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International Committee on Aeronautical Fatigue and Structural Integrity

Topical National Review
Structural Integrity for Composite Laminate

Daniele Fanteria (U. of Pisa) and Takao Okada (JAXA), June 28, 2023

Structural Integrity for Composite Laminate

Contents

Overview of the topic in NRs and in ICAF 2023 Program

- About 20% of topic in NRs are about SI for composite laminate
- About 20 presentations including poster are about SI for composite laminate
- Topic concerning about SI for composite laminate
  - Joints (Bolted, Bonded, Welded)
  - Fatigue (Matrix crack, delamination, etc.)
  - Impact damage and Crashworthiness
  - Lightning
  - Etc.

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Overview of the topic in NRs and in ICAF 2023 Program

- Joints (Bolted, Bonded, Welded)
  - Bolt fatigue in CFRP-CFRP joints, Z. Kapidzic (Saab)
  - Stacking sequence effect on the fatigue behavior of single lap shear bonded joints, F. M. Gonzalez Ramirez et. al (IVW) (Poster, on Wed.)
  - Investigation on Disbond Arrest Features in adhesive joints, (U. of Bologna)
  - Compliance methods for bonded joints: Part I - investigation of the standardized methods to obtain the Strain Energy Release Rate for Mode I, F. Madureira, et. al (U. of São Paulo and U. of Proto)
- Fatigue
  - Creating a digital-twin framework for the life prediction of composite materials, Jordy Schönthaler et al. (U. Twente) (Poster, on Mon.)
  - Delamination onset resistance of composite material systems, D. Fanteria et al. (U. of Pisa, Leonardo Helicopters)
  - Experimental investigation of planar delamination behavior of composite laminates under out-of–plane loading, W. Tu (TU Delft) (Oral, Session 10)

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Overview of the topic in NRs and in ICAF 2023 Program

- Impact damage and Crashworthiness
  - Virtual testing of low-velocity impact response of a composite laminate – from analytical to high-fidelity modeling, L. Li et. al. (NRC) (Poster, on Mon.)
  - Development of a numerical model of tire fragments for high-speed impact, J.-R. Augustin (DGA TA) (Poster, on Wed.)
  - Crashworthiness Pyramid Test Technology of Double Passageway Composite Fuselage Structure, W. Li, (COMAC Shanghai Aircraft Design & Research Institute)

- Lightning
  - Development of CFRP with improved lightening resistance using electrically conductive resin, T. Yokozeki et. al. (The U. of Tokyo, Yamagata U. and JAXA)
  - Clarifying Edge Glow Mechanisms of CFRP Exposed to Simulated Lightning Current in In-plane Direction, S. Kamiyama et. al (JAXA, Shoden and Tokyo U. of Agriculture and Technology)

Overview of the topic in NRs and in ICAF 2023 Program

- AFP and OoA
  - Robotic fibre placement of hybrid steel and carbon fibre for multifunction aerospace structure, M. M. A. Ammar et. al. (Monash U.)
  - High-Degree-of-Freedom Composite Technology using Thin-Layer Materials that Exploit the Potential of Composite Materials, D. Terayama et. al. (SUBARU)
  - Optimal Design and Static Load Testing of Tow-Steered Aircraft Fuselage Frames, H. Arizono et. al (JAXA and Kawasaki Heavy Industries, Ltd) (Poster, on Wed.)
  - Testing of an out of autoclave–liquid resin infused carbon-epoxy curved stiffened panel, D. Fanteria et al., (U. of Pisa in AIRGREEN2, CP to CleanSky2)

Structural integrity for composite laminate from Japanese NR

- A numerical scheme for fatigue simulation of laminated composites using CZM-XFEM and cohesive element by The U. of Tokyo
- Giga-cycle fatigue properties of transverse crack initiation in cross-ply CFRP laminates using ultrasonic fatigue testing by Waseda U.
- Development of CFRP with improved lightning resistance using electrically conductive resin by The U. of Tokyo, Yamagata U. and JAXA
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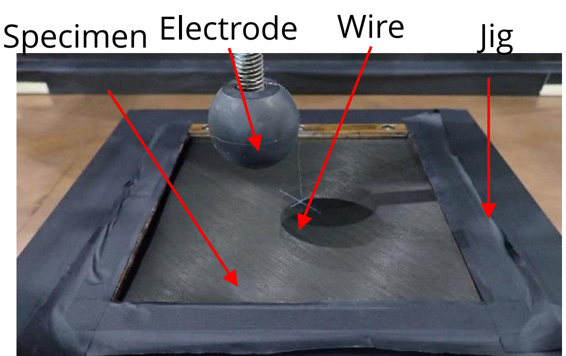
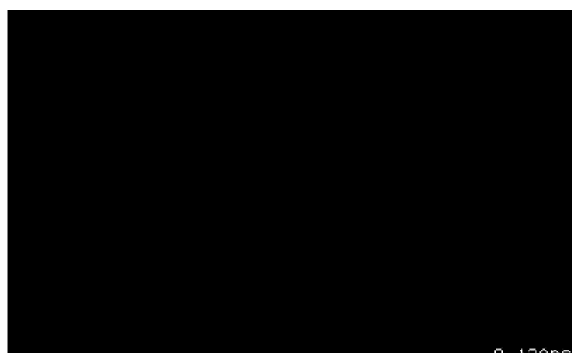
Lightening

- CFRP has low electrical conductivity compared to conventional metal structures and therefore greater damage is caused in case the lightning attaches to the aircraft structure using composite material.
- The damage mechanism of the CFRP under lightning is much complicated (Joule heating, thermal flux from the arc root, shock wave accompanying arc generation, thermal decomposition of resin, and etc.) and many research have been conducted.



Test setup



High speed camera (0.5μs/frame)

Thermography (10ms/frame)

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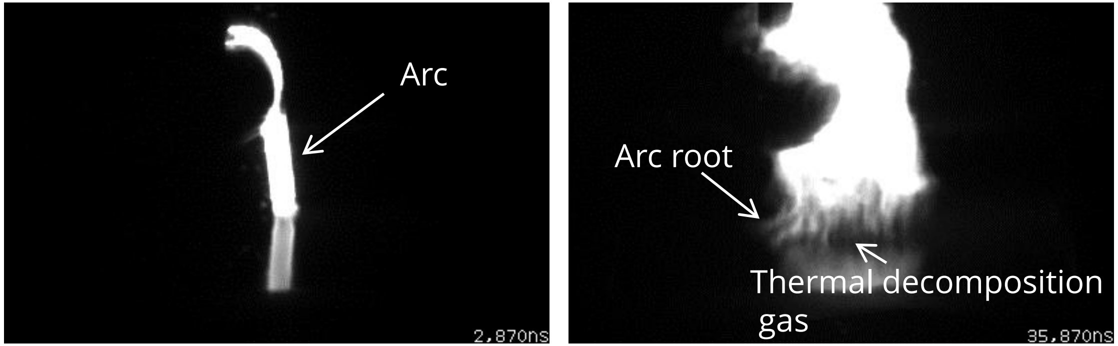
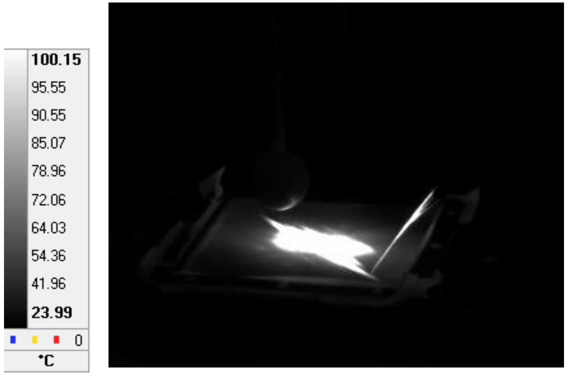


