile strength [MPa]	Shear strength [MPa]
Loctite® EA 9461™	Epoxy	150000 a 250000	2.758	30.3	13.8
Araldite®	Epoxy	Thixotropic	2	30.0	15.0
3M™	Acrylic	45000	0.862	11.4	6.9

STATIC FRACTURE TOUGHNESS



Modified Beam Theory (MBT)

$$G_{IC} = 3P\delta/2b(a+|\Delta|)$$

Compliance Calibration (CC)

$$G_{IC} = nP\delta/2ba$$

Modified Compliance Calibration (MCC)

$$G_{IC} = 3P^2C^{2/3}/2A_1bh$$

Results

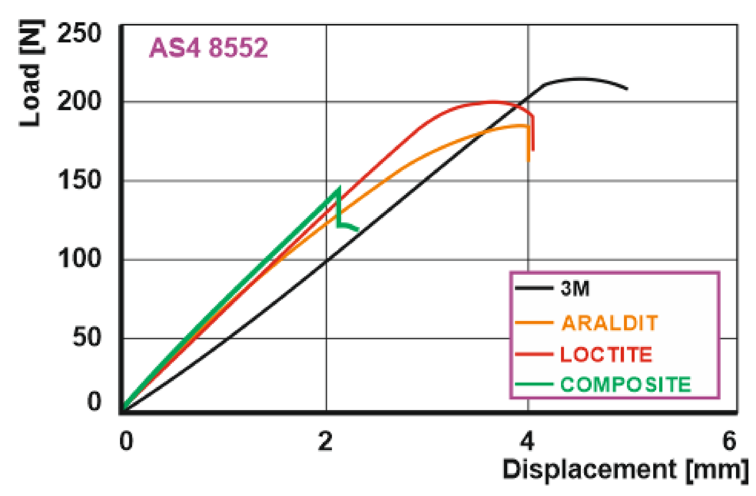
Base laminates show much lower delamination onset loads than adhesive joints.
Load–displacement slopes mainly influenced by the 8552 matrix, like epoxy adhesives.

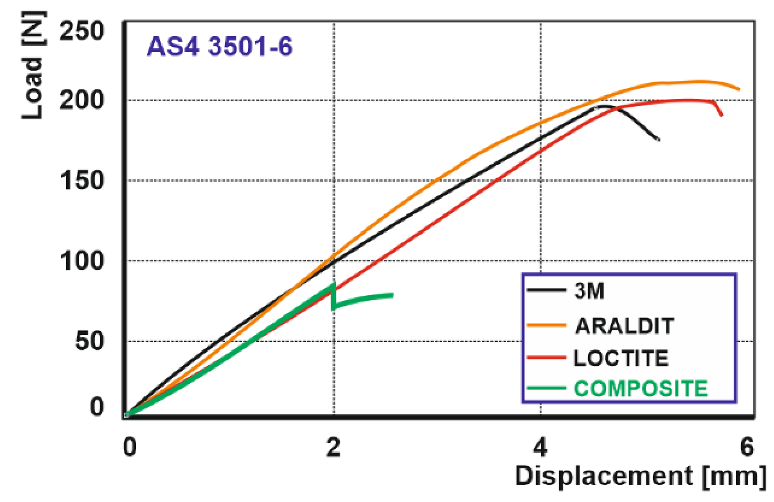
AS4/8552

- Higher deformation capacity then base material.
- Displacements nearly doubled.
- Epoxy adhesives show similar behavior: acrylic adhesive slightly higher.

AS4/3501-6

- All three adhesives show comparable performance.
- Epoxy adhesives behave almost identically.





AS4/8552 matrix

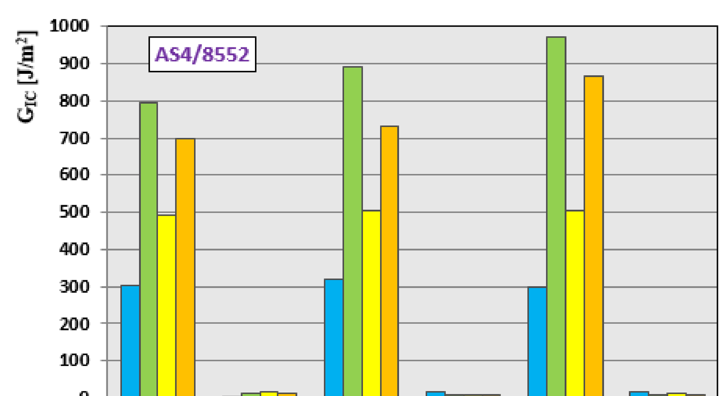
- Significantly higher fracture toughness (≈3× greater than 3501-6
- Calculation method has little influence; CC method yields slightly higher values (+5.6%).

