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Moment loading testing and data reduction for characterizing the fracture toughness of hybrid joints

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EXECUTIVE SUMMARY

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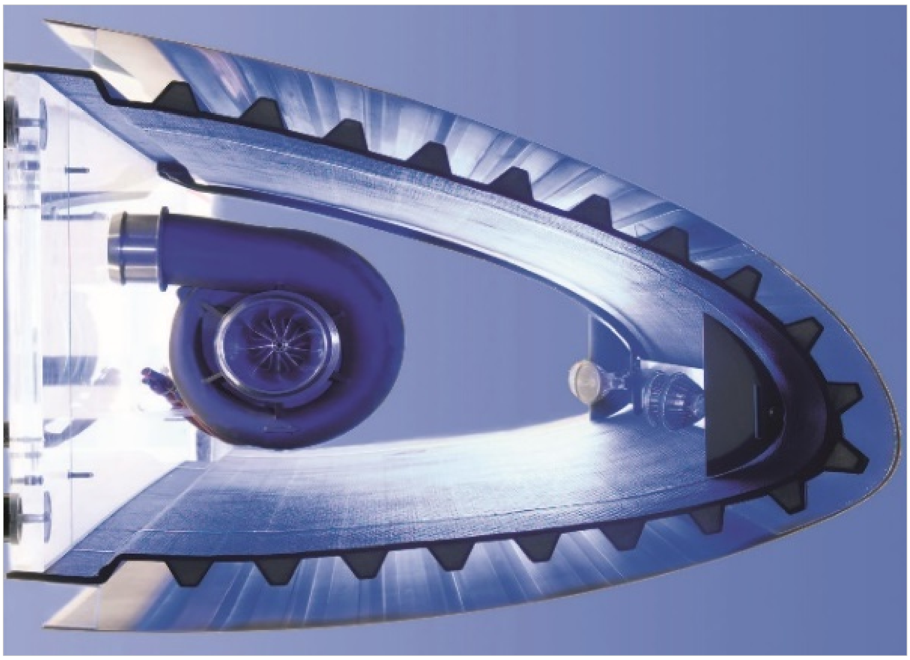

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KNOWLEDGE AREA(S)
Aerospace Structures
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DESCRIPTOR(S)
titanium
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Problem area

A new titanium-carbon composite structural adhesive joint for application in aircraft wing that is designed to use hybrid laminar flow control (HLFC) is studied in the Clean Sky 2 Titanium Composite Adhesive Joint (TiCoAJo) project, see Figure. The composite is the load carrying structure of the wing and leading edge and the titanium is bonded onto the composite. This bond needs to be tested thoroughly before application on an aircraft. The characterization of the strength and longevity of this titanium and composite joint is challenging because of the difference in stiffness and thermal properties. A novel type of fracture toughness testing of this interface between the titanium and composite is proposed to simplify the testing.

Description of work

Four different technologies for the manufacturing of the joint; namely, co-bonding with and without adhesive, secondary bonding for thermoset composites and secondary bonding with thermoplastic material have been constructed and tested. The titanium and composite adherents have different thicknesses, and two aluminum backing beams are applied on both sides of the specimen to ensure the non-yielding of the titanium. The in-house developed double cantilever beam test setup using moment loading, was prepared for the titanium/composite coupons. A special enclosure was manufactured to enable environmental conditions testing. The tests were performed on the coupons under different loads and conditions. An analytical model is developed to post-process the test data from the DCB-UBM test setup. Residual thermal stresses are considered in the analysis of test results.

Results

The test data showed that for the adhesive interface the fracture toughness results were satisfactory. The composite itself appears to be the weak point and delaminations start to form during the mode-I testing. In addition, the tests at elevated temperature showed that the connection between the titanium adherent and the aluminum backing was failing, mainly in the mode II test. This is probably a direct consequence of the coupon design with the backing and the optimal pre-treatment. Therefore, the test setup worked satisfactory despite the high loads involved. With data reduction the thermal effects of the hybrid structure can be included in the analytical model. The fracture toughness values could be extracted from the test results, which, however, in some cases showed high variation.

Applicability

The results from this paper are relevant for other research where the fracture toughness needs to be obtained such as composite material characterization for aerospace. The test setup using moment loading can be applied to a wide variety of monolithic, sandwich and hybrid structures e.g. aerospace of wind blades.

GENERAL NOTE
This report is based on a presentation held at the ECCOMAS conference on mechanical response of composite materials, Girona, Spain, September 2019.

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Summary

A new titanium-carbon composite structural adhesive joint for application in aircraft wing that is designed to use hybrid laminar flow control (HLFC) is studied in the Clean Sky 2 Titanium Composite Adhesive Joint (TiCoAJo) project. The titanium and CFRP adherents have different thicknesses, and two aluminum backing beams are applied on both sides of the specimen to ensure the non-yielding of the titanium.

The study includes different technologies for the manufacturing of the joint; namely, co-bonding with and without adhesive, secondary bonding for thermoset composites and secondary bonding with thermoplastic material. The aim of the research is to derive the fracture toughness of the titanium-CFRP joint under different loading and environmental conditions. Here, special attention is given to the in-house developed double cantilever beam (DCB) and the end-notched flexure (ENF) specimens using the moment loading test setup as investigated by Sorensen and co-workers, also called the DCB-UBM setup. An analytical model recently developed by the authors is extended here to enable data reduction in moment-loaded tests. Residual thermal stresses are considered in the analysis of test results.

The paper presents and discusses the results from quasi-static mode I and II DCB-UBM fracture tests at both room and elevated temperature conditions. The test results are evaluated to determine the fracture toughness and optimal bonding technology for the TicoAjo joint. The advantage of using the moment loading test setup is that the delamination crack distance does not need to be monitored during the test and that the mixed mode loading is easy to vary.