High speed camera (0.5μs/frame)

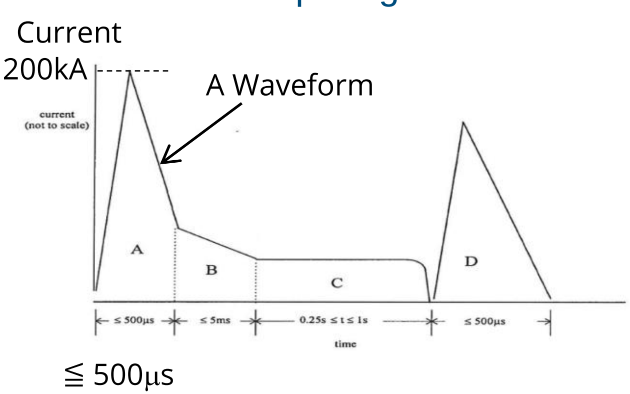


Thermography (10ms/frame)

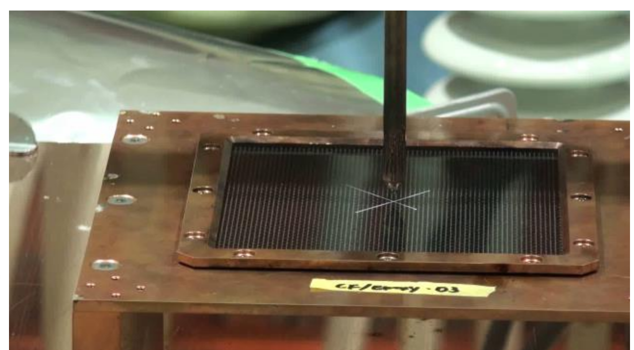
Development of CFRP with improved lightning resistance using electrically conductive resin

T. Yokozeki et. al. (The U. of Tokyo, Yamagata U. and JAXA)

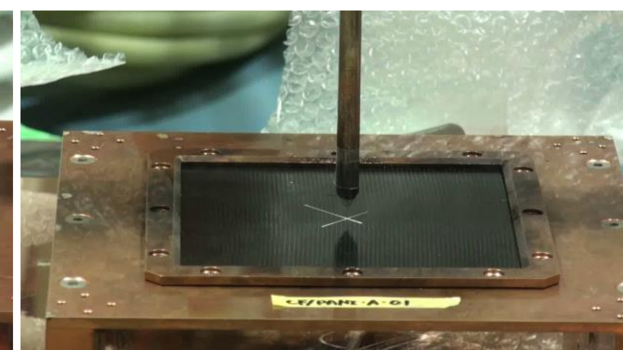
- Improve the electrical conductivity of the resin using electrically conductive polyaniline (PANI). Through the thickness electrical conductivity of CFRP using developed electrically conductive resin is 0.93 S/cm, while the conventional CFRP prepared for comparison is 0.06 S/cm.
- The lightning resistance of the developed CFRP is evaluated by the simulated lightning test based on the SAE ARP-5412 with peak current reduced to -40kA and -100kA.
- Test result indicates that lightning damage for developed CFRP is apparently suppressed comparing to that for conventional one.



Lightening test waveform (SAE-5412 B)



Conventional CFRP

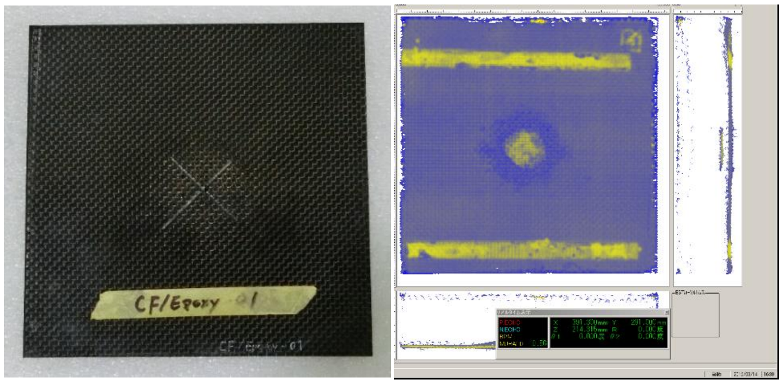


Electrically conductive CFRP

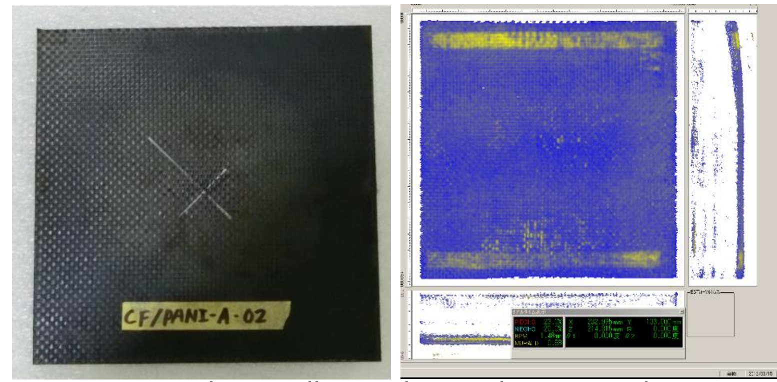
Lightening test (Modified A waveform)

Development of CFRP with improved lightning resistance using electrically conductive resin

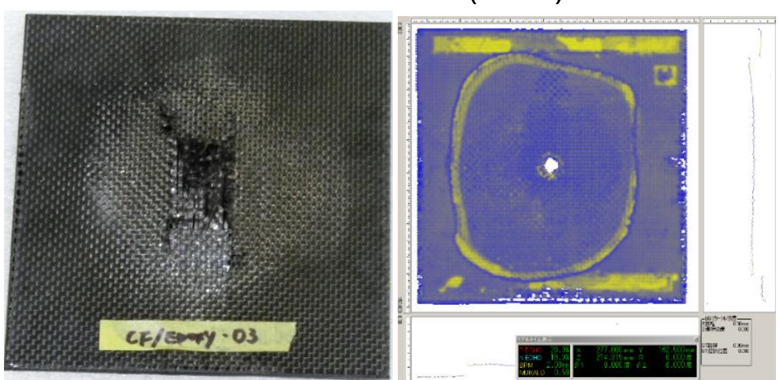
T. Yokozeki et. al. (The U. of Tokyo, Yamagata U. and JAXA)



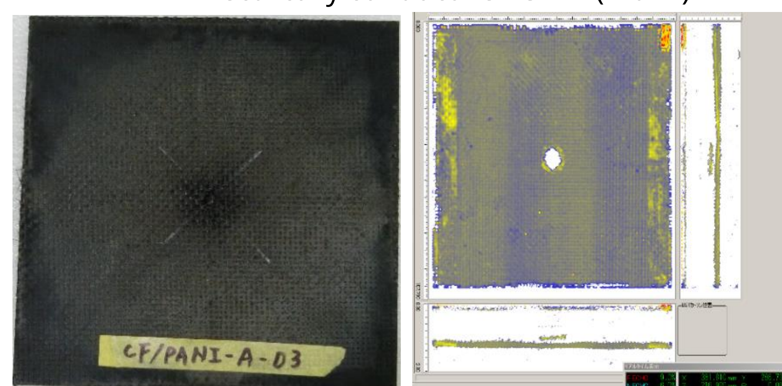
Conventional CFRP (-40kA)