AS4/3501-6 matrix

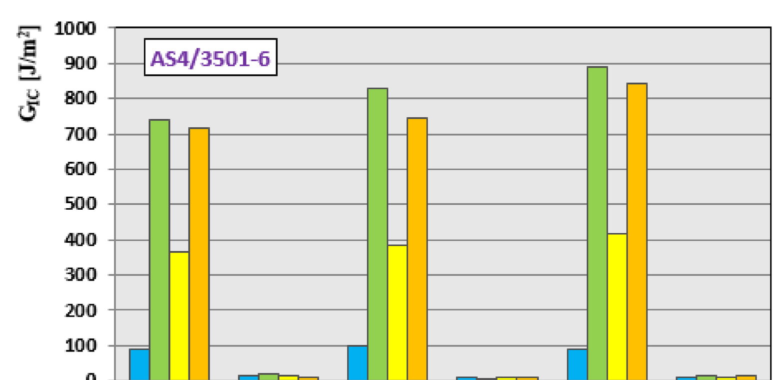
- Lower fracture toughness, regardless of adhesive used
- CC method gives slightly higher values (+9.9%)

Adhesives

- Acrylic adhesive (3M DP8810NS) provides the highest G_{IC} values
- Loctite (epoxy) close to acrylic; Araldite (epoxy) shows the lowest performance.



Data reduction method used	MBT	CV [%]	CC	CV [%]	MCC	CV [%]
Composite	302.1	6.0	319.5	15.0	298.1	16.0
3M	794.3	12.0	890.5	7.0	973.2	8.0
Araldit	493.3	15.0	504.2	10.0	506.5	14.0
Loctite	696.7	11.0	733.0	8.0	867.0	10.0

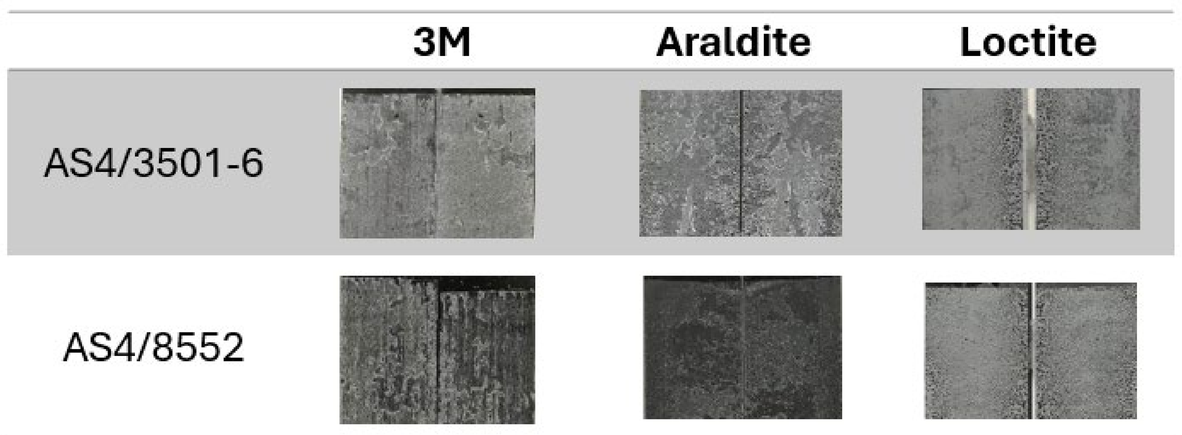


Data reduction method used	MBT	CV [%]	CC	CV [%]	MCC	CV [%]
Composite	88.6	15.0	99.1	12.0	90.6	8.0
3M	742.0	18.0	828.5	7.0	888.2	15.0
Araldit	363.4	15.0	383.5	10.0	414.7	12.0
Loctite	715.0	12.0	745.5	11.0	844.3	16.0

Overall: Substrate type (8552 vs. 3501-6) and adhesive selection strongly influence fracture toughness.

Fracture Surface

- Significantly Fracture surfaces mainly show cohesive failure.
- **3M acrylic adhesive (AS4/8552 substrate)**: dominant adhesive failure, though resistance is not reduced
- **Epoxy adhesives (Loctite, Araldite)**: mostly cohesive failure, with fiber bridging observed
- Fiber bridging artificially increases the measured fracture energy in epoxy joints.
- Substrate type (8552 vs. 3501-6) shows minor influence on fracture surface characteristics.



Conclusions

The base laminates show lower delamination onset loads compared to all tested structural adhesives. Load–displacement slopes are mainly influenced by the 8552 matrix, with similar behaviour to epoxy-based adhesives.

The 8552 matrix exhibits significantly higher fracture toughness than the 3501-6 matrix (up to three times greater), regardless of the calculation method applied.

The acrylic adhesive provides higher fracture toughness values than epoxy-based adhesives. Among the epoxy adhesives, Araldite shows the lowest performance.

The AS4/3501-6 laminate presents lower delamination resistance, independent of the adhesive used for repair.

Fracture surface analysis reveals minor differences related to the substrate type; however, epoxy adhesives show more deformation and fiber breakage, leading to fiber bridging that artificially increases the measured fracture energy.

Bibliography