Contents

Abbreviations

ACRONYM	DESCRIPTION
CD	Cold dry conditions
CFRP	Carbon Fibre Reinforced Plastic
DCB	Double Cantilever Beam
ENF	End Notch Fracture
ETW	Elevated Temperature Wet conditions
HLFC	Hybrid Laminar Flow Concept
MMB	Mixed Mode Bending
MO	Manufacturing Option
NLR	Netherlands Aerospace Centre
RTM	Resin Transfer Moulding
SERR	Strain Energy Release Rate
SLB	Single Lap Bending

MOMENT LOADING TESTING AND DATA REDUCTION FOR CHARACTERIZING THE FRACTURE TOUGHNESS OF HYBRID JOINTS

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Key words: Titanium-CFRP adhesive joint, Double cantilever beam-uneven bending moments, DCB-UBM, Aerospace applications

Summary. *A new titanium-CFRP structural adhesive joint for application in aircraft wing designed using hybrid laminar flow control (HLFC) is studied in the Clean Sky 2 Titanium Composite Adhesive Joint (TiCoAJo) project. The titanium and CFRP adherents have different thicknesses, and two aluminum backing beams are applied on both sides of the specimen to ensure the non-yielding of the titanium. The study includes different technologies for the manufacturing of the joint; namely, co-bonding with and without adhesive, secondary bonding for thermoset composites and secondary bonding with thermoplastic material. The aim of the research is to derive the fracture toughness of the titanium-CFRP joint under different loading and environmental conditions. Here, special attention is given to the in-house developed double cantilever beam (DCB) and the end-notched flexure (ENF) specimens using the moment loading test setup as investigated by Sorensen and co-workers, also called the DCB-UBM setup. An analytical model recently developed by the authors is extended here to enable data reduction in moment-loaded tests. Residual thermal stresses are considered in the analysis of test results. The paper presents and discusses the results from quasi-static mode I and II DCB-UBM fracture tests at both room and elevated temperature conditions. The test results are evaluated to determine the fracture toughness and optimal bonding technology for the TicoAjo joint. The advantage of using the moment loading test setup is that the delamination crack distance does not need to be monitored during the test and that the mixed mode loading is easy to vary.*

1 Introduction

Background

In aerospace there is a need to improve the efficiency and reduce the drag of the wings. This can be achieved by influencing the boundary layer on the wing using laminar flow control. The combination of active and passive systems to control this laminar flow is called hybrid laminar flow control (HLFC). This is achieved by extracting the (turbulent) boundary layer by perforated suction surfaces, as shown in Figure 1. The purpose of applying the HLFC technology on aircraft wing, empennage, or nacelle is to reduce drag and consequently fuel-burn and emissions.

First trials using micro-perforated titanium suction surfaces are being performed at leading edge sections of wings and tail airfoils. A promising structural solution is the combination of a micro-drilled outer titanium surface adhesively bonded with an inner, segmented, composite structure.

The aim of the Clean Sky 2 TicoAjo project is to characterize the interface behavior and failure strength of the adhesive joint between the titanium outer surface and the carbon fiber composite load carrying structure. For this purpose, novel technologies are developed in pre-treatment, test specimen design and the way of testing and data reduction.

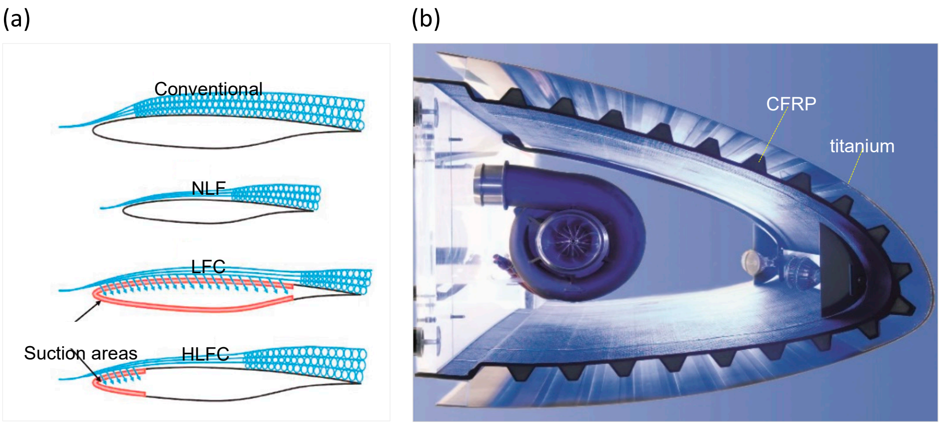

Figure 1: (a) Schematic representation of the airflow over a wing section. The hybrid laminar flow control (HLFC) design with suction areas will change the airflow and reduce drag (taken from [13]). (b) A demonstrator from the research conducted under the Clean Sky 2 HLFC project (photograph taken from [14]). The outer micro-drilled titanium sheet and the inner CFRP segmented structure are shown in the photograph.

Dissimilar metal-composite adhesive joints are finding increasing usage in many high-performance structural applications in several industries (e.g. aerospace, automotive, wind energy, etc.). A common combination of dissimilar materials in many industries are metals (aluminium, steel, titanium, etc.) and composites (CFRP, glass fiber reinforced plastics, etc.). The joining usually takes place after curing at elevated temperatures, at least in the high-performance cases, and this results in residual thermal stresses along the bi-material interface(s). Delamination or interfacial disbonding studies in the presence of residual thermal stresses need special attention and new experimental data reduction schemes. These failure modes are critical for the structural integrity of structural adhesive joints as they typically propagate in the interface between two layers or adherents compromising the structural performance of the joint.

2 Joint characterisation methods

Determination of the interface fracture resistance is vital from a design perspective. There are various experimental methods developed to determine the interface fracture toughness, such as the double cantilever beam (DCB) test, the mixed-mode bending (MMB) test, etc. Most of the devised experimental test methods were inspired by fracture test methods developed for laminate composites.