Electrically conductive l CFRP (-40kA)



Conventional CFRP (-100kA)



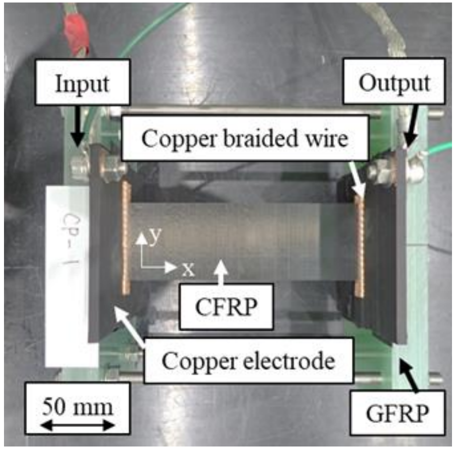
Electrically conductive l CFRP (-100kA)

Lightning test result

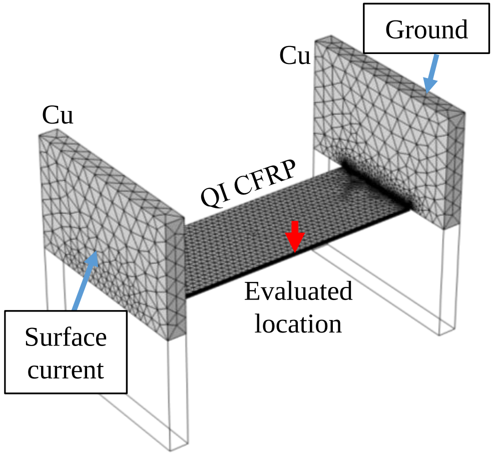
Clarifying Edge Glow Mechanisms of CFRP Exposed to Simulated Lightning Current in In-plane Direction

S. Kamiyama, et. al., (JAXA, Shoden and Tokyo U. of Agriculture and Technology)

- Edge glow is visible light at cut edge of CFRP structure due to lightning current passing through composite materials. Edge glow might be ignition risk when it occurs in the fuel tank made of composite material. Fundamental nature of the phenomena has not been generally understood.
- Objective of this study is to clarify the mechanisms of edge glow of CFRP exposed to lightning current. Simulated lightning current was directly applied to rectangular shape CFRP laminates specimen. Phenomena was observed by using a high-speed camera. Numerical analysis based on finite element analysis (FEA) was also carried out to estimate Joule heating generation and voltage distribution.



Conduction test setup

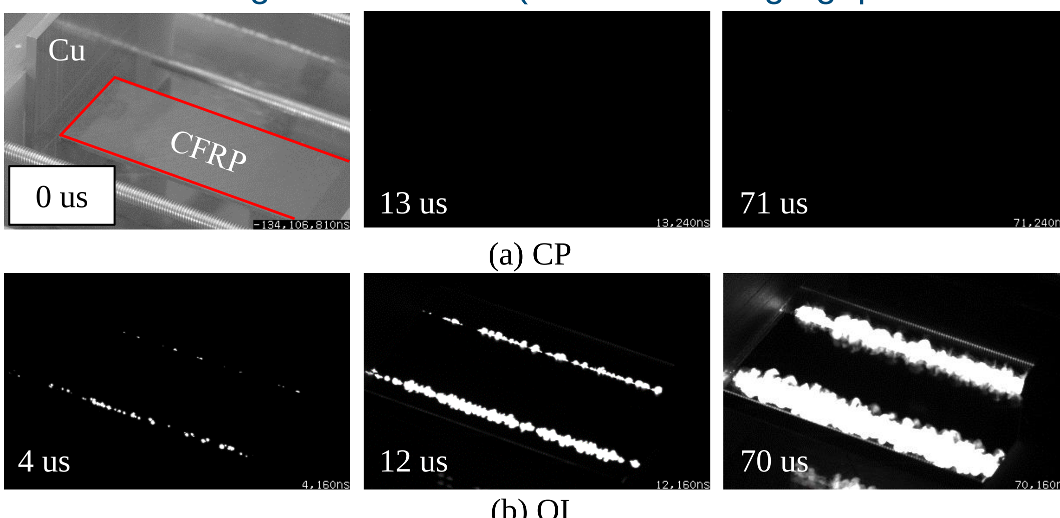


FEA model and boundary condition

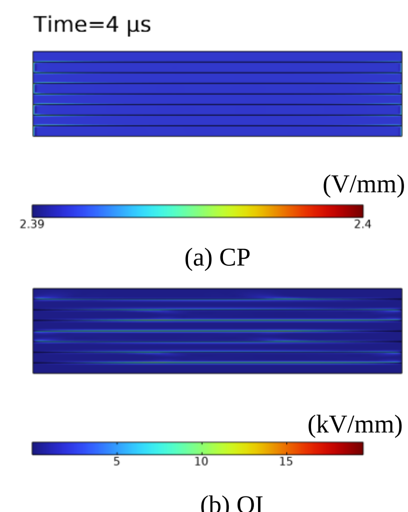
Clarifying Edge Glow Mechanisms of CFRP Exposed to Simulated Lightning Current in In-plane Direction

S. Kamiyama, et. al., (JAXA, Shoden and Tokyo U. of Agriculture and Technology)

- While nothing was observed in the CP(Cross Ply) laminate, edge glow was detected on long edge of specimen in the QI (Quasi-Isotropic) laminate. Electrical potential of CP laminate was distributed uniformly in thickness direction, while that of QI laminate was distributed ununiformly in thickness direction because of the effect of 45° layer.
- These results indicates that occurrence criteria of edge glow are not increasing temperature but increasing electrical field (electrical voltage gap between layers).



