COST Action CA18120

Reliable roadmap for certification of bonded primary structures

Certbond COST Action Final Conference

6-8 September 2023

Seville, Spain

Practical Information Guide
Technical Programme

(final version - 2023.09.25)

Funded by the European Union

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About COST

The European Cooperation in Science and Technology (COST) is a funding organisation for the creation of research networks, called COST Actions. These networks offer an open space for collaboration among scientists across Europe (and beyond) and thereby give impetus to research advancements and innovation.

COST is bottom up, this means that researchers can create a network – based on their own research interests and ideas – by submitting a proposal to the COST Open Call. The proposal can be in any science field. COST Actions are highly interdisciplinary and open. It is possible to join ongoing Actions, which therefore keep expanding over the funding period of four years. They are multi-stakeholder, often involving the private sector, policymakers as well as civil society.

Since 1971, COST receives EU funding under the various research and innovation framework programmes, such as Horizon 2020.

COST funding intends to complement national research funds, as they are exclusively dedicated to cover collaboration activities, such as workshops, conferences, working group meetings, training schools, short-term scientific missions, and dissemination and communication activities. For more information, please go to the Funding section of the COST website (https://www.cost.eu/).

The COST Association places emphasis on actively involving researchers from less research-intensive COST Countries (Inclusiveness Target Countries, ITC[1]). Researchers from Near Neighbour Countries and International Partner Countries can also take part in COST Actions, based on mutual benefit. For more information, please visit the global networking page (https://www.cost.eu/).

[1] Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Macedonia, Hungary, Latvia, Lithuania, Luxembourg, Malta, Montenegro, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Turkey

COST Action CA18120

With the increasing pressure to meet unprecedented levels of eco-efficiency, aircraft industry aims for superlight structures and towards this aim, composites are replacing the conventional Aluminium. The same trend is being followed by civil, automotive, wind energy, naval and offshore industry, in which the combination (or replacement) of steel with composites can increase the strength-to-weight ratio. However, the joining design is not following this transition. Currently, composites are being assembled using fasteners. This represents a huge weight penalty for composites, since holes cut through the load carrying fibres and destroy the load path.

Adhesive bonding is the most promising joining technology in terms of weight and performance. However, its lack of acceptance is limiting its application to secondary structures, whose failure is not detrimental for the structural safety. In primary (critical-load-bearing) structures, fasteners are always included along bondlines, as "back-up" in case the bond fails. The main reasons for this lack of acceptance are the limited knowledge of their key manufacturing parameters, non-destructive inspection techniques, damage tolerance methodology and reliable diagnosis and prognosis of their structural integrity.

The Action aims to deliver a reliable roadmap for enabling certification of primary bonded composite structures. Despite the motivation being aircraft structures, which is believed to have the most demanding certification, it will directly involve other application fields in which similar needs are required. This Action will tackle the scientific challenges in the different stages of the life-cycle of a bonded structure through the synergy of multi-disciplinary fields and knowledge transfer.

General information

Start of Action: 04/04/2019
End of Action: 30/09/2023

Main Contacts

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Domain website: https://www.cost.eu/actions/CA18120

Action Management Committee

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Action Vice Chair	Anastasios P. VASSILOPOULOS
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WG 2 - Design phase	Konstantinos TSERPES (kitserpes@upatras.gr)
WG 3 - Manufacturing phase	Nicolas CUVILLIER (nicolas.cuvillier@safrangroup.com)
WG 4 - In-service life phase	Wieslaw OSTACHOWICZ (wieslaw@imp.gda.pl)
WG 5 - Disassembly phase	Laurent BERTHE (laurent.berthe@ensam.eu)
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Database Coordinator	Michal BUDZIK (mibu@eng.au.dk)

Action Working Groups

WG 1 - Adhesive and interface chemistry
Leader: Ana MARQUES
Vice-leader: Åsa LUNDEVALL

- Evaluate current common practice in industry: adhesive chemistries and surface treatment processes for bonded joints.
- Collect the requirements and needs of the stakeholders and certification agencies, in terms of regulations (REACH).
- Propose novel non-toxic and environmentally friendly surface treatment processes and adhesive chemistries.
- Evaluate the quality of the new proposed eco-friendly solutions.

WG 2 - Design phase
Leader: Konstantinos TSERPES
Vice-leader: Norbert BLANCO

- Explore new design concepts (geometrical configurations and new crack arresting design features).
- Compare testing procedures for bondline characterization and models validation (under static, fatigue and impact loading, creep phenomena, imperfect bonding and environmental effects).
- Evaluate different design methodologies for the structural behaviour and progressive damage analysis of adhesively bonded structures.

WG 3 - Manufacturing phase
Leader: Nicolas CUVILLIER
Vice-leader: Rūta RIMAŠAUSKIENĖ

- Specify and select the key-parameters that influence the manufacturing process on an industrial scale.
- Evaluate destructive and non-destructive testing for quality control of manufacturing process.
- Propose novel embedded sensing solutions for the evaluation of adhesion strength.
- Evaluate of the effect of different manufacturing defects on the bondline performance.

WG 4 - In-service life phase
Leader: Wieslaw OSTACHOWICZ
Vice-leader: Theodoros LOUTAS

- Propose diagnostic tools for the structural integrity assessment of the bonded structure.
- Propose prognostic tools for the remaining useful life of the bonded structure.
- Develop guidelines towards bonded repairs application.

WG 5 - Disassembly phase
Leader: Laurent BERTHE

- Description of the state-of-the-art about disassembly technologies.
- Evaluation of the technologies and selection of the most promising technology.

WG 6 - Certification
Leader: Thomas KRUSE-STRACK
Vice-leader: Ranko PETKOVIC

- Define common nomenclature for all WG's activities and deliverables.
- Integrate the outcomes and build the roadmap.
- Establish contact with relevant certification bodies and large industry manufacturers in naval, civil, offshore, automotive and wind energy and disseminate the progress of the Action and the roadmap.

Agenda

Time	Day 1 – 6/9	Day 2 – 7/9	Day 3 – 8/9
Morning	Registration/ Welcome	CertBond Network at a Glance – Part III	CertBond Workshop: Impact and Future – Part I
	CertBond Network at a Glance – Part I		
	Coffee-break	Coffee-break	Coffee-break
	CertBond Network at a Glance – Part II	CertBond Network at a Glance – Part IV	CertBond Workshop: Impact and Future – Part II
Lunch break	Lunch	Lunch	Lunch
Afternoon	Technical Visit	CertBond Network at a Glance – Part V	MC Meeting (14:00 – 15:00)
		Coffee-break	
		CertBond Network at a Glance – Part VI	
Evening		Social Event	

Detailed Programme

Day 1 – September 6th 2023 (Morning)

09:00 – 09:30	**Registration**
09:30 – 09:35	**Welcome** **Chairs:** Sofia Teixeira de Freitas, Anastasios Vassilopoulos, Alberto Barroso
09:35 – 10:15	**WG3/WG5 activities** **Chairs:** Nicolas Cuvillier, Laurent Berthe
09:35 – 09:40	***Pitch of the WG3 highlights*** Nicolas Cuvillier
09:40 – 09:45	***Pitch of the WG5 highlights*** Laurent Berthe
09:45 – 10:00	*Continuous fibers reinforced composite structures production using FDM printing technology* Tomas Kuncius
10:00 – 10:15	*Additive Manufacturing of 3D ceramic-based composite heating elements* Alexander Katz-Demyanetz
10:15 – 12:15	**WG4 activities** **Chair:** Wieslaw Ostachowicz
10:15 – 10:20	***Pitch of the WG4 highlights*** Wieslaw Ostachowicz
10:20 – 10:35	*Health diagnosis of polymer 3D-printed plates using the electromechanical impedance method* Shishir Kumar Singh
10:35 – 10:50	*A comparison of different experimental techniques for crack tip localization in adhesive bonded CFRP-CFRP joints subjected to mode II fatigue loading* Michele Carboni
10:50 – 11:15	**Coffee-break**
11:15 – 11:30	*Comprehensive analysis of bonded composite structures using ultrasonic guided waves* Kaleeswaran Balasubramaniam
11:30 – 11:45	*Could listening to acoustic emissions be a valuable tool in understanding the complex toughening mechanisms of tailored adhesively bonded joints?* Rosemere de Araujo Alves Lima
11:45 – 12:00	*A practical approach for non-destructive testing of bonded joints to implement an acceptance-promoting in-line quality assurance* Christian Gundlach
12:00 – 12:15	*Bonded connection of recycled rubber decoupling system in infilled RC frames* Marko Marinković

Detailed Programme

Day 1 – September 6th 2023 (Morning)

12:15 – 12:35	**WG6 activities** **Chair:** Thomas Kruse
12:15 – 12:20	***Pitch of the WG6 highlights*** Thomas Kruse
12:20 – 12:35	*Uncertainty in the assessment of adhesively bonded joints* Fabio Santandrea
12:35 – 14:00	**Lunch**

Day 1 – September 7th 2023 (Afternoon)

14:00 – 17:00	**Visit to AIRBUS**

Detailed Programme

Day 2 – September 7th 2023 (Morning)

09:30 – 10:50	**WG1 activities** **Chair:** Ana Marques
09:30 – 09:35	***Pitch of the WG1 highlights*** Ana Marques
09:35 – 09:50	*Surface pre-treatment of aluminum alloy for mechanical improvement of adhesive bonding by maple assisted PLE technique* Oana Andreea Brincoveanu
09:50 – 10:05	*Mechanical performance of adhesives based on polyols from depolymerization of lignocellulose biomass* Alexandra Mocanu
10:05 – 10:20	*Microcapsules for eco-inovative adhesives* Ana Marques
10:20 – 10:35	*Adhesion of biobased composite repairs* Mohamed Amine Tazi
10:35 – 10:50	*The achievements in self-healing eco-epoxy adhesives for "CertBond" structures* Natasa Tomic
10:50 – 11:15	**Coffee-break**
11:15 – 11:35	**WG2 activities** **Chair:** Norbert Blanco
11:15 – 11:20	***Pitch of the WG2 highlights*** Norbert Blanco
11:20 – 11:35	*Adhesive bonding of Tow Based Discontinuous Composites (TBDC's)* Ioannis Katsivalis
11:35 – 11:50	*Experimental tests for material characterization of structural silicone Sikasil® SG-500 for the application of bonded point fixings on glass* Eliana Inca Cabrera
11:50 – 12:05	*Environmental durability of Kevlar composites reinforced with TiO2 nanoparticles* Vera Obradović
12:05 – 12:20	*Innovative CFRP composite and Fe-SMA bonded systems for structural glass flexural strengthening* José Sena-Cruz

Detailed Programme

Day 2 – September 7th 2023 (Morning)

12:20 – 12:35	*Experimental and numerical analysis of crack growth along patterned interfaces* Ping Hu
12:35 – 14:00	**Lunch**

Day 2 – September 7th 2023 (Afternoon)

14:00 – 16:00	**WG2 activities** **Chair:** Anastasios Vassilopoulos
14:00 – 14:15	*Analytical implementation of the non-conventional failures in cross-ply laminates under fatigue loading* Serafín Sánchez Carmona
14:15 – 14:30	*Bond behaviour of a stick shape CFRP reinforcement applied according to the NSM-ETS strengthening techniques* Luís Luciano Correia
14:30 – 14:45	*Multi-physics numerical modelling of EBR CFRP-concrete bonded joints under water immersion exposure* Aloys Dushimimana
14:45 – 15:00	**Coffeee-break**
15:00 – 15:15	*Machine learning in fatigue life of wind turbine blade adhesives* Dharun Vadugappatty Srinivasan
15:15 – 15:30	*Assessment of the existing shear strength models for RC beams externally strengthened with FRP* Amirhossein Mohammadi
15:30 – 15:45	*Snapshots from CertBond and project related ideas* Michal Kazimierz Budzik
15:45 – 16:00	**Closing session**

Day 2 – September 7th 2023 (Evening)

20:00 – 22:00	*Social event – dinner*

Detailed Programme

Day 3 – September 8th 2023 (Morning)

09:00 – 12:30	***CertBond Workshop: Impact and Future*** **Chairs:** Sofia Teixeira de Freitas, Anastasios Vassilopoulos, José Sena-Cruz
09:00 – 09:30	*Introduction* Sofia Teixeira de Freitas, Loucas Papadakis, José Sena-Cruz
09:30 – 11:15	*Group work* *All the participants in the Certbon Final Conference*
11:15 – 11:30	**Coffeee-break**
11:30 – 12:30	*Plenary Session* *All the participants in the Certbon Final Conference*

Day 3 – September 8th 2023 (Afternoon)

14:00 – 15:00	***MC Meeting*** *(*)* **Chairs:** Sofia Teixeira de Freitas, Anastasios Vassilopoulos

(*) Limited participation to the Management Committee of CertBond.

Social Event

On the second day of the Certbond Conference (September 7th), attendees will have the chance to enjoy a delightful dinner cruise along the Guadalquivir river. This exclusive event offers a remarkable opportunity to network, engage in discussions, and immerse oneself in the rich history of Seville, as the dinner will take place in the heart of this vibrant city. It's important to note that the dinner is not included in the conference package and **requires a separate payment of €30 (VAT included) per person**.

To secure your spot for this memorable experience, a GoogleForm will be circulated among the participants to confirm their attendance.

About Seville

Seville is located in the south of Spain and it is the **capital of Andalusia**. With a lot of history behind it, Seville is nowadays a very touristic city. In 1992, coinciding with the 500th anniversary of the discovery of America, Seville held a Universal Exposition in a part of the city known as "Cartuja Island", a place where today we can find the **School of Engineering of the University of Seville**, which will be the venue for this final Certbond meeting. In fact, the School of Engineering was the "American Pavillion" during the Universal Exposition. The **University of Seville**, founded in 1505, has today **69.800 students** (academic year 21-22) in different campus spread all along the city, only the School of Engineering has almost 6.000 students.






Useful links:

- Seville general info: https://visitasevilla.es/en/
- University of Seville: https://www.us.es/
- School of Engineering: https://www.etsi.us.es/
- Seville's Airport: https://www.aena.es/en/sevilla.html

Venue

Place: School of Engineering (University of Seville) (**Classroom 007** - Ground Floor)

Address: Camino de los Descubrimientos s/n, 41092 Sevilla (Spain)

Google Maps: https://maps.app.goo.gl/rDia3KYeggFAGYXf9

Note: The School of Engineering has several different entrances, the welcome venue will be in the Ground Floor, classroom 007.

Find a map of the ground floor at: https://www.etsi-old.us.es/planos_etsi/plantabaja

Local host (contact details): Alberto Barroso (abc@us.es) mobile phone: +34 657 210 893

UNIVERSIDAD D SEVILLA 1505

Escuela Técnica Superior de INGENIERÍA DE SEVILLA

How to reach Seville

Seville is reasonably well connected with different international airports (Seville Airport code: SVQ).

You can also consider these other alternatives:

- From Madrid: If you have direct connections to Madrid, there is a high speed train (AVE) which takes 2h 30m. Take into account that you need, at least, 1 hour to move from Madrid airport (Barajas), to Madrid railway station (Madrid-Atocha).
- From Málaga: There are also several direct flights to Málaga Airport (AGP), which is 2h 20m by car from Seville.

Seville's airport has only Bus and taxi services to the city center. Airport Special Bus (line EA) (Single ticket: 4 €/Return ticket: 6 €) from Plaza de Armas or cab (between 22,20 and 24,75 € per way depending on date and time). You can find further information of the airport Bus service at: https://www.aeropuerto-sevilla.com/transportes/autobus-aeropuerto-sevilla.htm

How to reach the venue:

- From the Airport: It takes 19 minutes by car, without entering the city center.
- From "Santa Justa" railway station: It takes 15 minutes by car, 27 minutes by bus (C2 line).
- Seville is reasonably small, and a taxi is always a good alternative.
- There is only one metro line which is not useful for the venue.
- From the city center: There are two circular lines which has a stop at the School of Engineering. Both have almost the same route, but one (**line C1**) circulates clockwise and the other (**line C2**) circulates counter-clockwise. Find all local bus information at: https://www.tussam.es/en

Venue bus stop name: Juan Bautista Muñoz (Esc. de Ingeniería)

C1 Bus line (clockwise)

C2 Bus line (counter-clockwise)

Accommodation

Seville is a very touristic city and September is not a high season in the city, so you will have no problem at all in finding a good accommodation at a reasonable price.

The venue (the School of Engineering) is almost outside the city. Although there is a hotel very close to the School of Engineering (★★★★★ Barceló Renacimiento Sevilla), you will be far away (more than 30 minutes) from the city center.

Seville has one of the biggest downtown areas in Europe, so if you arrive by car, be sure to have a parking service at the hotel, because it might be very difficult to find a parking outside.

Some recommendations:

NH Sevilla Plaza de Armas (★★★★)

- 30 minutes walking to venue and close to the city center.
- https://www.nh-hoteles.es/hotel/nh-sevilla-plaza-de-armas

Exe Sevilla Macarena (★★★★)

- 28 minutes walking to venue.
- https://www.eurostarshotels.com/exe-sevilla-macarena.html

Melia Lebreros (★★★★)

- A good option if arriving by train to Seville. 10 minutes walking from the railway station.
- https://www.melia.com/es/hoteles/espana/sevilla/melia-lebreros

Hesperia Sevilla (★★★★)

- More or less the same walking distance (19 minutes) to the railway station, and the city center.
- https://www.hesperia.com/es/hoteles/espana/sevilla/hotel-hesperia-sevilla

Petit Palace Puerta de Triana (★★★)

- Close to the city center.
- https://www.petitpalacepuertadetriana.com/en/

There are a lot of small and nice hotels at the very downtown with excellent views to the cathedral. It is up to you to find your most convenient location. Do not hesitate to contact the local host (Alberto Barroso Caro - abc@us.es) to ask for a particular accommodation.

Meals & coffee breaks

Lunches, drinks and coffee breaks will be provided by the local organiser.

Note: if you have any restrictions (e.g. any dietary preferences and/or allergies), please contact the local host (Alberto Barroso Caro - abc@us.es).

Presentations

Final meeting September 2023

WG3

WG3 – Manufacturing phase

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- Our objectives :
    - Goal 3.1 : Survey of industrial manufacturing process and analysis of the answers
    - Goal 3.2 : Survey of testing procedure used by the industrial and analysis of the answers
- Done via interviews of industrials in the aerospace domain
    - Mostly within Safran group but also a few outside
        - Process relatively similar with a few divergencies
    - A detailed analysis will be proposed as a final delivery for the project
    - When compared to other domains, one should be on the most controlled processes that may be “luxury” for less critical bonding !!!
- Today, only some major points will be presented

WG3 – Manufacturing phase

- Before the bonding
    - Optimize the design : maximize the bonded surface, reduce stress concentration, avoid peeling zone
    - Know the environmental conditions (and not only the mechanical loading) : temperature, fluids, aeging,…
    - Select the right adhesive => try to have “real” specifications
        - And not only “better than the actual adhesive” !!!!!
        - Don’t trust to much the productor’s data (technical data sheet)
    - Have a qualification phase
        - Test the adhesion to you specific substrates (! Hot wet aeging)
        - Validate the curing cycle (the official one may be not optimum for your specific case)
        - Check the limit of the process (open time, mixing ratio for 2K,…)
        - At the end, write everything
    - Train the operators
        - They should understand why we are strict on the process

WG3 – Manufacturing phase

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- During the bonding
  - Surface preparation mandatory, at least degreasing/sanding/degreasing
    - We should know on what we are bonding
  - Be careful with the environmental conditions (T°, HR)
  - Follow the procedures developed during the qualification phase
  - Register as many parameters as you can (depending on the criticity)
  - Automatize if you can to reduce variability

  - In case of problem, stop and analyze !

WG3 – Manufacturing phase

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- After the bonding
    - If curing in temperature, check the cure cycle
    - There is no way to measure the final mechanical performance but a NdT (typically Ultrasonic) may be done to verify the homogeneity of the joint
    - Don’t trash to early the process records
    - Stay aware of long term problems (e.g. client return after ageing)

WG3 – Manufacturing phase

- Conclusions
  - Thanks to all the members of the WG3
  - We have not done all the work initially planned
  - But we have done a great job after all

Acknowledgment

This STSM was developed under the COST Action CA18120 (CERTBOND) and supported by COST (European Cooperation in Science and Technology).

EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Funded by the Horizon 2020 Framework Programme of the European Union

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Thank You!

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the European Union

Continuous Fibers Reinforced Composite Structures Production Using FDM Printing Technology

Dr. Tomas Kuncius
Prof. Marius Rimašauskas
Assoc. Prof. Rūta Rimašauskienė

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Funded by the Horizon 2020 Framework Programme of the European Union

Outline

- Who I am?
- Where I am from?
- Why AM for composites production?
- How to do it
- Quality improvements methods of printed structures

Who I am?

Dr. Tomas Kuncius 1992.06.29

Lecturer and Young Researcher at the Department of Production Engineering

2011 – 2015 Manufacturing Engineering

2015 – 2017 Industrial Engineering and Management

2017 – 2022 Mechanical Engineering

Where I am from?

Lithuania is a country in the Baltic region of Europe. It is one of three Baltic states and lies on the eastern shore of the Baltic Sea.

Vilnius is a capital and the largest city. Population 2 840 758 (2022).

Lithuania is known for its love of basketball, cold pink soup, and lots of castles and lakes.





Where I am from?

Kaunas is the second largest city of Lithuania
Cultural Capital of Europe in 2022
Art deco city: UNESCO's World Heritage Tentative List
Population 298 753 (2022)

Where I am from?

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Based on the sport's popularity, a common joke goes that, **in Lithuania, there is only one religion: BASKETBALL**!

Where I am from?

Kaunas University of Technology is a public research university located in Kaunas, Lithuania. Established in 1922, KTU has been one of Lithuania's top science education centers. According to rankings, KTU was the second-best university in Lithuania.

- **6,700** bachelor’s students
- **2,010** master’s students
- **900** international students
- **320** PhD students

Research Aim

The main aim of the scientific research is to develop and validate an FDM technology for the rapid fabrication of geometry complex continuous fiber reinforced composite structures.

Why AM for Composites Production?

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- Could produce very complex parts;
- Short lead time;
- Almost no waste;
- Easy reusability and recycling;
- Fully automated process;
- Wide material selection;
- Support Lattice Structures
- Very high potential and adaptability.

Why AM for Composites Production?

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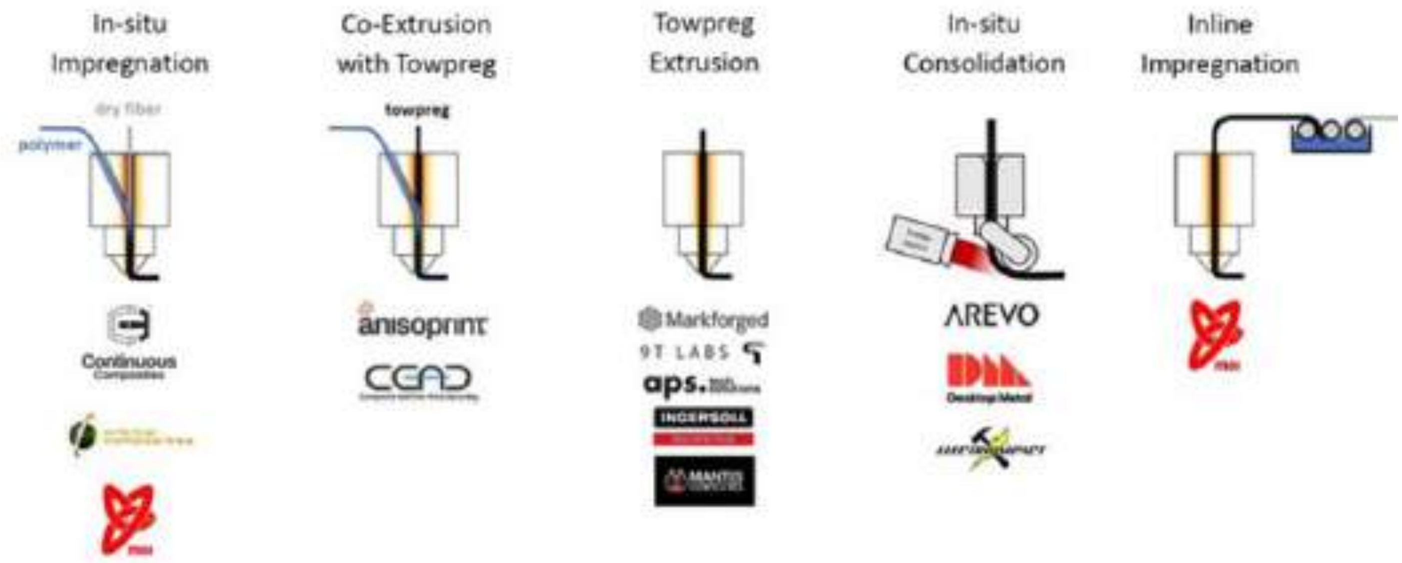

[3D printing with continuous fiber: A landscape | CompositesWorld]

Development of Impregnation Technology

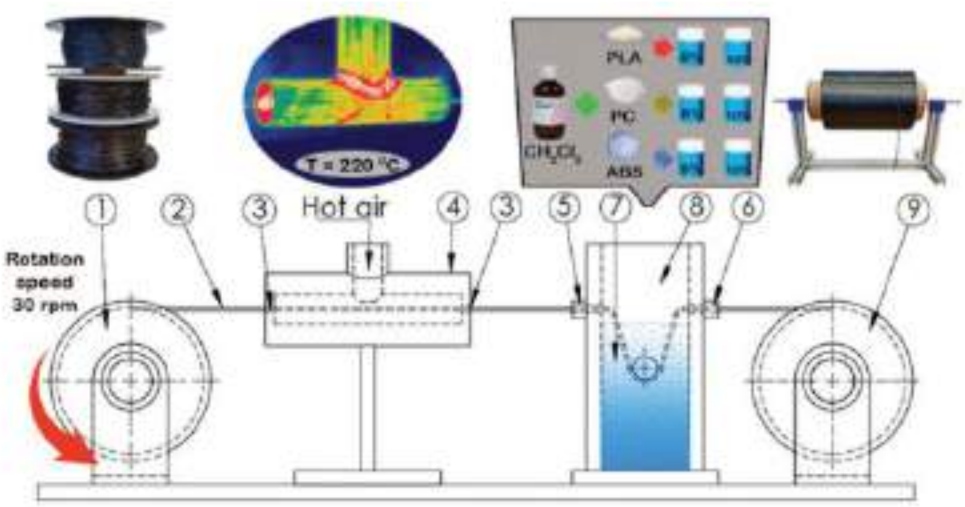

Fig. 1 Scheme for fiber impregnation: 1 – spool, 2 – impregnated CF, 3 – nozzle, 4 – heating section, 5 – 0.8 mm nozzle (1K), 6 – 1 mm nozzle (1K), 7 – solution, 8 – impregnation section, 9 – CF spool

Visual Analysis of Impregnated CF Tow

Visual analysis of CF tow impregnated at 10 % methylene chloride and PLA solution revealed an average 14 % air void volume inside the tow.

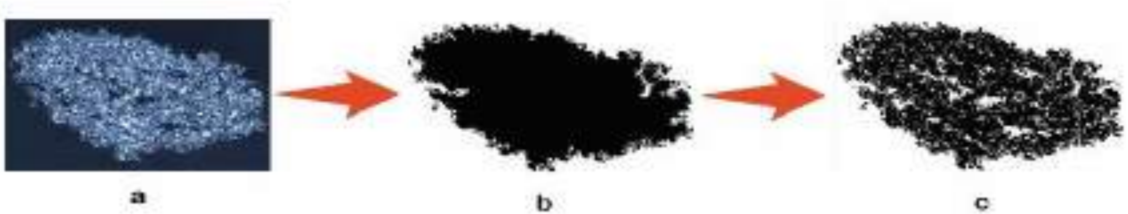

Fig. 2 Visual analysis of impregnated fiber void percentage: a – clear view of analyzing area, b – full section of area, c – filled section of area

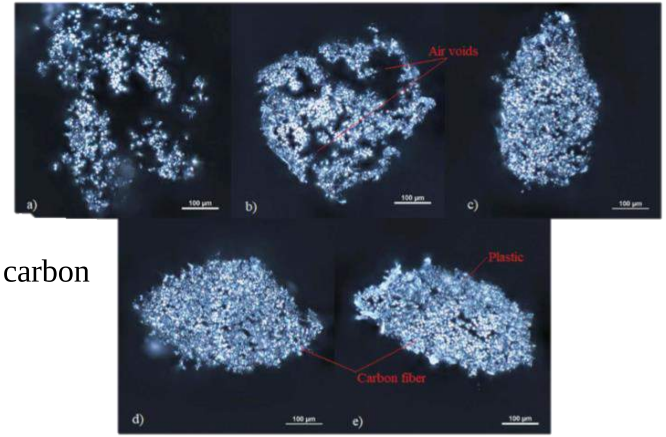

Fig. 3 The optical micrographs of the cross-section of impregnated carbon fiber: a – 2%, b – 4%, c – 6%, d – 8%, e – 10%.

Development of Printing Module

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Standard printing head

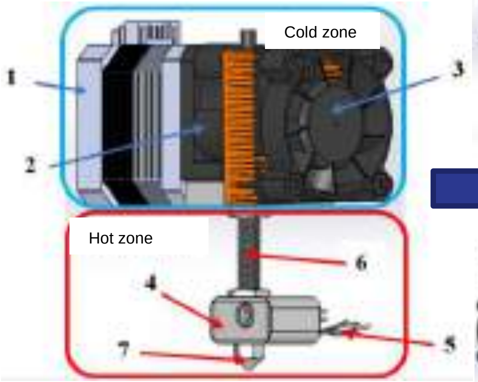

Fig. 4 Standard printing head:
1 – Step motor, 2 – Guiding element, 3 Cooling fan, 4 – Heating element, 5 – Thermocouple, 6 – Feeding tube, 7 – Nozzle

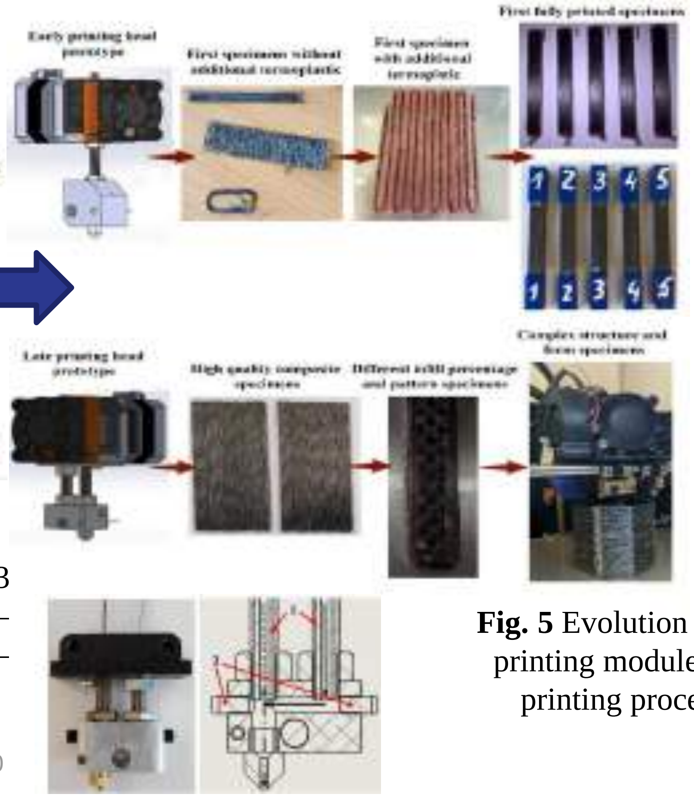

Fig. 5 Evolution of the printing module and printing process

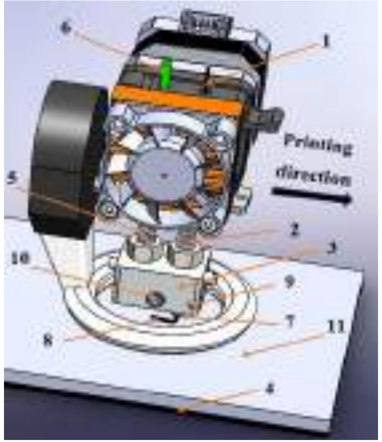

Fig. 6 Scheme of the printing process: 1 – impregnated CCF, 2 – CCF feeding channel, 3 – heating element, 4 – printing platform, 5 – thermoplastic feeding channel, 6 – thermoplastic, 7 – printing nozzle, 8 – homogenous composite filament, 9 – thermocouple, 10 – heater, 11 – borosilicate glass

Printing Parameters

Table 1 Experimentally determined printing process parameters

Carbon fiber tow	Nozzle diameter, mm	Extrusion multiplier, %	Line width, mm	Layer height, mm	Printing speed, mm/s	Cooling, %	Printing bed temperature, ^0C	Printing head temperature, ^0C
1K	1.6	60/80	1/1.2	0.3/0.4	3	60-90	80	220
3K	1.6	40/60	1.4/1.6	0.5/0.6	3	60-90	80	220

Fig. 7 Printing of the composite structure

Air Void Content

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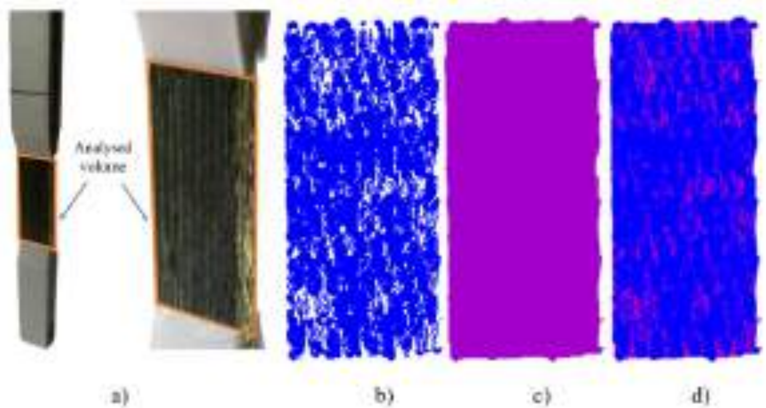

Fig. 8 CT analysis: a – analyzed volume, b – binary threshold, c – mask from the closing procedure, d – detected air voids

Fig. 9 Void content determination using computed tomography

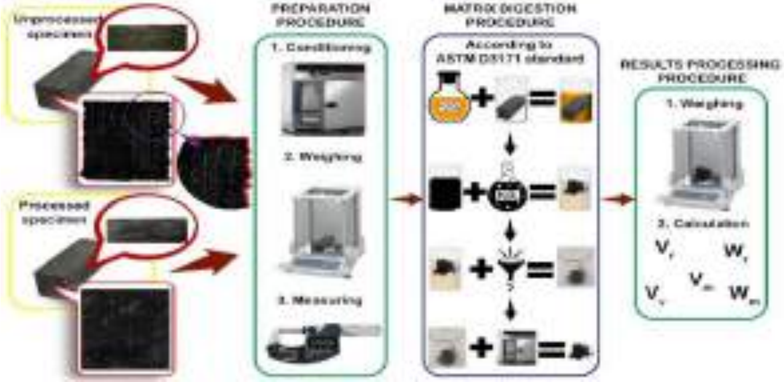

Fig. 10 Void content determination using matrix dissolving procedure

Air Void Content

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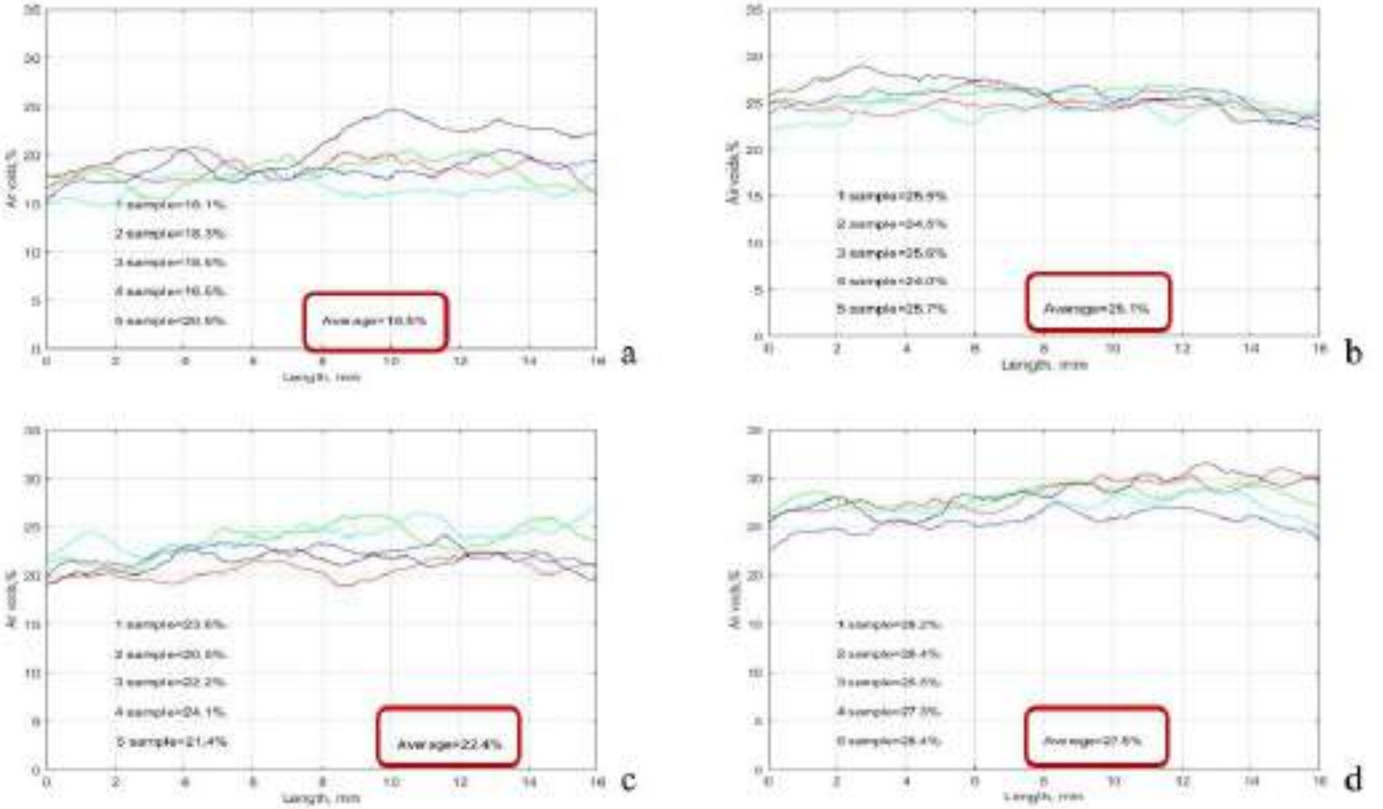

Fig. 11 Air voids content in the samples; a – Group 1, b – Group 2, c – Group 3, d – Group 4

Improvement of Mechanical Properties Using Impregnation

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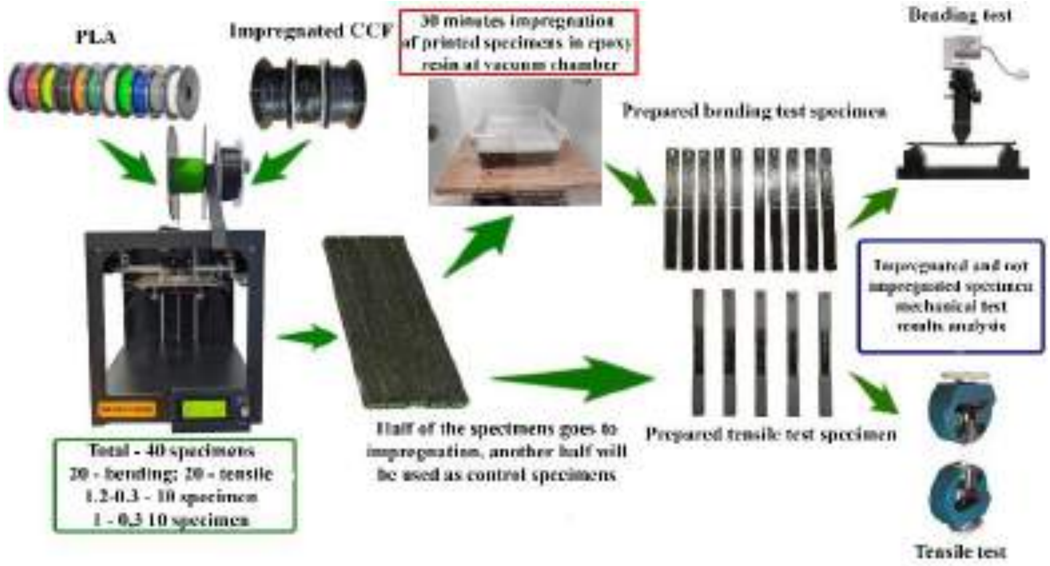

Fig. 12 Experiment working scheme; specimens prepared according to ASTM D 3039 and ASTM D 7264 standard

Fig. 13 Crossection of specimen: before and after the impregnation

Improvement of Mechanical Properties Using Impregnation

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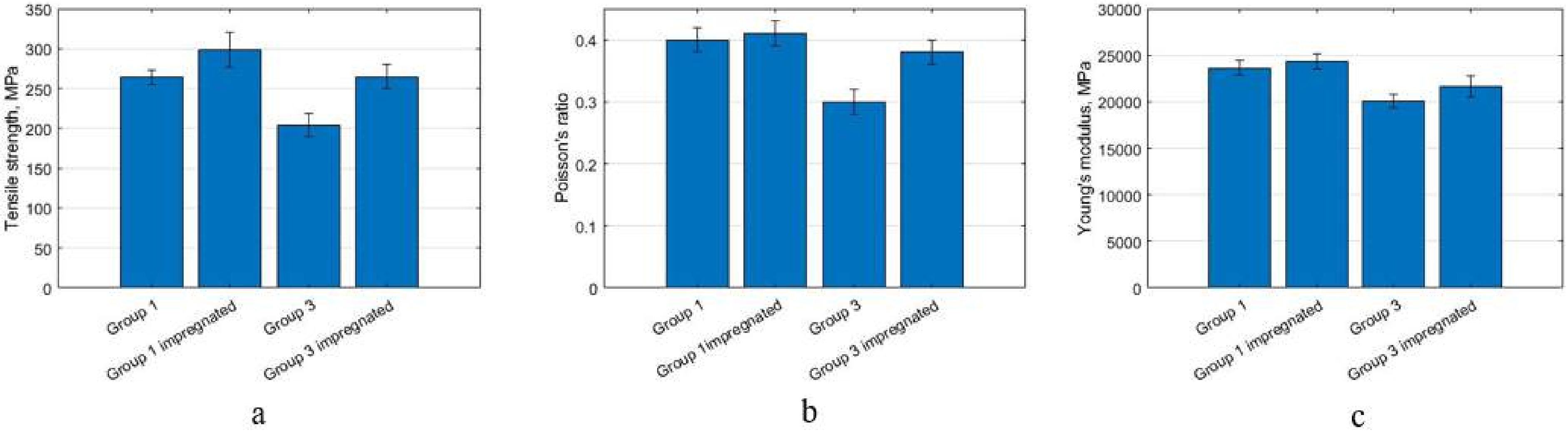

Fig. 14 Mechanical properties and prepared specimens: a – Tensile strength, b – Poisson's coefficient, c – Young's modulus

Improvement of Mechanical Properties Using Impregnation

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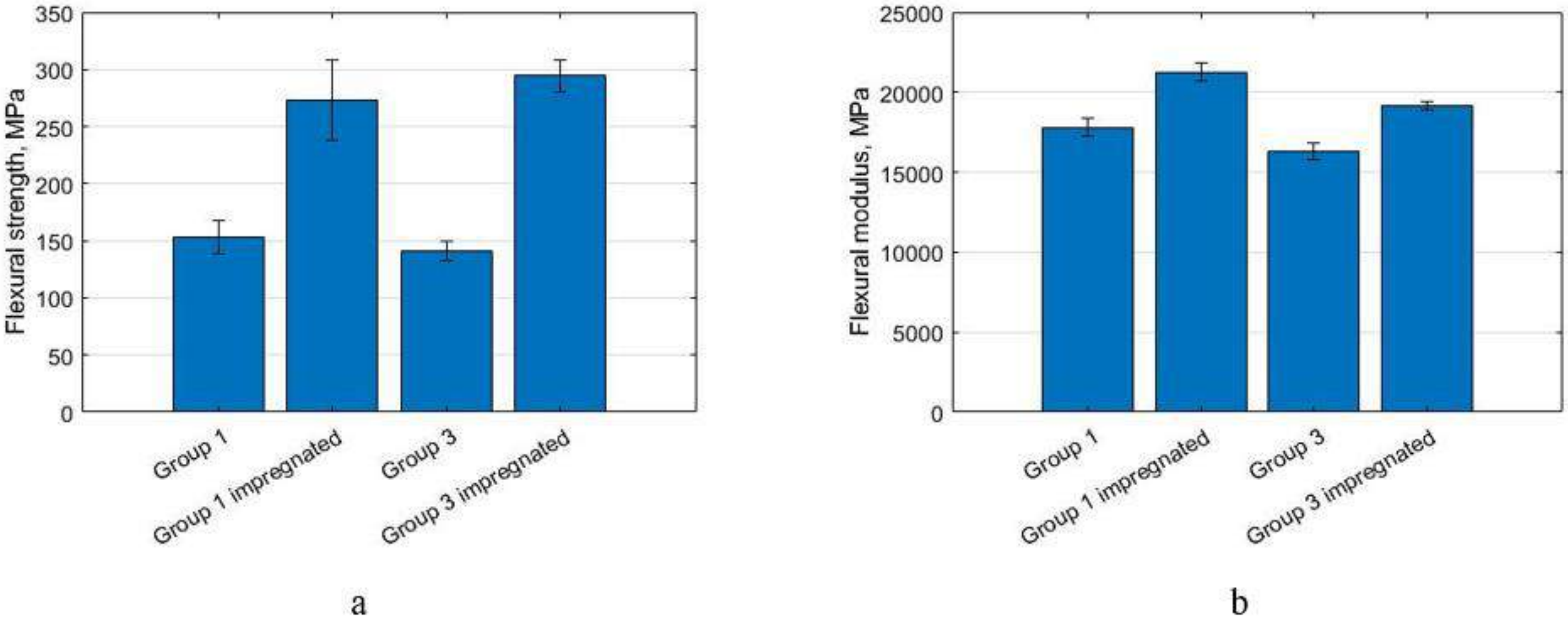

Fig. 15 Mechanical properties: a – Flexural strength; b – Flexural modulus

Conclusions

1. After the examination of various impregnation materials, it was found that fiber tow acquires the best properties after impregnation in 10 wt% thermoplastic and CH_2Cl_2. After impregnation, the adhesion force between the PLA matrix and the CCF reinforcement material increased by ~240%.

2. The air volume in the structure directly depends on the layer height and the print line spacing. The amount of air voids determined by both methods is very similar and ranges from ~19% to ~28% depending on the layer height and the print line spacing.

Conclusions

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3. The main mechanical properties of printed composite structures reinforced with CCF have been experimentally determined. The tensile strength reaches 264 MPa and 204 MPa, the flexural strength 153 MPa and 140 Mpa depending on the printing parameters.

4. After the secondary impregnation in epoxy resin, the tensile strength increased by 30.5%, while the flexural strength grew by 110%. As it can be observed from the obtained data, impregnation with epoxy resin exerts greater impact on the sample groups printed with a higher layer height and print line spacing.

Acknowledgment

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Additive Manufacturing of 3D ceramic-based composite heating elements

Dr. Alexander Katz-Demyanetz

Israel Institute of Materials Manufacturing Technologies

Technion Research and Development Foundation Ltd, Haifa, Israel

COST Action CA18120, Certbond COST Action Final Conference
6-8 September 2023, Seville, Spain

Technological demand

- Heating elements are in high demand in a wide range of industries, including HVAC, electronic, healthcare, water, home heating, appliance, industrial production, metallurgy, commercial food preparation, semiconductors, ceramics, and glass. Their varieties are used in industrial, commercial and consumer applications include immersion, quartz, flexible, infrared, wire, ceramic, electric, metal-based, and composite heating elements, among many others.

- Modern challenges, such as reducing CO_2 emissions, space exploration, the ever-increasing level of energy consumption, require innovative solutions from the engineering and scientific community in many areas, including the development of new materials, more efficient production methods, the miniaturization of electronic devices, etc. This statement is also actual for heating elements, which being individually produced with especially adjusted topology, can achieve significantly higher efficiency than the conventional ones.

Technological demand

- The aerospace, aviation, automotive, defense, and engineering industries are most in need of more innovative heating element solutions. This leads to the desire to reduce the weight of aircraft (reducing CO_2 emissions, reducing the cost of flights), space satellites (reducing the cost of launch), which in turn leads to the desire to obtain the necessary thermal energy while reducing the power consumption of the heating element. Existing solutions in this area often do not provide a complete and most effective answer, while there is still no qualitatively new solution for these problems. All solutions are carried out by means of heating elements of standard shapes and characteristics.

- Shape optimization and improved heat transfer are some of the more actual tasks to be addressed. Which, in turn, makes engineers think more and more in the direction of new technologies to produce heating elements. Additive Manufacturing (AM) techniques allow to create topologically optimized 3D objects that can address these challenges.

State of the art

Currently, the ceramic heating elements (SiC, Si_3N_4, $MoSi_2$) again and again are superseding the traditional heating elements based on metals. The unquestionable advantage of ceramic heating elements is their considerably longer service life as well as the resistance to oxidation and aggressive environment.

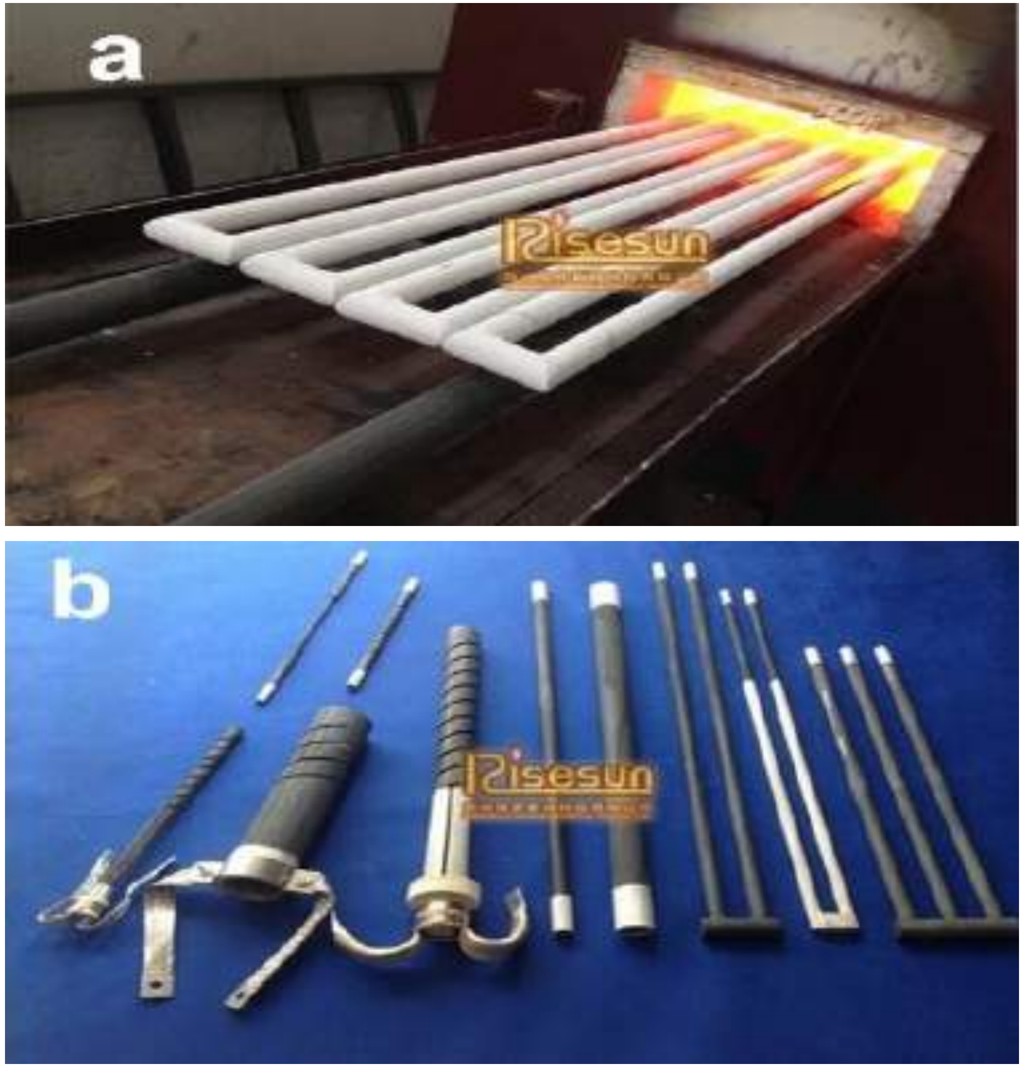
The used materials for ceramic heating elements are as follows.

- 40% α - $S_{i3}N_4$ (Grade M11 HP - H. C. Starck), D50=0,6 µm, BET12-15 m2/g
- 54% $MoSi_2$ (Grade C - H. C. Starck), D50=2,5 µm, BET1,5 m^2/g
- 2,4% α - Al_2O_3 (Symulox NO713-10 - Nabaltec)
- 2,4% Y_2O_3 (Grade A - H. C. Starck)
- 1,2% MgO (Reachim)

SiC heaters

Silicon carbide (SiC) is polymorphic and crystallizes at atmospheric pressure and room temperature into a diamond lattice. This basic structure is composed of tetragonal units of silicon and carbon atoms which are held together by strong, highly directional sp3 hybrid bonds. The bonds in SiC are essentially covalent and have 11.5% ionic character.

SiC is used in electrical resistance heating elements because of its high hardness, corrosion resistance, abrasion, and high thermal conductivity. This material exhibits outstanding properties at high temperatures up to 1550 °C, in oxidizing or 1250 °C reducing atmosphere condition; the creep and strength are very high when compared to other materials.



Existing SiC-made heaters for the use in furnaces

Traditional manufacturing and typical properties of SiC heaters

Silicon carbide products can be fabricated using either one or a combination of processes. The different types of products are named according to the sintering process they undergo:

- Recrystallized SiC
- Reaction sintered SiC
- Reaction bonded SiC
- Sintered SiC
- Hot pressed SiC
- Hot isostatically pressed SiC
- Surface coated SiC

Characteristics	Value	Characteristics	Value
Compound Formula	SiC	Molecular Weight	40.1
Density	3.0-3.2 g/cm^3	Young's Modulus	370 to 490 GPa
Electrical Resistivity	1 to 12 Ω·m	Poisson's Ratio	0.15-0.21
Specific Heat	670 to 1180 J/kg·K	Tensile Strength	210 to 370 MPa
Thermal Conductivity	120 to 170 W/m·K	Thermal Expansion	4.0 to 4.5 µm/m-K

Generally, there are two types of sintering mechanisms: evaporation-condensation and solid-state sintering leading to densification. The mechanisms take place in competition and generally only one is encouraged.

Additive Manufacturing of SiC heaters

- The production of 3D heaters is a new milestone in the development of heating elements. In addition to solving the above problems, AM has the potential to reduce the cost of heating elements. Nowadays, AM assisted industry is actively developing and covers almost all types of existing materials. At the same time, the technology itself is becoming more accessible and sustainable in production.

- One of the leading and intensively developing AM technologies is Binder Jetting (BJ). This technology has been originally developed for 3D printing of sand molds, the only material that does not require additional post-processing. This technology can be also applied for 3D printing of ceramic-based products, mainly because it can work with wide spectrum of materials, including electrical and thermal insulators. On the other hand, BJ printing is applicable also for any metallic alloys, as well as for metal/ceramic composites. From the technical point of view, BJ is a 3D printing process that uses a liquid binding agent (namely: glue) deposited onto a build platform to bond layers of powder material and form a part. Density improving post processing operations are mandatorily required to obtain a product with desired mechanical physical properties.

cost
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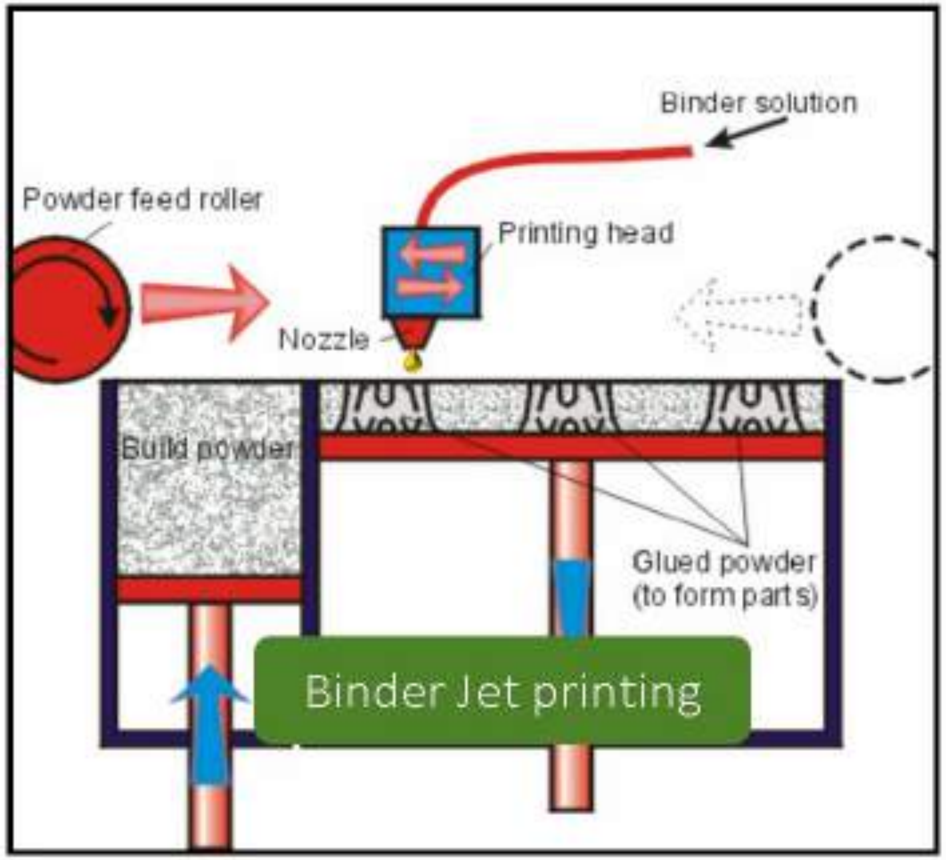
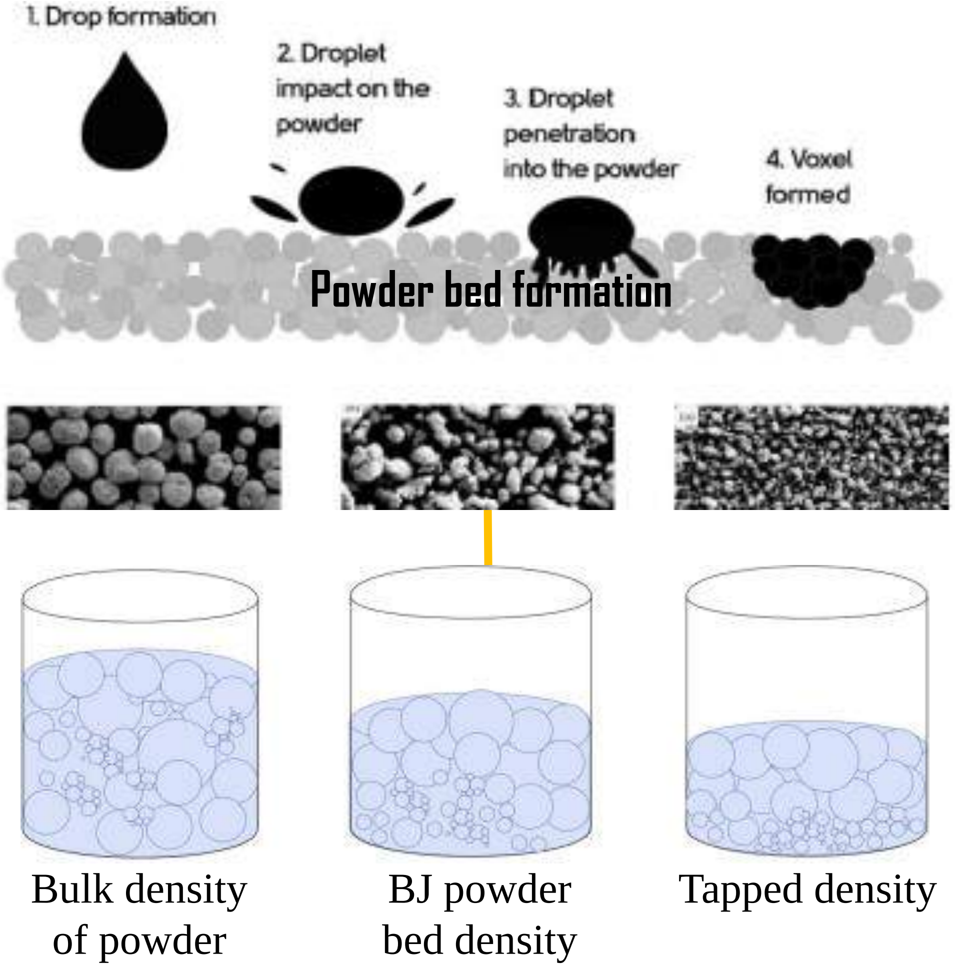
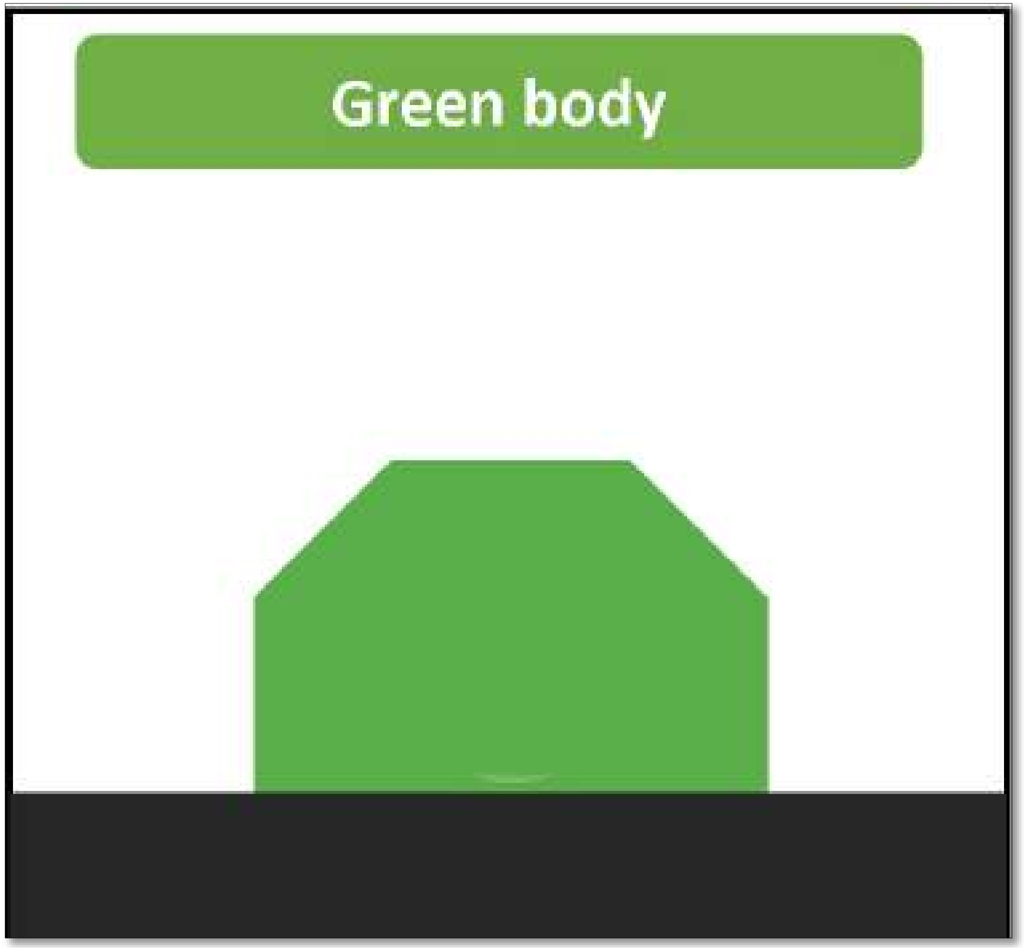
Binder Jet printing technology for RB-SiC





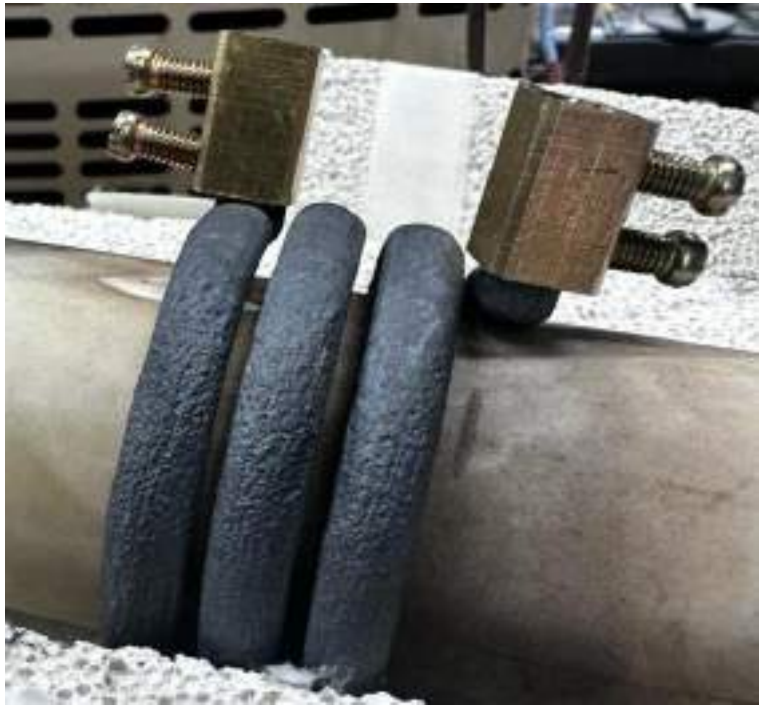
BJP – Post-process/Reaction-Bonding of Silicon Carbide (RBSiC)



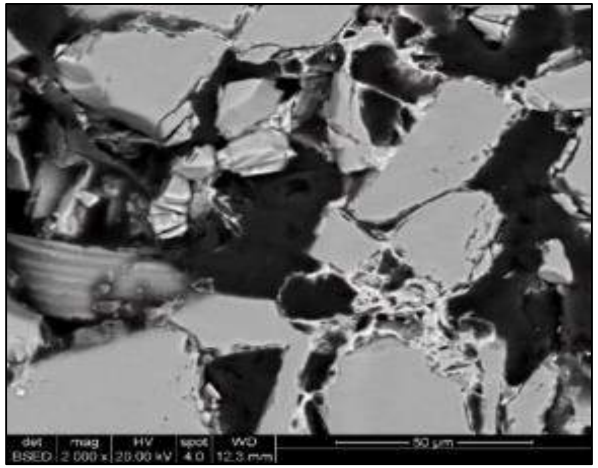
Impregnation, pyrolysis, and infiltration

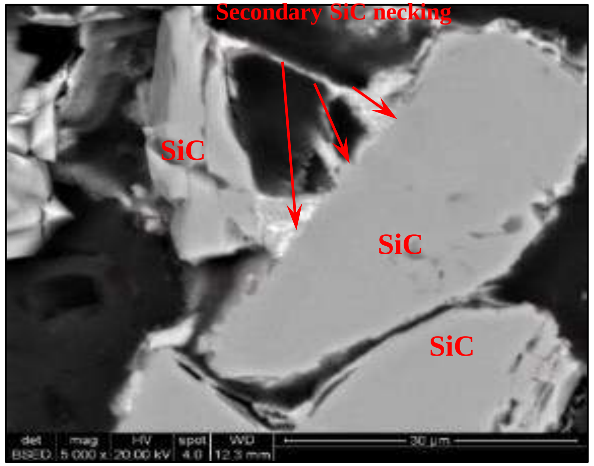
- The printed samples are cured at 220°C for 8 hours after printing.
- The impregnation of the green-printed porous samples is performed by dipping the samples into a phenol-based binder for 2 hours followed by a curing process.
- The pyrolysis is carried out in a furnace using a retort at a temperature of about 1050°C under a nitrogen atmosphere for 4 hours.
- Capillary Liquid silicon Infiltration is performed in a vacuum induction melting (VIM) furnace using a graphite crucible, under vacuum conditions of about 0.01 mPa at a temperature of 1550°C for 6 hours.

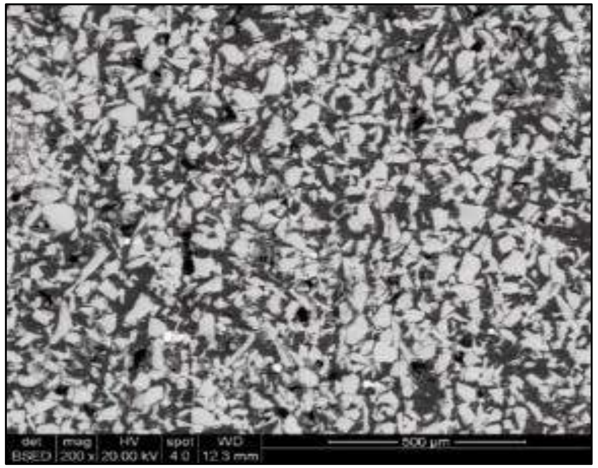
Examples of Additively Manufactured SiC heaters

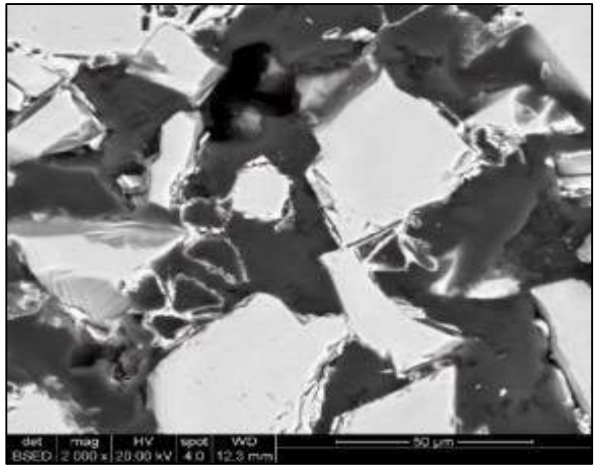


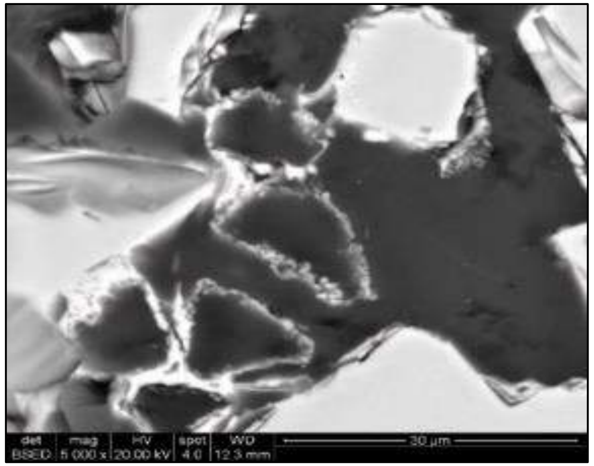
Typical Microstructure of Additively Manufactured SiC heater











Future Activities

1. Increasing the mechanical integrity of the heating element via promotion of more necking and reduction of the high porosity – increasing the content of Si in the powder blend.

2. Decreasing the very high resistance by tweaking the geometry of the heating element (i.e., increasing cross section and reducing length).

3. Reducing the inhomogeneity in the heating element's microstructure.

4. Exploring the possibilities of printing complex asymmetrical shapes of heaters.

5. Effect of complex conductor geometry on heater efficiency.

Thank you for attention!

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המכון הישראלי לטכנולוגיות ייצור חומרים

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CERTBOND Final conference

University Seville, Spain

Damage diagnosis of 3D printed structure using Electromechanical Impedance Method

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IMP PAN GDAŃSK

Mechanics of Intelligent Structures Department

Health monitoring of **AD**ditively manufactured structur**ES** (**HADES**)

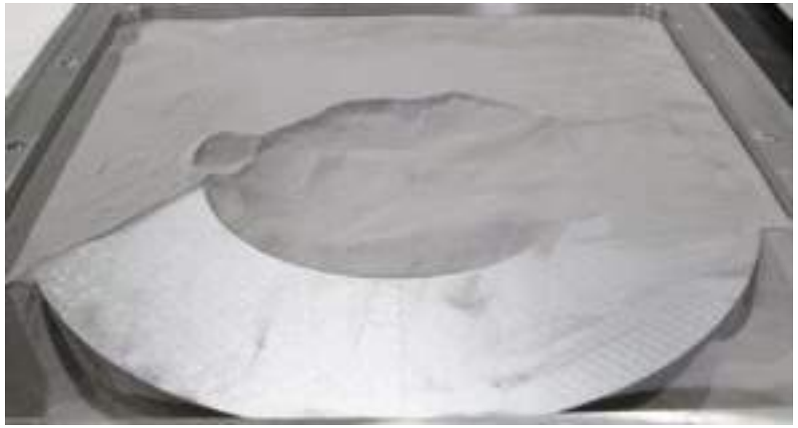
NATIONAL SCIENCE CENTRE POLAND

Outline

- Introduction to 3D printing
- Background on the Electromechanical Impedance (EMI) method
- Sensitivity study of ABS(Acrylonitrile butadiene styrene)
- Classification of the M3-X multi-plate
- Inbuilt damage detection in the poly lactic acid (PLA) plate
- Conclusion

Introduction

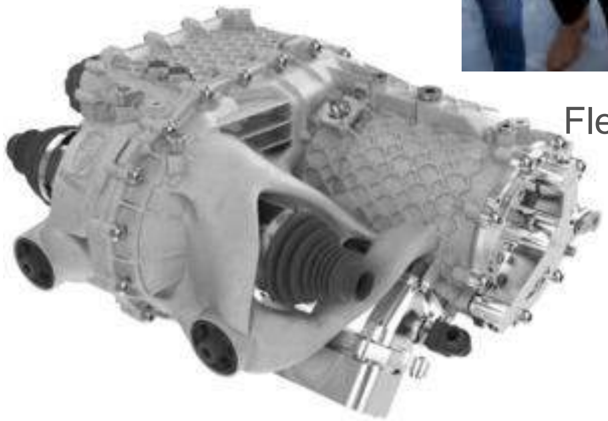
Agricultural equipment (GVL Poly snouts)
https://www.maywes.com/product-categories/corn-head/poly-corn-snouts/



A 3D printed brake disc in the build chamber via Eplus3D
Source:https://3dprintingindustry.com/transport/

Fleet Space's 3D printed Alpha small satellite

Medical implants
https://www.photonics.com/Articles/Medical_Implants_Aerospace_Innovations_Drive/a65737



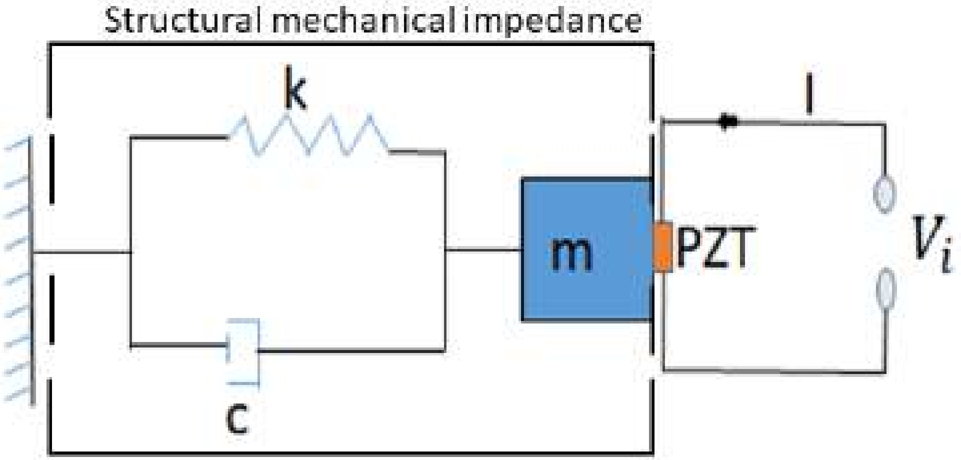
3D printed electrical drive housing by Porsche
https://additiv-tech.ru/en/news/porsche-present-40-lighter-3d-printed-electric-drive-housing.html

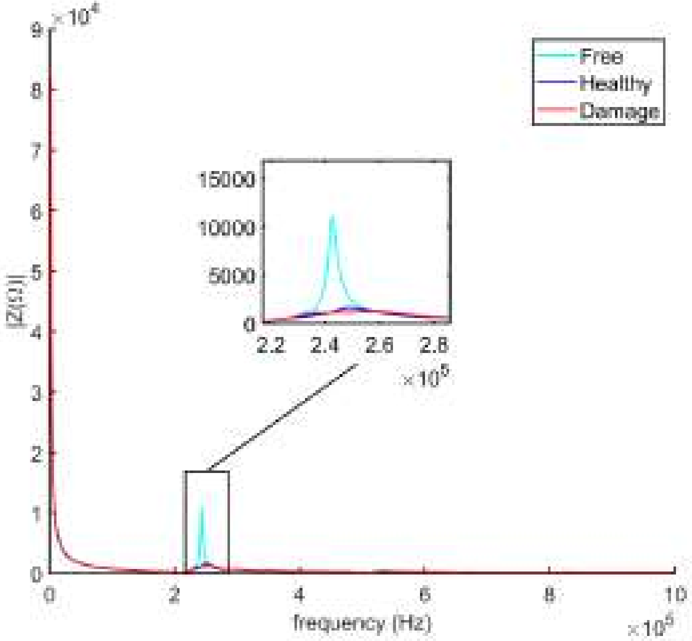
Electromechanical Impedance (EMI)

- **EMI method works in the high frequency range and due to electro-mechanical coupling the electrical response contains information about mechanical condition of the structure.**
- **Need for damage detection tools in nondestructive testing (NDT) and structural health monitoring (SHM) of structural parts with efficient signal processing techniques.**

Electrical response → mechanical coupling → Structural condition

- ✓ **High frequency ranges**
- ✓ **High sensitivity**

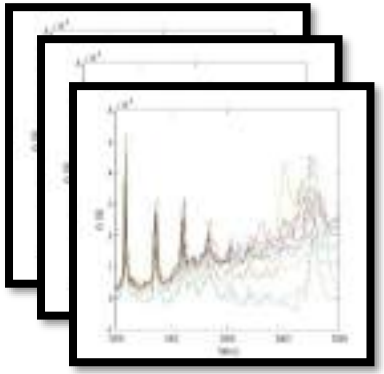




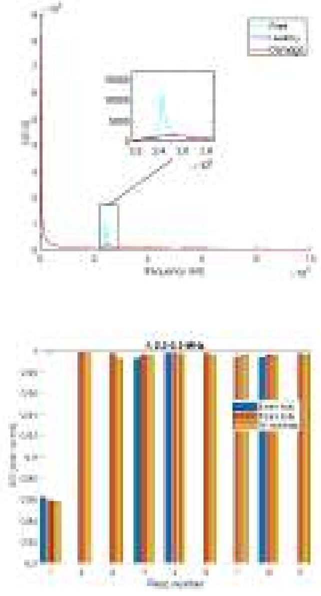
Electromechanical Impedance (EMI) based damage detection

Inspect the structure using an impedance analyser

Signal acquisition



Signal processing



Result

Healthy

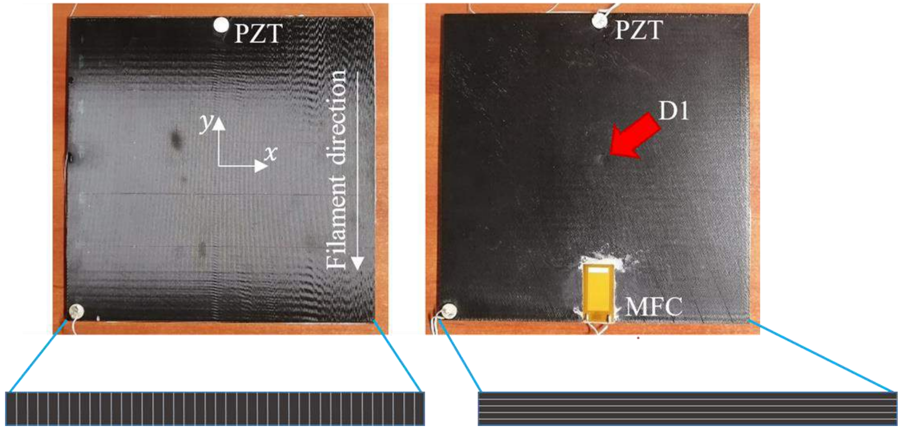
Damaged

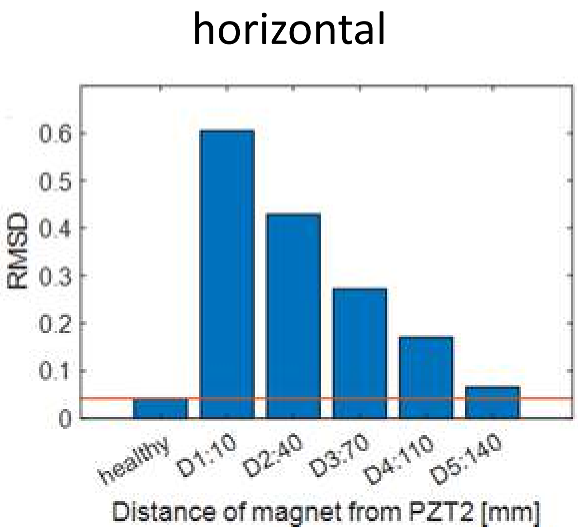
Sensitivity study of ABS(Acrylonitrile butadiene styrene)

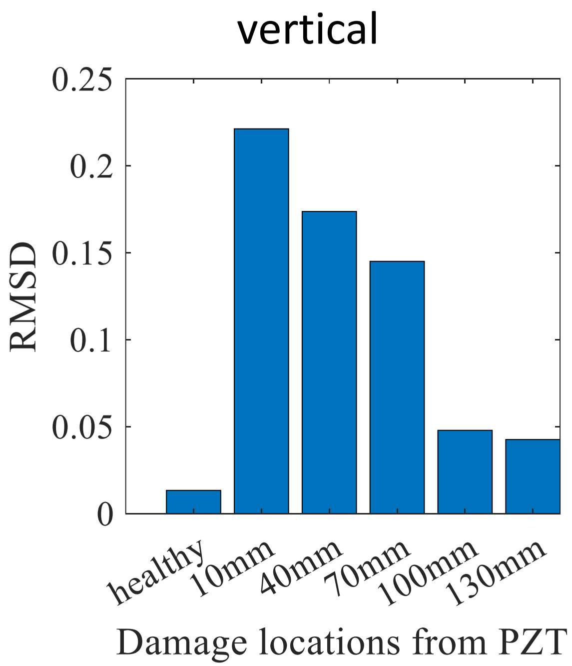
- The 3D additively manufactured ABS(Acrylonitrile butadiene styrene)

  -horizontal and vertical filament direction

  The dimensions of the plate = 200×200×3mm^3
- The sensitivity study was performed for two plate types using artificial/simulated damage introduced in a 3D-printed ABS plate.



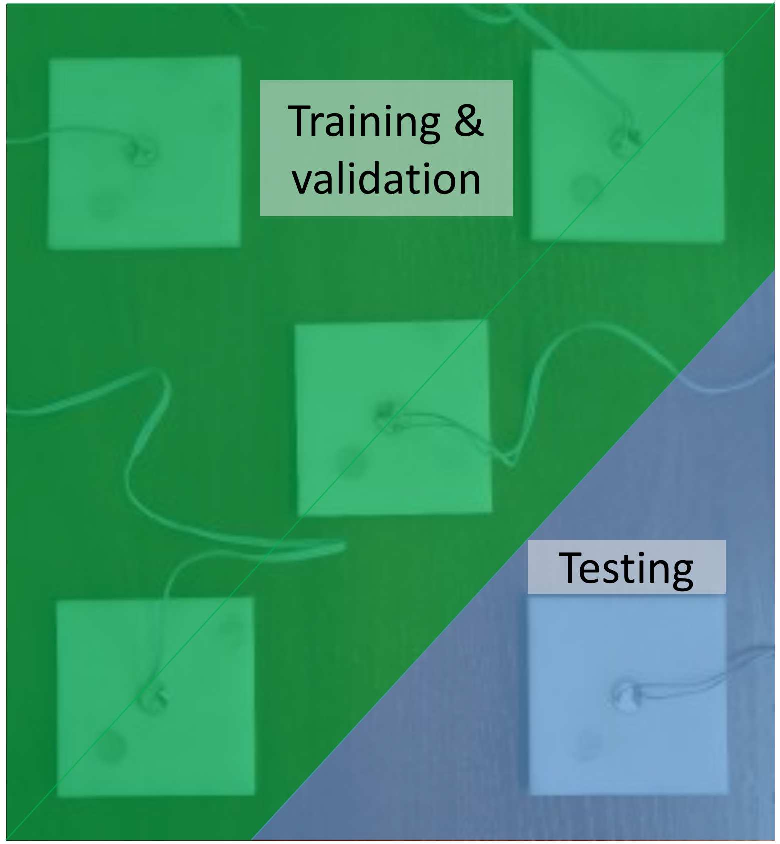




Multiple health conditions: process, data gathering, & data splitting

Five 3D-printed M3X plates:

- multi-jet printing technique (MJP);
- ProJet 3500 HD Max machine ;
- each is: $6 \times 6 \times 0.5\ cm^3$.

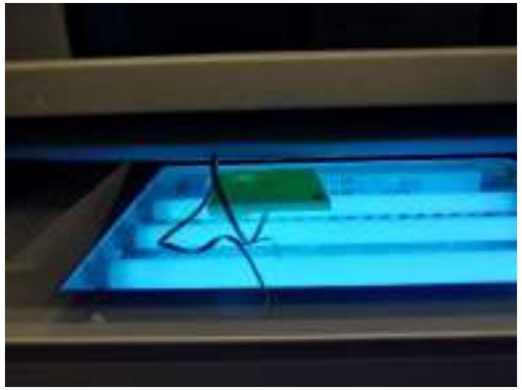


Initial state

10-mm straight hole:
1) 1.5-mm depth
2) 4.5-mm depth

Repeat until filled

Add material



Cure using UV light

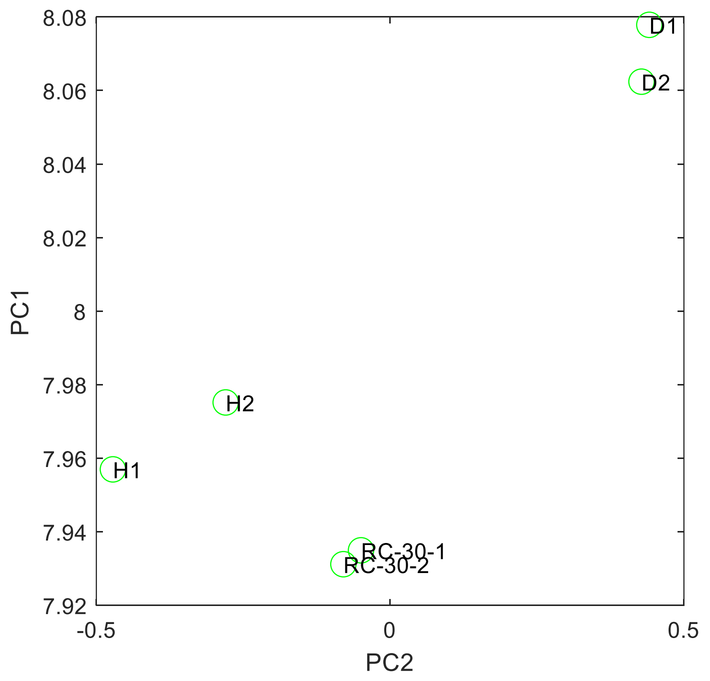
Repaired state

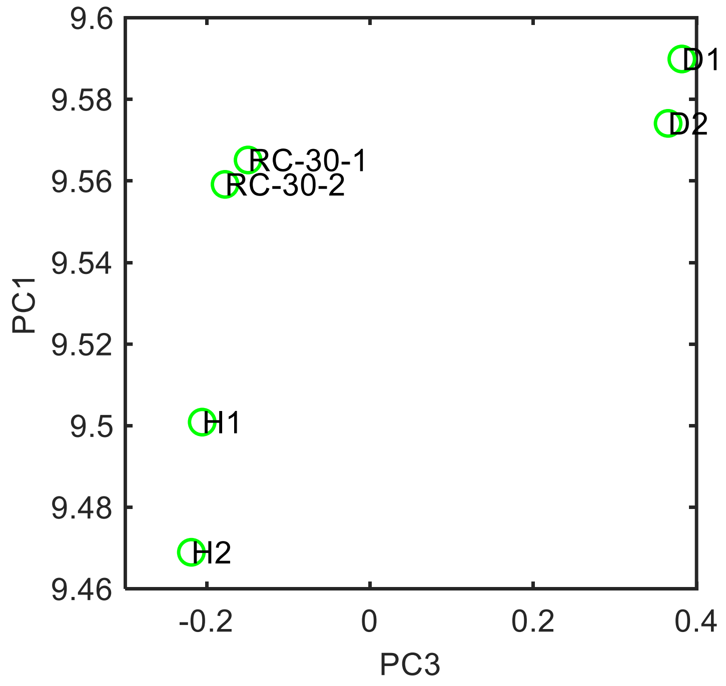
Class / Sample	Number of EMI measurements (data examples)				Frequency bandwidth [kHz]	Signal length after fusing G and R [data points]	Signal length after applying PCA feature reduction
	H	D1	D2	Rp			
1	4	4	3	2	1-5000 sampled at 0.2	49992	10
2	4	4	3	-	1-5000 sampled at 0.2	49992	10
3	4	4	3	2	1-5000 sampled at 0.2	49992	10
4	4	4	3	2	1-5000 sampled at 0.2	49992	10
5	4	4	3	2	1-5000 sampled at 0.2	49992	10

Principal component analysis based classification

H1 and H2 = Initial healthy state based conductance data;
D1 and D2= Damage state based conductance data (10 mm diameter with 3 mm depth);
RC-30-1 and RC-30-2= Filled plate with crystallization at 30 degree C

Frequency range = 1kHz-1MHz

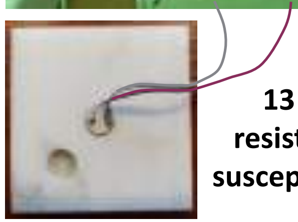




Our objective: proof of concept on small 3D-printed samples

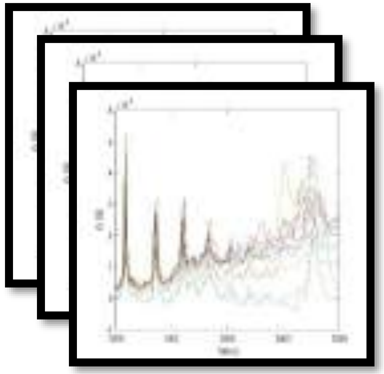
Conductance & Resistance measurements were fused together.
Training data were augmented by adding artificial noise.
PCA was employed to reduce the large number of features down to 10 features.
Overfitting was solved using 10-fold cross-validation, L2 regularization, dropout regularization, and early stopping.

Inspect the structure using an impedance analyser

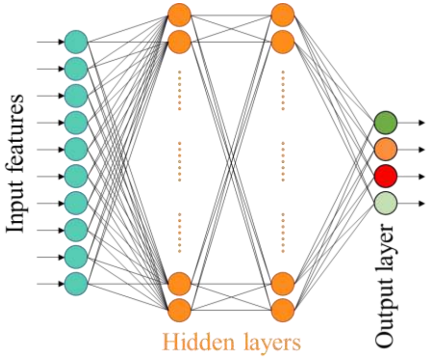


EMI data ⇒
13 types of measurements:
resistance (R), conductance (G),
susceptance (B), reactance (X), etc.

Signal acquisition



Deep learning



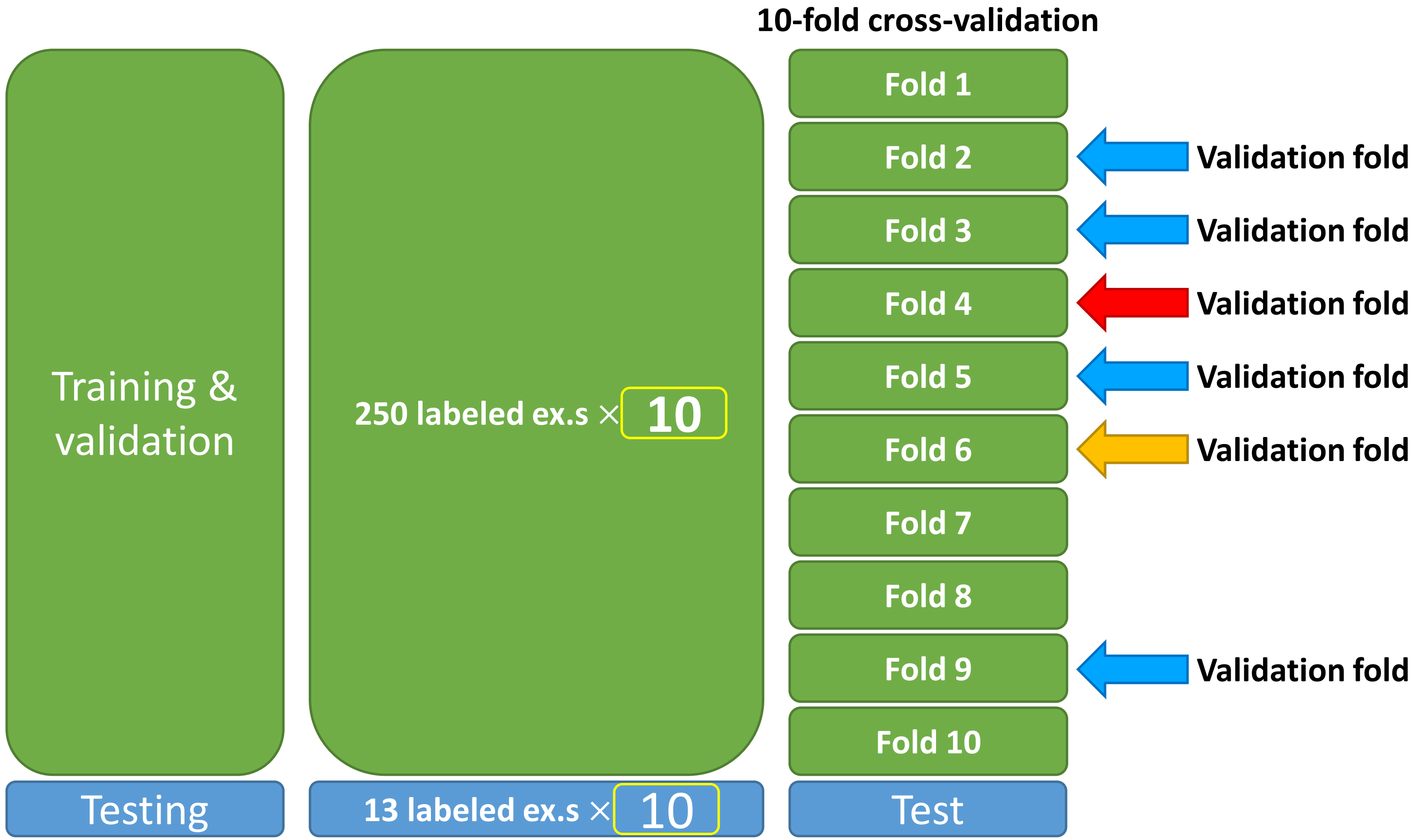
ReLU act.