A mixed-mode test configuration, the DCB specimen loaded with uneven bending moments (DCB-UBM), has been proposed in literature for fracture mechanics characterization of mixed-mode cracking. The strain energy release rate (SERR) of a double cantilever beam (DCB) loaded with pure bending moments is independent of the crack length, allowing stable crack growth in even truly brittle materials. A special test fixture is needed to create uneven bending moments. By varying the ratio between the two applied moments, the crack-tip stress state can be varied from pure mode I to pure mode II for the same specimen geometry.

The double cantilever beam loaded with uneven (or unequal) bending moments (DCB-UBM), capable of achieving a wide array of mode mixity conditions was first introduced by Sørensen et al. [1, 2], for monolithic laminate composite specimens, and was later extended to sandwich composites by Østergaard et al. [4] and Lundsgaard-Larsen et al. [5]. In the DCB-UBM specimen, pure bending moments M_1 and M_2 are applied to both crack flanks. For a fixed moment ratio M_1/M_2, the mode mixity phase angle remains constant. Therefore, by holding the moment ratio constant throughout the crack propagation during the fracture testing, toughness characterization can be performed at a fixed mode mixity phase angle. For the DCB-UBM test configuration, some analytical solutions based on the path-independent J-integral can be found in [3, 7] for isotropic and multidirectional laminated materials, as well as for cohesive interfaces [8].

In [2], the development of the novel DCB-UBM test configuration is described and the testing results from two distinct ceramics, one with constant fracture toughness and one possessing R-curve behavior due to phase transformation, are reported. Stable crack growth was obtained in both materials. In [3], the DCB-UBM specimen was used for characterizing fracture of adhesive joints between two laminates of thermoset glass fiber reinforced plastic. A special loading fixture based on steel wires was developed. A linear elastic fracture mechanics analysis was conducted to give the SERR and mode mixity analytically for both isotropic and orthotropic materials. In [5], a novel method was used for the determination of mixed-mode cohesive laws and bridging laws for the characterization of crack bridging in DCB-UBM composites. In [6], a novel DCB-UBM method was proposed, where pure bending moments were applied to the beams at the crack end using torsional actuators. Fracture testing was performed on a typical marine grade sandwich configuration consisting of PVC H45 foam core and glass fiber face sheets to demonstrate the applicability of the test method. In [7], analytical expressions for the SERR and phase angle were derived for a sandwich composite DCB fracture specimen with the faces reinforced by stiff plates. Only pure moment loading is considered. The J-integral coupled with laminate beam theory was employed to derive closed-form expression for the SERR in terms of the applied moments, geometry, and material properties. In [8], the DCB-UBM test configuration was used for the fracture testing of aerospace-grade honeycomb core sandwich composites. The sandwich specimens were reinforced with steel doublers to reduce excessive rotation of the face sheets.

Summarizing, the advantages of using the DCB-UBM test setup over the standard DCB test setup loaded with transverse forces are:

- Test results are independent of crack length and shear modulus [1]. Thus, the delamination crack distance does not need to be monitored during the test.
- A full range of mode mixity (from pure mode I to pure mode II) can be obtained, depending on the moment ratio. Thus, possible error sources associated with processing differences are reduced.
- No transverse loading is applied on the specimens which allows for a wider range of laminates to test, e.g. with low transverse shear stiffness and strength such as foam sandwich structures.

In the present work, the moment-loaded double cantilever beam (DCB-UBM) configuration is introduced to characterize the joint. The primary objective of the present research is to explore the use of the DCB-UBM test method for the hybrid joint structures and to bring the method a step further into material characterization of hybrid coupons. The testing method is used to characterize the interface behavior under challenging environmental conditions including hot/wet and cold/dry.

Because of the dissimilar material that poses different stiffness properties, special attention is given to an in-house developed moment loading double cantilever beam test setup. Residual thermal stresses are considered in the analysis and data reduction of the test results. The paper presents and discusses the results from mode I and mode II static interlaminar fracture tests at elevated and room temperature conditions and the data reduction techniques. The test results are evaluated to determine the fracture toughness and optimal bonding technology for the titanium and composite joint. A previous application for hybrid titanium and CFRP has not been found however it is believed that the features of the DCB-UBM test configuration make it an attractive approach to investigate the joint behavior in hybrid structures.

The paper is organized as follows. In Section 3, the underlined technical problem and the experimental part of the work is presented. The titanium-CFRP adhesive joint under study, the DCB-UBM test setup, and useful observations from the experiments conducted are presented. In Section 4, a new set of equations that can be used for experimental data reduction is presented. Last, in Section 5, conclusions are presented.

3 Experimental

3.1 The titanium-CFRP adhesive joint

The interfacial fracture toughness of a titanium-CFRP structural adhesive joint, both adherents of which are very thin, is investigated. The design of fracture toughness tests on the present adhesive joint, as well as its envisioned application in future aircraft, are both presented in a previous paper [15]. The titanium-CFRP joint was cured at high temperature, which induces high residual thermal stresses to the joint after curing. After completion of the curing process and since the thickness of the titanium is too low, the titanium-CFRP joint was backed from both titanium and composite sides with two stiffening beams, as shown in Figure 2a. In the present work, the interface fracture of the backed joint with residual thermal stresses is experimentally investigated under moment-loaded tests.

The following four adhesive joint Manufacturing Options (MO) are evaluated:

- MO 1: Vacuum infusion/resin transfer molding (RTM) of CFRP plates followed by secondary bonding of the titanium sheet using film adhesive (FM 94K).
- MO 2: Co-bonding using film adhesive (FM 300M) on the titanium-CFRP interface and vacuum infusion/RTM.
- MO 3: Co-bonding without using adhesive on the titanium-CFRP interface and vacuum infusion/RTM. Bonding is achieved by the RTM6 resin of the composite.
- MO 4: Secondary bonding of a thermoplastic CFRP to a titanium sheet using the FM 94K adhesive.