High-speed images when 10 kA of lightning current was applied

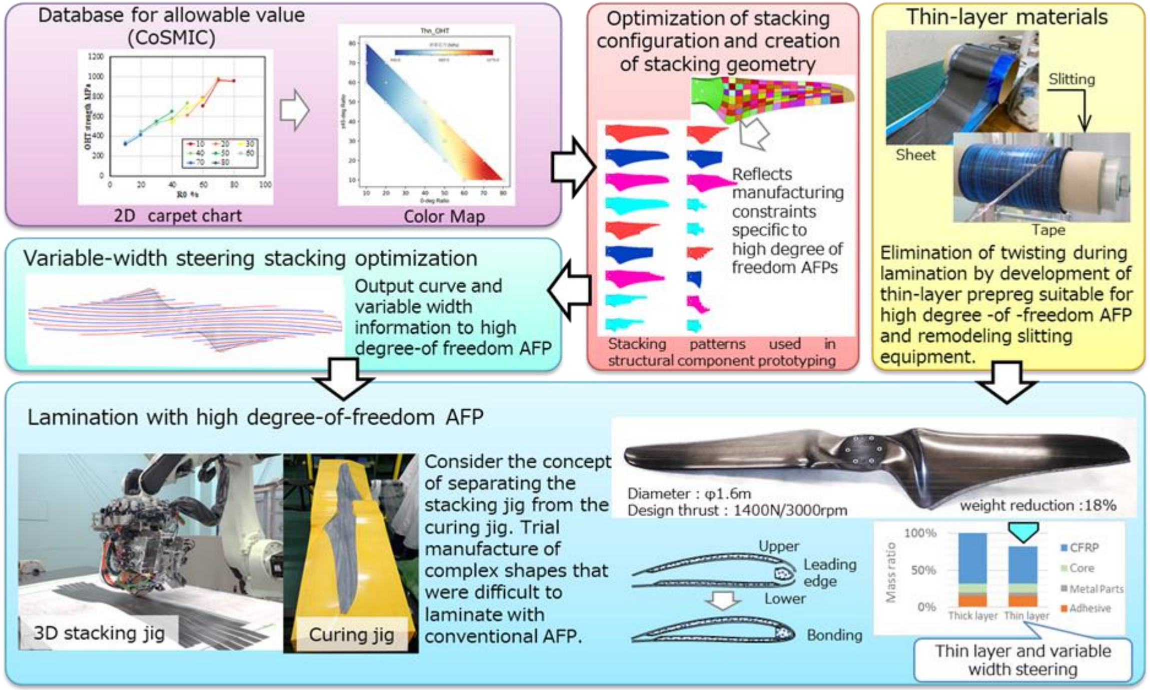


Electrical field norm distribution

High-Degree-of-Freedom Composite Technology using Thin-Layer Materials that Exploit the Potential of Composite Materials

D. Terayama et. al. (SUBARU)

- Develop a high degree of freedom composite technology that removes these restrictions, increases the degree of freedom in design and manufacturing, and further brings out the characteristics of composite materials.



The schematic of this study

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High-Degree-of-Freedom Composite Technology using Thin-Layer Materials that Exploit the Potential of Composite Materials

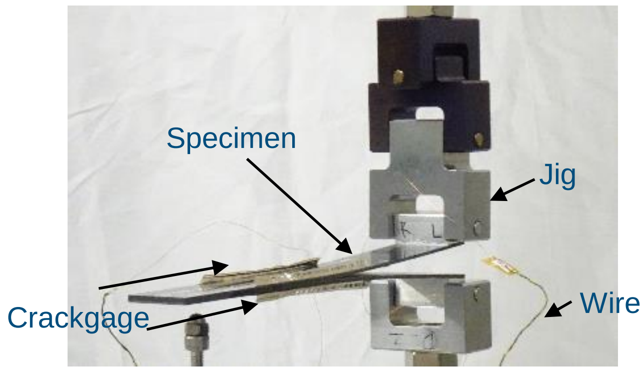
D. Terayama et. al. (SUBARU)

- In material technology, we developed and introduced a one-step manufacturing line for thin-layer prepreg sheets, which enables production at a speed equivalent to that of ordinary prepreg.
- In the manufacturing technology, SUBARU succeeded in changing the width of the laminate while steering for the first time in the world. SUBARU has also demonstrated the feasibility of manufacturing actual structural parts by manufacturing a prototype propeller for use in an aircraft. The propeller made with thin-layer material and variable-width steering was approximately 18% lighter than a propeller made with conventional thick-layer material.
- In the design analysis technology, composite strength prediction was achieved through highly accurate multi-scale analysis using CoSMIC (Comprehensive System for Materials Integration of CFRP) . A carpet chart was also created for use in structural design, which was used to derive the lamination configuration directly from the internal loads. Furthermore, from the optimized lamination configuration, variable width steering lamination was also optimized and the optimal lamination path was successfully output.

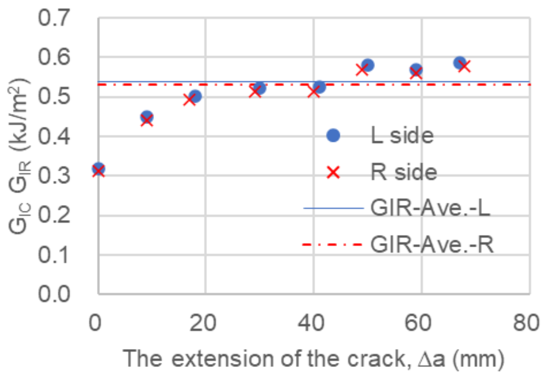
DCB test automated with crackgages

E. Hara et. al. (JAXA)

- Double Cantilever Beam (DCB) test method requires to control cross head depending on the crack length and to measure the crack length on both side of the specimen. It is time consuming especially for some test standard.
- The automating DCB test procedure using the crackgage attached on both sides to measure the crack length is proposed.
- The obtained interlaminar fracture toughness are close to that obtained by the conventional procedure and the test duration becomes about 1/4 of that for conventional one.



Setup of automated DCB test



R-curve from automated DCB test

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Structural integrity for composite laminate from Italian NR

- Investigation on Disbond Arrest Features in adhesive joints by the University of Bologna – Forlì Campus
- Structural Health Monitoring by means of Optical Fibres by the University of Bologna – Forlì Campus
- Delamination onset resistance of composite material systems by the University of Pisa and Leonardo Helicopters
- Meso-scale models for the interaction of damage modes in composites laminates by the Polytechnic of Milan and Leonardo Helicopters
- Testing of an Out of Autoclave–Liquid Resin Infused carbon-epoxy curved stiffened panel by the University of Pisa (within EU Proj. CleanSky2)

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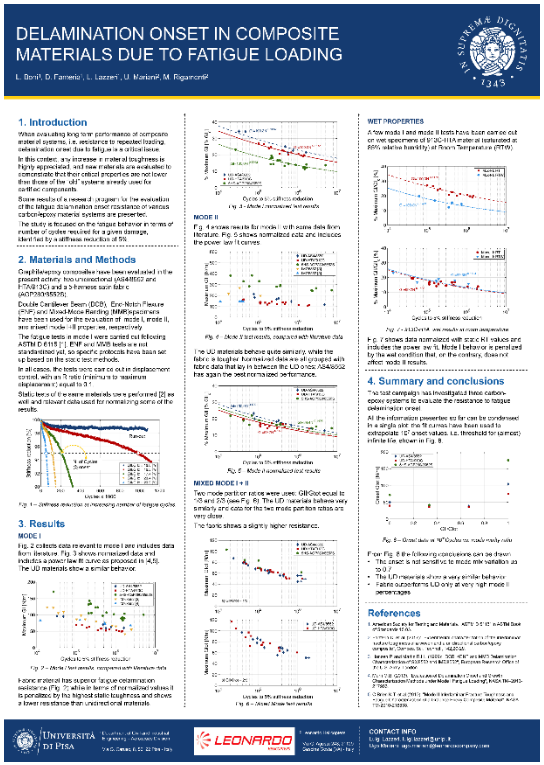
Delamination onset resistance of composite material systems

by the University of Pisa and Leonardo Helicopters



Preliminary results were presented in a poster at ICAF 2019

A collaboration between the University of Pisa and the Leonardo Helicopter Division has been set up with the aim of studying the phenomenon of **the onset of delamination growth** at a high number of cycles in a group of composite material systems commonly used in helicopter structures: the **focus** of the research has been on the assessment of the **"endurance" limit** that allows the designer to be confident of an **infinite life**, thus requiring long duration tests.

Material	Mode I (DCB)	Mode II (ENF)	Mode I+II (MMB)
UD AS4/8552	6	6	27
UD HTA/913C	13	19	28
5HS AGP280/8552S	17	18	5

Mode I, Mode II and Mode I+II fatigue tests for 3 materials (139 tests).