Result

Healthy
Damage L1
Damage L2
Repaired

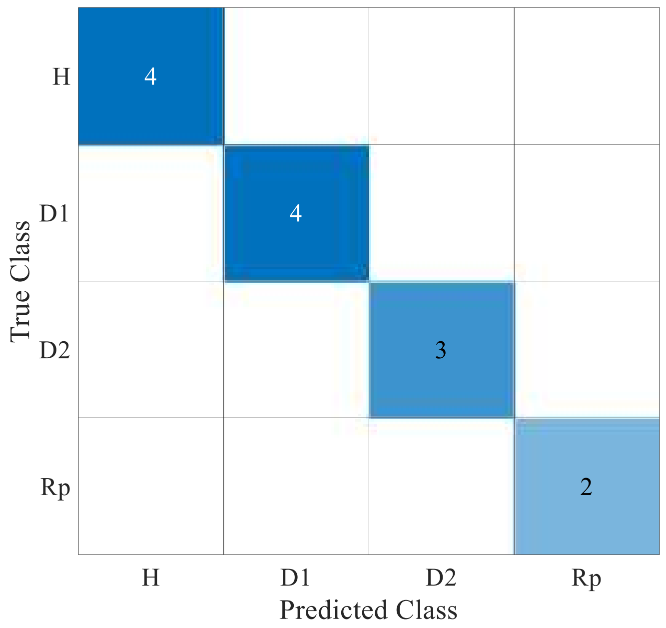
Final cross-validation + testing!

100% accuracy was attained in 5 testing cases out of 10-fold validations



Categorical accuracy

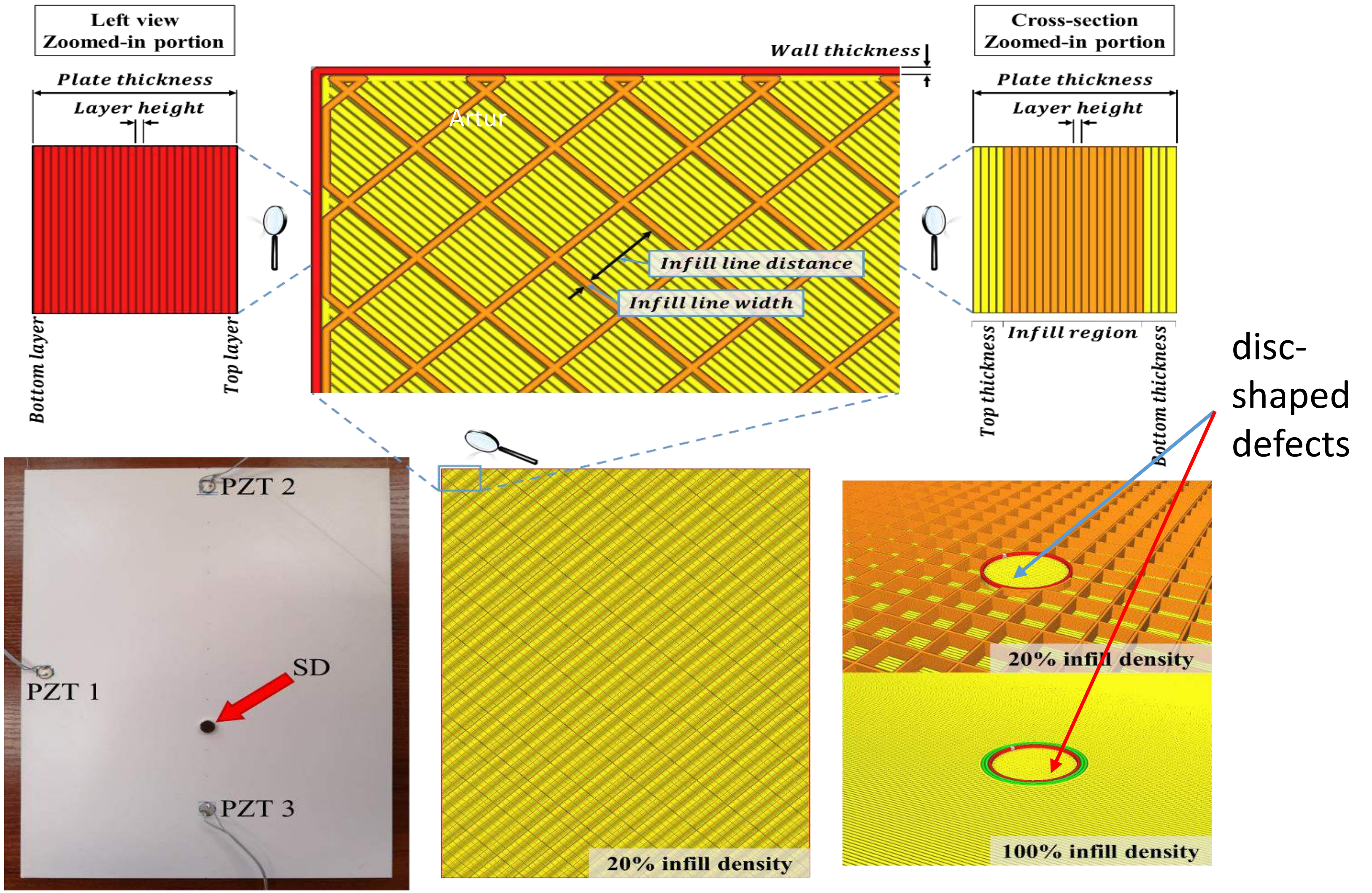
Dataset	Accuracy
Training	98.67-100%
Validation	100%
Testing	100%



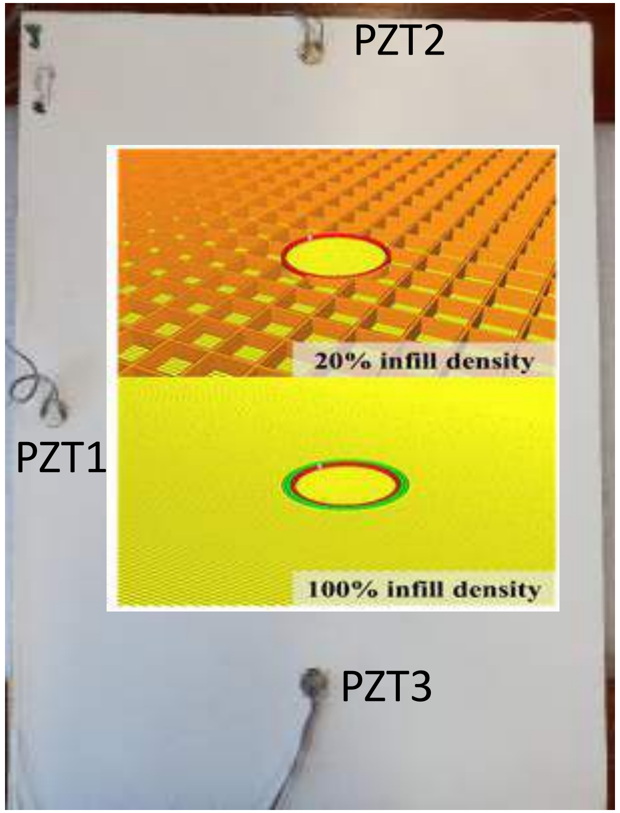
Inbuilt damage detection : process, data gathering

10 3D-printed poly (lactic acid) (PLA) with different infill densities plates:

- Fused deposition modeling (FDM) method
- Each additively manufactured plates of dimension 325×235×4 mm^3.
- The plates were printed using FDM with 20%, 40%, 60%, 80%, and 100% infill densities
- The second set of built-in disc-shaped defects including a void of 10 mm diameter and 0.6-mm height was printed within the center of the damage plates.
- Impedance analyser used for data acquisition of Conductance (G) and Resistance (R)

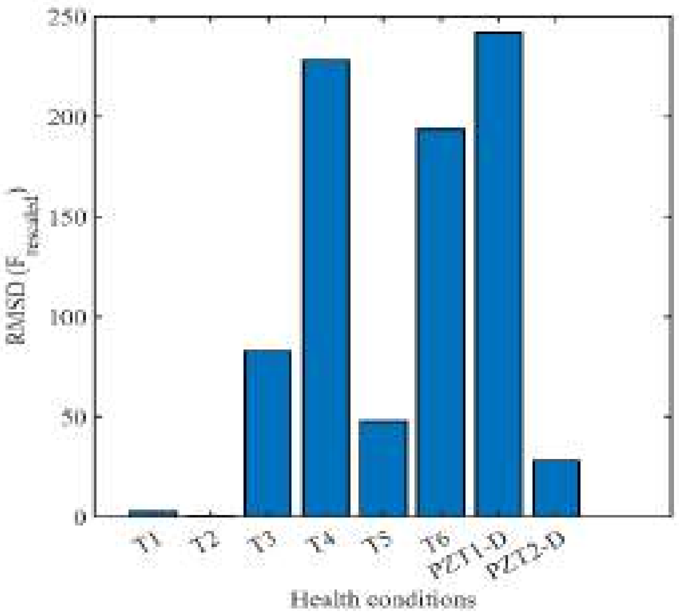


Inbuilt damage detection using PZT 1 and PZT 2

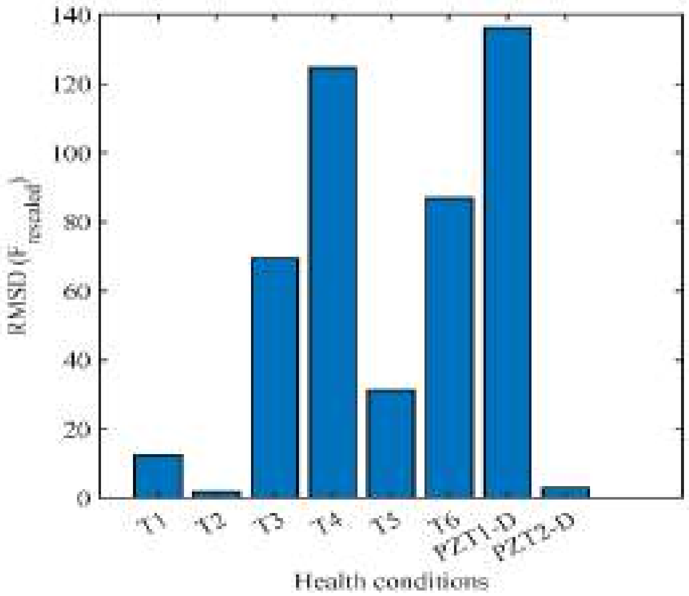


Symbols	Descriptions
T1	RMSD of PZT1 for the repeated measurements
T2	RMSD of PZT2 for the repeated measurements
T3	RMSD of PZT1 w.r.t PZT2
T4	RMSD of PZT2 w.r.t PZT1
E1	|RMSD of PZT1 w.r.t PZT3 − RMSD of PZT2 w.r.t PZT3|
T5	T3-E1
T6	T4-E1
PZT1-D	RMSD of damage plate w.r.t healthy plate for PZT1 using $F_{rescaled}$ data
PZT2-D	RMSD of damage plate w.r.t healthy plate for PZT2 using $F_{rescaled}$ data

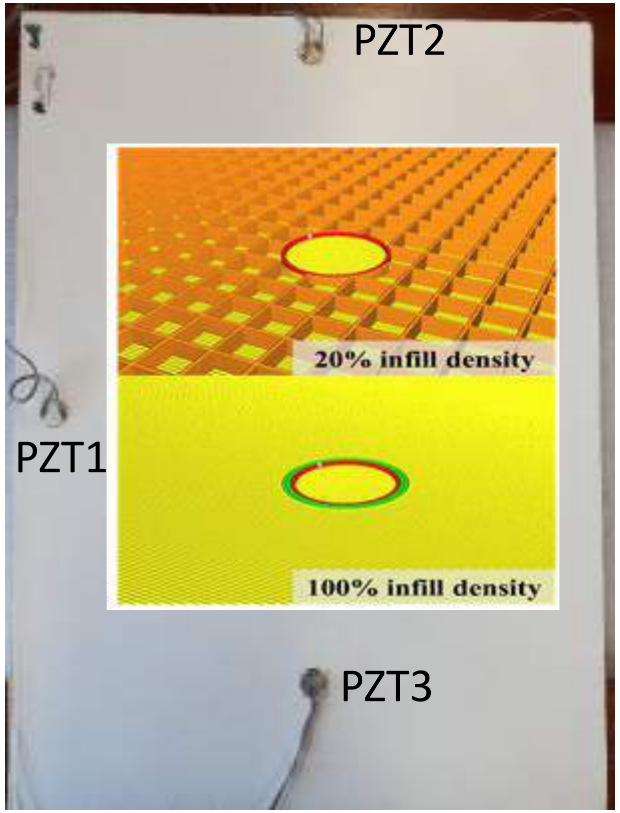
100%-infill plate



80%-infill plate

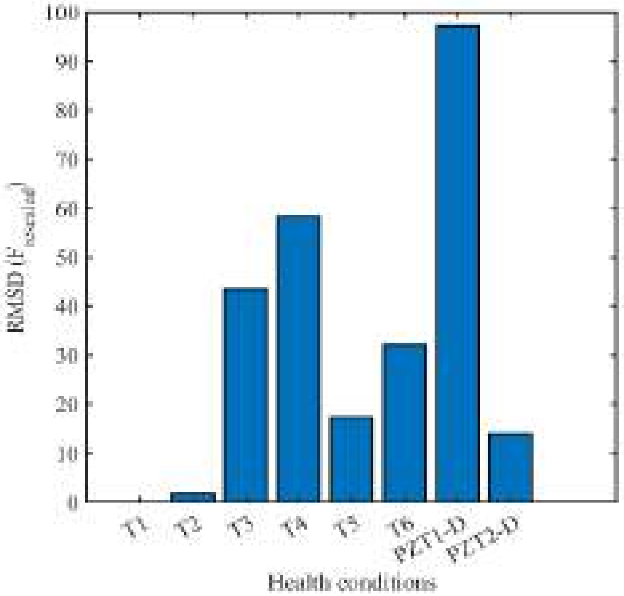


Inbuilt damage detection using PZT 1 and PZT 2

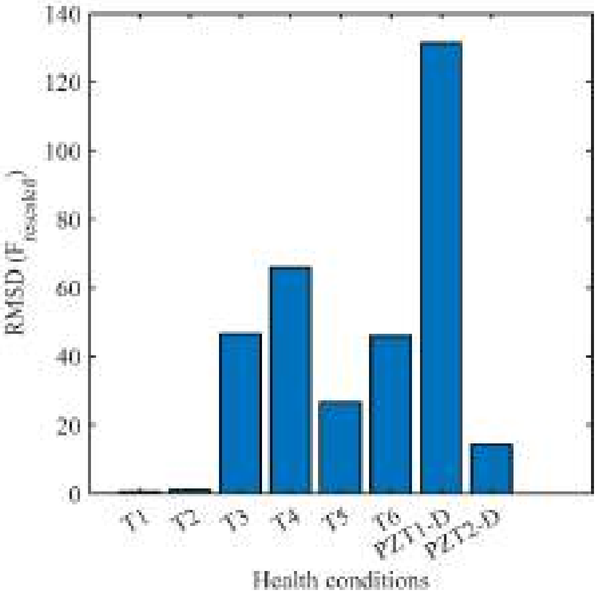


Symbols	Descriptions
T1	RMSD of PZT1 for the repeated measurements
T2	RMSD of PZT2 for the repeated measurements
T3	RMSD of PZT1 w.r.t PZT2
T4	RMSD of PZT2 w.r.t PZT1
E1	|RMSD of PZT1 w.r.t PZT3 − RMSD of PZT2 w.r.t PZT3|
T5	T3-E1
T6	T4-E1
PZT1-D	RMSD of damage plate w.r.t healthy plate for PZT1 using $F_{rescaled}$ data
PZT2-D	RMSD of damage plate w.r.t healthy plate for PZT2 using $F_{rescaled}$ data

40%-infill plate



20%-infill plate



Conclusion

- EMI-based approach was used to evaluate the health condition of 3D-printed ABS, M3-X, poly (lactic acid) (PLA) with different infill densities plates.

- Higher damage sensitivity by the horizontal layup 3D printed ABS plate.

- EMI-based Deep-Learning was used to evaluate the health condition of 3D-printed M3-X plates among four classes: H, D1, D2, and Rp (healthy, damaged, and repaired states).

- Identical AM healthy and damaged plates were used for built-in damage identification in the varying infilled plate. The built-in damage-detection capacity has been shown for 20%, 40%, 80%, and 100% infilled PLA plates. The damage was detected in all the examined infill densities and using all the proposed thresholds by PZT1, positioned at a center distance of 102.5 mm from the damage. However, the damage was not detected by PZT2 placed at 147.5 mm from the damage.

Thank you!

Acknowledgements

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The author also would like to acknowledge CertBond funding support for the presentation of the work in CERTBOND final conference.

NATIONAL SCIENCE CENTRE POLAND

OPUS project: 2019/35/B/ST8/00691

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A comparison of different experimental techniques for crack tip localization in adhesive bonded CFRP-CFRP joints subjected to Mode II fatigue loading

Andrea Bernasconi, **Michele Carboni**, Alessandra Panerai

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Mode II fatigue crack propagation

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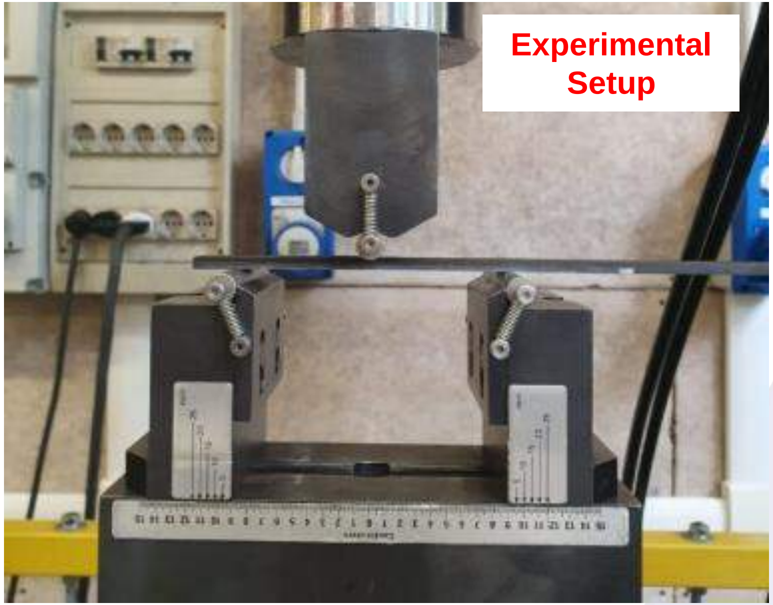
- Part of the Round Robin on the mechanical behaviour of bonded joints
- Tests according to protocol CA18120_STM_M2022.01: SOP for Mode-II fatigue crack growth of CFRP adhesive joints
- End Notched Flexure (ENF) tests
- Crack length monitoring by Visual Testing (VT) and Compliance Method (CM)
- Crack monitoring at 5, 10, 100, 500, 1000, 5.000, 10.000, 20.000, 50.000, 100.000, 500.000 and 1.000.000 cycles

- 2 tests according to protocol V1 (Load Control Fatigue tests)
  - Specimen 3.14 – Applied load 40% $F_{precrack}$
  - Specimen 4.13 – Applied load 50% $F_{precrack}$



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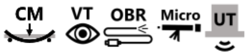
Mode II fatigue crack propagation

- 4 tests according to the newest protocol (V3):
  - Static pre-cracking under displacement control
  - Displacement Control Fatigue tests (R=0.1)
  - 2 Experimental setups:



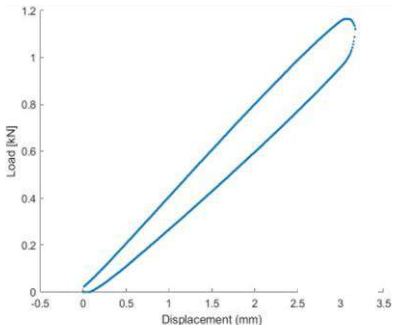
Specimen 2.14 – δ_{Max} = 80% $\delta_{Precrack}$

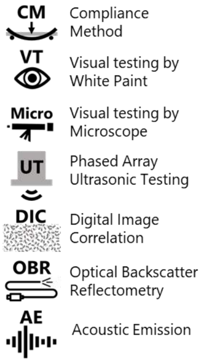
Specimen 4.41 – δ_{Max} = 60% $\delta_{Precrack}$

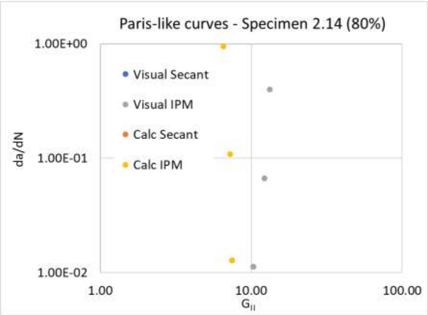
Specimen 2.18 – δ_{Max} = 40% $\delta_{Precrack}$

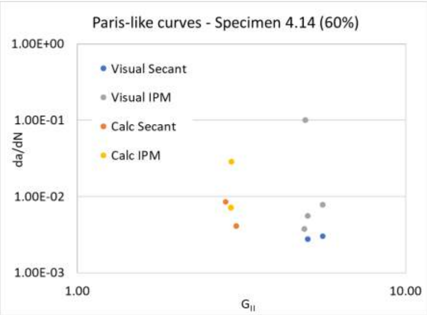
Specimen 3.18 – δ_{Max} = 40% $\delta_{Precrack}$

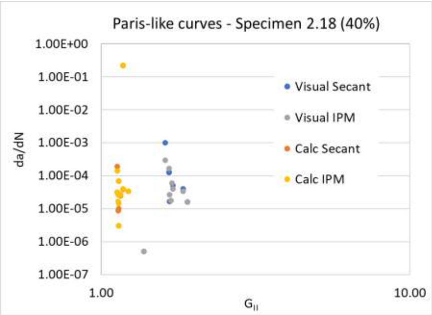
Precracking – Specimen 3.18

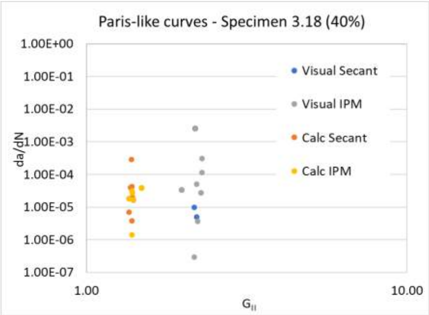












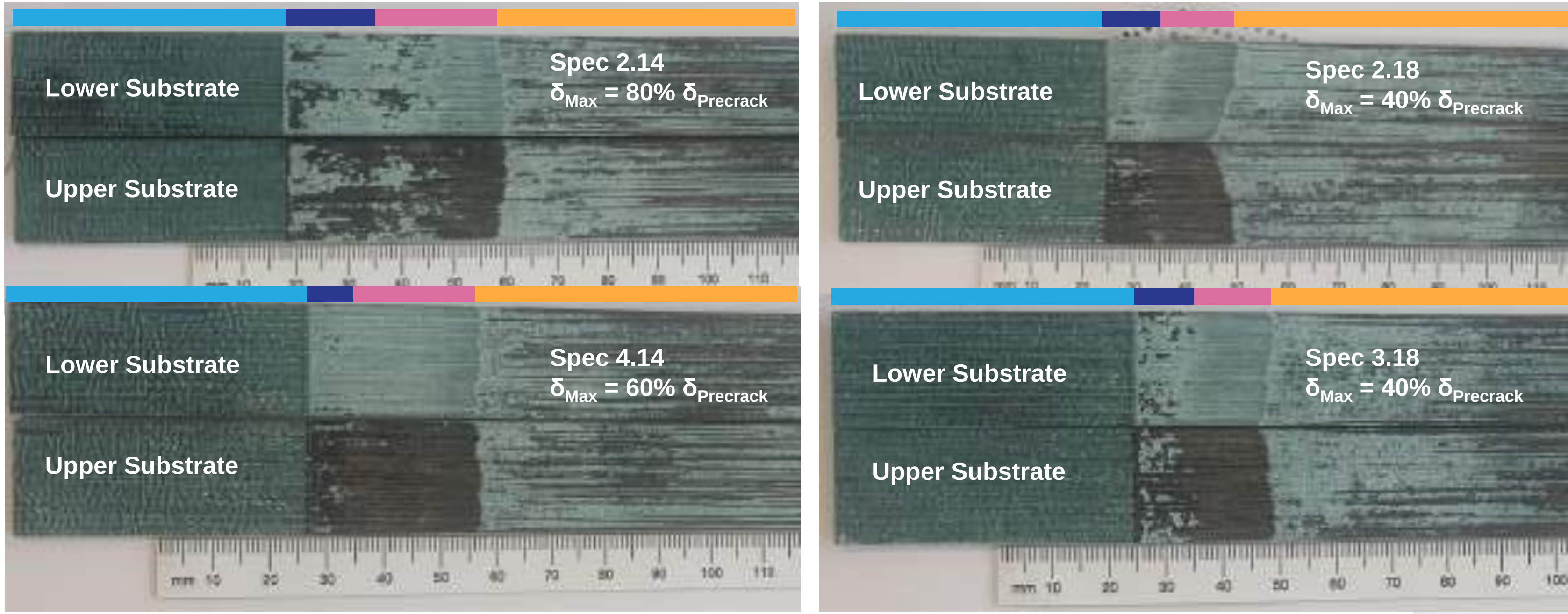
Fracture surfaces

PTFE insert

Precrack

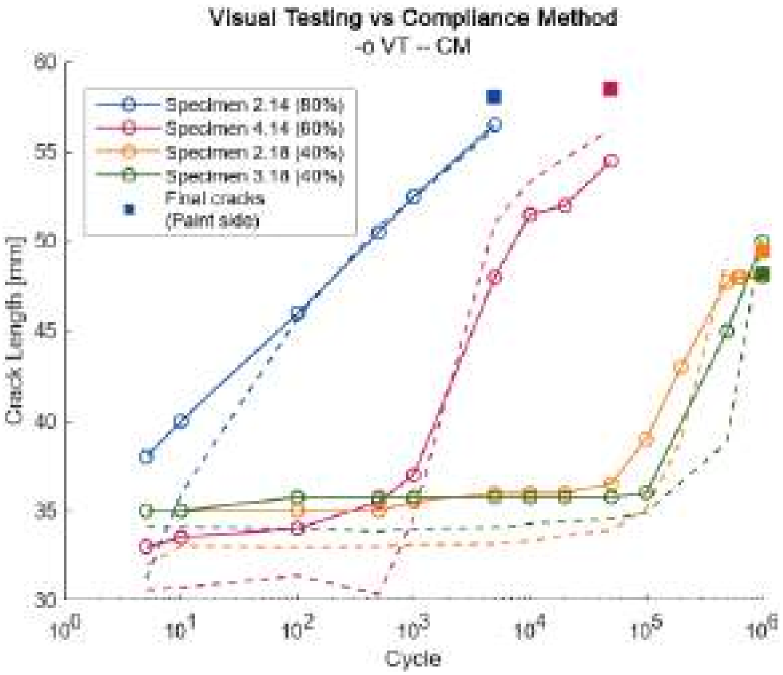
Fatigue Crack Propagation

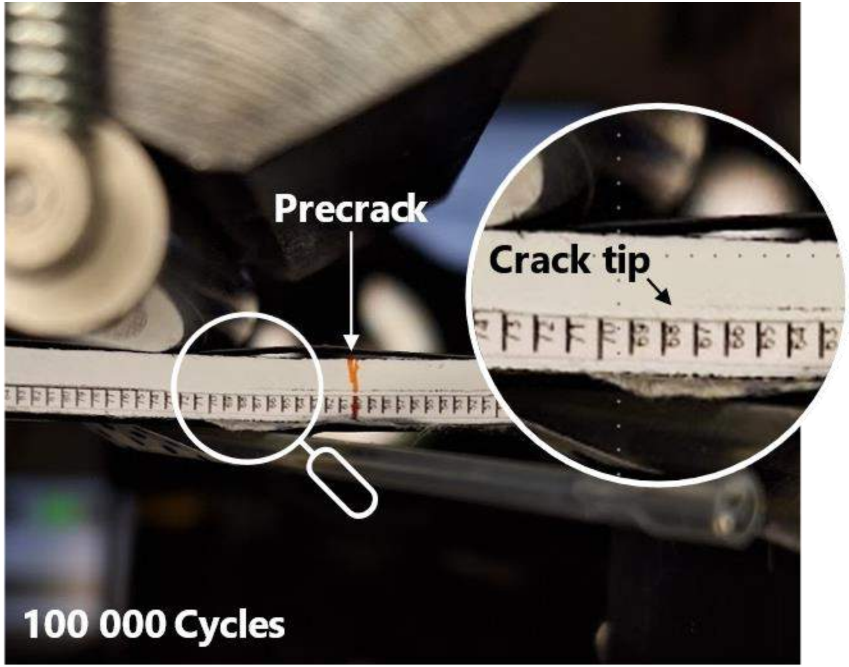
Final Adherend Separation (Mode I)



Visual Testing VT

Specimen 2.18



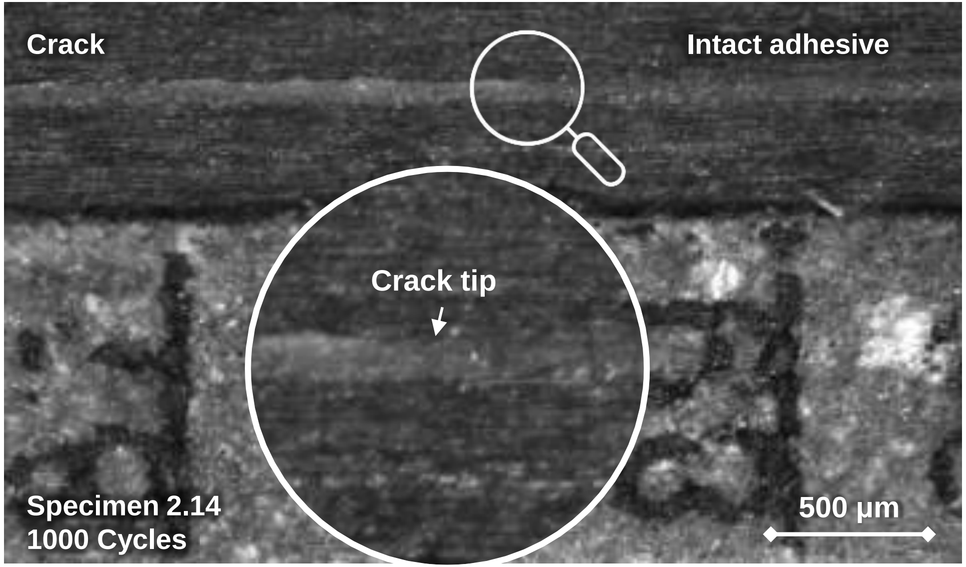


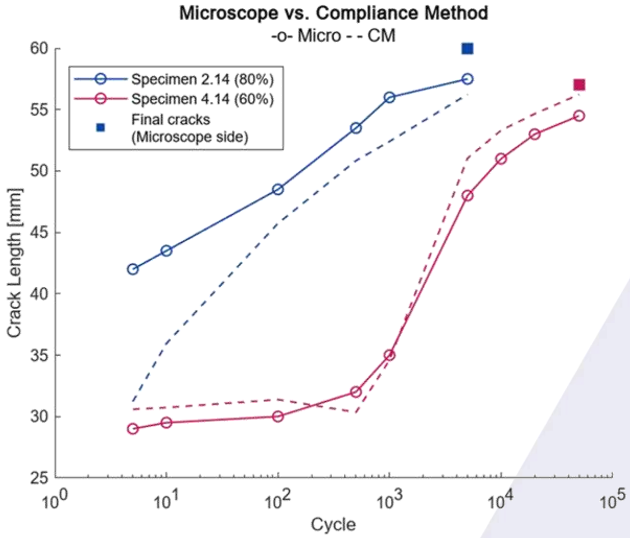
Visual Testing

Micro

- Manta G-201-30fps 1/1.8" Monochrome CCD 2MP Camera
- Specimens polished with 2500 grit sandpaper and 1 μm diamond paste prior to testing

Specimen 2.14





Phased Array Ultrasonic Testing

UT

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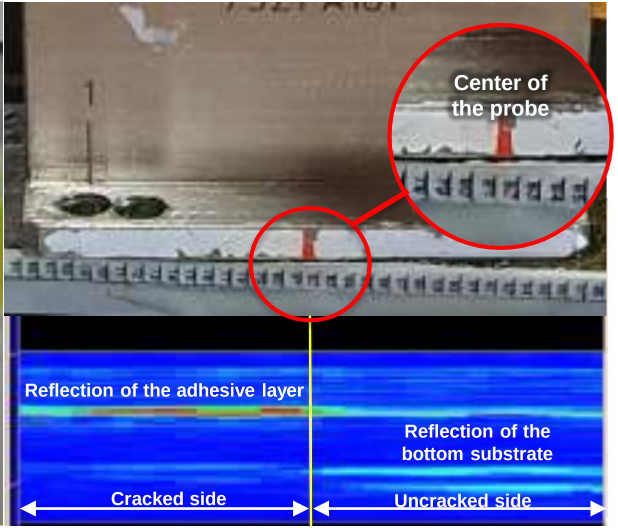
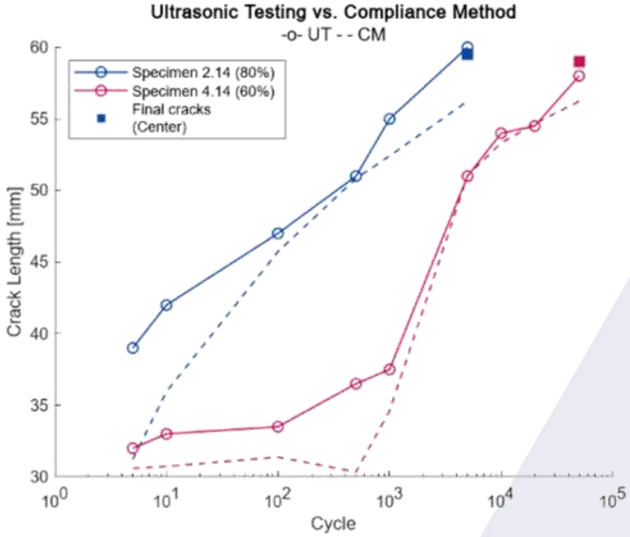
- Mantis M2M system by Eddyfi technologies equipped with a Phased Array 10 MHz probe with 32 elements
- Linear scan using longitudinal ultrasonic waves

Specimen 2.14





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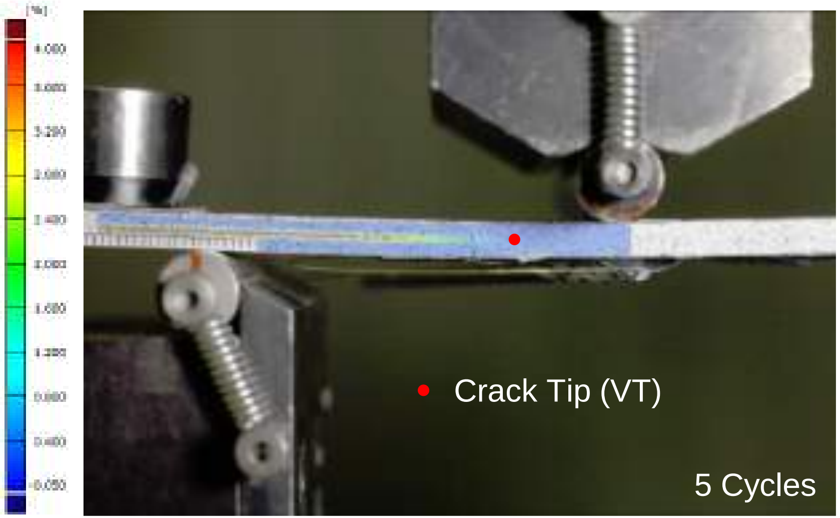
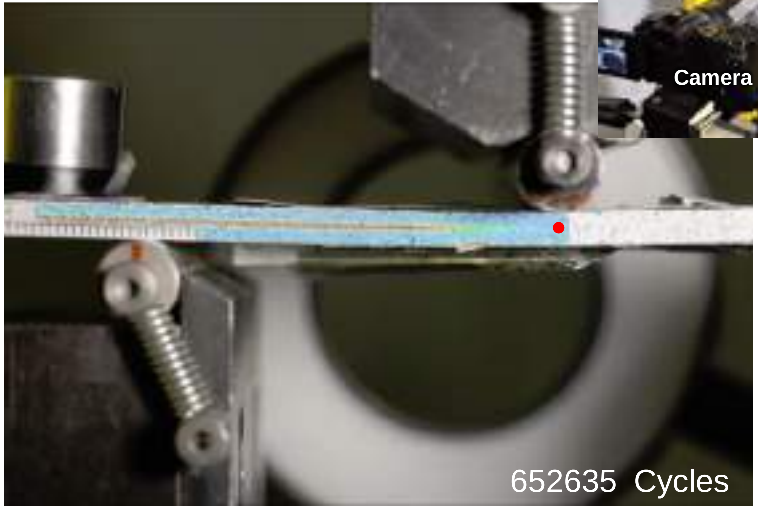
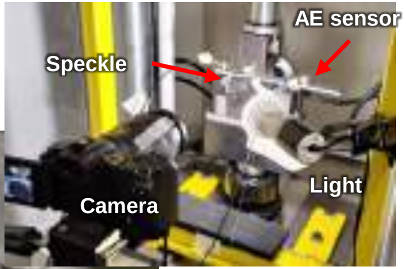
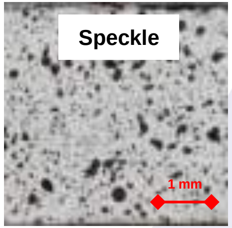
Digital Image Correlation

Max. Principal Strain – Specimen 2.18





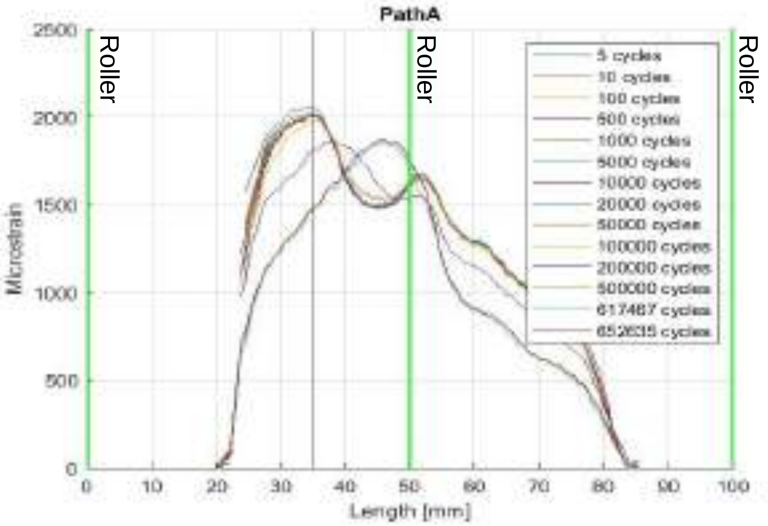


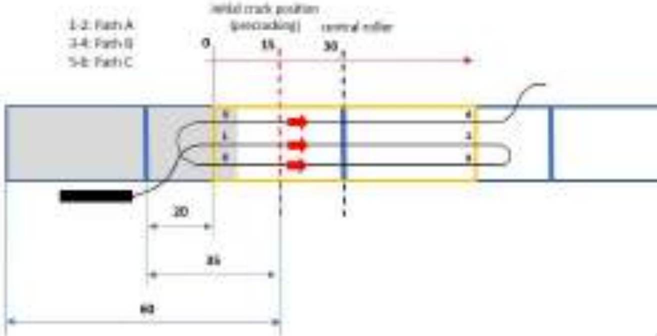


The profile of the maximum principal strain follows the crack tip observed by VT

The analysis of the experimental outcomes is in progress

Optical Backscatter Reflectometry



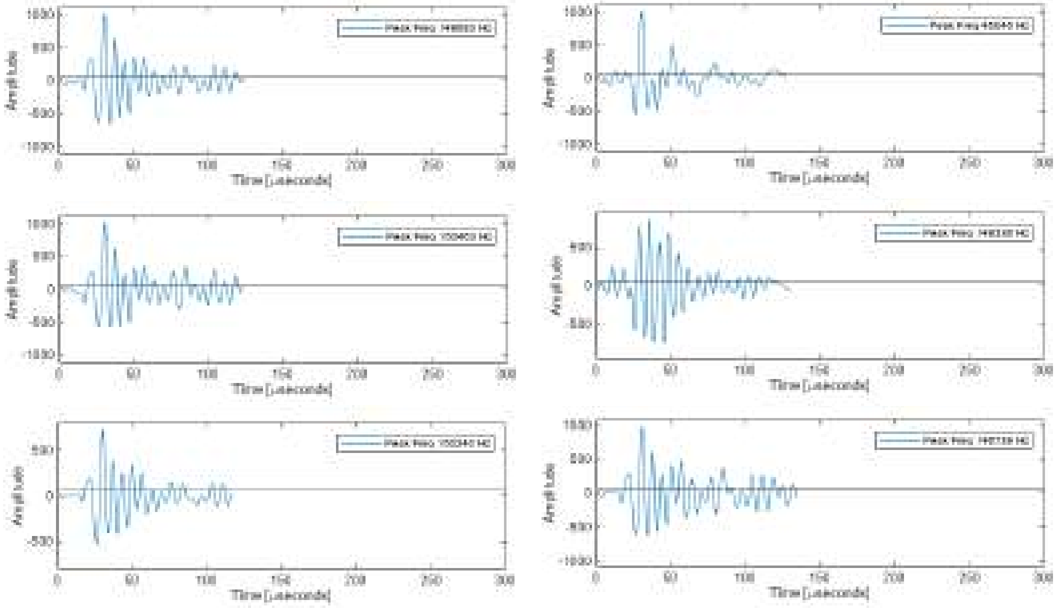


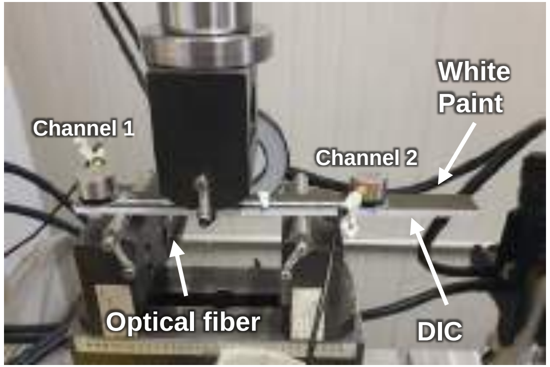
- The backface strain profile evolves from 2 peaks to 1 with crack advancement (already observed in the literature, by the present authors, as well)
- Further work is ongoing to understand the relationship between the recorded backface strain profile and the physical crack length

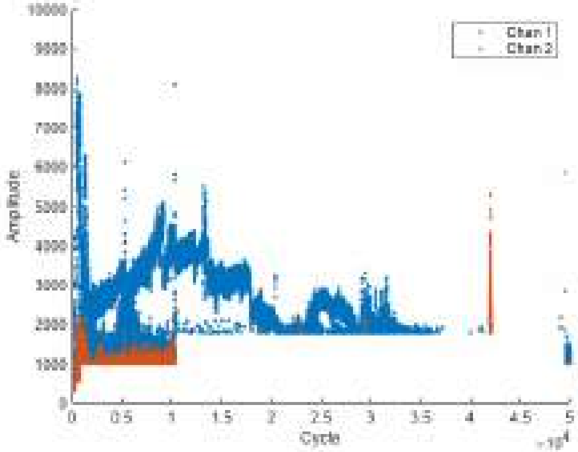
Acoustic emission

AE

- Waveforms are typical of damage mechanisms
- Post-processing is in progress





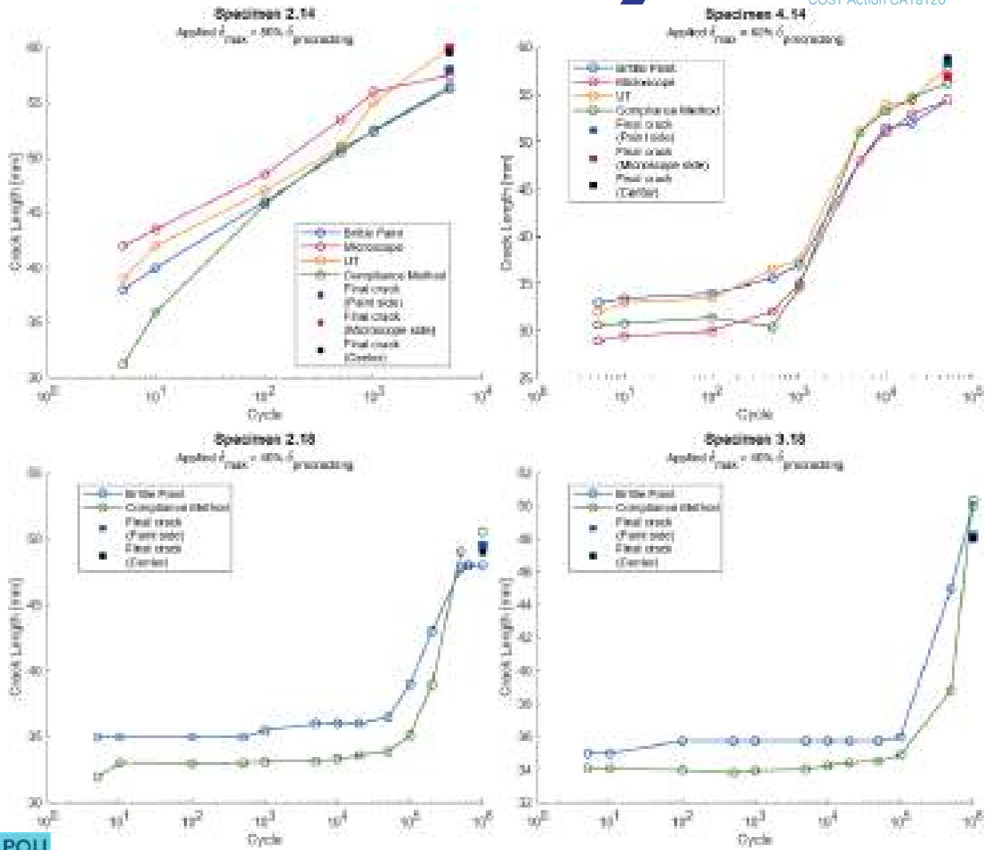


Conclusions

- Qualitatively, all the post-processed techniques show the same trend, even if, quantitatively, there are some differences

- Between the post-processed techniques, Ultrasonic Testing is the closest to the final physical crack length

- Further work is going on to conclude the post-processing of the other adopted techniques



Thank You!

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Acknowledgment

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This STSM was developed under the COST Action CA18120 (CERTBOND) and supported by COST (European Cooperation in Science and Technology).

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The authors would like to thank Ms. B. Oneda for the help given to the research

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A Comprehensive Analysis of Bonded Composite Structures using Ultrasonic Guided Waves

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IMP PAN, Gdansk, Poland

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Outline

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- Aim
- Debond analysis in honeycomb panels
- Debond analysis in GFRP plates
- Multiple debond analysis in GFRP plates
- Conclusion
- Acknowledgements

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Studying multiple debond inside Honeycomb structures

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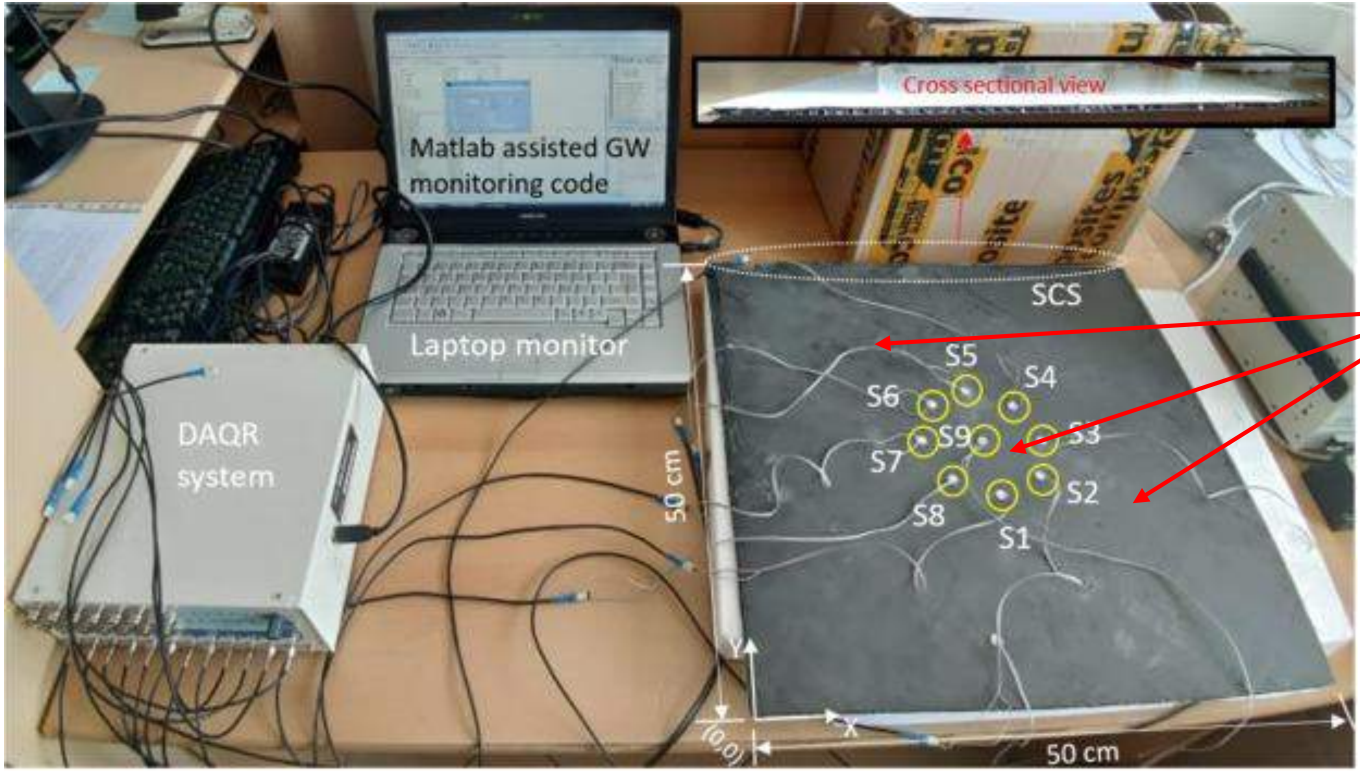
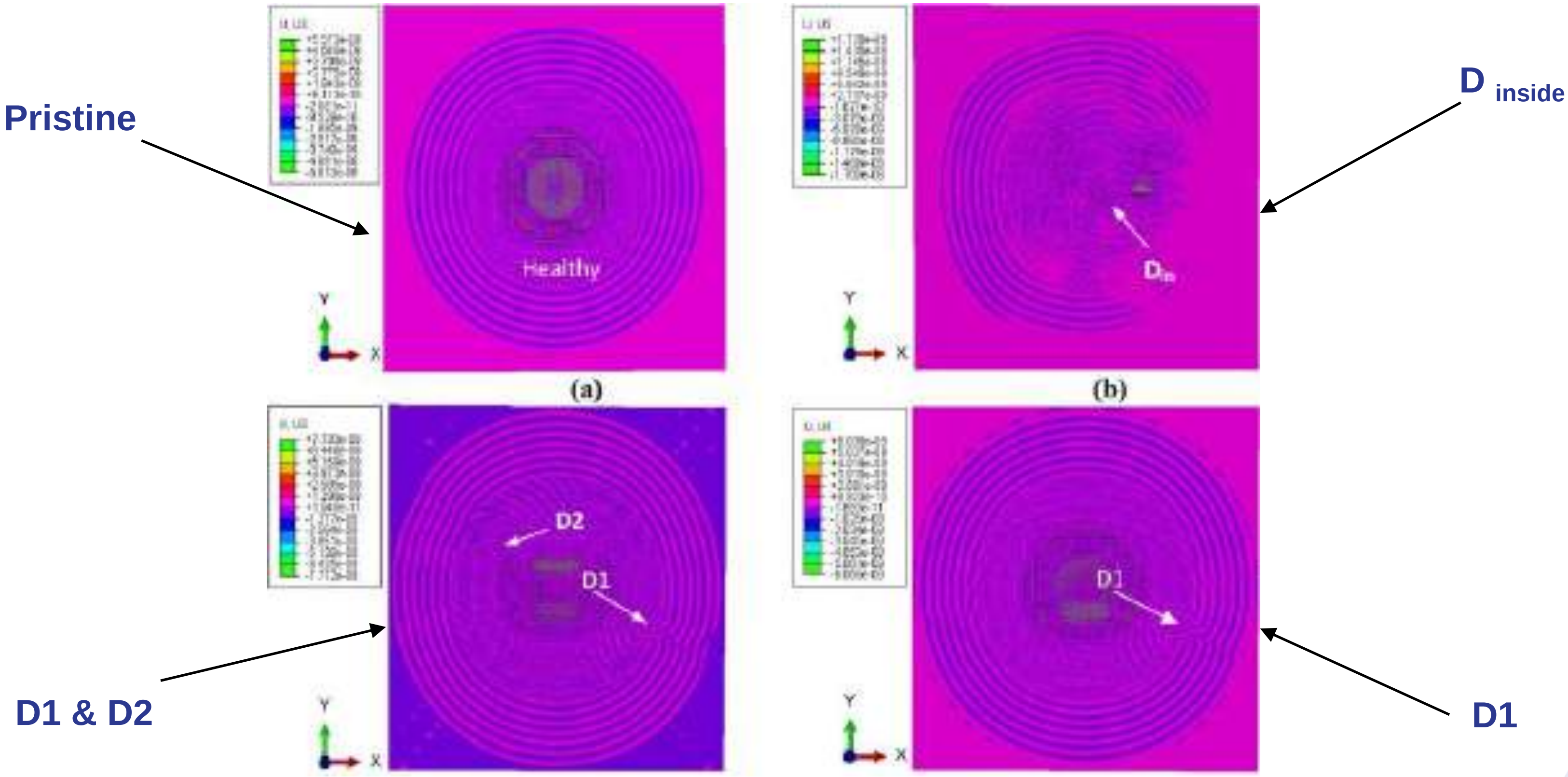
Experimental study of the debond cases

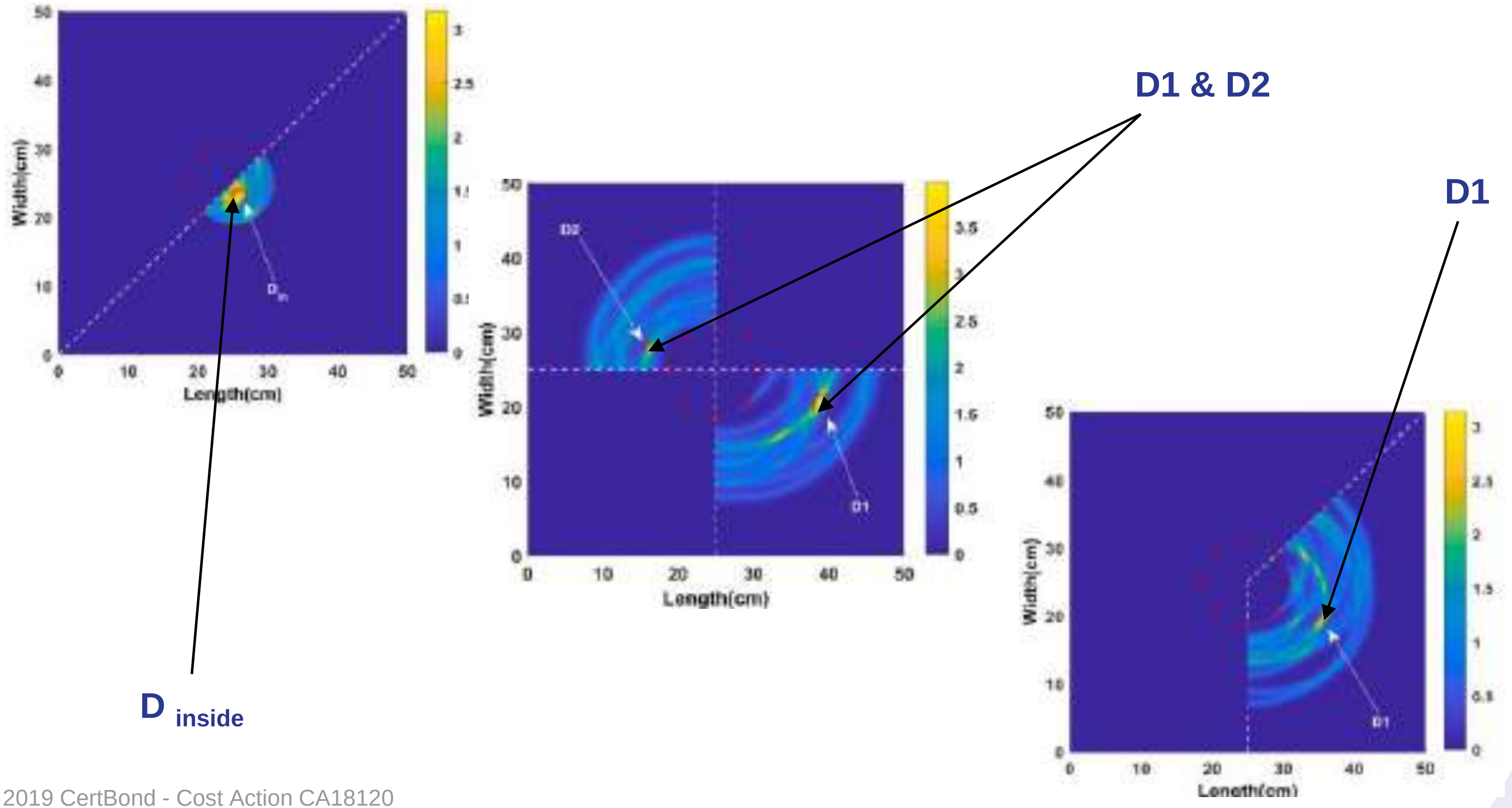


Multiple debond Inside the structure

Numerical GW Simulation of the debond cases



GW algorithm localization of the debond cases



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Studying debond inside stiffener region of GFRP structures

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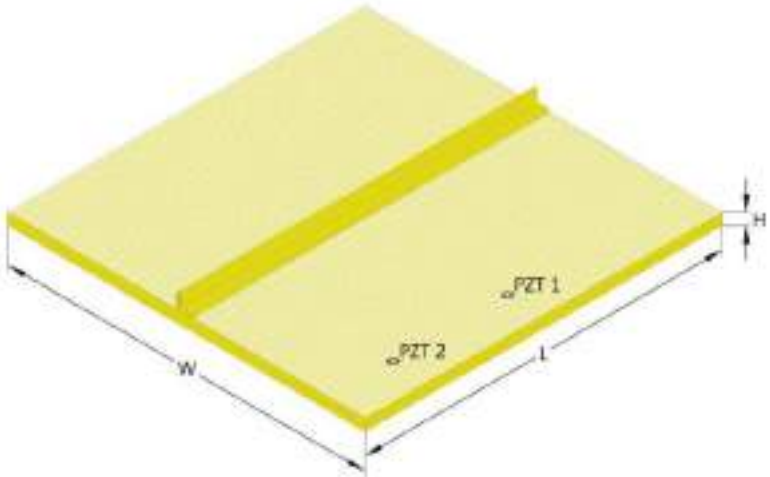
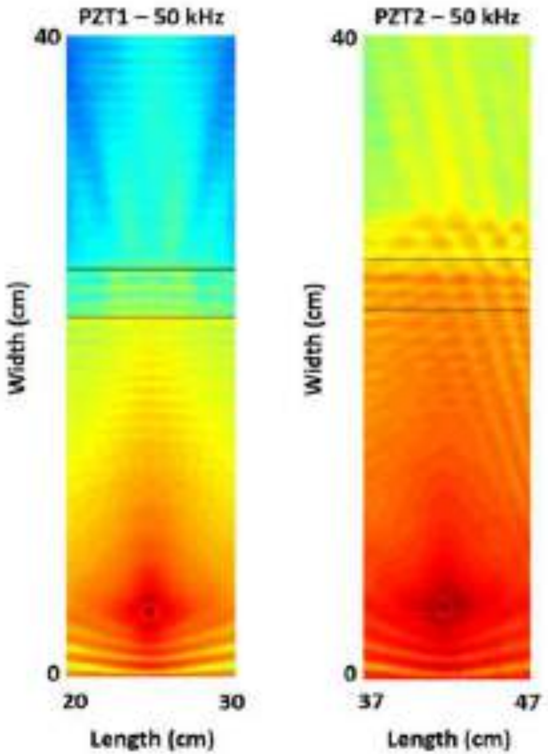
LDV measurement of debonding case study

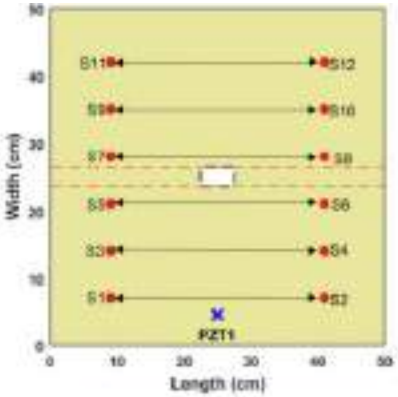
GFRP plate with bonded PZT sensors

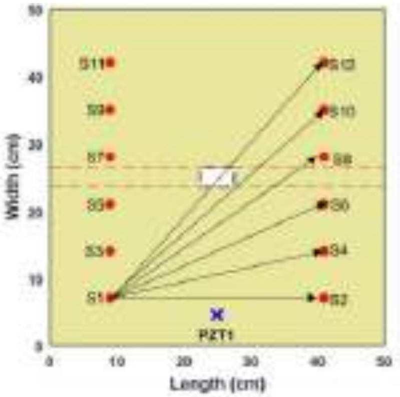


RMS results after performing the LDV study

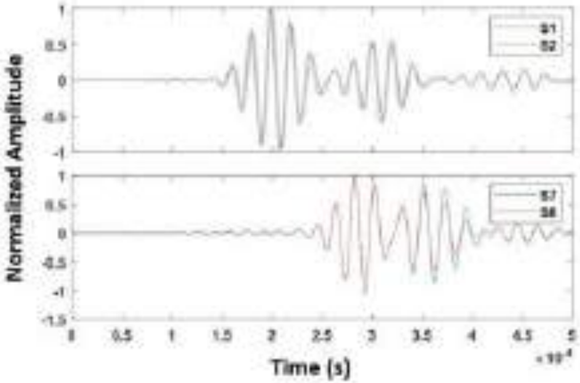


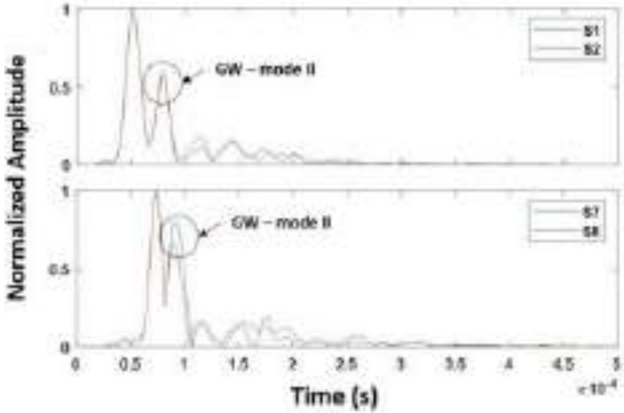
SHM-GW analysis of the structure



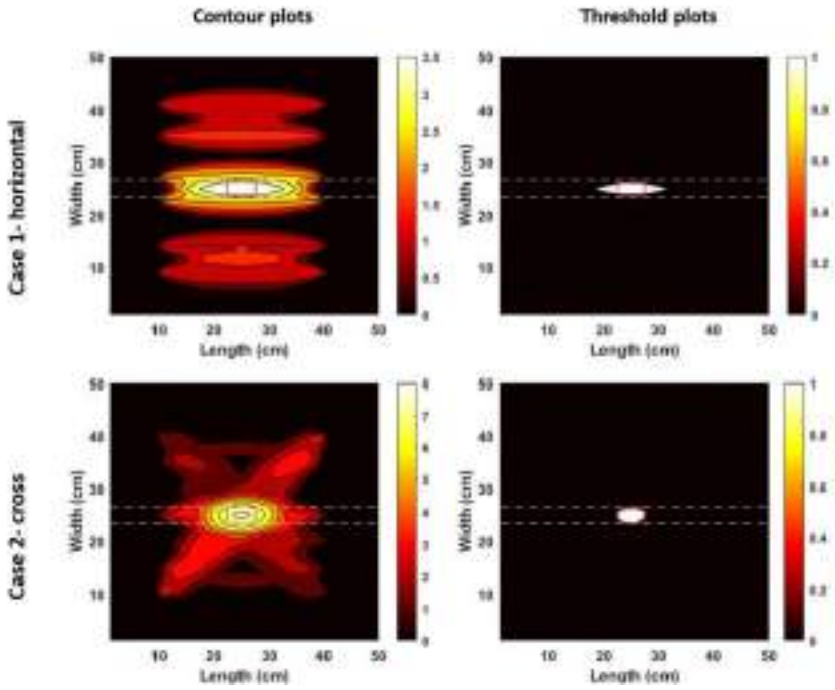


- SHM analysis using signal difference coefficient algorithm (SDC) was performed.
- With two types of sensor arrangements : linear and cross-signal path arrangements.
- HT envelope peak values were chosen for the study.



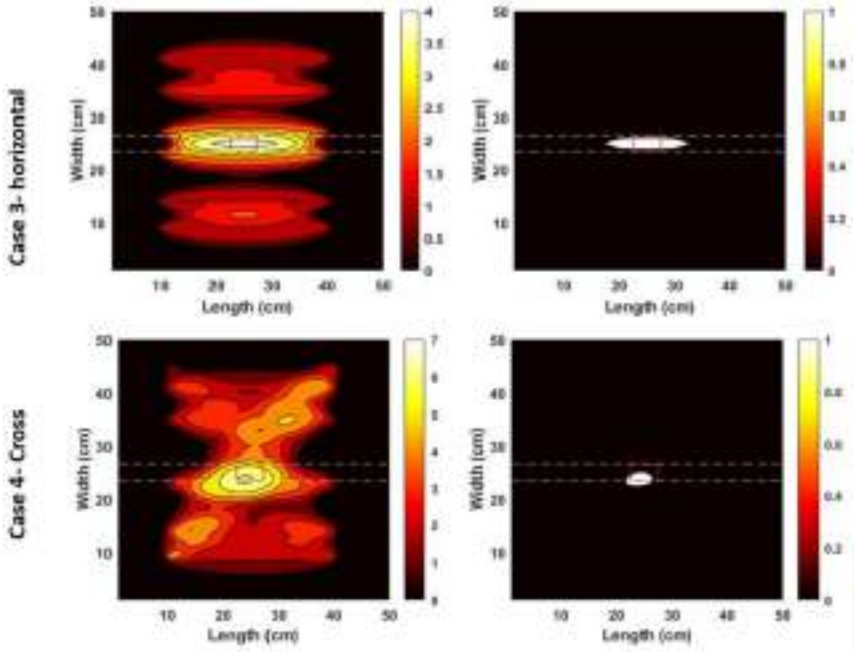


SHM-GW debond results



Debond localization using linear-signal paths

Debond localization using cross-signal paths



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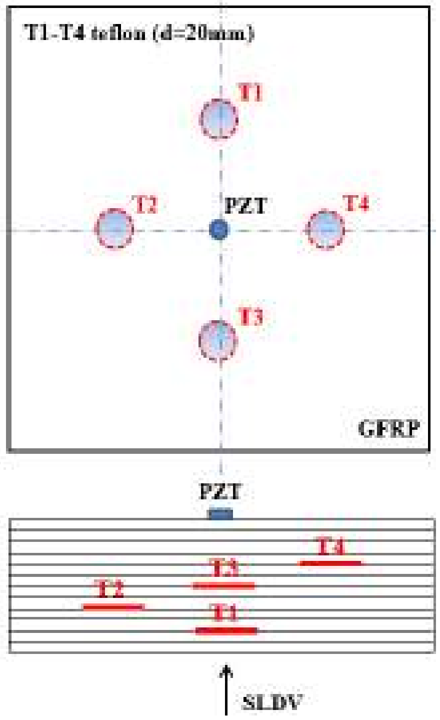
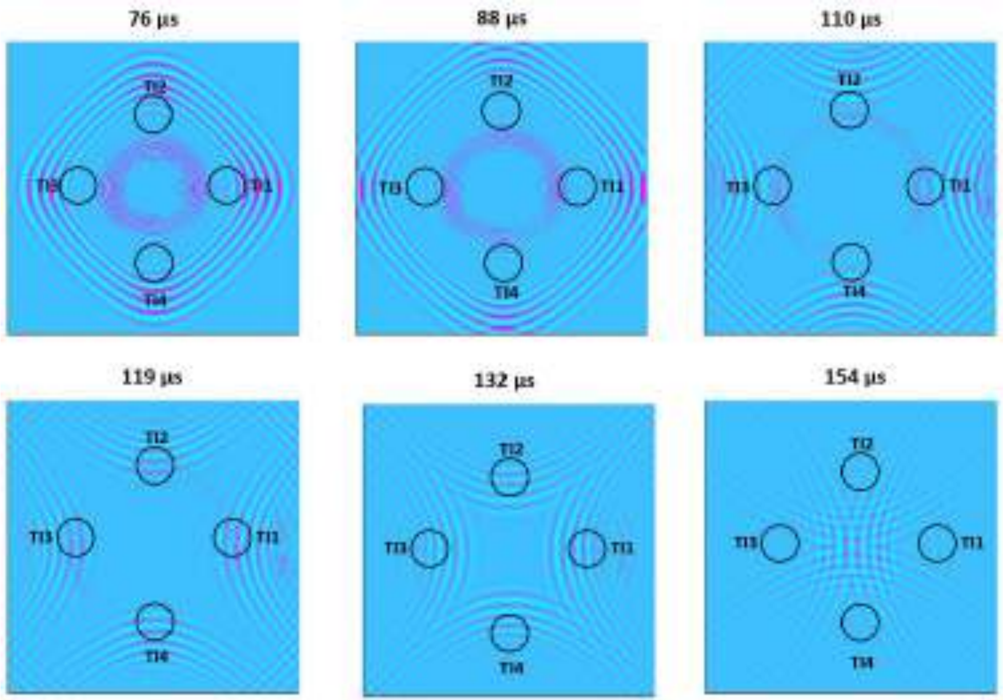
LDV measurement of debond case study



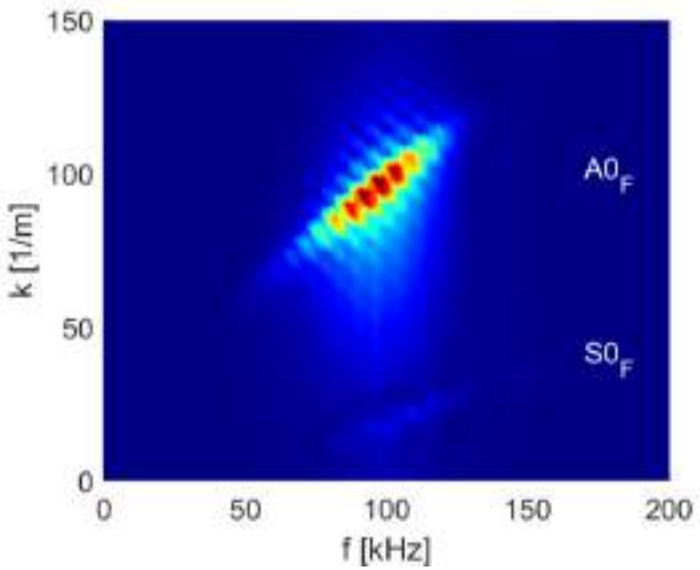


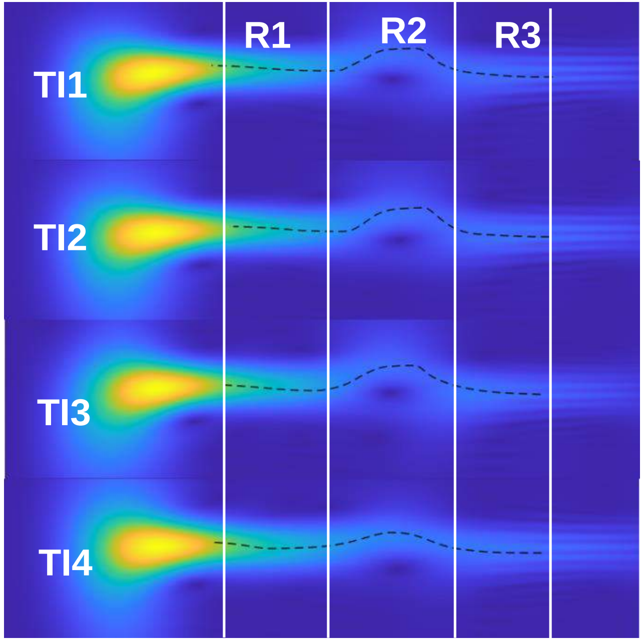
Debond study using NDT-LDV studies

Debond visualization using GW wave spread

LDV measurement of debond case study

- NDT-based wave number filter of GW signals.
- Forward and backward scattering of signal separation.





Region	R1 (k)	R2(k)	R3(k)
TI1	232	219	231
TI2	232	218	233
TI3	233	220	232
TI4	231	222	233

Conclusion

- A comprehensive analysis of detecting debonding in different types of composite structures was presented.
- The research provides more insights into the in-service monitoring of bonded structures.
- A combination of SHM and NDT approaches was presented to study, characterise and judge the severity of the debonding in structures.
- The results showed that it is capable of detecting even smaller debond in large structures.

Acknowledgment

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COST Action CA18120 (CERTBOND) supported by COST (European Cooperation in Science and Technology).

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COULD "LISTENING" TO ACOUSTIC EMISSIONS BE A VALUABLE TOOL IN UNDERSTANDING TOUGHENING MECHANISMS OF BONDED JOINTS?

R. A. A. Lima ,R. Tao, A. Bernasconi , M. Carboni , S. Teixeira de Freitas

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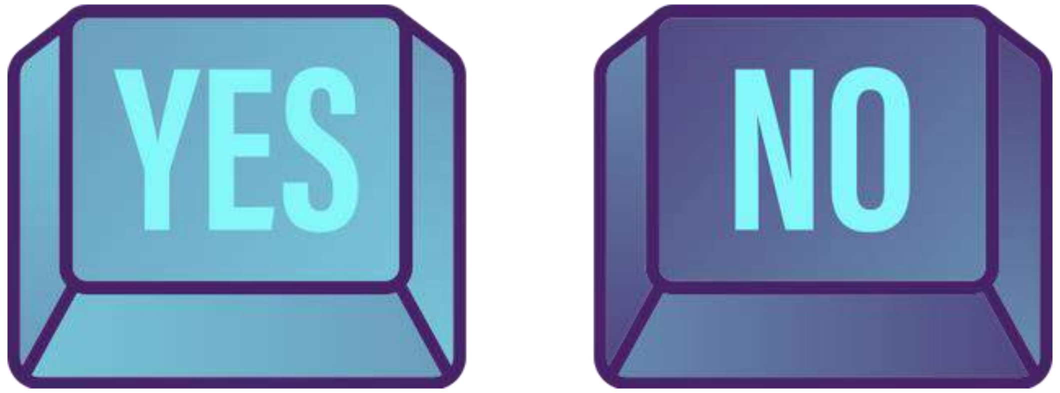

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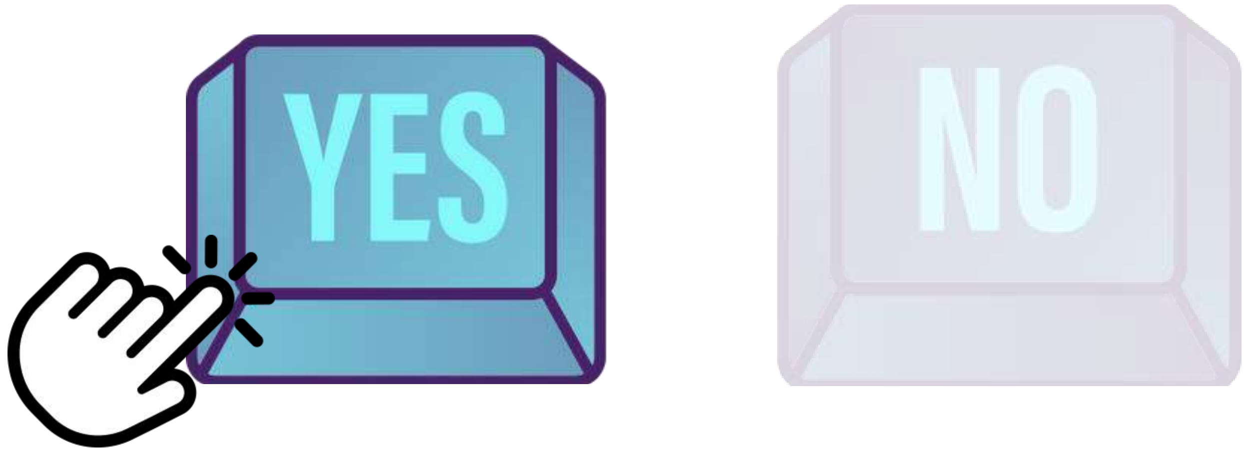
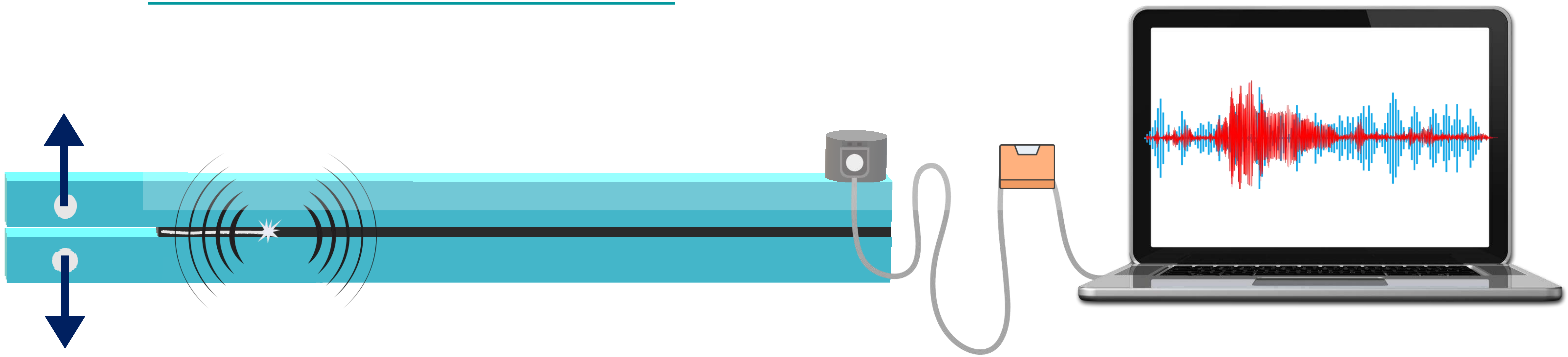


Research Background & Motivation

"The Acoustic Emission (AE) method is based on the assessment of ultrasonic elastic waves produced inside a material when its energy of deformation is released"



Research Background & Motivation

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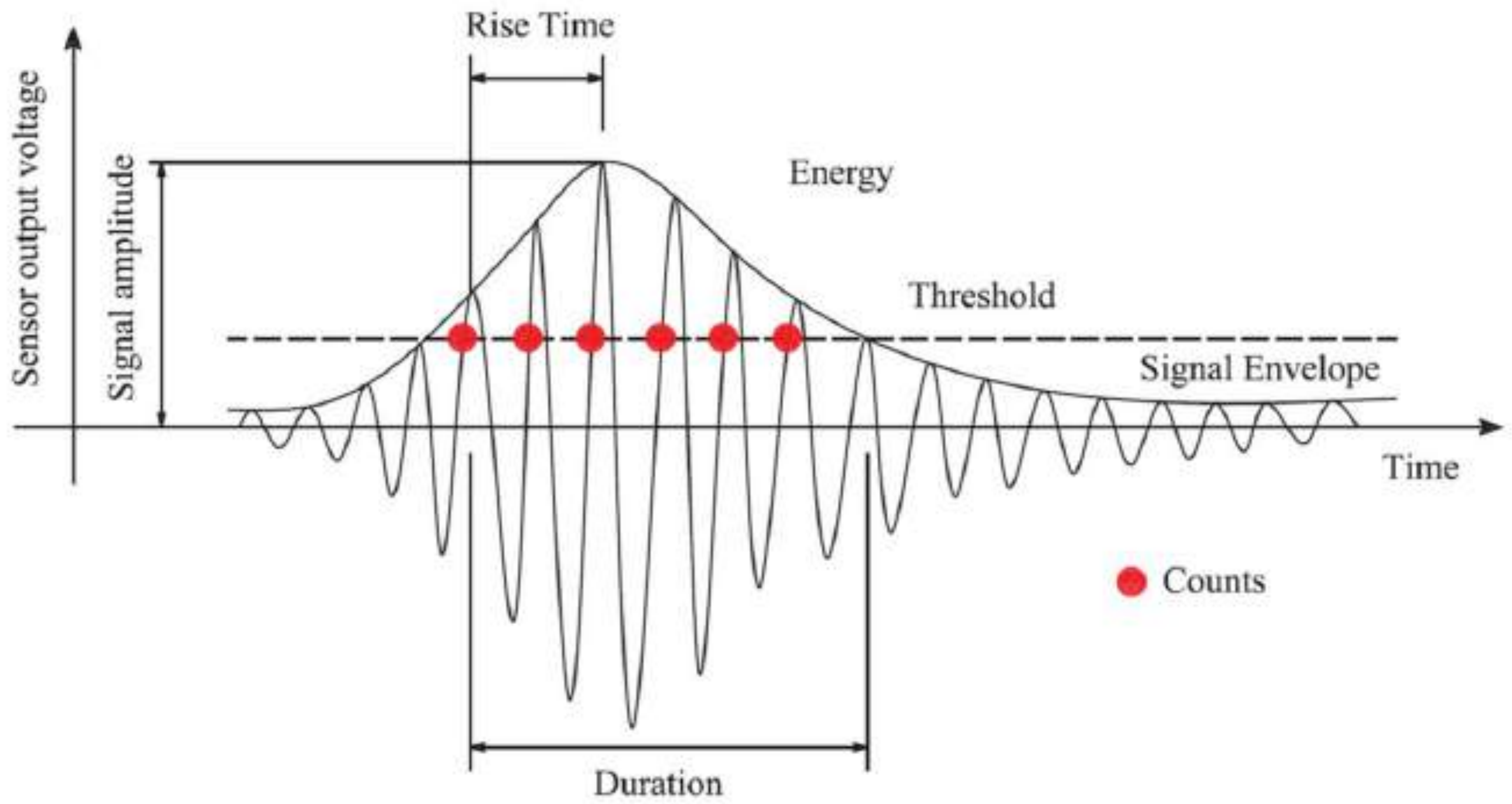

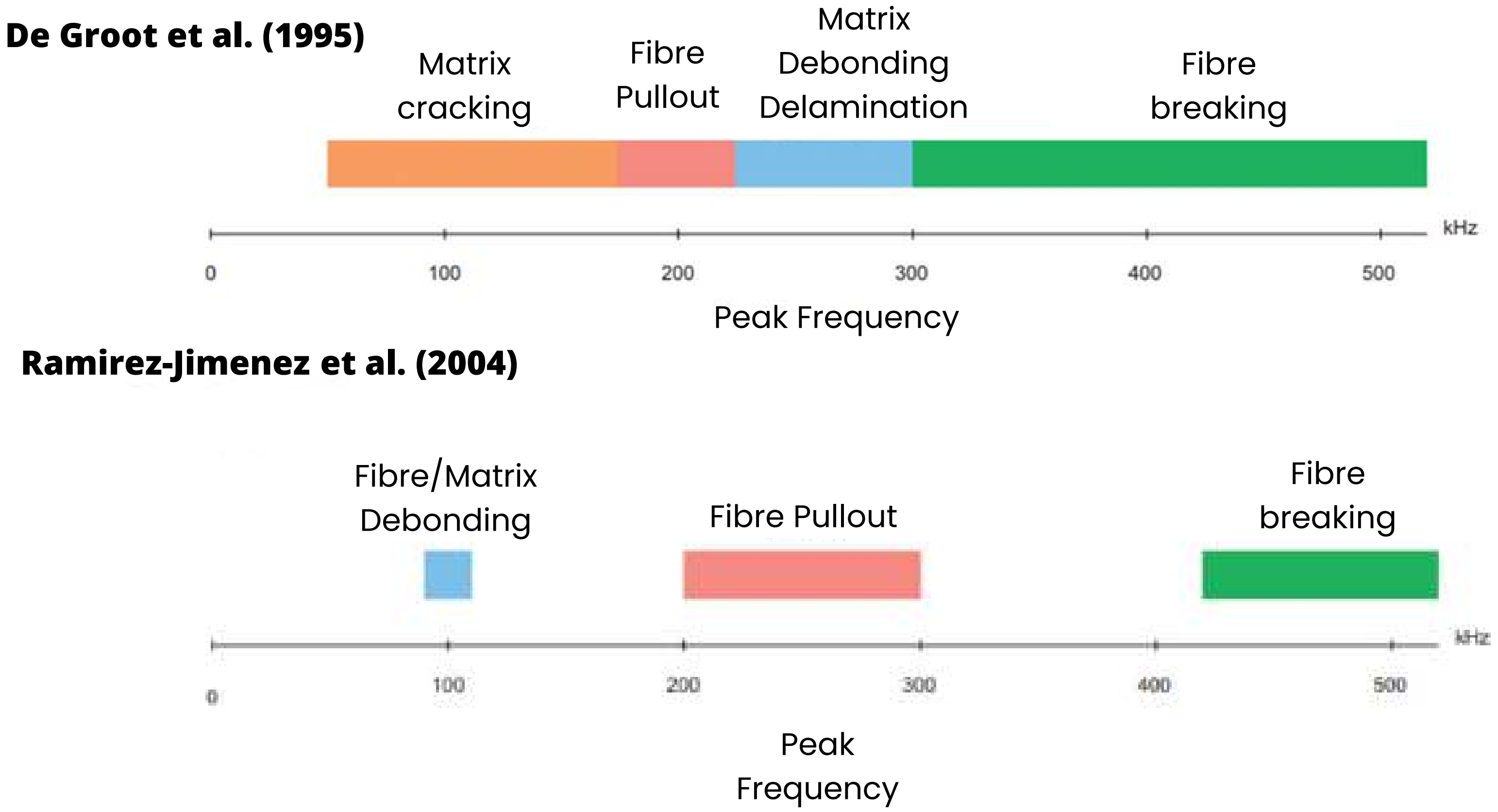

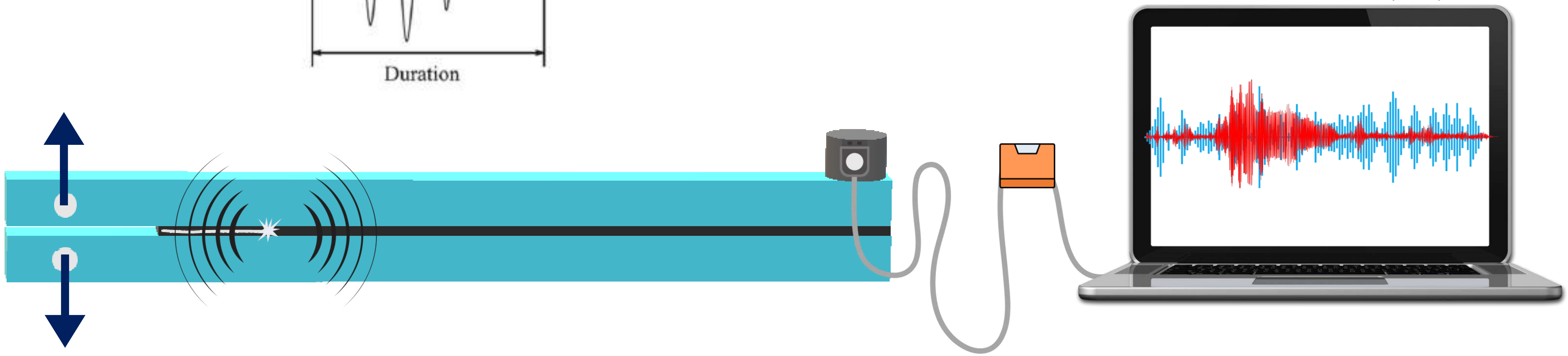

Tailored adhesively bonded joints

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Tailoring CFRP layup of the secondary joints can trigger various toughening mechanisms simultaneously, affecting crack propagation paths and, in some cases, delaying crack advancement!