The manufacturing process of the titanium-CFRP adhesive joint, as well as full information on the materials used, are presented in a previous paper [16].

3.2 DCB-UBM test setup

The interface fracture tests are performed at NLR using the in-house DCB-UBM test setup shown in Figure 2b, at three different environmental conditions; room temperature, cold/dry (-55 °C), and hot/wet (70 °C) conditions. In total 32 tests are done. Adjustments to the setup were made to enable the hybrid material and the environmental testing by creating an enclosure. The specimen size is 25 mm width and 280 mm in length, while the total thickness including the backing material is around 12.4 mm. Because the adherents including the backing material are thick, the expected moments are higher than usual. The test setup performed as expected with and without the environmental condition enclosure.

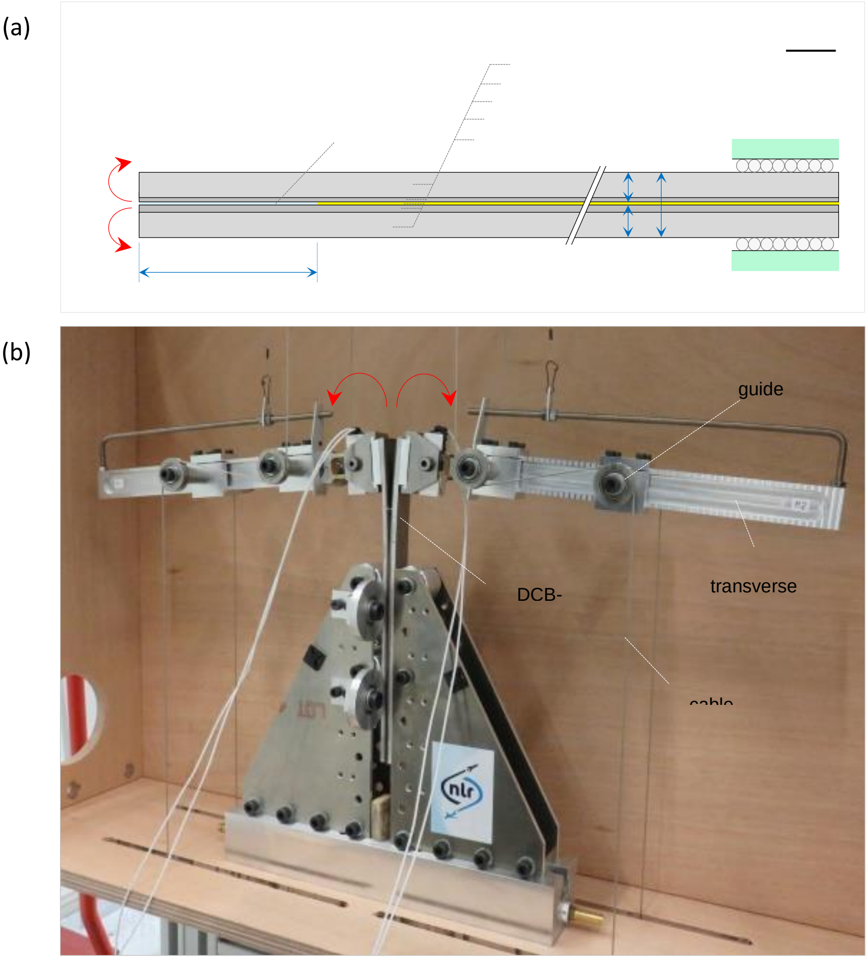

Figure 2: (a) Schematic of the DCB-UBM test specimen. (b) A photograph of the DCB-UBM test setup at the facilities of the NLR, The Netherlands, taken after a cold/dry test.

3.3 Observations from the experiments

Figure 3 gives an example of the results from a single representative test. From Figure 3 it can be seen that the moments M_1 and M_2 tend to stabilize at specific values. Those values will be used to determine the fracture toughness of the interface.

During the tests performed, photographs were made at an interval of one photo per second. Two representative test sequences are shown in Figures 4 and 5, for the mode I and II tests, respectively. The following observations were made during the testing, unfortunately rendering some test results invalid:

- Delaminations in the CFRP and not in the joint were observed during the testing. Delaminations have also been seen in previous tests [16] and indicate that the adhesion is stronger than the composite (RTM-6) itself (Figure 6a).
- In some high-temperature tests a separation of the backing structure was observed (Figure 6b).

Despite the observed failure modes in the specimens, the test setup worked satisfactory and the full set of specimens were tested.