All the tests were performed under constant displacement amplitude, at 0.1 ratio between the minimum and maximum displacements.

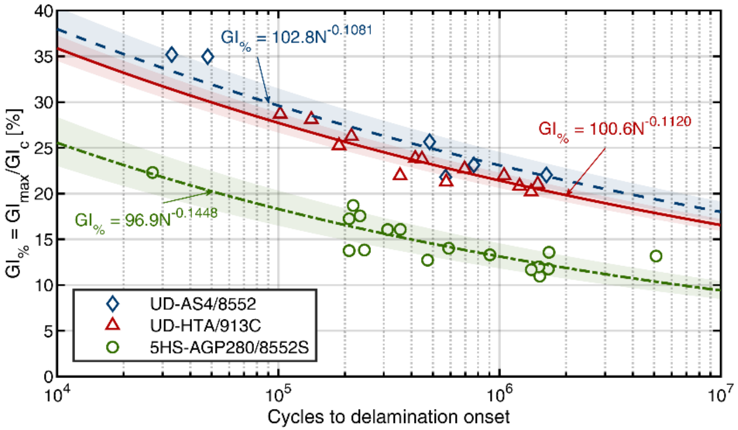
Delamination onset resistance of composite material systems

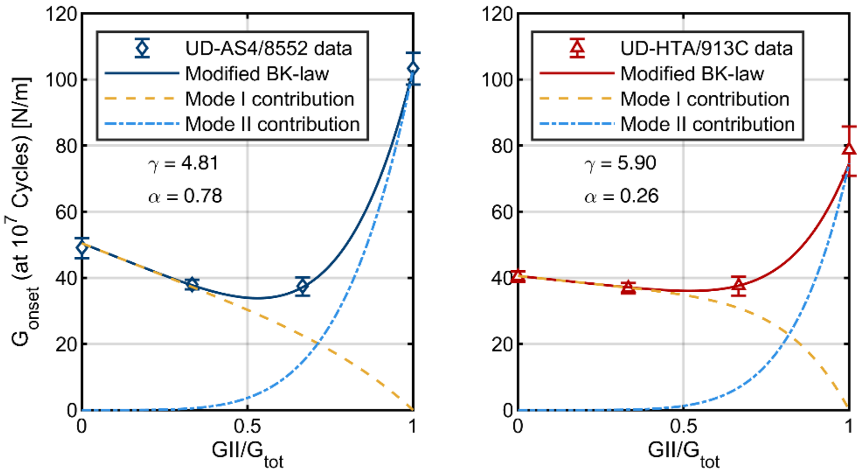
by the University of Pisa and Leonardo Helicopters

Refined fitting procedure to consider the influence of run-outs on the values of the fitting curve parameters and on the standard deviation of each group of data.

Scatter bands (of one standard deviation amplitude) were then added to the G-N curves.

A fitting law, obtained by modifying the classical B-K law, was developed to interpolate the onset results at 10^7 cycles.





By using the proposed fitting law, the fatigue onset performance of materials can be rationally compared.

More details can be found in: Boni L., Fanteria D., Lazzeri L., Mariani U., Rigamonti M. (2022): **Delamination onset in composite materials due to fatigue loading**, ***Journal of Composite Materials, 56 (16),*** 2585–2598.

Testing of an OoA–LRI carbon-epoxy curved stiffened panel

by the University of Pisa (within EU Proj. CleanSky2)

This research has been carried at the University of Pisa as a contribution to the Regional Platform of Clean Sky 2, in which the University of Pisa participated as partner of the AIRGREEN 2 cluster.

Activities were focused on the development of design approaches and manufacturing processes for primary structures of a regional aircraft in carbon/epoxy composites. The reference structure chosen was a curved stiffened panel, representative of the outer wing box upper skin, produced by Liquid Resin Infusion (LRI) from dry preforms, then cured by an Out of Autoclave (OoA) process.

The research is a joint effort of some of the members of the AIRGREEN 2 cluster, namely Hellenic Aerospace Industry (HAI) for the manufacturing activities, Leonardo Aircraft (LDO), the Italian Centre for Aerospace Research (CIRA) and the University of Naples "Federico II" (UNINA) for the introduction of impact damage and for the ultrasonic Non-Destructive Inspection (US NDI) and, finally, the University of Pisa (UNIPI) for the static and fatigue testing.

Co-funded by the European Union

CLEAN AVIATION

This work was funded by Clean Sky 2 Joint Undertaking,
under the European’s Union Horizon 2020 research and innovation Programme,
under grant agreement No 807089 – REG GAM 2018 – H2020-IBA-CS2- GAMS-2017;
WAL (Work Area Leader): Leonardo Aircraft.

Testing of an OoA–LRI carbon-epoxy curved stiffened panel

by the University of Pisa (within EU Proj. CleanSky2)

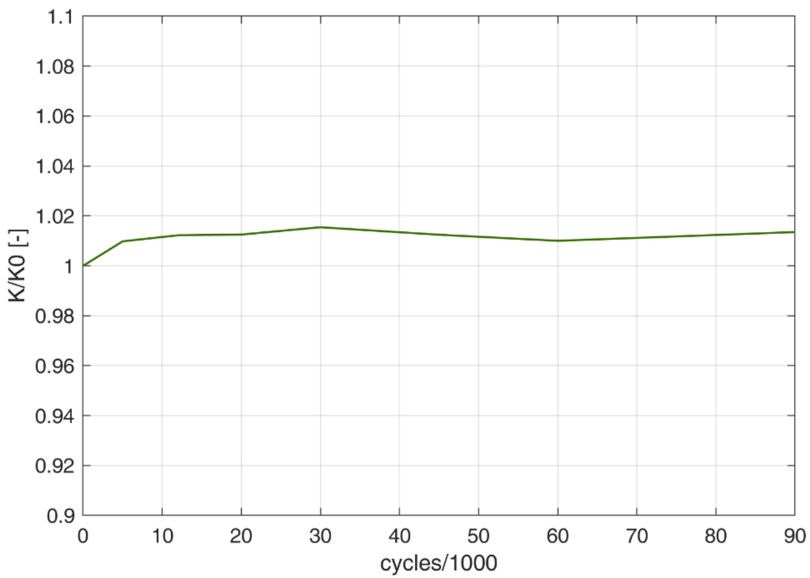
- The panel was instrumented with 44 uniaxial SGs and 4 rosettes in a back-to-back configuration.
- The panel was mounted on a 3 MN servo-hydraulic fatigue testing machine and the specific support fixtures (side supports and rib end clamps) were installed.
- Buckling load was re-evaluated considering the tests boundary conditions (500 kN in pristine condition).
- Effective UL of the test article set at 440 kN
- Consequently, the effective LL s 293.3 kN
- Following Leonardo indication about the max cyclic load for a single equivalent cycle per flight (producing the same damage as all cycles in an average flight, representative of AC life), maximum fatigue load has been assumed equal to LL (including a 1.15 LEF), with R=(max cyclic load)/(min cyclic load)=0.2.
- The number of flights is 90k (DSGx1.5)
- Test is stopped at 10k, 20k, 30k, 45k, 60k and 90k Cycles for reading SGs and check possible compliance variations