Methodology – experimental test

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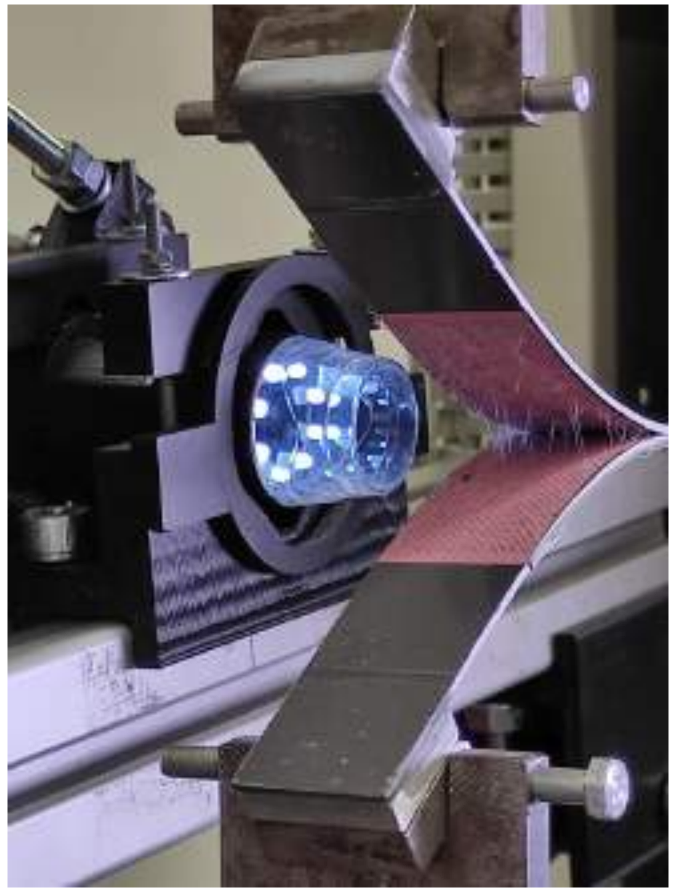
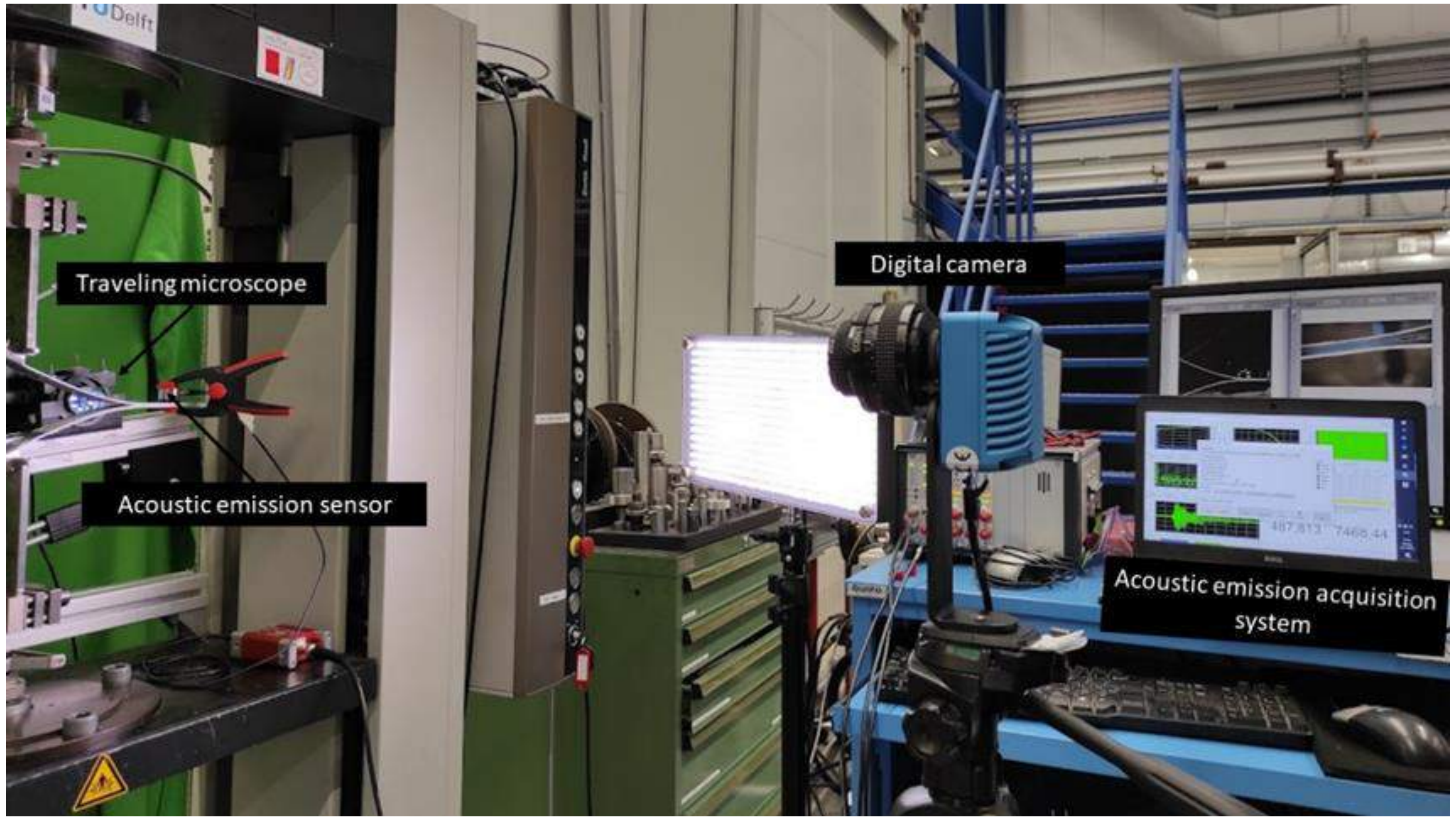


Nomenclature	Stacking sequence
CFRP	$[0]_{16}$
AF-0	$[0]_8$
AF-0/90	$[0/90_2/0]_S$
AF-90/0	$[90/0_2/90]_S$
AF-90/45	$[90/45/-45/0]_S$
AF-90/60	$[90/60/90/-60/0]_S$

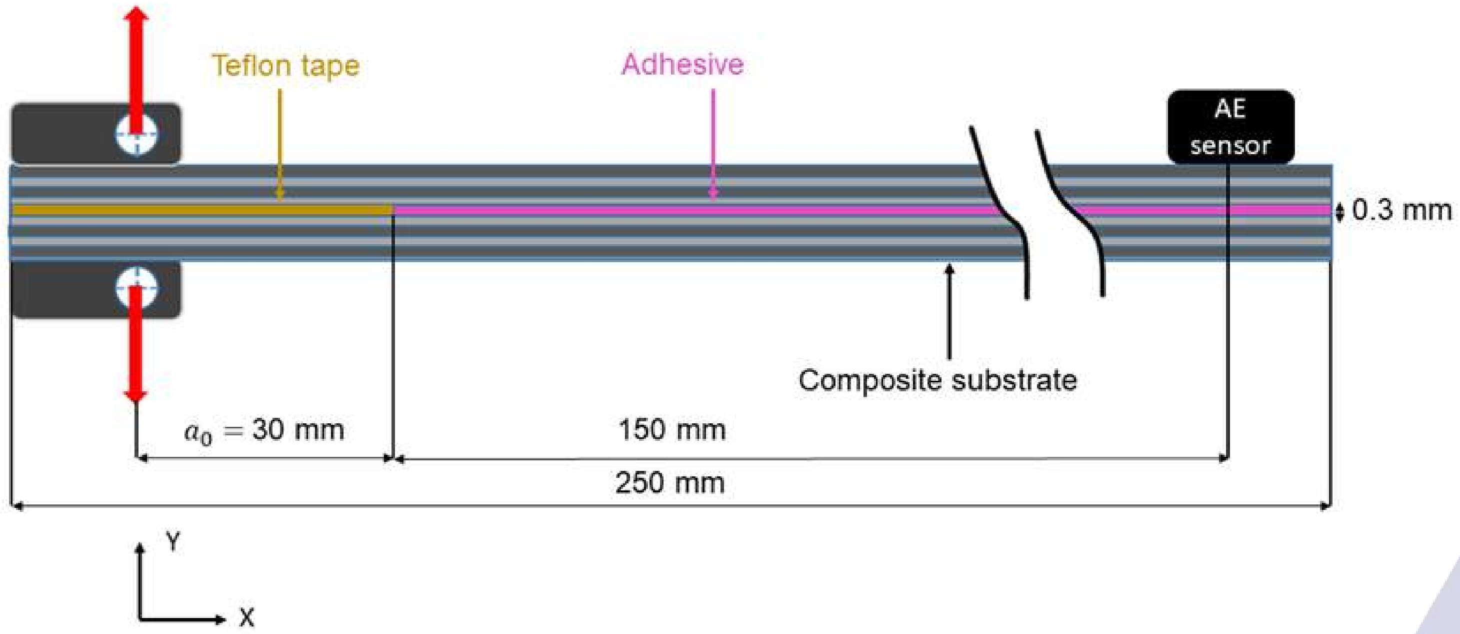
- **Pre-preg HexPly® 8552 – CF UD toughened epoxy resin system**
- **Adhesives: AF 163-2k**

Methodology – experimental test



Acoustic emission acquisition system:

- Two-channel Vallen ASMY-6 acquisition unit
- One Vallen VS150-M piezoelectric resonant transducer
- 34 dB Vallen AEP5 preamplifier
- Vallen AE-Suite Software R2017.0504.1



AE raw data and post processing

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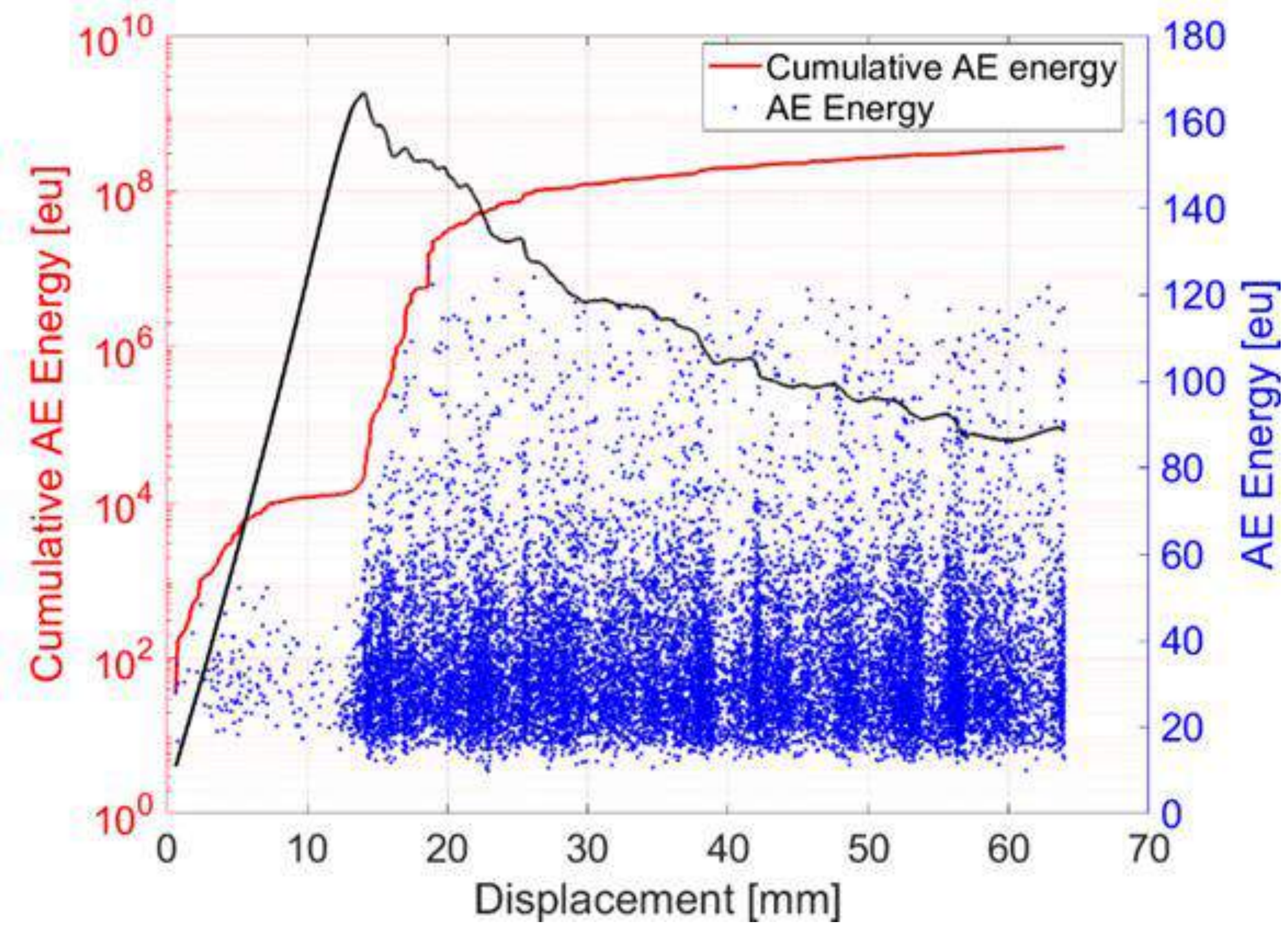
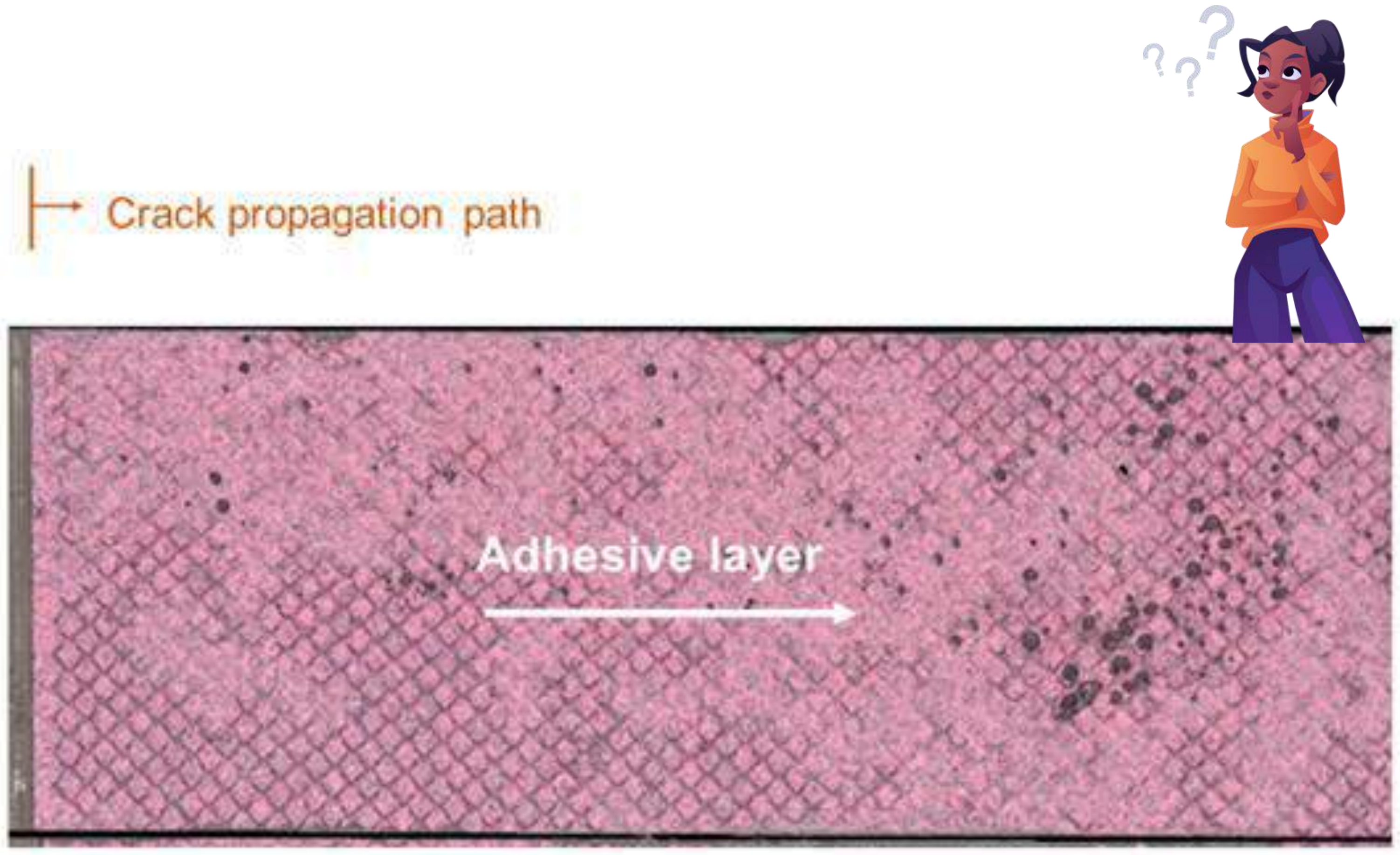


AF-0 – around 30000 waveforms



AE raw data and post processing

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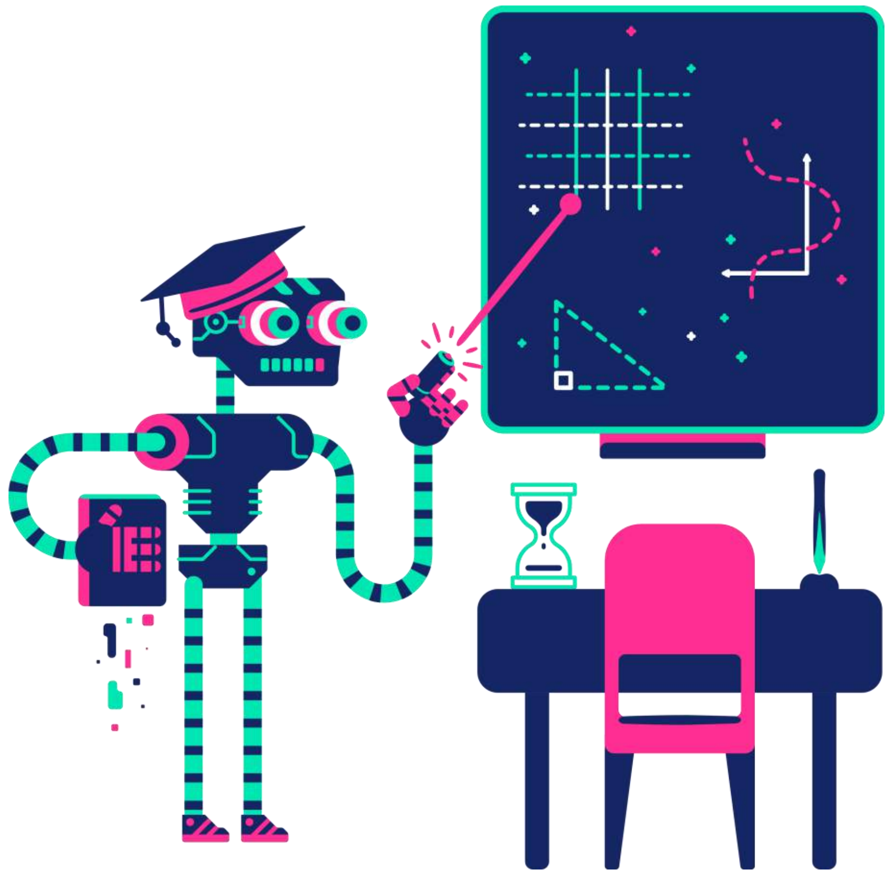
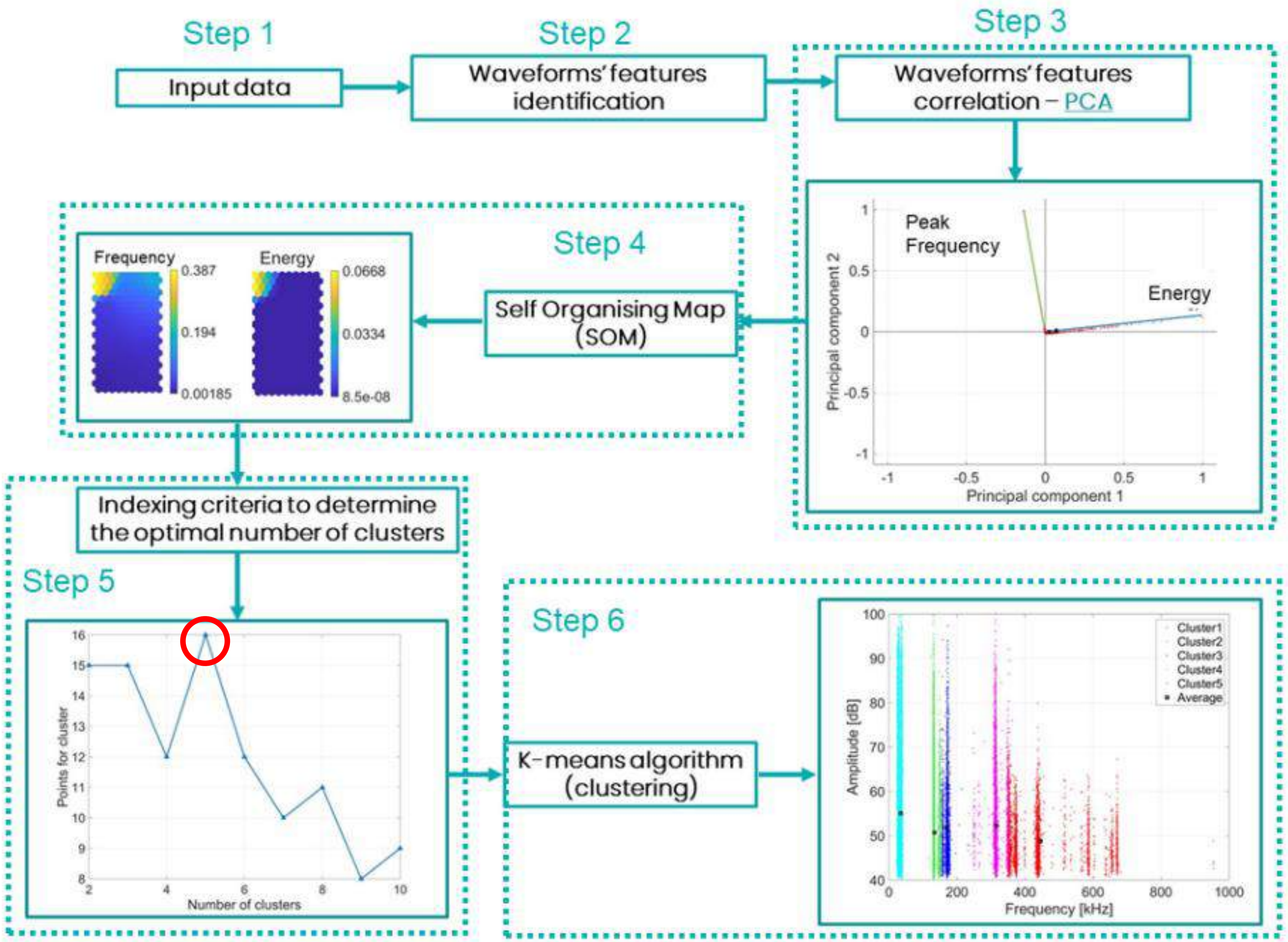
Unsupervised Artificial Neural Network





AE clustering results and physical interpretation

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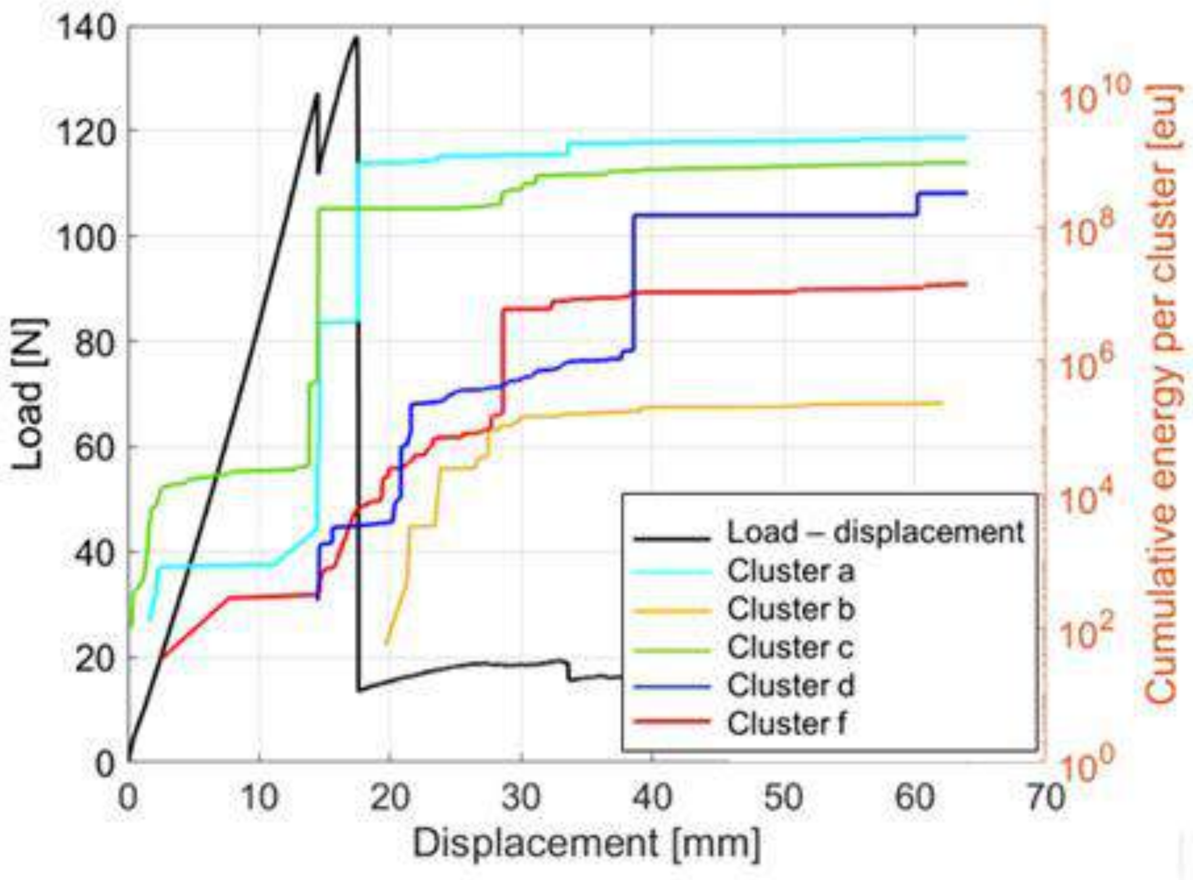
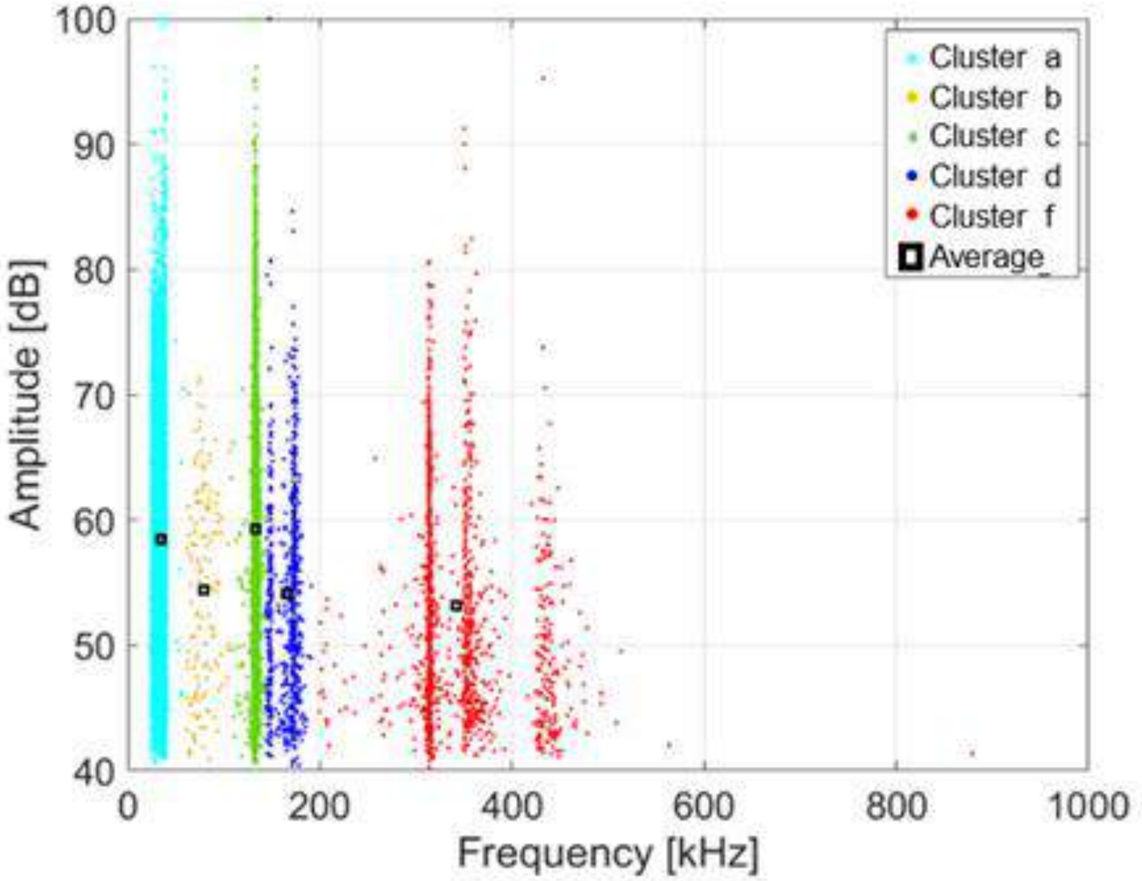
AF-0 /90





Cluster	Colour	Average frequency
a	Light blue	35 kHz
b	Orange	60 kHz
c	Light green	130 kHz
d	Dark blue	170 kHz
e	Pink	255 kHz
f	Red	Higher than 300 kHz
g	Dark green	120 kHz

Fixed number of optimal clusters: 5

AE clustering results and physical interpretation

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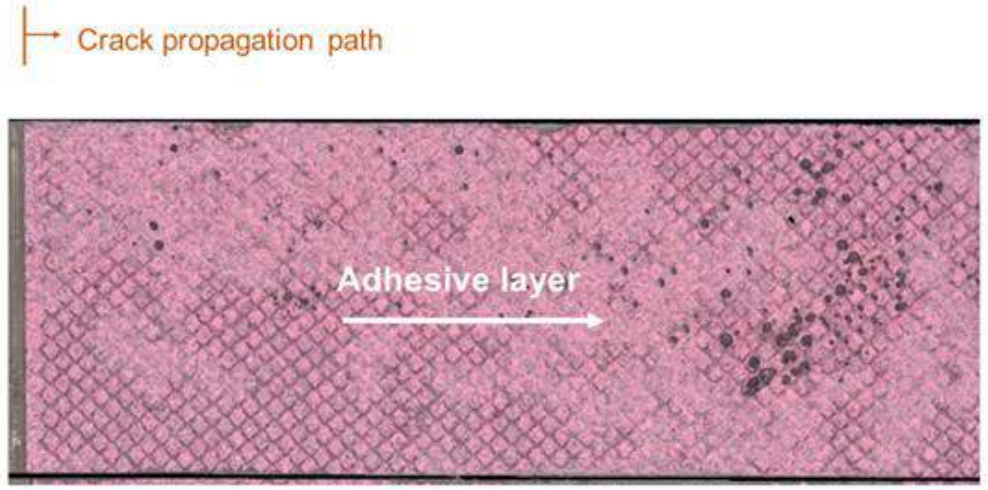
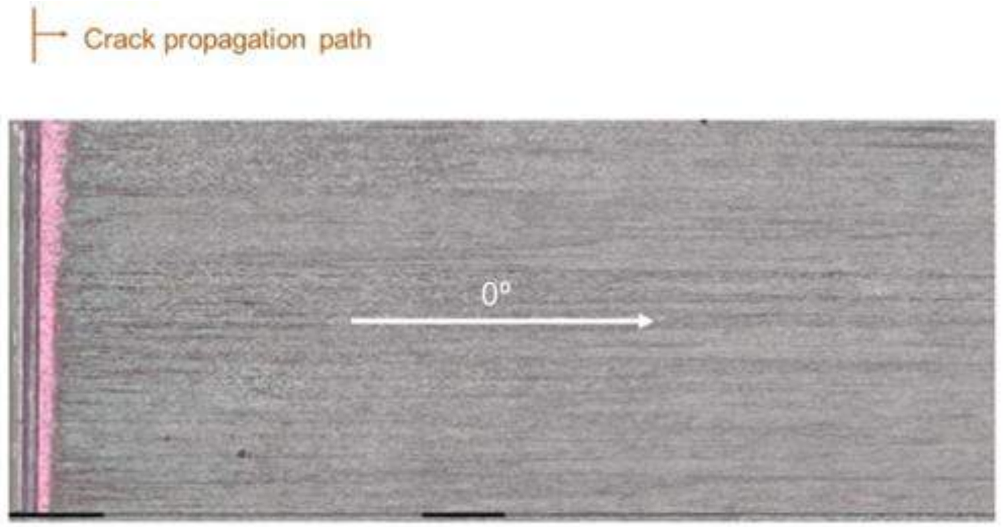
CFRP

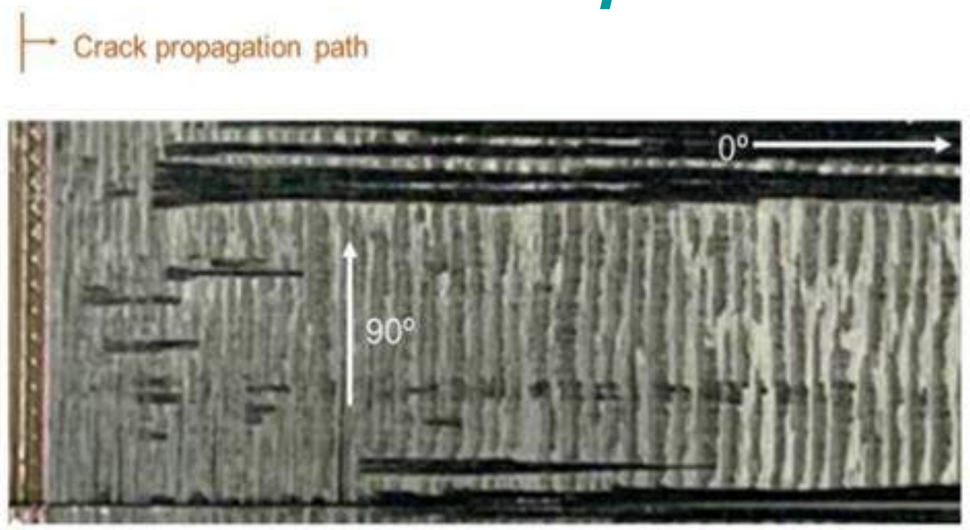
AF-0



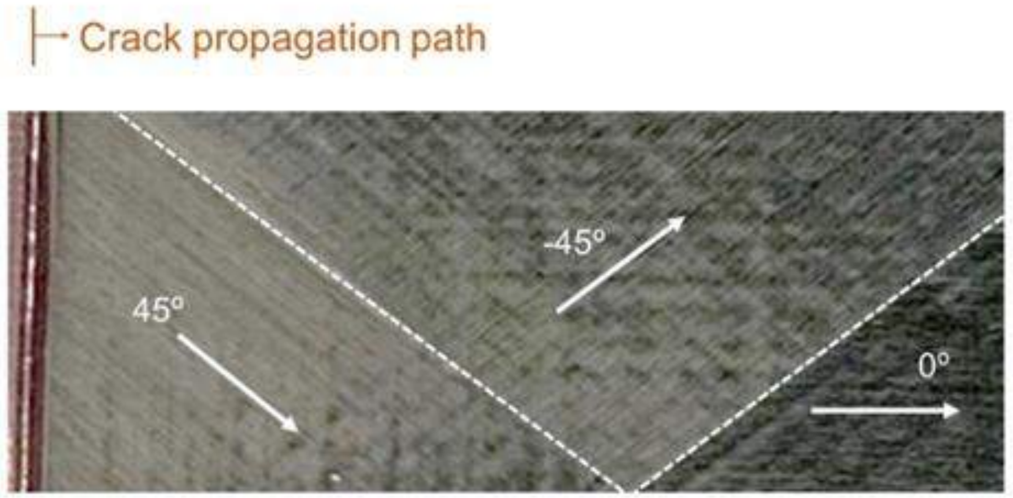
AF-0 /90



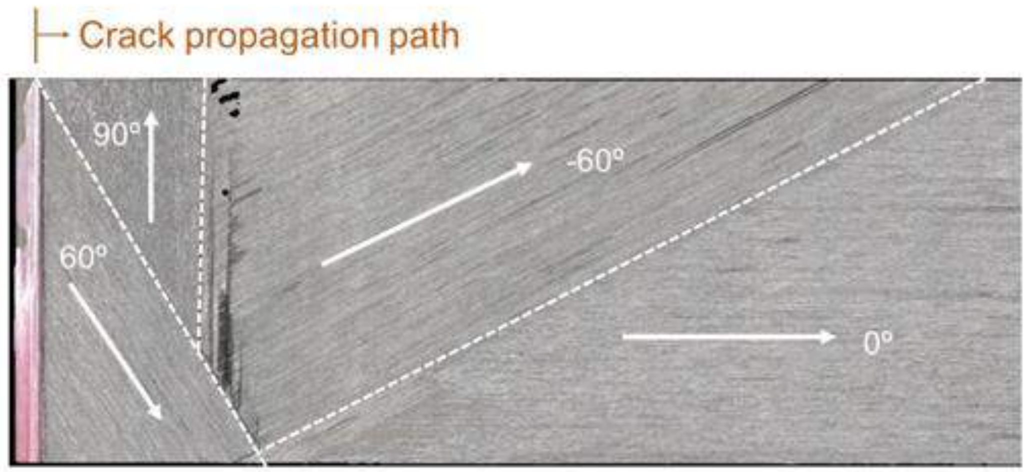
AF - 90/0



AF - 90/45



AF - 90/60



- Cohesive failure;
- Delamination;
- Fibre breaking;
- Fibre pull-out;
- Matrix cracking;
- Matrix/fibre debonding.

V

AE clustering results and physical interpretation

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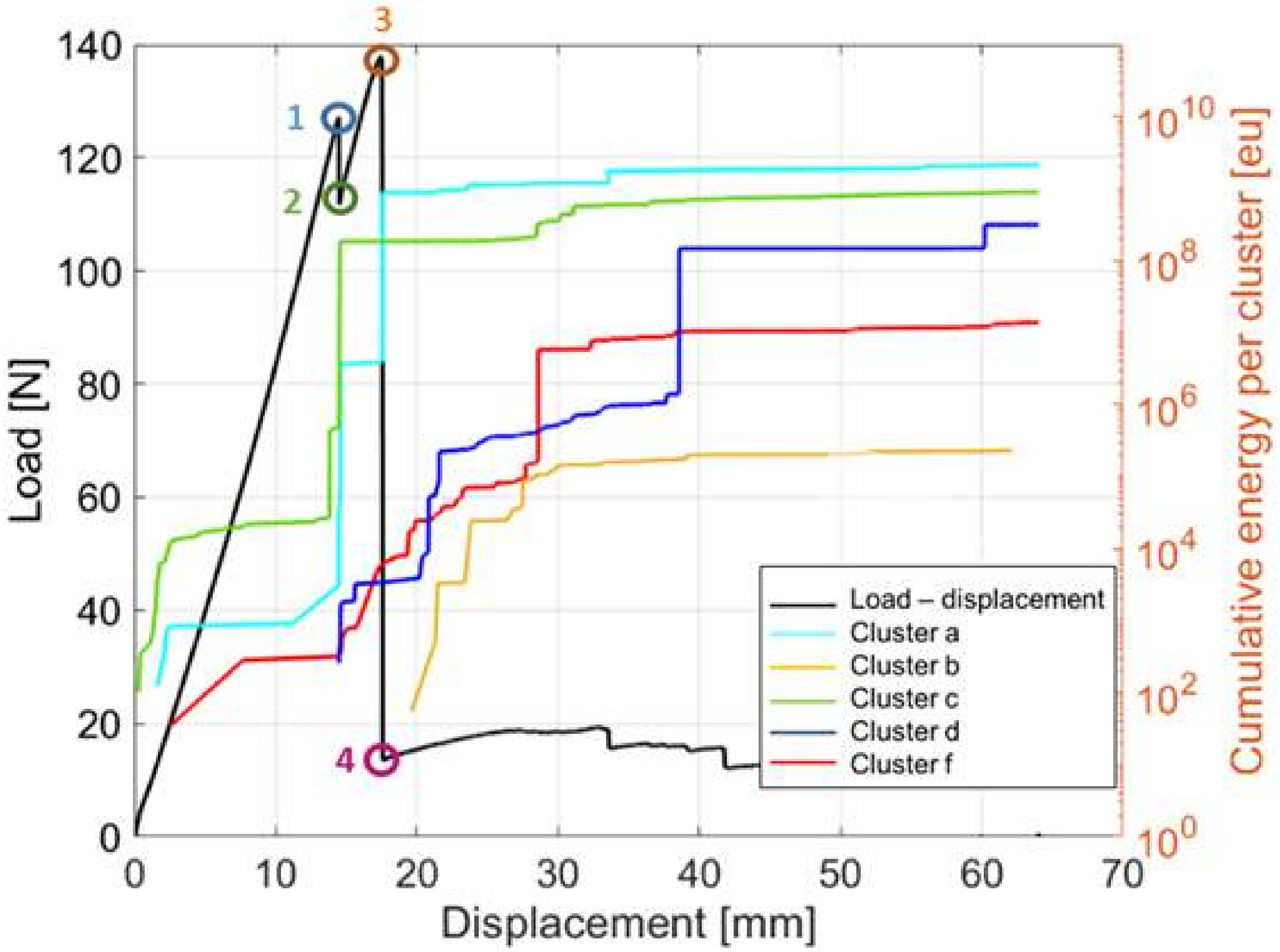
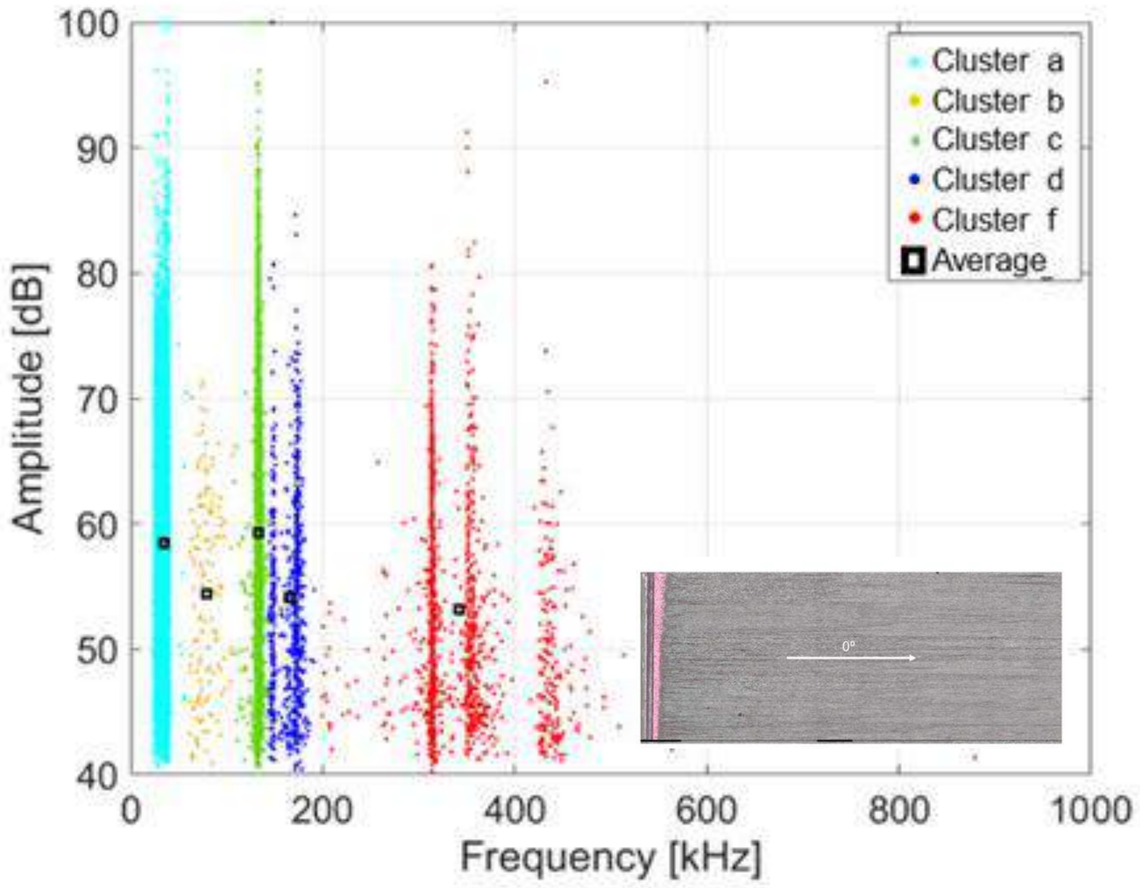
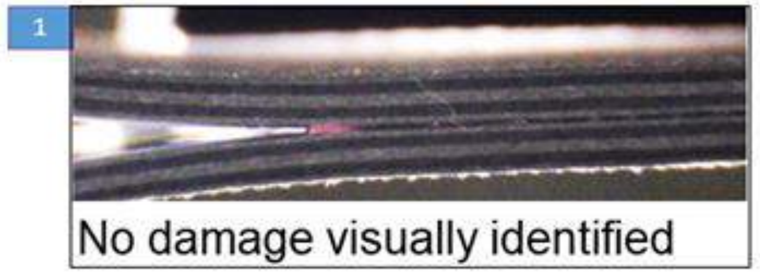
AF-0 /90







AE clustering results and physical interpretation

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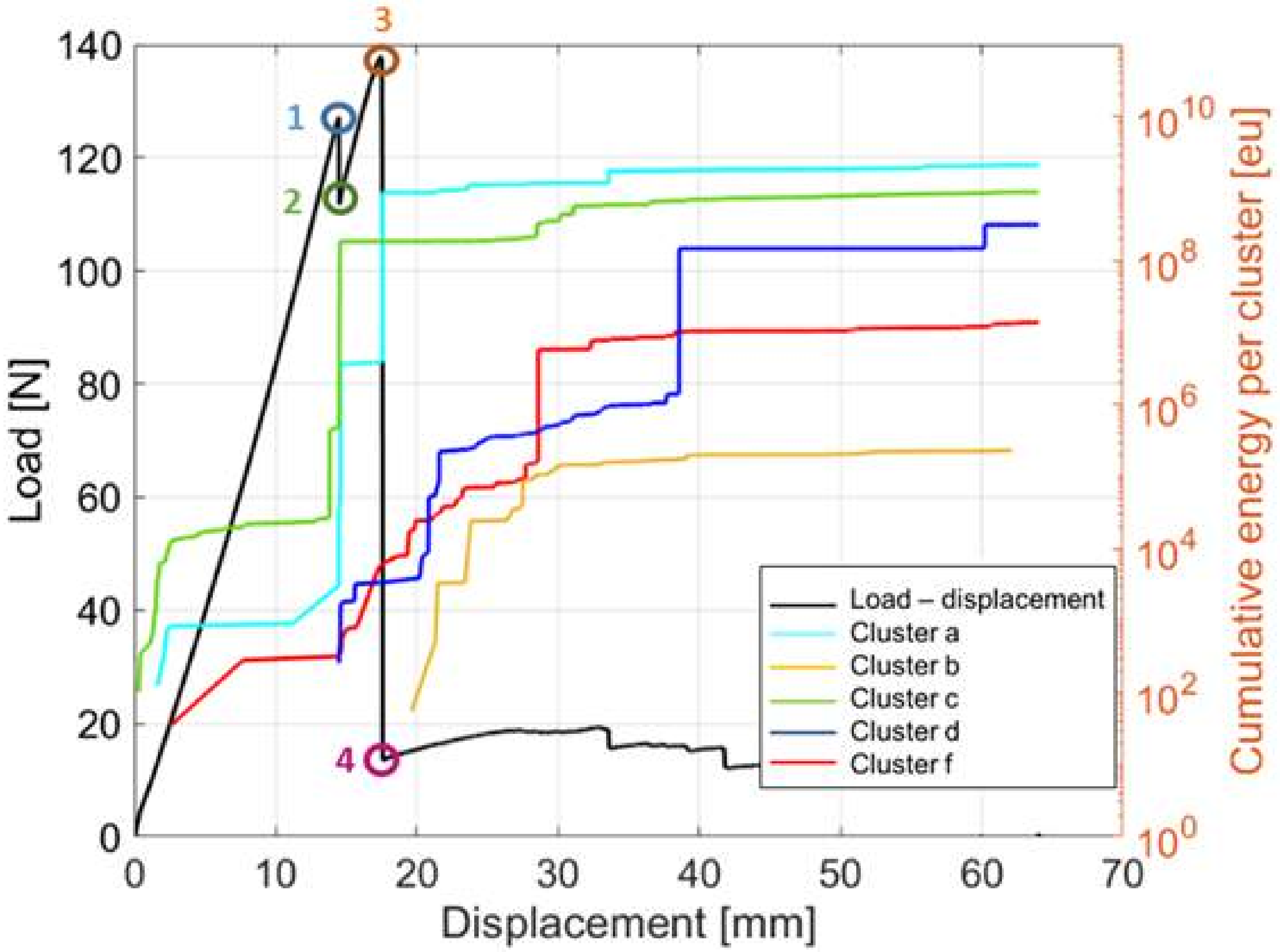
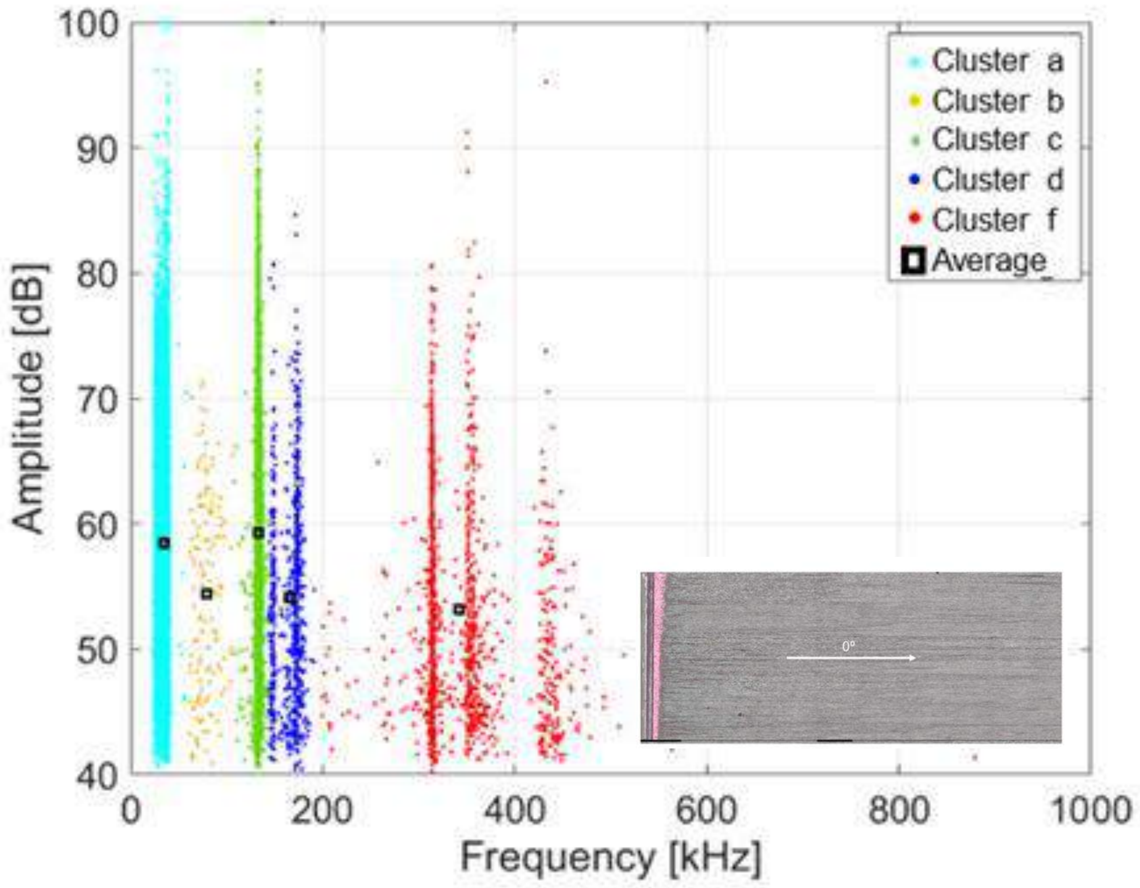
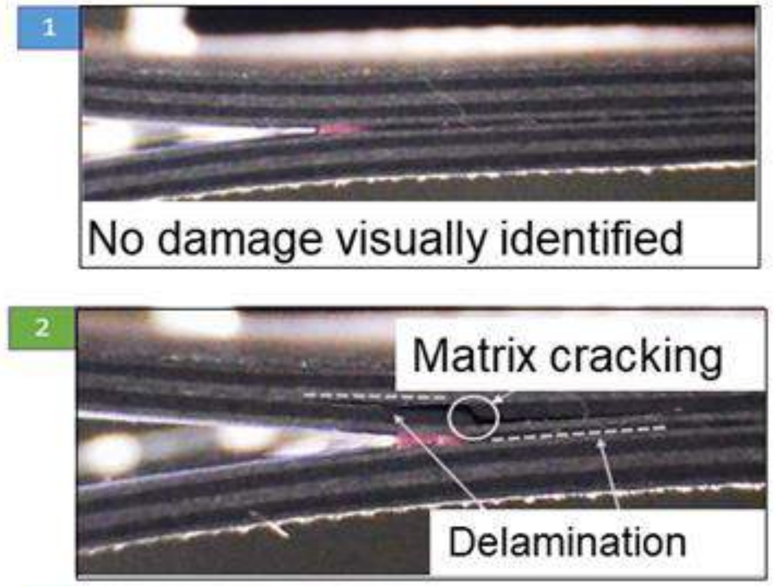
AF-0 /90



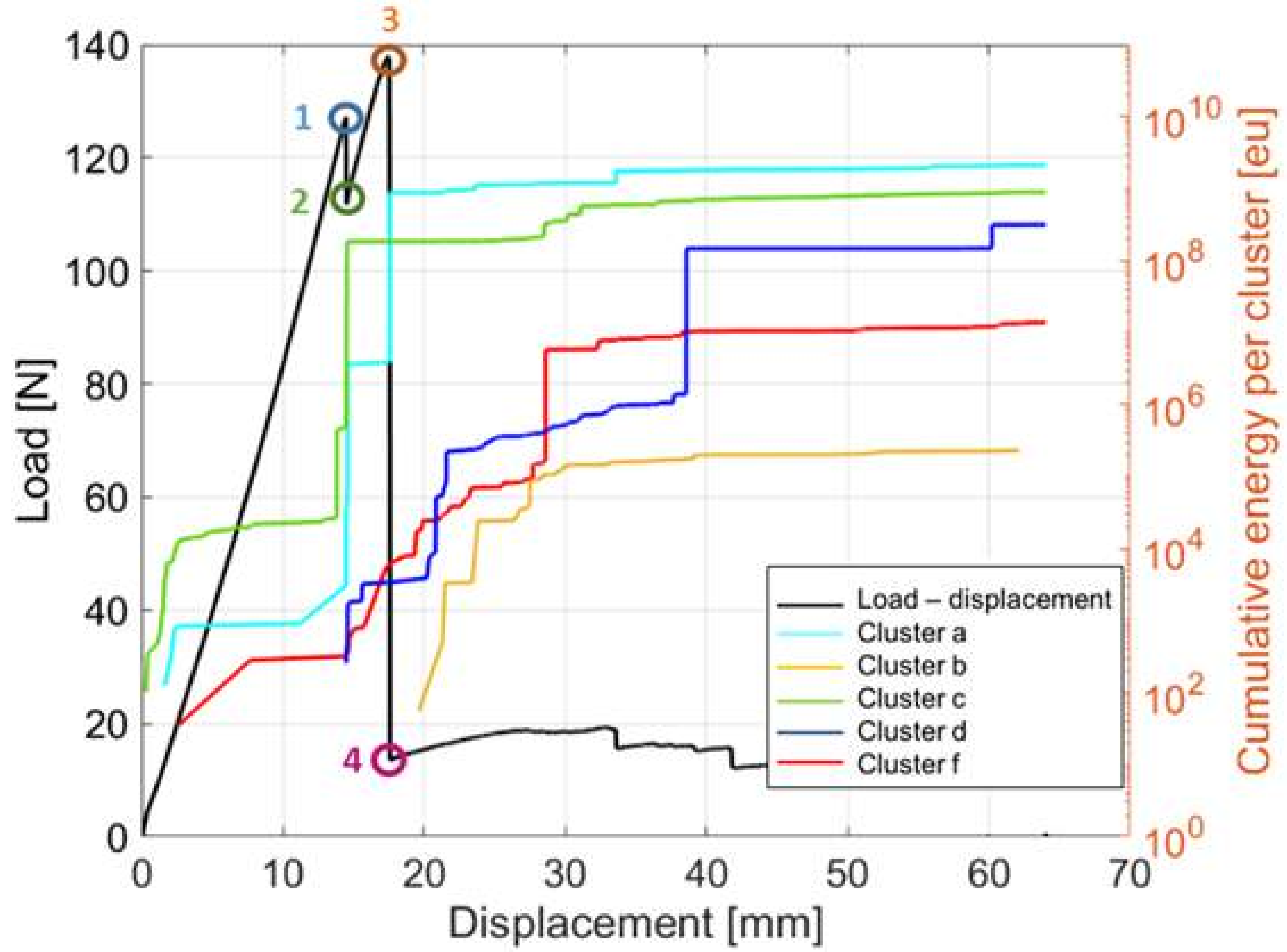


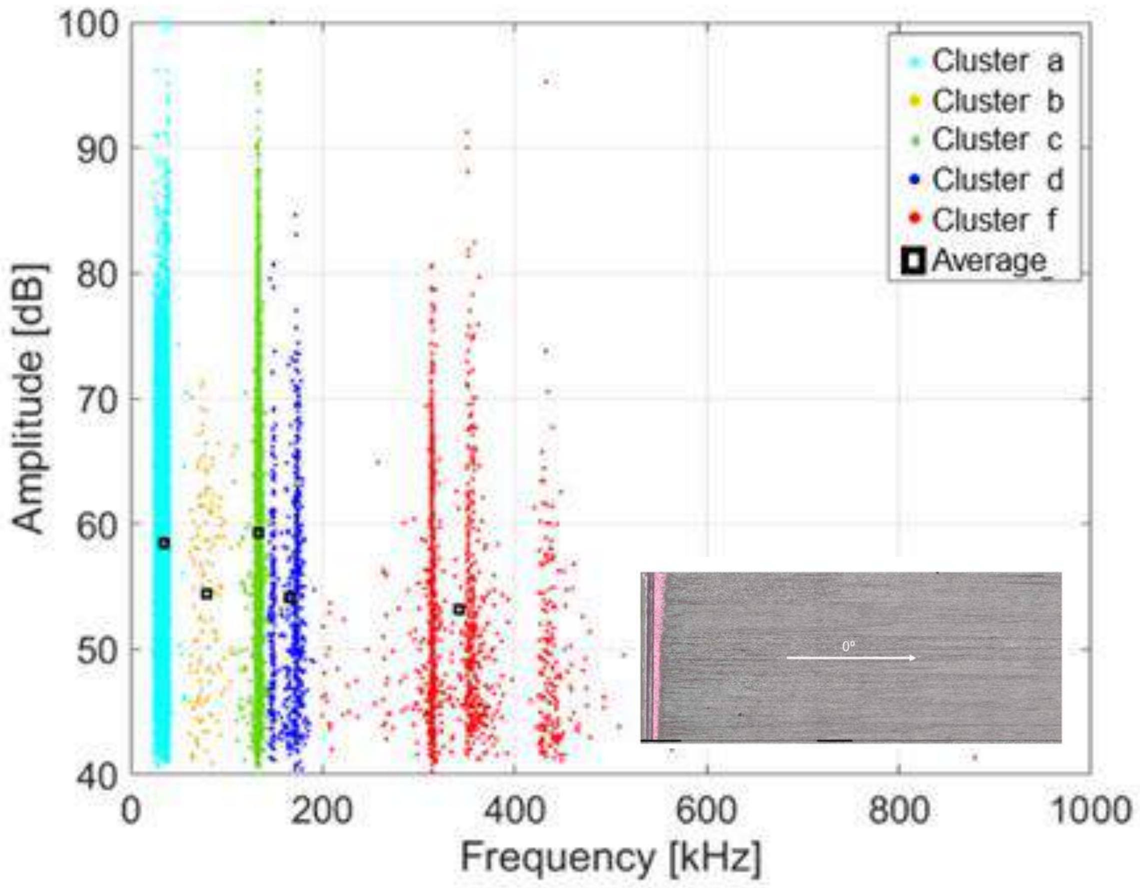


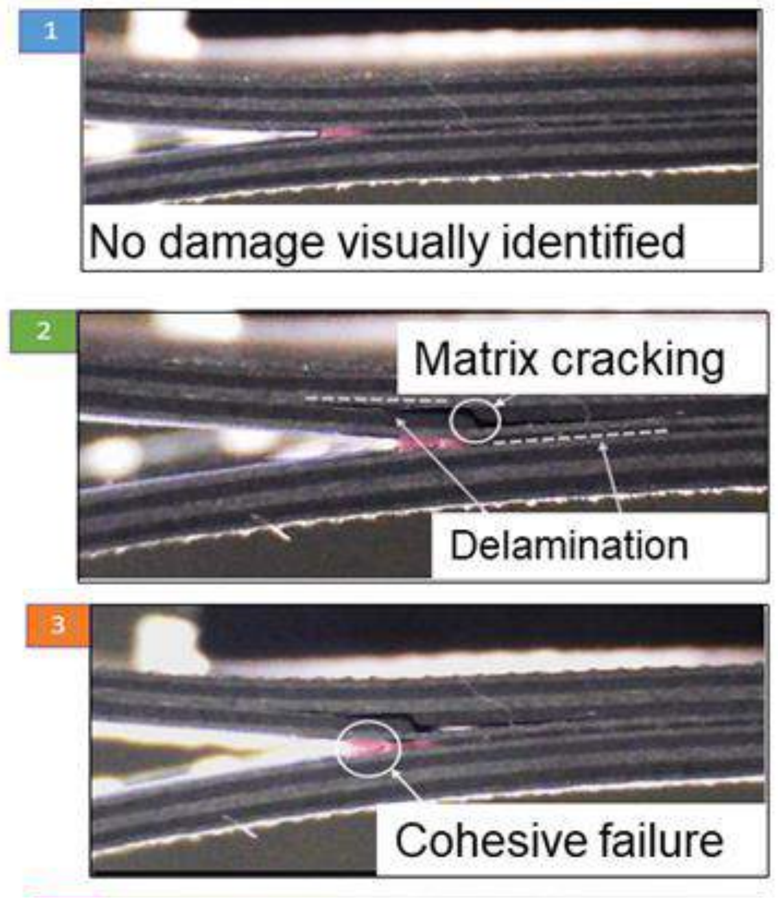
AE clustering results and physical interpretation

CertBond
COST Action CA18120

AF-0 /90



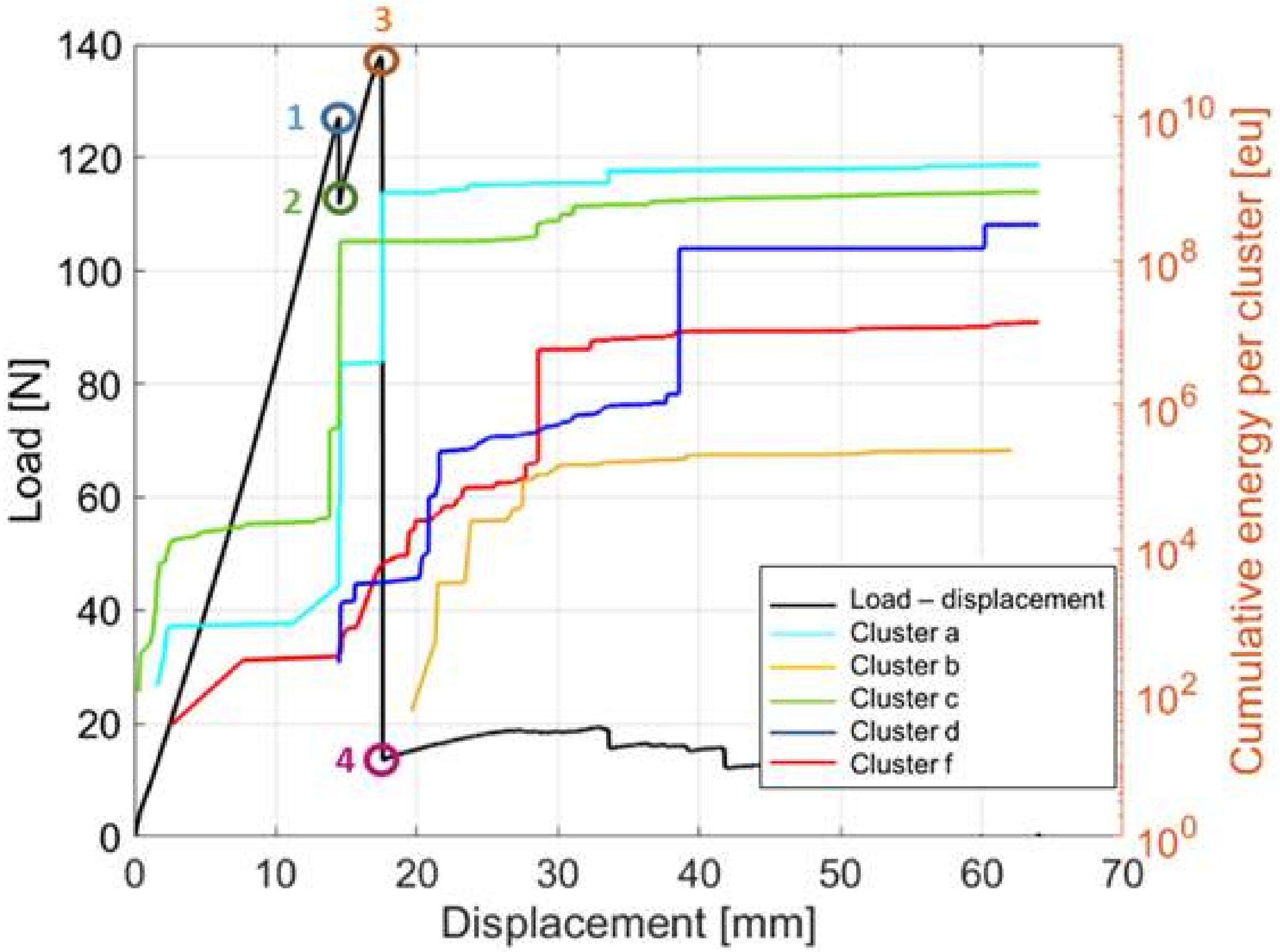


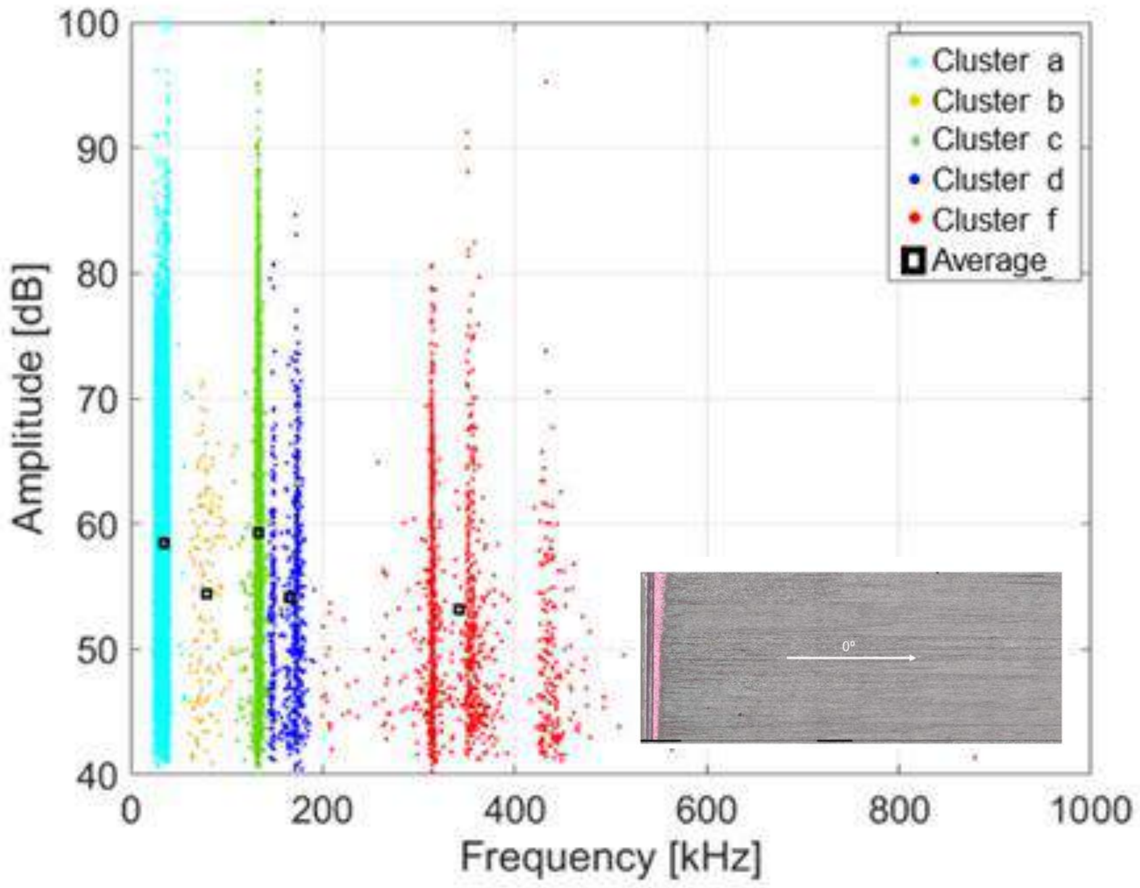


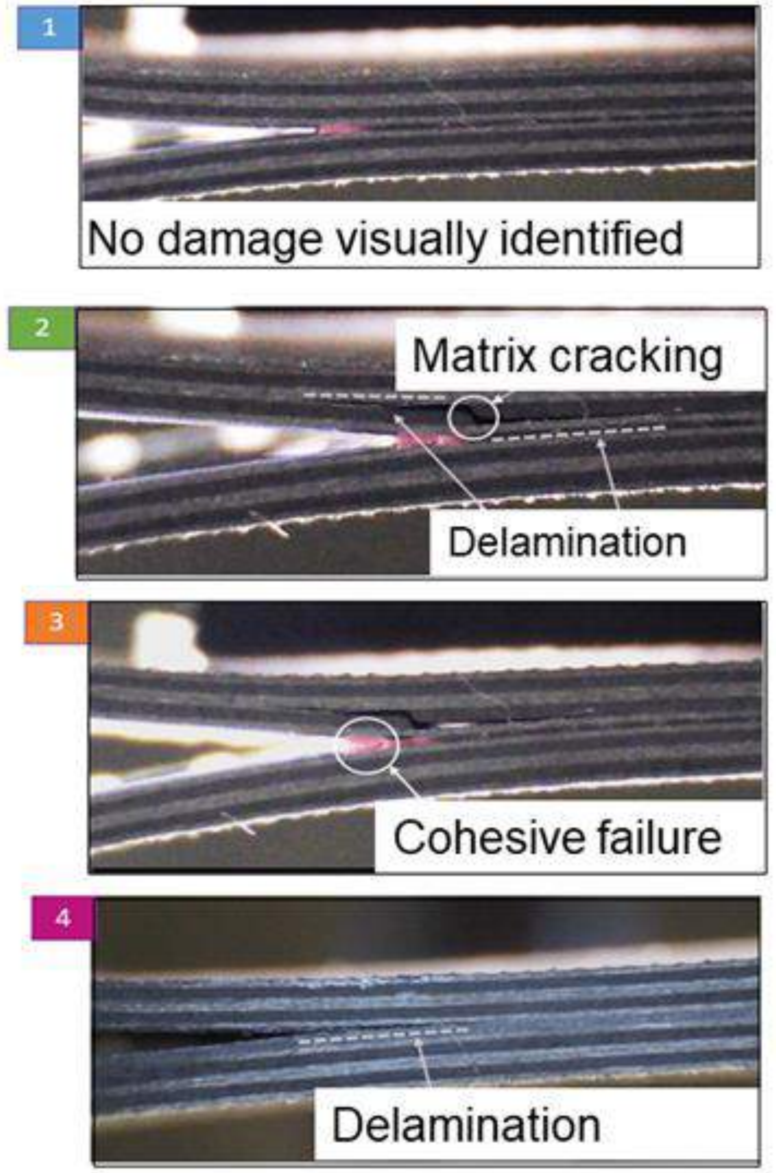
AE clustering results and physical interpretation

CertBond
COST Action CA18120

AF-0 /90



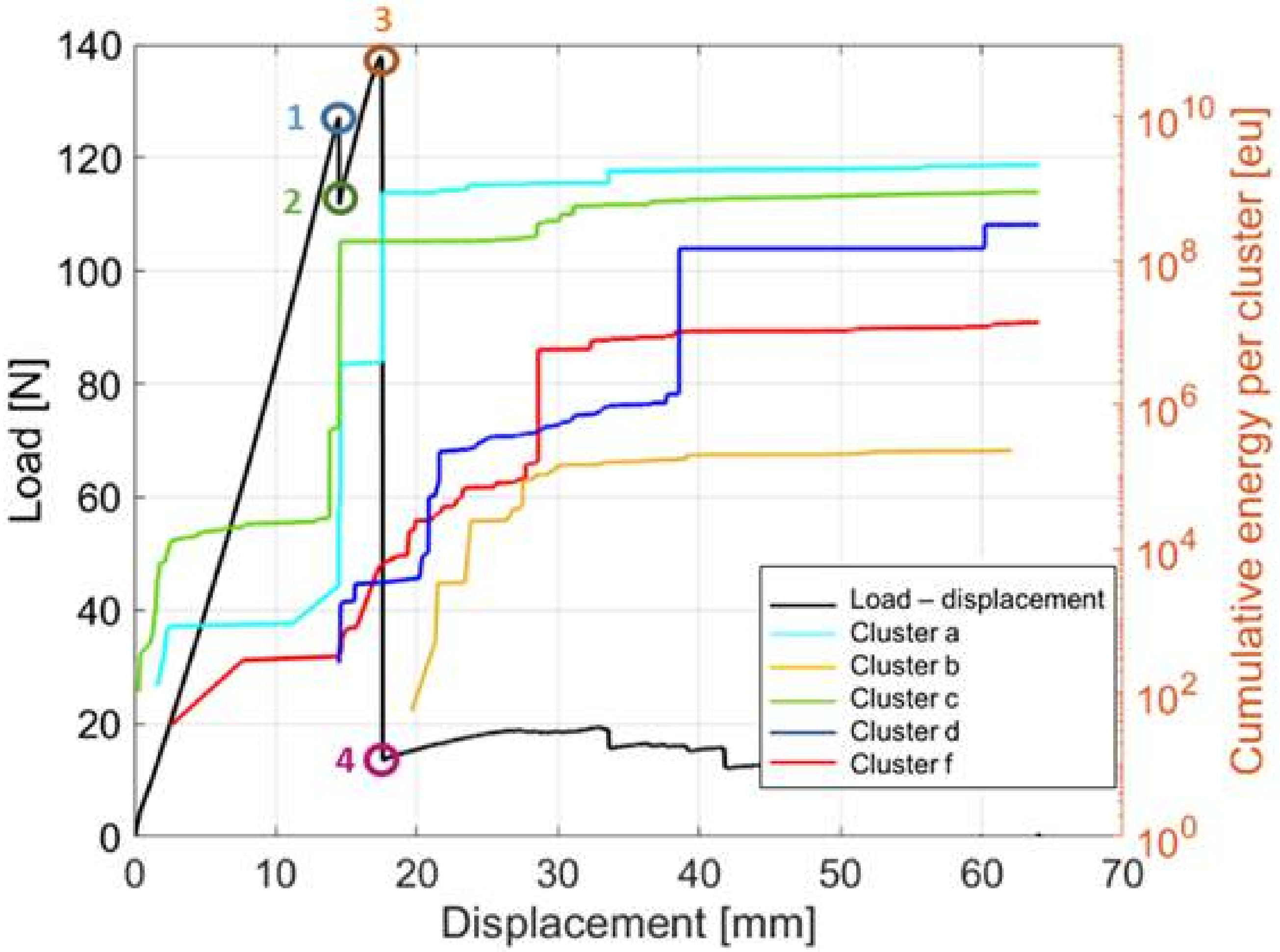


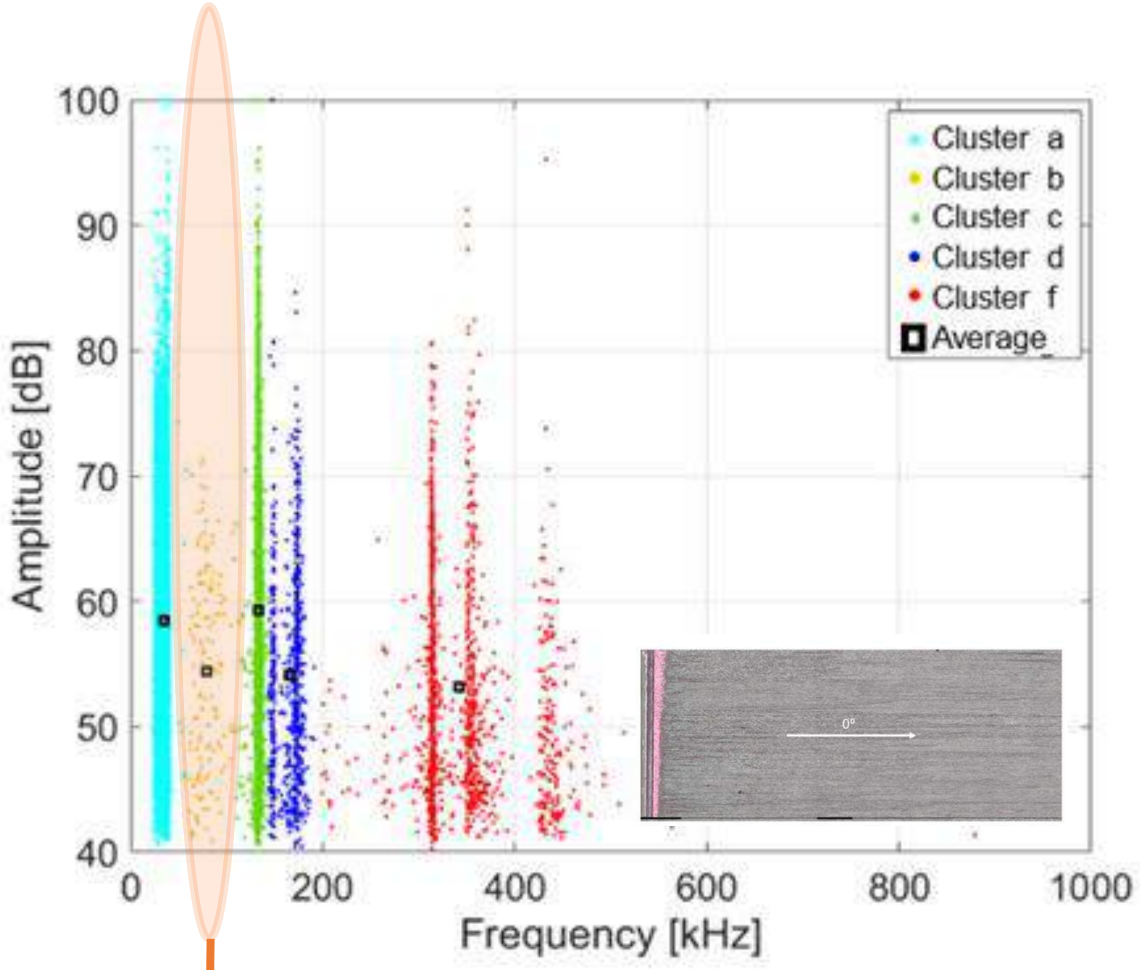


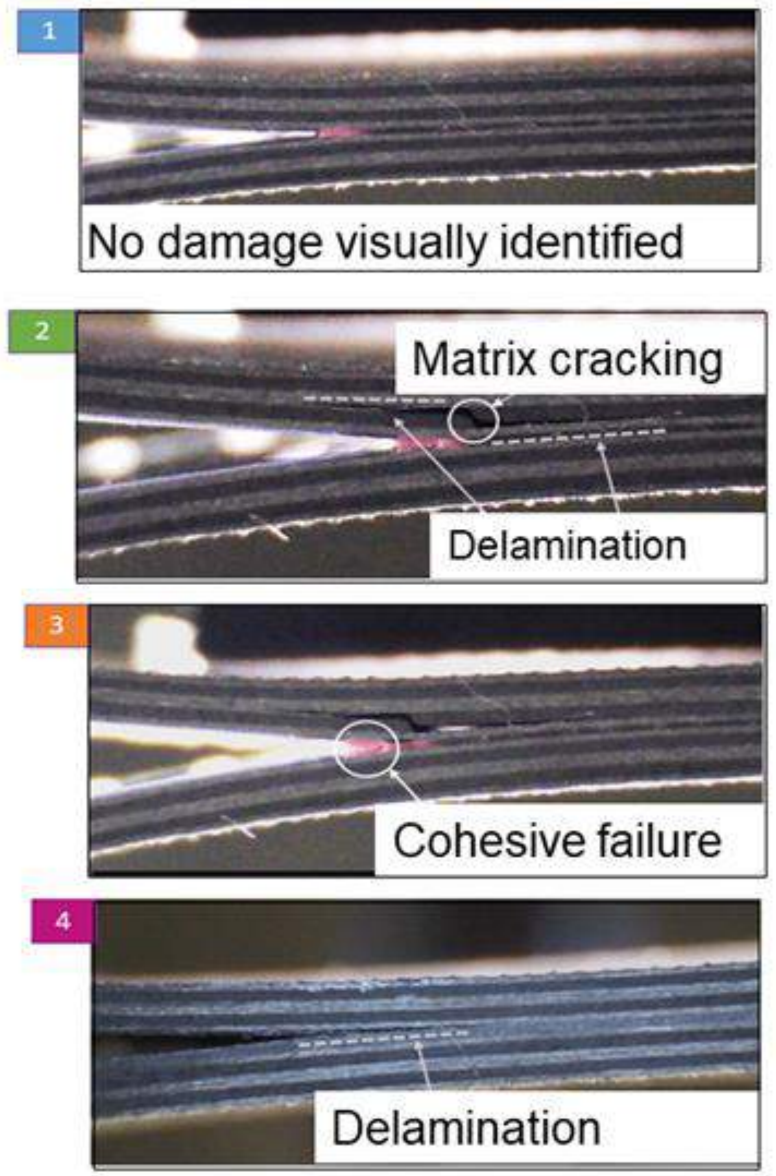
AE clustering results and physical interpretation

CertBond
COST Action CA18120

AF-0 /90







Delamination

AE clustering results and physical interpretation

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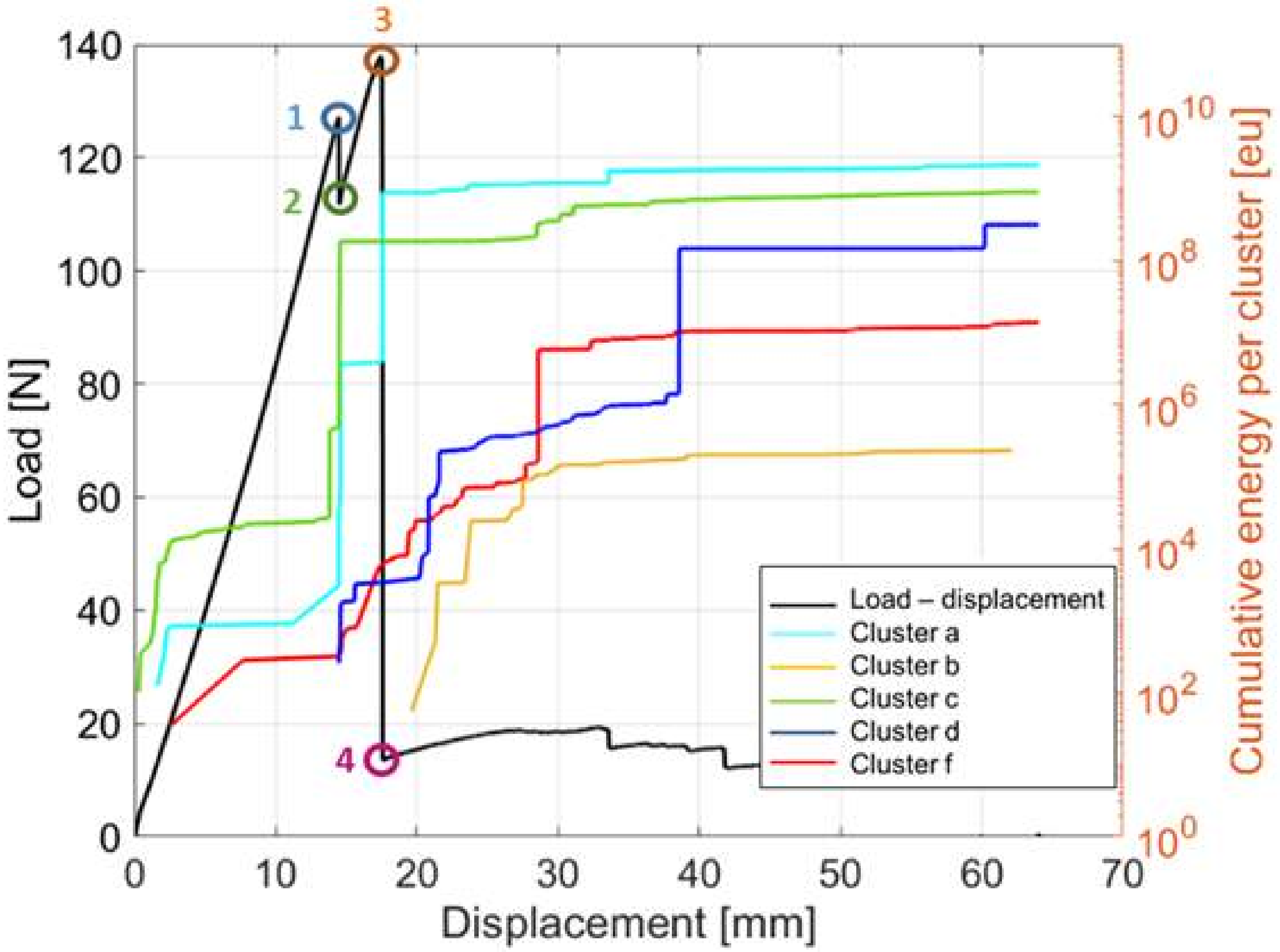
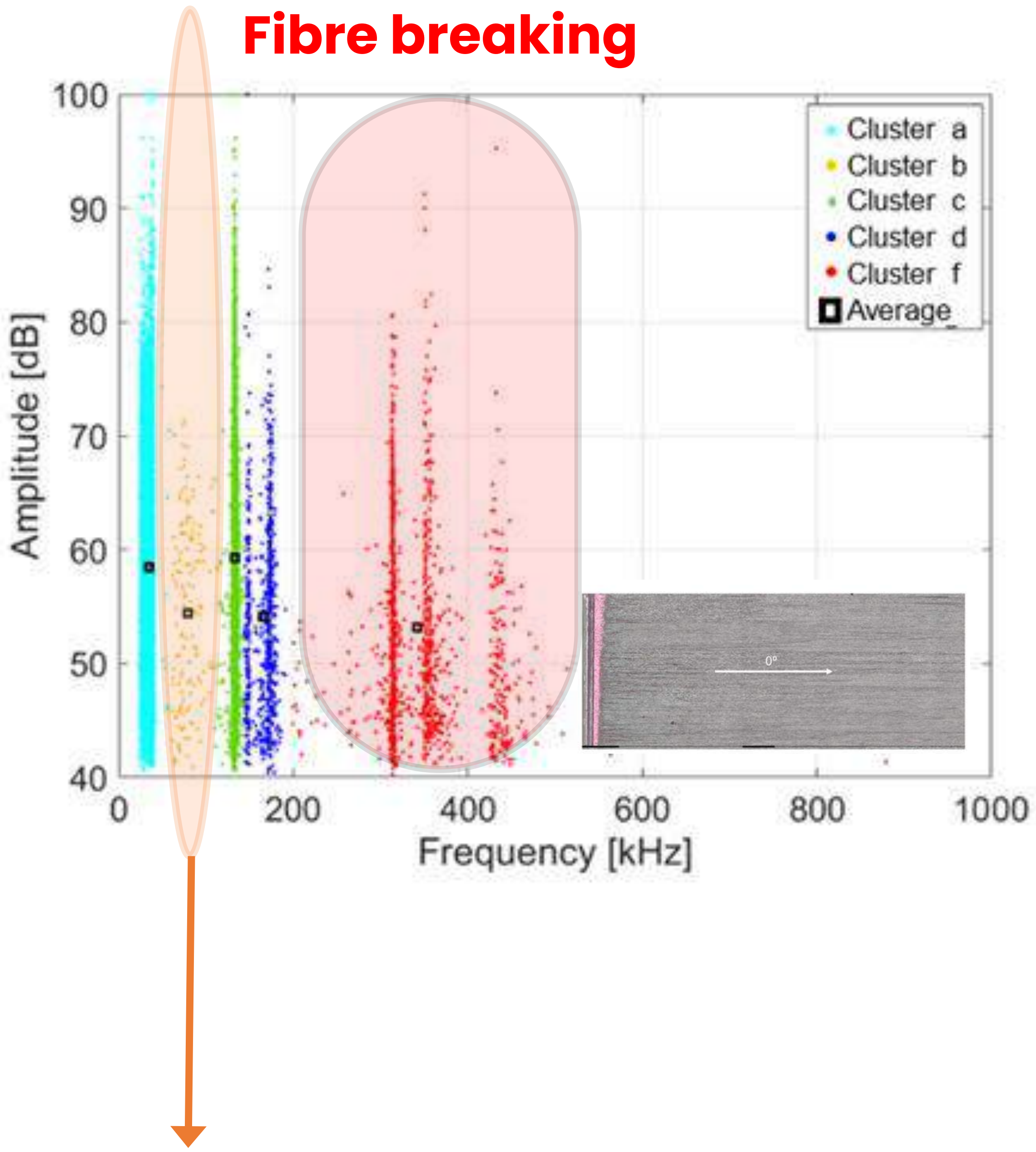
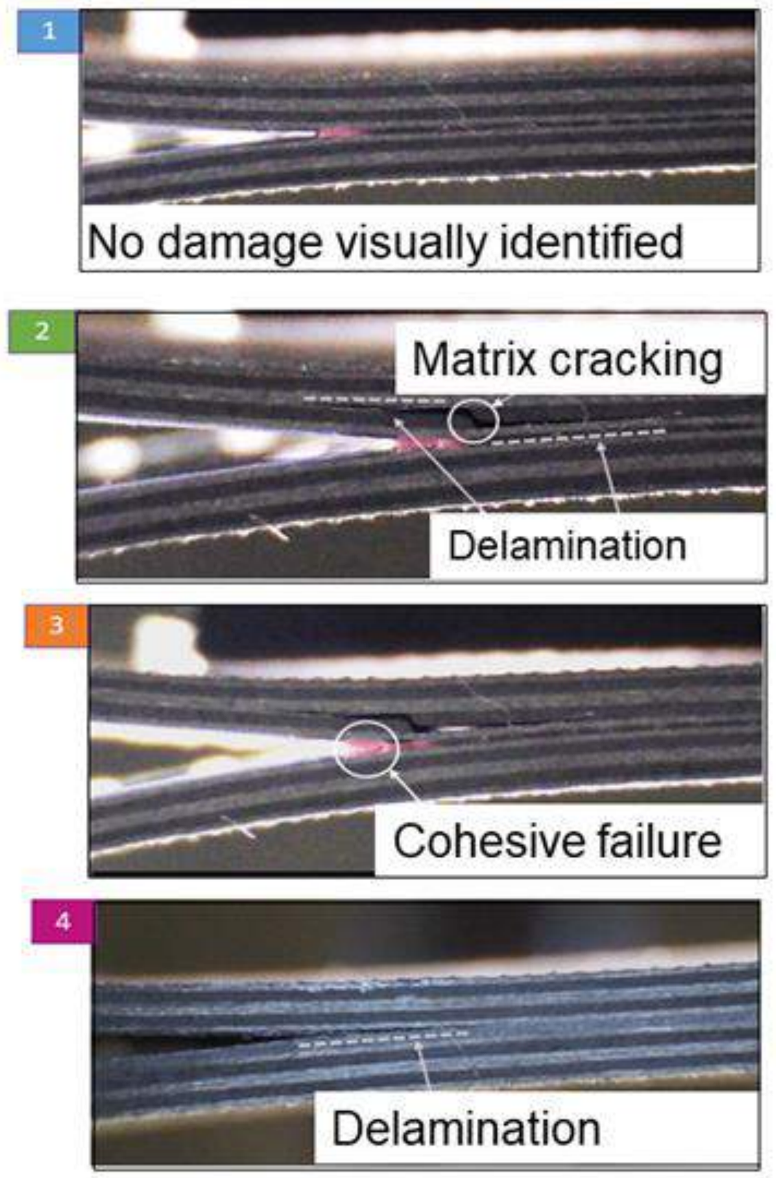
AF-0 /90