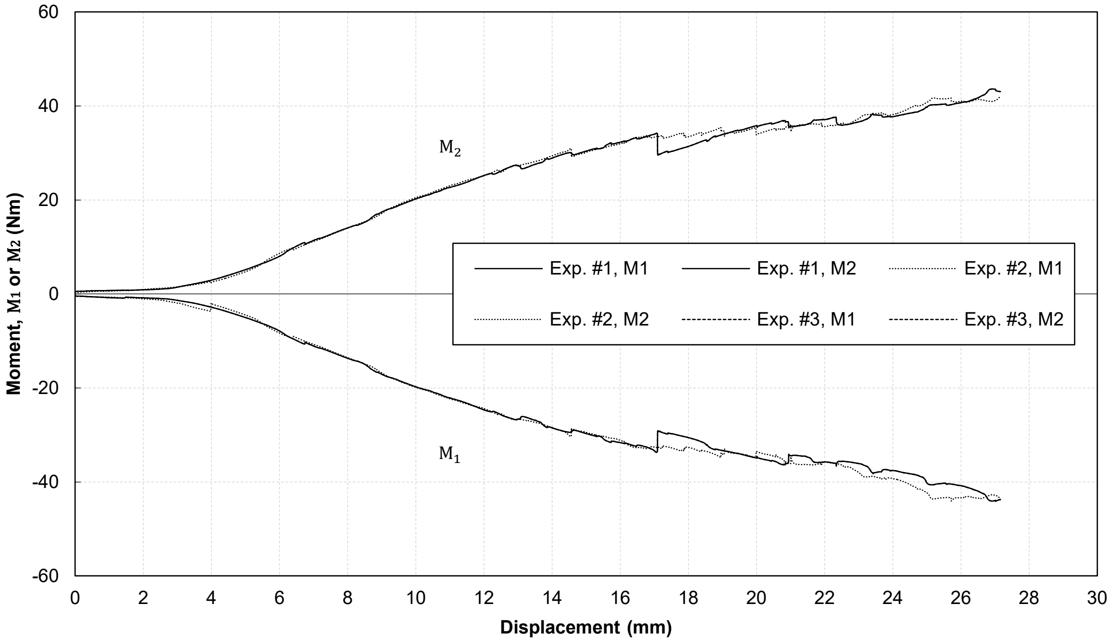

Figure 3: Moment-displacement curves from three mode I DCB-UBM experiments on the titanium-CFRP adhesive joint.

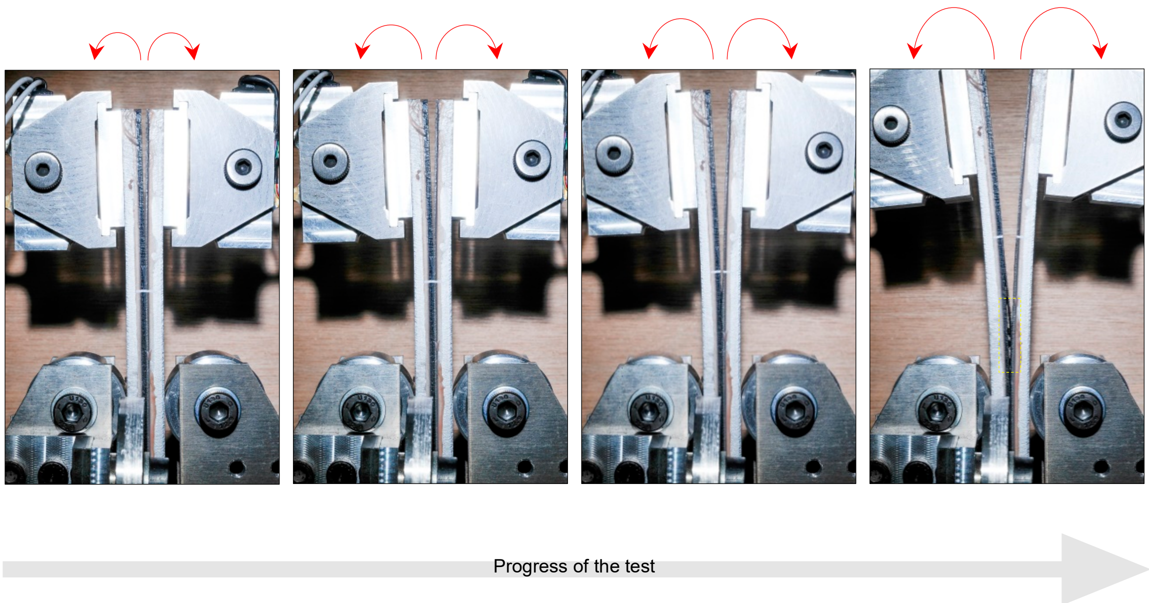

Figure 4: Snapshots that capture the progress of one of the mode I DCB-UBM experiments at NLR. In the first snapshot, the initial opening is established and the Upilex foil initiates the starter crack. In the last snapshot, a titanium-CFRP disbonding can be observed. In the same snapshot, a delamination crack inside the CFRP can also become apparent.

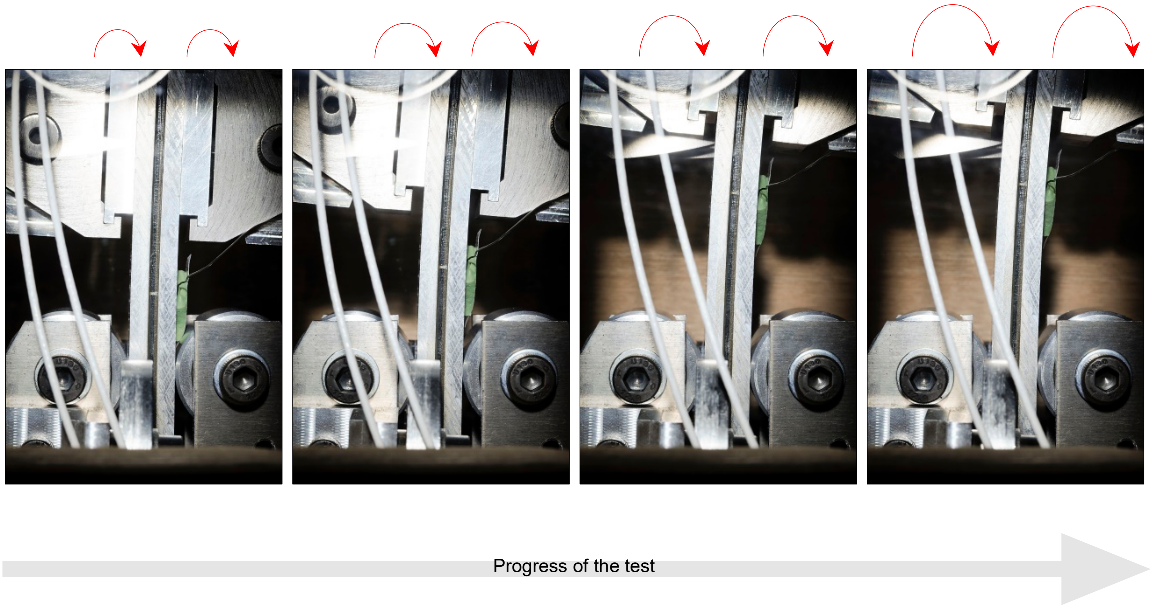

Figure 5: Progressive snapshots during one of the mode II DCB-UBM experiments. In the last snapshot, bending to the right of the entire specimen, initiating damage growth on the interface, can be observed.