LRI curved panel ready for Testing

Testing of an OoA–LRI carbon-epoxy curved stiffened panel

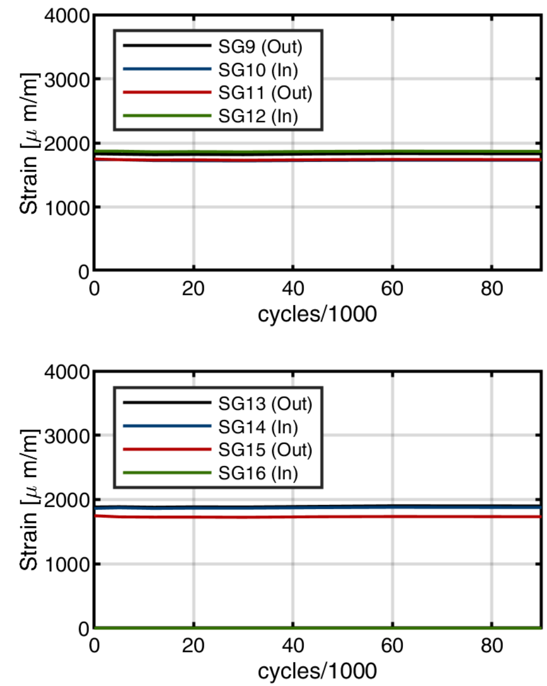
by the University of Pisa (within EU Proj. CleanSky2)

Variation of axial stiffness (K) with fatigue cycles



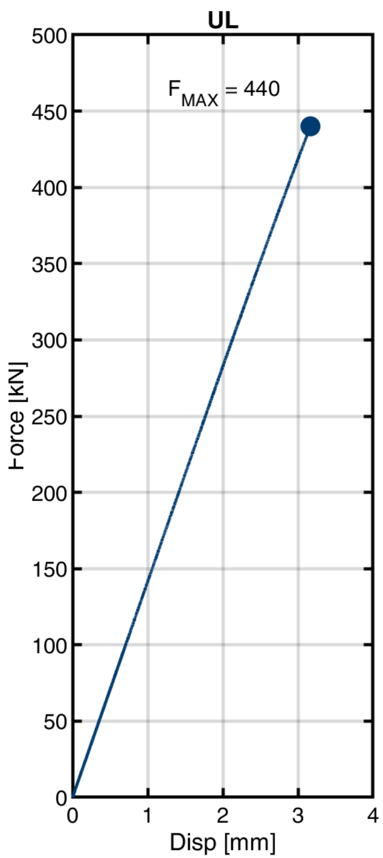
After 90k Cycles no compliance variation is appreciable

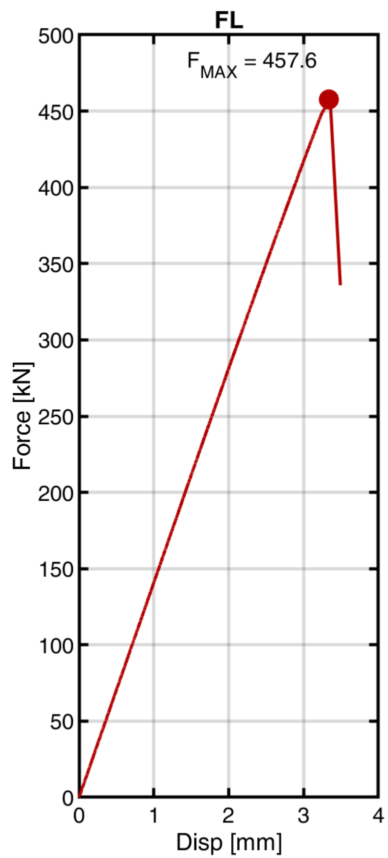
Variation of the SG reading in the vicinity of stringer disbonding with fatigue cycles

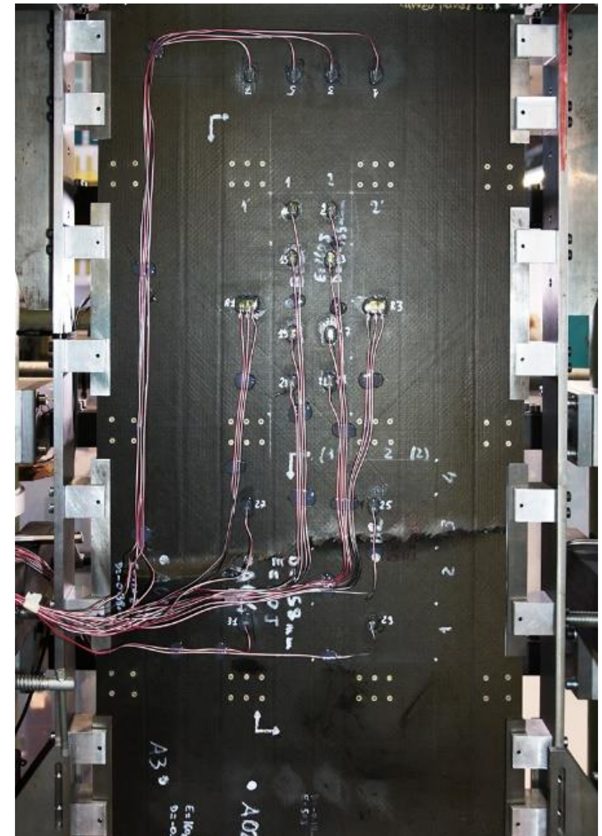


Testing of an OoA–LRI carbon-epoxy curved stiffened panel

by the University of Pisa (within EU Proj. CleanSky2)

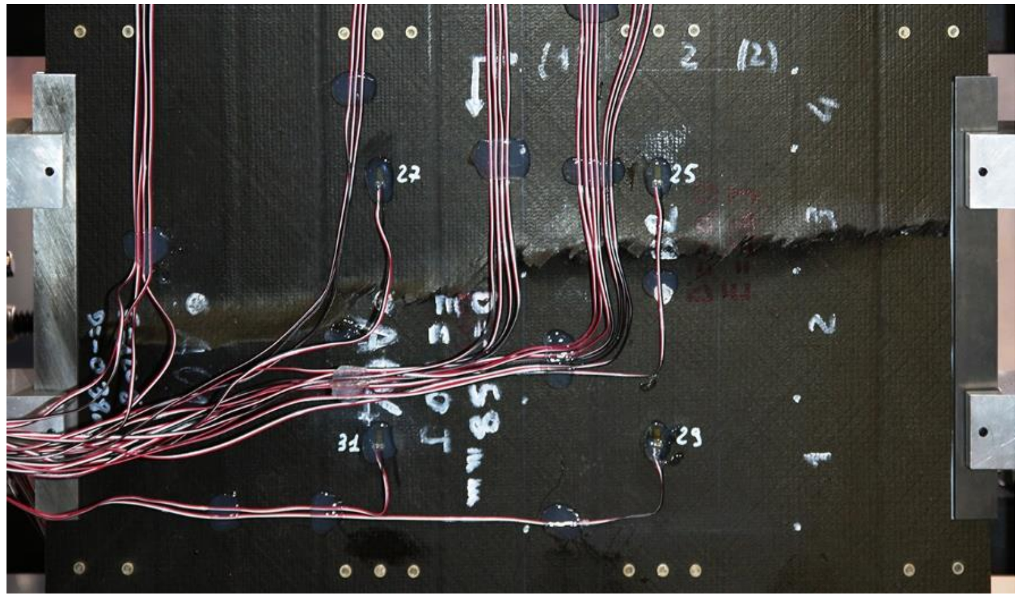






Testing of an OoA–LRI carbon-epoxy curved stiffened panel

by the University of Pisa (within EU Proj. CleanSky2)