Fibre breaking



Delamination



AE clustering results and physical interpretation

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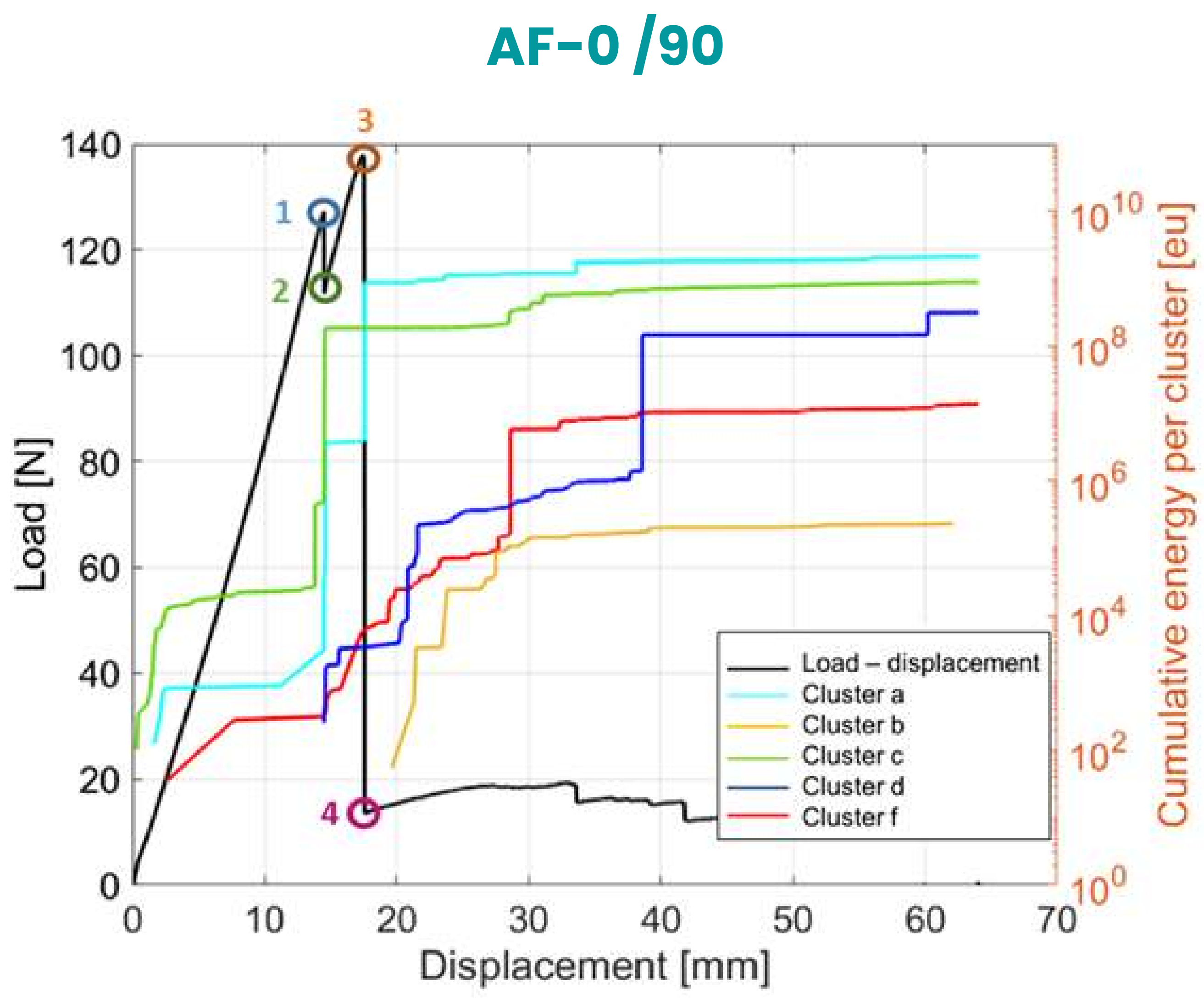
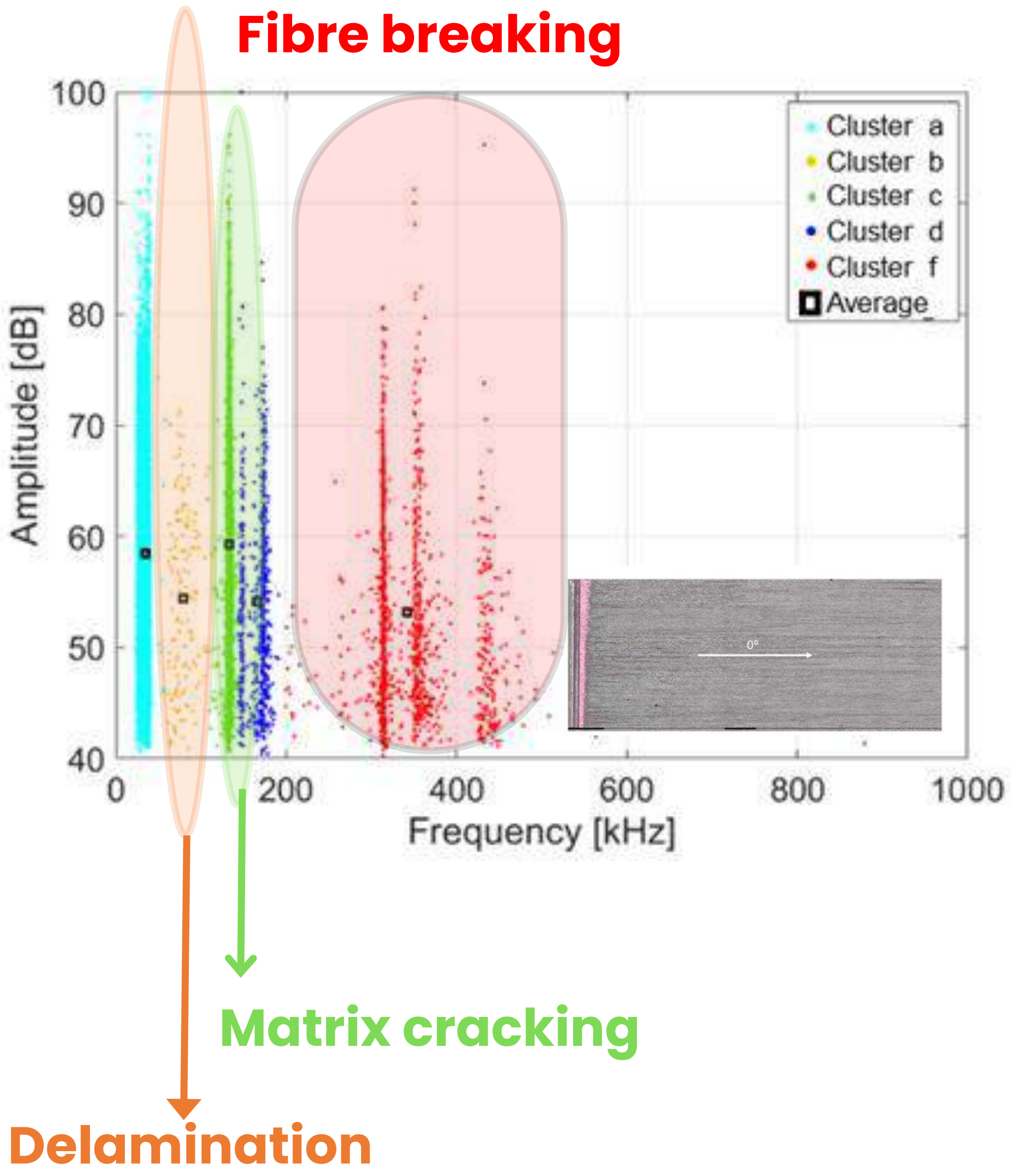
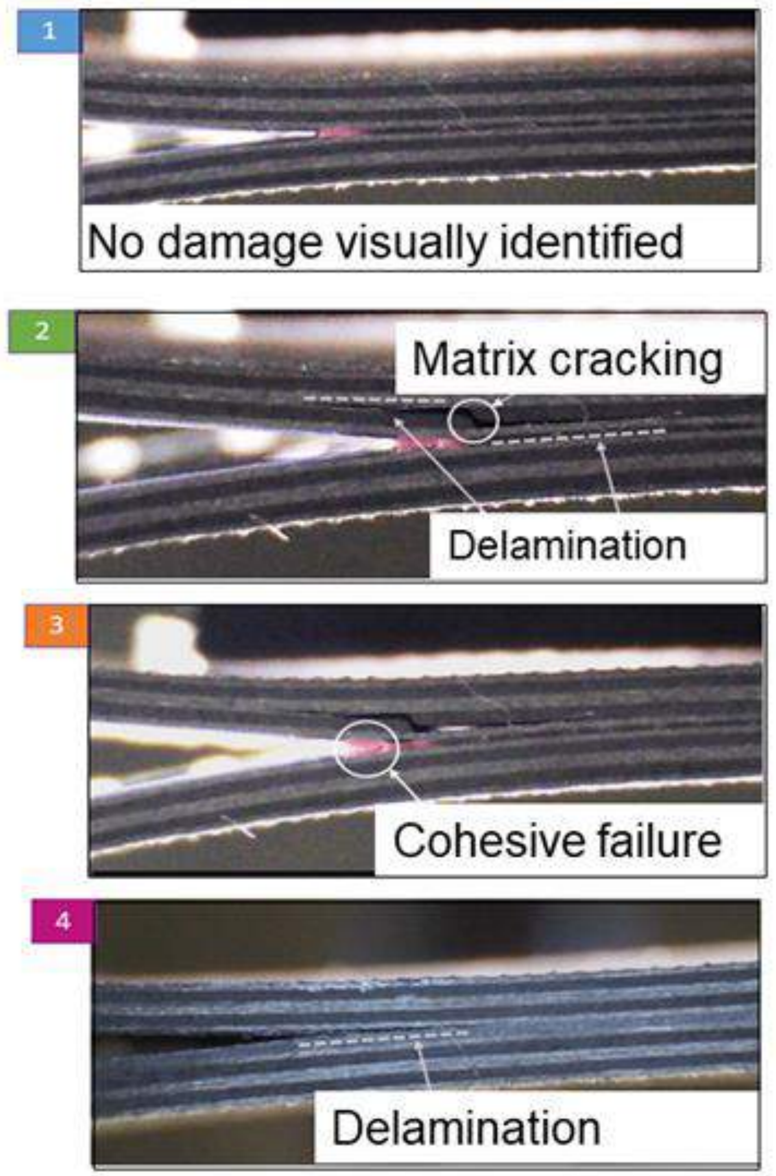
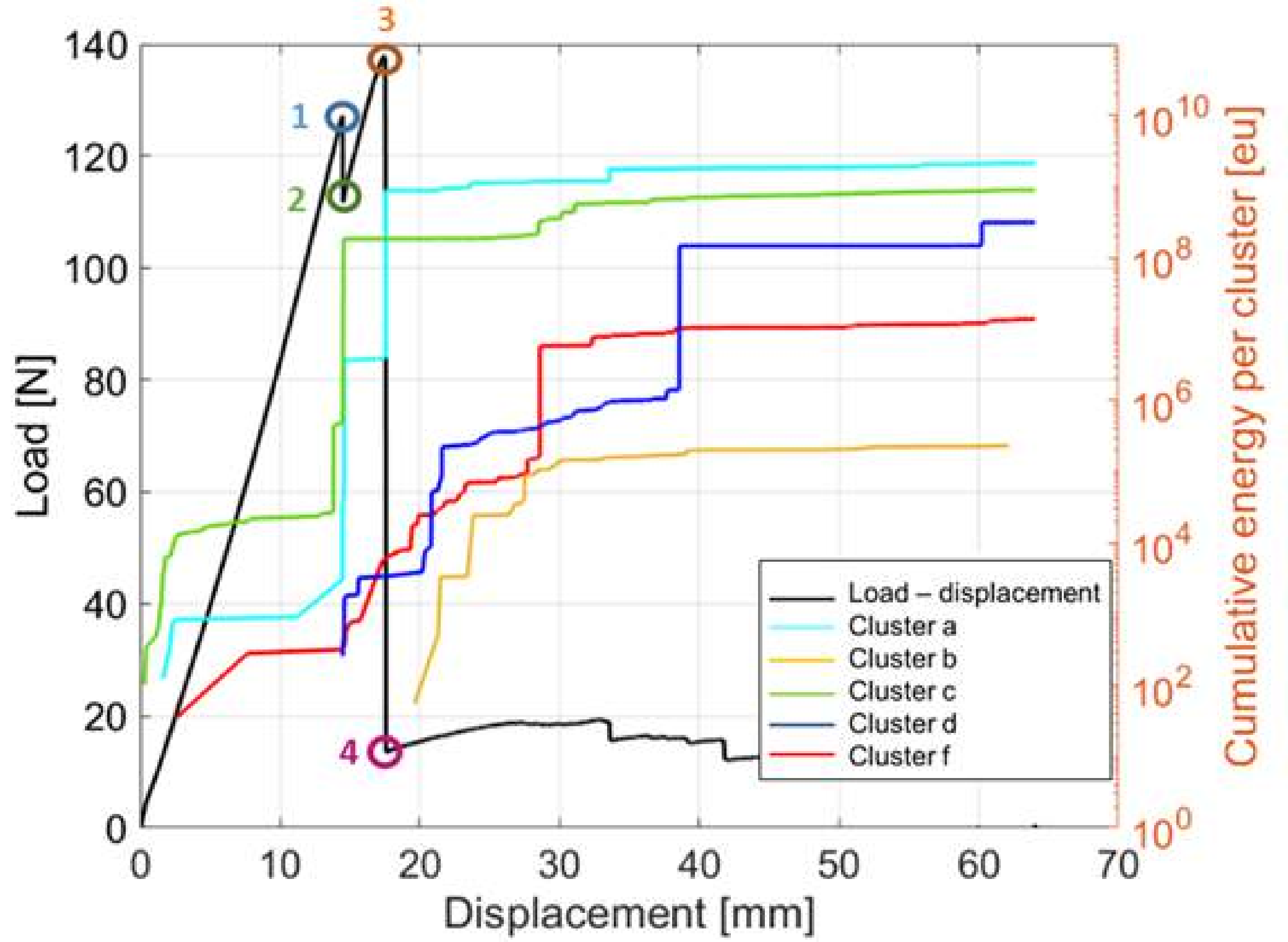


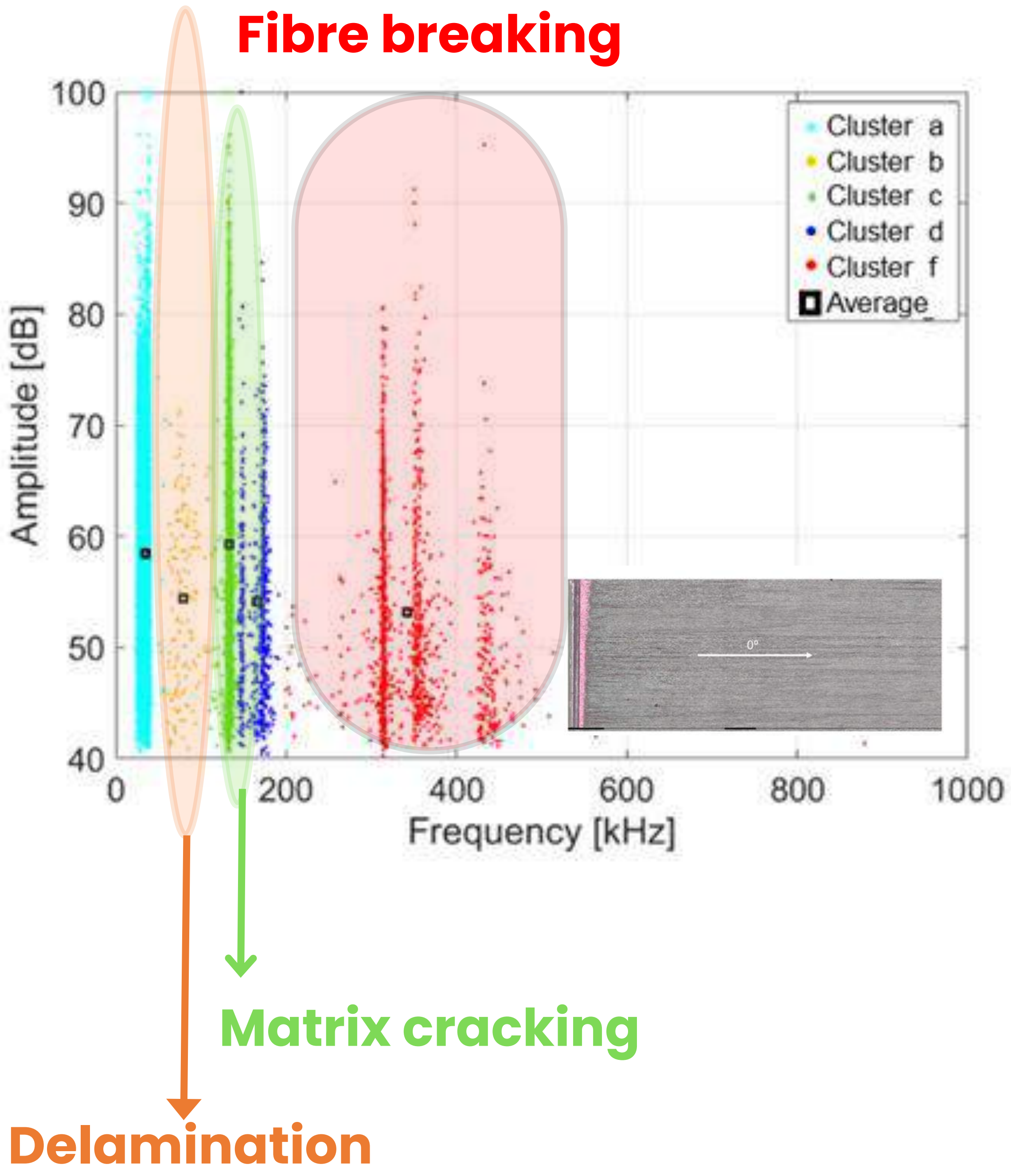


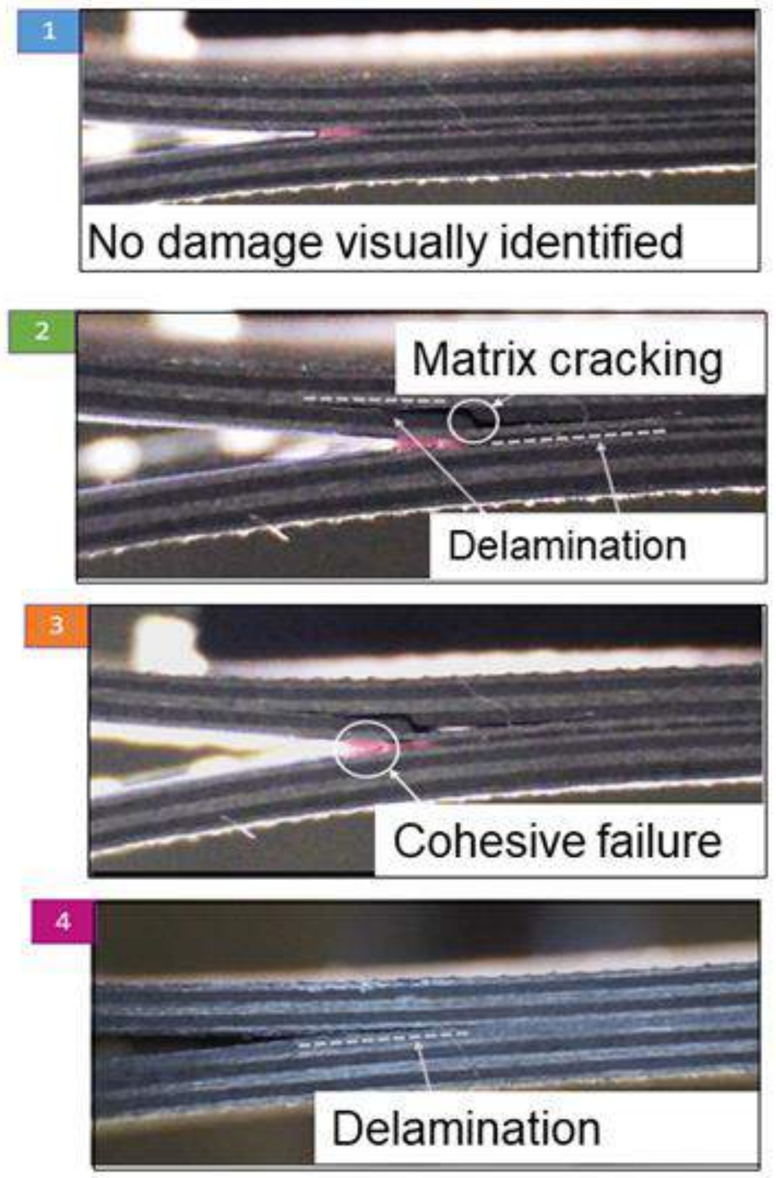


AE clustering results and physical interpretation

AF-0 /90







- Cluster d (170 kHz) -
- Cluster a (35 kHz) -

AE clustering results and physical interpretation

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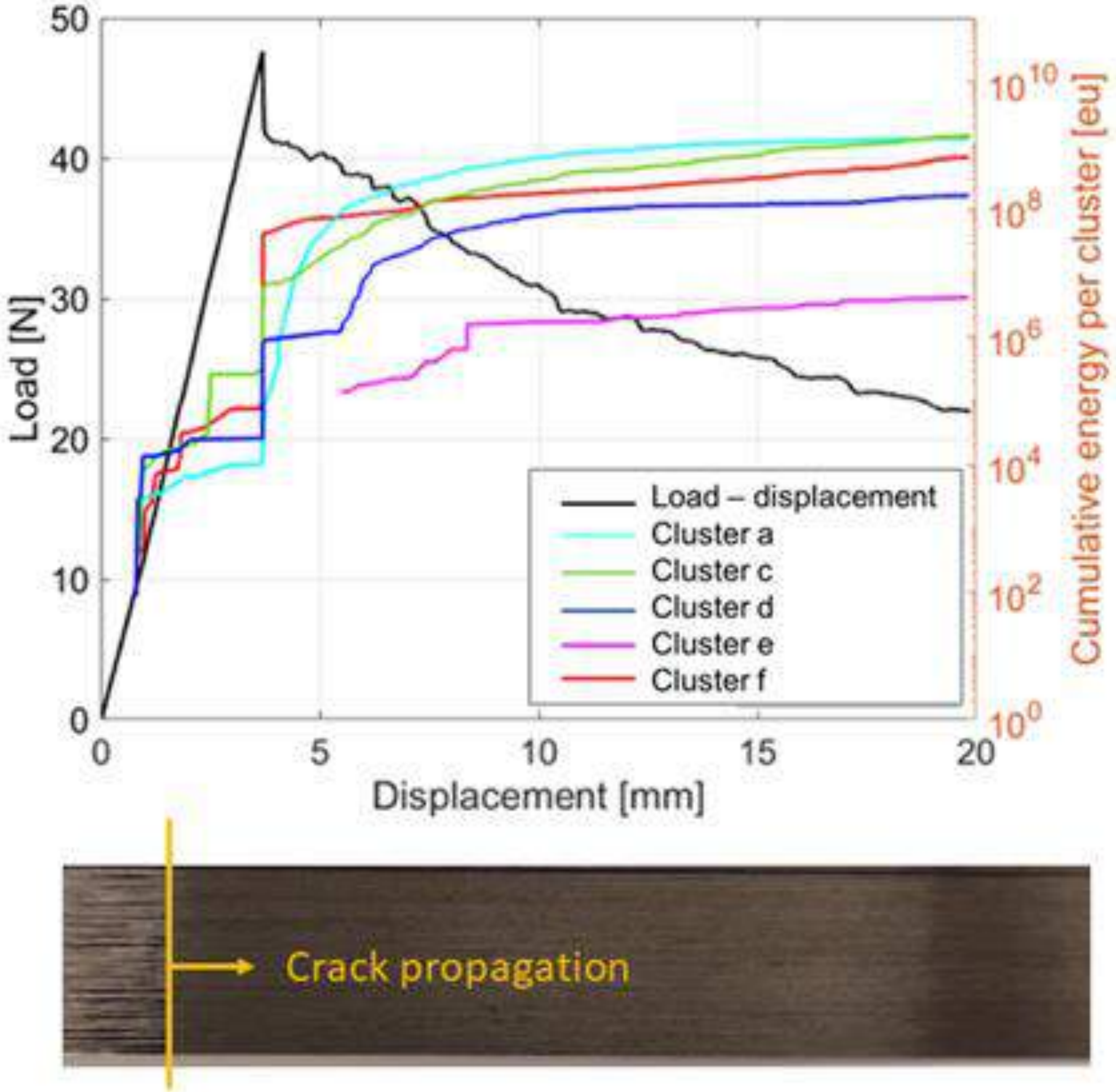
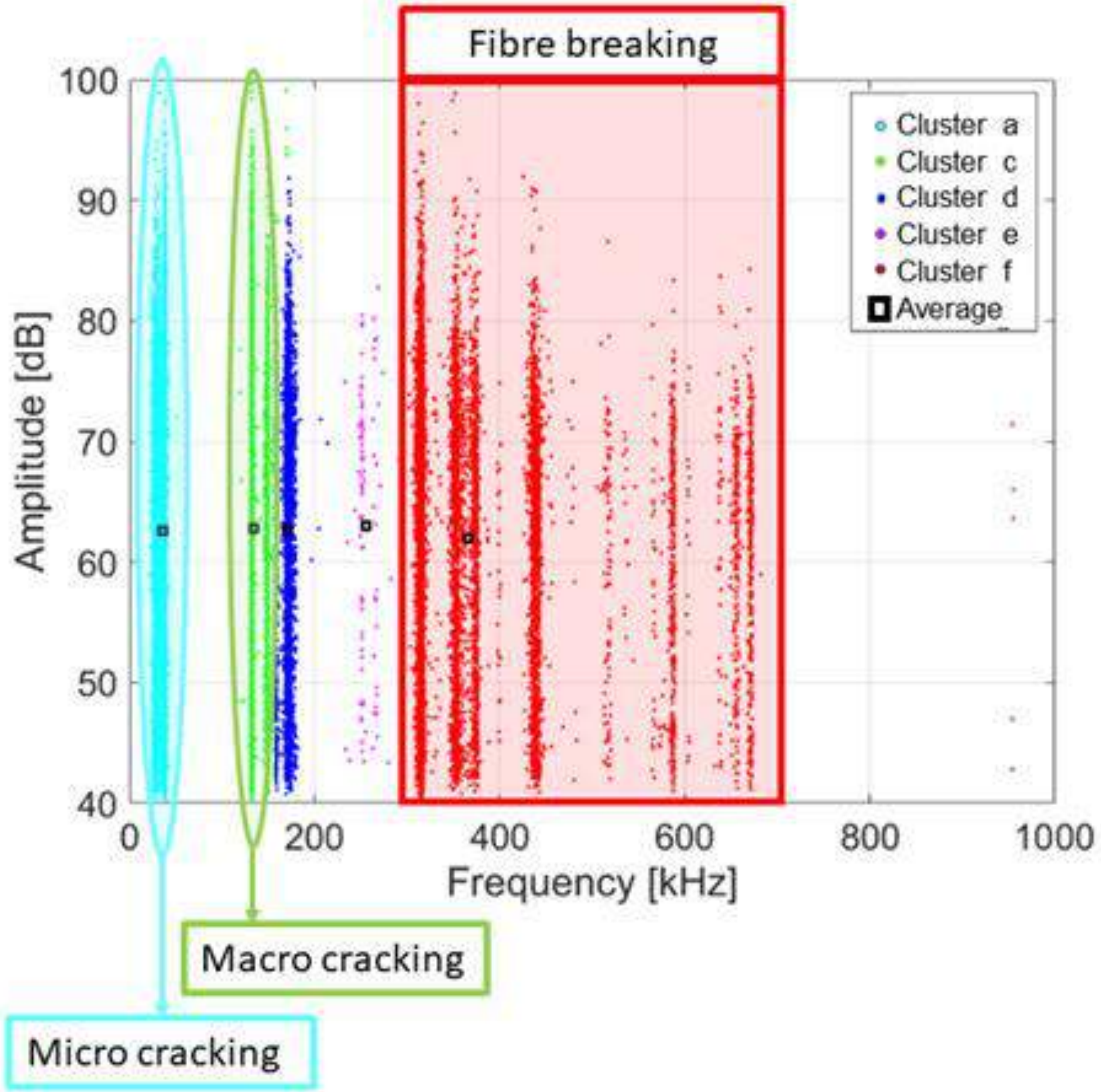
CFRP





Clusters d (170 kHz) and e (255 kHz) are still not defined!

AE clustering results and physical interpretation

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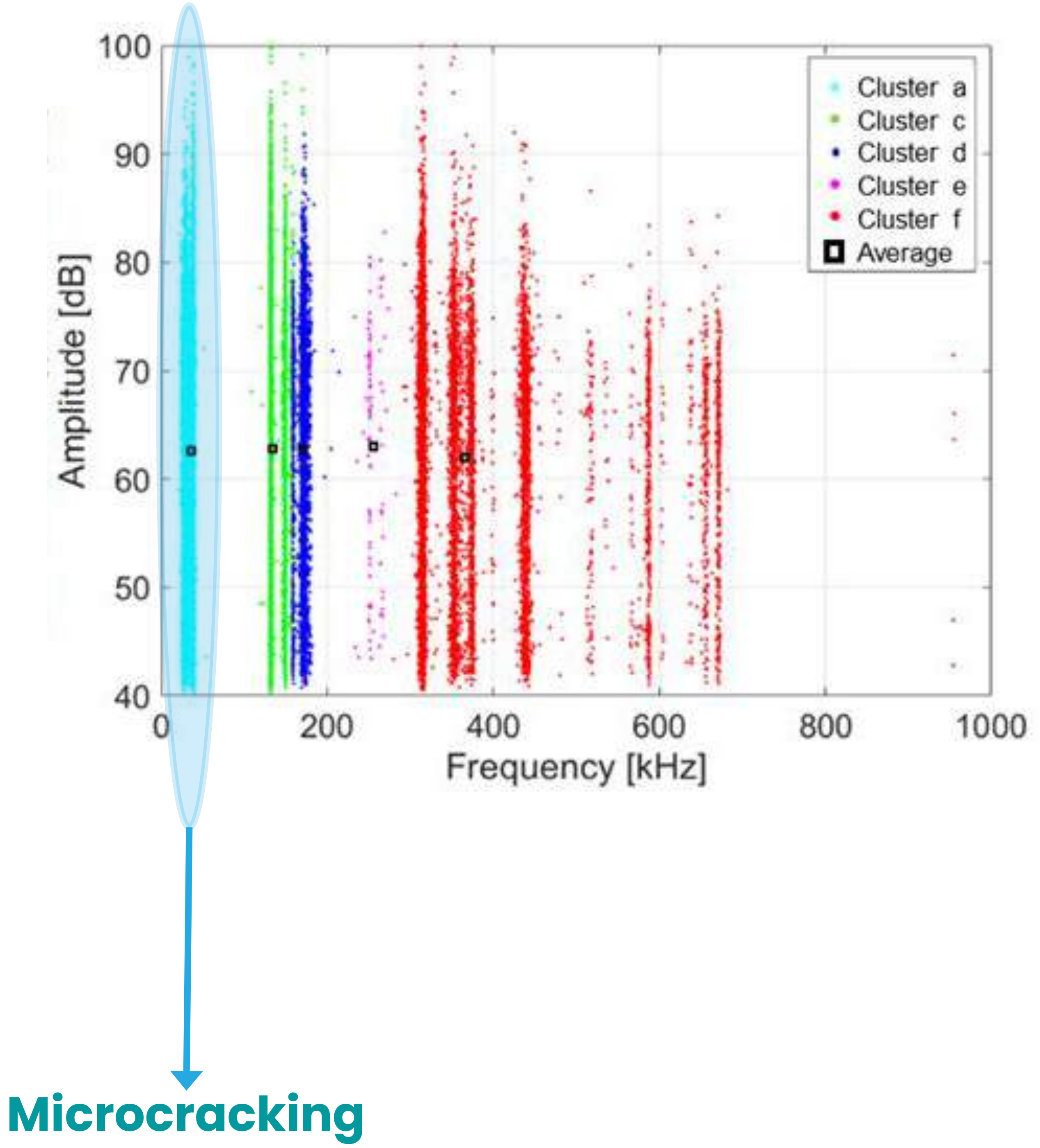
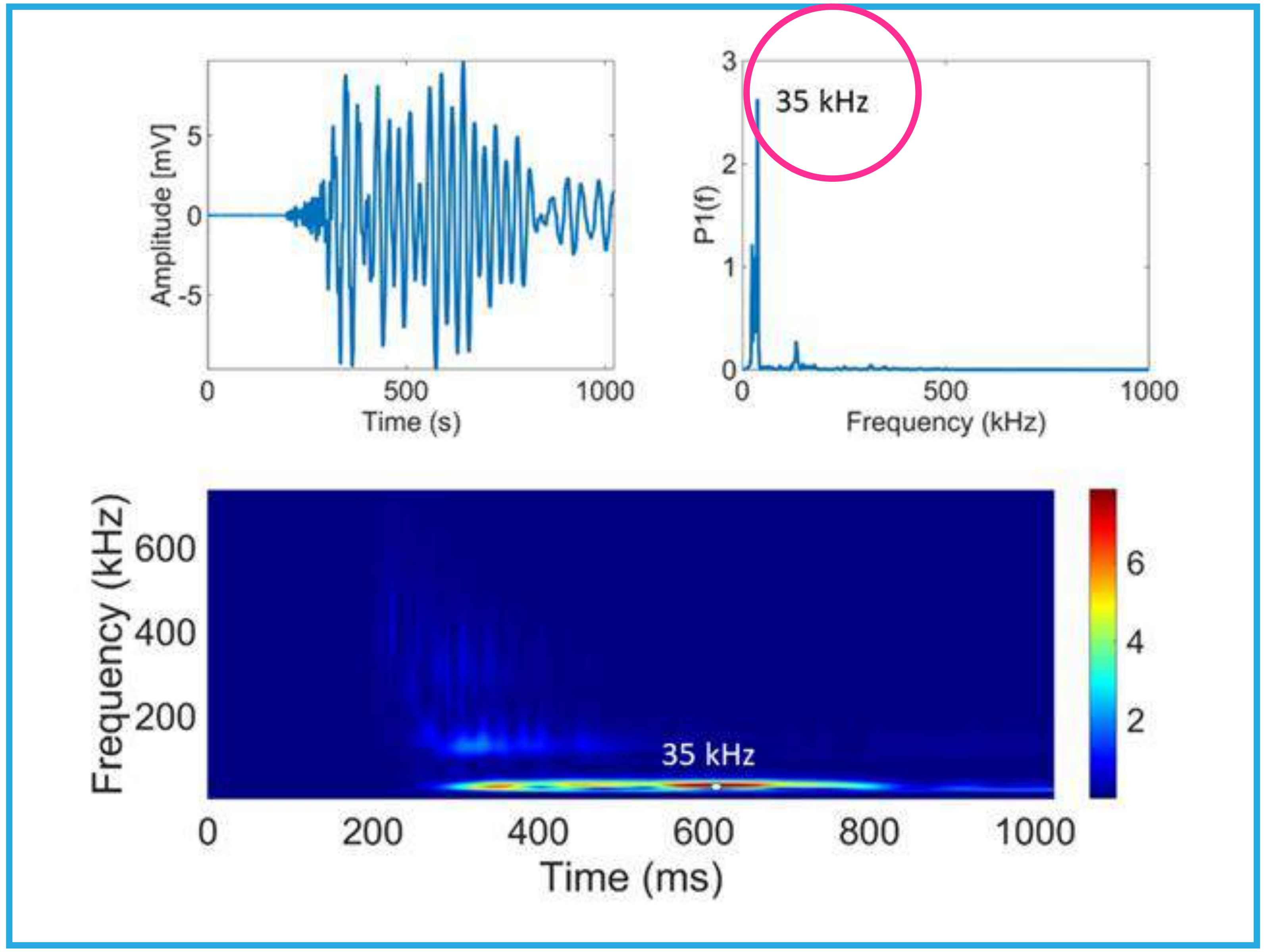
CWT - Morlet transformation





AE clustering results and physical interpretation

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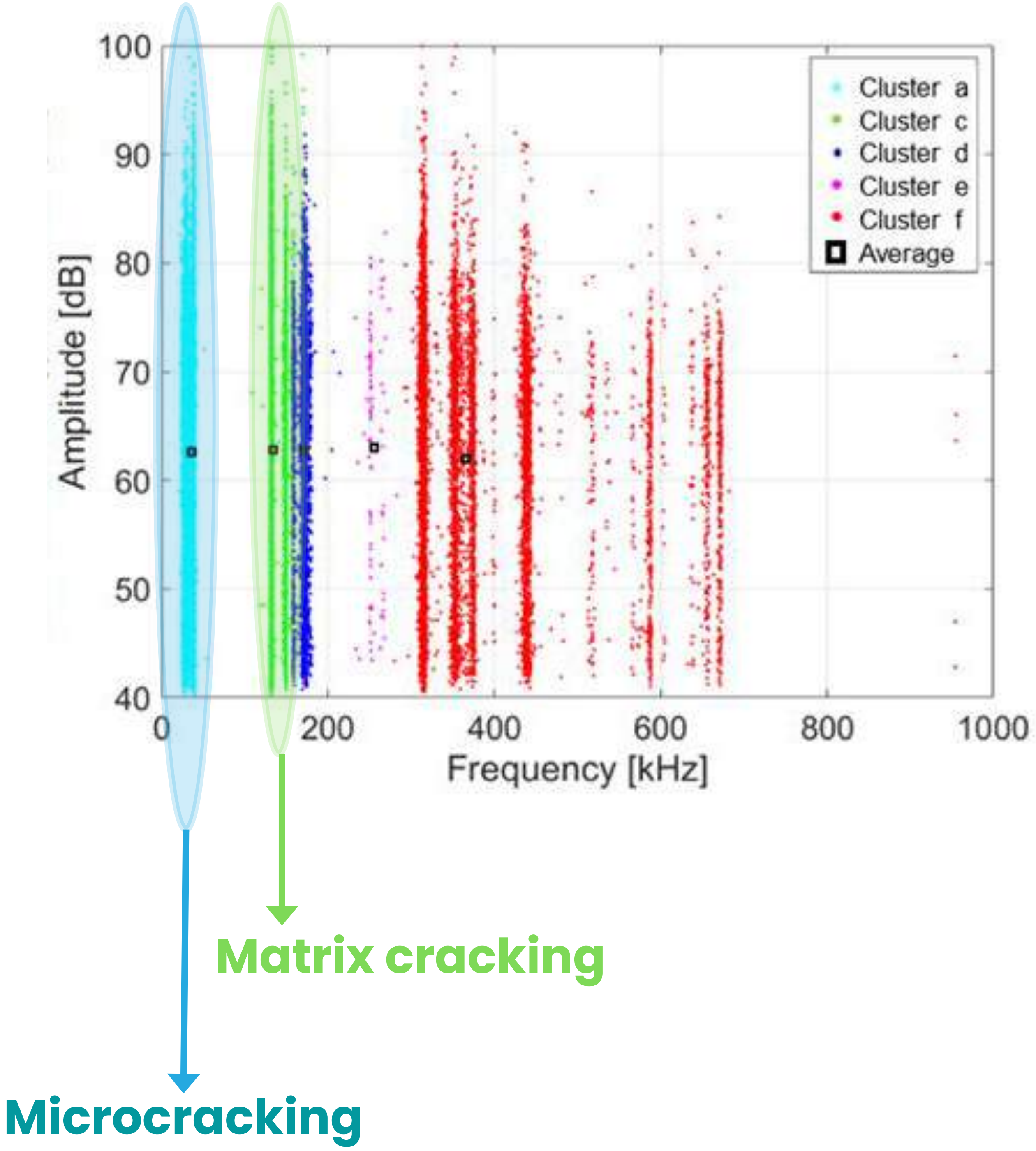
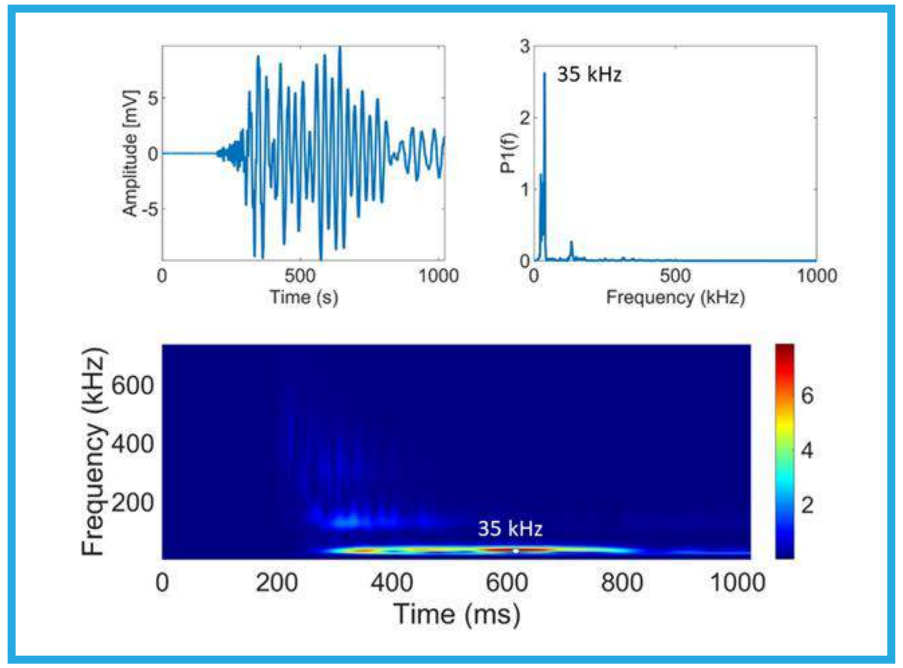
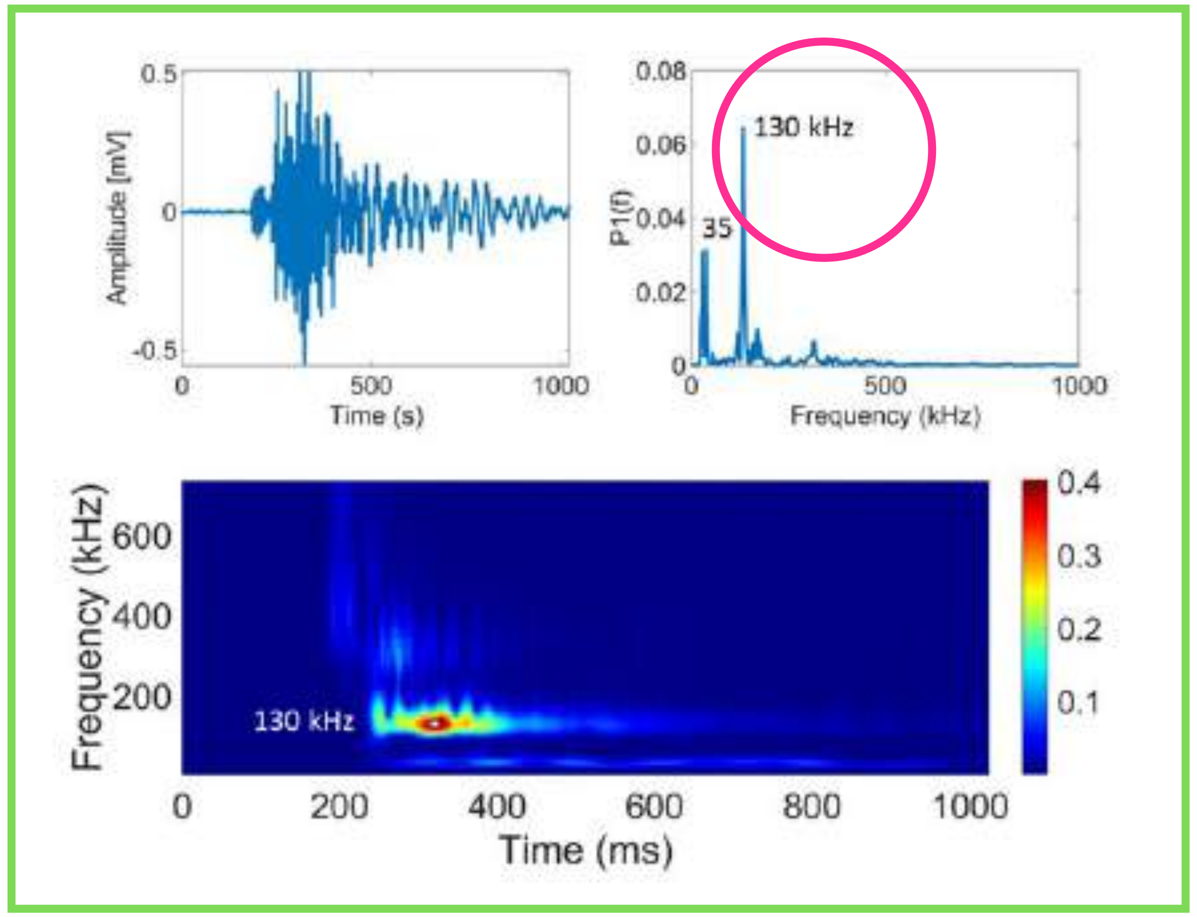
CWT - Morlet transformation







AE clustering results and physical interpretation

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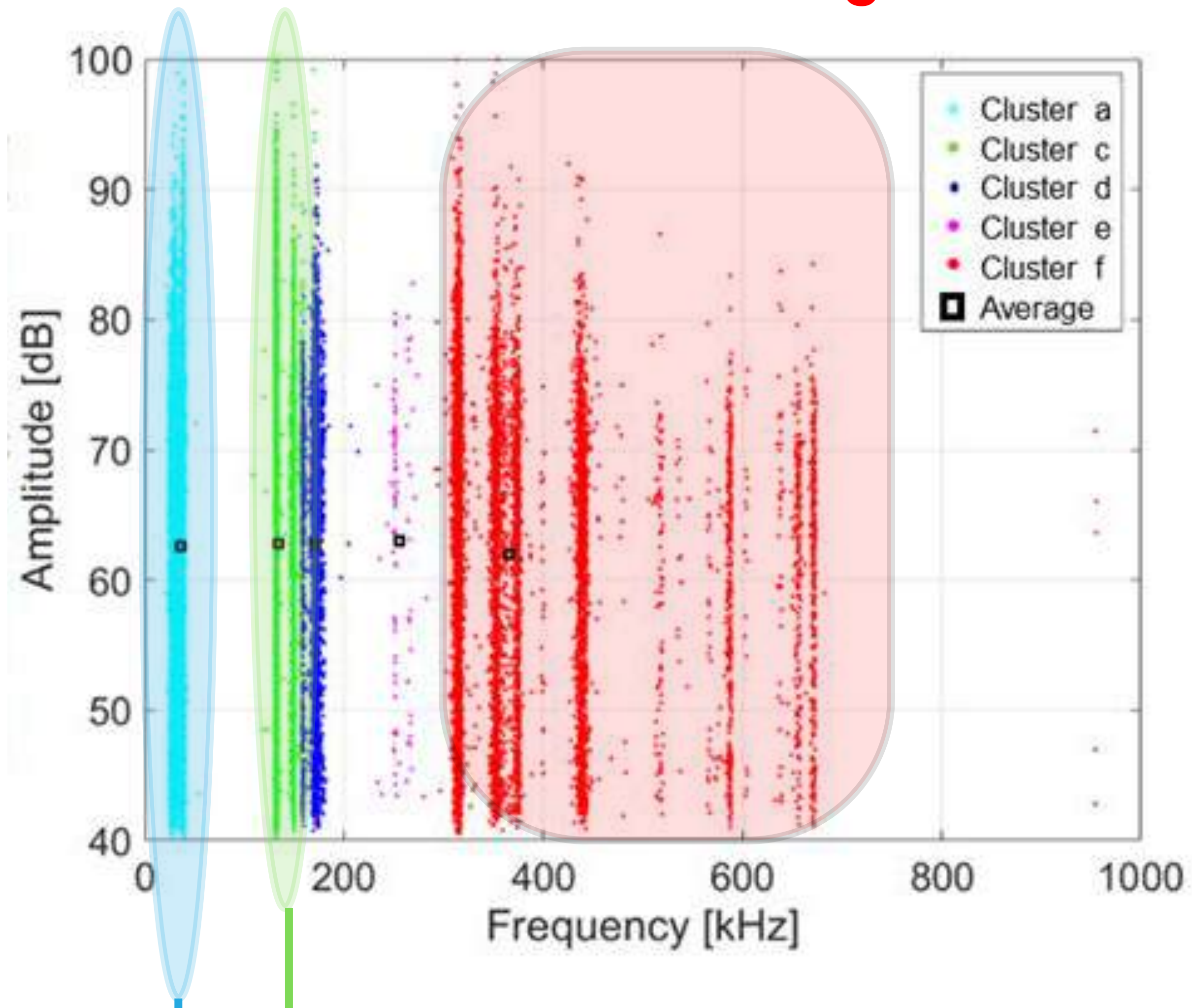
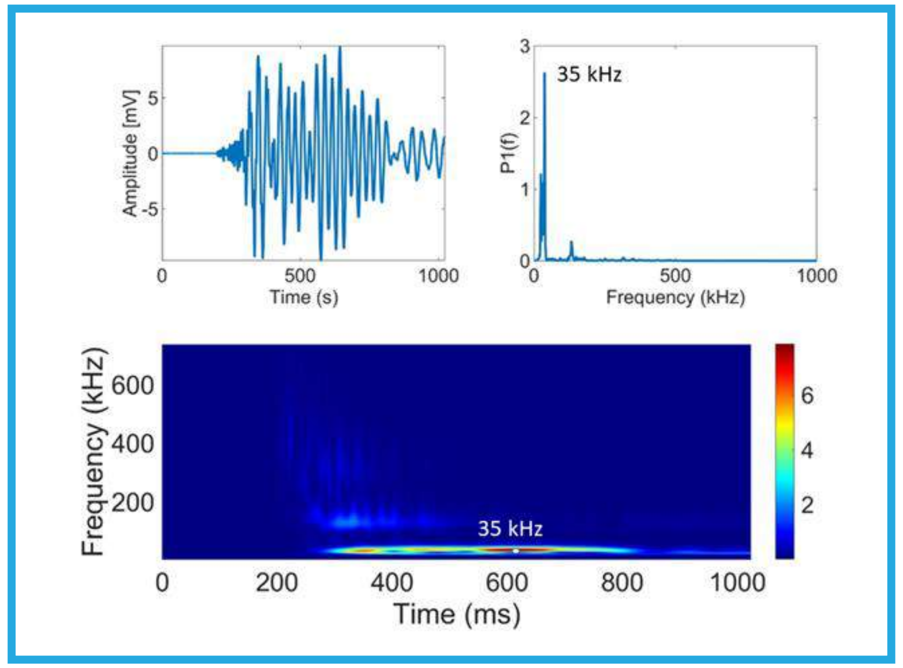
CWT - Morlet transformation

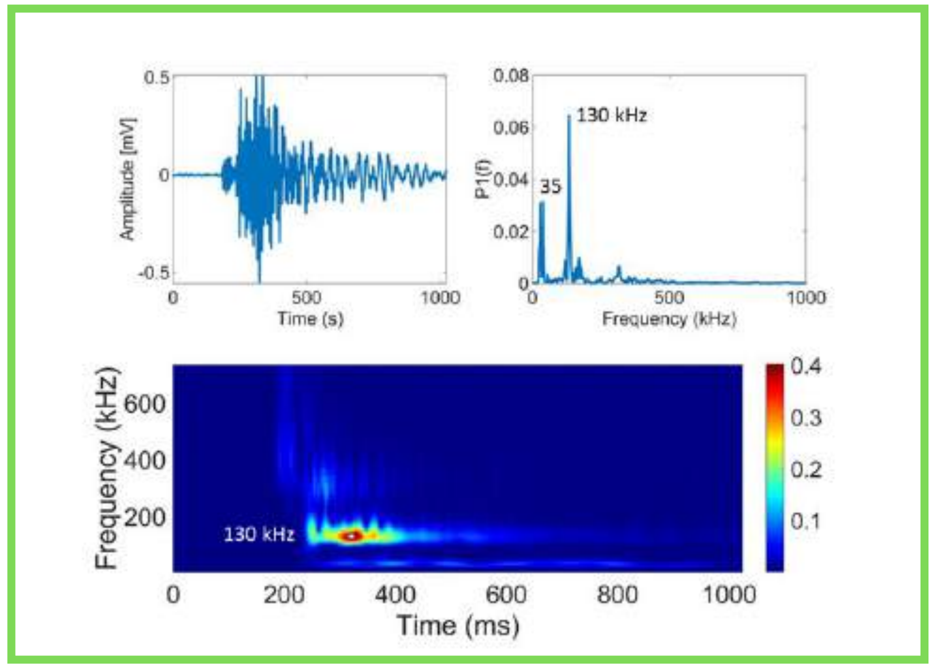
Fibre breaking

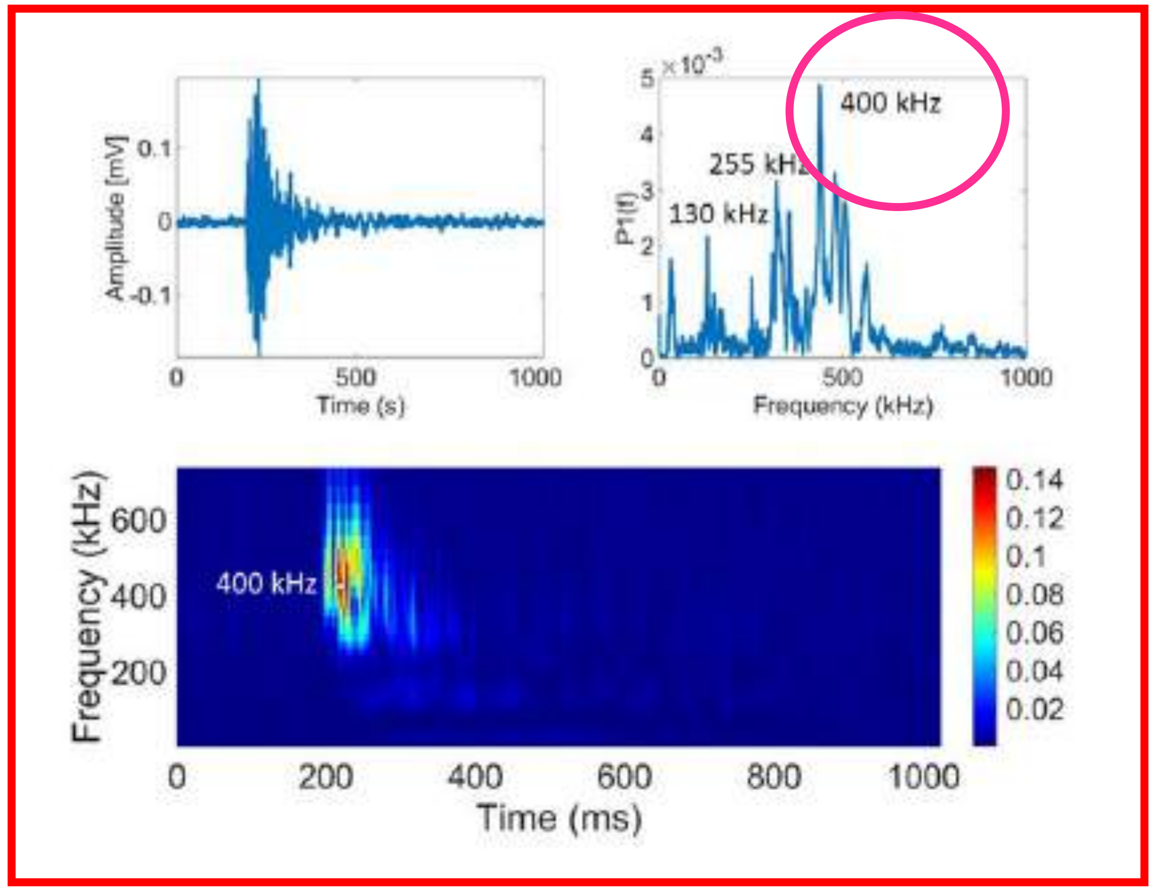


Matrix cracking

Microcracking







AE clustering results and physical interpretation

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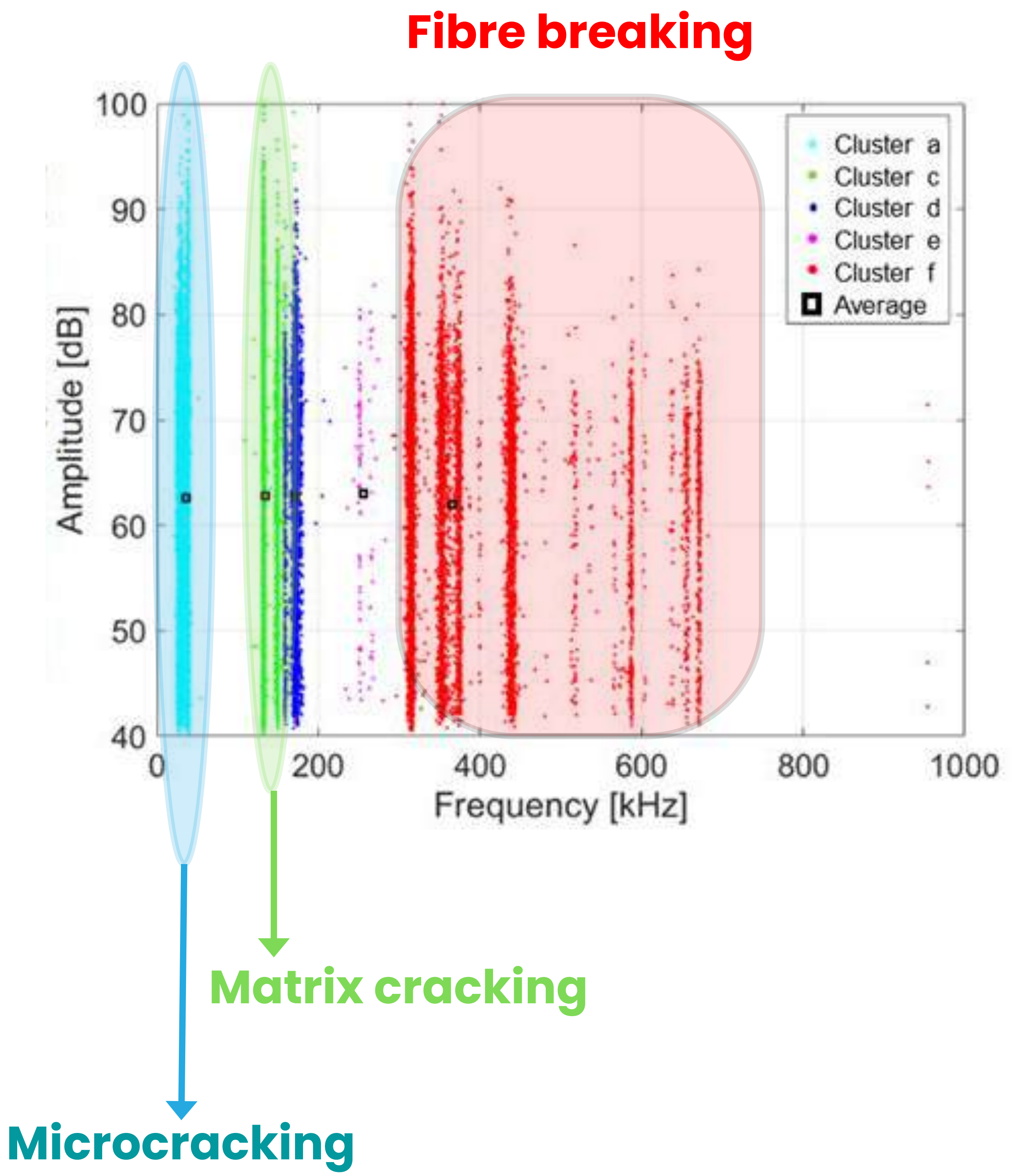
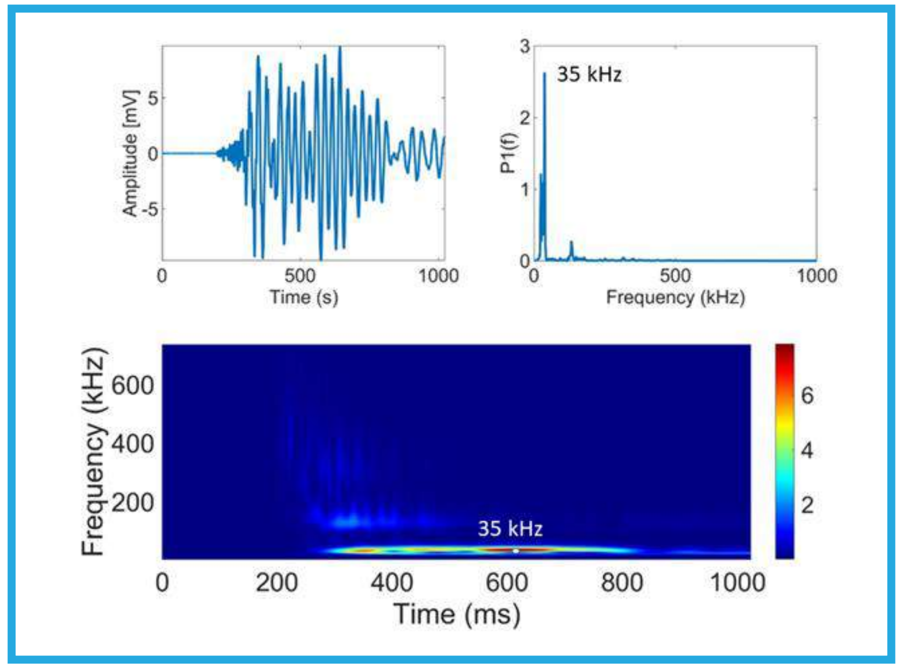
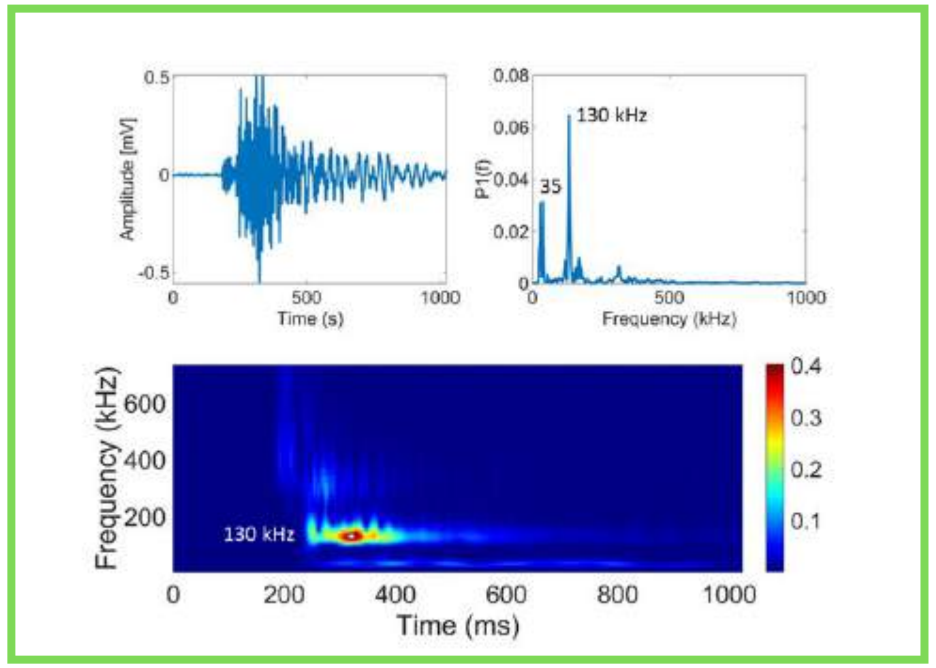
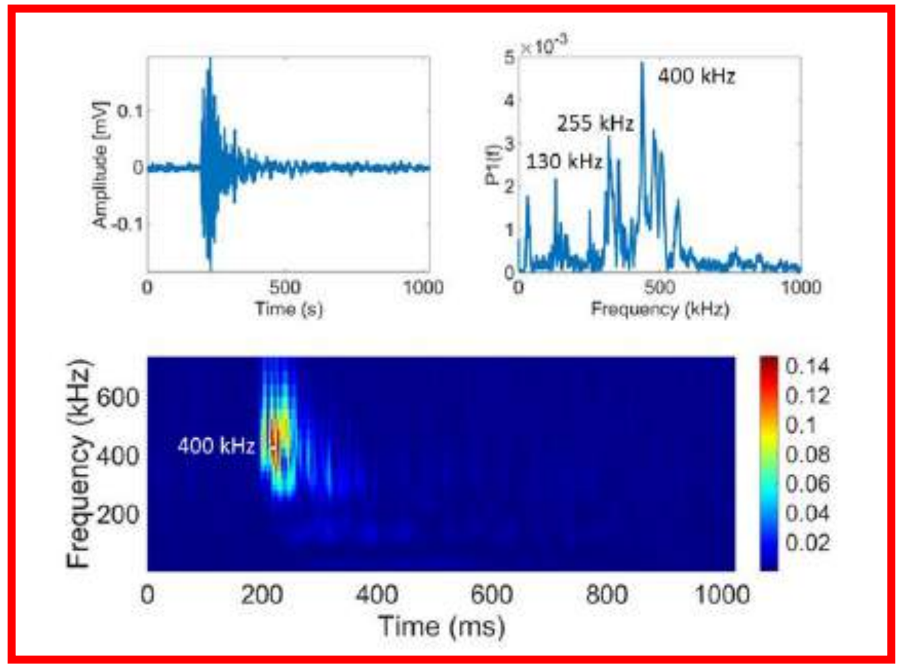
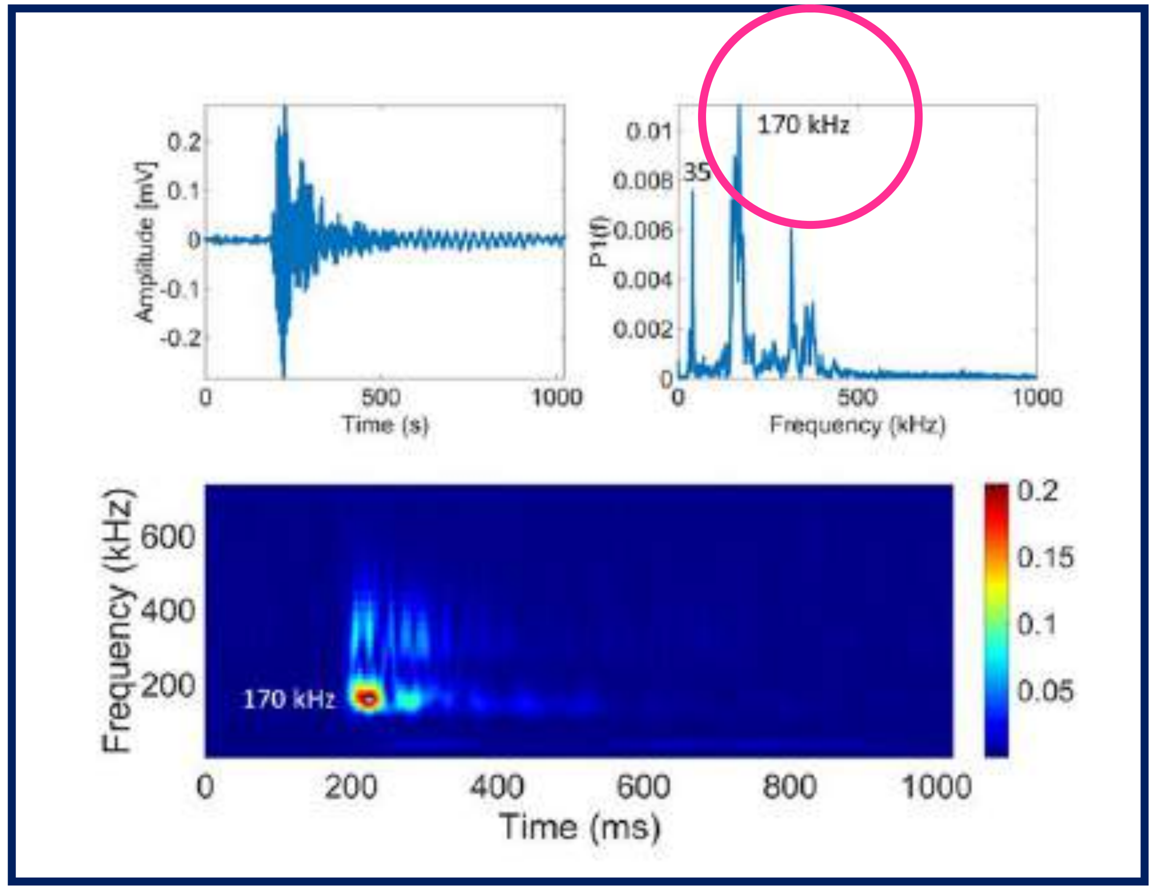
CWT - Morlet transformation











AE clustering results and physical interpretation

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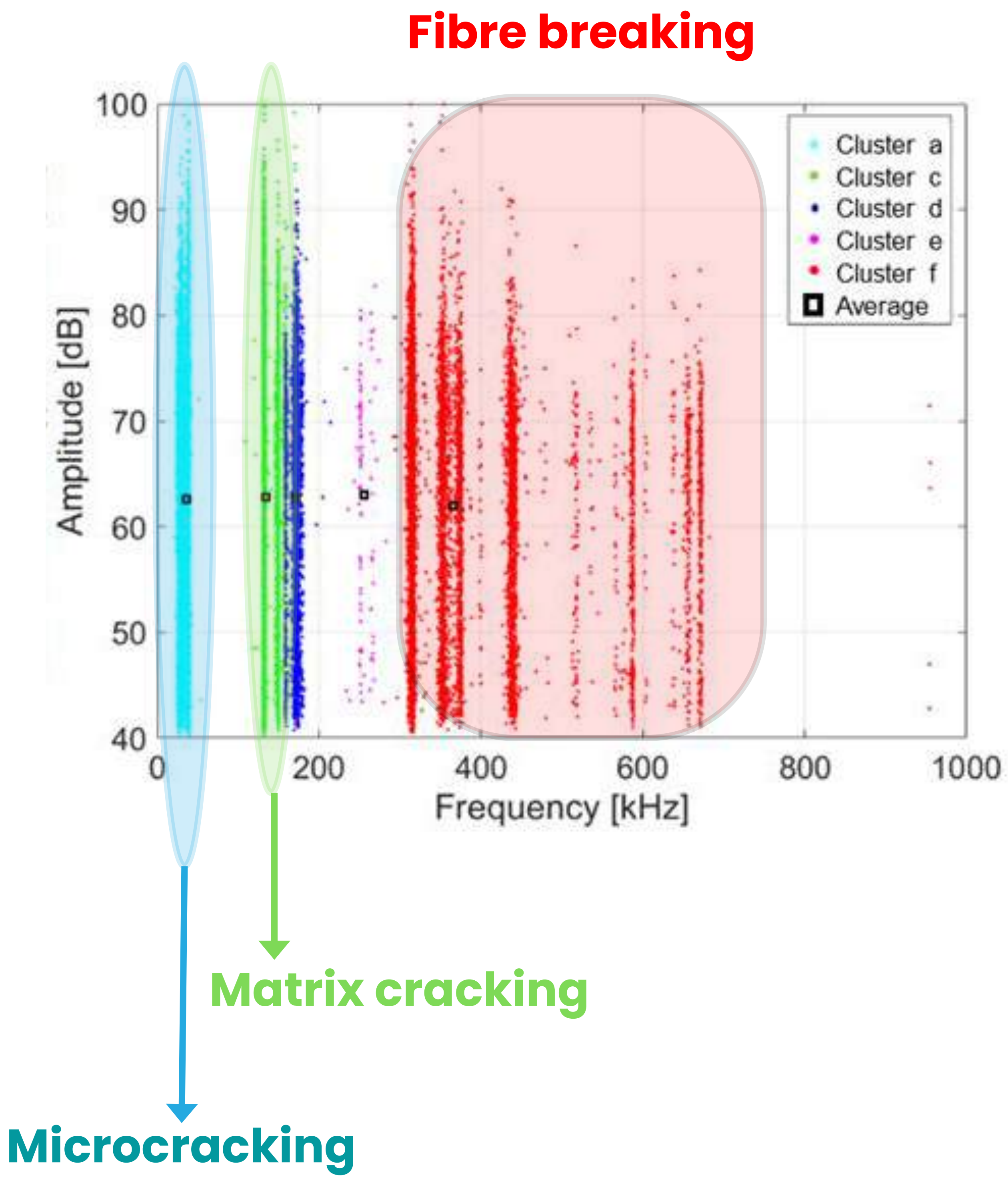
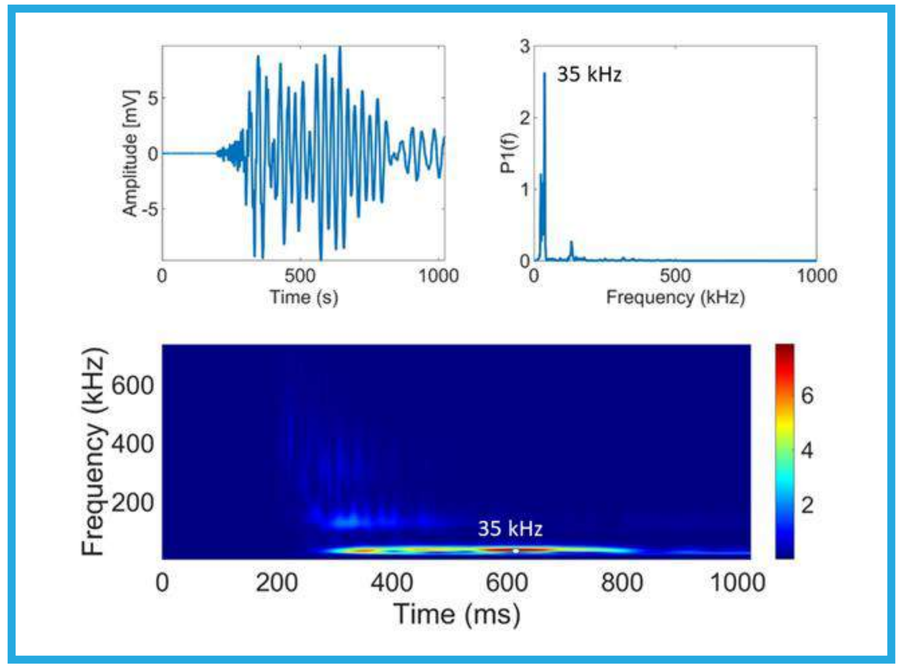
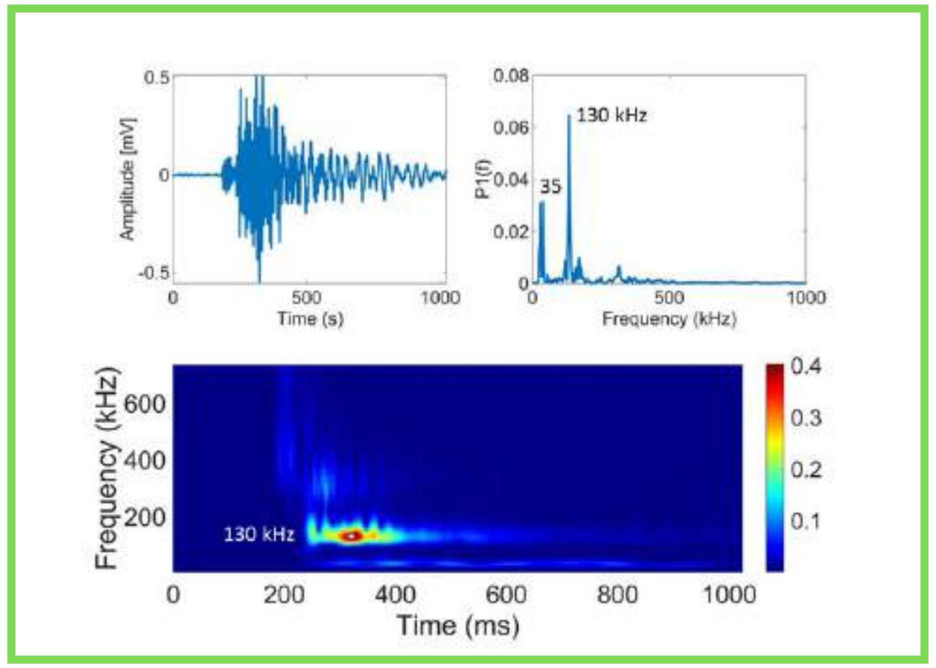
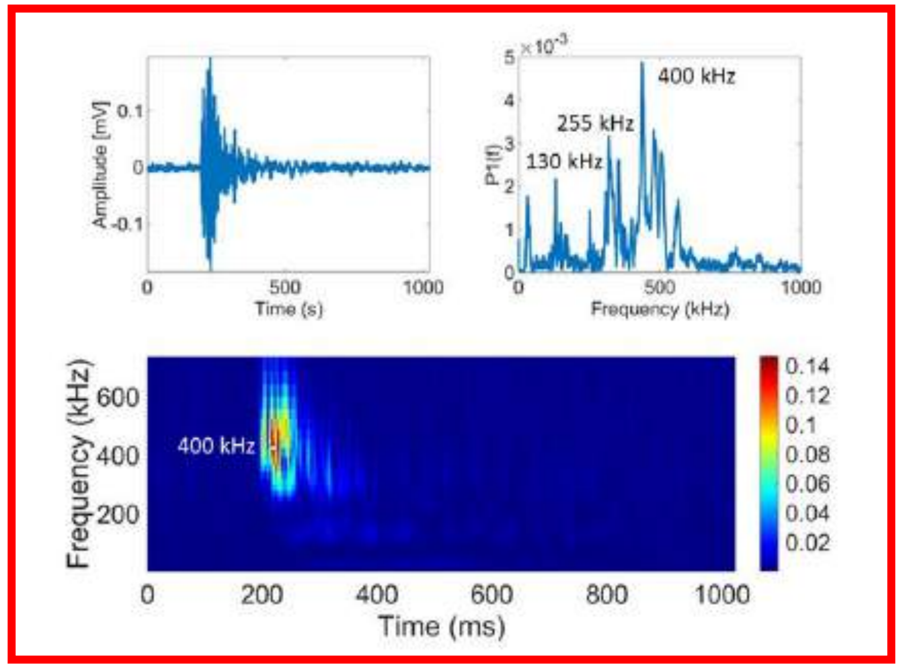
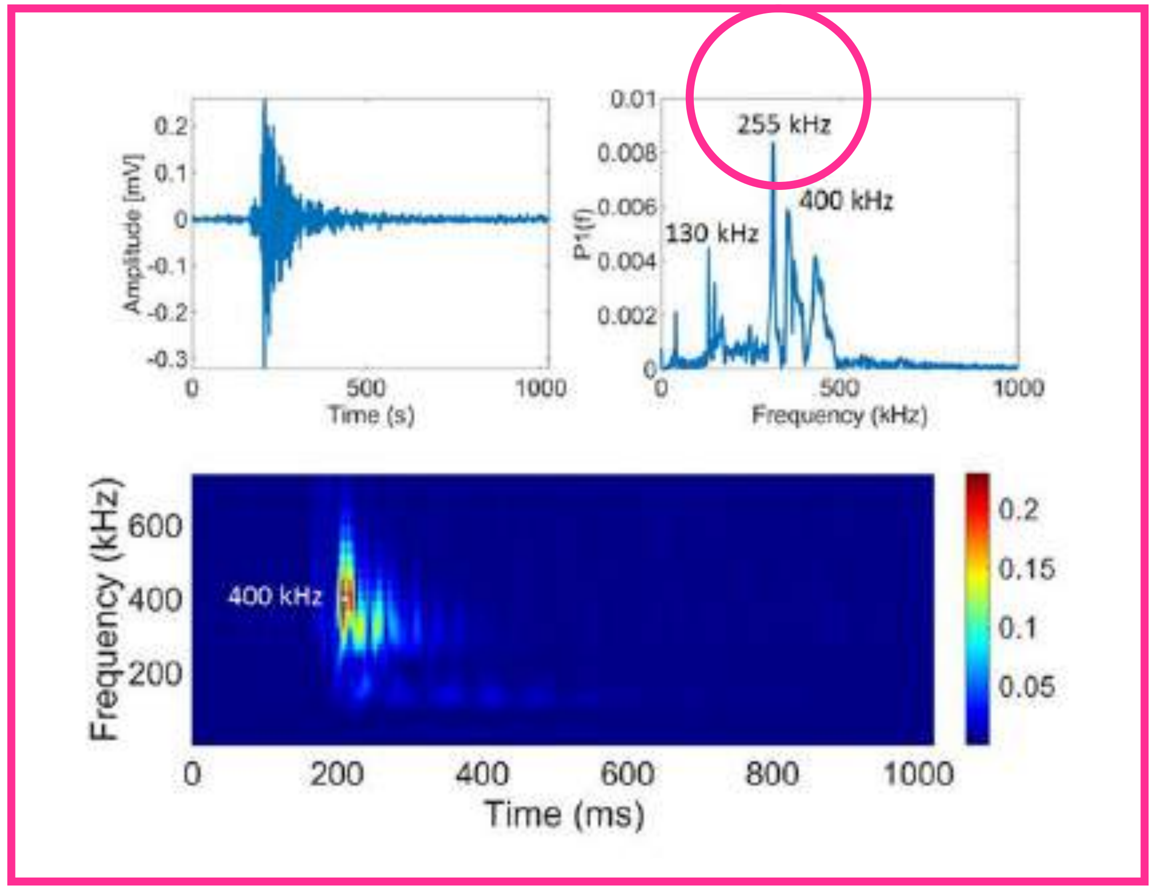
CWT - Morlet transformation











AE clustering results and physical interpretation

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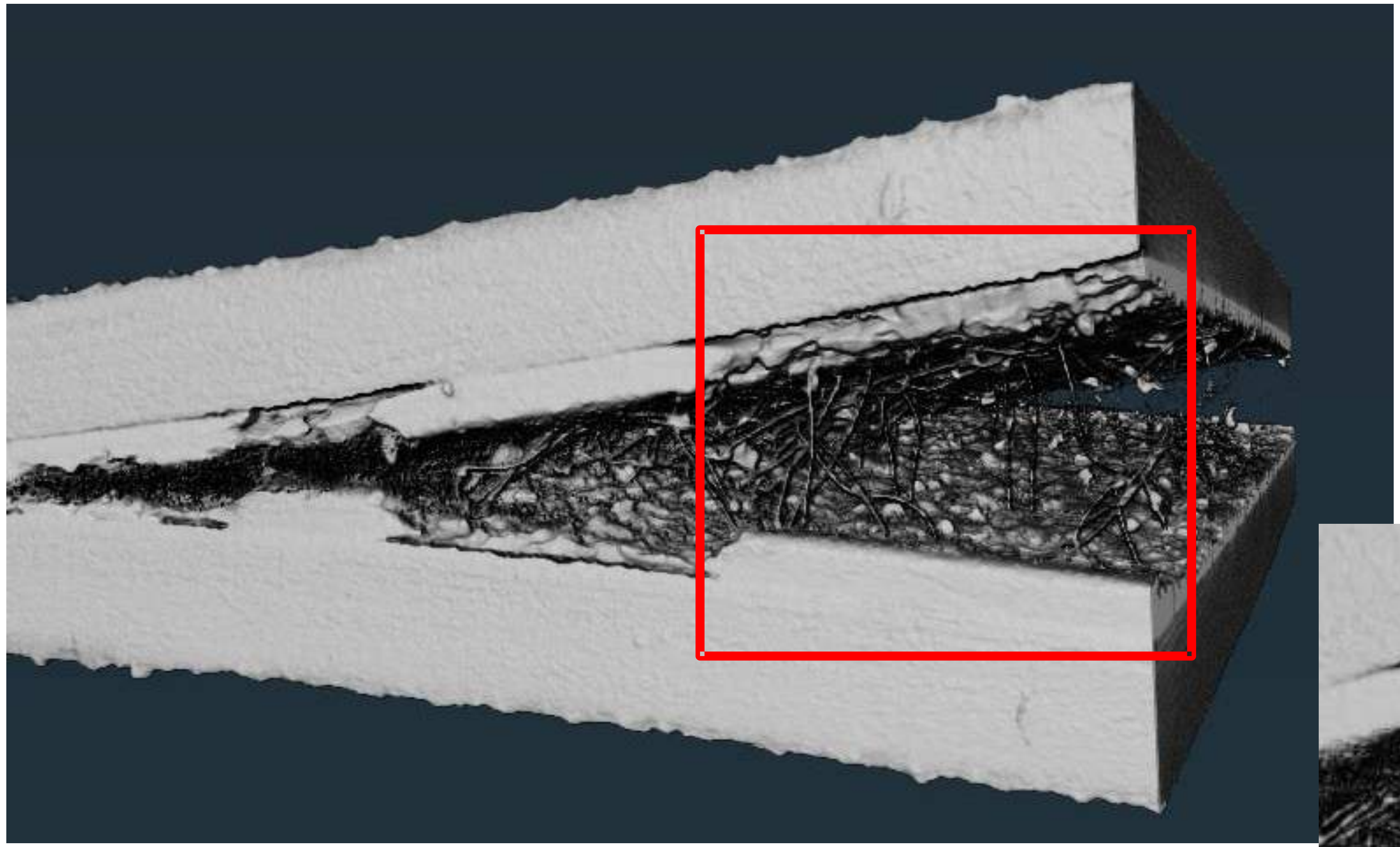
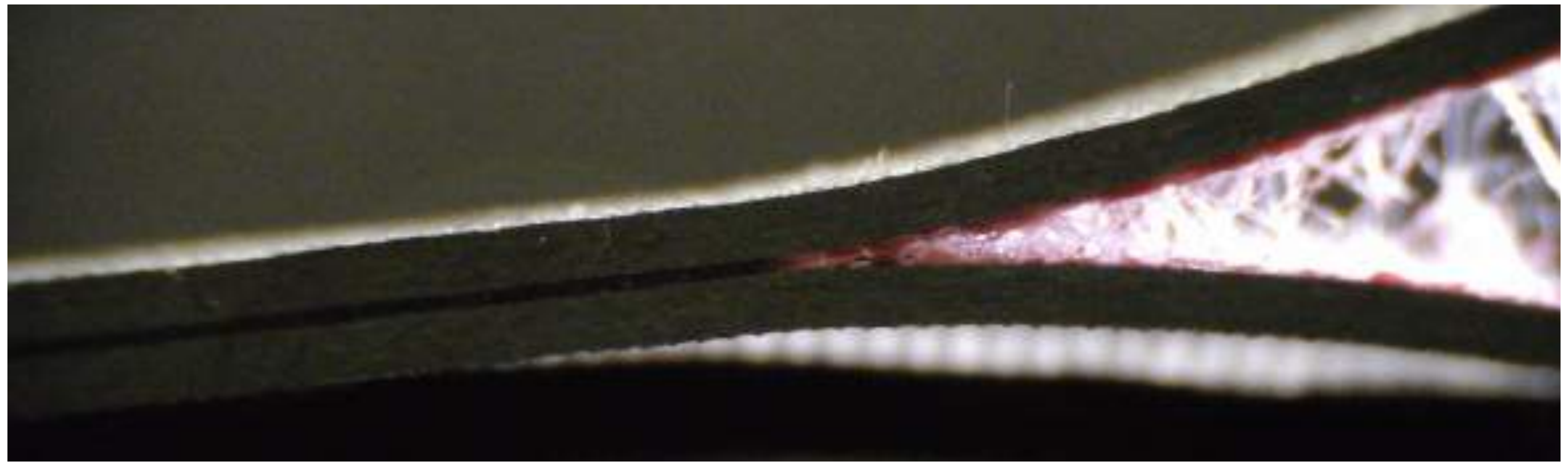
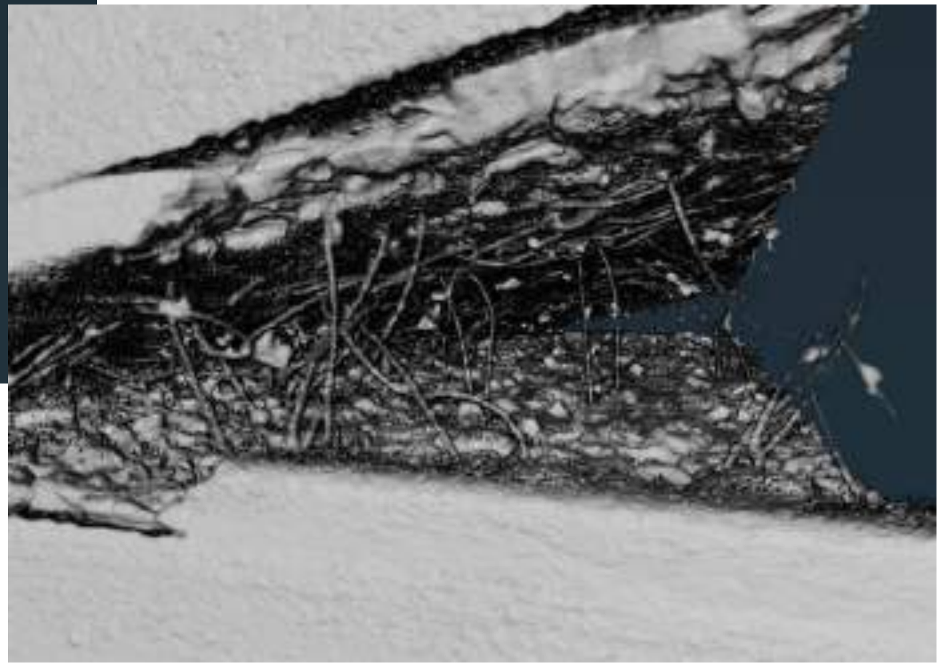
Damage mechanisms	Micro-cracking	Delamination	Matrix cracking	Fibre-matrix debonding	Fibre pull-out	Fibre failure
Cluster	*a*	*b*	*c*	*d*	*e*	*f*
Associated colour	Light blue	Orange	Green	Dark blue	Pink	Red
Peak frequency (kHz)	35	60	130	170	255	300 to higher values
CFRP	✓	✗	✓	✓	✓	✓
AF-0	✓	✗	✓	✓	✓	✓
AF-0/90	✓	✓	✓	✓	✓	✓
AF-90/0	✓	✓	✓	✓	✓	✓
AF-90/45	✓	✓	✓	✓	✓	✓
AF-90/60	✓	✓	✓	✓	✓	✓

AE clustering results and physical interpretation

3D imaging -







VI

Main outcomes

highly-sensitive to the micro-damage formation and their final coalescence

no difference AE signature of cohesive failure and the matrix cracking of CFRP specimen

A fixed number of clusters for all the specimens can not always be the best clustering solution

CWT spectrogram showing the co-occurrence of different damage phenomena

Acknowledgment

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This STSM was developed under the COST Action CA18120 (CERTBOND) and supported by COST (European Cooperation in Science and Technology).