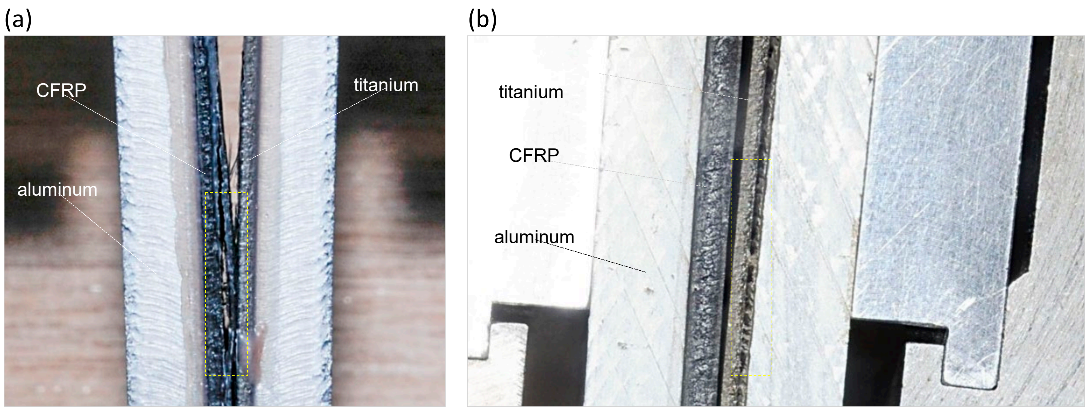

Figure 6: Photographs showing the two undesirable failure modes observed during some of the experiments, which made the respective experiments invalid. (a) A delamination inside the CFRP, observed during some of the mode I DCB-UBM experiments. (b) A separation of the bonding between titanium and aluminum, observed during some of the hot/wet experiments.

4 Data reduction approach

The present metal-composite adhesive joint consists of two sub-laminates that exhibit bending-extension coupling as well as residual thermal stresses due to the high-temperature curing. The analytical model presented in recent paper [17] considers both effects, but data reduction equations have been given for test specimens loaded with vertical loads. In the present paper, the analytical framework of [17] is extended to be able to estimate the total SERR and "parasitic" mode mixity of the moment-loaded case.

4.1 Calculation of the crack-tip forces ($\mathcal{N}_c$ and $\mathcal{Q}_c$)

In this paragraph, the general expressions for the mode I, mode II, and total SERR (see Eqs. (6) in [17]) are reduced for two delamination fracture tests (Figure 8): the mode I-loaded double cantilever beam loaded with uneven bending moments (DCB-UBM) and the mode II-loaded DCB-UBM. In the first test, the specimen is loaded by two opposite pure moments M_1 and M_2 (Figure 8b) while in the second case (Figure 8c), the M_1 and M_2 have the same directions.

The loading conditions of Figure 8a are converted to the following internal loads at crack-tip cross-sections A and B:

$$\begin{array}{ccc} \mathcal{N}_{10} = 0 & \mathcal{N}_{20} = 0 & \mathcal{N}_{T}(0) = 0 \\ \mathcal{Q}_{10} = 0 & \mathcal{Q}_{20} = 0 & \mathcal{Q}_{T}(0) = 0 \\ \mathcal{M}_{10} = \mathcal{M}_1 & \mathcal{M}_{20} = \mathcal{M}_2 & \mathcal{M}_{T}(0) = \mathcal{M}_1 + \mathcal{M}_2 \end{array} \tag{1}$$

The internal forces and moment of the sub-laminate 1 at the crack tip ($\mathcal{N}_{10}$, $\mathcal{Q}_{10}$, and $\mathcal{M}_{10}$) are related to the crack-tip forces ($\mathcal{N}_c$ and $\mathcal{Q}_c$) as shown in Eqs. (B.6) in Appendix B in [17]. By combining Eqs. (B.6) in Appendix B in [17] with Eqs. (1), the following expressions are obtained:

$$\mathcal{N}_c = \frac{2}{h_1\xi + 2\eta}\left[\xi M_1 + \left(b_2 + \frac{h_2}{2}d_2\right)(M_1 + M_2) - \alpha_{N1} + \alpha_{N2} + \frac{h_1}{2}\alpha_{M1} + \frac{h_2}{2}\alpha_{M2}\right] \tag{2a}$$

$$\mathcal{Q}_c = -\lambda M_1 + (M_1 + M_2)\lambda\frac{2d_2\eta + (h_1 + h_2)d_2\xi + 2b_2\xi}{2(d_1 + d_2)\eta + [2b_1 + 2b_2 + (h_1 + h_2)d_2]\xi} + \frac{2\lambda\xi\left[\alpha_{N2} - \alpha_{N1} + \frac{\eta}{\xi}(\alpha_{M2} - \alpha_{M1}) + \frac{h_1 + h_2}{2}\alpha_{M2}\right]}{2(d_1 + d_2)\eta + [2b_1 + 2b_2 + (h_1 + h_2)d_2]\xi} \tag{2b}$$

To the best of the authors knowledge, the Eqs. (2a) and (2b) are given for the first time in literature and can be used for the fracture analysis of the test configurations shown in Figure 8, with generic (non-symmetric, unbalanced, and coupled) sub-laminates and under the effect of residual hygrothermal stresses.