- The panel sustained 90k fatigue cycles (1.5DSG) without appreciable variation of either the global or local stiffnesses.
- After fatigue cycles it was able to withstand Ultimate Load without failure.
- In the subsequent loading the panel reached 104% of UL before failure.
- It is likely that the failure was triggered by the interaction of skin buckling and the presence of impact damage in the lower bay

Thank you for your kind attention

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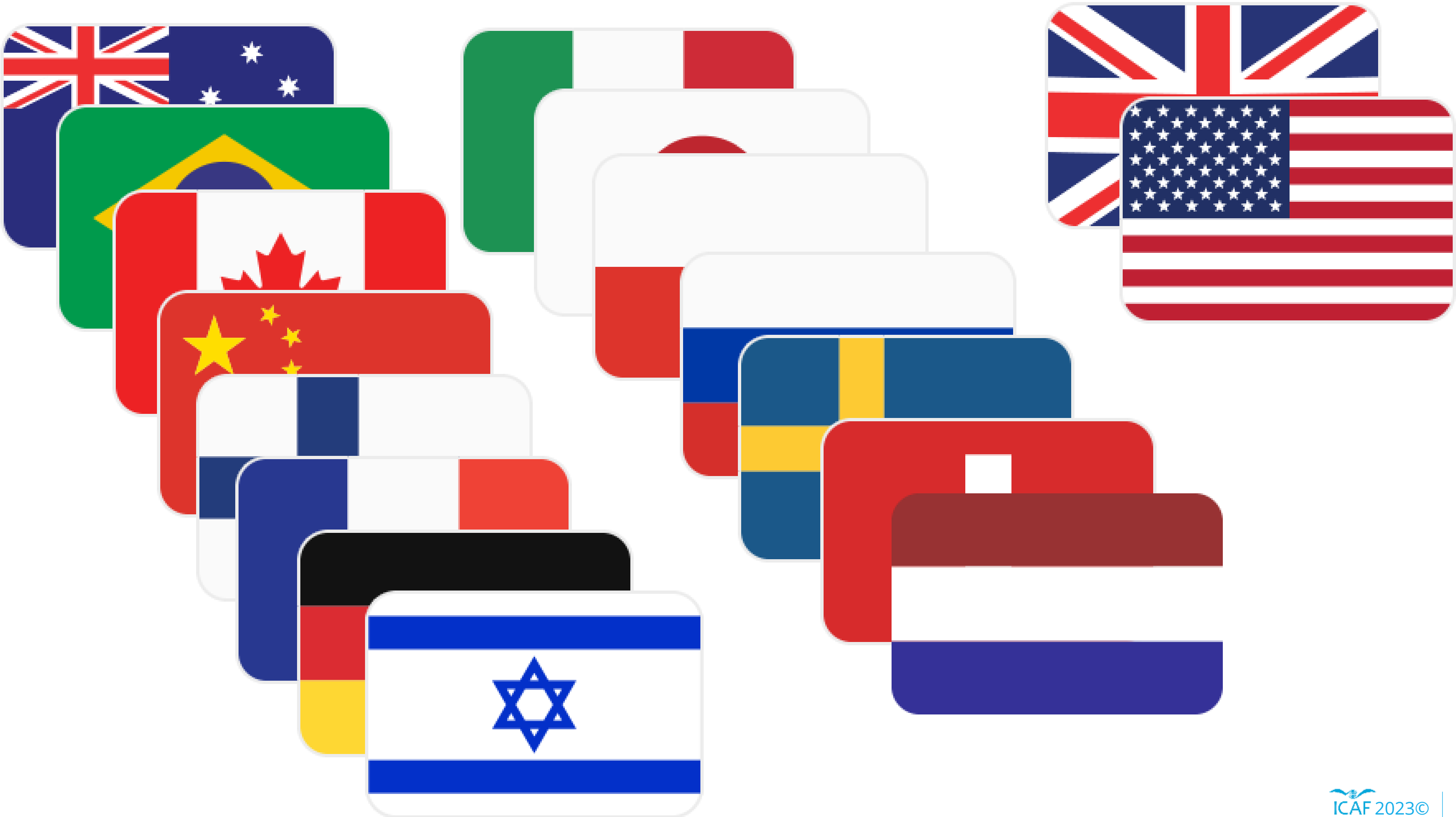
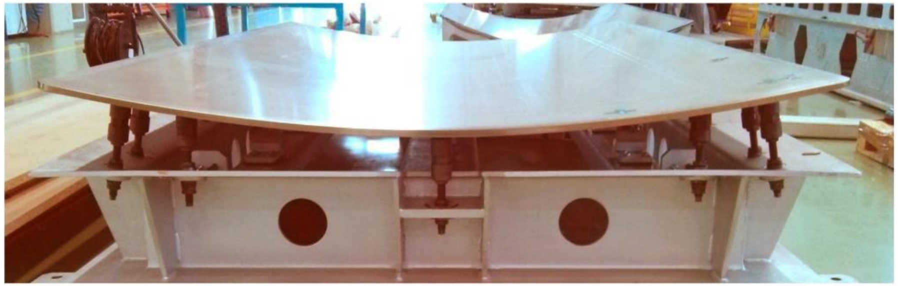
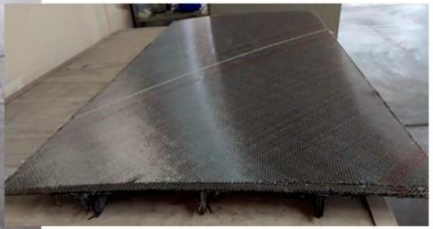
Flags

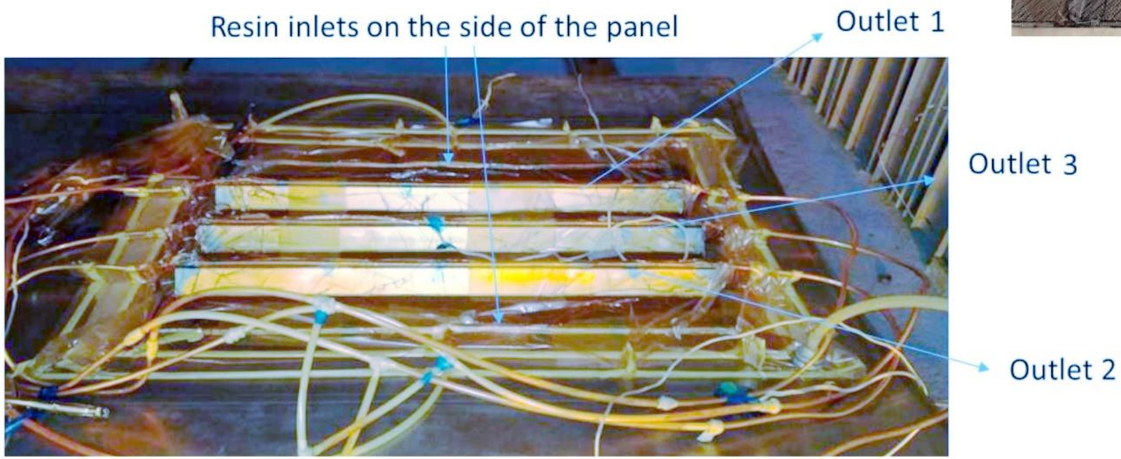


Testing of an OoA–LRI carbon-epoxy curved stiffened panel
by the University of Pisa (within EU Proj. CleanSky2)