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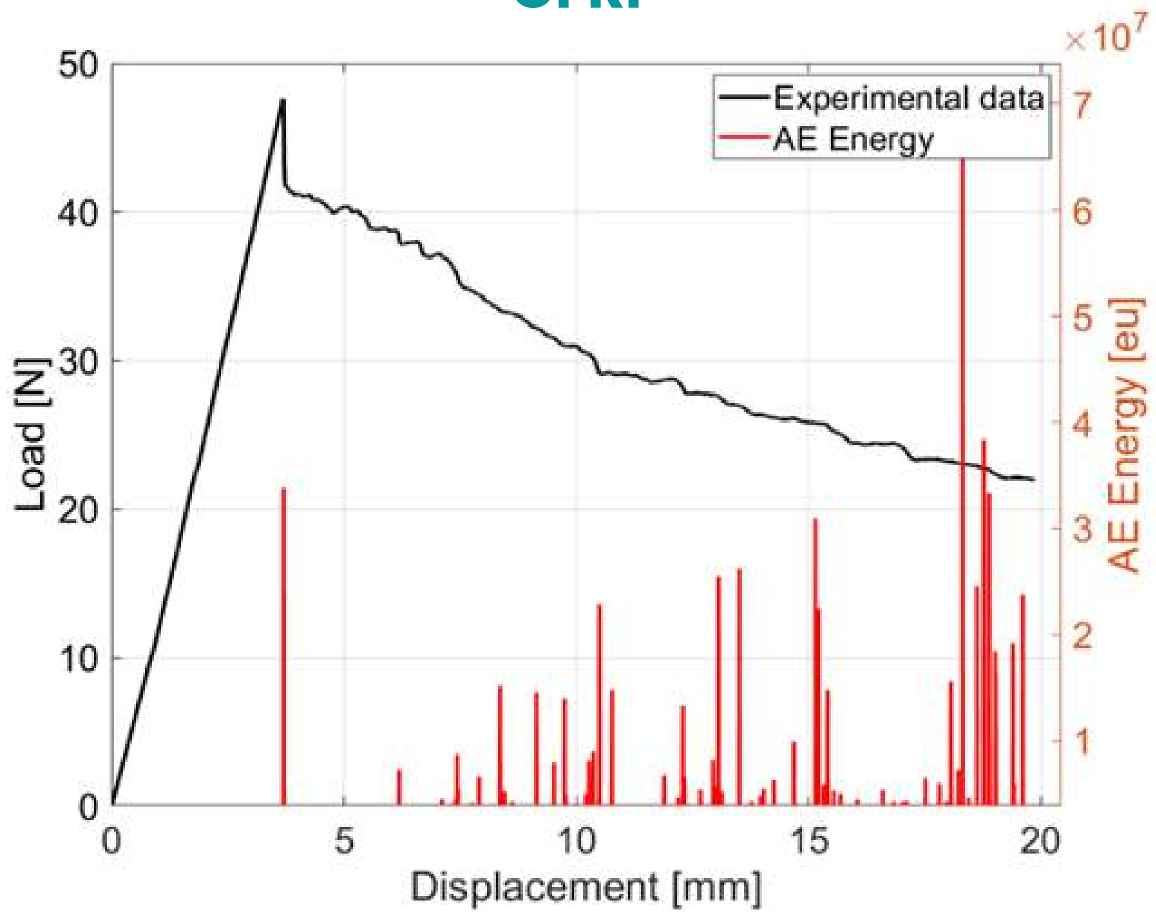
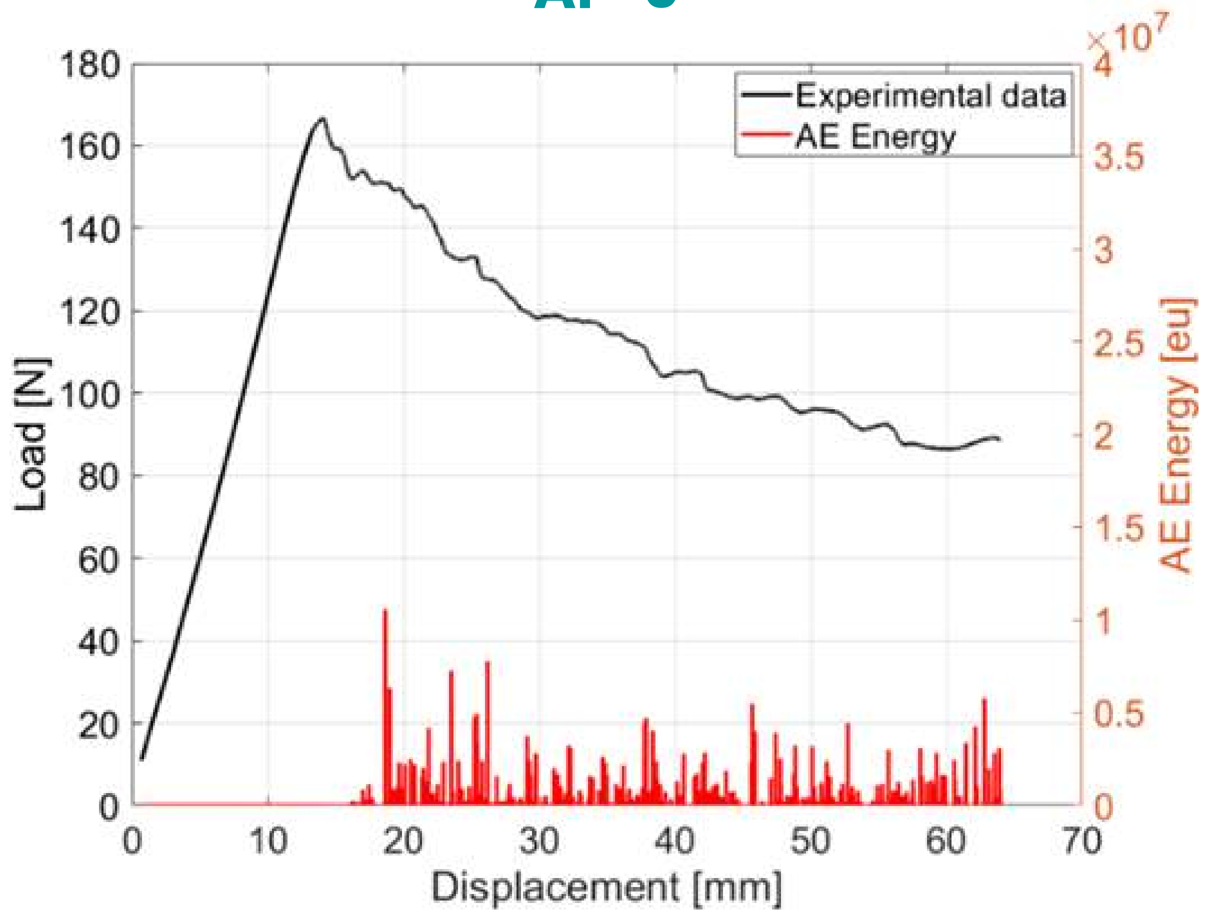
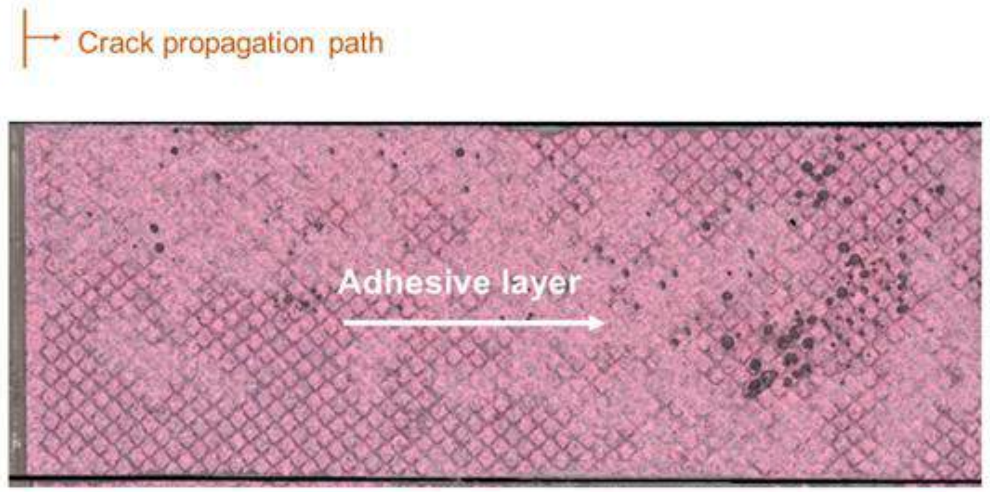
AE raw data and post processing

CFRP

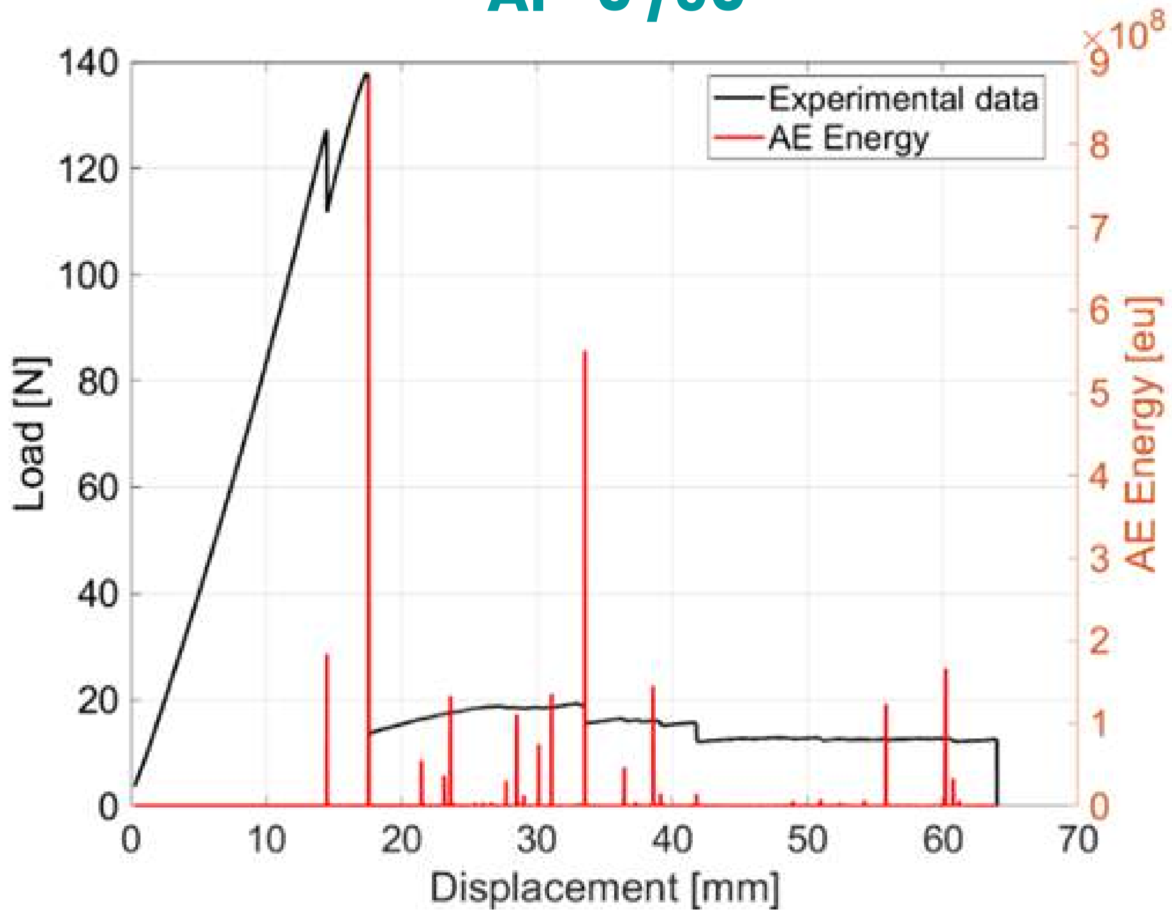


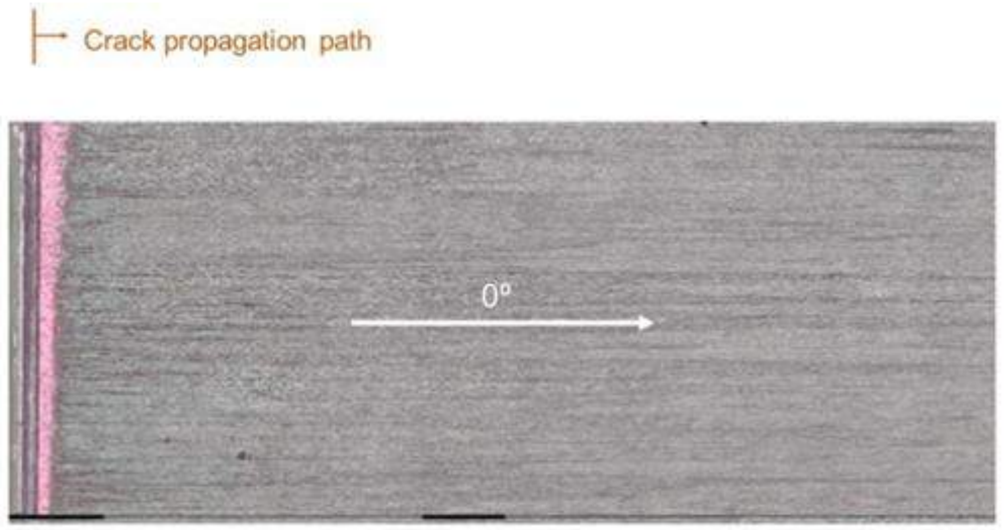
AF-0





AF-0 /90





AE raw data and post processing

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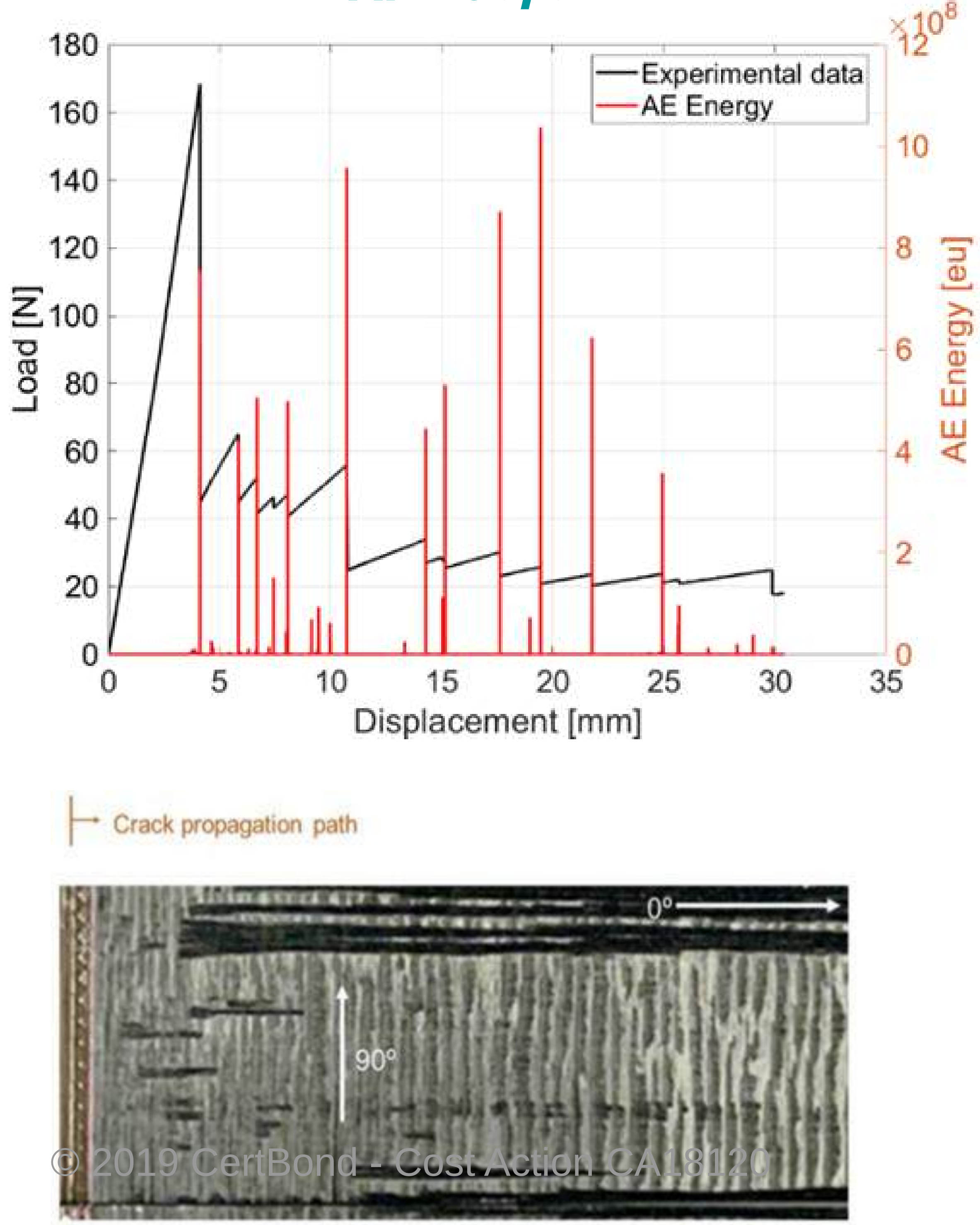
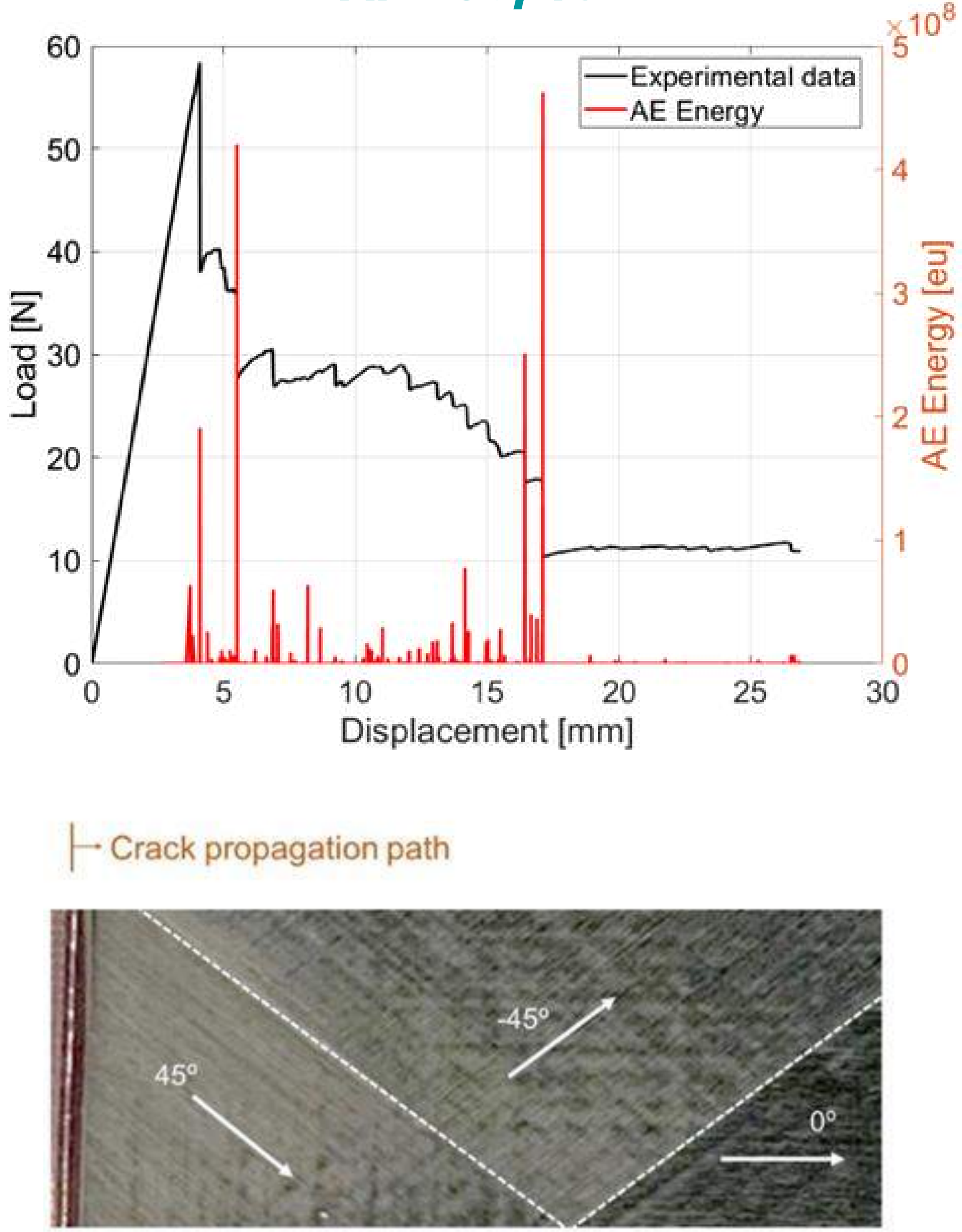
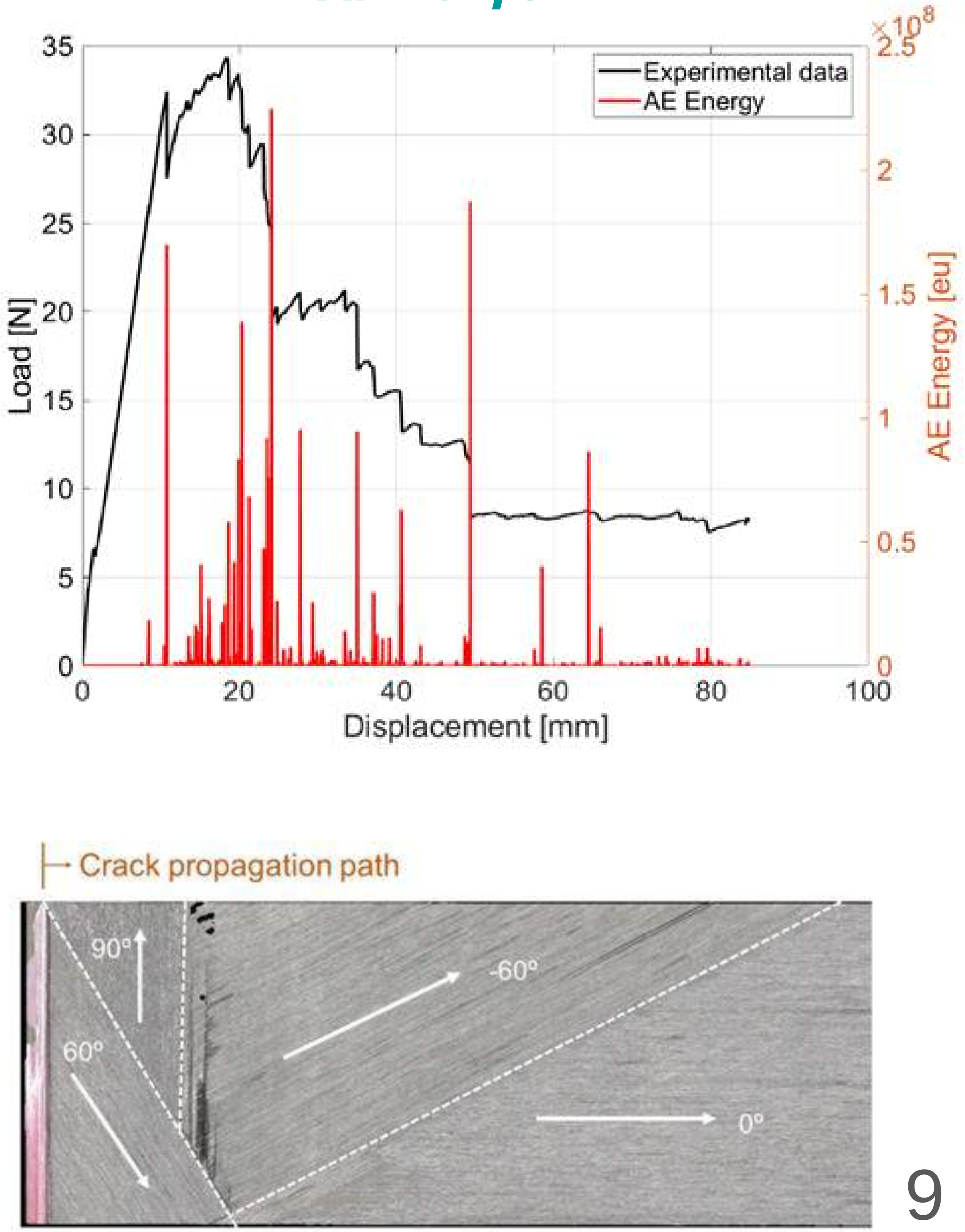
AF - 90/0



AF - 90/45



AF - 90/60



A Practical approach for non-destructive testing of bonded joints to implement an acceptance-promoting in-line quality assurance

Christian Gundlach, Sven Hartwig
Institute of Joining and Welding, Technische Universität Braunschweig, Germany
CertBond COST Action Final Conference, Sevilla, 6-8 September 2023

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Institute of Joining and Welding - Divisions & Competencies

Bonding Technology and Mechanical Joining

- Application, dosing, dispensing
- Accelerated curing of adhesives
- Simulation & local characterization
- Destructive & non-destructive testing

Advanced Composites and Interfaces

OHLF

- Joining of different materials
- Surface treatment & process technologies
- Surface & interface characterization
- Destructive & non-destructive testing

Strength and Component Behavior

- Residual stresses & deformation
- Strength of welds at cyclic & impact loads
- Simulation & non-destructive testing
- Fracture analysis

Welding and Beam Technology

- Laser & electron beam welding
- Additive manufacturing
- Residual welding stresses
- Fatigue resistance & repair welding

Fibre Composite and Electric Mobility

BLB

- Electrode drying, cutting & structuring
- Contacting & Welding
- Binder modification
- ASSB sintering & separation

Light Metal Die Casting

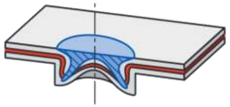
LMZS Leichtmetallzentrum Soltau

- Process optimization & energy efficiency
- Tooling technologies
- Joining of die casted parts
- Testing and failure analysis

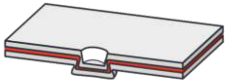
Structural adhesive bonding in automotive construction

Hybrid joining

Riveting + Bonding



Clinching + Bonding



Welding + Bonding

Additional joints = backstops

Elementary adhesive bonding

Glass-Metal
Metal-Metal
Plastic-Metal

No backstops

Adhesive bond alone must withstand loads over lifetime to ensure structure's integrity

Design and manufacturing according to requirements essential to avoid failure

Trust that adhesive bond can withstand loads over lifetime is missing

NDT of adhesive bond to validate manufacturing (and possibly design)

Figures based on: Geiß, P.I., Fritzsche, C., Kleiner, F., Peschka, M., Rauscher, M., Schmale, H.C., Vogt, D., Zanotti, A., Weber, C., Wibbeke, M., 2012. Merkblatt 382 Kleben von Stahl und Edelstahl Rostfrei. Düsseldorf.

Structural adhesive bonding in automotive construction

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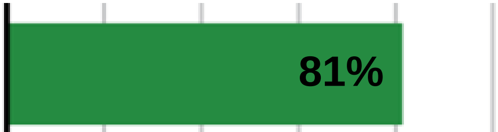
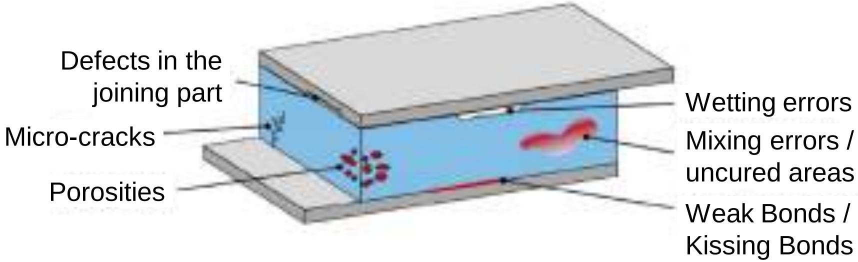
Challenges from the user perspective

A suitable non-destructive test method is missing.



ISGATEC, 2022. Fehlendes Wissen ist der rote Faden bei Klebproblemen. DICHT! Dichten.Kleben.Polymer.verstehen



Many NDT methods available in research literature →

- Problem 1: Method only validated in lab environment
- Problem 2: Method only suitable for lab environment or no implementation for industrial application

Defects \ NDT methods	Visual	Radiographic	Thermography	Acoustic resonance	Utrasonic
Delamination	×	✓	✓	✓	✓
Kissing bond	×	O	E	O	E
Porosity	×	✓	✓	✓	✓
Constriction	O	✓	✓	✓	✓
Faulty mixing ratio	×	✓	✓	✓	✓
Insufficient mixing	×	✓	✓	✓	✓
Missing adhesive	✓	✓	✓	✓	✓
Crack	×	O	O	O	✓

✓: Safely detectable, O: Conditionally detectable (depending on position and orientation), E: extension of method required, ×: not detectable. Source: own review of research literature

Structural adhesive bonding in automotive construction

Challenges from the user perspective

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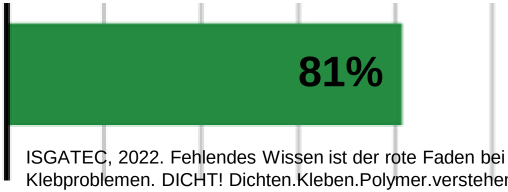

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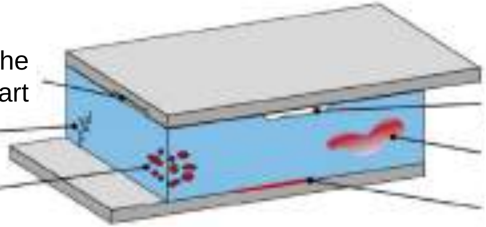


Many NDT methods available in research literature

- Problem 1: Method only validated in lab environment
- Problem 2: Method only suitable for lab environment or no implementation for industrial application

Aim of our work

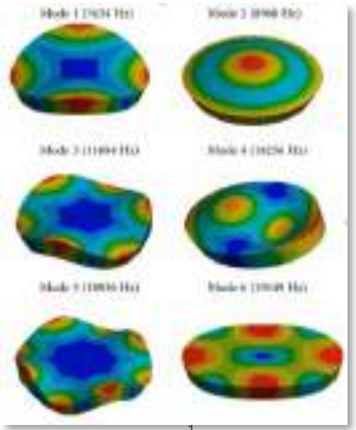
Pushing NDT of structural adhesive bonds from lab to in-line environment

(1) Why is Electromechanical Impedance (EMI) method a superior method for in-line NDT of structural adhesive bonds?

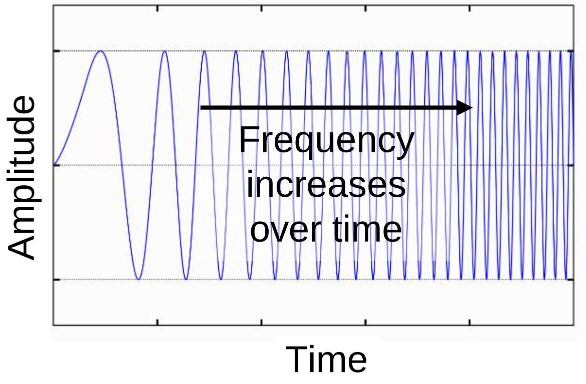
(2) How can EMI method be implemented for in-line quality assurance?

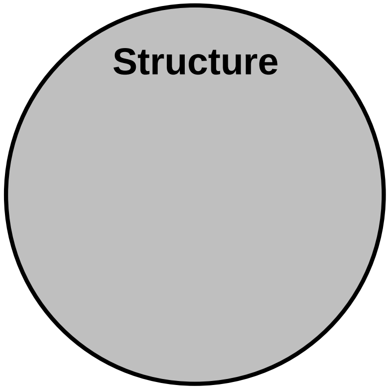
EMI-Method: Harmonic oscillation analysis

- Structure excited by sinusoidal signal containing great range of frequencies
- Structure oscillates at different specific frequencies (resonance frequencies) showing oscillation modes; other frequencies are damped.
- Spectrum = unique fingerprint of structure at the time of measurement

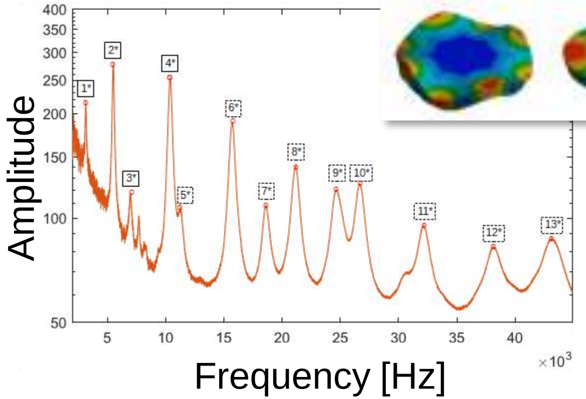


Excitation signal





Response signal of structure



EMI-Method: General implementation

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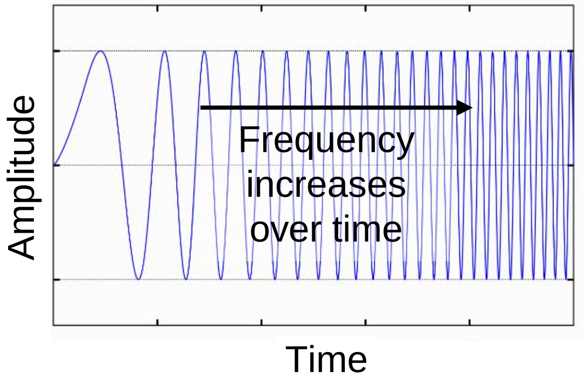
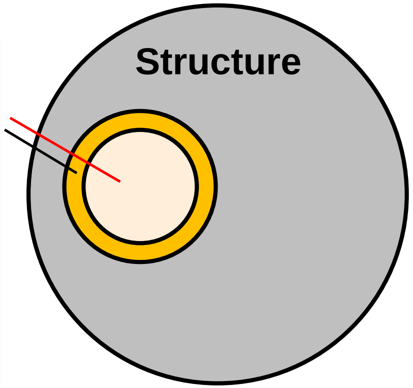
- Piezo element in contact with structure (bonding, clamping, …)
- Exciting Piezo by frequency sweep (increasing frequency over time)
- Electrical impedance of Piezo ~ Mechanical impedance of structure
- Piezo element as actor and sensor at the same time

Excitation signal





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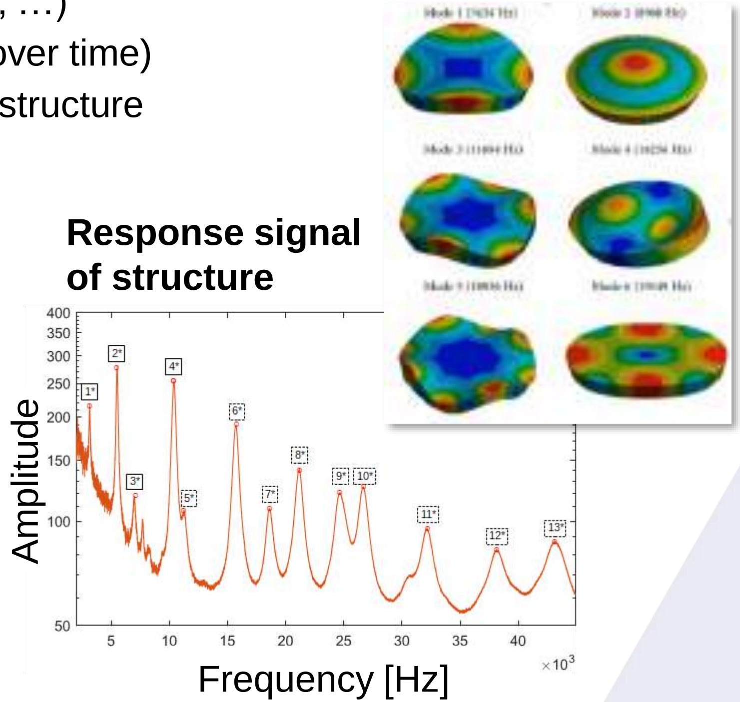
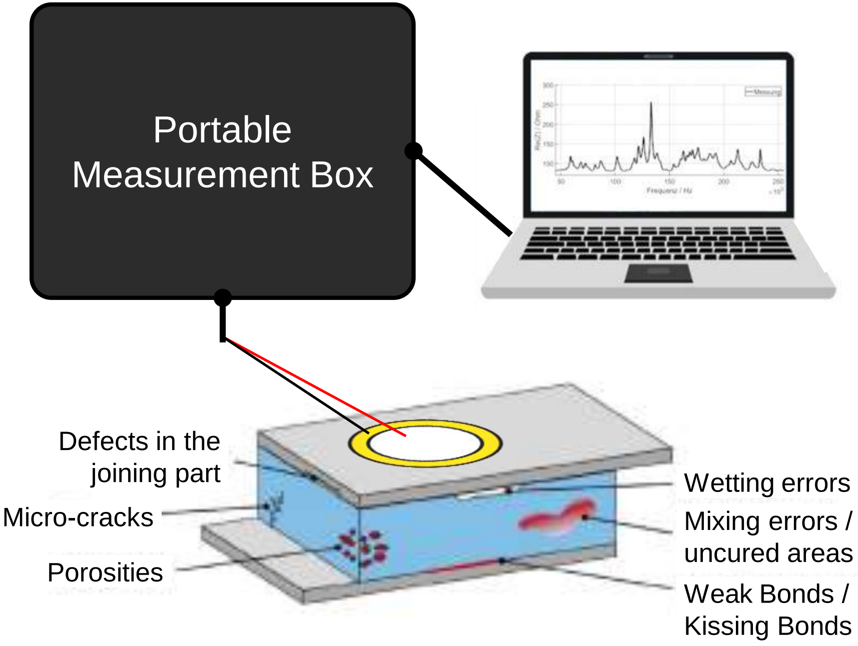


EMI-Method: Implementation for QA of adhesive bonds



EMI-Method: Implementation for QA of adhesive bonds

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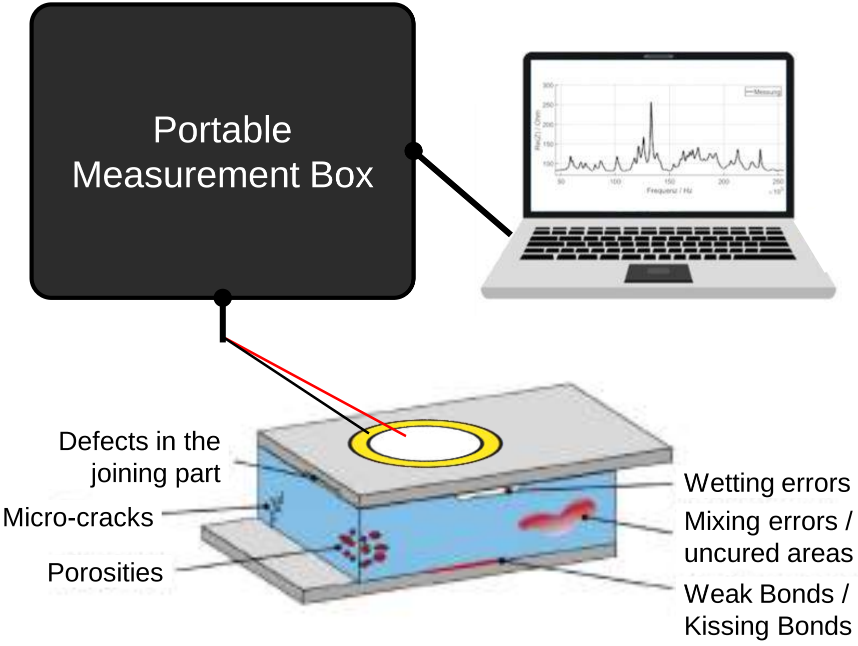
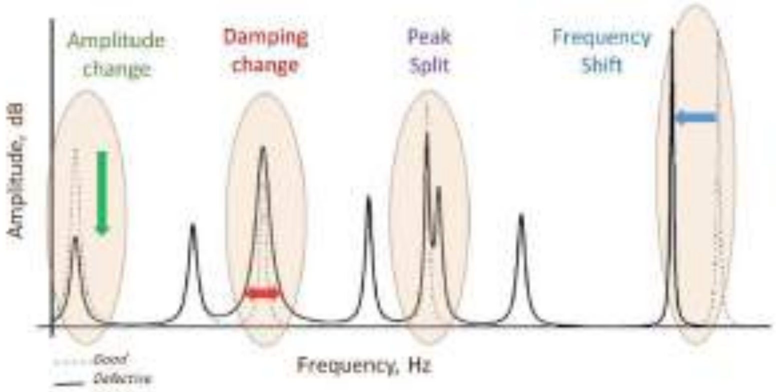


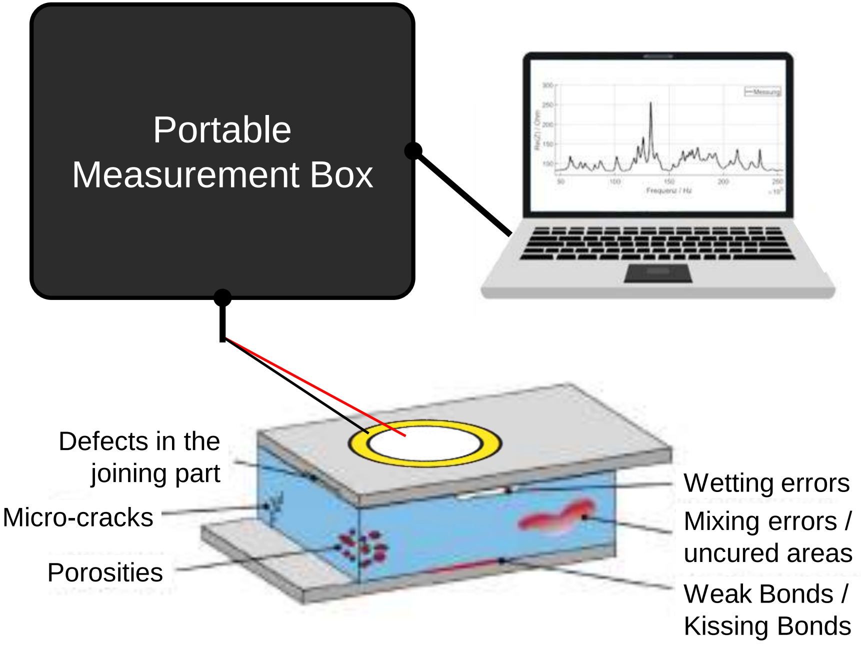
Basic measurement principle

(1) Obtain frequency fingerprints of reference bonds
(2) Obtain frequency fingerprint of another bond
(3) Compare both measurements
(4) Detect defects by changes in the spectrum
(5) Correlate defects and changes



Source: https://www.eddysonix.com/index.php/products/ar

EMI-Method: Implementation for QA of adhesive bonds



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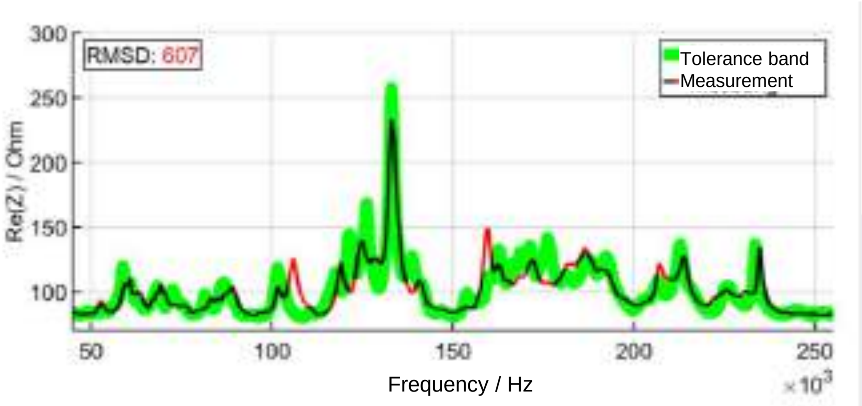
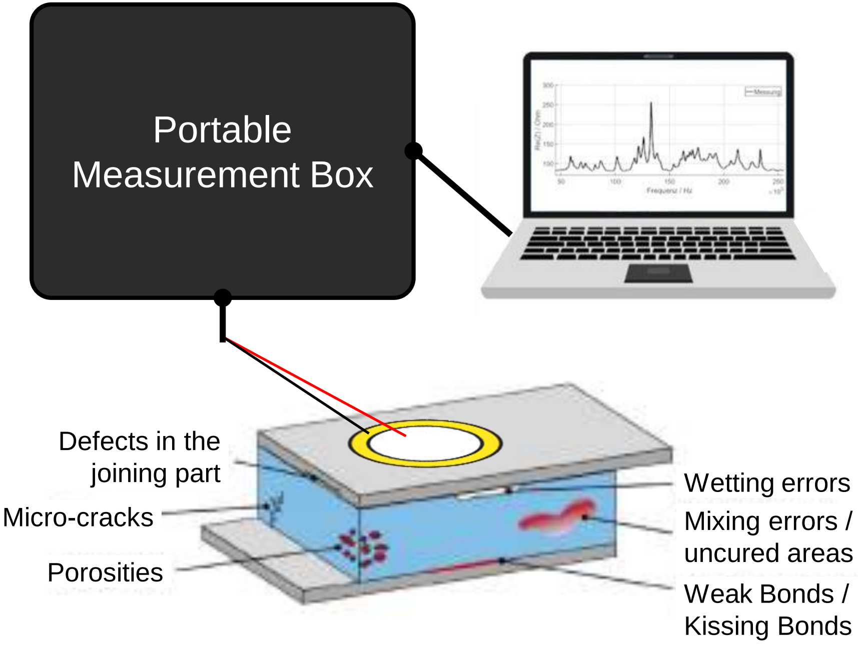


EMI-Method: Implementation for QA of adhesive bonds



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(2) Obtain frequency fingerprint of another bond
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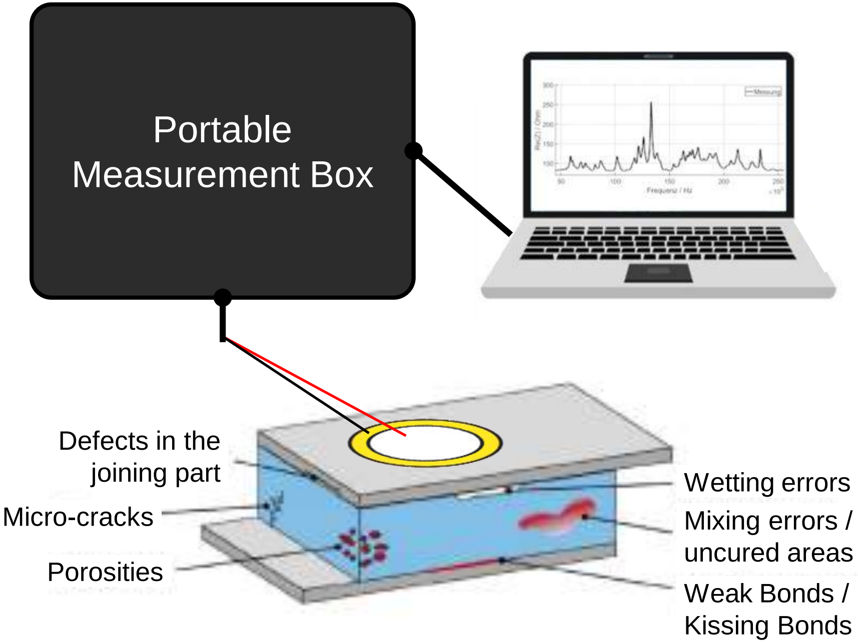
Advantages of EMI method

- Simple and cost-effective measurement setup
- Only one-sided accessibility required
- Duration of measurement: seconds
- Detection of defects shown in literature & own measurements (≈ ultrasound), very sensitive
- To ultrasonic testing: greater measurement range around piezo, comparable handling

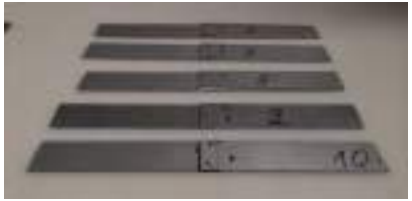
EMI-Method: Implementation for QA of adhesive bonds



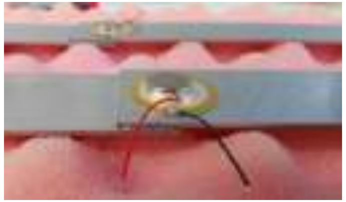
Current aim

Qualification of EMI method for industrial in-line environment on lap-shear samples considering all possible circumstances (→ **Lab to practical use**)

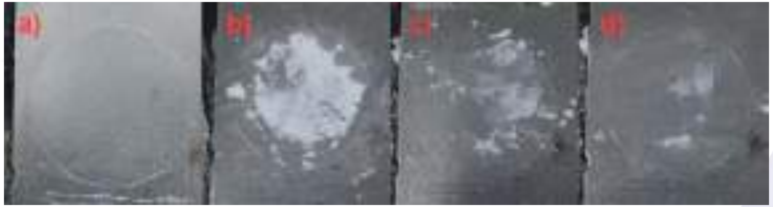
Construction-related variations



Coupling piezo-structure



Practical in-line challenges (uneven surface, dirt, scratches)



Further important things to work on

- Full qualification of suitability of EMI method for QA of adhesive bonds
  → **Which defects can be found/localized/quantified under which circumstances?**
- Implementation of a test head holding the piezo (analogue to ultrasonic testing)
- Further development of hardware and software for practical use on the assembly line

Any questions or use cases? Please contact me!

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Acknowledgment

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This work was developed in the context of the COST Action CA18120 (CERTBOND) and attendance at 2nd Training School and Final Conference were supported by COST (European Cooperation in Science and Technology).

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Bonded connection of recycled rubber decoupling system in infilled RC frames

Marko Marinković
Faculty of Civil Engineering, University of Belgrade, Serbia

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CWE Center for Wind and Earthquake Engineering

Outline

- Introduction
- Developed decoupling system
- Tests on bonded connection
- Results
- Conclusions

Introduction

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Masonry infill walls

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- Masonry infills: used to fill RC frames
- Exterior and interior walls
- Simple construction process
- Thermal and sound isolation
- Fire resistance
- Significant portion of the building inventory

Masonry infill walls

- RC frame structures

Extensive damage in earthquakes

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- Lorca, 2011

Extensive damage in earthquakes

Abbruzzo earthquake, 2009

Hermanns et al., 2013

Hermanns et al., 2013

Extensive damage in earthquakes

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2023 Turkey earthquakes

Extensive damage in earthquakes

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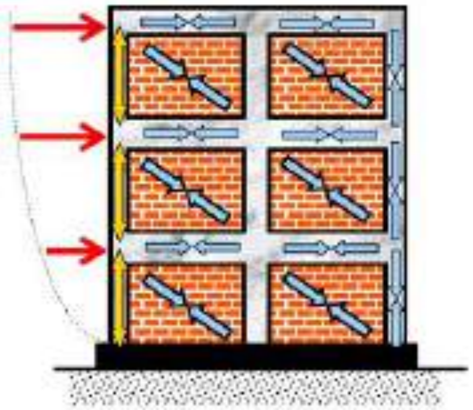

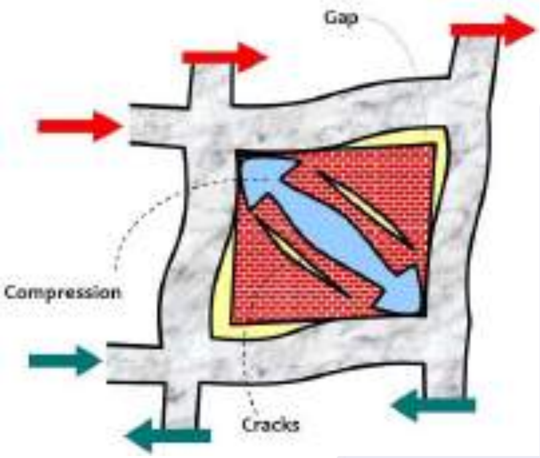

Proposals for improvement

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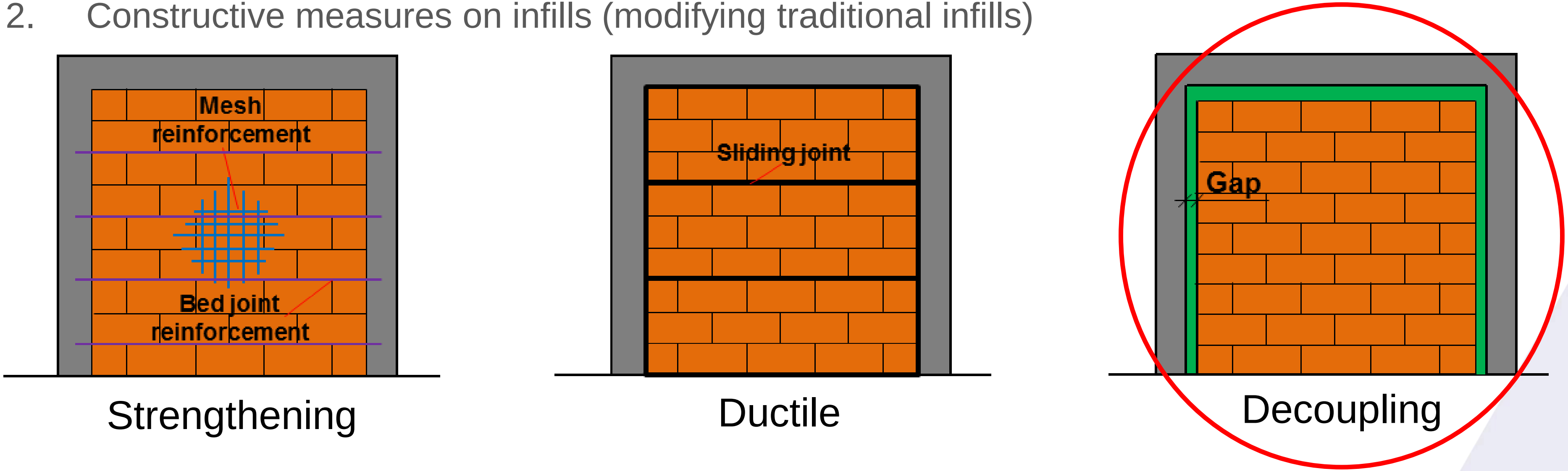
1. Reduction of interstorey drifts (increase of the size and number of the RC element, adding RC shear walls etc.) → not popular, limits the space etc.
2. Constructive measures on infills (modifying traditional infills)



- Decoupling (applicable to all types of the bricks, reduction of stress in infills and columns, providing out-of-plane restrain)

Marinković, M. and Butenweg, C. (2019). Innovative decoupling system for the seismic protection of masonry infill walls in reinforced concrete frames. *Engineering Structures*, 197, 109435.

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Proposed decoupling system

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System INODIS (Innovative Decoupled Infill System)

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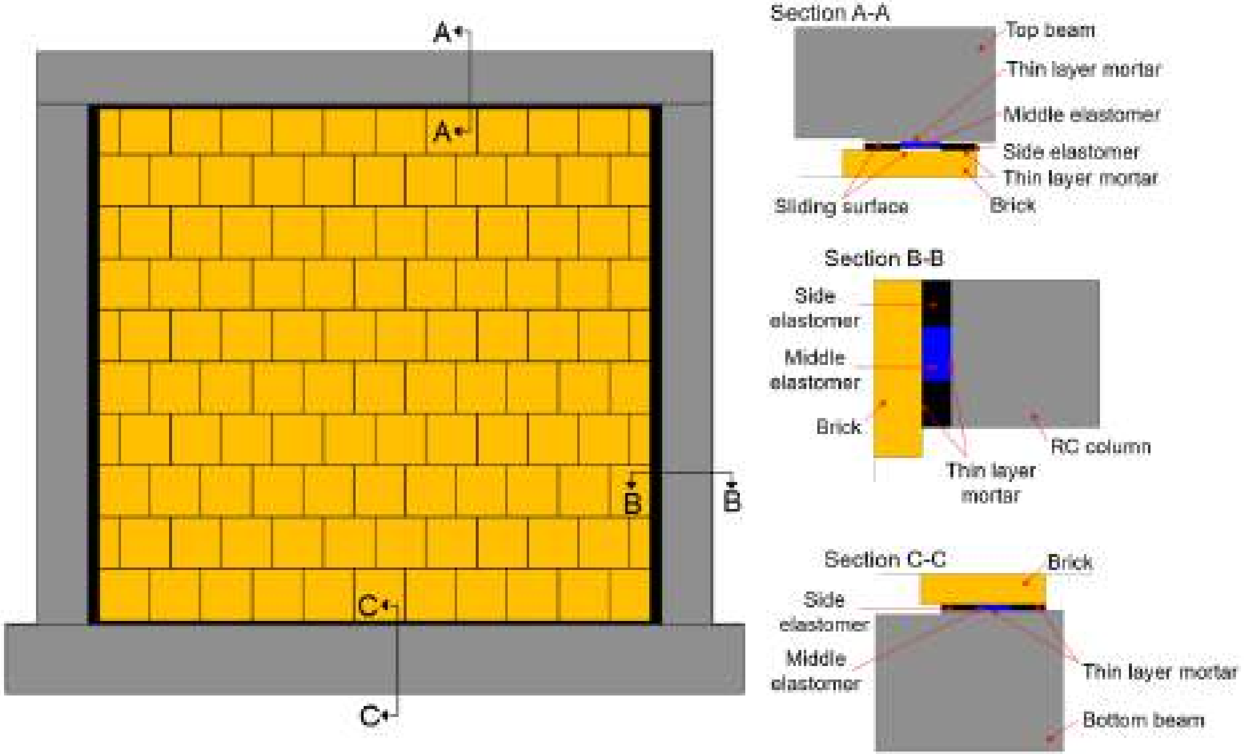
- Elastomer between the frame and infill at the top and sides
- In-plane decoupling
- Damage reduction
- Recycled rubber
- Horizontally movable
- Out-of-plane restrain



Tests on bonded connection

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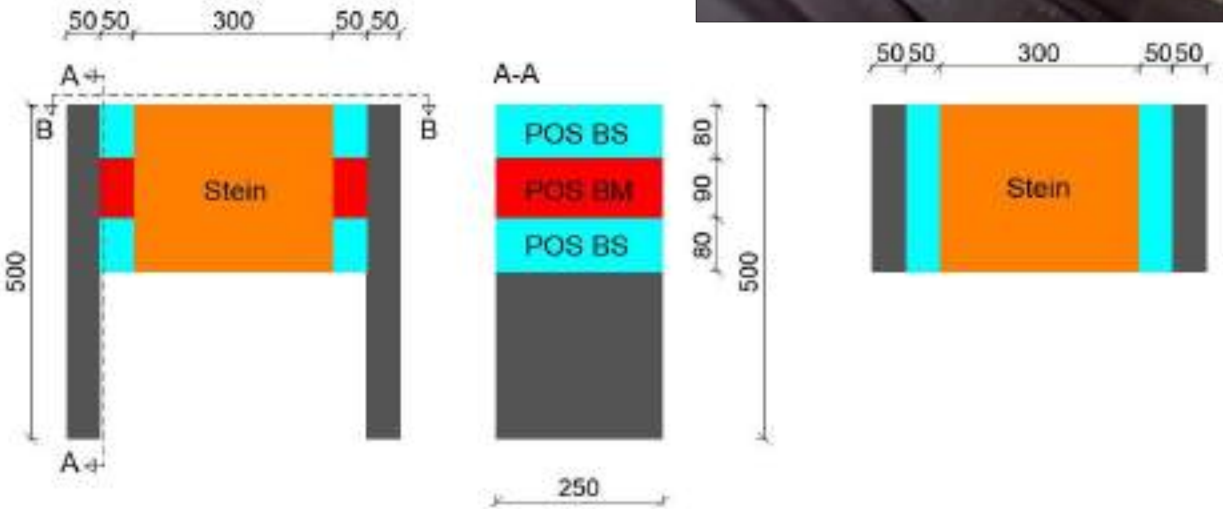
Test setup

- Glued bond
- Load bearing capacity

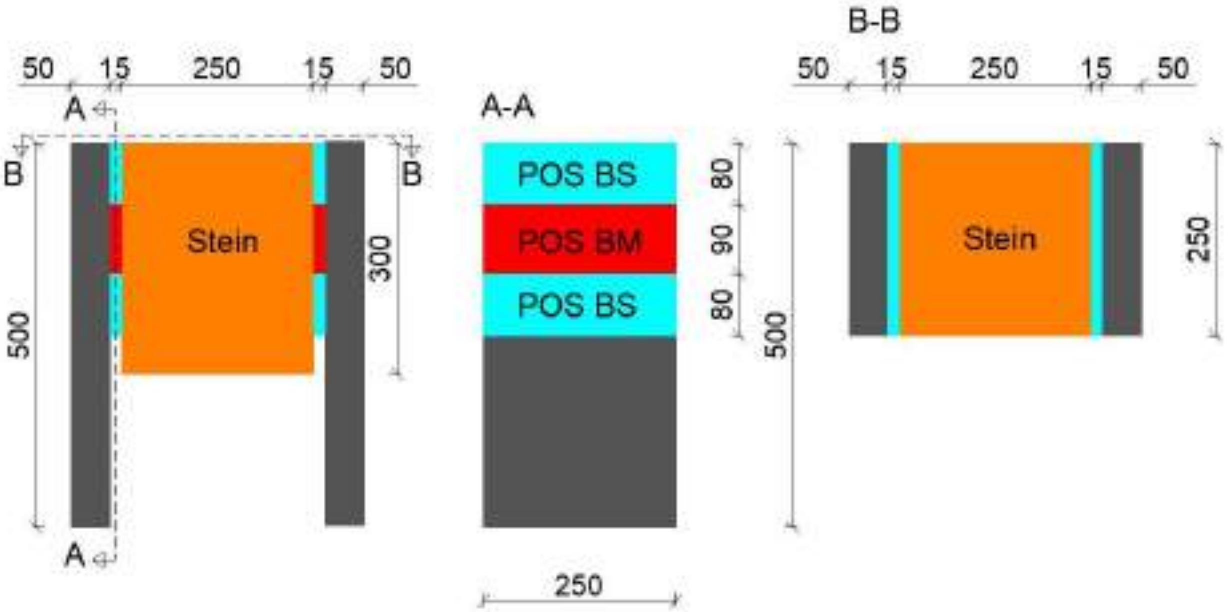
a) Connection to the columns



Test setup

- Glued bond
- Load bearing capacity

b) Connection to the top beam



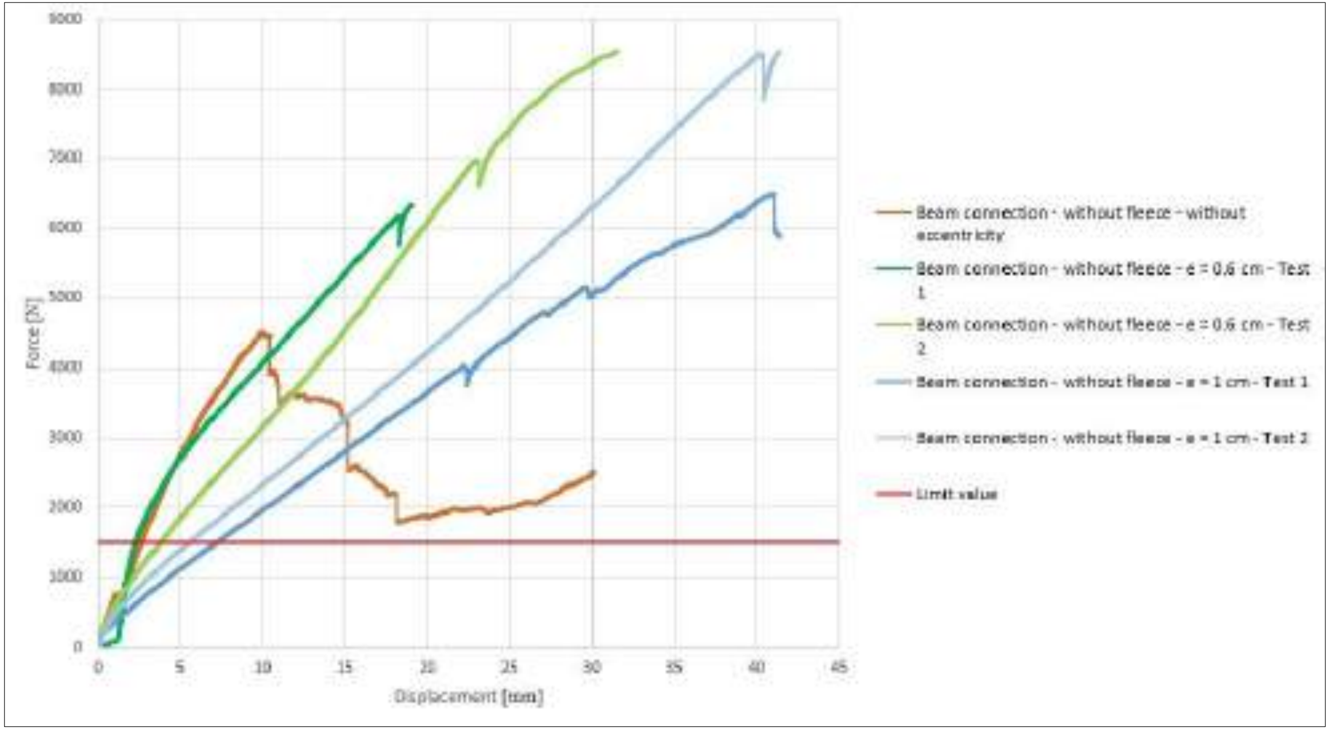
Test setup

- Different loading conditions

Test	Fleece	Eccentricity	Number of tests	Capacity [kN]
Beam connection	No	No	1	4.5
		0.6 cm	2	6.1 / 7
		1 cm	2	6.4 / 8.5
	Yes	No	1	4
		0.6 cm	1	2.1
		1 cm	1	3
Column connection	No	No	1	3.5
		2 cm	2	2.2 / 2.2
		3 cm	2	1.4 / 1.75
	Yes	No	1	2.5
		2 cm	1	1.75
		3 cm	1	1.6

Results

- High load levels
- Can be used in regions with high seismicity level



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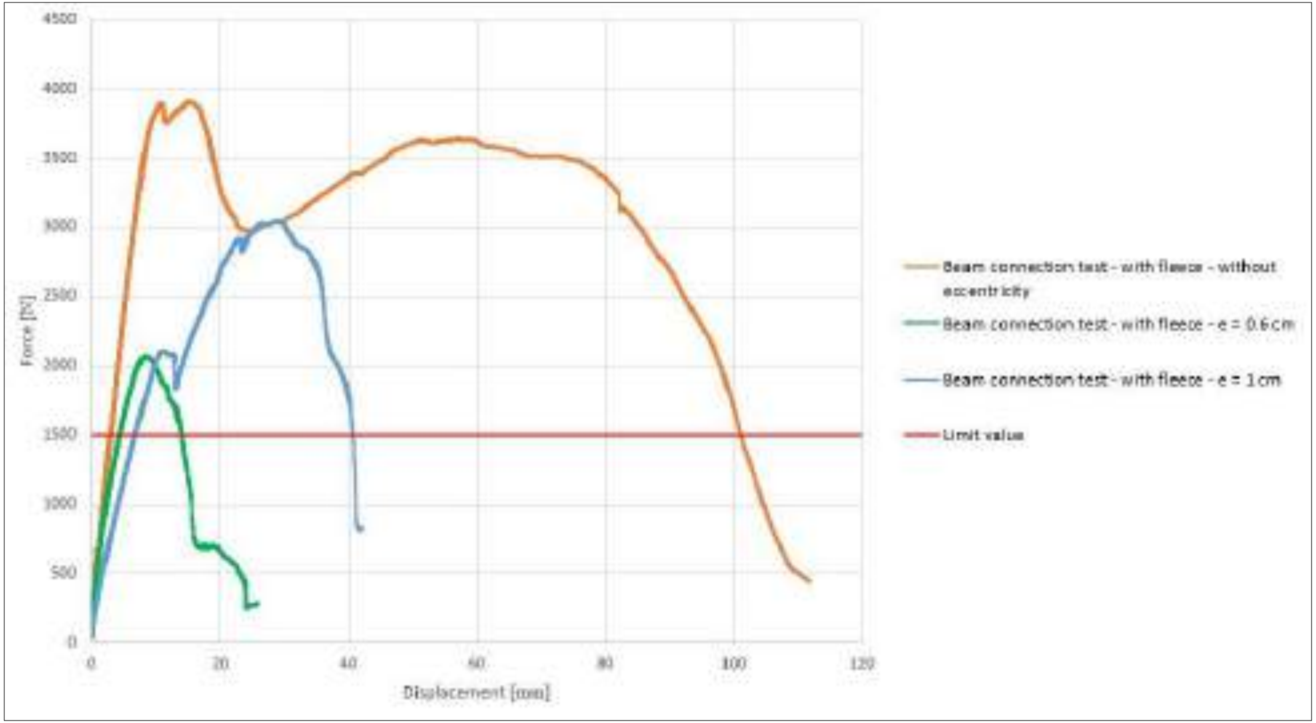

Conclusions

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Conclusions

- Decoupling of frame and infill
- Rubber-based material is adequate for infills decoupling
- Postponed activation of infill wall
- Bonded connection is designed for combined loading

→ continuous and stable connection

- Prevention of stress concentrations in the frame
- Simple and reliable design
- Applicable to all types of bricks
- Cheap and easy to apply in practice

Thank You!

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This presentation is based upon work from COST Action CA18120 (CERTBOND - https://certbond.eu/), supported by COST (European Cooperation in Science and Technology).

Part of the work on connection tests was done during the STSM of COST Action CA18120 (CERTBOND – https://certbond.eu/), supported by COST (European Cooperation in Science and Technology).

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Uncertainty Quantification in the analysis of adhesive bonds

CERTBOND Final Conference, 06/09/2023

Fabio Santandrea, RISE – Research Institutes of Sweden

This presentation is based upon work from COST Action CA18120 (CERTBOND - https://certbond.eu/), supported by COST (European Cooperation in Science and Technology).

Outline

- What is Uncertainty Quantification?
- Highlights from literature
- Role of UQ in product certification
- Take-home message

What is UQ

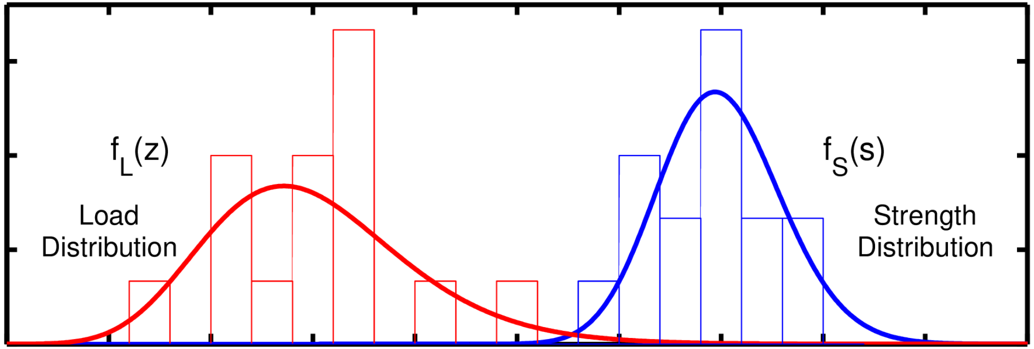
Uncertainty in load

Will the product performs as expected in its intended application?

Uncertainty in strength

- **Site variations**
- **Environment**
- **Load estimation**

- **Material**
- **Manufacturing**
- **Life modelling**
- **Life testing**



Load/ Demand

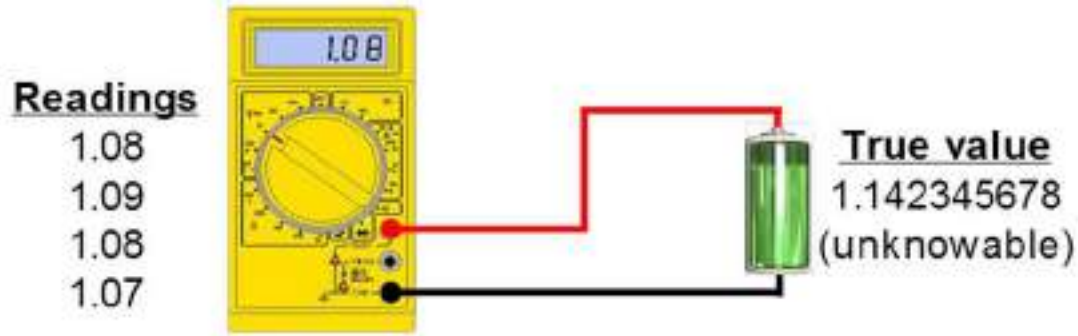
Strength/ Capacity

Predictions are uncertain

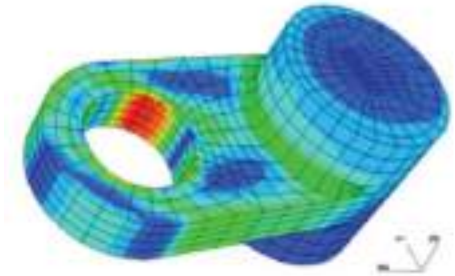
Uncertainty = deviation from (unknown) truth

How to cope with uncertainty?

Models development and testing in controlled environment



Physical
&
Virtual



Highlights from literature

Contents lists available at ScienceDirect

International Journal of Adhesion and Adhesives

journal homepage: www.elsevier.com/locate/ijadhadh

Are probabilistic methods a way to get rid of fudge factors? Part I: Background and theory

Till Vallée[a,*], Marvin Kaufmann[a], Robert D. Adams[b], Matthias Albiez[c], João R. Correia[d], Thomas Tannert[e]

[a] Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM, Wiener Str. 12, 28359, Bremen, Germany
[b] Department of Engineering Science, University of Oxford, Parks Road, Oxford, UK
[c] KIT Stahl- und Leichtbau, Versuchsanstalt für Stahl, Holz und Steine, Karlsruhe Institute of Technology, Karlsruhe, Germany
[d] CERIS, Instituto Superior Técnico, University of Lisbon, Av. Rovisco Pais, 1049-001, Lisboa, Portugal
[e] Integrated Wood Design, University of Northern British Columbia, University Way, 3333 Prince George BC, Canada V2N 4Z9

Link to Part I (theory)

Link to Part II (applications)

Highlights from literature

- Context: prediction of failure of adhesive joints (stress concentration, brittleness, scatter in material strength)
- Shortcomings of capacity verification in continuum mechanics ($S \leq R$):

$$\sigma_{max} = \frac{N}{A} \pm \frac{M}{W} \leq f_R \rightarrow \sigma_{max} \leq \kappa f_R$$

- Practical use of fracture mechanics is often limited (extensive experimental characterization and numerical processing)

- Probabilistic methods: rationale to make fudge factors unnecessary
- Proposed approach: $S \leq R \rightarrow p_f = \prod_{i=1}^{n} \exp\left(-\frac{V_i}{V_0}\left(\frac{\phi_i(\sigma,\tau)-\gamma}{\beta}\right)^{\alpha}\right)$

  Breaking load from given p_f (e.g., 0.5) → predictive capacity verification

Highlights from literature

Example from the past

Monte Carlo techniques applied to finite element modelling of adhesively bonded joints

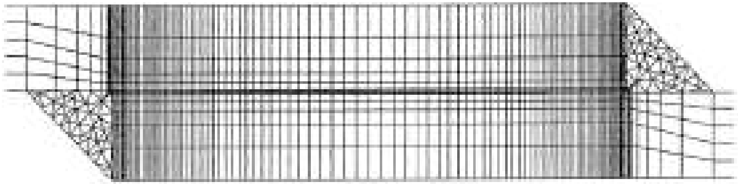
G. Van Vinckenroy, W.P. De Wilde

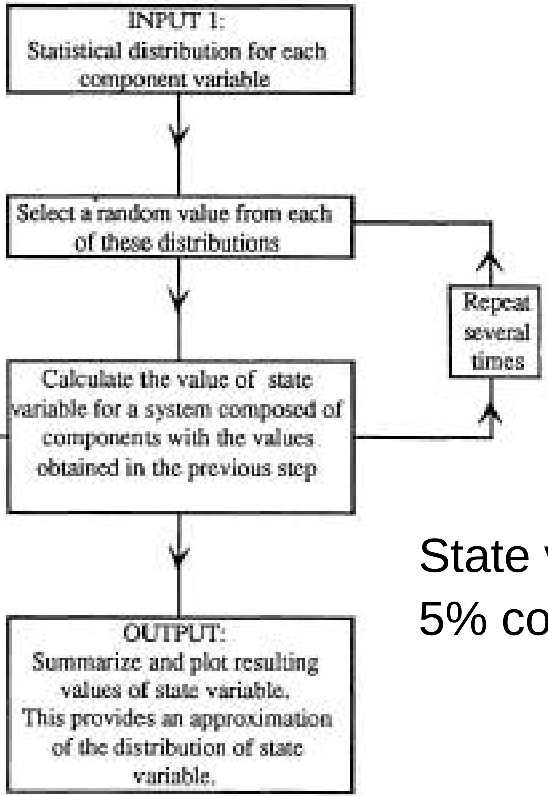
Analyse van Strukturen - Vrije Universiteit Brussel, Pleinlaan, 2 1050 Brussel, Belgium

Transactions on Modelling and Simulation vol 5, © 1993 WIT Press, www.witpress.com, ISSN 1743-355X

link

Highlights from literature





Material: / Property:	strength	Young's modulus	Poisson's ratio
Aluminium:	Weibull (corr. = 0.987) η = 481.6930 σ = 482.4364	Weibull (corr. = 0.962) η = 58.8986 σ = 72.7797	Log- Normal (corr. = 0.893) μ = −1.1143 σ = 0.0097
Adhesive:	Log- Normal (corr. = 0.966) μ = 3.8712 σ = 0.0120	Log- Normal (corr. = 0.985) μ = −0.9187 σ = 0.0537	Log- Normal (corr. = 0.893) μ = −0.9408 σ = 0.0319

State variable = peel stress σ_y

5% cov input → 10% cov output

Highlights from literature

Example from the present

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

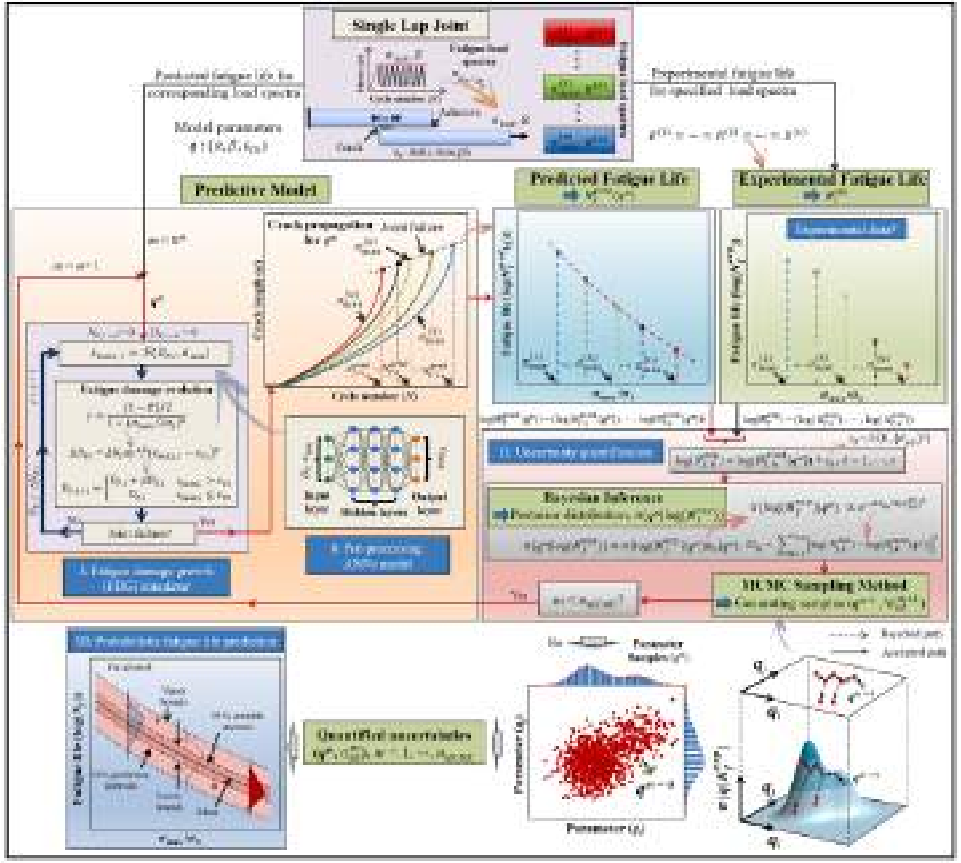
A probabilistic fatigue life prediction for adhesively bonded joints via ANNs-based hybrid model

Karthik Reddy Lyathakula, Fuh-Gwo Yuan *

Department of Mechanical and Aerospace Engineering, North Carolina State University, Raleigh, NC 27695, USA

https://doi.org/10.1016/j.ijfatigue.2021.106352

Highlights from literature



UQ and certification

On certifying adhesively bonded structures in different industries

F. Santandrea[1], G. G. Momm[2], P. Tsokanas[3], V. Rajcic[4], D. Skejic[4], T. Kruse-Strack[5], D. Rajnovic[6], L. F. M. da Silva[7]

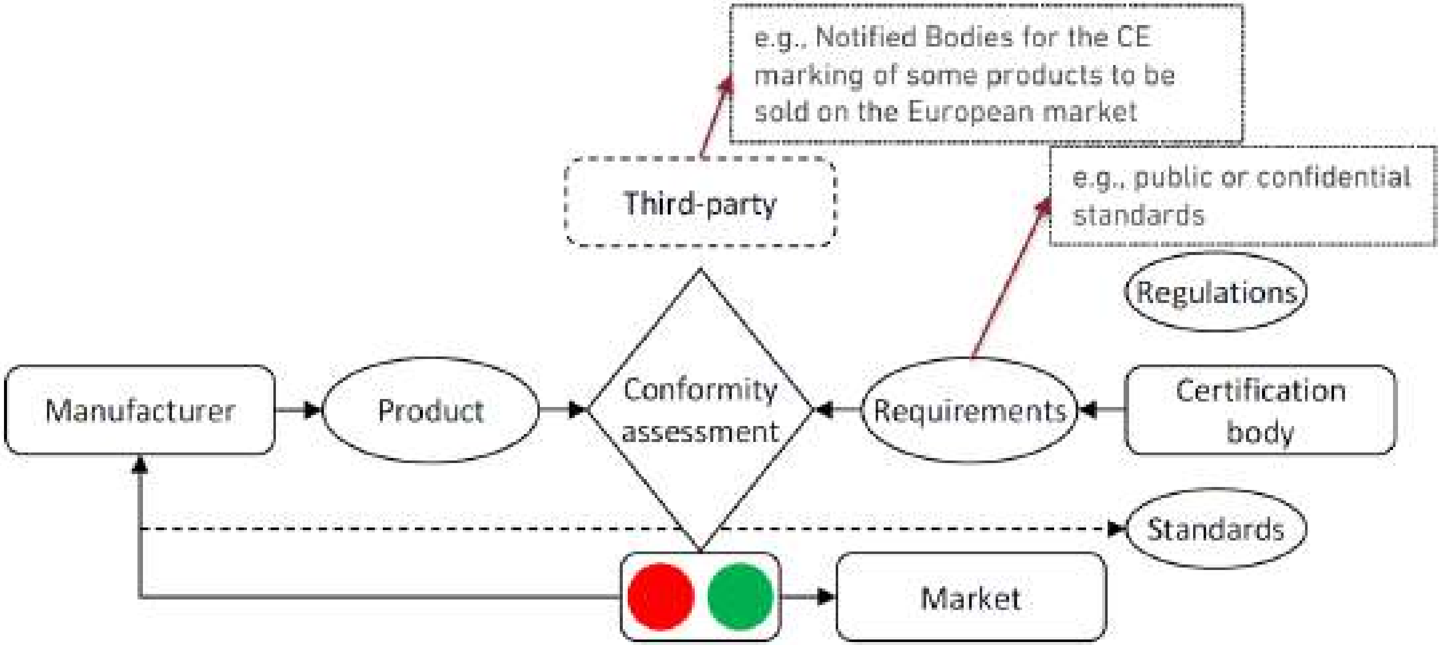
Review of certification schemes for bonded structures in various industrial sectors:

- Civil aviation
- Building
- Maritime
- Automotive

Presented at DMRS
Porto, 17 March 2023

UQ and certification

- **Certification (ISO's definition):** *"The provision by an independent body of written assurance (a certificate) that the product, service, or system in question meets specific requirements"*



On certification-by-analysis

- There is a significant time lag between (*adoption of simulations by manufacturers*) and (*acceptance of simulations in regulations*) and therefore (*acceptance of simulations by certification bodies*) – with some recent exceptions (e.g. FDA).

- The problems with simulation for Certification Bodies (CB)*:
  - (Necessarily) limited information from manufacturers — (CBs) no access to full checks and validation knowledge done in years at Ms. Limited knowledge of organisational processes.
  - Organisations use different tools — Limited knowledge of capabilities and weaknesses of tools.
  - Computational process is a ”black box” — How to ensure the results are real and not manipulated.

*H. Ro… NAFEMS Seminar on ”Simulation supporting certification” 22-23 June 2021

On certification-by-analysis

Challenges to achieve *trust* and *confidence*:

- Regulations must be clear on the requirements (specifically, for simulations).
  - Requirements about model features or credibility (?)
- Traceability and credibility of the simulation toolchain
- Transparency, standards and rigour
- Development of a shared understanding between industry and regulators
- Quality Management of the toolchain
- Ongoing dialogue between industry and regulators
  - Reporting of anomalies after certification
  - Information on tool changes or upgrades
  - Ongoing reduction of the risks inherent to simulations (?)

*H. Ross (VCA), presented at NAFEMS Seminar on ”Simulation supporting certification” 22-23 June 2021

RI.
SE

Take-home message

- Would the development of novel certification schemes for primary bonded structures increase the acceptance of adhesive bonding in industry?

- Would the explicit consideration of uncertainty in the design process contribute to establish more confidence in the structural performance of adhesive bonding? (That is, analysis of variability instead of ”fudge” factors (e.g. safety factors or fitting parameters→ paper by Vallée et al)

- The problem of defining a transparent and practical process to assess the predictive capability of numerical models is getting more relevant as product development relies more and more on virtual testing.

- Let’s collaborate to address these (and other) questions! ☺

Fabio Santandrea

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Mechanical performance of adhesives based on polyols from depolymerization of lignocellulose biomass

Edina Rusen[1], Gabriela Toader[2], Aurel Diacon[1,2], Florin Marian Dîrloman[2],
Liviu Cristian Matache[2], Florentina Alexe[3], Adrian Dinescu[4], Alexandra Mocanu[1,4*]

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COST EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Funded by the European Union

Outline

- 1. Introduction
  - Biomass – definition and context
  - The purpose of our study
- 2. Materials synthesis
  - Polyols synthesis from lignocellulose biomass
  - Polyurethane adhesive formulations
- 3. Characterization
- 4. Results and discussions
- 5. Conclusions

1. Introduction

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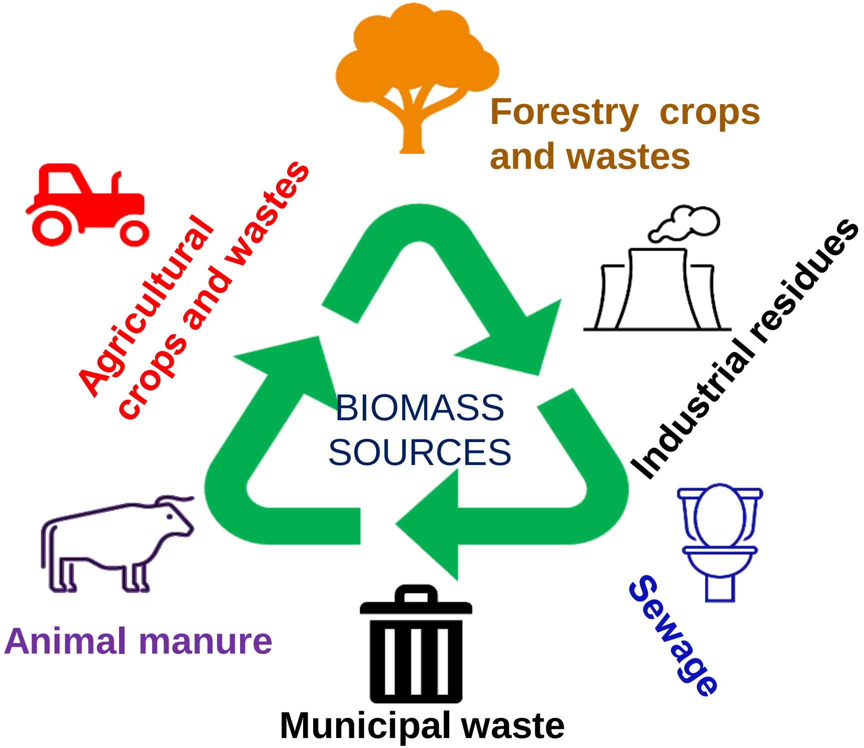
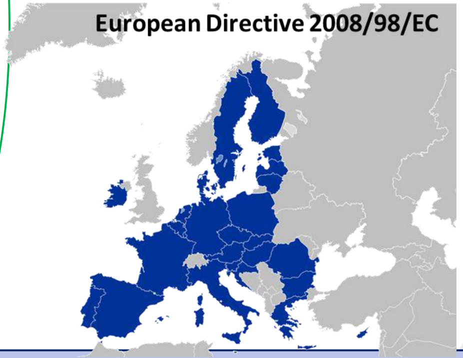
Mechanical performance of adhesives based on polyols from depolymerization of lignocellulose biomass

Biomass definition and context



Biomass (ecology) - the weight or total quantity of living organisms of one animal or plant species (species biomass) or of all the species in a community (*community biomass - commonly referred to a unit area or volume of habitat*).

Biomass (bioenergy) - matter from recently living (but now dead) organisms



Biomass - means the biodegradable fraction of products, waste and residues from biological origin from agriculture, including vegetal and animal substances, from forestry and related industries, including fisheries and aquaculture, as well as the biodegradable fraction of waste, including industrial and municipal waste of biological origin used to produce **energy/fuels**

Mechanical performance of adhesives based on polyols from depolymerization of lignocellulose biomass

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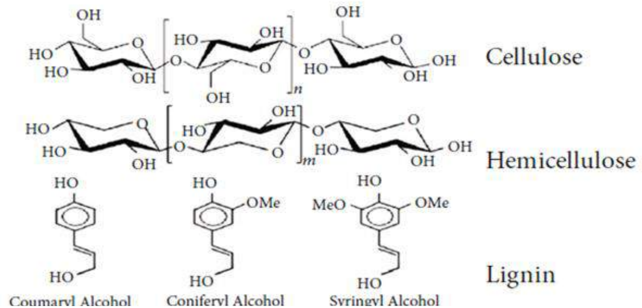
Project GREENOL – Biopolyols obtained by waste valorization through unconventional technology (POC – European financing)

Wood panels

Lignocellulosic biomass



Cellulose, hemicellulose and lignin structure

REACH REGULATIONS – Registration, Evaluation, Authorisation and Restriction of Chemicals

Valorization through microwave technology of lignocellulosic biomass to create added value products

Forestry wastes **Agricultural wastes**

↓

Microwave technology

↓

- ❖ Polyurethane foams
- ❖ Polyurethane adhesives
- ❖ Filling agents for composites

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2. Materials and methods

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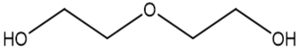
Our strategy

Project GREENOL – Biopolyols obtained by waste valorization through unconventional technology

Lignocellulose glycolysis

Birch saw dust



HO O OH

diethylene glycol

Acid catalyst

160 °C,
4 hours

Cakes after filtration

❖ Filling agents for composites

Glycolysis products after filtration

❖ Polyurethane adhesives

❖ Polyurethane foams

3. Characterization

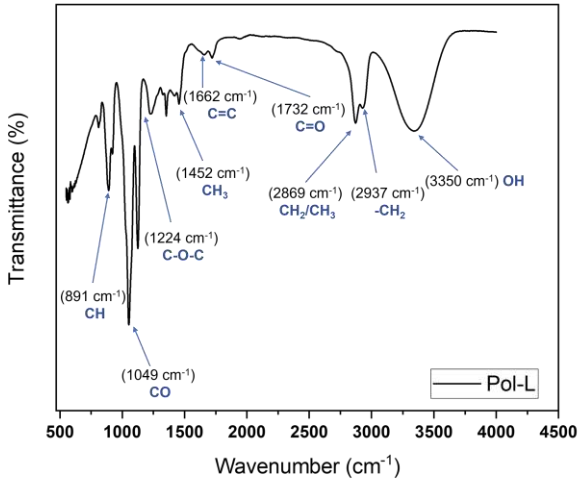
Mechanical performance of adhesives based on polyols from depolymerization of lignocellulose biomass

Synthesis and characterization of glycolysis product

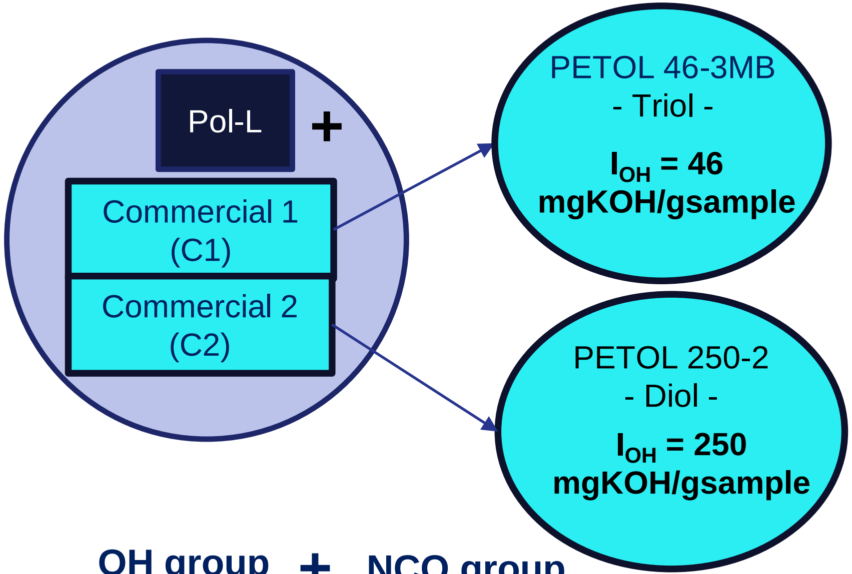
Sample	Biomass, g	Solvent (DEG), g	Catalyzer, mL	Acid catalyzer	Temperature, °C	Time, h	I_{OH}, mgKOH/gsample*
Pol-L	15	145	4	Sulfuric acid	160	4	466,9

*ASTM D4274-99-Method A

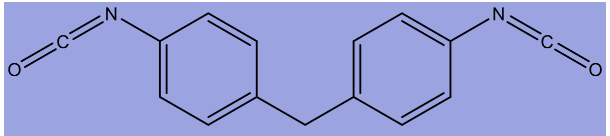
FT-IR analysis



Mechanical performance of adhesives based on polyols from depolymerization of lignocellulose biomass



OH group + NCO group



4,4'-methylenediphenyl diisocyanate

Polyurethane Adhesive Formulations						
Sample	Polyols			NCO/ OH ratio	Blank sample	NCO/ OH ratio
A1	Pol-L	C1	C2	1.8	M1	1.8
A2	Pol-L	C1	C2	1.7	M2	1.7
A3	Pol-L	C1	C2	1.6	M3	1.6
A4	Pol-L	C2	C1	1.5	M4	1.5
A5	Pol-L	C2	C1	1.4	M5	1.4
A6	Pol-L	C2	C1	1.3	M6	1.3

4. Results and discussions

Mechanical performance of adhesives based on polyols from depolymerization of lignocellulose biomass

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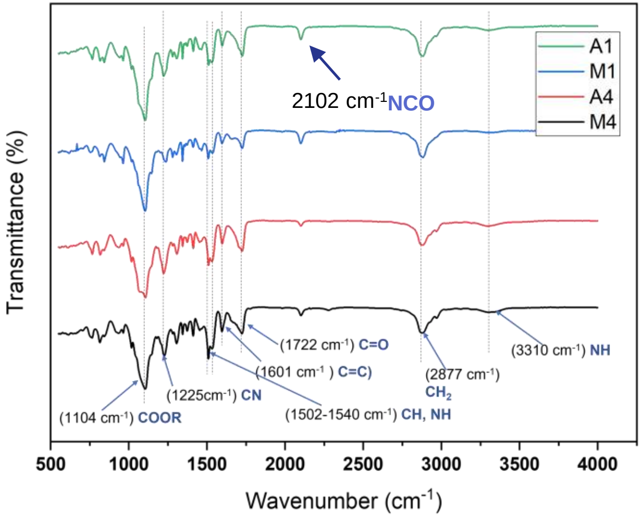
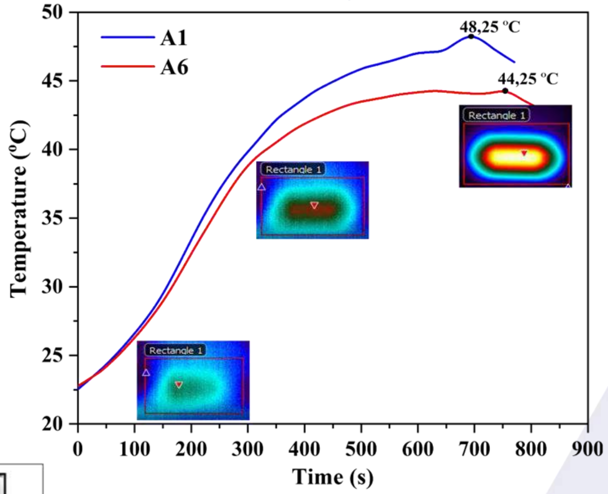
FT-IR analysis of adhesives formulations



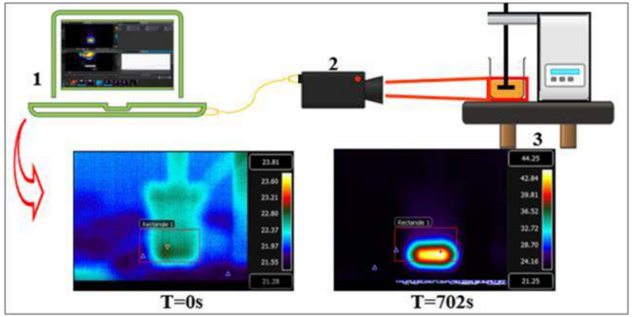
Determination of pot life/working time



1 – data acquisition

2 – FLIR camera

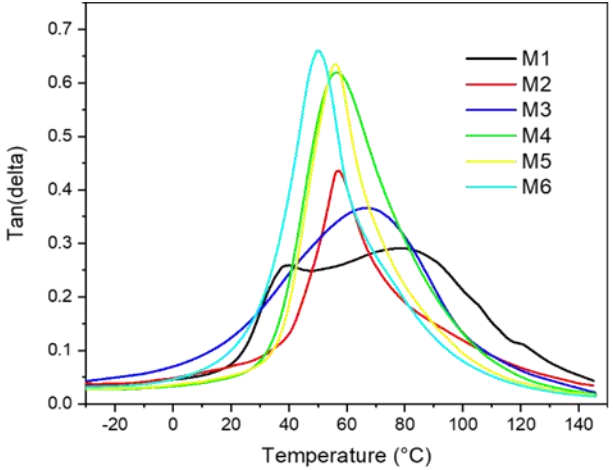
3 – mixture stirring



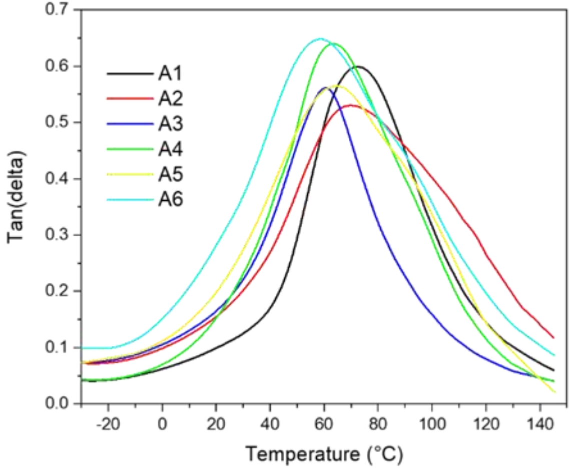
Mechanical performance of adhesives based on polyols from depolymerization of lignocellulose biomass

DMA analysis

DMA analysis of blank formulations



DMA analysis of Pol-L based adhesives formulations

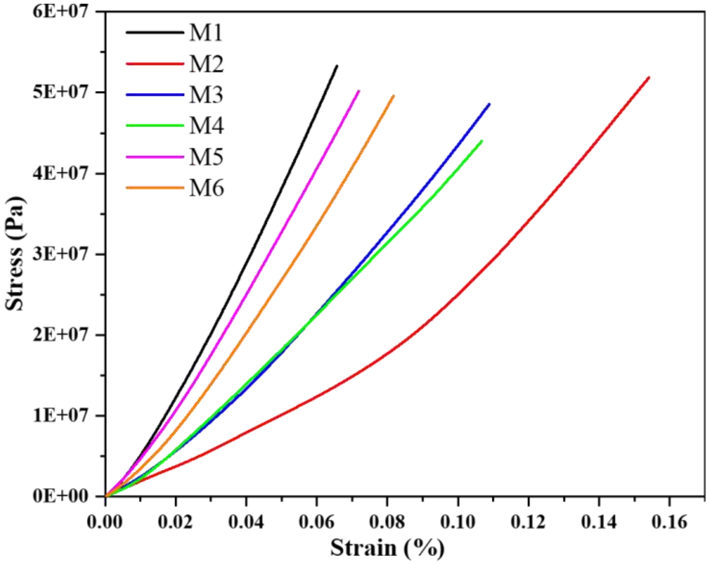


Sample	Tg (°C)	Sample	Tg (°C)
M1	80	**A1**	**73**
M2	57	**A2**	**69**
M3	65	**A3**	**60**
M4	56	**A4**	**63**
M5	55	**A5**	**63**
M6	50	**A6**	**58**

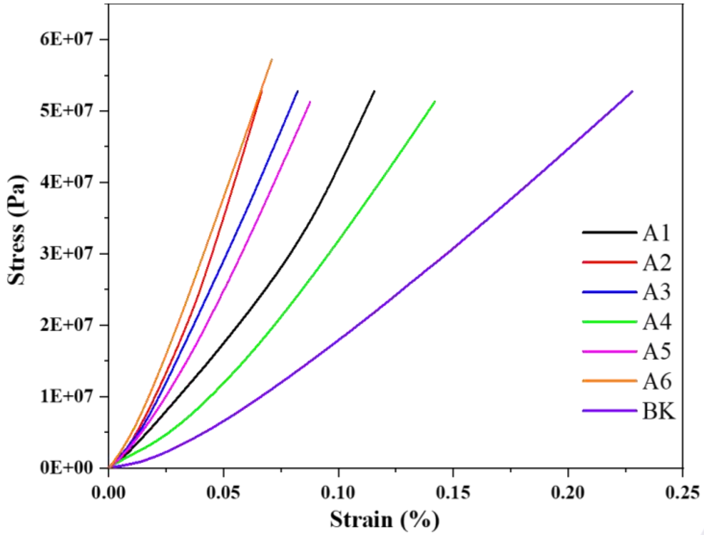
Mechanical performance of adhesives based on polyols from depolymerization of lignocellulose biomass

3 point bending mechanical test – Stress vs. strain*

Bending tests for blank samples



Bending tests for Pol-L based adhesive formulations



*adjustment of the ASTM D790-17

BK – wood specimens without adhesive

Mechanical performance of adhesives based on polyols from depolymerization of lignocellulose biomass

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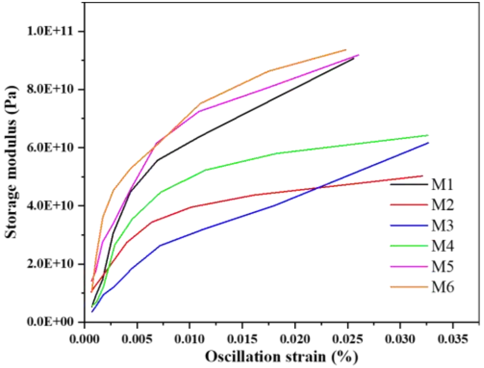
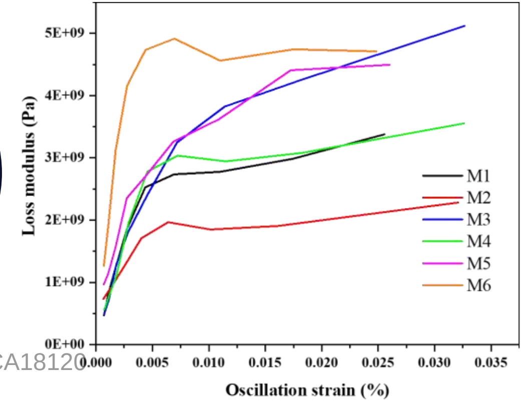
3 point bending mechanical test – Stress vs. strain

Bending tests for blank samples

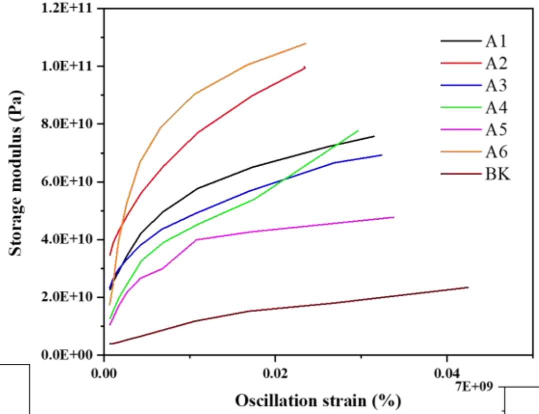




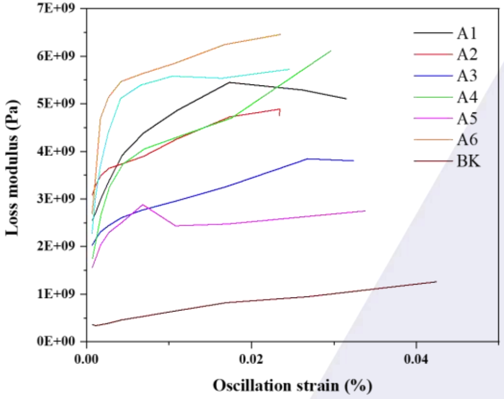
Testing Conditions

Room temperature
1 Hz
Amplitude 10 ÷100μm

Bending tests for Pol-L based adhesive formulations



**BK – wood specimens without adhesive*



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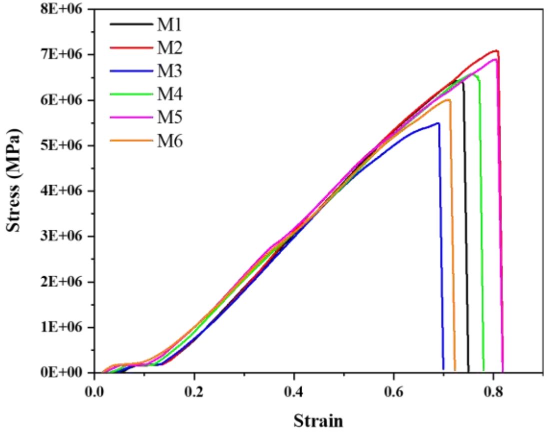
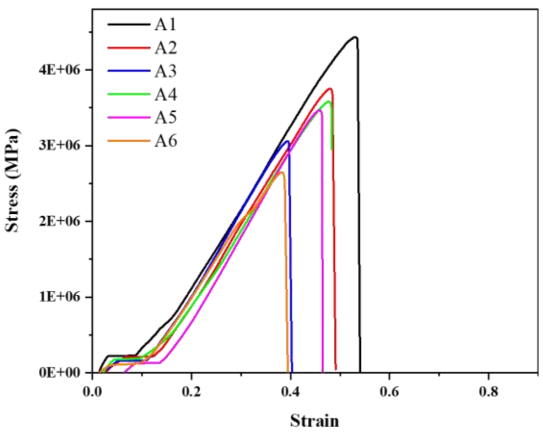
Tensile tests*





The values of maximal failure stress and failure strain for all PUR adhesive specimens

Sample	Failure Stress (MPa),	Failure strain	Sample	Failure Stress (MPa)	Failure strain	MDI, %
M1	6.4 ± 0.20	0.7 ± 0.020	A1	4.4 ± 0.16	0.53 ± 0.014	45.9
M2	7 ± 0.15	0.8 ± 0.013	A2	3.7 ± 0.18	0.48 ± 0.011	44.4
M3	5.5 ± 0.12	0.68 ± 0.021	A3	3.1 ± 0.23	0.39 ± 0.016	42.8
M4	6.5 ± 0.21	0.76 ± 0.016	A4	3.6 ± 0.19	0.47 ± 0.015	45.9
M5	6.8 ± 0.10	0.8 ± 0.13	A5	3.5 ± 0.12	0.45 ± 0.010	44.4
M6	6 ± 0.17	0.71 ± 0.014	A6	2.6 ± 0.11	0.38 ± 0.017	42.8

**EN 205-2016 (Wood adhesives for non-structural applications – Determination of tensile shear strength of lap joints)*

Mechanical performance of adhesives based on polyols from depolymerization of lignocellulose biomass

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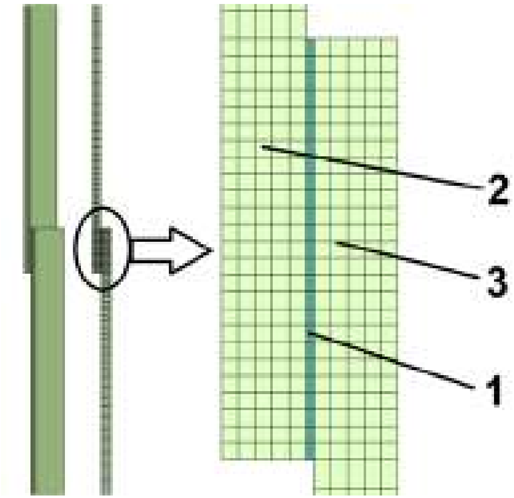
LS-DYNA tensile test modeling – EN ISO 1421



Simulated model of the adhesive joint –
1 – adhesive; 2 – mobile wood strip;
3 – fixed wood strip

Simulation analysis

Conditions

Three dimensions -**hexahedral mesh**, with SOLID 3 type elements, fully integrated quadratic 8 node element with nodal rotations.