Eqs. (2a) and (2b) are written in such a way that the are comparable with Eqs. (10a) and (10b), respectively, in [17]. As expected, they are independent of the crack length. Also, the terms of the thermal effect are the same as for the vertically-loaded test cases (i.e. DCB, ENF, SLB, and MMB tests).

4.2 Calculation of the strain energy release rates (SERR) (G_I, G_{II}, and G)

The mode I, mode II, and total SERR can be expressed in terms of the crack-tip forces [17]:

$$G_I = \frac{1}{2}\delta_I \mathcal{Q}_c^2 \tag{3a}$$

$$G_{II} = \frac{1}{2}\delta_{II} \mathcal{N}_c^2 \tag{3b}$$

$$G = G_I + G_{II} \tag{3c}$$

where δ_I and δ_{II} are given as [17]:

$$\delta_I = c_1 + c_2 \tag{4a}$$

$$\delta_{II} = a_1 + a_2 - h_1 b_1 + h_2 b_2 + \frac{h_1^2}{4} d_1 + \frac{h_2^2}{4} d_2 \tag{4b}$$

δ_I and δ_{II} are the flexibility coefficients, i.e. a measure of the elastic deformability of the Coefficient of Thermal Expansion (CTE).

The final expressions used in the present work are presented in Table 1.

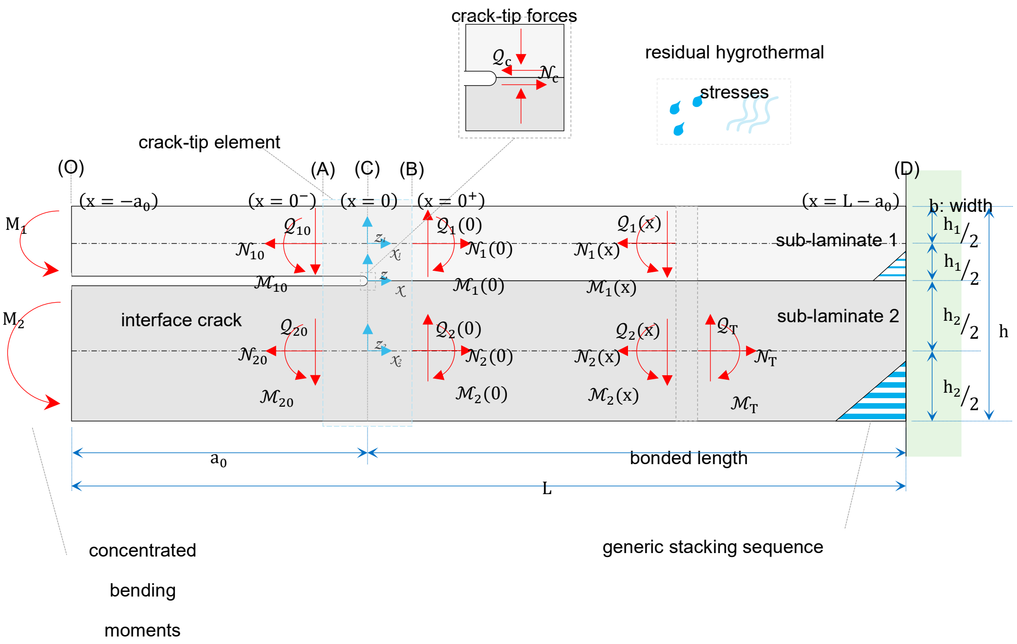

Figure 7: Mechanical model for the analysis of the fracture toughness of the titanium-CFRP adhesive joint. An elastic laminated beam consisting of two sub-laminates with arbitrary stacking sequences and an asymmetric through-the-width delamination/interfacial disbonding, under concentrated bending moments and with residual hygrothermal stresses. The geometry, basic dimensions, basic nomenclature, and local and global coordinate systems are shown.

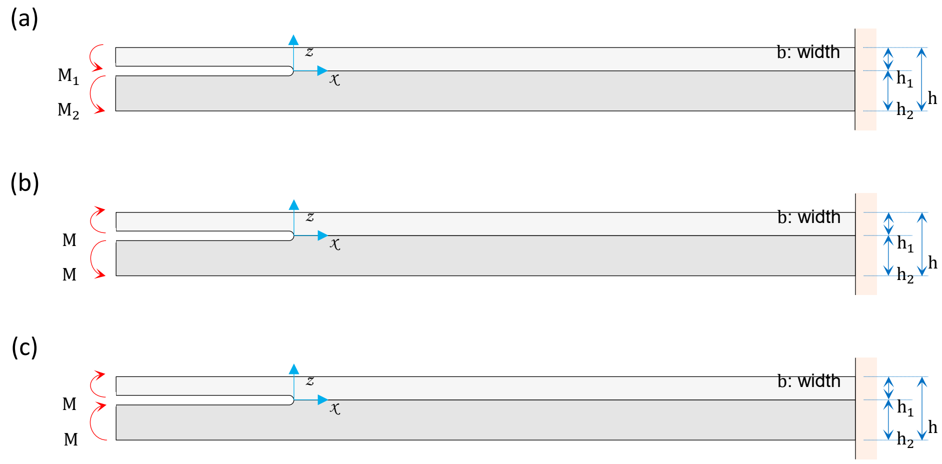

Figure 8: Schematic of the three cases of double cantilever beam-uneven bending moments (DCB-UBM) configurations. (a) Unified DCB-UBM configuration. (b) Mode I DCB-UBM configuration. (c) Mode II DCB-UBM configuration.