Manufacturing via LRI/OoA process (HAI)







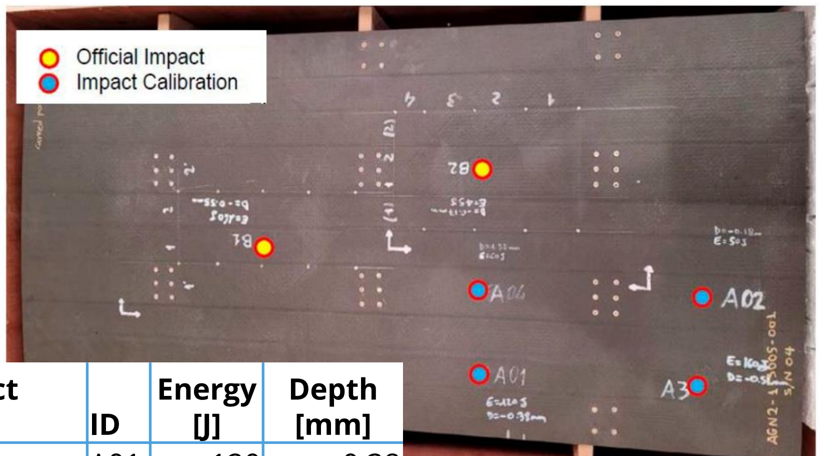
Testing of an OoA–LRI carbon-epoxy curved stiffened panel

by the University of Pisa (within EU Proj. CleanSky2)

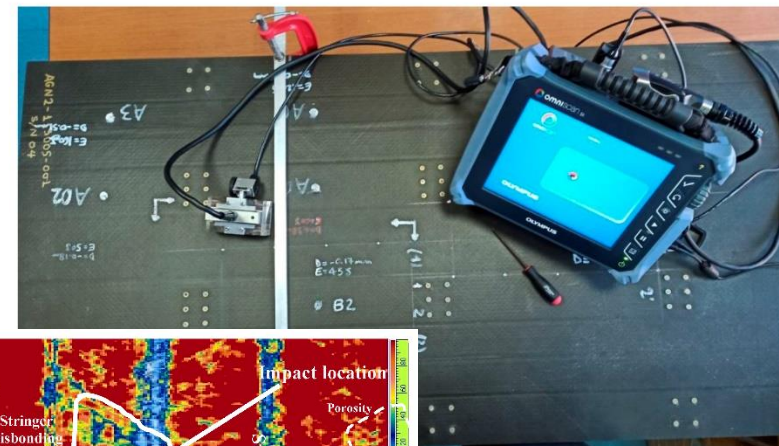
Barely visible Impact damage (LDO/CIRA/UNINA)

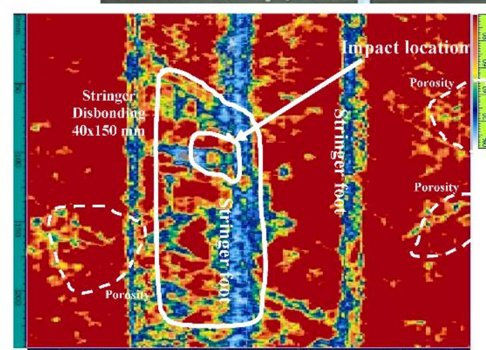
To evaluate the panel response, before and after the damage, through a SHM system different impact damages have been introduced.

US scanning NDI has been used to assess delaminations and set a benchmark for SHM



Impact type	ID	Energy [J]	Depth [mm]
Calibration	A01	120	0.38
	A02	50	0.18
	A03	160	0.51
	A04	60	1.58
Official	B01	160	0.55
	B02	45	0.17





Testing of an OoA–LRI carbon-epoxy curved stiffened panel

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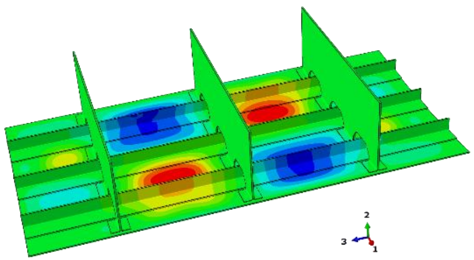
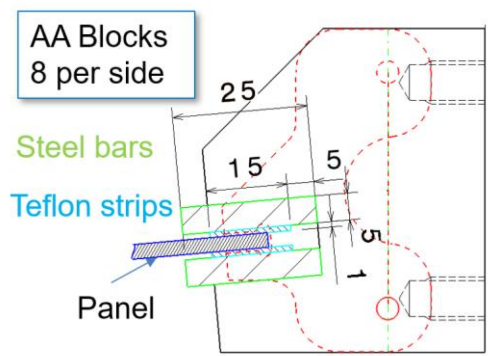
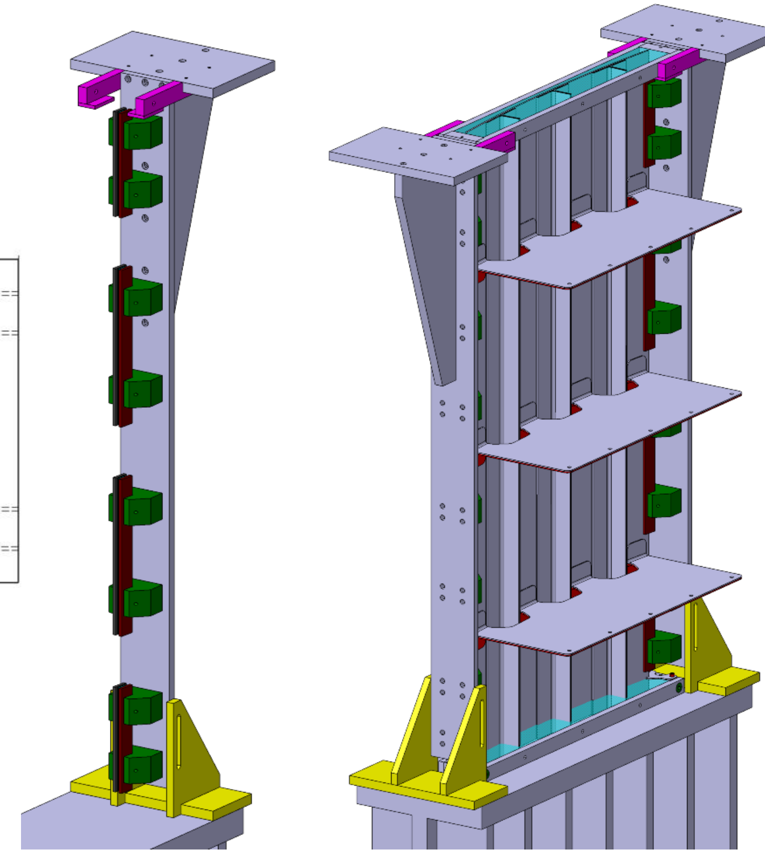
Due to a 3 stringers/4 spacing width design side support fixtures were needed to avoid premature skin buckling of the straight edges

Non-linear FE analyses of the test set-up were developed to support fixture design and panel tests







Side and rib support design inspired by FE results:

- Side supports Independent from rib supports
- Side supports stabilized laterally
- Rib edges fixed to the testing machine frame
- Retaining system for the top potting frame