Nodes	Elements	Parts	Materials
15 750	13 000	3	2

Mechanical performance of adhesives based on polyols from depolymerization of lignocellulose biomass

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LS-DYNA tensile test modeling – EN ISO 1421

Simulation analysis

Plastic-kinematic material model

Conditions

Cowper-Symonds model*

$$\sigma_y = \left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{\frac{1}{P}}\right]\left(\sigma_0 + \beta E_p \varepsilon_p^{eff}\right)$$

$$E_p = \frac{E_{tan} E}{E - E_{tan}}$$

σ_0 - initial yield stress
ε - is the strain rate
C and P – the Cowper–Symonds strain rate parameters
β – the strain hardening parameter, (adjusts the contribution of isotropic and kinematic hardening)
$\varepsilon^{ff}{}_p$ - the effective plastic strain
Ep - the plastic hardening modulus which is given in terms of the elastic modulus E and the tangent of elastic modulus Etan

Nr. crt.	Component	Material	ρ (Material density, g/cm³)	E (module of elasticity, MPa)	v (Poisson's coefficient)	σ_y (tension at flow)	E_{tan}
1.	Adhesive	Polyurethane	1,0	2	0,35	1	0

Mechanical performance of adhesives based on polyols from depolymerization of lignocellulose biomass

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LS-DYNA tensile test modeling – EN ISO 1421

Elastic material model

Conditions

$$F_i^{n+1} = F_i^n + \left(1 + \frac{DA}{\Delta t}\right) \cdot \Delta F_i^{n+\frac{1}{2}}$$

$$M_i^{n+1} = M_i^n + \left(1 + \frac{DB}{\Delta t}\right) \cdot \Delta M_i^{n+\frac{1}{2}}$$

- isotropic hypoelastic material (available for beam, shell, and solid elements in LS-DYNA)

F_i – force resultant

M_i – moment resultant

The update of the force resultants and moment resultants includes the damping factors

The axial (DA) and the bending (DB) damping factors are used to damp down numerical noise.

Nr. crt.*	Component	Material*	ρ (Wood density, kg/m^3)*	E (Module of elasticity, MPa)*	v (Poisson's coefficient)*
1.	Pieces of wood	***Fagus sylvatica L.***	672	12.1e+3	0,3

Acuña, L et. al. Construction and Building Materials 2023, 371, 130750.

Mechanical performance of adhesives based on polyols from depolymerization of lignocellulose biomass

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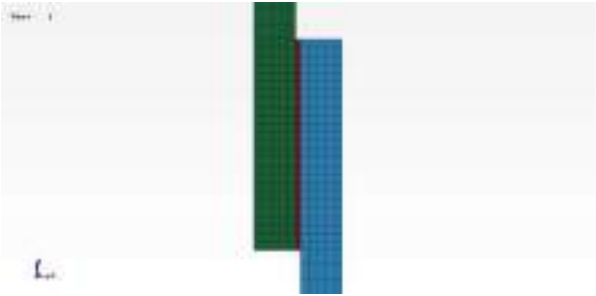
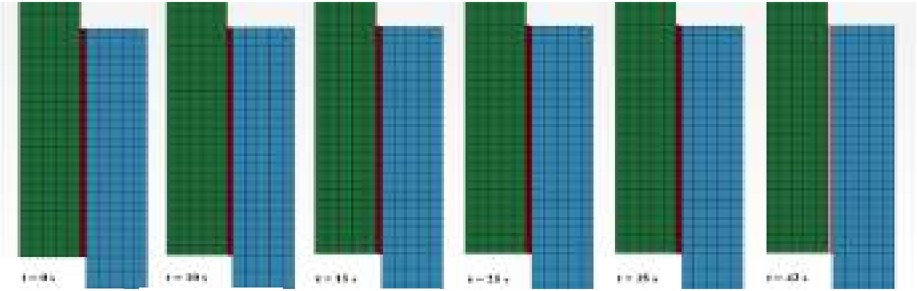
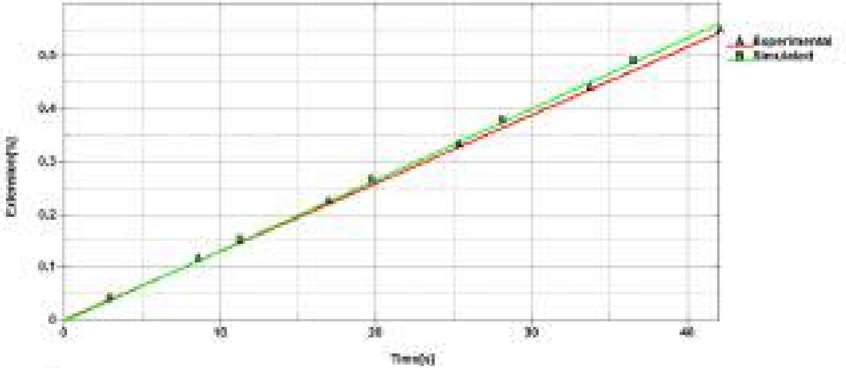
LS-DYNA tensile test modeling – EN ISO 1421

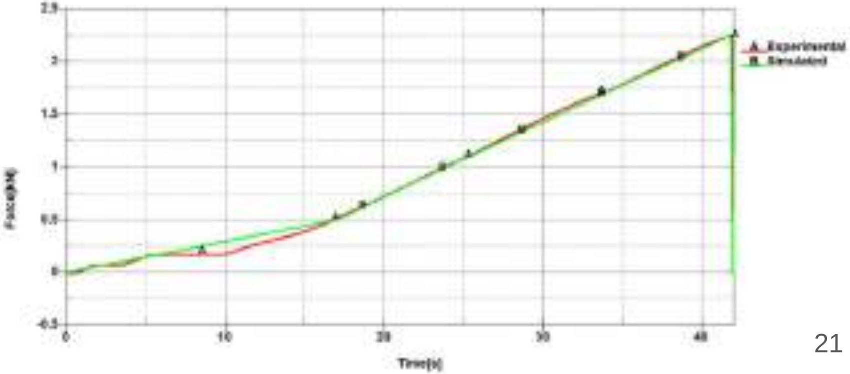




t = 0 s t = 10 s t = 15 s t = 25 s t = 35 s t = 42 s

Results of simulation analysis





5. Conclusions

Mechanical performance of adhesives based on polyols from depolymerization of lignocellulose biomass

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- ✓ The glycolysis process of birch saw dust resulted in the synthesis of lignocellulosic based polyol (Pol-L);
- ✓ The glycolysis product was analyzed by I_{OH}, and FT-IR analysis;
- ✓ Based on the I_{OH} value of Pol-L, 6 bicomponent formulations of polyurethane adhesives were proposed in which NCO/OH ratio was varied from 1.3 to 1.8;
- ✓ The adhesives were analyzed by FT-IR, working time, 3-point bending test and tensile tests and compared with the blank samples (without Pol-L);
- ✓ The mechanical performances demonstrated that the adhesives strength was higher compared with blanks in terms of bending tests, while in the case of the tensile test relatively similar behavior was evidenced but lower values of the strength were obtained;
- ✓ The simulation analysis performed by LS DYNA - EN ISO 1421 provided a good approximation of the experimental data with errors below 5%.

Acknowledgment

This STSM was developed under the COST Action CA18120 (CERTBOND) and supported by COST (European Cooperation in Science and Technology).

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Thank You!

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Experimental assessment of interface adhesion of bio-based composite repairs for steel reinforcement

Mohamed Amine TAZI
CESI Lineact, Aix-en-Provence, France

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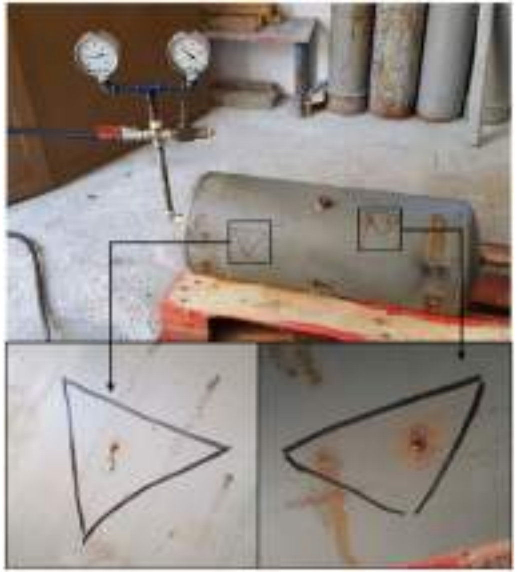
TU Delft
GeM

Outline

- Context of study
- Composite patch repair technology
- Work motivation
- Experimental plan
- Results

Context of study

Corroded pipelines of produced oil (Courtesy: Petrobras, Rio de Janeiro, Brazil) [1]



Corroded pressure vessel with details of fluid leakage [2]

High loads

Infrastructures

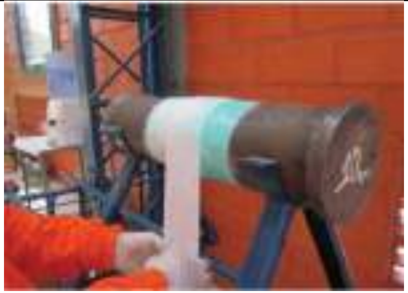
Aging

Environment

Damage

Demand for repair

Composite patch repair system

Process	
	
1) Surface preparation	2) Surface cleaning
	
3) Applying of resin/adhesive on treated surface	4) Fiber deposition, impregnation and curing

Procedure for repairing a steel tube using glass fibre/epoxy composite in an offshore unit (Courtesy: Petrobras, Rio de Janeiro, Brazil) [1]

- Good mechanical performances
- Adhesive bonding > welding, riveting, bloting
- Successful implementation of synthetic composite patch repairs

are synthetic fibers the most sustainable option ?

Work motivation

- How to reduce the environmental burdens associated with synthetic materials ?

  → Developing bio-based composites

Natural fibers

Bio-polymers (matrix and adhesive)

Advantages

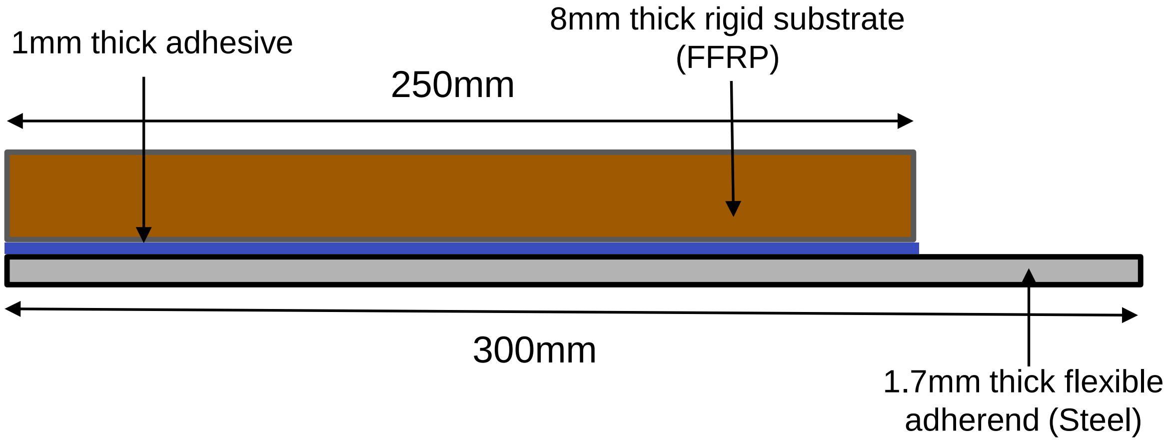
- Inexpensive
- Abundant
- Recyclable
- Easy handle
- Biodegradability
- Renewable materials

Disadvantages

- Fiber's hydrophilic nature
- Poor interfacial adhesion to the matrix
- Lower mechanical properties

Experimental plan

- Assess the interface adhesion of Carbon steel – Flax FRP bonded joint, using three types of adhesives through floating roller peel tests



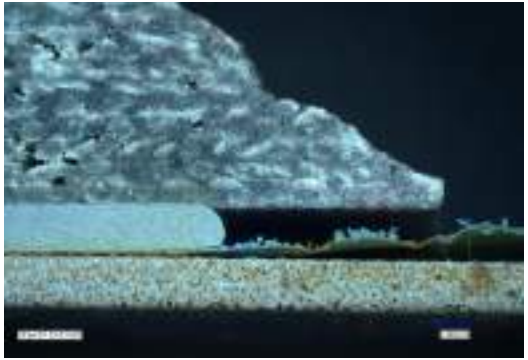
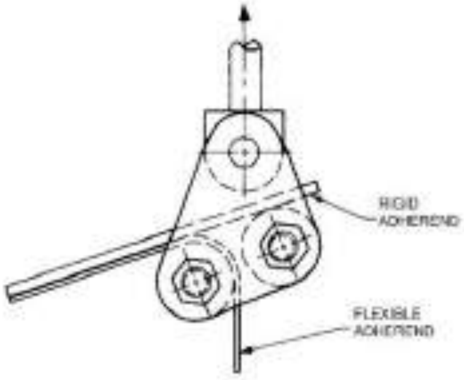


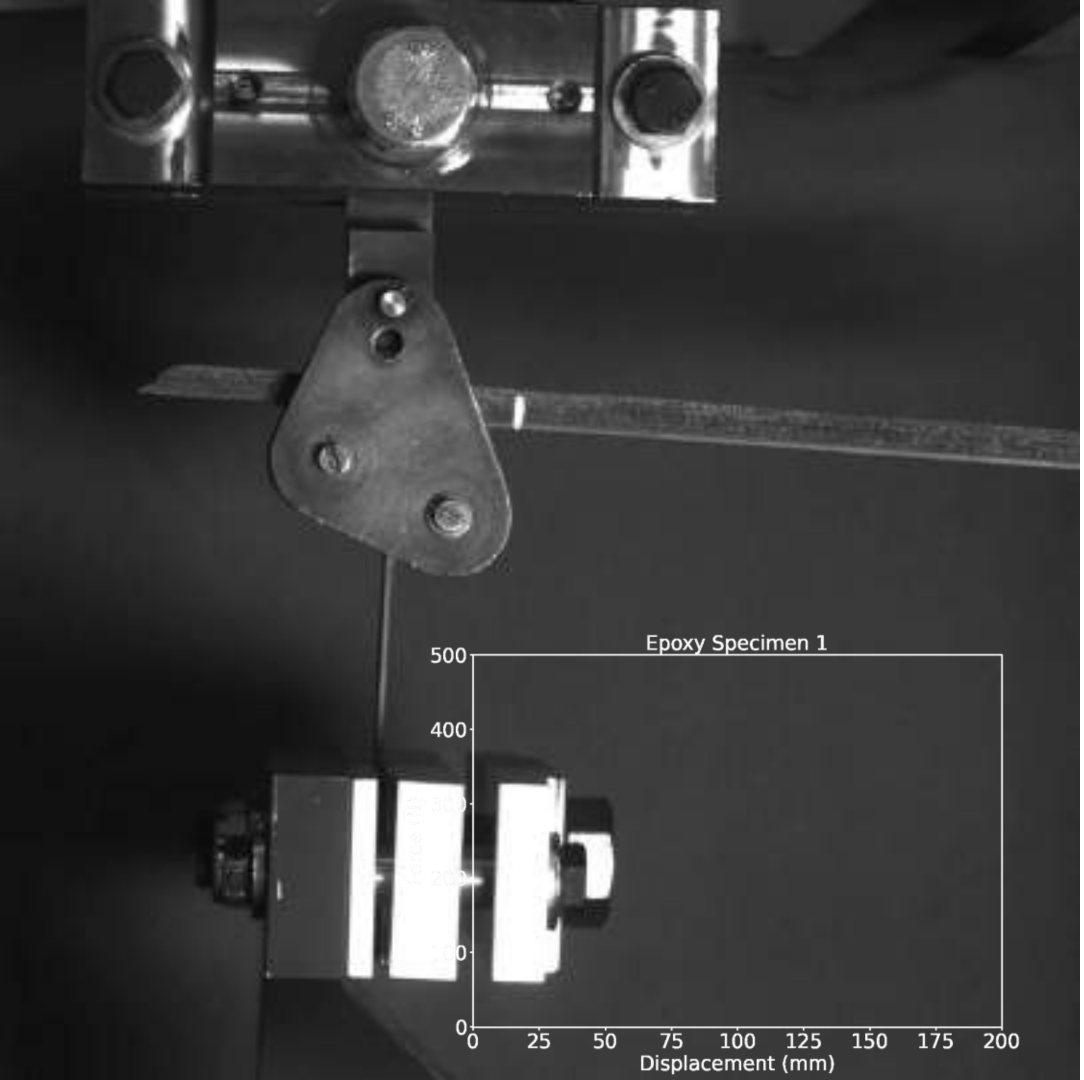
Image of manufactured specimen

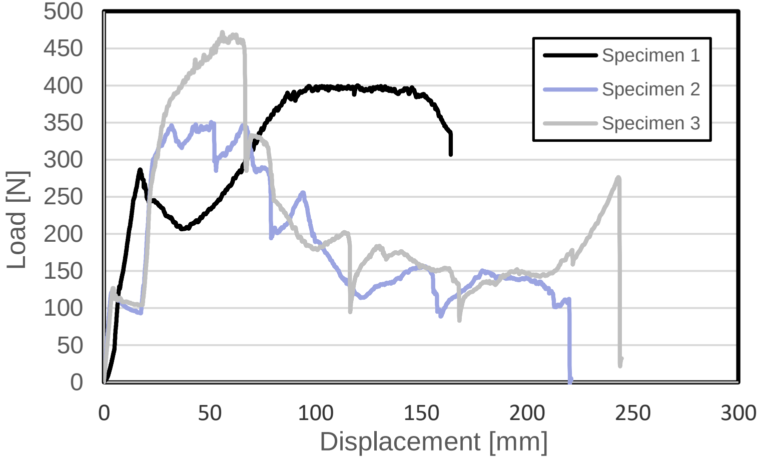
Specimens' nomenclature	Adhesive Material	Steel surface treatment	Bonding technique
Epoxy	Epoxy AxsonSika® ADEKIT A155 / H9955	Sand blasting + acetone	Secondary bonding
PU	Polyurethane Sikaflex®-554	Sand blasting + acetone	Secondary bonding
BioPU	Castor-oil-derived Polyurethane Kehl®	Sand blasting + acetone	Secondary bonding



Scheme of floating roller peel test [3]

Epoxy specimen results

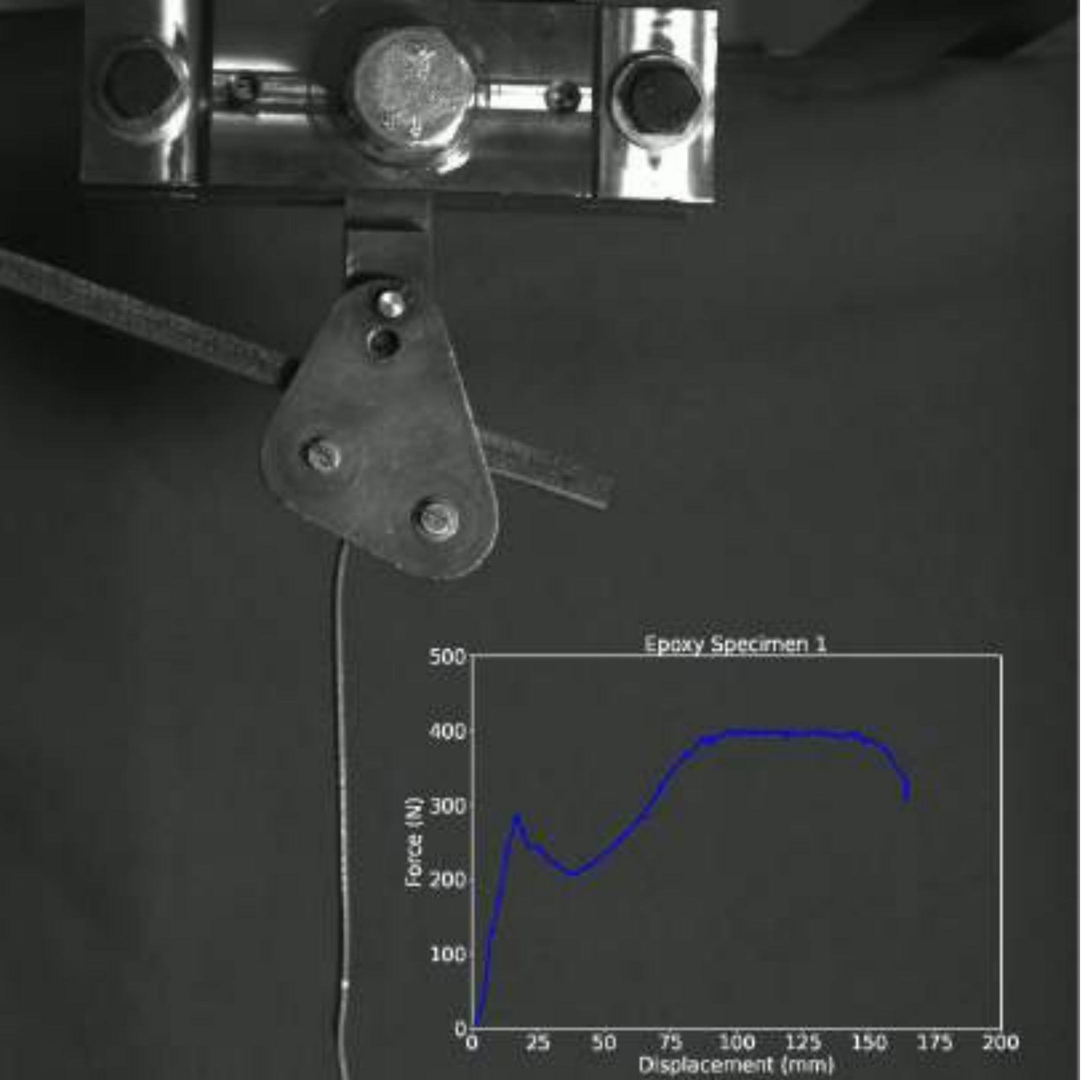




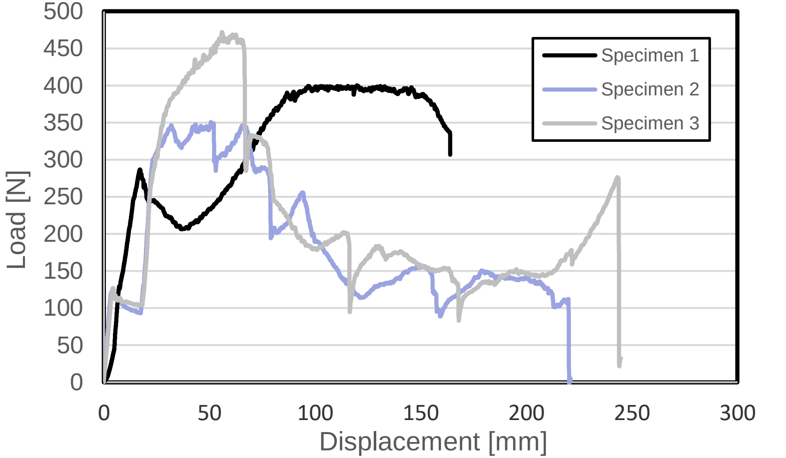
Composite side

Steel side

- Peel load of 276,6 ± 104,2 N (ASTM Standard D3167) [4]
- 100% adhesive failure



Epoxy specimen results




Composite side


Steel side

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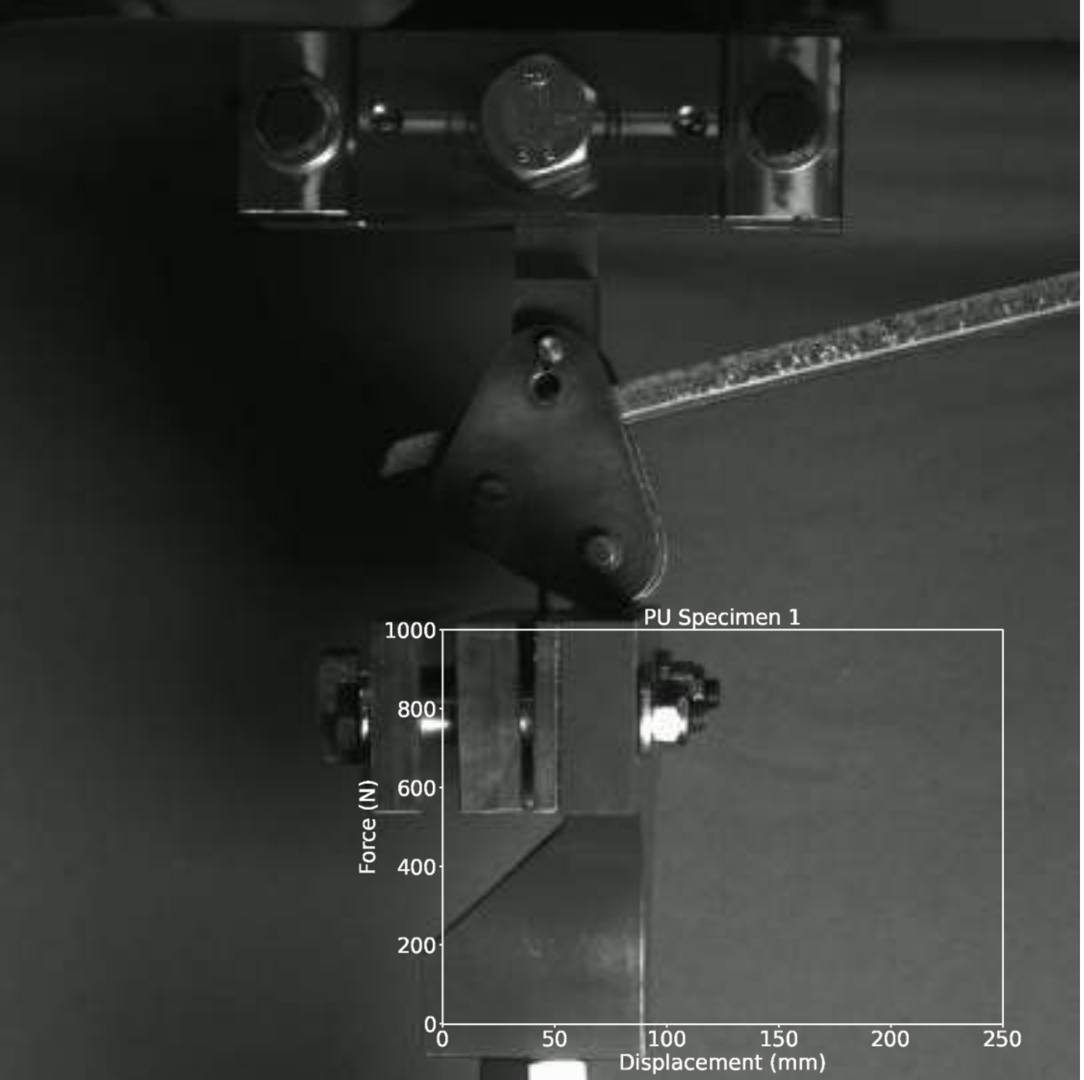
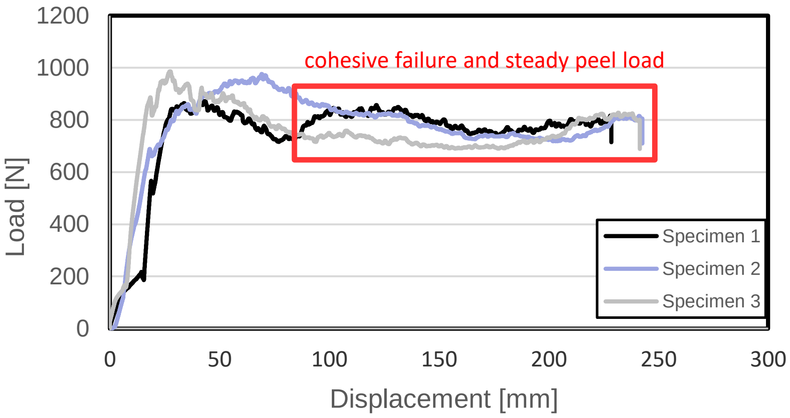
- 100% adhesive failure



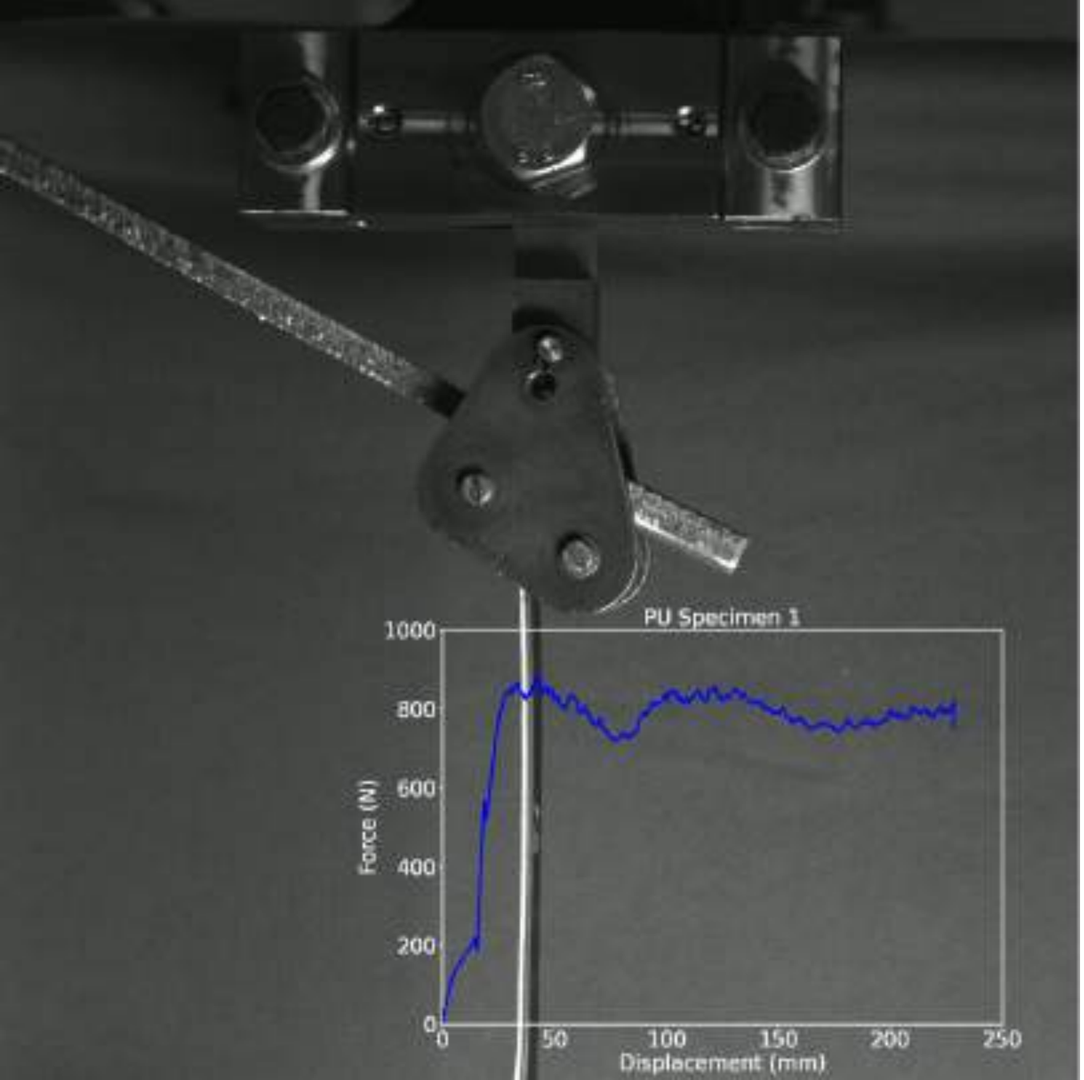
PU specimen results



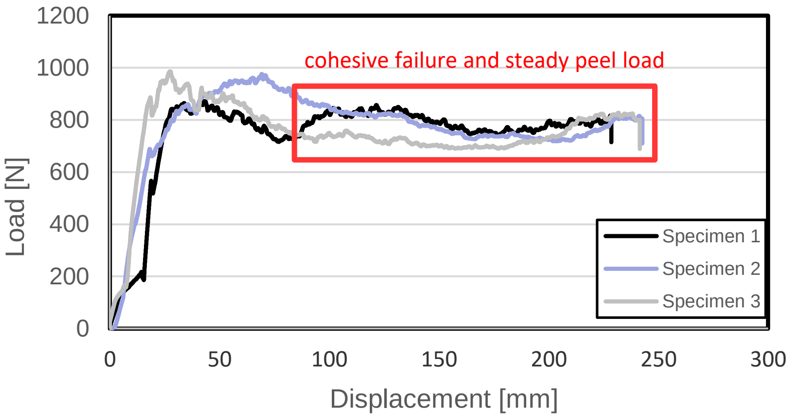
Composite side

Steel side

- Peel load of 807.7 ± 66.8 N
- 100% cohesive failure
- Steady peel load



PU specimen results



Composite side

Steel side

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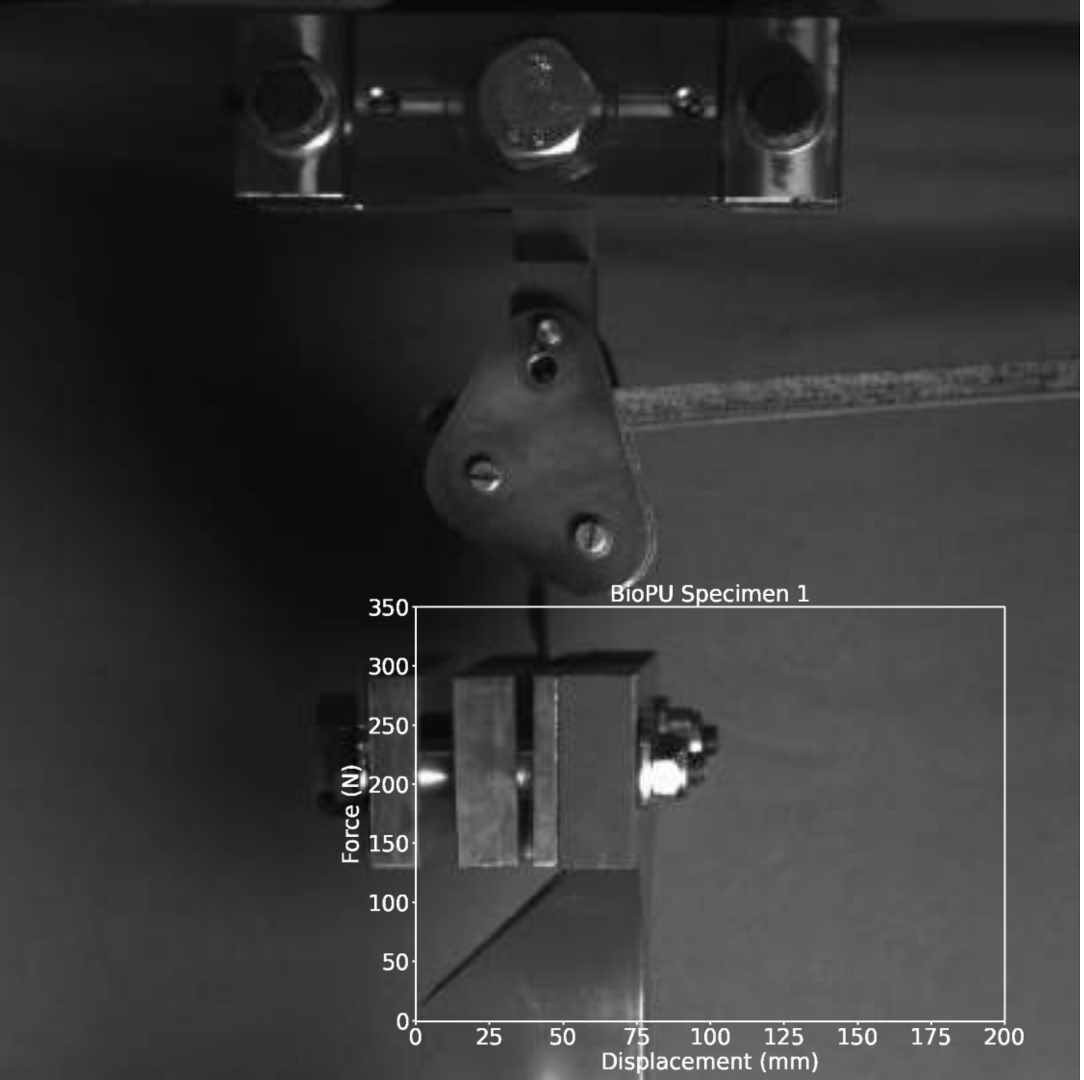
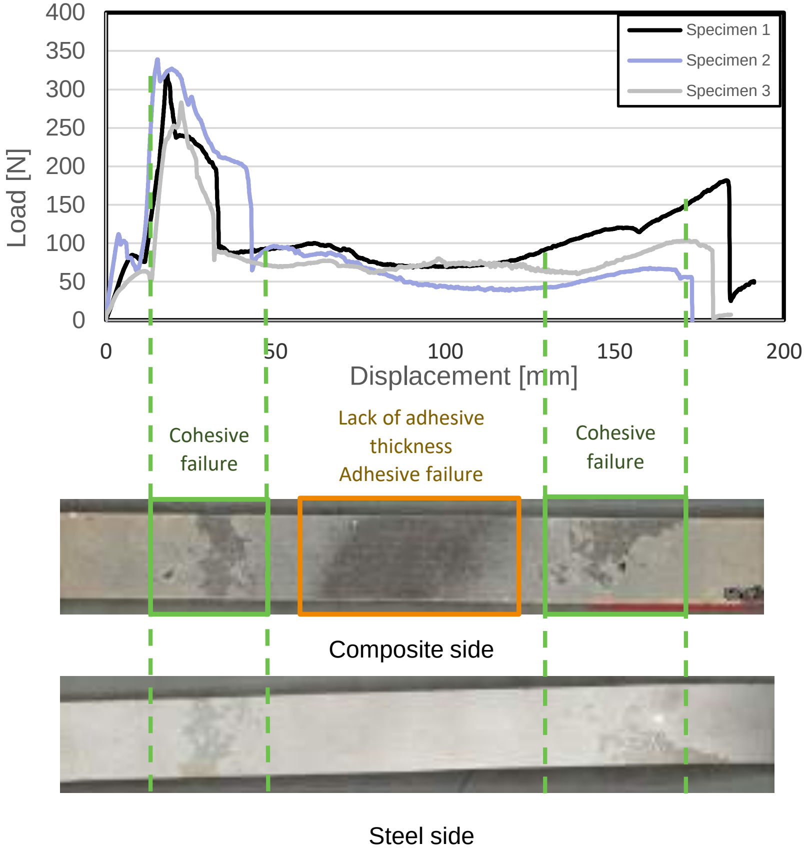
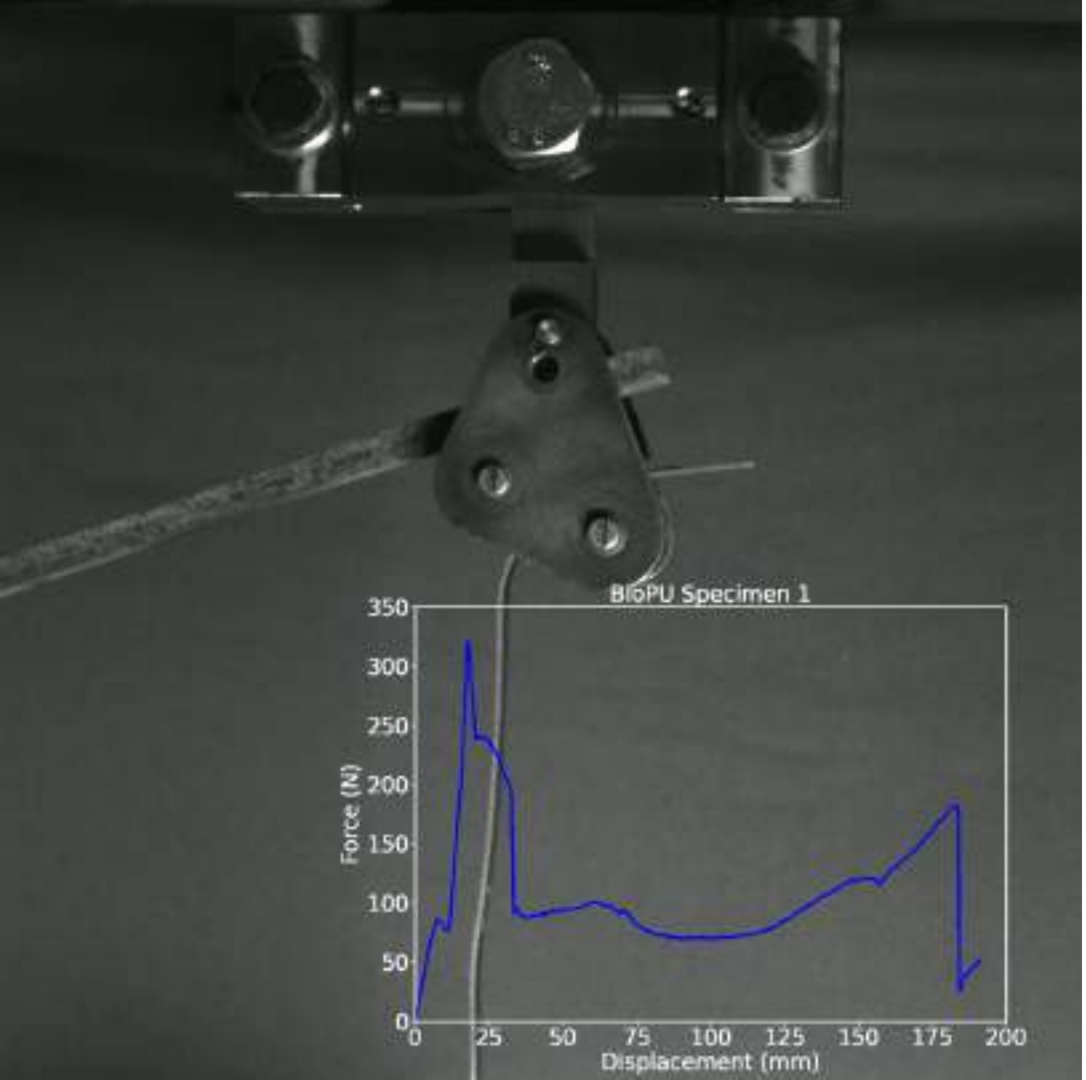
- Steady peel load



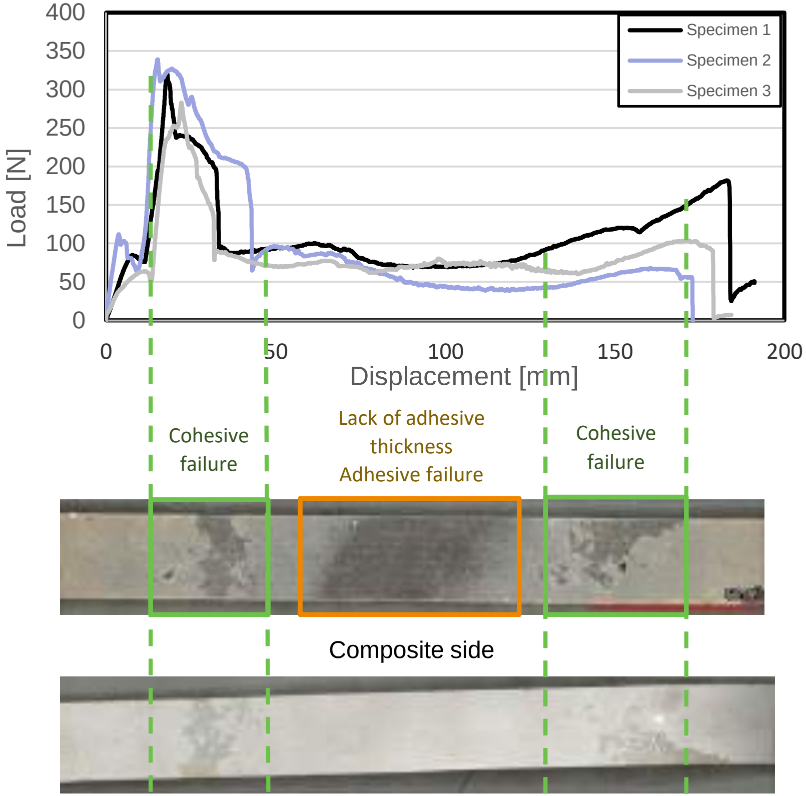
BioPU specimen results



- Peel load of 74.8 ± 18.5 N
- 14% cohesive failure
- Challenges regarding adhesive application



BioPU specimen results



Steel side

- Peel load of 74.8 ± 18.5 N
- 14% cohesive failure
- Challenges regarding adhesive application

Conclusion and perspectives

- PU is a promising material for steel-to-FFRP bonded joints. Sika® PU showed high peel loads and full cohesive failure, hence good adhesion. This justifies the interest towards developping BioPU.

- Further optimization of the application process of Kehl® BioPU are necessary to reach higher cohesive failure mode ratio, and higher peel loads.

- Floating roller peel tests are an easy, quick and reliable test method to assess the interface adhesion properties of steel-to-composite bonded joints.

References

[1] S. de Barros, M.D. Banea, S. Budhe, C.E.R. de Siqueira, B.S. P Lobão, L.F.G. Souza, « Experimental analysis of metal-composite repair of floating offshore units (FPSO) » *The Journal of Adhesion,* vol. 98, no. 1-2, 2017.

[2] G. Vukelic, G. Vizentin, « Composite wrap repair of a failed pressure vessel – Experimental and numerical analysis » *Thin-Walled Structures*, vol.169, 2021

[3] S. Teixeira de Freitas, M. Banae, S. Budhe, S. de Barros, « Interface adhesion assessment of composite-to-metal bonded joints under salt spray conditions using peel tests » *Composite Structures*, vol. 164, pp. 68-75, 2017

[4] ASTM D3167: Standard Test Method for Floating Roller Peel Resistance of Adhesive, 2010.

Acknowledgment

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This STSM was developed under the COST Action CA18120 (CERTBOND) and supported by COST (European Cooperation in Science and Technology).

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The achievements in self-healing eco-epoxy adhesives for "CertBond" structures

Nataša Tomić
Technology Innovation Institute, Abu Dhabi, UAE

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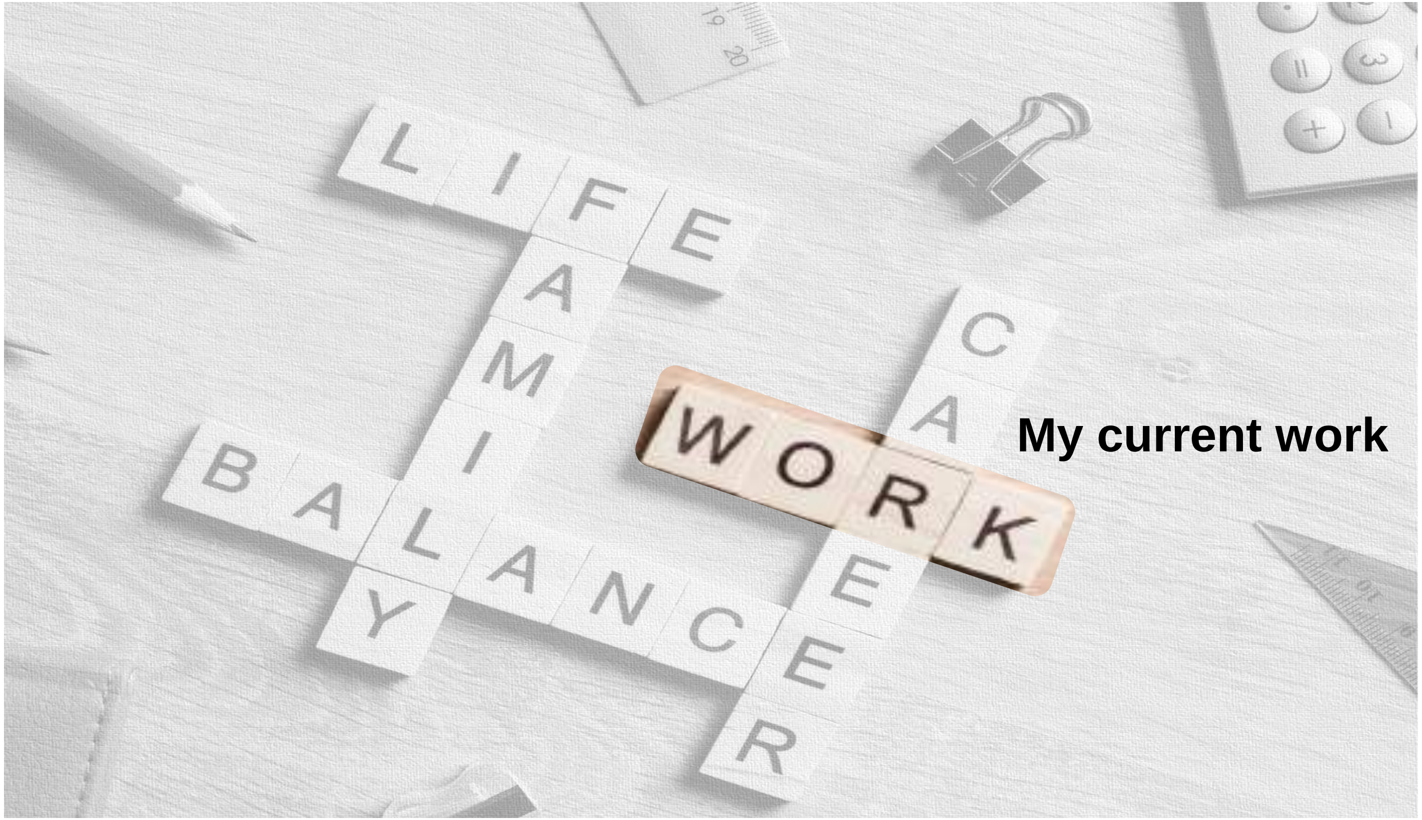
Technology Innovation Institute

Outline – Impact of CertBond

Networking and life

Outline – Impact of CertBond

Outline – Impact of CertBond



My current work

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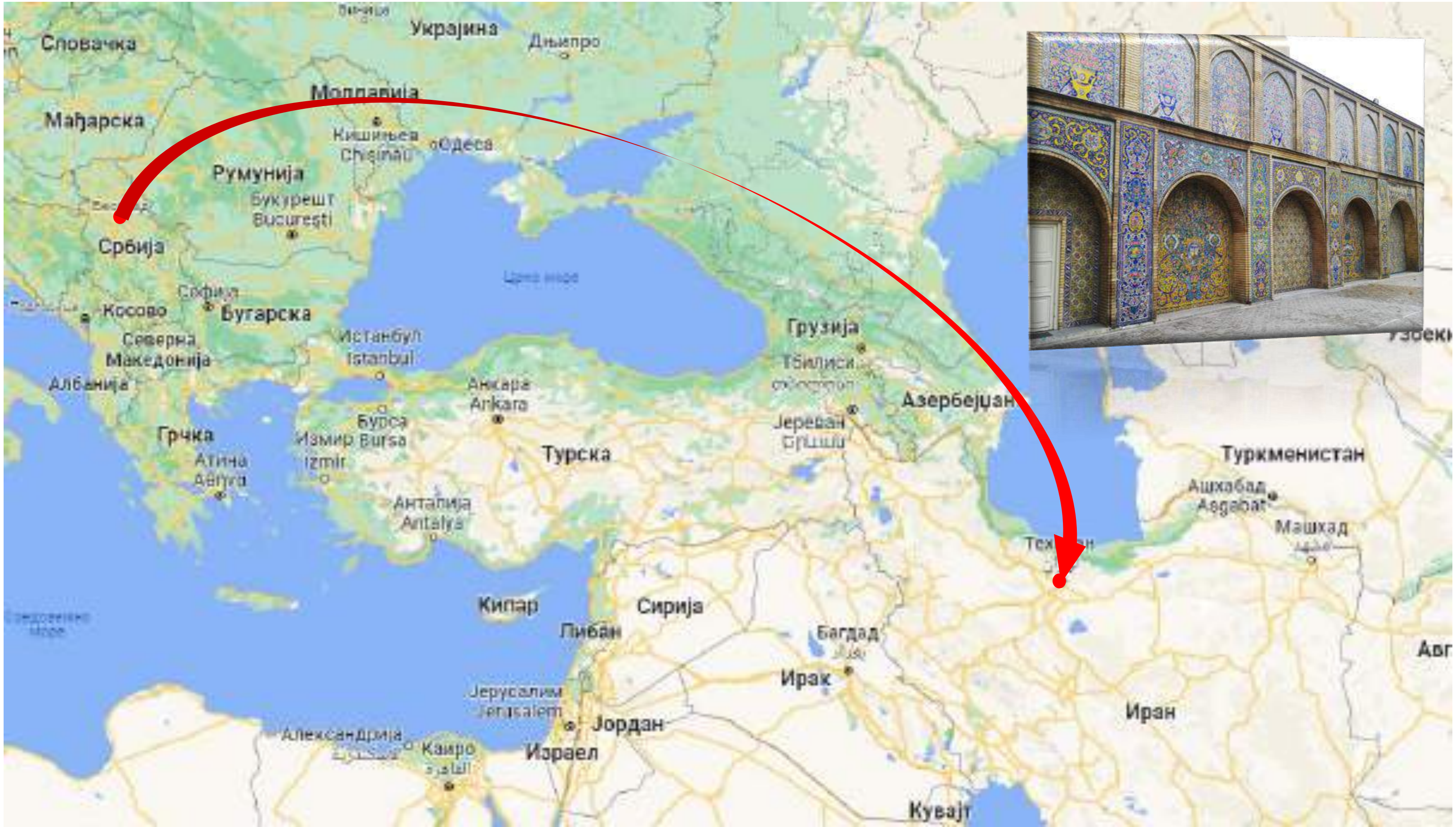

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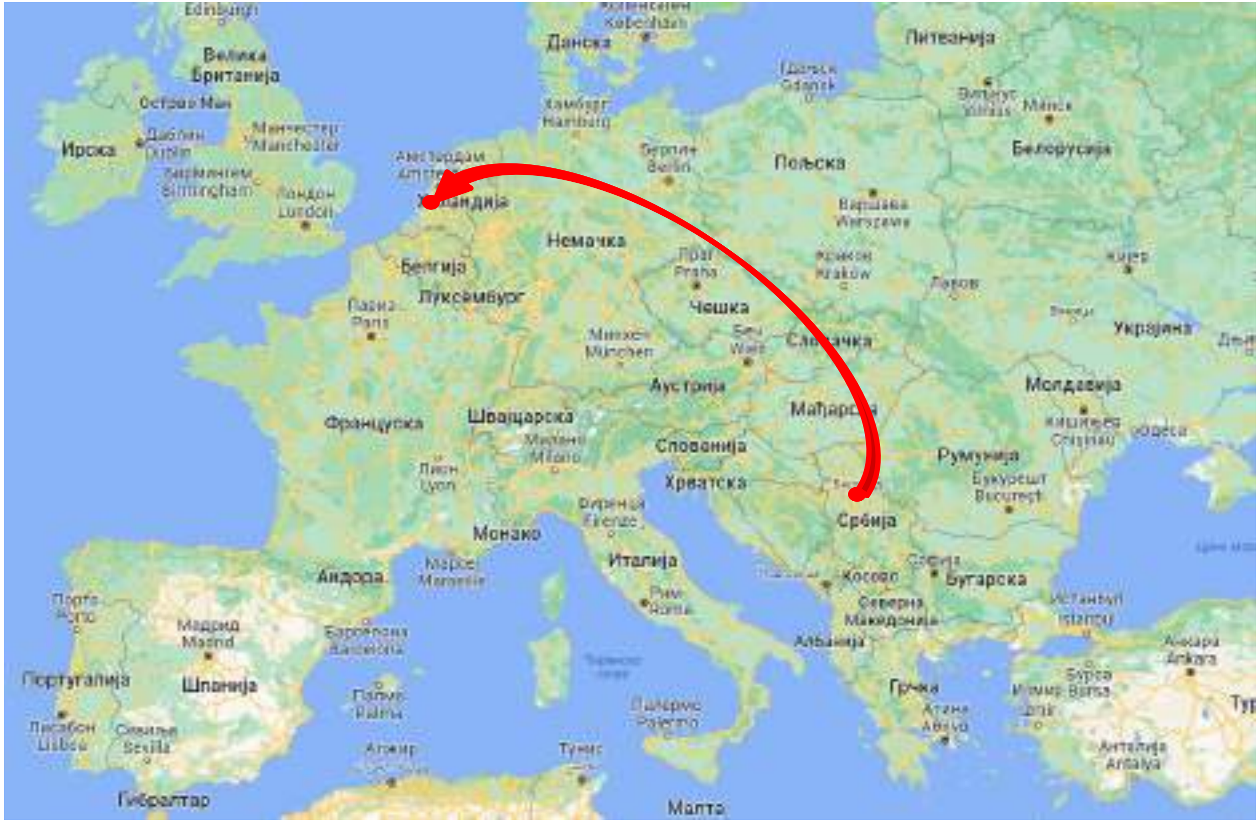


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Published paper 5 in total

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polymers

MDPI

Article

Enhanced Interface Adhesion by Novel Eco-Epoxy Adhesives Based on the Modified Tannic Acid on Al and CFRP Adherends

Nataša Z. Tomić [1,*], Mohamed Nasr Saleh [2,*], Sofia Teixeira de Freitas [2], Andreja Živković [3], Marija Vuksanović [4], Johannes A. Poulis [2] and Aleksandar Marinković [3]

Polymers **2020**, *12*, 1541; doi:10.3390/polym12071541

Published paper

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Polymer Testing 96 (2021) 107122

Contents lists available at ScienceDirect

Polymer Testing

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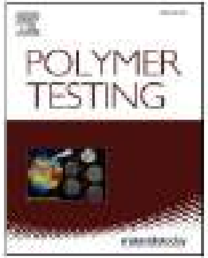

Check for updates

The effect of modified tannic acid (TA) eco-epoxy adhesives on mode I fracture toughness of bonded joints

Mohamed Nasr Saleh [a,*,1], Nataša Z. Tomić [b,1], Aleksandar Marinković [c], Sofia Teixeira de Freitas [a]

Published paper

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International Journal of Adhesion & Adhesives 117 (2022) 103013

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International Journal of Adhesion and Adhesives

journal homepage: www.elsevier.com/locate/ijadhadh

Adhesion & Adhesives

Check for updates

Self-healing capability of novel eco-epoxy adhesives based on the modified tannic acid on Al adherends tested in a single lap joint

Nataša Z. Tomić [a,*], Mohamed Nasr Saleh [b,c], Milad Saeedifar [b], Aleksandar Marinković [d], Sofia Teixeira de Freitas [b,**]

Published paper

CertBond
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Polymer Testing 106 (2022) 107444

Contents lists available at ScienceDirect

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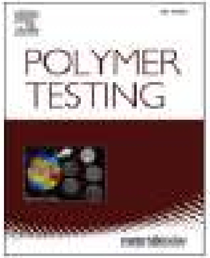

Synthesis and characterization of novel eco-epoxy adhesives based on the modified tannic acid for self-healing joints

Nataša Z. Tomić [a,*], Milad Saeedifar [b], Mohamed Nasr Saleh [b,d,**], Aleksandar Marinković [c], Dimitrios Zarouchas [b], Sofia Teixeira de Freitas [b]

Published paper

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materials

MDPI

Review

Review on Adhesives and Surface Treatments for Structural Applications: Recent Developments on Sustainability and Implementation for Metal and Composite Substrates

Ana C. Marques [1], Alexandra Mocanu [2], Nataša Z. Tomić [3], Sebastian Balos [4], Elisabeth Stammen [5], Asa Lundevall [6], Shoshan T. Abrahami [7], Roman Günther [8,9], John M. M. de Kok [10] and Sofia Teixeira de Freitas [11,*]

Materials 2020, 13, 5590. https://doi.org/10.3390/ma13245590

Current work

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Final Conference

September 7, 2023
Seville, Spain

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WG2: Design Phase

Chair: Prof. Konstantinos Tserpes (University of Patras)
Vice Chair: Prof. Norbert Blanco (University of Girona)

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WG2 General objectives

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- To coordinate research related to the design of adhesively bonded composite structures considering geometrical configurations, new design features, fatigue and impact loading, creep phenomena, damage tolerance, imperfect bonding and environmental effects

- To propose a universal progressive damage algorithm that incorporates the aforementioned parameters and complies with the engineering allowable and design rules

WG2 Tasks

- **Task 2.1**. Explore new design concepts (geometrical configurations and new crack arresting design features)
- **Task 2.2**. Compare testing procedures for bondline characterization and model validation (under static, fatigue and impact loading, creep phenomena, imperfect bonding and environmental effects)
- **Task 2.3**. Evaluate different design methodologies for the structural behaviour and progressive damage analysis of adhesively bonded structures

WG2 Milestones

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- New design concepts
- Comparison of testing procedures
- Evaluation of design methodologies
- Training school

WG2 Specific objectives

Objective	Status
Develop common definitions for different industrial sectors on design concepts (design configurations and crack stopping features), testing procedures and numerical models for simulation of debonding and adherent damage.	**Completed**
Collect existing knowledge and perform a critical review on design concepts, testing procedures and design methods.	**Completed**
Define adhesive bonding applications (joints and repairs) from different industrial sectors. List of adherents, adhesives, scale, boundary conditions, etc.	**Completed**
Finalization and reporting of the glossary (common definitions).	**Completed**
Evaluation and reporting of existing and new crack arresting design features.	**Completed**

WG2 Outcome

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- **A review paper on test methods has been published.**
- **A review paper on models and failure theories has been published.**

THE JOURNAL OF ADHESION
2021, AHEAD-OF-PRINT, 1-77
https://doi.org/10.1080/00218464.2021.1953479

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Testing mechanical performance of adhesively bonded composite joints in engineering applications: an overview

Michal K. Budzik[a], Markus Wolfahrt[b], Paulo Reis[c], Marcin Kozłowski[d], José Sena-Cruz[e], Loucas Papadakis[f], Mohamed Nasr Saleh[g], Klara V. Machalicka[h], Sofia Teixeira de Freitas[g], and Anastasios P. Vassilopoulos[i]

[a] Department of Mechanical and Production Engineering, Aarhus University, Aarhus, Denmark [b] Polymer Competence Center Leoben, Leoben, Austria [c] Department of Electromechanical Engineering, University of Beira Interior, Covilhã, Portugal [d] Faculty of Civil Engineering, Department of Structural Engineering, Silesian University of Technology, Gliwice, Poland [e] Department of Civil Engineering, University of Minho, Guimarães, Portugal [f] Department Mechanical Engineering, Frederick University, Nicosia, Cyprus [g] Department of Aerospace Structures and Materials, Delft University of Technology, Delft, The Netherlands [h] Klokner Institute, Czech Technical University in Prague, Klokner Institute, Prague, Czechia [i] Composite Construction Laboratory (Cclab), Ecole Polytechnique Fédérale De Lausanne (EPFL), Lausanne, Switzerland

THE JOURNAL OF ADHESION
2021, AHEAD-OF-PRINT, 1-61
https://doi.org/10.1080/00218464.2021.1941903

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A review on failure theories and simulation models for adhesive joints

Konstantinos Tserpes[a], Alberto Barroso-Caro[b], Paolo Andrea Carraro[c], Vinicius Carrillo Beber[d], Ioannis Floros[a], Wojciech Gamon[e], Marcin Kozłowski[f], Fabio Santandrea[g], Moslem Shahverdi[h], Davor Skejić[i], Chiara Bedon[j], and Vlatka Rajčić[i]

[a] Laboratory of Technology & Strength of Materials, Department of Mechanical Engineering & Aeronautics, University of Patras, Patras, Greece [b] Group of Elasticity and Strength of Materials, University of Seville, Seville, Spain [c] Department of Management and Engineering, University of Padova, Padova, Italy [d] Polymeric Materials and Mechanical Engineering, Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM, Bremen, Germany [e] Faculty of Transport and Aviation Engineering, Silesian University of Technology, Silesian, Poland [f] Faculty of Civil Engineering, Silesian University of Technology, Silesian, Poland [g] Department of Applied Mechanics, RISE, Research Institutes of Sweden, Sweden [h] Empa, Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, Switzerland [i] Faculty of Civil Engineering, University of Zagreb, Zagreb, Croatia [j] Department of Engineering and Architecture, University of Trieste, Trieste, Italy

WG2 Outcome

- **Participation to 1st Training School in Trieste**

WG2 Outcome

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- **Participation to the WG5 Workshop on Disassembly**

UNIVERSITY OF PATRAS

University of Patras
Laboratory of Technology
& Strength of Materials

Delamination of composite laminates and debonding of adhesive joints: Mechanical testing and numerical simulation

Assoc. Prof. Konstantinos Tserpes

Laboratory of Technology & Strength of Materials, Department of Mechanical Engineering & Aeronautics, University of Patras, Patras 26500, Greece

kitserpes@upatras.gr

CertBond WG5: Workshop on Disassembly

WG2 Outcome

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- **Contribution to the Glossary of terms and definitions**

WG 2 Alphabetical order glossary

Field-sensitive origin of provided definition:

- (A) aerospace
- (AT) automotive
- (C) civil engineering
- (M) marine
- (W) wind energy

Active Multiple Load Path: Structure providing two or more load paths that are all loaded during operation to a similar load spectrum (A)

Adherend: a body held to another body by an adhesive (C)

Adhesive: a polymeric material which is capable of holding two materials together by surface attachment (C)

Adhesive, structural: A bonding agent used for transferring required loads between adherends exposed to service environments typical for the structure involved. An adhesive of proven reliability in engineering structural applications in which the bond can be stressed to a high proportion of its maximum failing load for long periods without failure. A material employed to form high-strength bonds in structural assemblies which perform load-bearing functions, and which may be used in extreme service conditions, e.g., high- and low-temperature exposure (C)

Adhesive failure (?)

Adhesion: The attraction between surfaces whereby work must be done to separate them once they have been brought into contact (C)

AMC (Acceptable Means of Comply): Specific requirements and methods defined by the certification institution necessary to certify for a product (A)

Arrested-growth approach: Method that requires demonstration that the structure, [illegible]

Certification documents: As actual certification documents, only the Federal Aviation Regulations FAR issued by FAA (Large Transport Category Airplanes – FAR25) and the Certification Specifications CS issued by EASA (for large airplanes – CS25) can be referred to. Additionally, the FAA and EASA are issuing Advisory Circular (AC) and Memorandums which can be considered as an explanation of the certification documents and as "one" way of achieving certification (A)

Co-bonding: Assembling process for joining together already cured composite or metal parts with still un-cured composite parts, during the cure cycle of the un-cured composite part (A)

Co-curing: Assembling process for two or more composite parts/materials, assembled as wet-in-wet (semi-cured prepreg material is also considered wet). All parts/materials are fully cured and simultaneously bonded in a single shot technique. Different materials may be co-cured if the same cure cycle is used (A)

Cohesion: The state in which the particles of a single substance are held together by primary or secondary valence forces. In adhesives, cohesion is the state in which the particles of the adhesive or adherend are held together (C)

Cohesive failure (?)

Collapse: Complete failure of a blade impossible to repair. Replacement needed (W)

Component: A major section of the airframe structure (e.g. wing, body, fin, ...) which can be tested as a complete unit to qualify the structure (A)

Coupon: A small test specimen (e.g., usually a flat specimen) for evaluation of basic lamina or laminate properties or properties of generic structural features (e.g. bond or mechanical fastened joints) (A)

Crack: Refers to a damage (yet resulting from a stress overload) in a material leading to the local separation of material. Voids or holes resulting from the manufacturing process are not considered a crack as they are not caused by a stress state (A)

Crack stopping: Controlling of the propagation of a crack. This can include diverting,

WG2 Outcome

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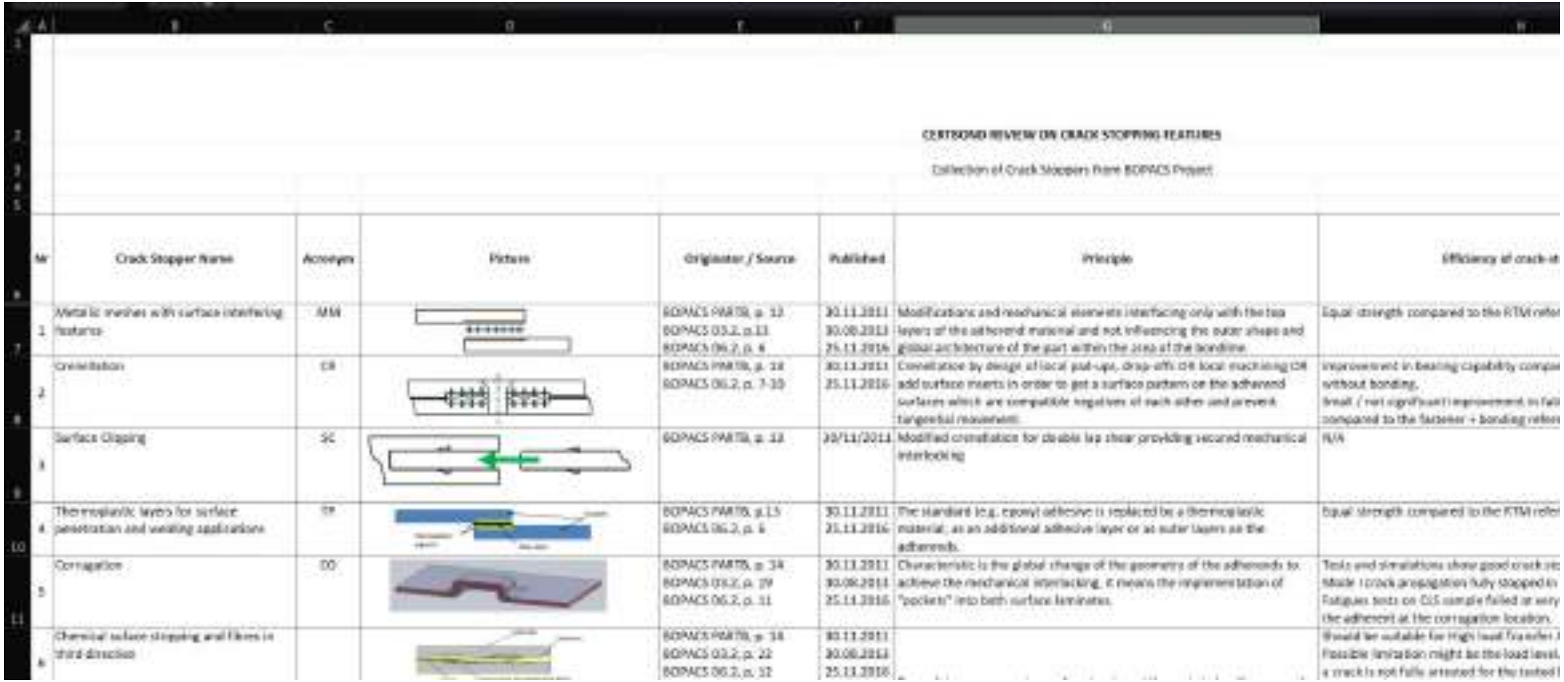
- **Review on Crack Stopping Features**



WG2 Outcome

- **Round Robin on testing of adhesive joints (in progress)**
- **Round Robin on simulation of adhesive joints (in progress)**

Testing	Simulation	Uncertainty quantification
Carrillo Veber Vinicius	Carrillo Veber Vinicius	Fabio Santandrea
Michal Budzik	Chiara Bedon	
Markus Wolfahrt	Loucas Papadakis	
Dharun Vadugappatty Srinivasan	Martin Alexander Eder	
Jose Manuel Sena Cruz	Philipp Ulrich Haselbach	
Konstantinos Tserpes	Konstantinos Tserpes	
Anthony Fraisse	Vlatka Rajcic	
Sofia Texeira de Freitas	Paolo Andrea Carraro	
Alberto Barroso	Nikola Perković	
Vlatka Rajcic	Davor Skejić	
Silvio de Baros	Fabio Fernandez	
Aleksija Djuric		
Paulo Reis		
Norbert Blanco		
Fabio Fernandez		
Klara Vokac Machalicka		

Conclusions

- WG2 has gathered more than 40 researchers from more than 20 countries.

- Most of the participants were active.

- The group has fulfilled its main objectives as it has contributed to the development and evaluation of experimental and numerical methods for the design of crack stoppers in adhesive joints.