Table 1: Strain energy release rates (SERR) (G_I and G_{II}) of the three cases of DCB-UBM configurations of Figure 8. (a) Unified DCB-UBM configuration. (b) Mode I DCB-UBM configuration. (c) Mode II DCB-UBM configuration. The expressions are given for generally layered sub-laminates and under the effect of residual hygrothermal stresses. More information in [17].

Case[1]	SERR (G_I and G_{II})
(a)	$G_I = \frac{1}{2}(c_1 + c_2)\left\{-\lambda M_1 + (M_1 + M_2)\lambda \frac{2d_2\eta + (h_1 + h_2)d_2\xi + 2b_2\xi}{2(d_1 + d_2)\eta + [2b_1 + 2b_2 + (h_1 + h_2)d_2]\xi} + \frac{2\lambda\xi\left[\alpha_{N2} - \alpha_{N1} + \frac{\eta}{\xi}(\alpha_{M2} - \alpha_{M1}) + \frac{h_1 + h_2}{2}\alpha_{M2}\right]}{2(d_1 + d_2)\eta + [2b_1 + 2b_2 + (h_1 + h_2)d_2]\xi}\right\}^2$ $G_{II} = \frac{1}{2}\left(a_1 + a_2 - h_1b_1 + h_2b_2 + \frac{h_1^2}{4}d_1 + \frac{h_2^2}{4}d_2\right)\left\{\frac{2}{h_1\xi + 2\eta}\left[\xi M_1 + \left(b_2 + \frac{h_2}{2}d_2\right)(M_1 + M_2) - \alpha_{N1} + \alpha_{N2} + \frac{h_1}{2}\alpha_{M1} + \frac{h_2}{2}\alpha_{M2}\right]\right\}^2$
(b)	$G_I = \frac{1}{2}(c_1 + c_2)\left\{\lambda M + \frac{2\lambda\xi\left[\alpha_{N2} - \alpha_{N1} + \frac{\eta}{\xi}(\alpha_{M2} - \alpha_{M1}) + \frac{h_1 + h_2}{2}\alpha_{M2}\right]}{2(d_1 + d_2)\eta + [2b_1 + 2b_2 + (h_1 + h_2)d_2]\xi}\right\}^2$ $G_{II} = \frac{1}{2}\left(a_1 + a_2 - h_1b_1 + h_2b_2 + \frac{h_1^2}{4}d_1 + \frac{h_2^2}{4}d_2\right)\left\{\frac{2}{h_1\xi + 2\eta}\left[-\xi M - \alpha_{N1} + \alpha_{N2} + \frac{h_1}{2}\alpha_{M1} + \frac{h_2}{2}\alpha_{M2}\right]\right\}^2$
(c)	$G_I = \frac{1}{2}(c_1 + c_2)\left\{\lambda M - 2\lambda M \frac{2d_2\eta + (h_1 + h_2)d_2\xi + 2b_2\xi}{2(d_1 + d_2)\eta + [2b_1 + 2b_2 + (h_1 + h_2)d_2]\xi} + \frac{2\lambda\xi\left[\alpha_{N2} - \alpha_{N1} + \frac{\eta}{\xi}(\alpha_{M2} - \alpha_{M1}) + \frac{h_1 + h_2}{2}\alpha_{M2}\right]}{2(d_1 + d_2)\eta + [2b_1 + 2b_2 + (h_1 + h_2)d_2]\xi}\right\}^2$ $G_{II} = \frac{1}{2}\left(a_1 + a_2 - h_1b_1 + h_2b_2 + \frac{h_1^2}{4}d_1 + \frac{h_2^2}{4}d_2\right)\left\{\frac{2}{h_1\xi + 2\eta}\left[-\xi M - 2\left(b_2 + \frac{h_2}{2}d_2\right)M - \alpha_{N1} + \alpha_{N2} + \frac{h_1}{2}\alpha_{M1} + \frac{h_2}{2}\alpha_{M2}\right]\right\}^2$

[1] Schematic representation of the three cases is given in Figure 8

It is noted that unlike the analytical models of the relevant literature, the present model calculates the mode mixity following the William's global decomposition approach. In the equations of Table 1, the effect of the residual hygrothermal stresses on the SERR is identical with that of the delamination tests studied in [17], namely DCB, ENF, SLB, and MMB test.

From the experiments and the data reduction it was observed that the DCB-UBM performed as expected, however the joint design showed some issues. Therefore a considerable part of the experiments were not valid. Overall conclusions could be made that the thermoplastic and FM94 adhesive joint performed most consistent. Lower temperatures at cold dry (CD) reduced the fracture toughness of the joint as expected. Elevated temperatures testing (ETW) results were not very consistent, also because of the backing material separation observed in some cases. Further evaluation of data and comparison with the conventional DCB test results are needed.

5 Summary and concluding remarks

Within the TICOAJO project the aim is to characterize the adhesive connection between titanium and composite material for the Hybrid Laminar Flow Control (HLFC) design application. The characterization is done under various loading and environmental conditions. Due to the small thickness of the titanium plate in the design and its low yield stress, additional backing material is needed to avoid plastic deformation. Four different types of adhesive and joining options have been manufactured and evaluated using experimental testing.

The testing interface characterization presented in this paper was done using the novel moment loaded double cantilever beam (DCB-UBM) setup. The test results showed that for the adhesive interface using FM-94 and FM-300 adhesive the results were satisfactory. The composite itself appears to be the weak point and delaminations start to form during the mode-I testing. Also, the tests at elevated temperature showed that the connection between the titanium adherent and the aluminum backing was failing, mainly in the mode II test. Since this is probably a direct consequence of the coupon design with the backing and the optimal pre-treatment, it can be concluded that the test setup worked satisfactory despite the high loads involved. In the future this test setup will be used for further characterization of material and joints.

The data reduction showed that the thermal effects of the hybrid structure can be included in the closed form solutions. The fracture toughness values could be extracted from the test results, which, however, in some cases showed high variation.

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