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Adhesive bonding of Tow Based Discontinuous Composites (TBDC’s)

Ioannis Katsivalis, Rosemere De Araujo Alves Lima, Florence Moreau, Leif Asp, Sofia Teixeira de Freitas

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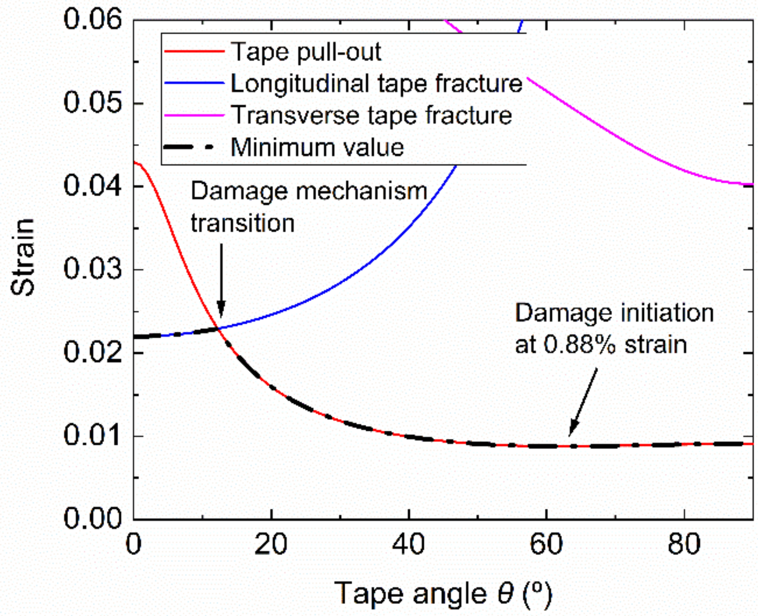
Background

- Quasi-isotropic composites can be manufactured from randomly distributed CFRP tapes
- Tow Based Discontinuous Composites (TBDC) can:
  - utilise unconventional micro-architectures allowing for random fibre orientation leading to in-plane quasi-isotropic performance
  - increase the attainable fibre volume fractions leading to increased strength
  - provide enhanced manufacturability
  - expand the design space
- The use of low tape thickness (50 x 20 x 0.02 mm) and high fibre modulus leads to significantly stronger and stiffer materials compared to the commercially available TBDC

Thin Tow-Based Discontinuous Composites (TBDCs)

Cross section at magnification x 20

Material performance



Tensile testing	Stiffness (GPa)	Poisson's ratio	Strength (MPa)	Strain to failure	Failure mechanism
Experimental	69.9 ± 3.2	0.363 ± 0.043	674 ± 49	0.96 ± 0.10	Tape pull-out
Analytical	67.6	0.332	594	0.88	Tape pull-out
Difference	3.3%	8.9%	12.6%	8.7%	

Katsivalis, I., Persson, M., Johansen, M., Moreau, F., Kullgren, E., Norrby, M., Zenkert, D., Pimenta S., Asp L.E., (2023), Strength analysis and failure prediction of thin tow-based discontinuous composites, *Composites Science and Technology*

Adhesive joints for TBDC materials

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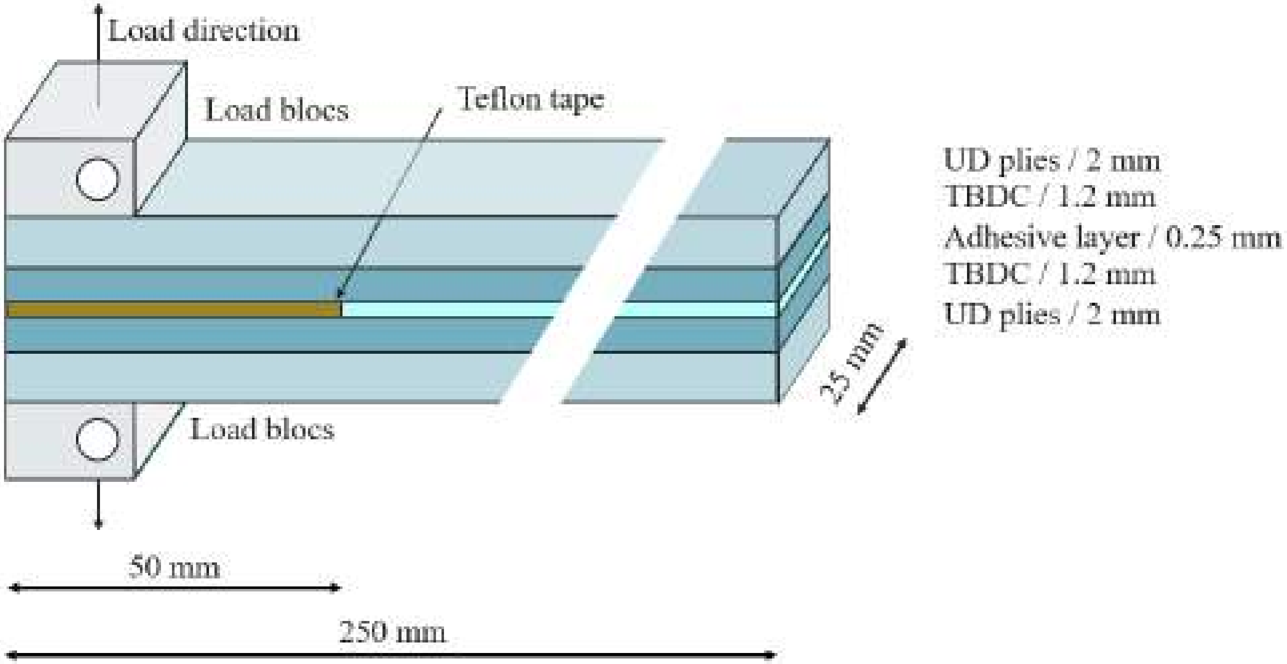
- The TBDC material proposed combines low tape thickness with random orientations and therefore challenges the usual uniform substrate surface assumption
  - How does this affect the performance of the joint?
  - What is the stress distribution in the joint?
  - Are the stress concentrations in the joint corners or the stress concentrations in the tape ends more decisive?
  - Does the random tape distribution deflect the crack in bonded joints and can it act as a toughening mechanism?
- We performed DCB and SLJ to investigate such effects using two different adhesives

Matrix of tests

Test	Substrates	Adhesives	Measurements
DCB testing	TBDC	Araldite 2015-1	Load-displacement, crack monitoring, acoustic emission
	TBDC	3M Scotch-Weld AF163-2	
SLJ testing	TBDC	Araldite 2015-1	Load-displacement, extensometer, DIC, acoustic emission
	TBDC	3M Scotch-Weld AF163-2	

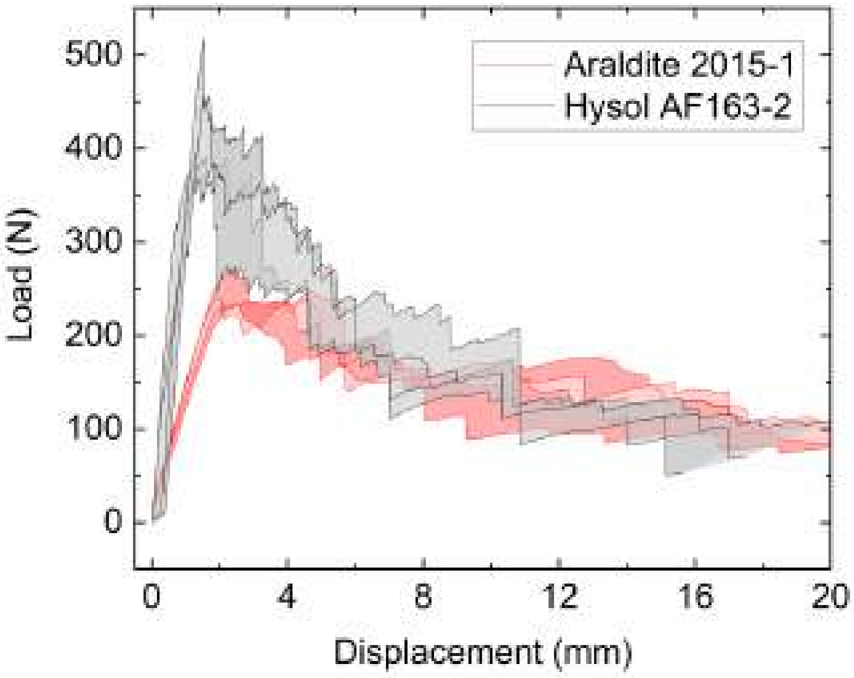
DCB testing



Load direction
Load blocs
Teflon tape
UD plies / 2 mm
TBDC / 1.2 mm
Adhesive layer / 0.25 mm
TBDC / 1.2 mm
UD plies / 2 mm
25 mm
Load blocs
50 mm
250 mm

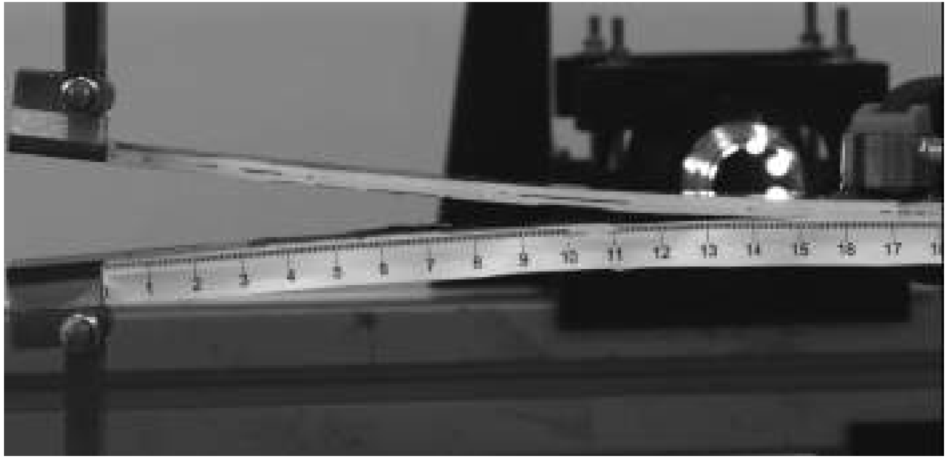
DCB testing

DCB results

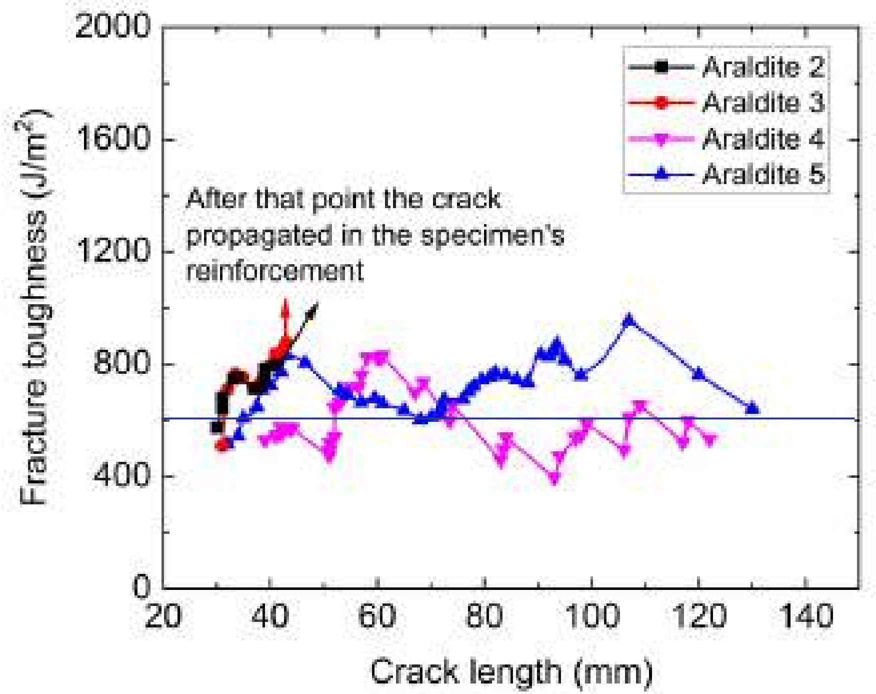


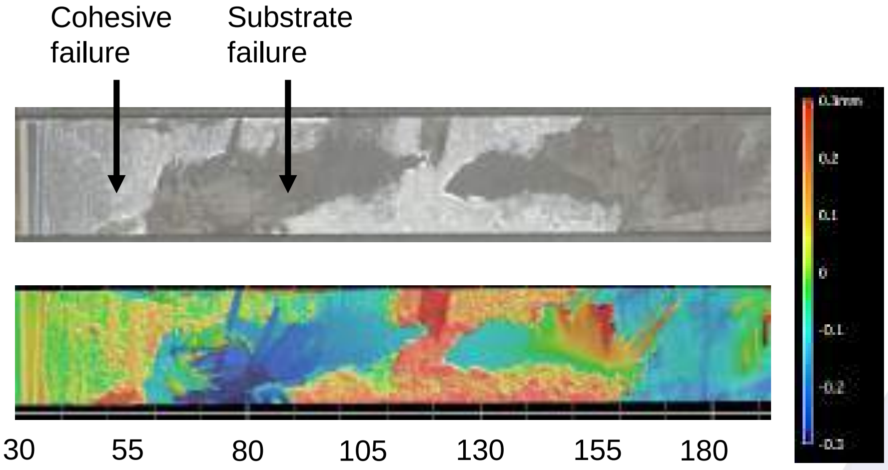
Araldite 2015-1
Hysol AF163-2
Load (N)
Displacement (mm)
500
400
300
200
100
0
0
4
8
12
16
20

DCB Araldite 2015-1



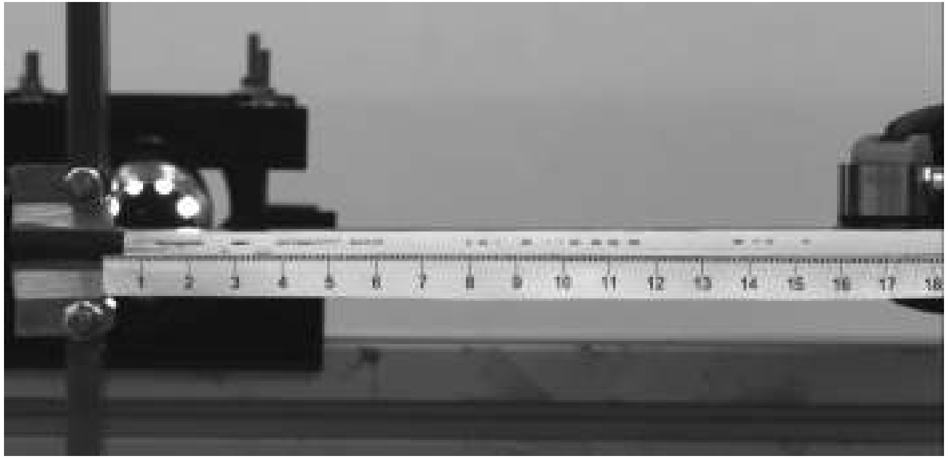
R-curve Araldite 2015-1





Araldite 5

DCB AF163-2



R-curve AF163-2

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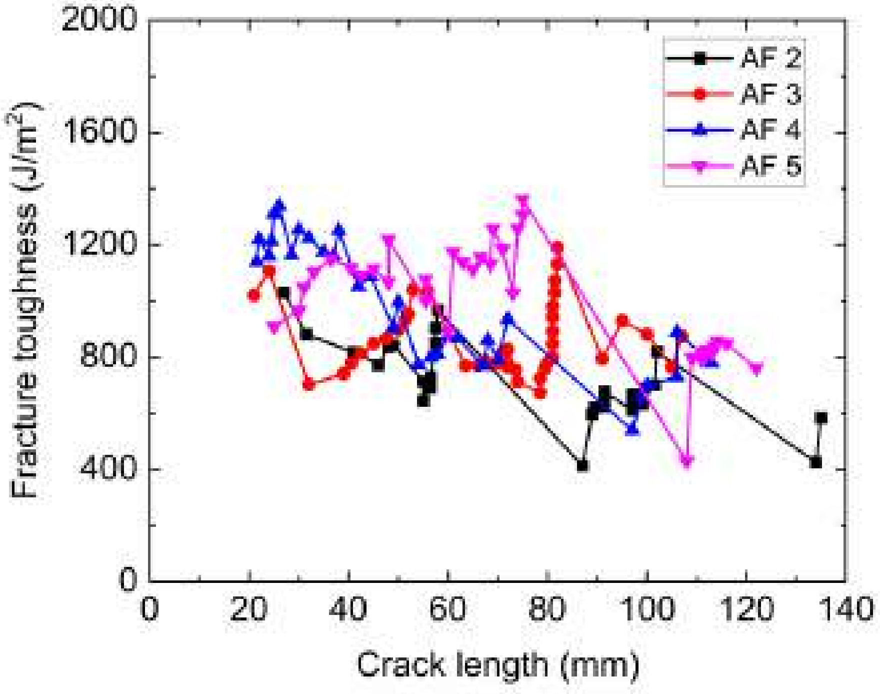
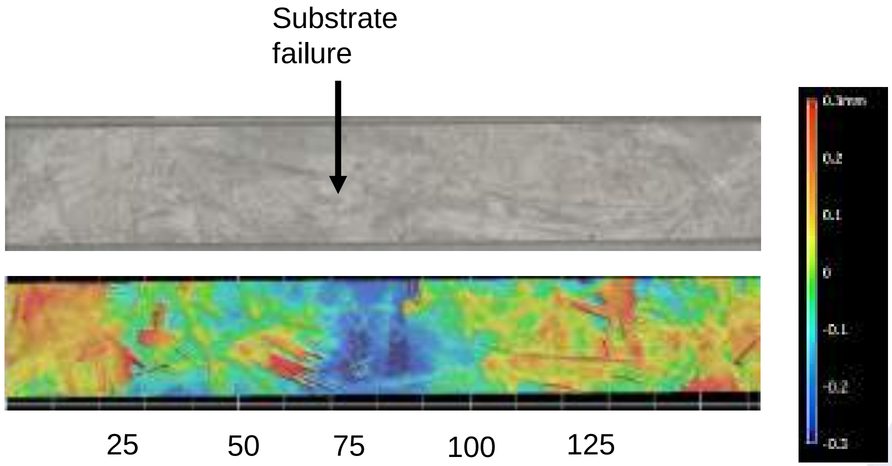
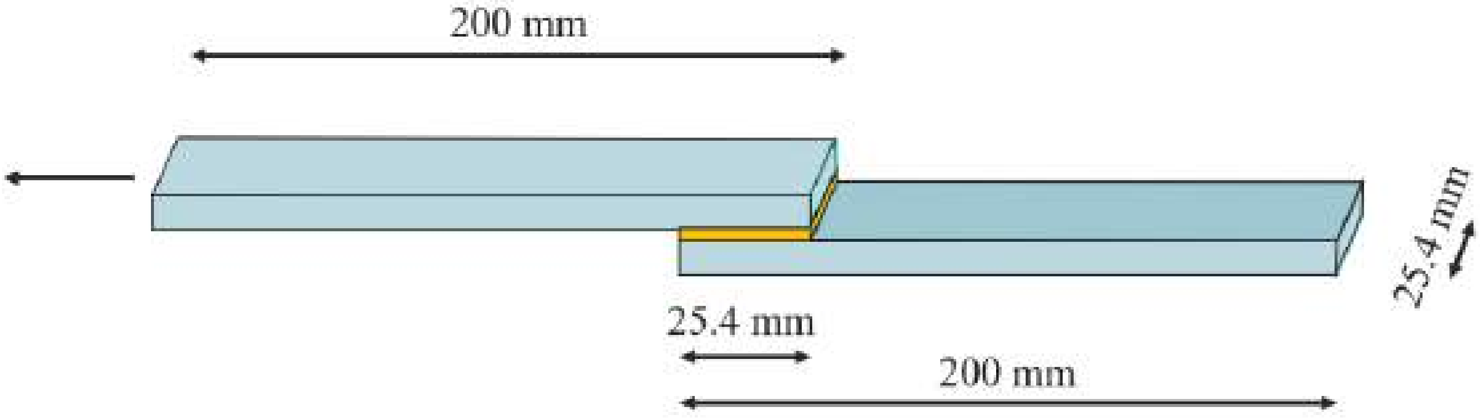


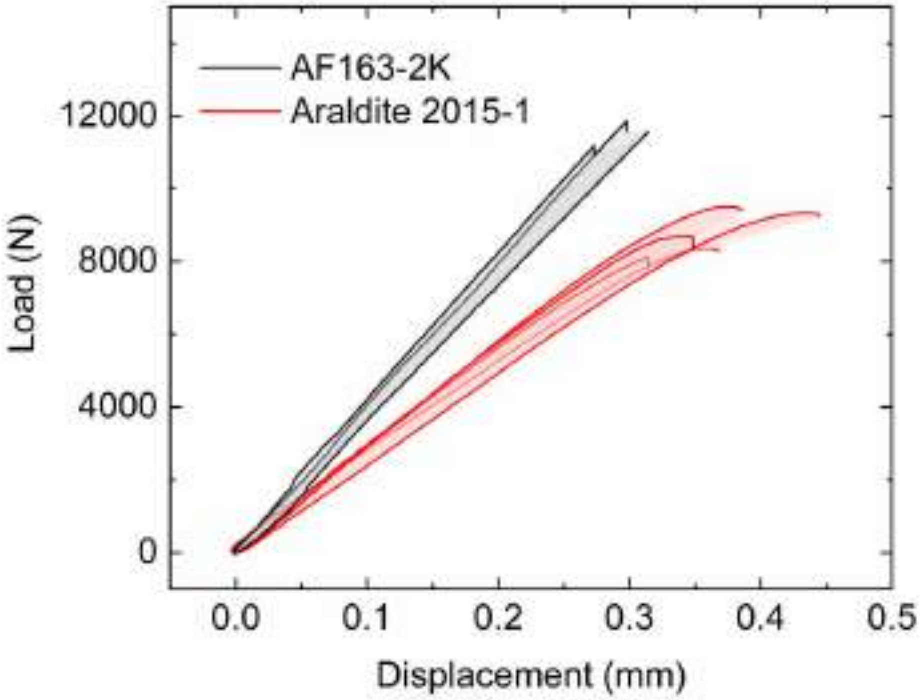


AF 4

SLJ testing

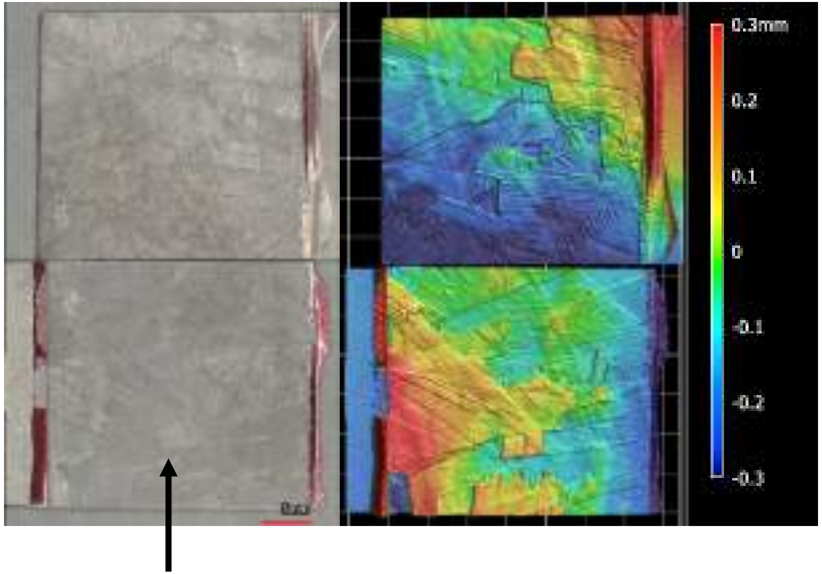


SLJ load-displacement



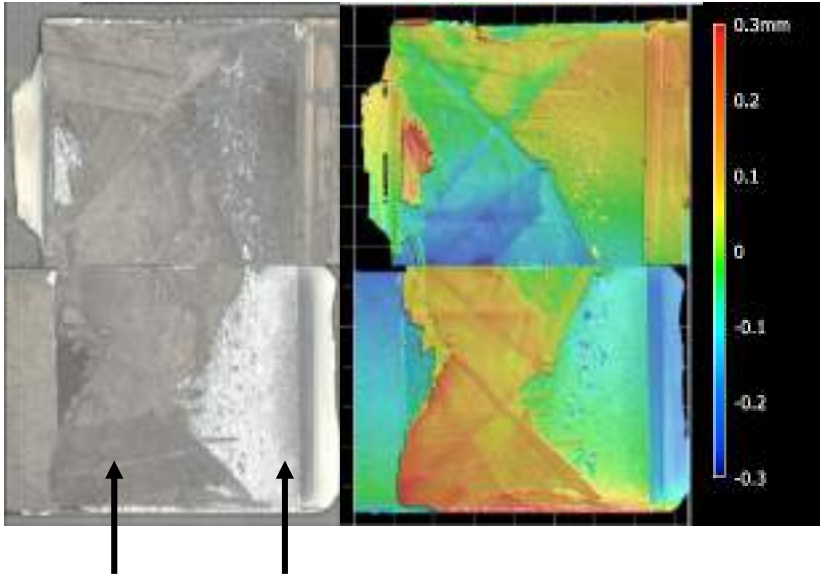
Tensile testing		Max load (kN)	Max displacement (mm)	Damage
TBDC AF163-2	Average	**12.04**	**0.295**	Composite at the interface
	Standard deviation	**0.78**	**0.017**	
TBDC Araldite 2015-1	Average	**8.80**	**0.369**	Cohesive and composite at the interface at different ratios
	Standard deviation	**0.54**	**0.045**	

SLJ failed interfaces



Substrate failure

AF2

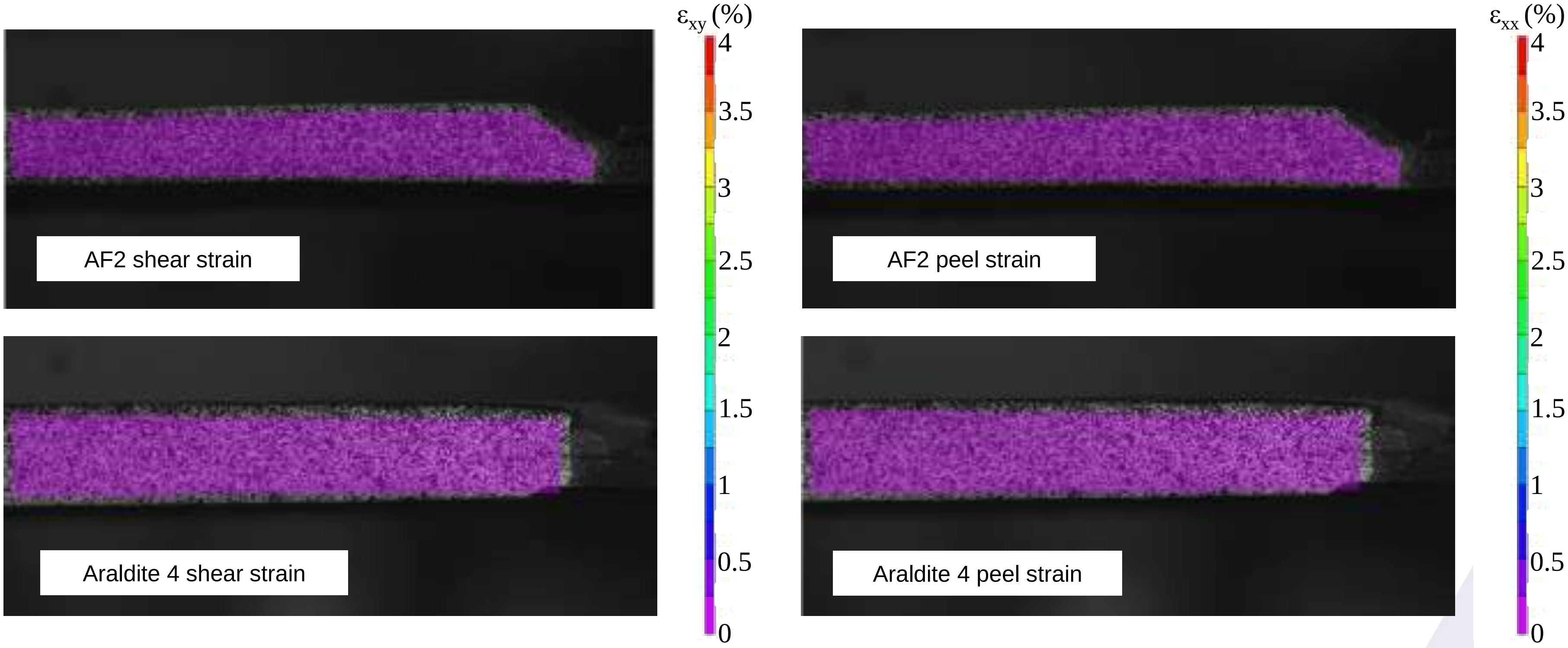


Substrate failure

Cohesive failure

Araldite 4

SLJ DIC analysis



SLJ stress analysis

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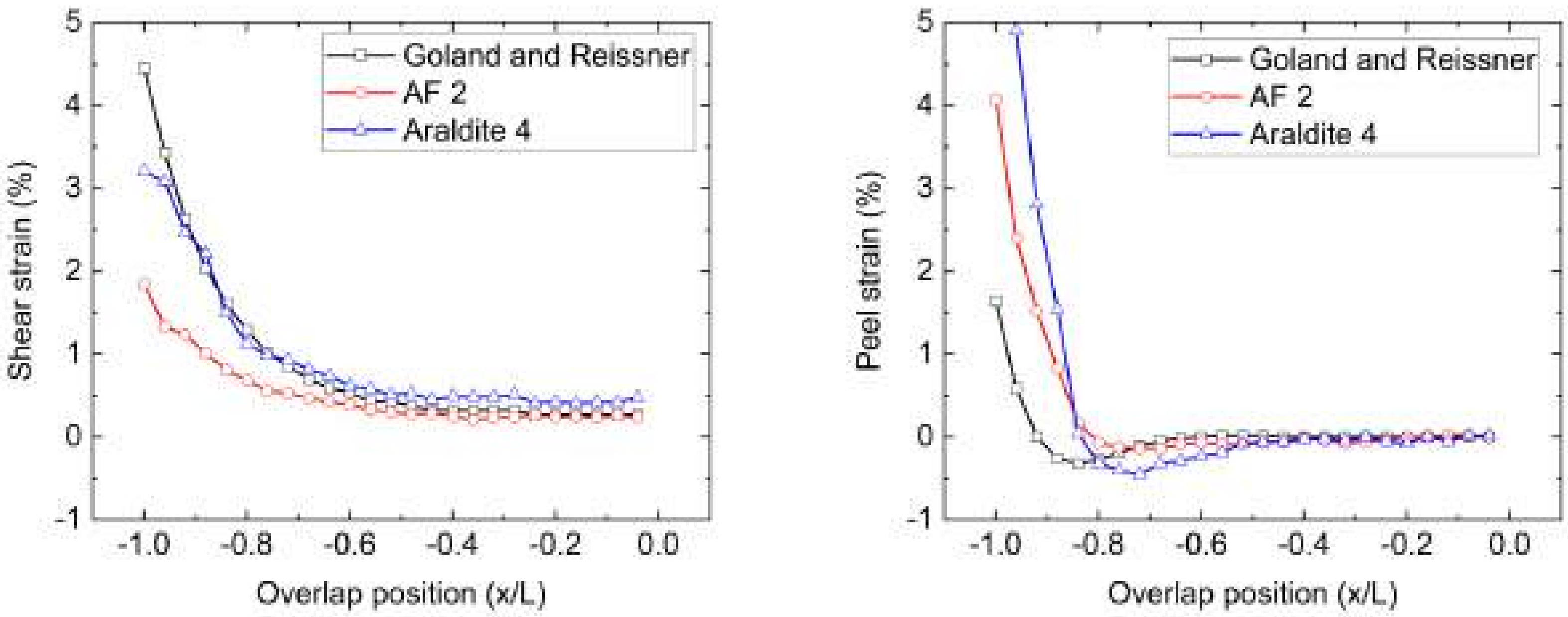

Conclusions

- Tow-Based Discontinuous Composites are a new class of composite materials with significant advantages over conventional continuous fibre reinforced plastics
- The mode I fracture toughness for the Araldite 2015-1 DCB specimens shows increased values compared to the literature despite the cohesive damage mode being predominant
- The mode I fracture toughness for the AF163-2 DCB specimens displays increased scatter which is consistent to the random tape orientation and the damage propagating exclusively in the composite
- The AF163-2 SLJ failed at 30% higher loads in a brittle manner while the Araldite 2015-1 joints failed at lower loads but displayed a progressive damage mechanism with a large plastic zone developing along the overlap
- The DIC observations were validated against analytical solutions and will form the basis for an extended stress analysis utilising AE data

Acknowledgment

This STSM was developed under the COST Action CA18120 (CERTBOND) and supported by COST (European Cooperation in Science and Technology).

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Thank You!

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Funded by the European Union

Experimental Tests for Material Characterization of Structural Silicone Sikasil® SG-500 for the Application of Bonded Point Fixings on Glass

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Final Conference

1290
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Outline

1. Introduction

- **Maximum transparency**: the glass surface is supported by metal connectors *i.e.* spiders, as slender as possible.

Portafolio Pentagonal Company
https://pentagonal.com/portfolio_page/fitechnic-hospital-da-horta/

BIOCANT, Cantanhede, 2006, Designed by Arq. Roboredo e Oliveira

Fig. 1: Examples of facades and roofs with point fixed glass panels

1.1 Pointed Fixed Glass Facade Systems (PFGFS)

- Glazing elements, are usually considered as **non-structural elements**, they are designed to sustain their self-weight and primarily wind loads.

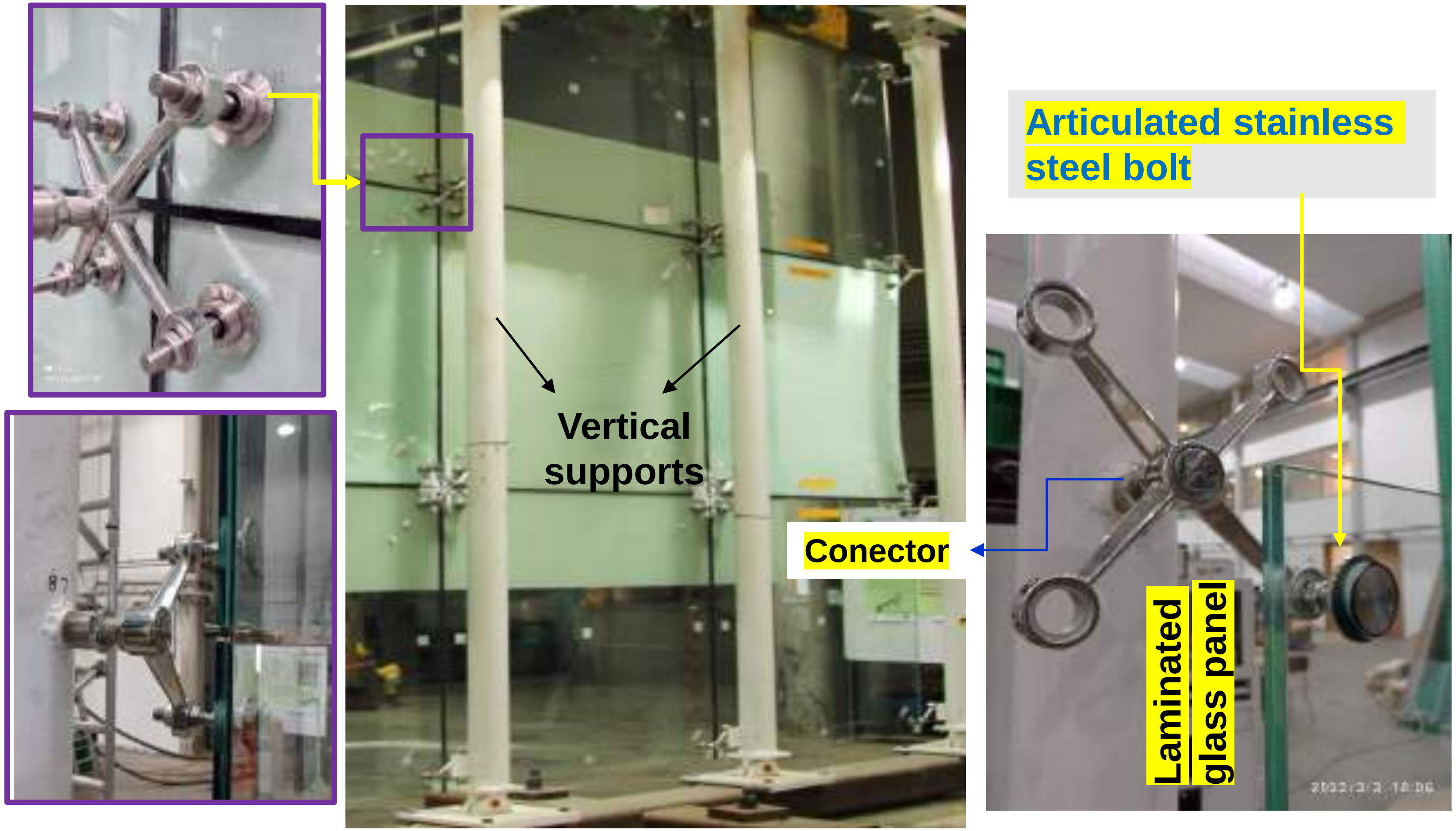


Fig. 2 Point fixed glass facade system | **GF-Seismic project**

Fig. 3 Different types of spider arms

“Less, but better”- Dieter Brams

Adhesive point fixings in structural glass reduce the concentration of stresses close to the drilled holes, avoiding thermal losses while enhancing the transparency of elements in comparison to traditional mechanical systems.

EMBEDDED

COUNTERSUNK

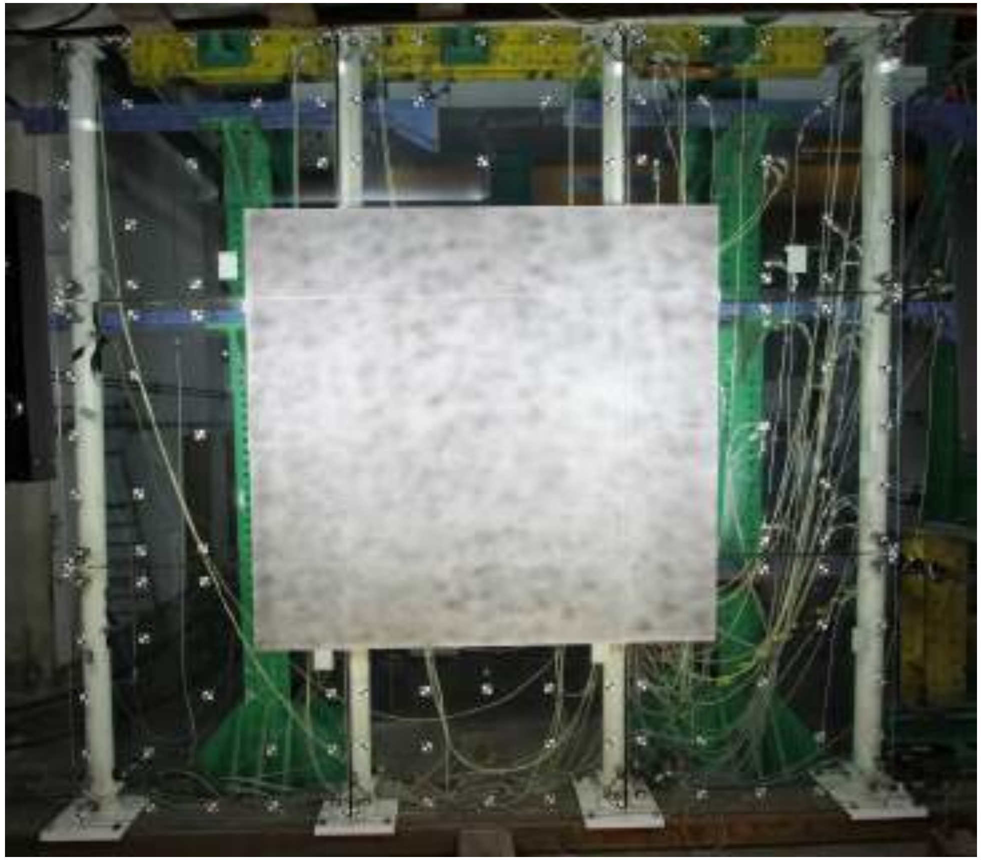


Fig. 4 Full scale section of a façade system under quasi-static cyclic load

ADHESIVELY BONDED BOLT--TO- GLASS

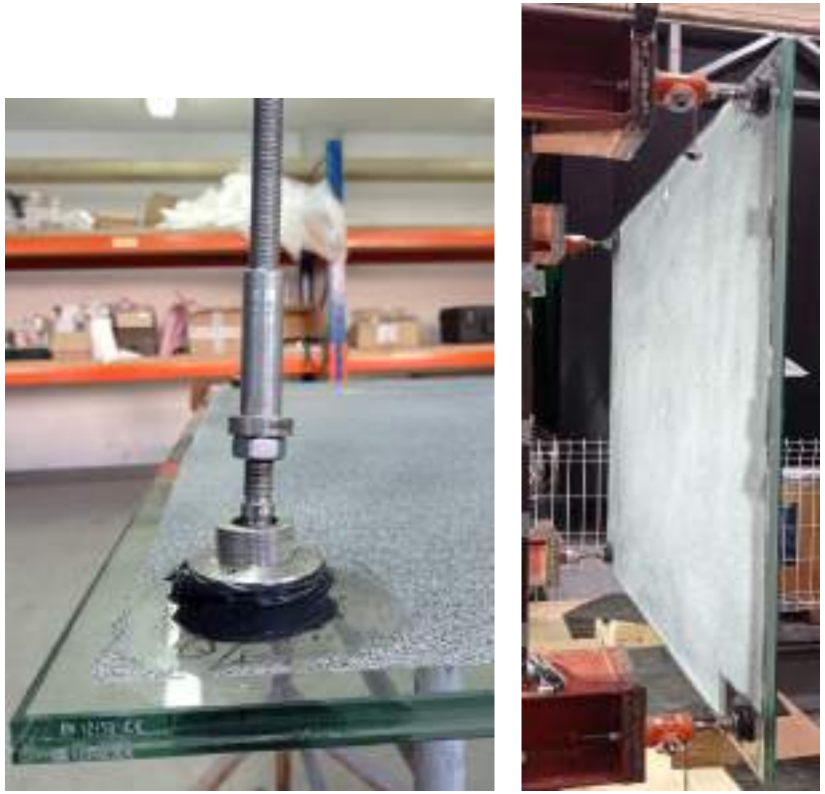
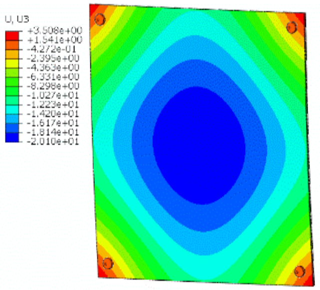


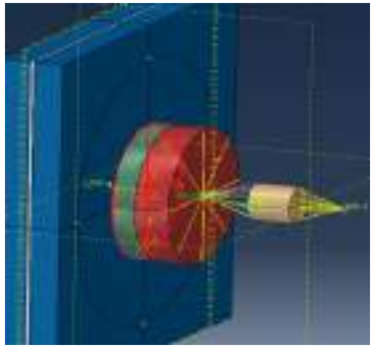
Fig 5. Adhesively bonded point fixings on laminated glass | **GF-Seismic project**

1.2 Assessment of Hyperelastic Material Models

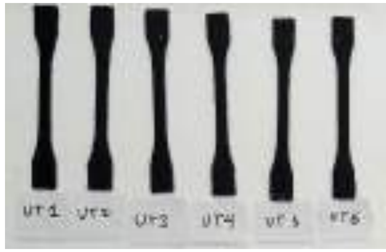
- Adhesive type: Structural silicone SikaSil® SG-500 - two-component | cured by polycondensation.
- Complex numerical models affected by non-linearities.
- To implement realistic mechanical behaviour into the finite element software, an appropriate material model needs to be calibrated i.e. calibration of material models.

Fig 6. Details bonded fixings





Experimental tests on bulk material



Calibration of material model using mathematical expressions

Small scale experimental tests for bonded glass-bolt connections

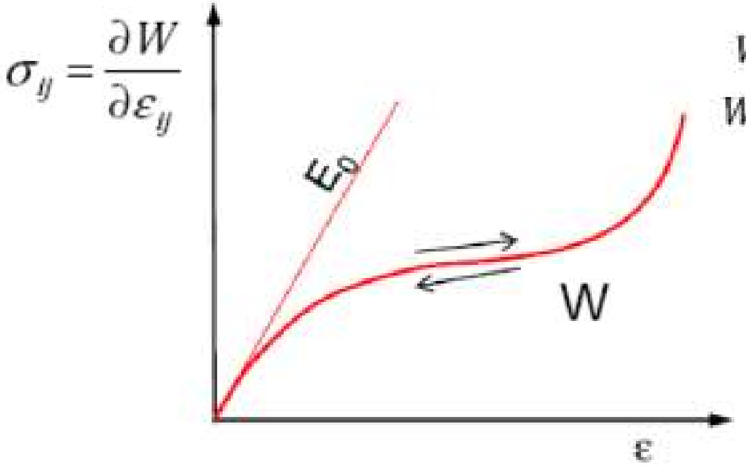
FEA to calibrate hyperelastic material models from bulk material

Calibration of material model with experimental results of LGP under uniform load

1.2 Hyperelastic material

- A hyperelastic material is still an elastic material, that **returns to it's original shape after the forces have been removed.**
- Hyperelastic material also is Cauchy-elastic, which means that the **stress is determined by the current state of deformation**, and not the path or history of deformation.
- **The stress-strain relationship** derives **from a strain energy density function** dependent of the stretch invariants, contrary to linear elastic material where the stress is just a linear function of strain.

$W = f(I_1, I_2, I_3)$ or principal stretch ratios $W = f(\lambda_1, \lambda_2, \lambda_3)$



$$\left.\begin{aligned} W &= f(I_1, I_2, I_3) \\ W &= f(\lambda_1, \lambda_2, \lambda_3). \end{aligned}\right\}$$ Depend on invariants (I_i) or extension Ratios (λ_i)

Fig. 7 Example of a stres-strain curve for hyperelastic material

W: Strain energy

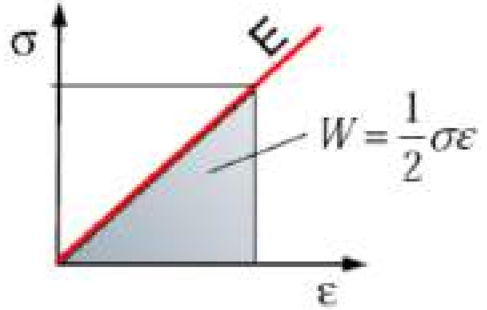


Fig. 8 Example of stress - strain curve for linear elastic material

❑ Matemathical expressions for material models

Model	Year of publication	Strain energy density function W	Parameters
Mooney-Rivlin	1940	$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3)$	C_{10}, C_{01}
Neo-Hooke	1943	$W = C_{10}(I_1 - 3)$	C_{10}
Extension ratio-based models			
Ogden	1972	$W = \sum_{i=1}^{N} \frac{\mu_i}{\alpha_i}(\lambda_1^{\alpha_i} + \lambda_2^{\alpha_i} + \lambda_3^{\alpha_i} - 3)$ For N = 1: $W = \frac{\mu_1}{\alpha_1}(\lambda_1^{\alpha_1} + \lambda_2^{\alpha_1} + \lambda_3^{\alpha_1} - 3)$	μ_1, α_1
Van der Waals	1986	$W = G\left\{-(\lambda_m^2 - 3)[\ln(1-\theta) + \theta] - \frac{2}{3}\alpha\left(\frac{\bar{I} - 3}{2}\right)^{\frac{3}{2}}\right\}$ with $\theta = \sqrt{\frac{\bar{I} - 3}{\lambda_m^2 - 3}}$ $\bar{I} = \beta I_1 + (1-\beta) I_2$	$G, \lambda_m, \alpha, \beta$
Yeoh	1990	$W = \sum_{i=1}^{\infty} C_{i0}(I_1 - 3)^i$ for N = 3: $W = C_{10}(I_1 - 3) + C_{20}(I_1 - 3)^2 + C_{30}(I_1 - 3)^3$	C_{10}, C_{20}, C_{30}

❑ The mathematical models depend on three principal strech rations (λ_1, λ_2, λ_3), and material constants C_{ij}, α_i, μ_i, etc., that are **determined by tests.**

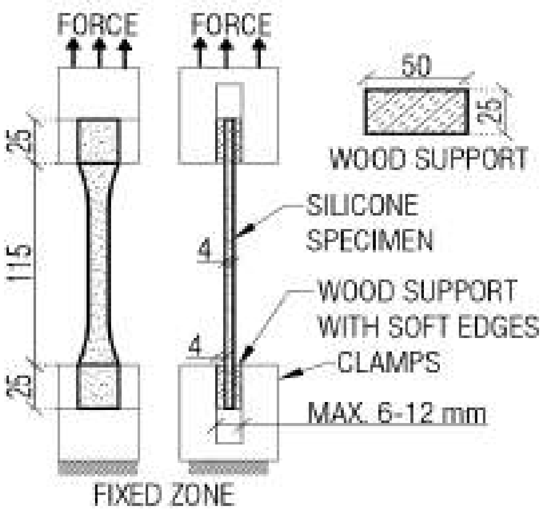
❑ Adhesive point-fixings for façade systems will mainly be loaded in compression, tension and shear, as a result of the **pressure or suction effects of the wind's load and self-weight.**

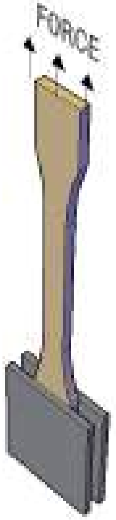
❑ In this study, uniaxial tensile tests, uniaxial compressive tests, simple shear tests and planar tension tests under monotonic load were conducted.

2. Experimental campaign

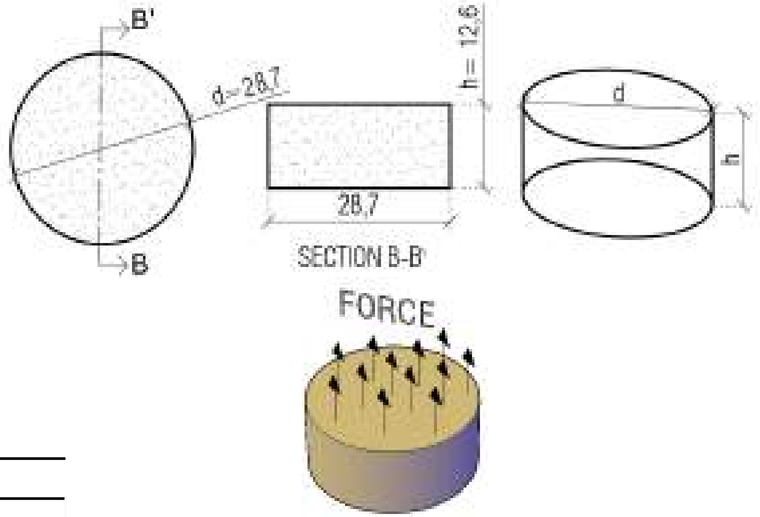
- Objective: **Calibrate suitable material models for structural silicone SikaSil® SG-500**, **fitting** the experimental results on bulk material to **mathematical models**, with the aid of FEA. Finally, to **use the calibrated material models** for the **glass-to-bolt connection** on an adhesively bonded point fixed laminated glass panel for a **façade system**.

Uniaxial Tension (UT)
EN-ISO-527 Part 1, part 2 (2012)





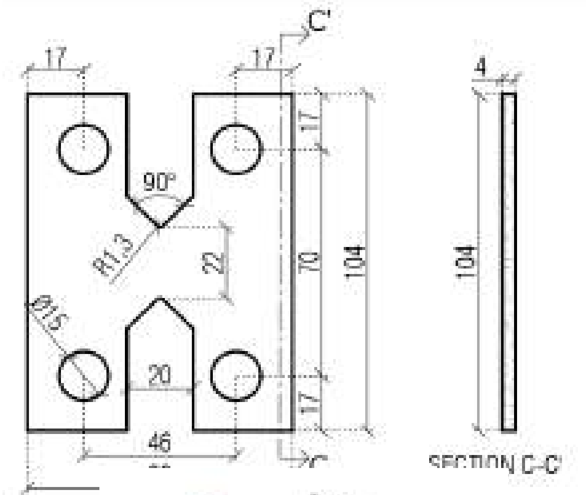
Uniaxial Compression (UC)
ISO-7743 (2004)

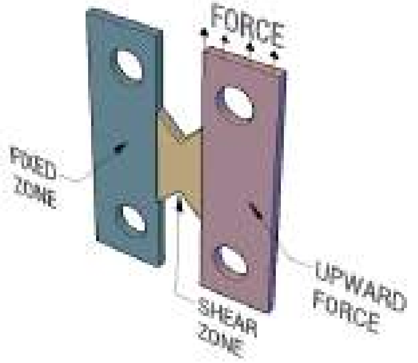


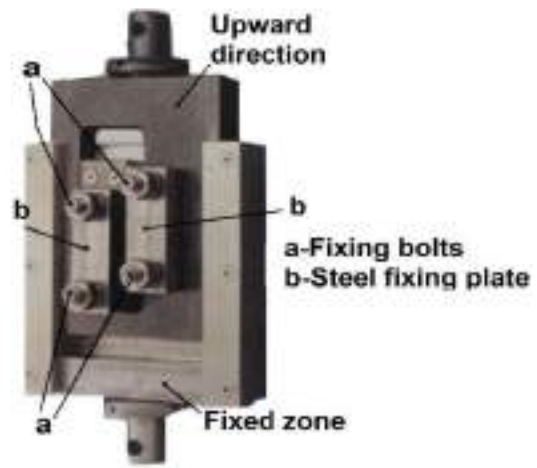
Name	Test	Type of test	Displ. Rate	Quant.	Material
TSG-T01 → T06	Static	- Uniaxial tension	5 [mm/min]	6	Silicone
TSG-C01→ C06	Cycle	- Uniaxial compression	10 [mm/min]	6	Sikasil
TSG-S01→ S06	Static	- Simple shear	2 [mm/min]	6	SG-500
TSG-PT01 → PT06	Static	- Planar tension	5 [mm/min]	6	(SG500)

2. Experimental campaign

Planar tension (PT)

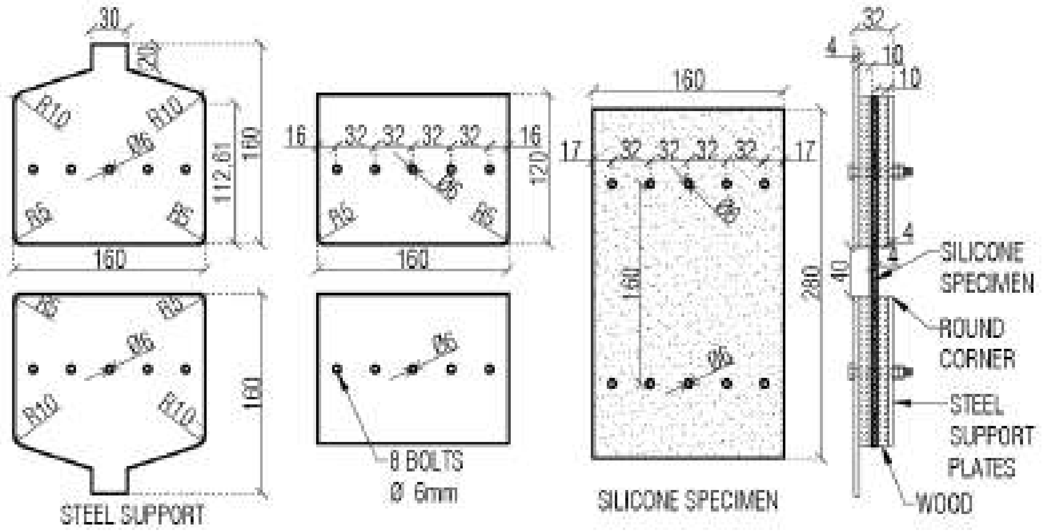


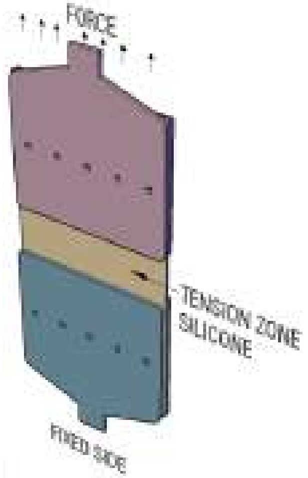




Simple shear (SS)

ASTM D7078M-05





Name	Test	Type of test	Displ. Rate	Quant.	Material
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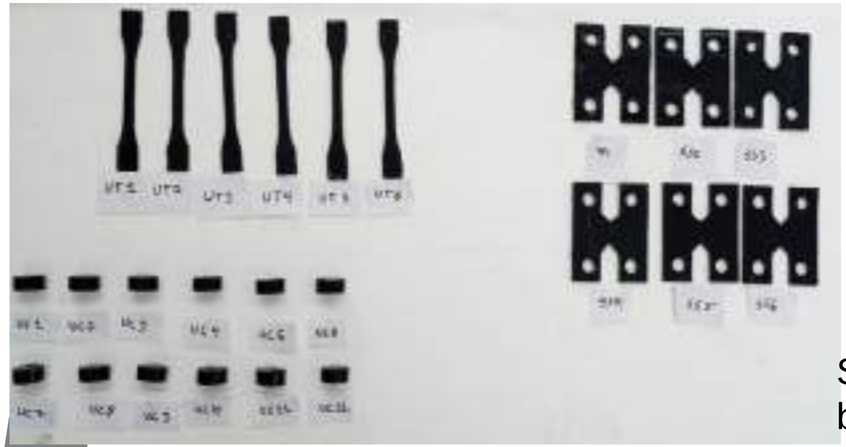
TSG-C01→ C06	Cycle	- Uniaxial compression	10 [mm/min]	6	Sikasil
TSG-S01→ S06	Static	- Simple shear	2 [mm/min]	6	SG-500
TSG-PT01 → PT06	Static	- Planar tension	5 [mm/min]	6	(SG500)

2. Experimental campaign

Specimen's molds

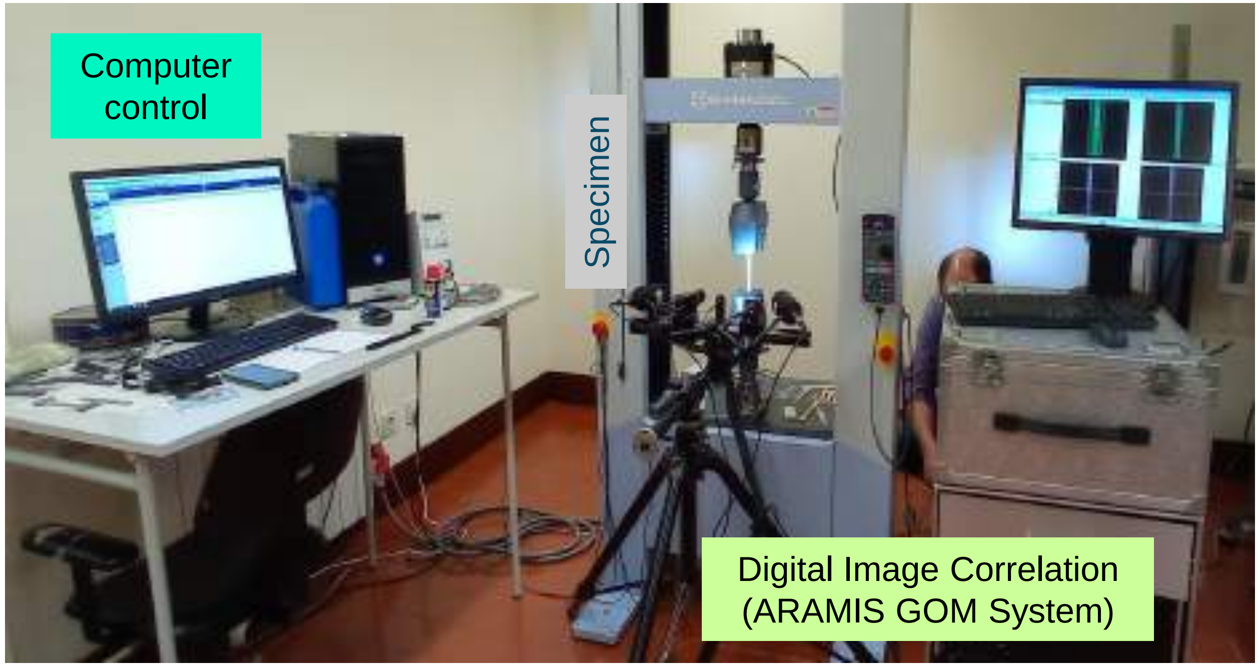
SikaSil® SG-500

Butterfly test



Specimens before test

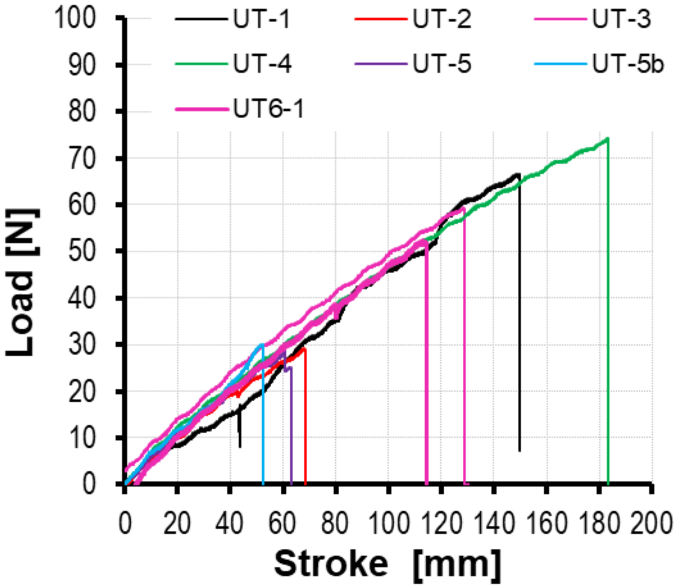
UTM SHIMADZU AGS-X-100kN
Load Cell 100 kN

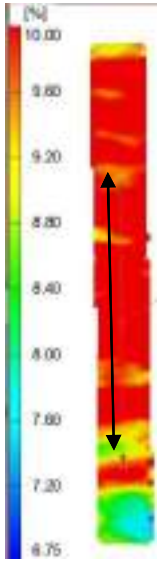


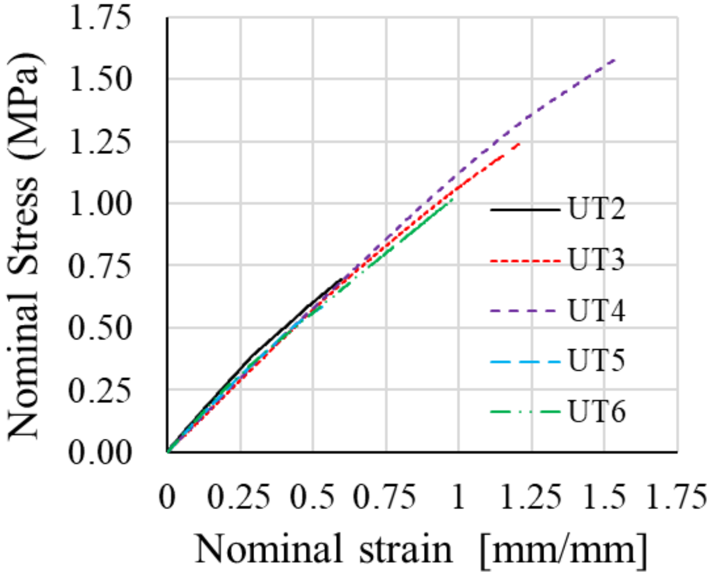
Uniaxial tension specimens painted with white speckle pattern for DIC

2. Experimental campaign

Uniaxial Tension (UT) - Results



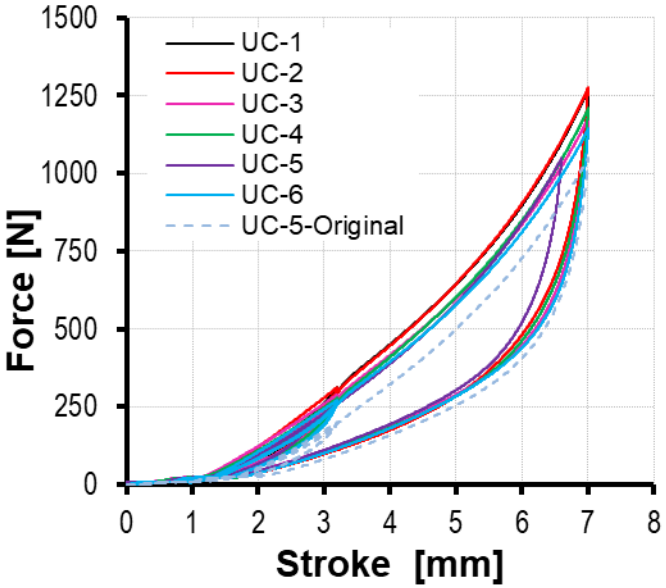




- The results of uniaxial tensile tests were satisfactory, having obtained the rheological stress-strain curves up until 158% of longitudinal strain.
- The secant tensile modulus calculated corresponds to the reported values provided by the manufactures.

Specimen	Max. nominal dis-placement [mm]	Nominal breakage stress [MPa]	Nominal strain at rupture [-]	Secant tensile modulus [MPa]
UT 3	130.4	1.28	1.28	1.00
UT 4	183.9	1.58	1.54	1.03
UT 6	114.4	1.10	1.06	1.04
Average		1.32	1.29	1.02
S.D.		0.24	0.24	0.02
C.V		5.88%	5.77%	0.04%

Uniaxial Compression (UC)



Mechanical conditioning
Rate [mm/min]
10 mm/min 3 cycles up to 3.2 mm (25 % strain); 4th cycle 7 mm (55 % strain)

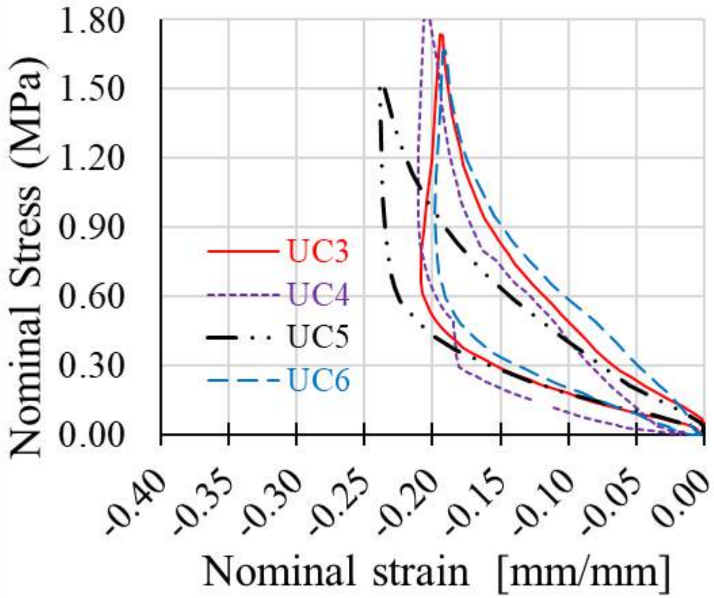
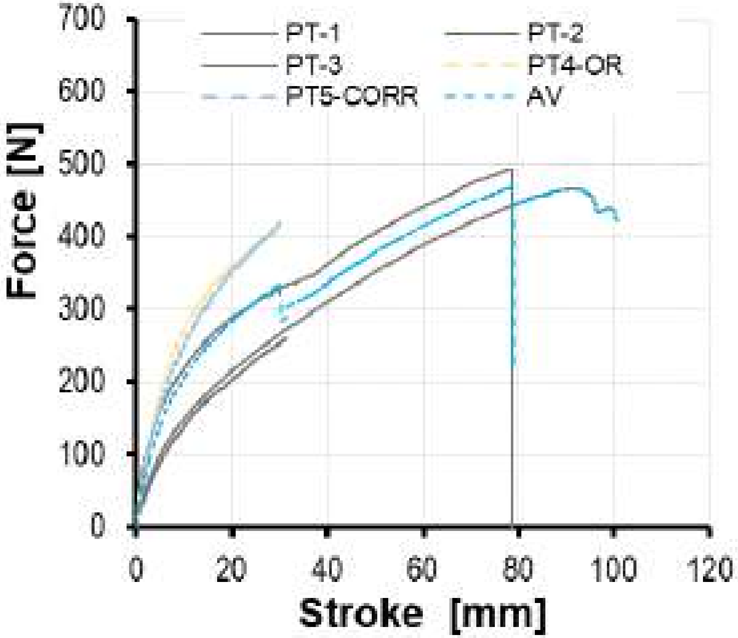


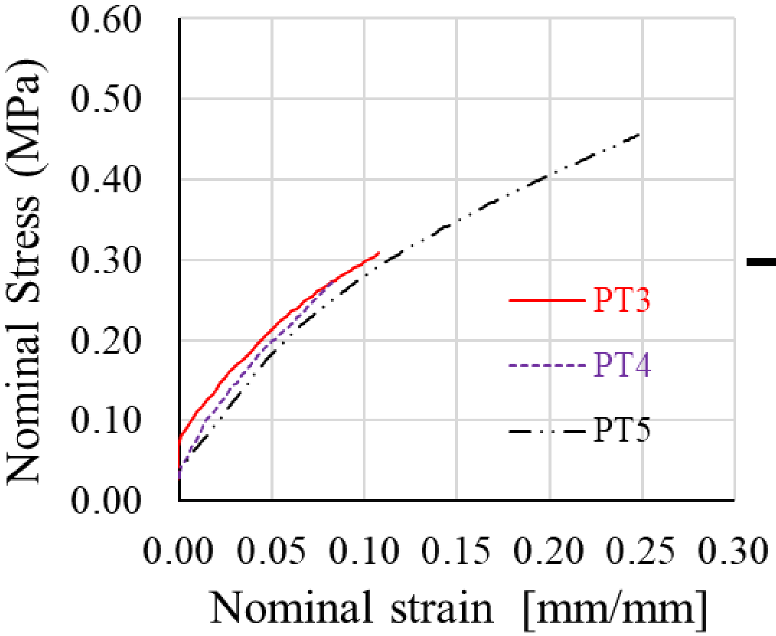
Table 3: Results from uniaxial compression test for structural adhesive *SikaSil SG500*

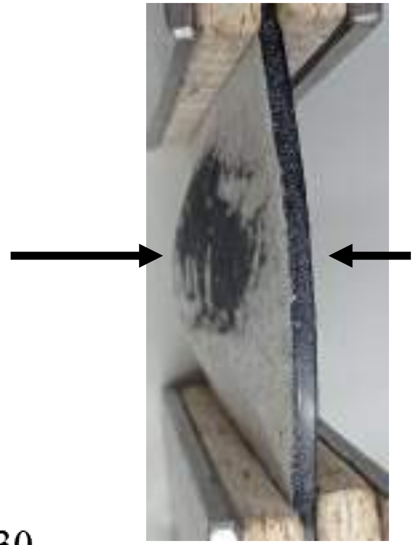
Specimen	Nominal breakage Stress [MPa]	Nominal strain at rupture [-]
UC 3	1.74	-0.19
UC4	1.81	-0.20
UC 5	1.53	-0.24
UC 6	1.67	-0.19
Average	1.69	-0.21
S.D.	0.12	0.02
C.V	1.43%	0.04%

- It was verified the importance of having a mechanical conditioning for the samples.
- Even though, the friction was prevented using a lubricant between the plates and the specimen, it was not possible to guarantee a uniform lubrication for the 4th cycle for all the specimens.

Planar tension (PT)- Resul







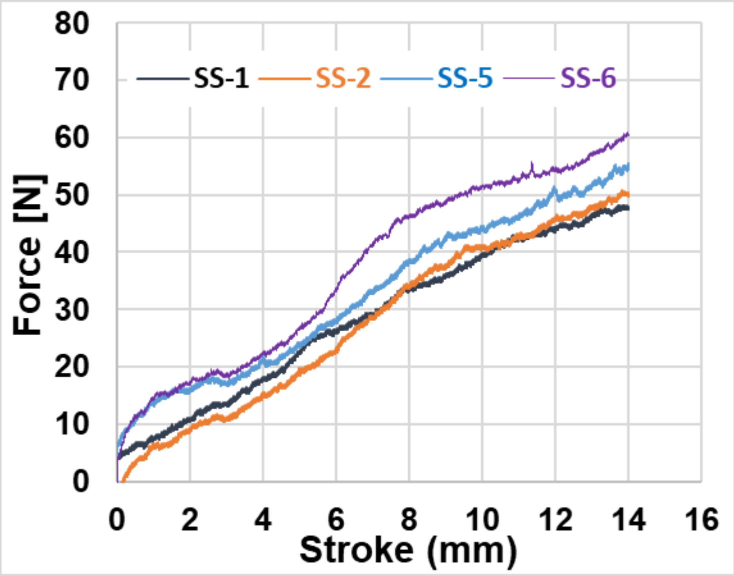
Elastic Recovery

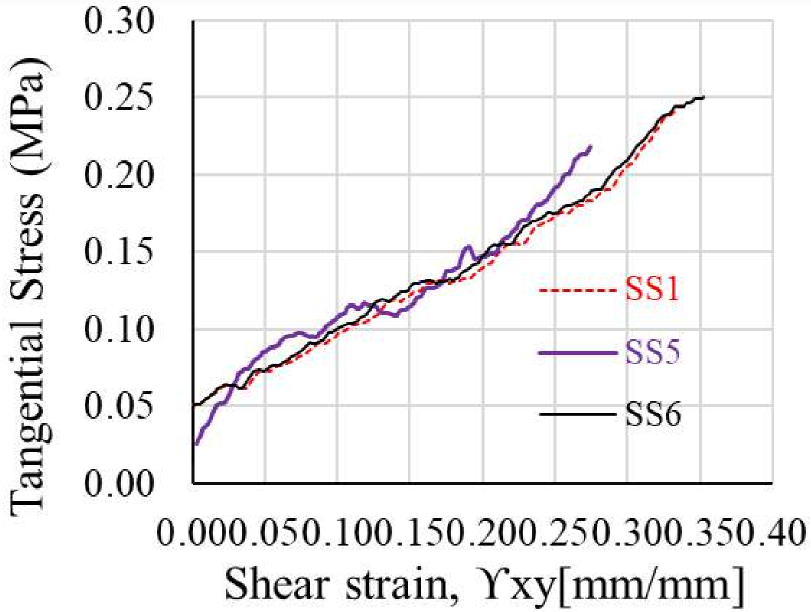
Table 4: Results from planar tension test for structural adhesive SikaSil SG500

Specimen	Nominal Stress [Mpa]	Nominal strain [-]	Secant Modulus [MPa]
PT 3	0.31	0.11	2.82
PT 4	0.27	0.08	3.38
PT 5	0.45	0.25	1.80
Average	0.34	0.15	2.66
S.D.	0.09	0.09	0.80
C.V	0.89%	0.82%	63.79%

The loosening of the grip constrain, lead to a lateral reduction (thickness), reflecting the low levels of planar strain obtained. Nevertheless, the rheological behaviour obtained, is valuable for the calibration of hyperelastic constitutive material laws initially intended in this work.

Simple shear (SS)- Results





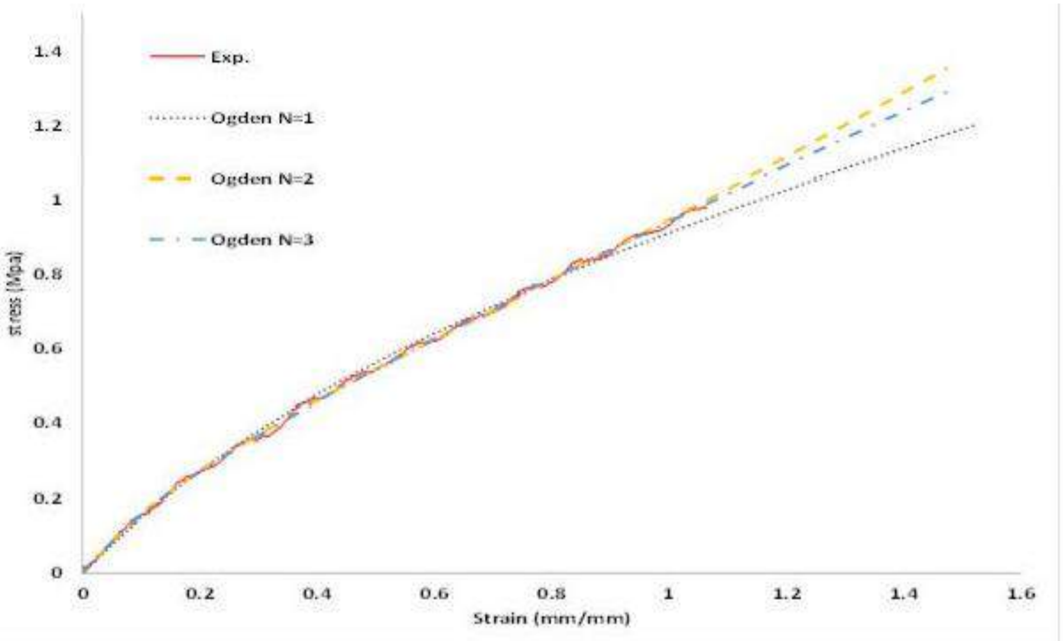
Specimen	Max. Tangential Stress [Mpa]	Max. Shear strain, tan ϒ [Rad]	Shear Modulus (G) [MPa]
SS1	0.24	0.34	0.70
SS5	0.22	0.25	0.78
SS6	0.45	0.25	0.73
Average	0.30	0.28	0.74
S.D.	0.13	0.05	0.04
C.V	1.62%	0.27%	0.16%

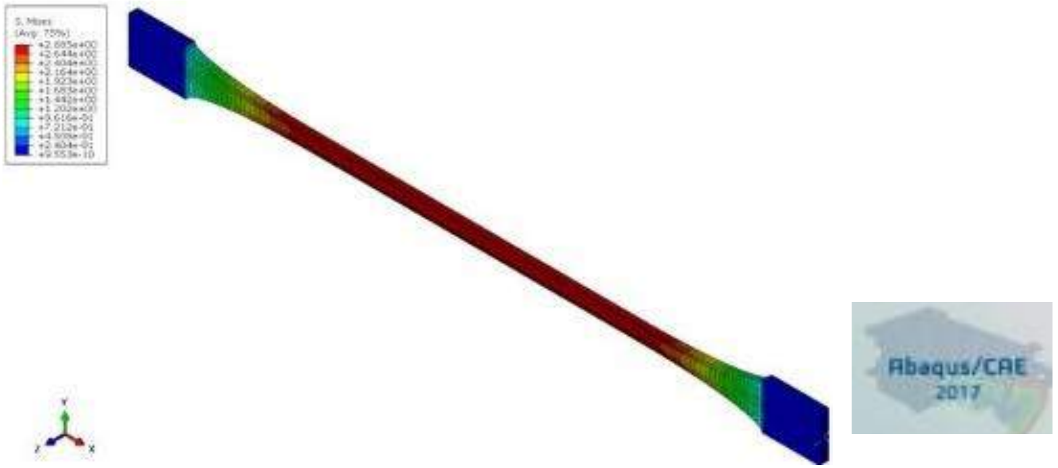
Numerical models

Extension ratio-based models

Ogden	1972	$W=\sum_{i=1}^{N}\frac{\mu_i}{\alpha_i}(\lambda_1^{\alpha_i}+\lambda_2^{\alpha_i}+\lambda_3^{\alpha_i}-3)$ For N = 1: $W=\frac{\mu_1}{\alpha_1}(\lambda_1^{\alpha_1}+\lambda_2^{\alpha_1}+\lambda_3^{\alpha_1}-3)$	μ_1, α_1

Ogden	N=1	I	Mu-I	Alpha_I	D_I
		1	0.549032	1.849586	0
	N=2	I	Mu-I	Alpha_I	D_I
		1	0.278323	1.907145	0
		2	0.347837	-6.15952	0
	N=3	I	Mu-I	Alpha_I	D_I
		1	-3.37349	-1.90855	0
		2	1.845188	-0.30242	0
		3	2.163554	-3.73226	0

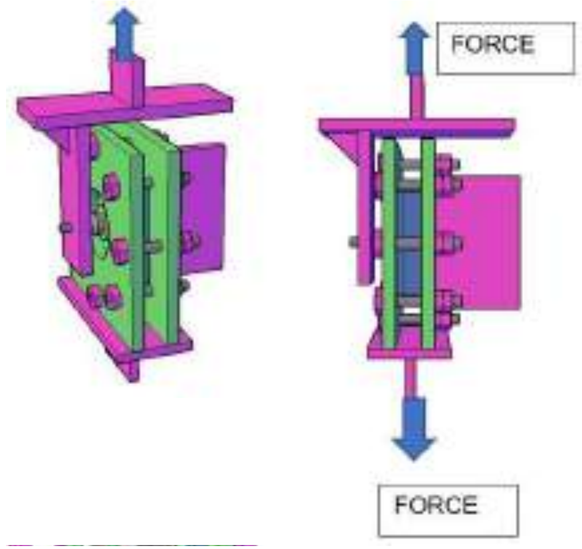


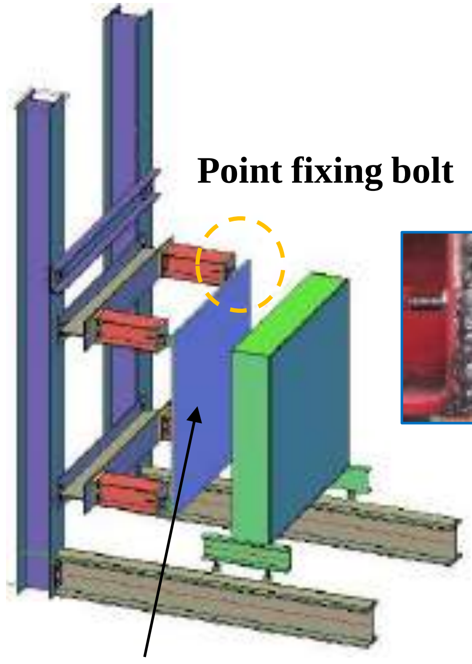


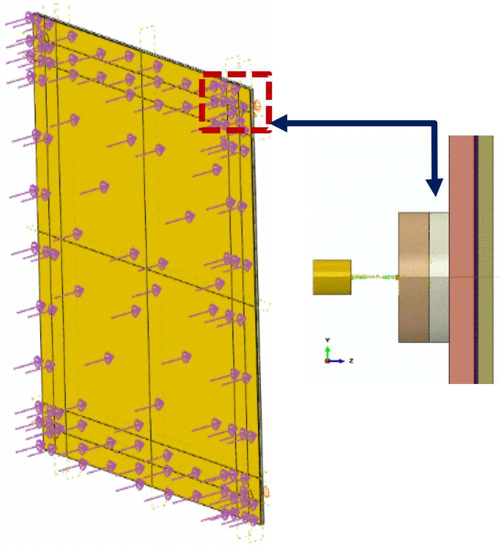
3. Remarks and ongoing work

The ongoing work relates to:

- Numerical calibration of hyperelastic constitutive material laws.
- Benchmark numerical models with experimental test results for embedded bolts, followed by a parametric study of the façade system, including a dynamic loading (time history analysis)







Acknowledgment

- The Portuguese Foundation for Sciences and Technology (Fundação da Ciência e Tecnologia) under first author's studentship under grant agreement 2021.06822.BD is gratefully acknowledged.

- **COST Action CA18120 (CERTBOND) and supported by COST (European Cooperation in Science and Technology).**

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www.gfseismic.com

Thank you for your attention !

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ENVIRONMENTAL DURABILITY OF KEVLAR COMPOSITES REINFORCED WITH TiO_2 NANOPARTICLES

Vera Obradović, Petr Sejkot, Klára V. Machalická, Miroslav Vokáč

COST EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Funded by the Horizon 2020 Framework Programme of the European Union

Outline

- Introduction
- Preparation of the specimens
- Characterization
- Results and discussion
- Conclusion

Introduction

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- The fabrics produced from the para-aramid (*p*-aramid) fibers have had a wide range of applications in the design of multi-layered composite structures for body and vehicle armors, civil engineering, aircraft and automotive industries
- The *p*-aramid fibers are characterized by their low density, high stiffness and excellent impact behavior
- Kevlar belongs to the aramid group of fibers
- Poly (vinyl butyral) (PVB) is a flexible and industrially significant polymer which acts as a matrix

Introduction

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- The addition of nanoscale reinforcement to the polymer matrix can greatly improve the mechanical characteristics of the composite structure
- The TiO_2 nanoparticles were used as reinforcement
- The effect of the TiO_2 nanoparticles and long-time immersion on the mechanical properties of the Kevlar/PVB composites have been studied
- The tensile and bending properties of the dry specimens were compared with the ones that underwent the water absorption in duration of 8 weeks

Preparation of the Specimens

- The specimens were made from the Kevlar fabrics impregnated with the 10 wt.% poly (vinyl butyral)/ethanol (PVB/ethanol) solution which contained the TiO_2 nanoparticles
- The reinforcement content in all the composites was 1 wt.% or 2 wt.% in regard to PVB
- Each composite sample consisted of two layers of the impregnated Kevlar fabrics, which had been processed in the heat press machine (170 °C, 30 min)
- The PVB/fabric weight ratio for the impregnation of the Kevlar fabric was 0.2 (20 wt.%)

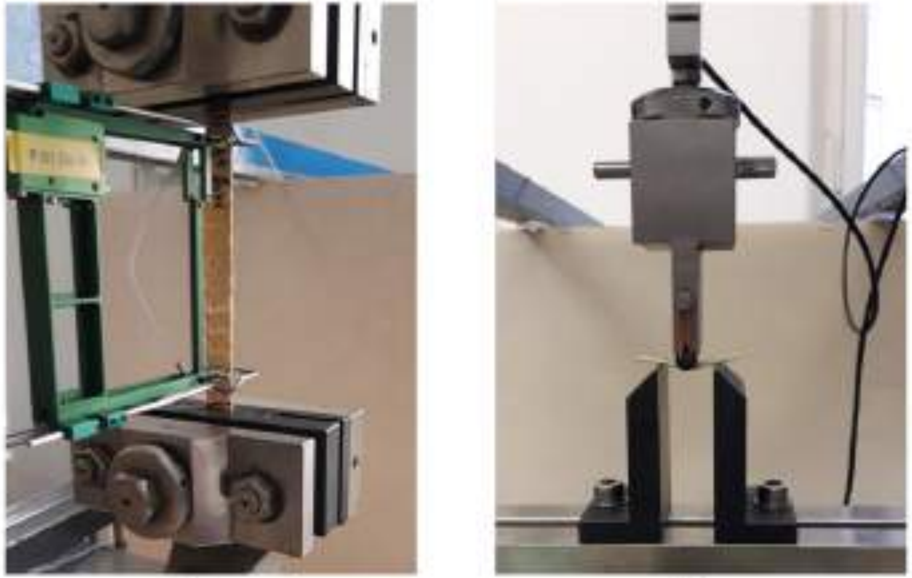
Characterization

- The water immersion of the square specimens in the distilled water (40 °C) was performed according to the ISO 62 standard
- The dimensions of the square specimens for the water absorption measurements were 50 mm × 50 mm x 1 mm
- The water immersion period lasted 8 weeks (56 days)
- The specimens for both the tensile and bending test were immersed under the same conditions
- The Kevlar/PVB specimens were tested in accordance with the ASTM D3039 standard for the tensile properties of the composite materials with the polymer matrix

Characterization

- The dimensions of the specimens for the tensile test were 200 mm × 15 mm × 1 mm
- The length of the specimen between the clamps was 130 mm
- The strain was determined by using the 100 mm long extensometer with the cross-head displacement rate 2 mm/min
- In accordance with the ASTM D 790-03 standard the three-point bending test of the Kevlar/PVB specimens was carried out for the flexural properties where the cross-head displacement rate was 1 mm/min
- The dimensions of the specimens for the bending test were 50.8 mm x 15 mm x 1 mm (2 inches x 15 mm x 1 mm)

Mechanical Characterization Devices



(a) (b)

Figure 1. TIRA TEST 2300 testing machine set-up for (a) the tensile test and (b) the bending test

Water Absorption Equation

$$M(t) = \left(\frac{m_t - m_0}{m_0}\right) \times 100$$

- $M(t)$ - the water absorption percentage,
- m_t - the weight of the specimen at the immersion time t,
- m_0 - the initial weight of the dry specimen at $t = 0$.

Water Uptake Results

- The water uptake of the nanocomposites decreased due to the presence of nanoparticles which made the barriers properties

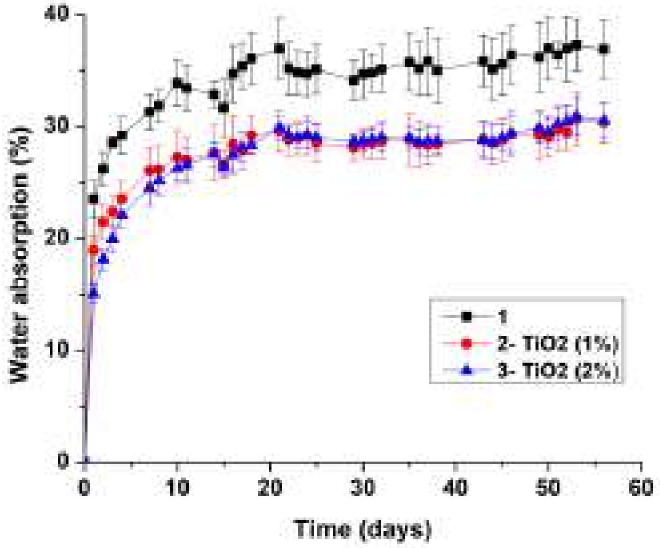


Figure 2. Water absorption of the Kevlar/PVB composites with the immersion time

Tensile Test Results

- The specimen ends were not damaged in the clamps of the tensile test machine
- All the specimens underwent an incomplete rupture
- The addition of the 2 wt.% TiO_2 nanoparticles produced the 39.8% and 24.3% improvement in the tensile strength and tensile modulus, respectively, compared to the dry Kevlar/PVB specimens with no reinforcement
- The decrease of the tensile strength and the tensile modulus was determined in all the specimens after water immersion

Table 1. The tensile test results of the Kevlar/PVB composite specimens

Specimen	Tensile Strength (MPa)	Tensile Modulus (GPa)	TEA (N/mm^2)
Kevlar/PVB - dry	369.71 ± 30.00	24.85 ± 4.42	7.70 ± 2.65
- wet	293.09 ± 15.34	19.02 ± 2.51	7.80 ± 0.47
Kevlar/PVB/1% TiO_2 - dry	423.80 ± 29.05	23.15 ± 2.31	5.87 ± 1.53
- wet	351.41 ± 21.41	22.02 ± 1.11	5.12 ± 2.43
Kevlar/PVB/2% TiO_2 - dry	516.84 ± 42.01	30.90 ± 1.99	8.85 ± 2.99
- wet	426.03 ± 20.45	25.98 ± 2.48	6.51 ± 1.47

Tensile Test Results

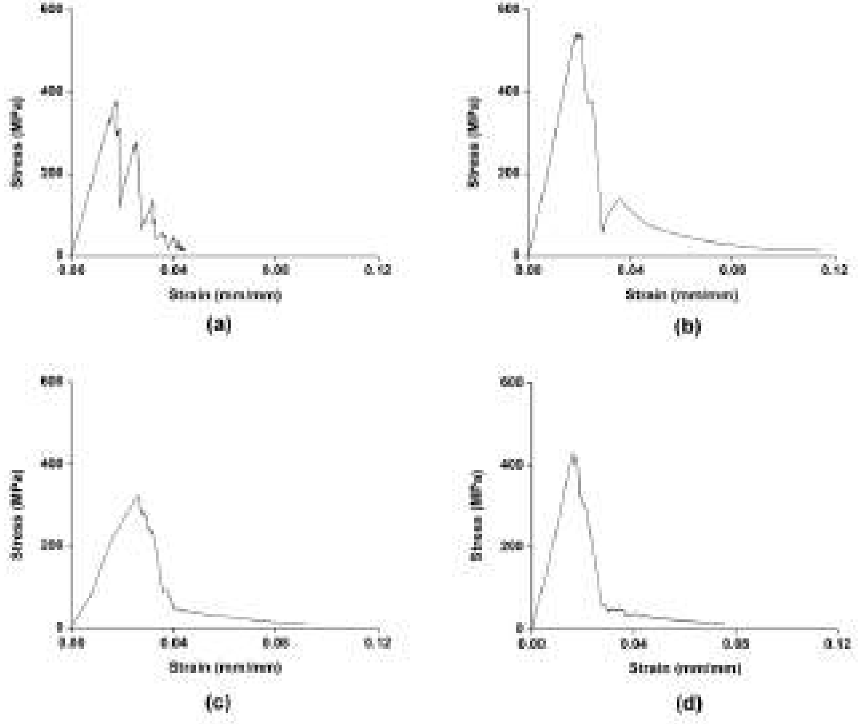


Figure 3. The stress-strain diagrams of the Kevlar/PVB specimens: (a) neat, (b) with the 2 wt.% TiO_2 nanoparticles; and immersed: (c) neat, (d) with the 2 wt.% TiO_2 nanoparticles

SEM Images

- The fibers of the wet Kevlar composite specimens are wider and their surface is rougher

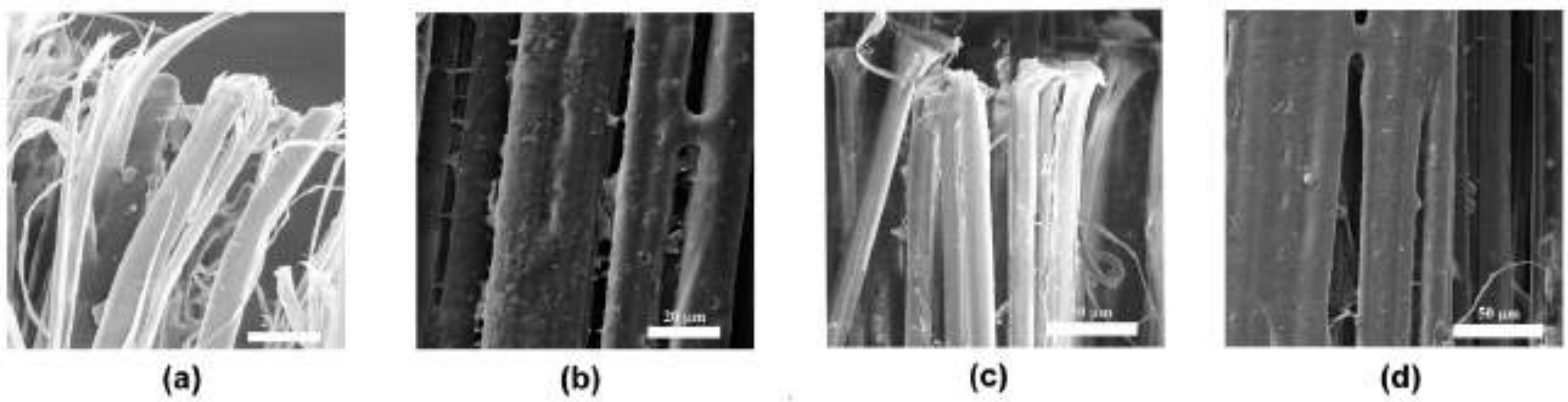


Figure 4. The SEM images of: (a) the dry and (b) the wet Kevlar/PVB/1 wt.% TiO_2 specimens; (c) dry and (d) wet Kevlar/PVB/2 wt.% TiO_2 specimens

Bending Test Results

- The best flexural properties (strength and modulus) were achieved with the dry specimens with no particles due to the better bonding between their two impregnated fabric layers
- The presence of the TiO_2 nanoparticles reduced the shear connection between the layers
- The largest decrease for the bending strength at the 5% strain was observed for the immersed Kevlar/PVB specimens
- There was not such a large decline in the bending strength properties of the wet specimens with nanoparticles

Table 2. The bending test results of the Kevlar/PVB composite specimens

Specimen	Flexural Strength, 5% strain (MPa)	Flexural Modulus (GPa)
Kevlar/PVB - dry	98.58 ± 4.99	5.61 ± 0.89
- wet	38.02 ± 2.11	4.40 ± 0.62
Kevlar/PVB/1% TiO_2 - dry	72.76 ± 5.00	3.98 ± 0.20
- wet	45.62 ± 8.44	3.50 ± 1.29
Kevlar/PVB/2% TiO_2 - dry	71.45 ± 10.65	3.70 ± 1.13
- wet	48.80 ± 8.73	3.01 ± 1.06

Bending Test Results

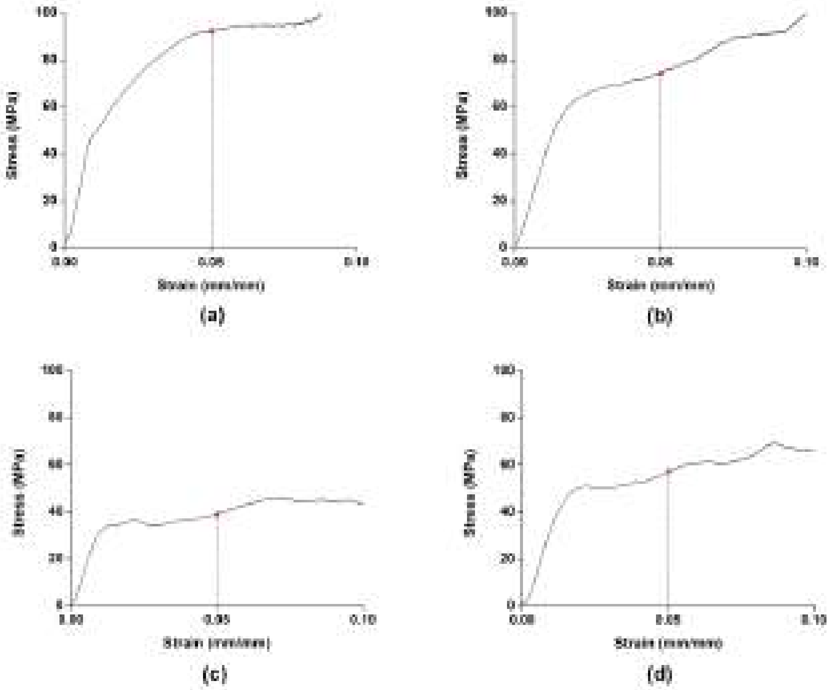


Figure 5. The flexural stress-strain diagrams of the Kevlar/PVB specimens: (a) neat; (b) with the 1 wt.% TiO_2 nanoparticles; and immersed: (c) neat; (d) with the 1 wt.% TiO_2 nanoparticles

Conclusions

- The effect of the water immersion on the mechanical properties of the Kevlar composites has been analyzed
- The complete fracture of the specimens did not occur during the tensile and the bending tests
- The addition of the 2 wt.% TiO_2 nanoparticles produced the 39.8% and 24.3% improvement in the tensile strength and tensile modulus, respectively, compared to the dry Kevlar/PVB specimens with no reinforcement
- The tensile strength and tensile modulus of all the immersed Kevlar/PVB composite specimens had decreased values in comparison with the ones of their dry specimens
- All the immersed Kevlar/PVB composite specimens had lower values of their flexural properties compared to the ones that were not water treated

Acknowledgment

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Research on Durability and Aging on Materials and Structures in Buildings

Editor-in-Chief

Prof. Dr. David Arditi
Construction Engineering and Management Program, Department of Civil, Architectural, and Environmental Engineering, Illinois Institute of Technology, 3201 South Dearborn Street, Chicago, IL 60616, USA

Message from the Editor-in-Chief

Current urban environments are home to multi-modal transit systems, extensive energy grids, a building stock, and integrated services. Sprawling neighborhoods are composed of buildings that accommodate living and working quarters. However, it is expected that the cities and communities of the future will face complex and enormous challenges, including maintenance, interconnectivity, resilience, energy efficiency, and sustainability issues, to name but a few. A smart city uses advanced technologies and a digital infrastructure to improve the outcomes in every aspect of a city's operations. A smart building optimizes the experience of occupants, staff, and management by using a modern and connected environment. Innovations in technology that can bring dramatic improvements to design, planning, and policy are critical in developing the cities and buildings of the future.

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Guest Editors

Dr. Klára V. Machalická

Dr. Petr Pokorný

Dr. Vera Obradović

Deadline for manuscript submissions:
31 March 2024

Message from the Guest Editors

We are pleased to invite you to contribute to this Special Issue entitled "Research on Durability and Aging on Materials and Structures in Buildings". Mechanical properties of polymeric materials are key of importance in all applications where polymers are used as a structural building material. The mechanical properties of polymers can be highly modified by the environment, which often acts as a degradation factor, and degradation can be also increased by the simultaneous action of mechanical stress.

Therefore, this Special Issue aims to collect original research studies, review papers, and experimental and/or numerical investigations that are focused on the durability and aging of polymers and coatings in structural applications in buildings. Topics of particular interest include, but are not limited to:

- adhesive joints and sealants;
- interlayers of laminated glass;
- composites with polymeric matrix;
- comparison of artificial aging methods and natural aging;
- corrosion of coated steel in concrete;
- stabilization of corrosion products against aging;
- passivation conversion coatings;
- bond strength of coated reinforcement with concrete.

Thank you!

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Innovative CFRP composite and Fe-SMA bonded systems for structural glass flexural strengthening

Jorge de Araújo Rocha, Eduardo Pereira, **José Sena-Cruz**

Seville, September 7th, 2023

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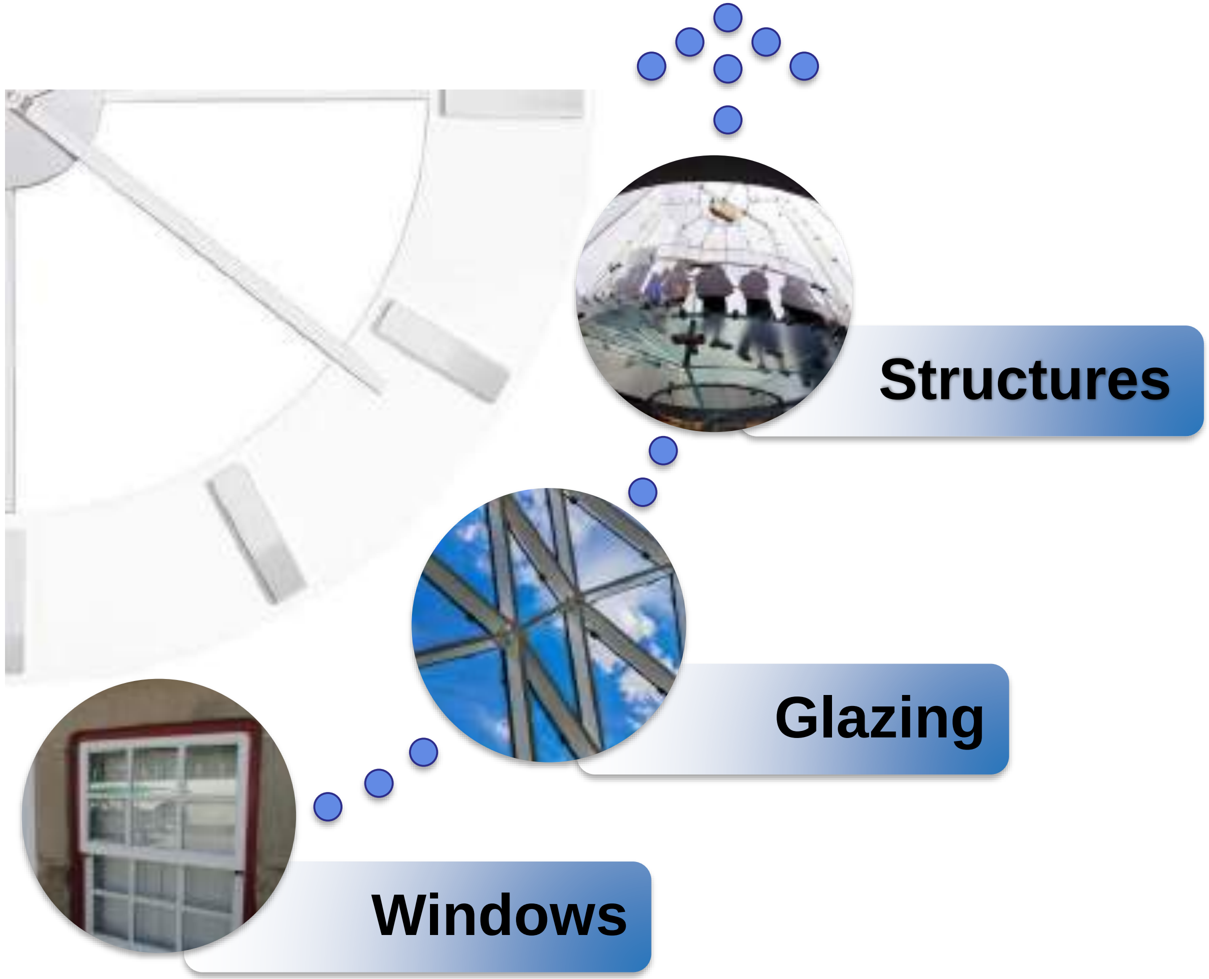
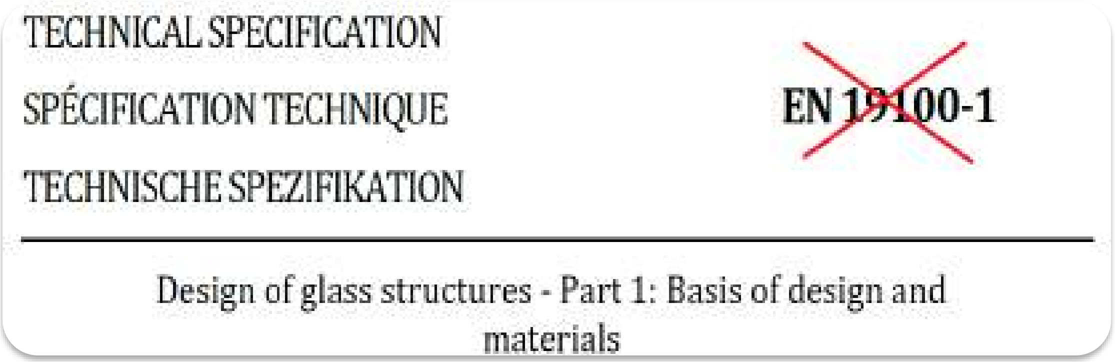
Applications



Challenges


TECHNICAL SPECIFICATION
SPÉCIFICATION TECHNIQUE
TECHNISCHE SPEZIFIKATION

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Design of glass structures - Part 1: Basis of design and materials

Material behaviour

- Brittle nature
- Unreliable resistance
- Time-dependent behaviour

Structural design

- No Eurocode for structural glass
- Over-designing methods
- Panels under out-of-plane loads

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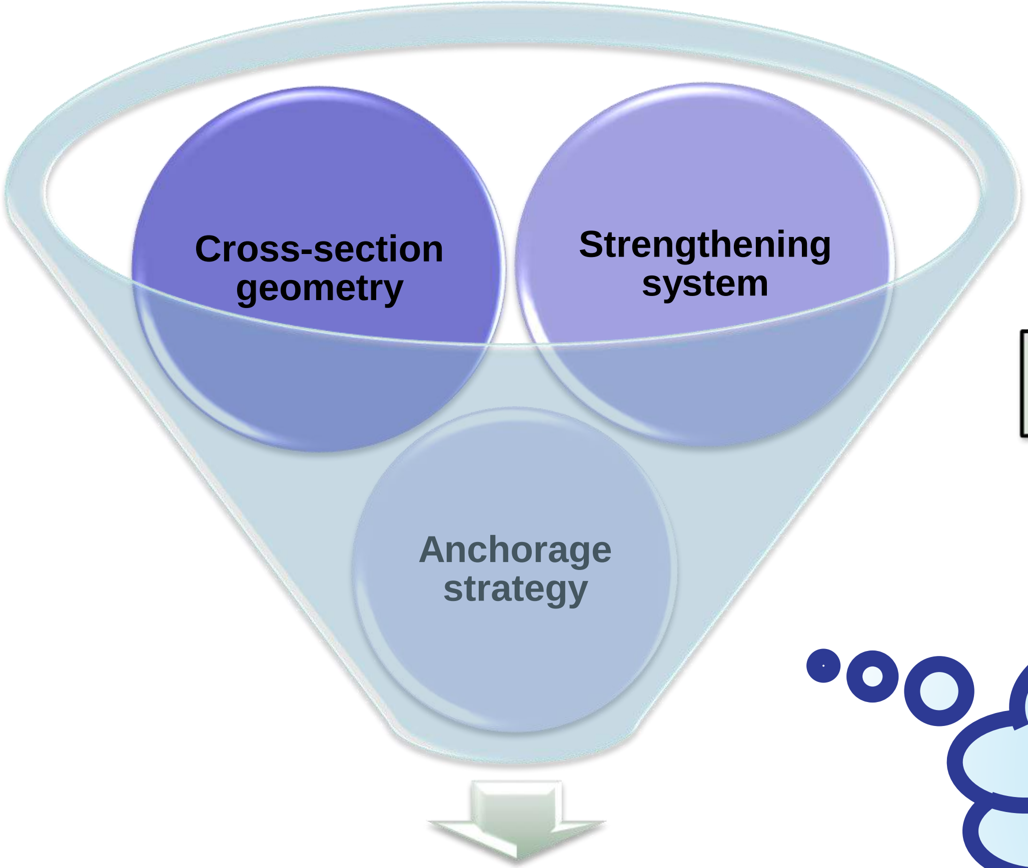
Strengthened glass

Timber

FRP's

Steel



Post-cracking performance

Shape memory alloys (SMA)

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Objectives

Developing **glass-CFRP composite systems** with relatively **ductile failure modes**

- Bond behaviour of glass-to-CFRP connections → Paper 1
- Flexural behaviour of CFRP reinforced glass beams → Paper 2
- Numerical simulation of the both experimental results → Paper 3

Reducing the unpredictability of glass fracture strength by prestressing CFRP and/or activating SMA reinforcements

- Flexural behaviour of glass beams with EBR Fe-SMA strips
- Efficiency of hybrid strengthening systems

→ Paper 4

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Research methodology

Paper 1: Tensile behaviour of CFRP-glass adhesively bonded connections: double-lap joint tests and numerical modelling

Paper 2: Influence of adhesive stiffness on the post-cracking behaviour of CFRP-reinforced structural glass beams

Paper 3: Feasibility of mechanical post-tensioning of annealed glass beams by activating externally bonded Fe-SMA reinforcement

Paper 4: Flexural behaviour of post-tensioned laminated glass beams with hybrid strengthening systems using CFRP and Fe-SMA reinforcements

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Paper 1: Tensile behaviour of CFRP-glass adhesively bonded connections: double-lap joint tests and numerical modelling

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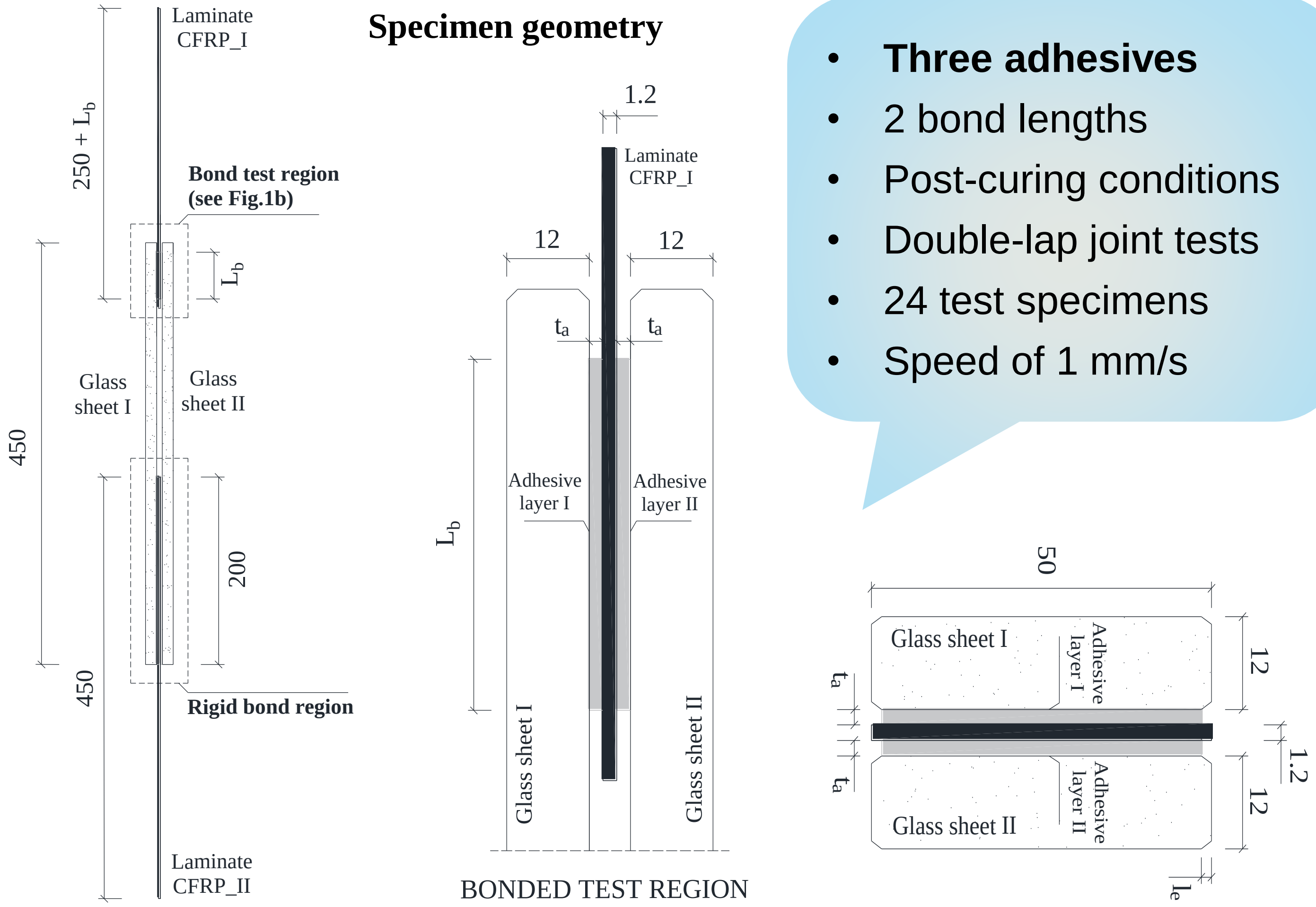
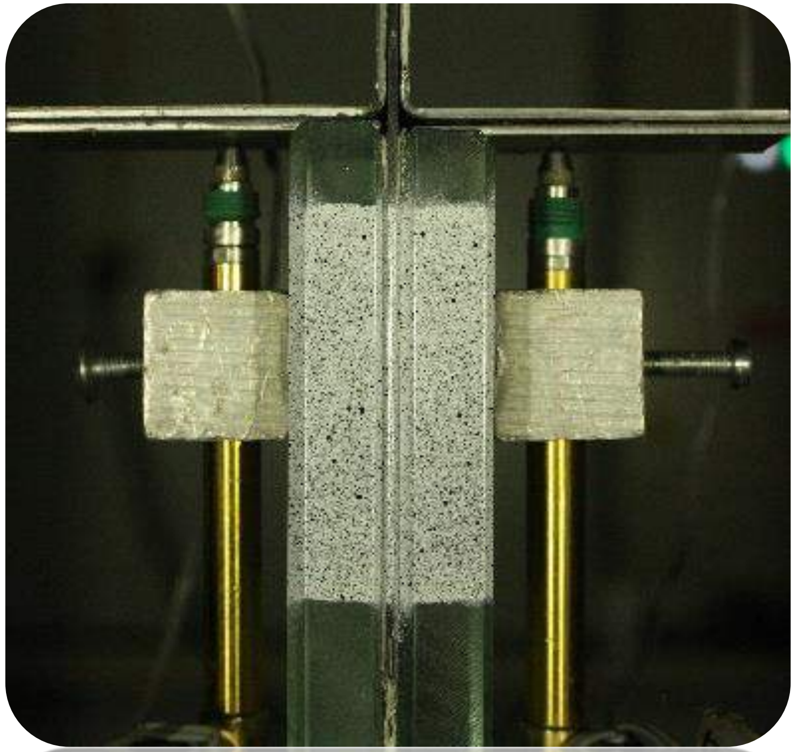
Paper 1: Glass-to-CFRP adhesive connections (1/3)



- **Three adhesives**
- 2 bond lengths
- Post-curing conditions
- Double-lap joint tests
- 24 test specimens
- Speed of 1 mm/s



DIC technique

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Paper 1: Glass-to-CFRP adhesive connections (2/3)

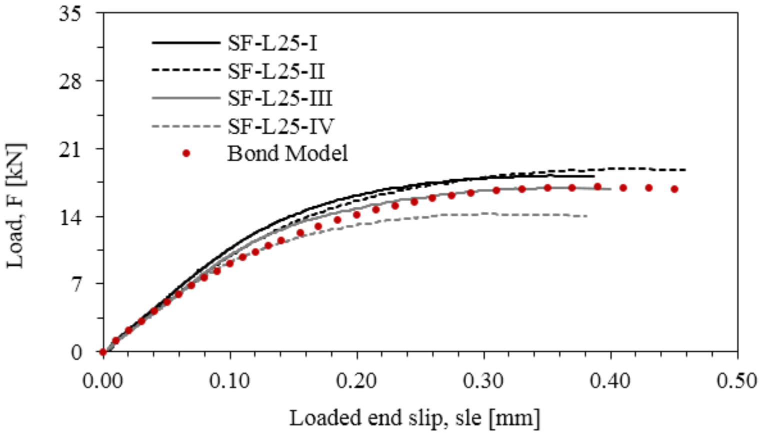
Stiffer adhesive

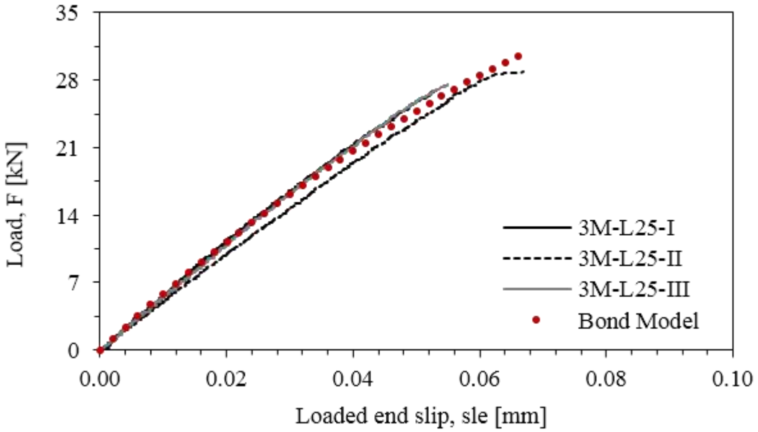


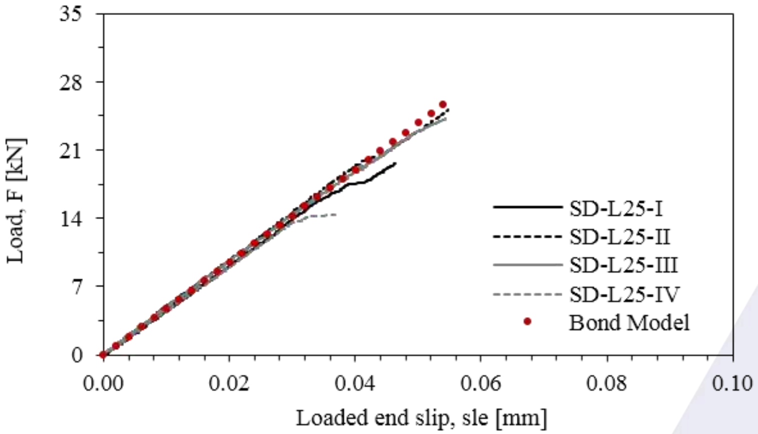
SikaForce

3M DP490

SikaDur



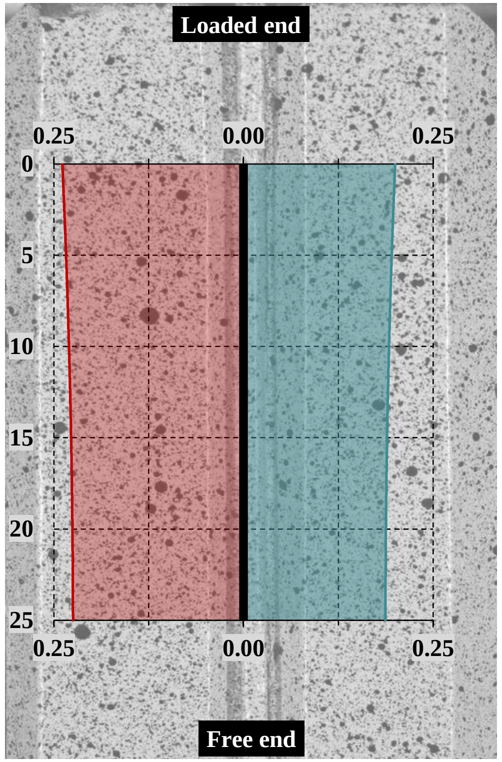


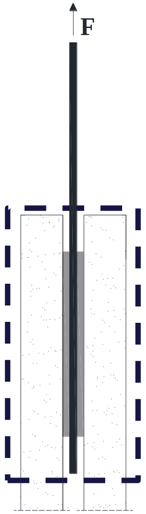


Paper 1: Glass-to-CFRP adhesive connections (3/3)

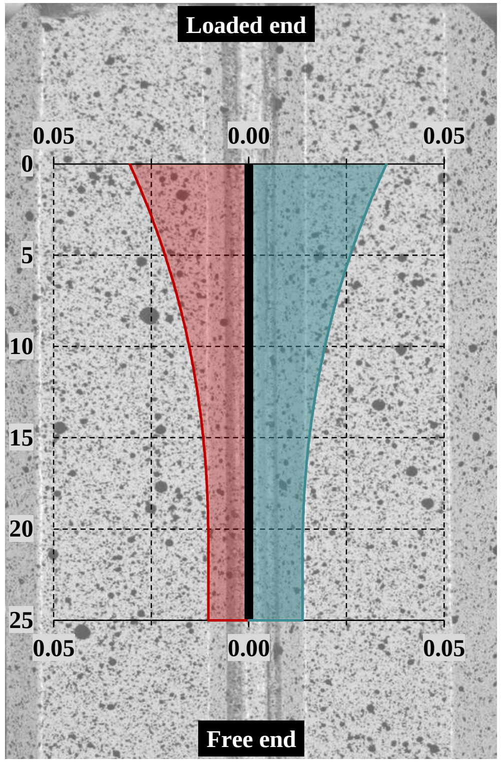
Stiffer adhesive

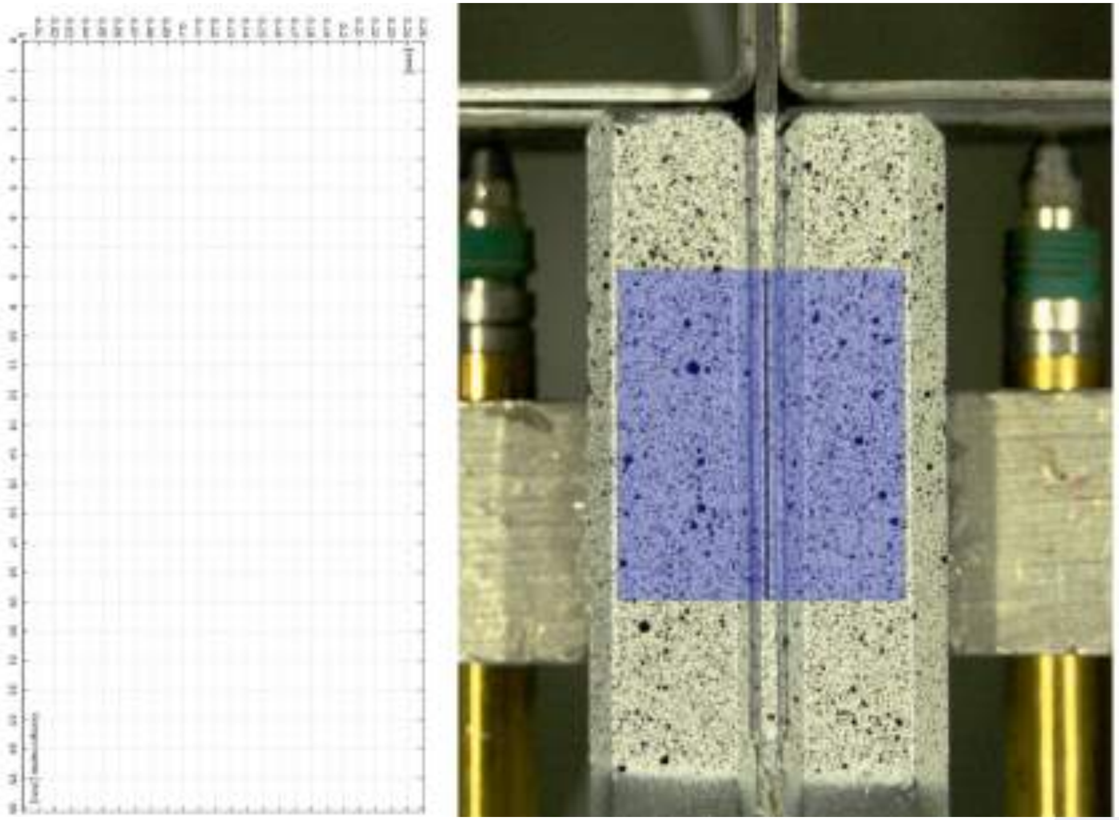
SikaForce





SikaDur





Paper 2: Influence of adhesive stiffness on the post-cracking behaviour of CFRP-reinforced structural glass beams

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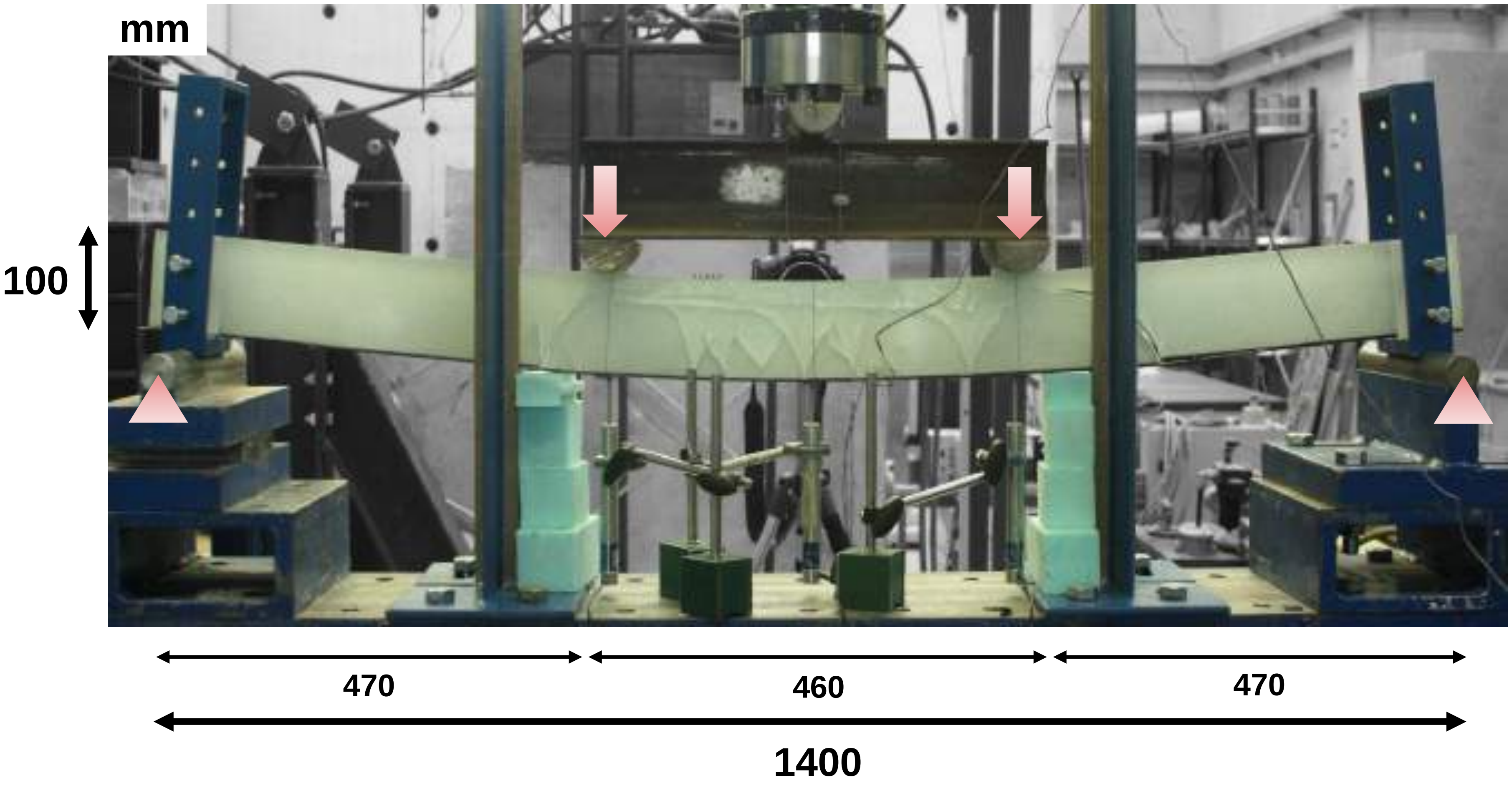
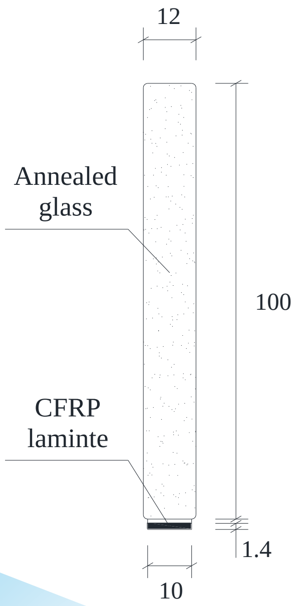
Paper 2: CFRP reinforced glass beams (1/3)

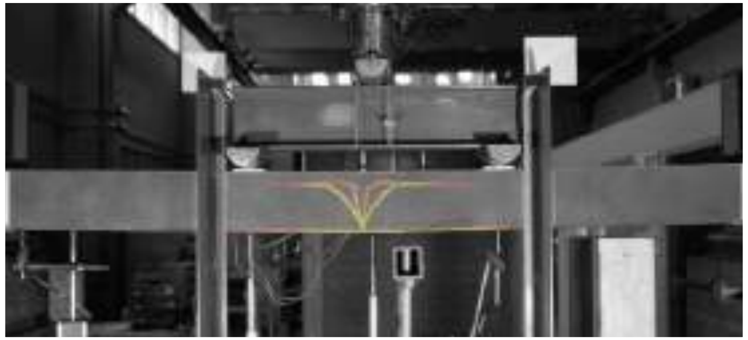




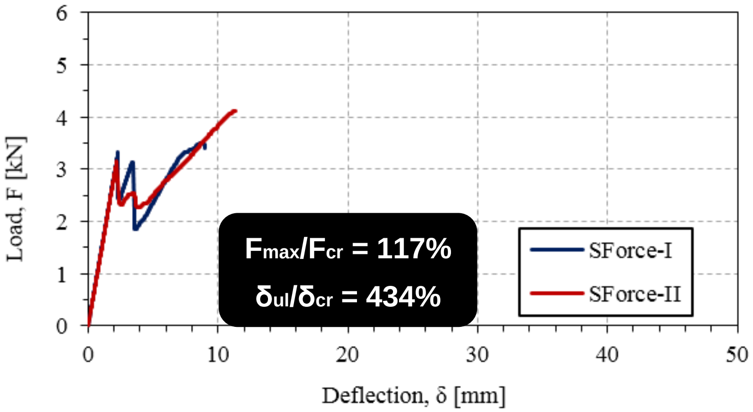
- 3 adhesives
- Four-point bending test (span of 1.4 m)
- Post-curing conditions
- Speed of 1 mm/s

Paper 2: CFRP reinforced glass beams (2/3)

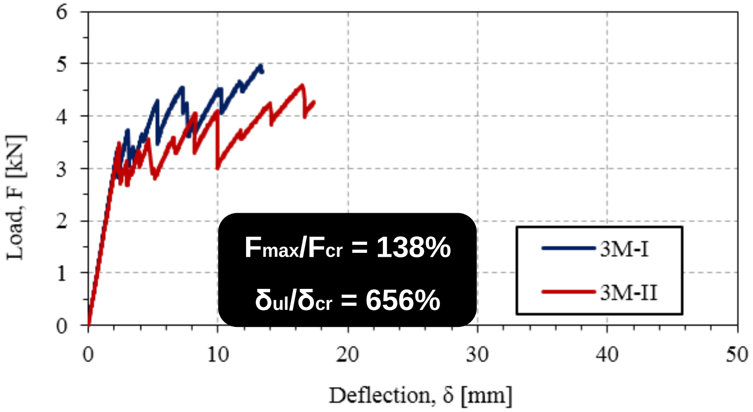
Stiffer adhesive



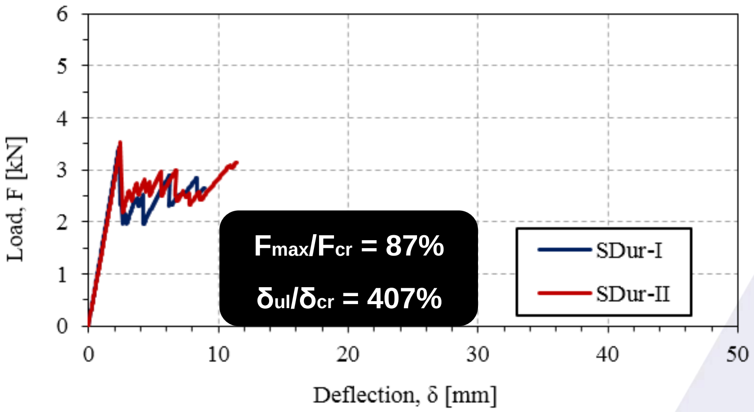
***SForce* beams**



3M beams

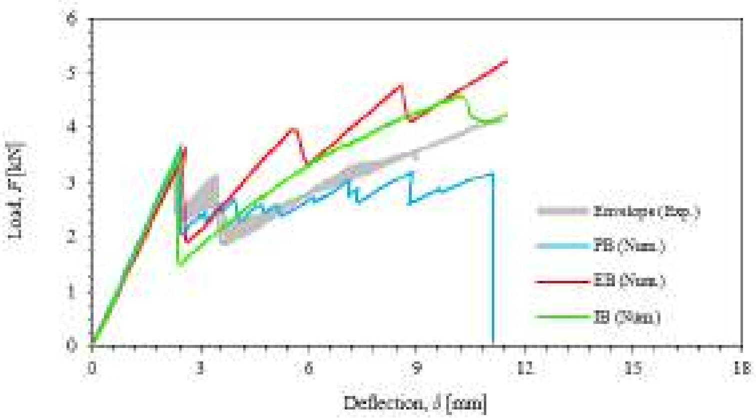


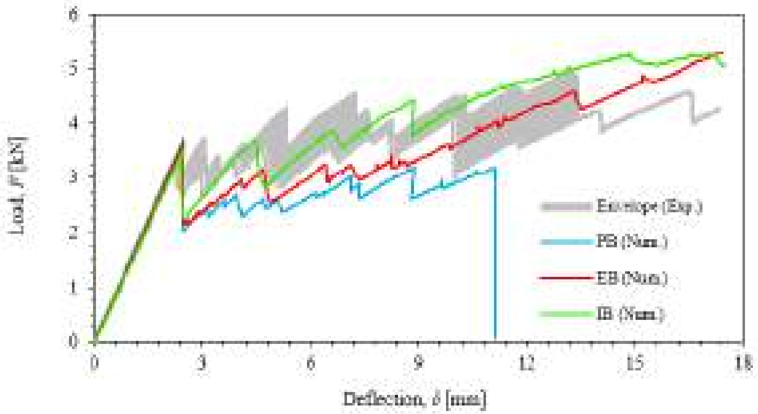
***SDur* beams**

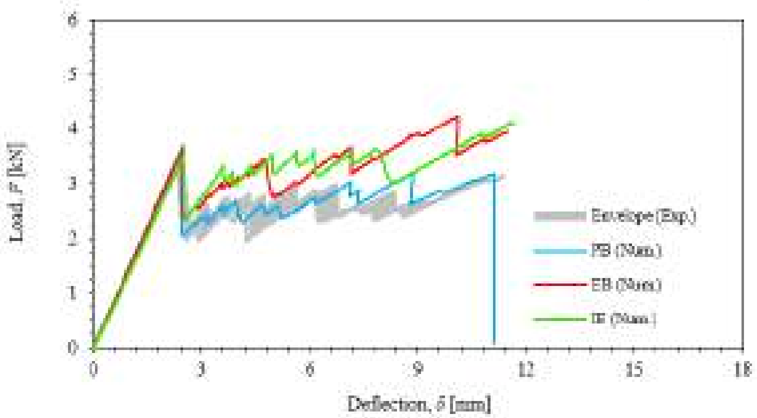


Paper 2: CFRP reinforced glass beams (3/3)

Stiffer adhesive

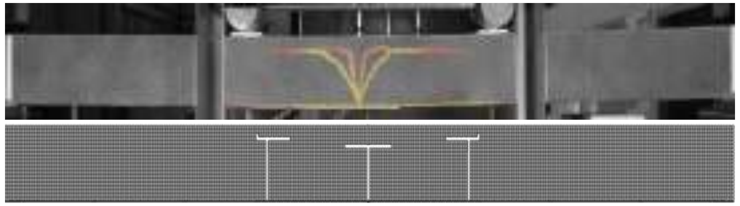






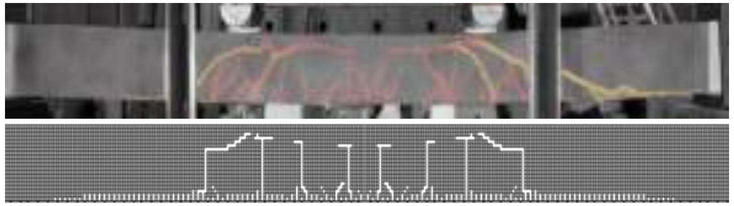
IB HYPOTHESIS: the interface behaviour of adhesive connection is considered

Input: local bond stress (τ) – slip (s) laws



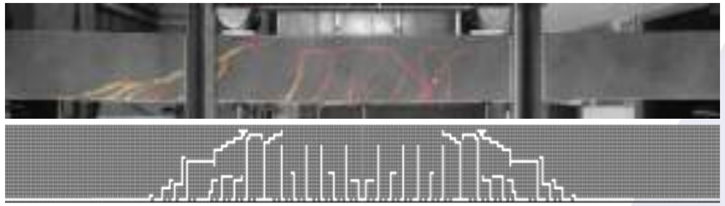
EB HYPOTHESIS: only the elastic behaviour of the adhesive is simulated

Input: stress (σ) – strain (s) tensile curves



PB HYPOTHESIS: the physical existence of the adhesive joint is neglected

Input: -



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Paper 3: Feasibility of mechanical post-tensioning of annealed glass beams by activating externally bonded Fe SMA reinforcement

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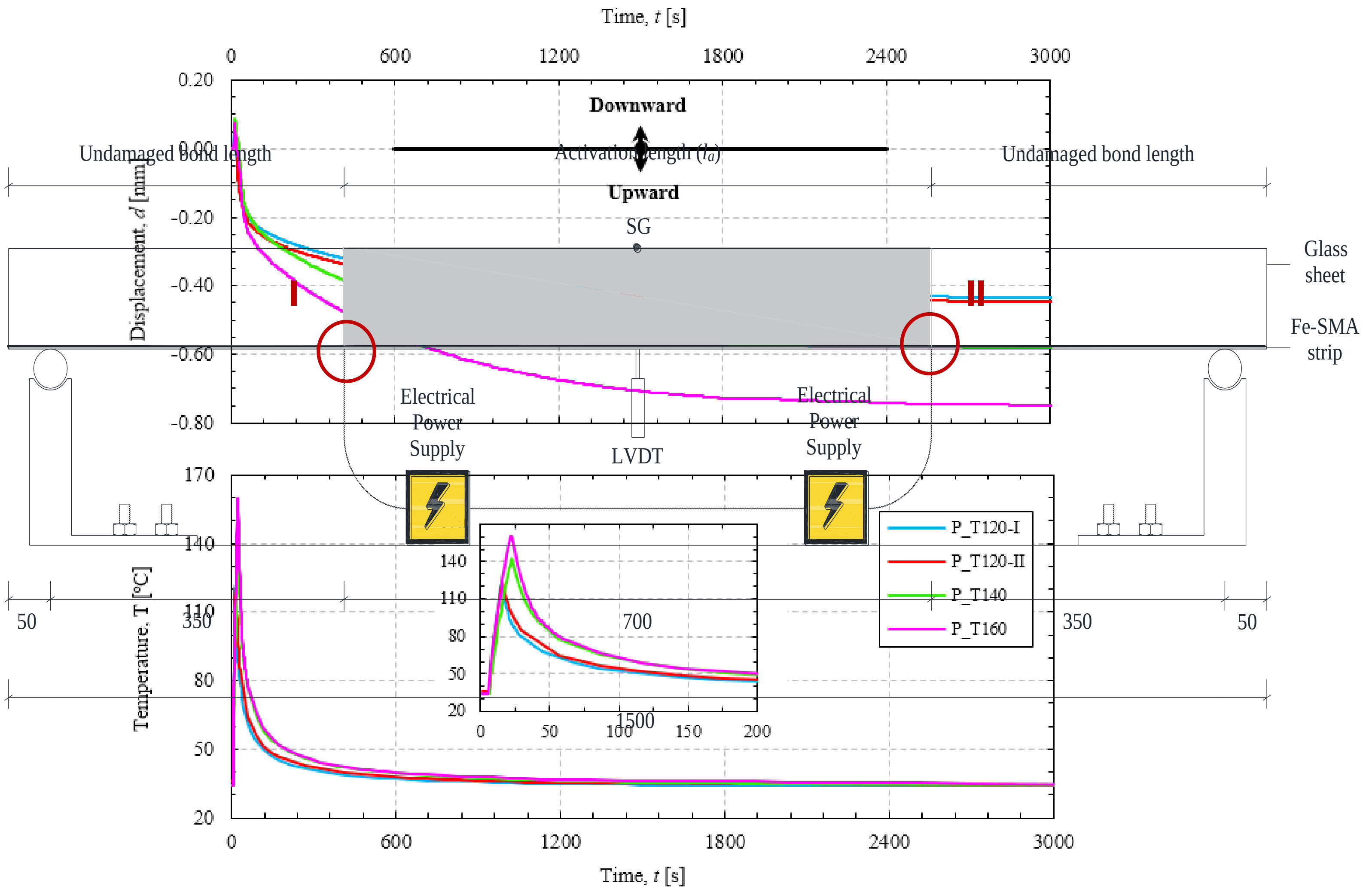
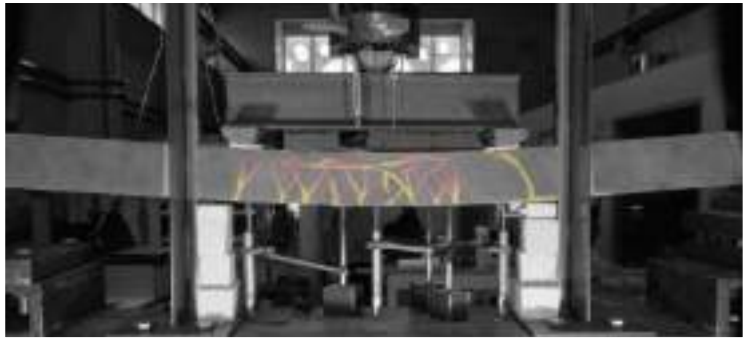
Paper 3: Fe-SMA reinforced glass beams (1/2)

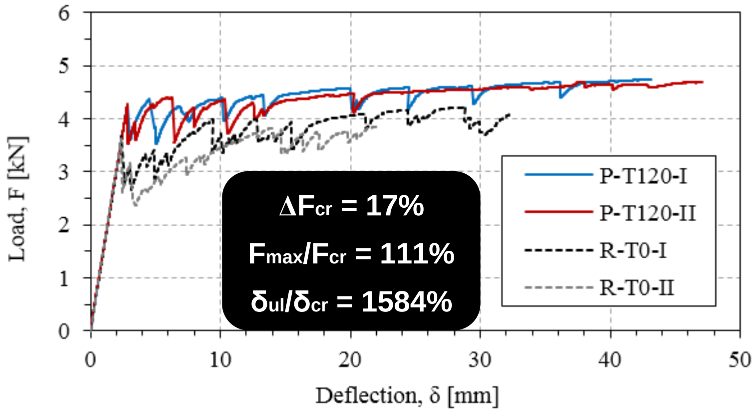


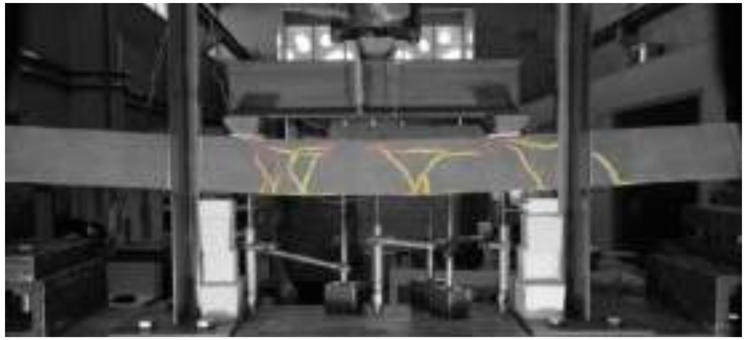
Paper 3: Fe-SMA reinforced glass beams (2/2)

Higher activation temperature

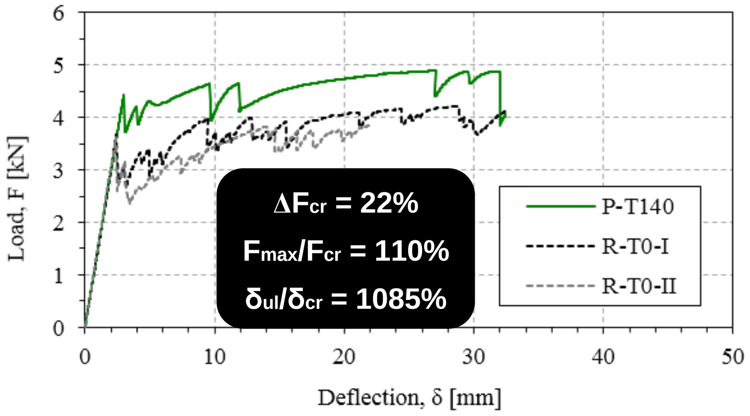


T_a = 120 ºC

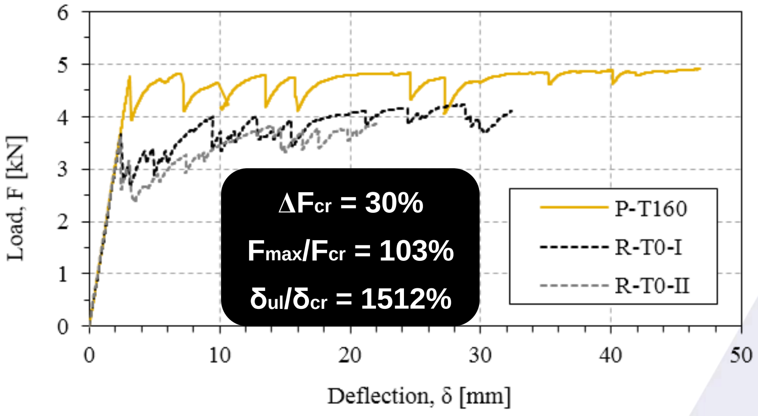




T_a = 140 ºC



T_a = 160 ºC



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Paper 4: Flexural behaviour of post-tensioned laminated glass beams with hybrid strengthening systems using CFRP and Fe-SMA reinforcement

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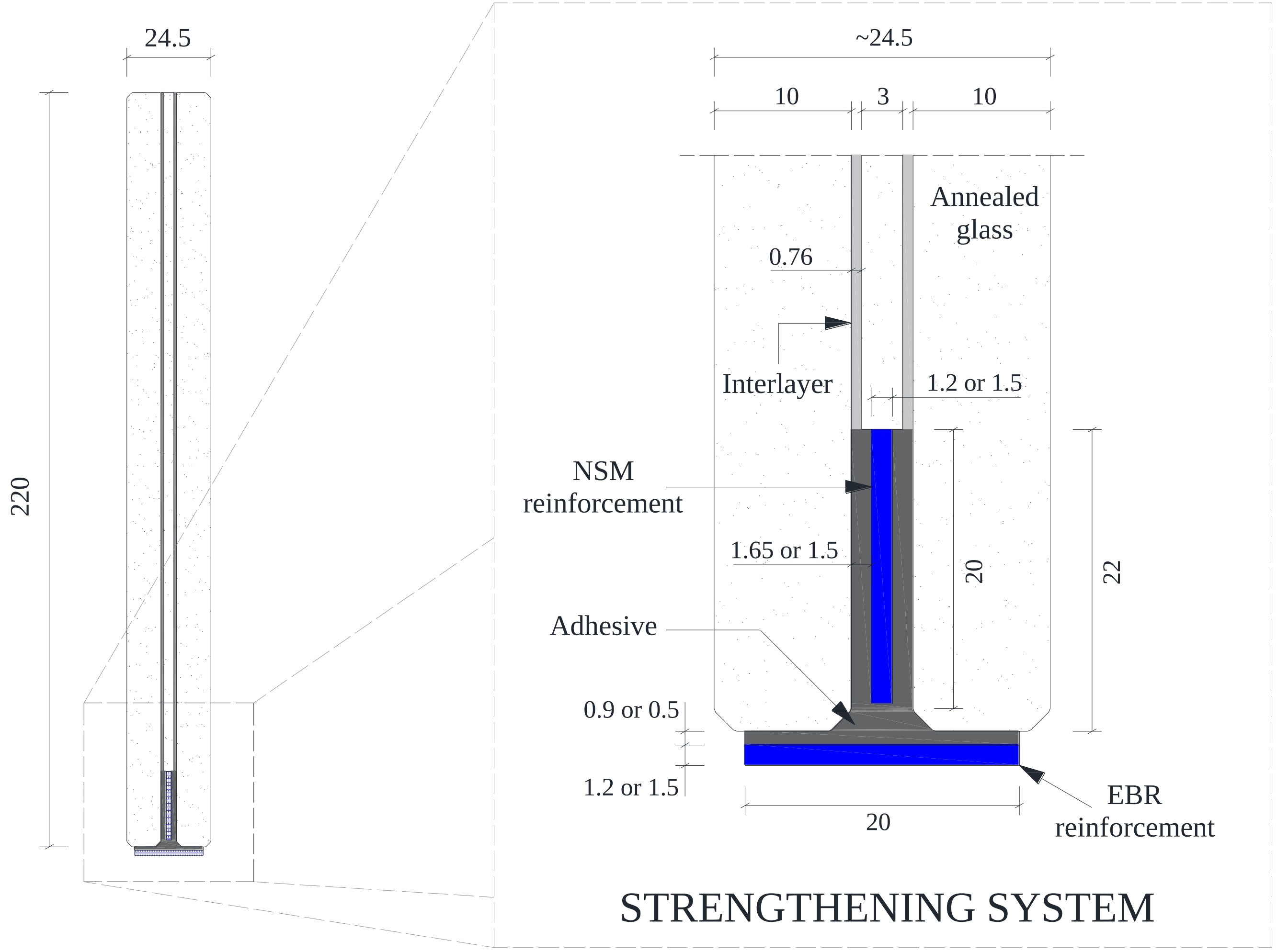
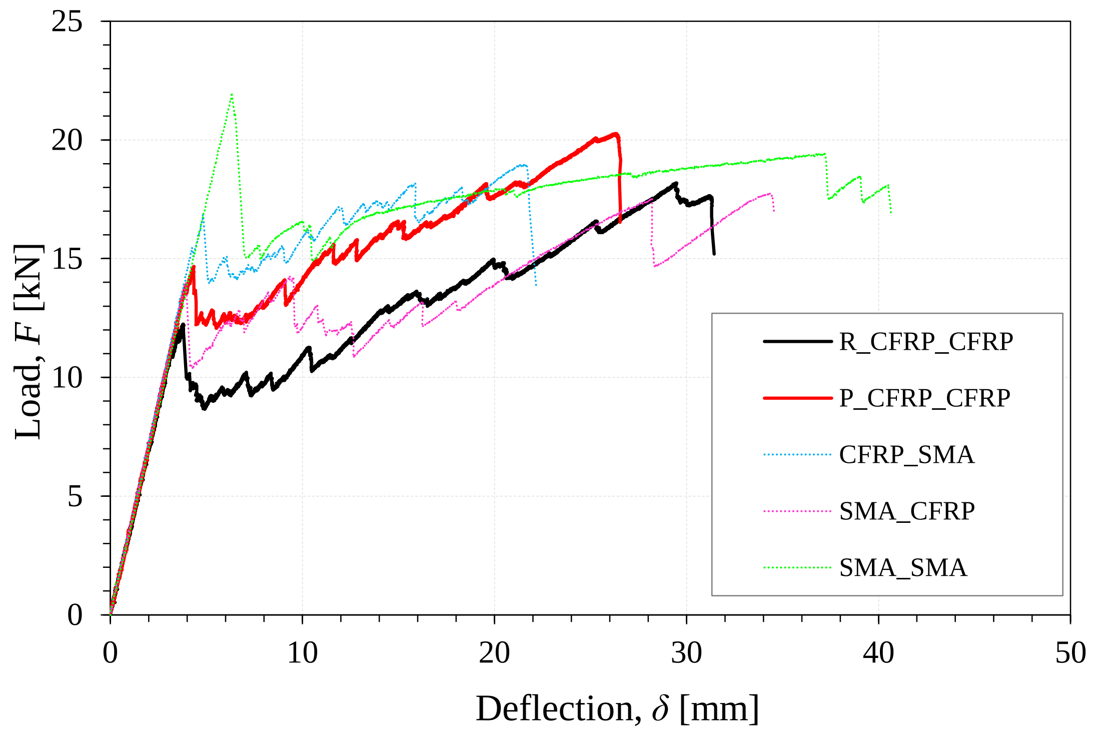
Paper 4: Hybrid strengthening systems (1/4)

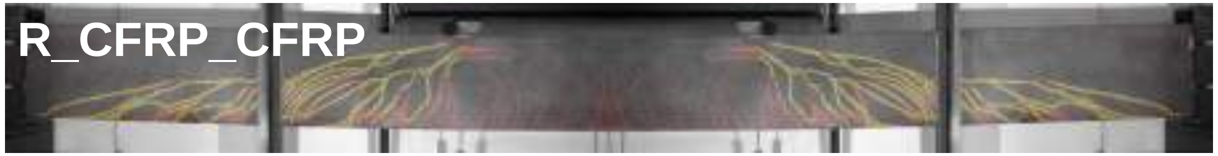


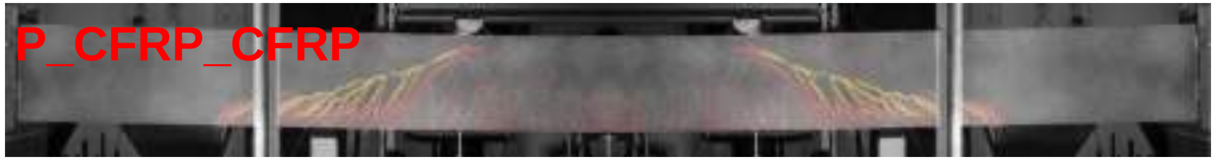
vs.

- **5 strengthening systems**
- NSM-CFRP reinforcement has been prestressed up to 2.00 ‰
- Fe-SMA has been activated at 120 ºC (EBR) and 200 ºC (NSM)
- Four-point bending tests (span of 2.9 m)

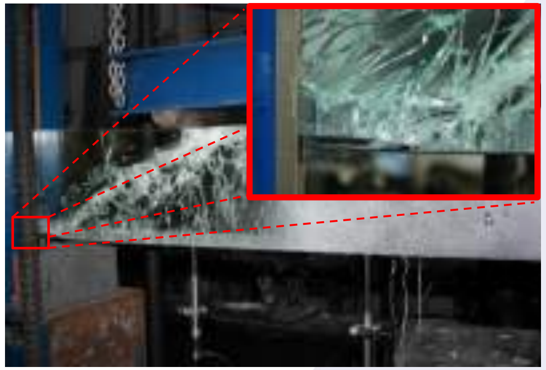
Paper 4: Hybrid strengthening systems (2/4)



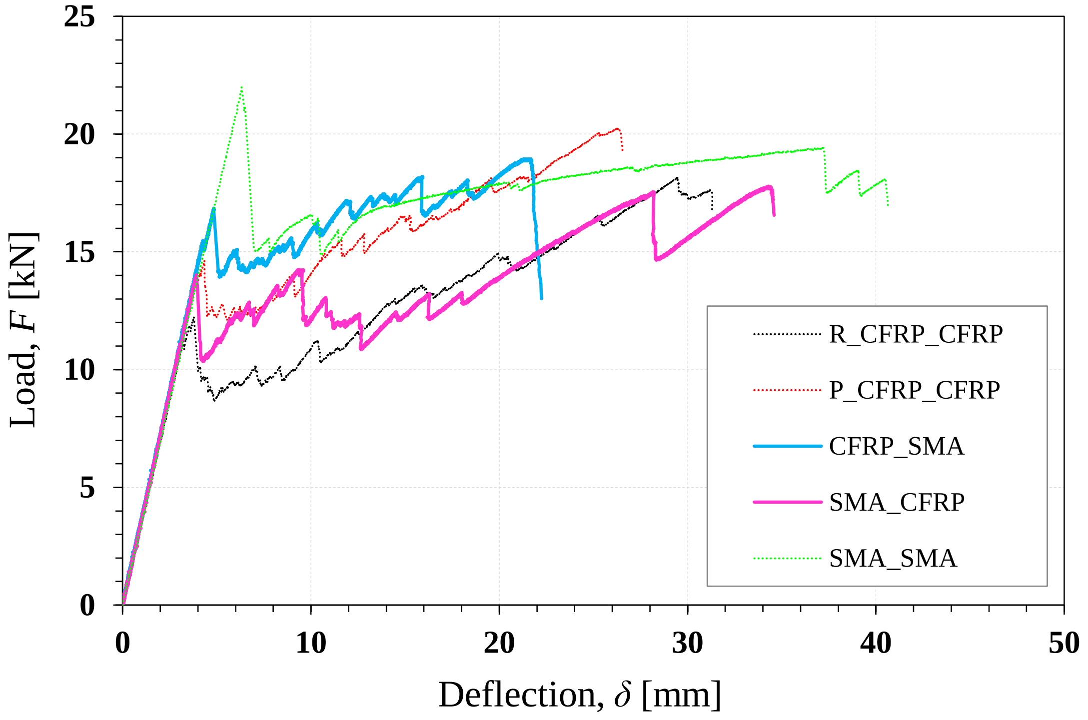


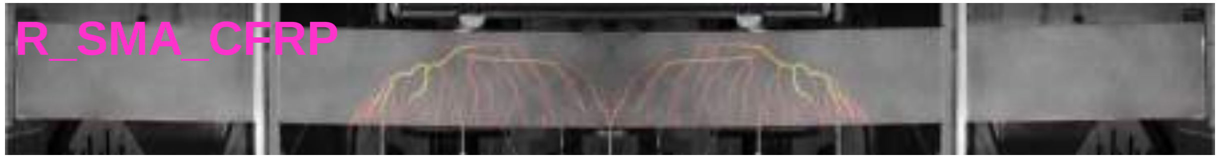


- In general, the proposed system allows a better utilization of glass, given the observed damage.
- Pre-stressing the system allows higher cracking load.



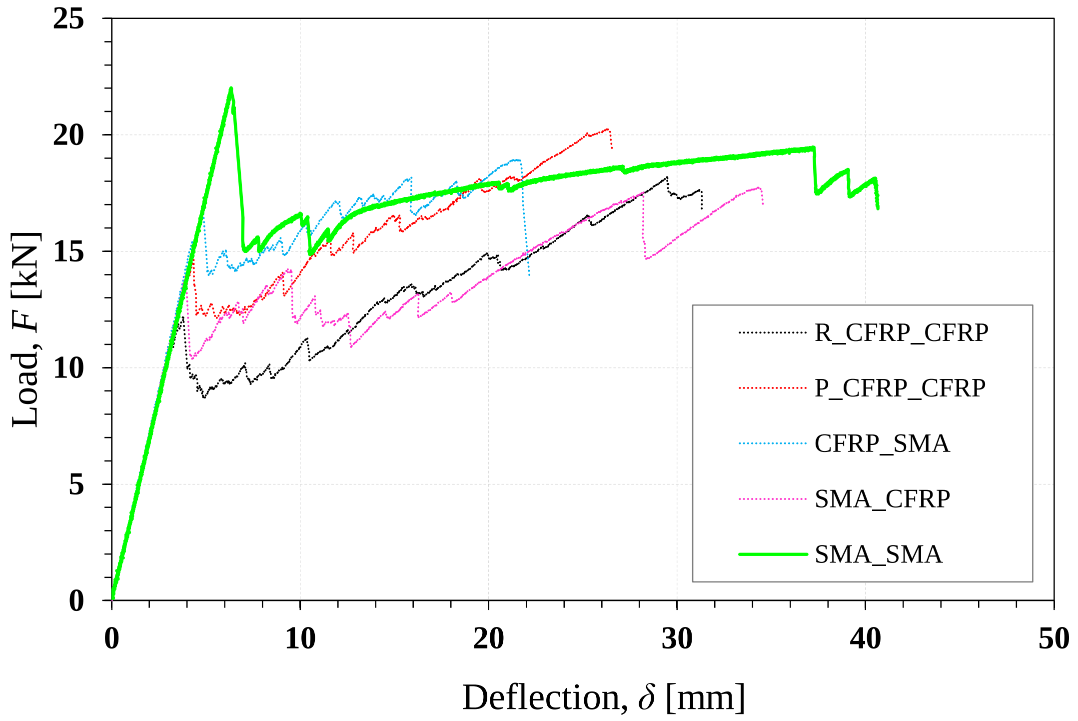
Paper 4: Hybrid strengthening systems (3/4)

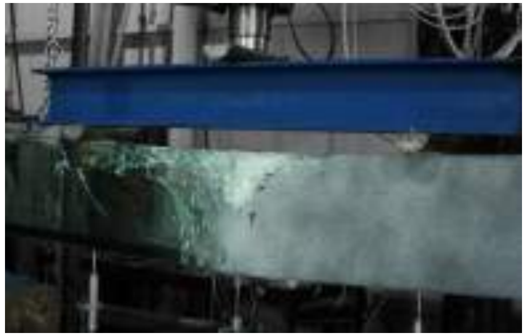




- Both reinforcements can be safely post-tensioned.
- Activating EBR-SMA reinforcement smoothes stress concentrations at the glass substrate.
- No significant load drop happens when cracks propagate beyond of the activation region.
- CFRP reinforcement provides residual strength capacity after Fe-SMA yields.

Paper 4: Hybrid strengthening systems (4/4)





- The tensile strength reserve of Fe-SMA was not sufficient to provide sufficient load-carrying capacity after initial cracking.
- No shear cracks appeared due to Fe-SMA yielding and V-shaped cracks prevailed.
- Neutral axis moved upwards due to SMA yielding, promoting high compression stress in the upper glass zone and instability phenomena.

Conclusions

Conclusions

❑ PAPER 1 – GLASS-TO-CFRP ADHESIVE CONNECTIONS

- **Adhesive properties** (stiffness and resistance) play a **critical role** in the **bond behaviour** and **failure mode** of glass-to-CFRP connections.

- **Stiff** (and brittle) **adhesives** introduce high **stress concentrations** at the glass substrate, **promoting the growth of initial surface flaws**.

❑ PAPER 2 – CFRP REINFORCED GLASS BEAMS

- Both the **adhesive's damping capacity** and its **toughness strongly influence** the **post-cracking performance** of CFRP reinforced glass beams.

- The **structural behaviour** of glass composite systems can be **numerically predicted** using the results obtained from simple tests, such as **mechanical characterization tests** and **adhesion tests**.

Conclusions

❑ PAPER 3 – Fe-SMA REINFORCED GLASS BEAMS

- Glass was **successfully post-tensioned** by activating SMA reinforcement. **Fe-SMA reinforced glass beams** extended the **ductile responses** of glass-CFRP composite beams.
- The **Fe-SMA yielding** prevents high **stress concentrations** at the bottom glass edge, **but premature debonding is still a concern** in glass structures (without transverse reinforcement).

❑ PAPER 4 – HYBRID STRENGTHENING SYSTEMS

- **Hybrid strengthening systems** were much **more effective than EBR systems** in preventing **premature debonding** and exploiting the tensile capacity of the **reinforcement material**.
- **Combining CFRP and Fe-SMA** reinforcements proved to be an effective strategy to **overcome concerns** involving each material. While **CFRP** provides **stiffness** until failure, **Fe-SMA** yielding **prevents** stress concentrations at the glass substrate.

Acknowledgments

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FCT Fundação para a Ciência e a Tecnologia

isise Institute for Sustainability and Innovation in Structural Engineering

GLASSOLUTIONS SAINT-GOBAIN

Sika BUILDING TRUST

re-fer.eu strengthening solutions

S&P A Simpson Strong-Tie® Company

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Analytical implementation of the non-conventional failures in cross-ply laminates under fatigue loading to predict the initiation of the fibre/matrix interface debonding

S. Sánchez-Carmona[1], P. A. Carraro[2], A. Barroso[1] , M. Quaresimin[2]
[1] Group of Elasticity and Strength of Materials, Department of Continuum Mechanics and Theory of Structures, School of Engineering, University of Sevilla (Seville, Spain)
[2] Department of Management and Engineering, University of Padova (Vicenza, Italy)

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Outline

- Motivation
- Objective
- Work developed during stay
- Is the objective achieved?

Motivation

Motivation

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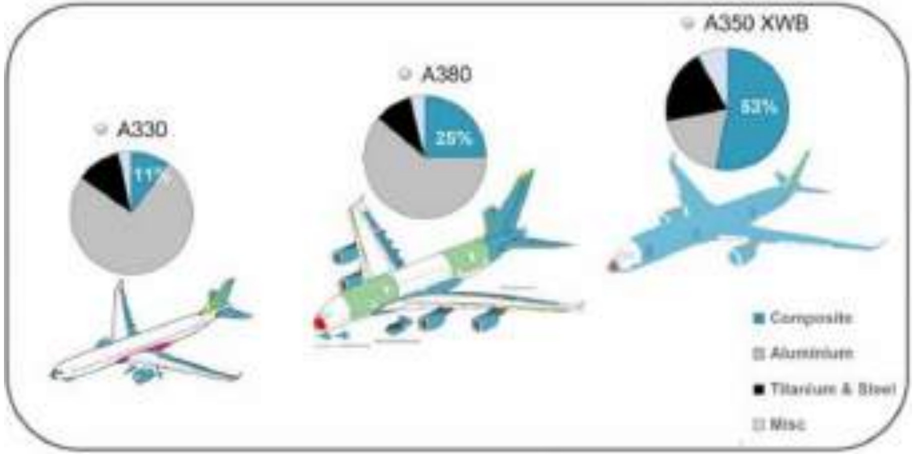
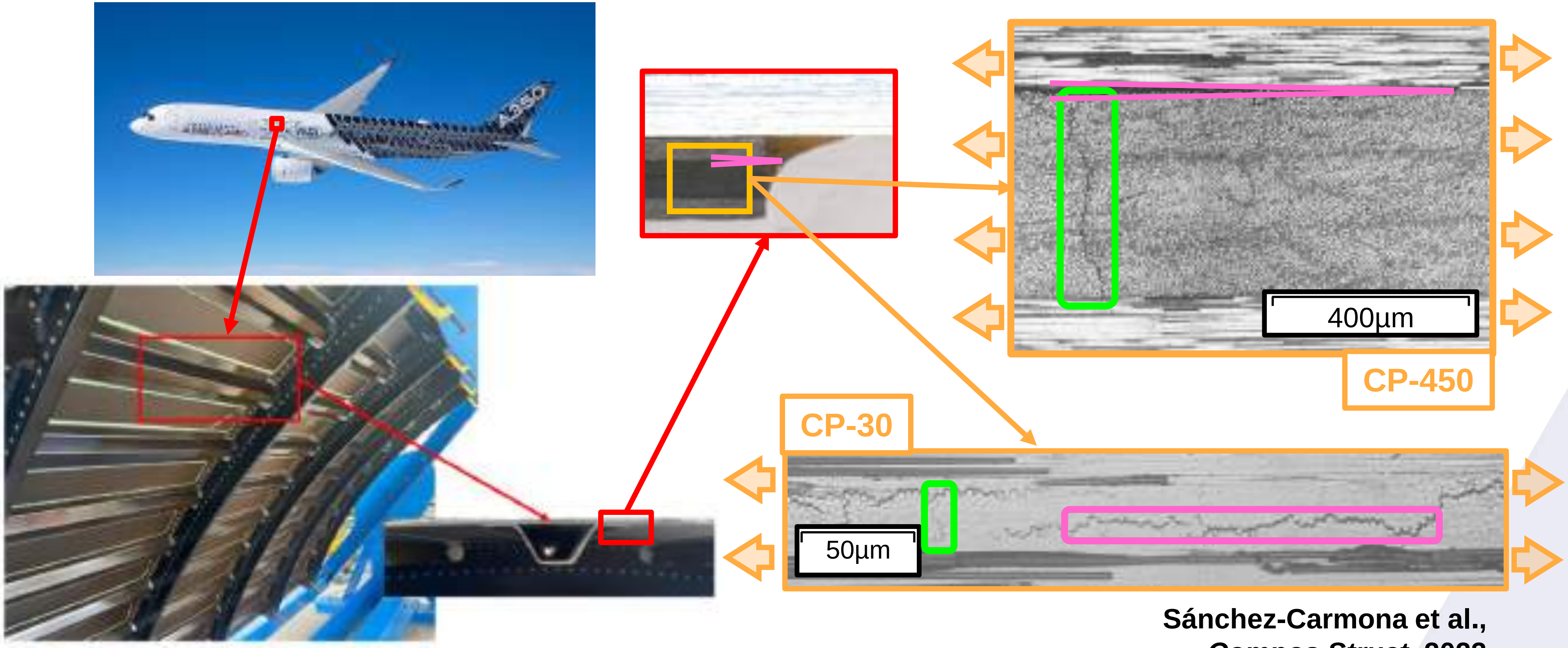


Motivation



Sánchez-Carmona et al., *Compos Struct*, 2023

Objective

Objective

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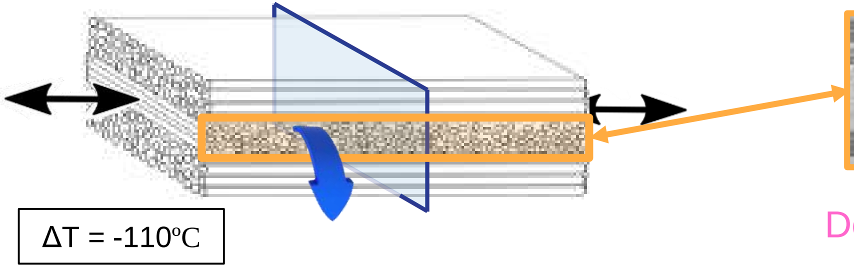
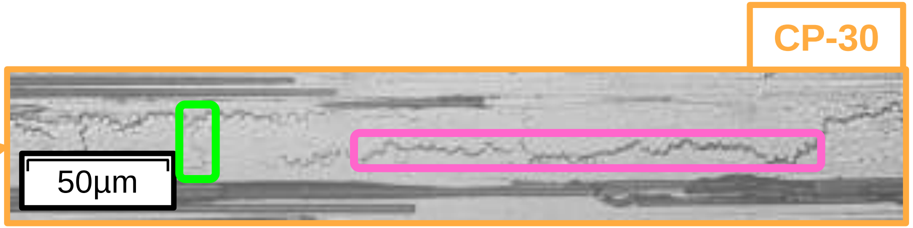
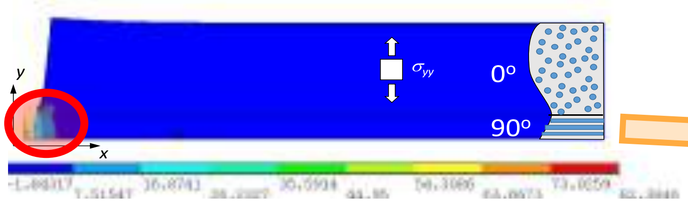
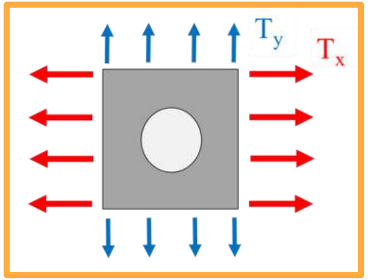




Do these non-conventional fibre/matrix interface debonds impair in the adhesive-laminate interface behaviour?



Sánchez-Carmona et al., Compos Part B, 2023

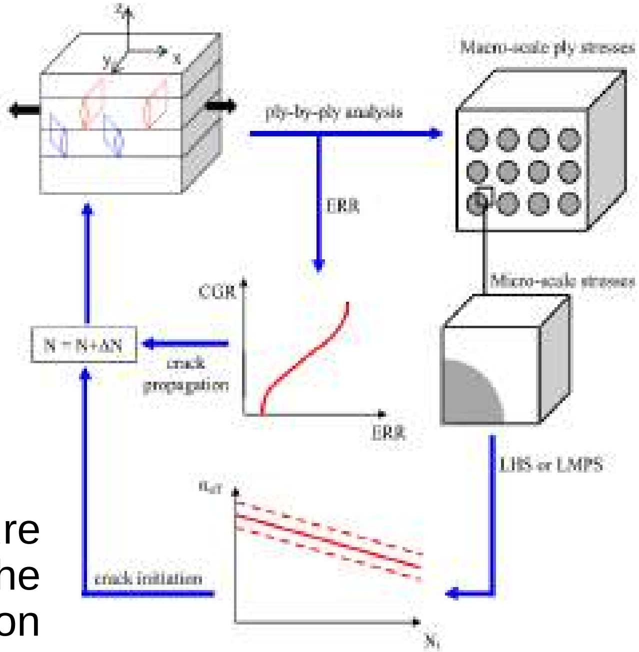


Can the first fibre/matrix interface debonds be predicted considering this biaxial stress state?

In the group of Prof. Quaresimin (Univesity of Padova):

VICENZA, ITALY

Semi-analytical procedure for the prediction of the crack density evolution



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Work developed during stay

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Prediction of the initiation of the total crack density

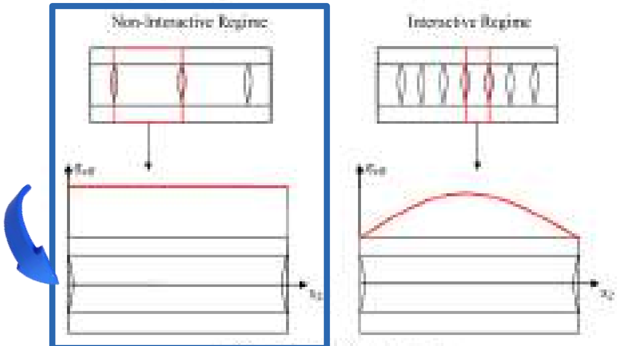


Fig. 5. Non-interactive and interactive regimes.

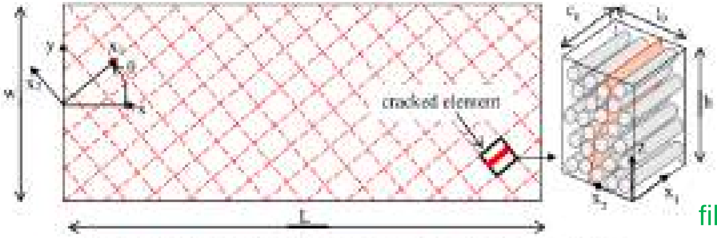


Fig. 4. Ply discretisation in elements representative of the crack initiation process zone.

$$c_0 = h = t_{90}$$

$$l_0 = n\Phi_f$$

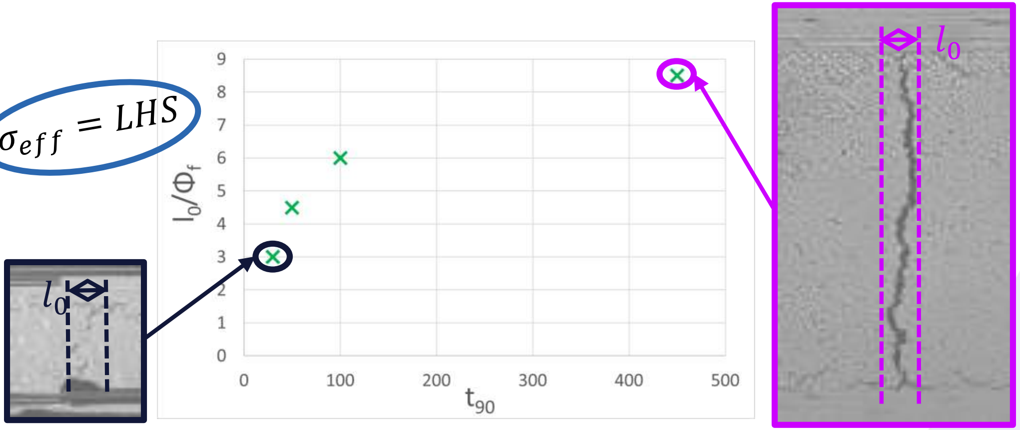
being n the number of the fibre diameters which control the crack initiation process

$$\rho(N) = \frac{w}{l_0 c_0}\left[1 - exp\left(-\sigma_{eff}/K_0 N^a\right)^m\right]$$

$$\sigma_{eff} = LHS$$

Carraro et al., Compos. Sci. Technol., 2017

$a, m \; and \; K_0$ defined from the statistical nature of the fatigue strength to crack onset



Calculation of the LHS for each 90º ply block

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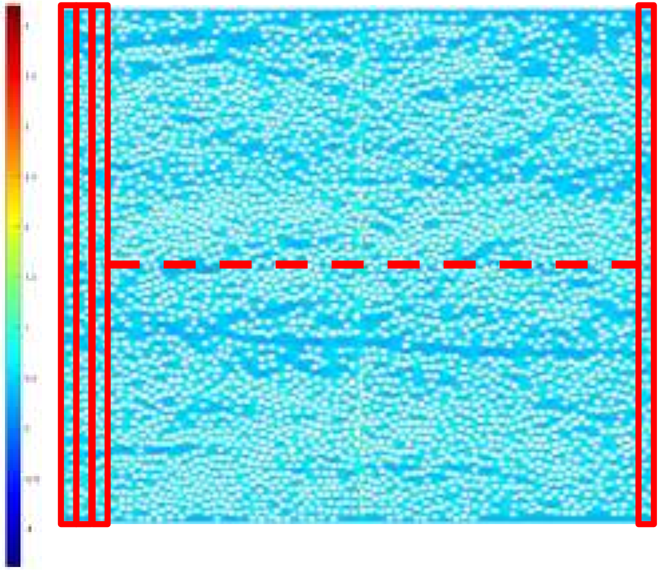
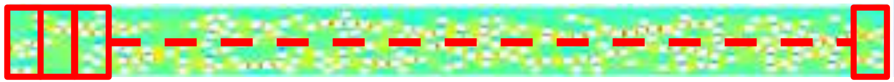
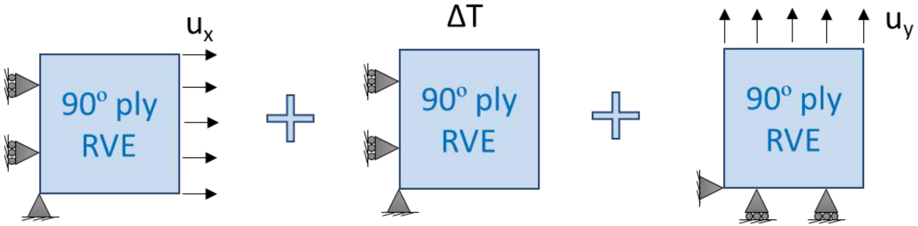


Maragoni et al., Compos. Part A, 2019



$$\sigma_{eff} = LHS = \frac{\sigma_x + \sigma_y + \sigma_z}{3}$$



$$\sigma_x = \sigma_x^{matrix}\frac{\sigma_2}{\sigma_x^{ERV}} + \sigma_x^{matrix}\frac{\Delta T_{real}}{\Delta T_{ERV}} + \sigma_x^{matrix}\frac{\sigma_3}{\sigma_y^{ERV}}$$

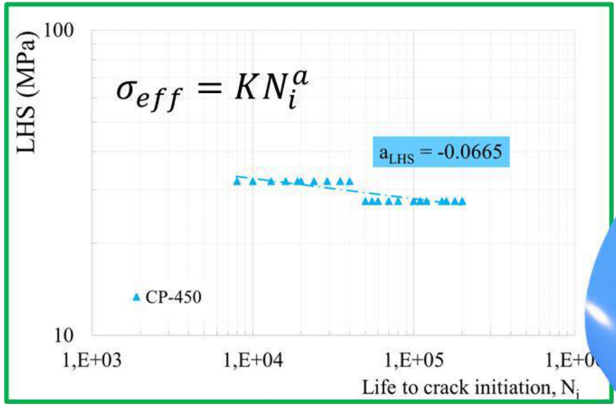
$$\sigma_y = \sigma_y^{matrix}\frac{\sigma_2}{\sigma_x^{ERV}} + \sigma_y^{matrix}\frac{\Delta T_{real}}{\Delta T_{ERV}} + \sigma_y^{matrix}\frac{\sigma_3}{\sigma_y^{ERV}}$$

$$\sigma_z = \sigma_z^{matrix}\frac{\sigma_2}{\sigma_x^{ERV}} + \sigma_z^{matrix}\frac{\Delta T_{real}}{\Delta T_{ERV}} + \sigma_z^{matrix}\frac{\sigma_3}{\sigma_y^{ERV}}$$

Statistical nature of the fatigue strength to crack onset

$$\boxed{\rho(N) = \frac{w}{l_0 c_0}\left[1 - exp\left(-\sigma_{eff}/K_0 N^a\right)^m\right]}$$

$\sigma_{eff} = LHS$

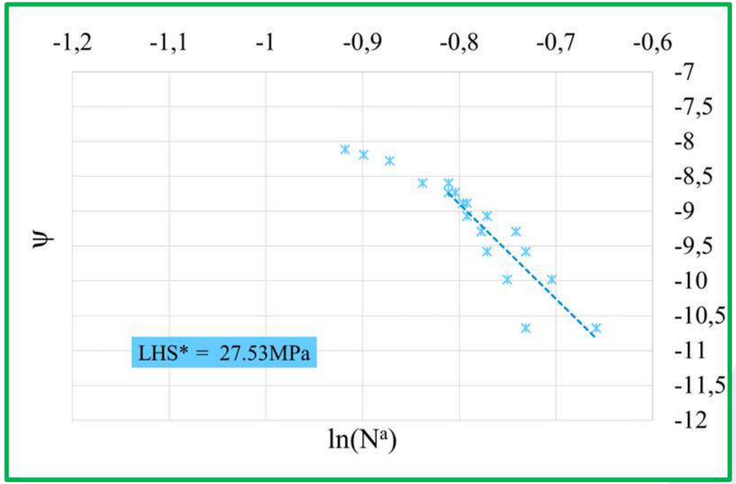


Weibull distribution assigned to K

$$P(K) = 1 - \exp\left[-\left(\frac{K}{K_0}\right)^m\right]$$

m and K_0 are the shape and the scale parameters of the Weibull distribution

$$\psi = \mathrm{Ln}\left[\mathrm{Ln}\left(\frac{1}{1 - \mathrm{P(N_i)}}\right)\right] = -m \cdot Ln(N^a) + m \cdot Ln\left(\frac{\sigma_{eff}}{K_0}\right)$$



Statistical nature of the fatigue strength to crack onset

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- ✓ a is taken as the same as CP-450
- ✓ Also m as the same as CP-450 and K_0 is estimated using a thickness aproximation:

$$\boxed{K_0^{CP-X} = K_0^{CP-450} \cdot \left(\frac{h^{CP-450}}{h^{CP-X}}\right)^{1/m}}$$

CP-450

$[0_4/90_3/0_4]$ (t_{90}~450g/m^2)

a	-0.0665

m	13.6417
K₀	117.6027

CP-30

$[0_4/90/0_4]$ (t_{90}~30g/m^2)

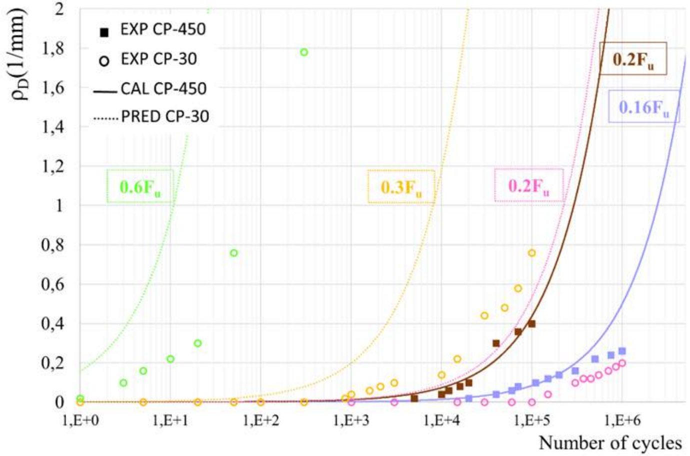
a	-0.0665

m	13.6417
K₀	139.9931

$$\boxed{\rho(N) = \frac{w}{l_0 c_0}\left[1 - exp\left(-\sigma_{eff}/K_0 N^a\right)^m\right]}$$

$$\sigma_{eff} = K N_i^a$$

$$\psi = -m \cdot Ln(N^a) + m \cdot Ln\left(\frac{\sigma_{eff}}{K_0}\right)$$



Is the objective achieved?

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Conclusions

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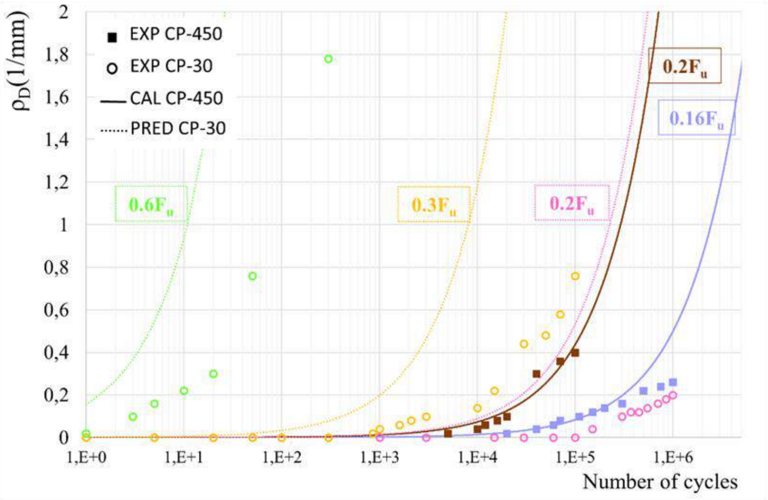
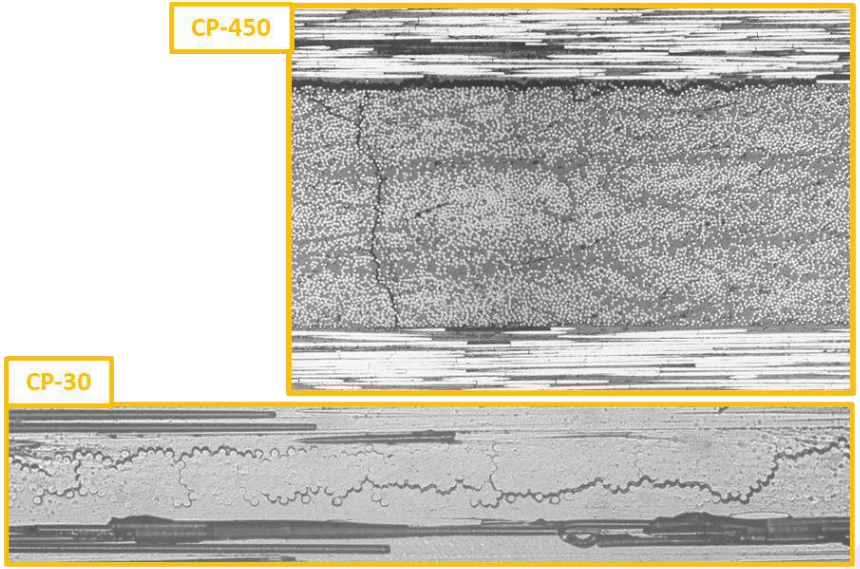
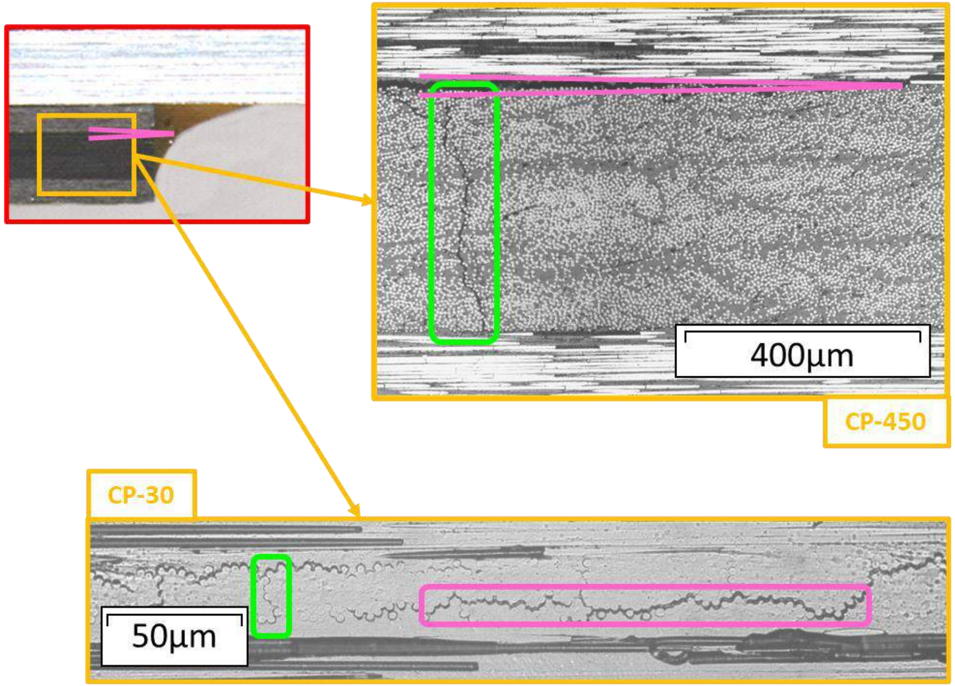




- Conclusions:
  - The first fibre/matrix interface debonds seem not to be well correlated using this semi-analytical procedure because only transverse damages seem to be captured, although biaxial stress state is considered.

Conclusions



Sánchez-Carmona et al., *Compos Struct*, 2023

- Conclusions:
  - The non-conventional fibre/matrix interface debonds appear previous to the first transverse damages also experimentally, which seem to delayed, or even supressed, the appearance of delaminations.
  - The lack of delaminations implies that the likely premature failure of the adhesive-laminate interface may be delayed.

Acknowledgment

This STSM was developed under the COST Action CA18120 (CERTBOND) and supported by COST (European Cooperation in Science and Technology).

Funded by the Horizon 2020 Framework Programme of the European Union

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BOND BEHAVIOUR OF A STICK SHAPE CFRP REINFORCEMENT APPLIED ACCORDING TO THE NSM-ETS STRENGTHENING TECHNIQUES

Luís Correia, Joaquim Barros, Pedram Ayyobi, Hossein Malekinejad

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Funded by the European Union

Outline

- Motivation
- Direct pull-out tests
- Interlaminar shear tests
- Conclusions

Motivation

Motivation

Nepal | 2015

Motivation

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- FRP MATERIALS have been successfully used for the RETROFITTING OF EXISTING STRUCTURES.
- Within this topic, EBR and NSM are the most common techniques, and both can be used for SHEAR AND FLEXURAL STRENGTHENING.

Motivation

NSM

EBR

Motivation

- FRP MATERIALS have been successfully used for the RETROFITTING OF EXISTING STRUCTURES.
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Motivation

- FRP MATERIALS have been successfully used fo ... ISTING STRUCTURES.
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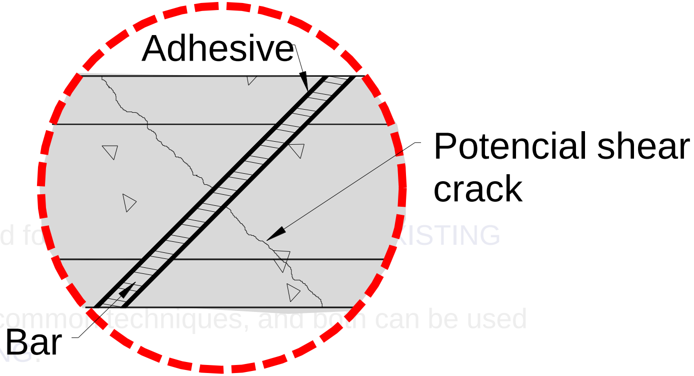
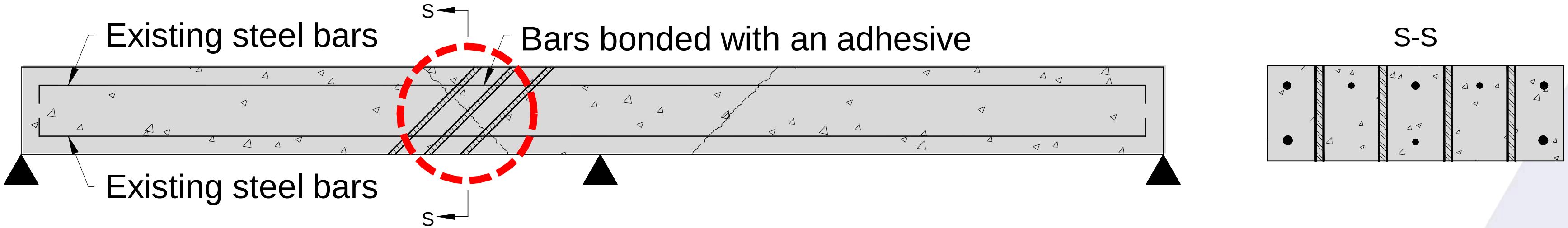


- The ETS technique an attractive option for strengthening structures in harsh or HIGH-RISK ENVIRONMENTS, and for the SHEAR AND PUNCHING STRENGTHENING OF SLABS.



Motivation

- FRP MATERIALS have been successfully used for the RETROFITTING OF EXISTING STRUCTURES.
- Within this topic, EBR and NSM are the most common techniques, and both can be used for SHEAR AND FLEXURAL STRENGTHENING.
- The ETS technique an attractive option for strengthening structures in harsh or HIGH-RISK ENVIRONMENTS, and for the SHEAR AND PUNCHING STRENGTHENING OF SLABS.

- END-DEBONDING (OR RIP-OFF FAILURE) can be expected in EBR and NSM strengthening solutions, thus conditioning the EFFICIENCY of these techniques, and the use of the FRP material.

Motivation

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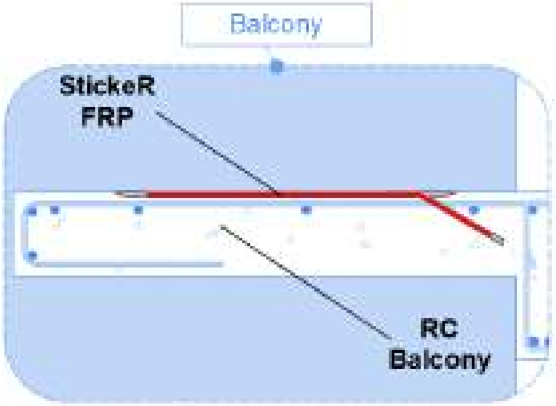
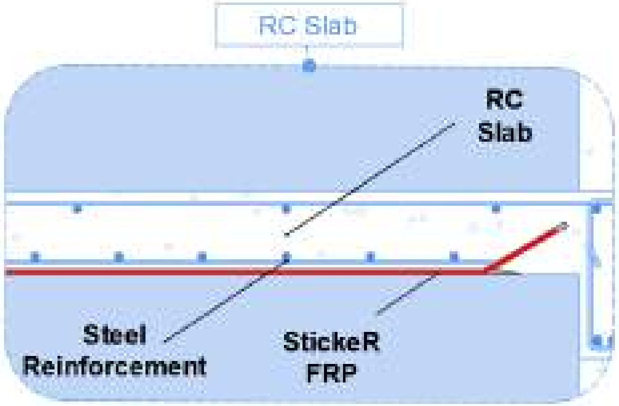
- **STICKER project :** To develop a hybrid strengthening technique that combines the near-surface-mounted (NSM) technique for flexural strengthening with the embedded through section (ETS) technique for shear strengthening using innovative stick-shaped CFRP rebars.





Motivation

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- To achive such strenghethening solution the following steps must be followed:

  1. DEVELOP A CFRP COMPOSITE MATERIAL (REBAR) IN A STICK-SHAPE FORMAT WITH SIMILAR MECHANICAL PROPERTIES TO THE STANDART FRP COMPOSITES

  2. ACCESS THE BEHAVIOUR OF THIS SYSTEM WHEN APPLIED TO DIFFERENT TYPES OF STRUCTURES (BEAMS, SLABS, BALCONIES)

Motivation

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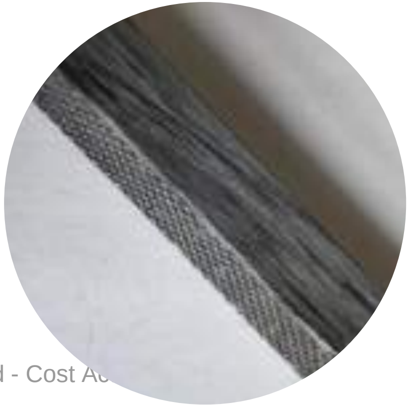
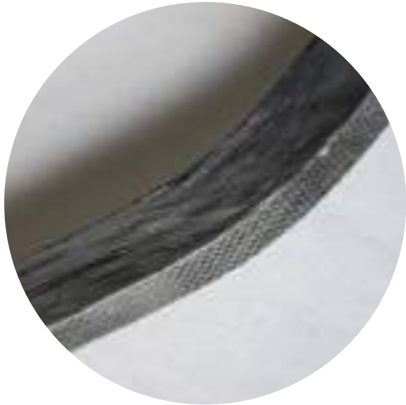
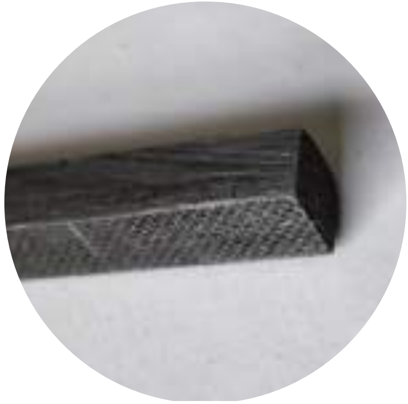
1. DEVELOP A CFRP COMPOSITE MATERIAL (REBAR) IN A STICK-SHAPE FORMAT WITH SIMILAR MECHANICAL PROPERTIES TO THE STANDART FRP COMPOSITES
2. ACCESS THE BEHAVIOUR OF THIS SYSTEM WHEN APPLIED TO DIFFERENT TYPES OF STRUCTURES (BEAMS, SLABS, BALCONIES)







Motivation

- To achive such strenghethening solution the following steps must be followed:

1. DEVELOP A CFRP COMPOSITE MATERIAL (REBAR) IN A STICK-SHAPE FORMAT WITH SIMILAR MECHANICAL PROPERTIES TO THE STANDART FRP COMPOSITES
2. ACCESS THE BEHAVIOUR OF THIS SYSTEM WHEN APPLIED TO DIFFERENT TYPES OF STRUCTURES (BEAMS, SLABS, BALCONIES)

>> STUDY THE BOND BEHAVIOUR OF THIS SOLUTION <<

Outline

- Motivation
- Direct pull-out tests
- Interlaminar shear Tests
- Conclusions

Direct pull-out tests

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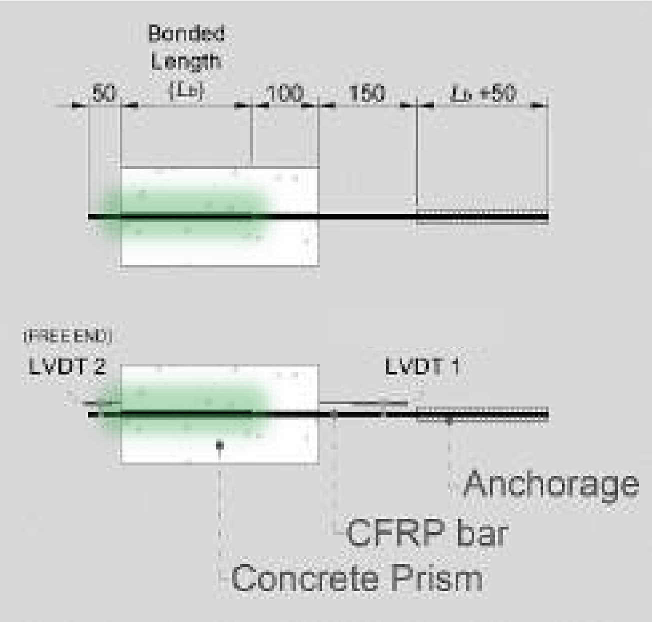
Direct pull-out tests

Direct pull-out tests:
Experimental program

- The performance of a new generation of CFRP bars adhesively bonded to concrete were evaluated by the use of 18 direct pull-out tests (DPT).



Geometry

- Concrete prism of 150 mm squared cross section
- L_b of 100 mm, 200 mm, and 300 mm (Variable A)
- Two types of CFRP surface finish were used (Variable B):
  |1| with a roughness surface, and
  |2| without a roughness surface
- CFRP bar has a 7 mm squared cross section

Direct pull-out tests:
Experimental program

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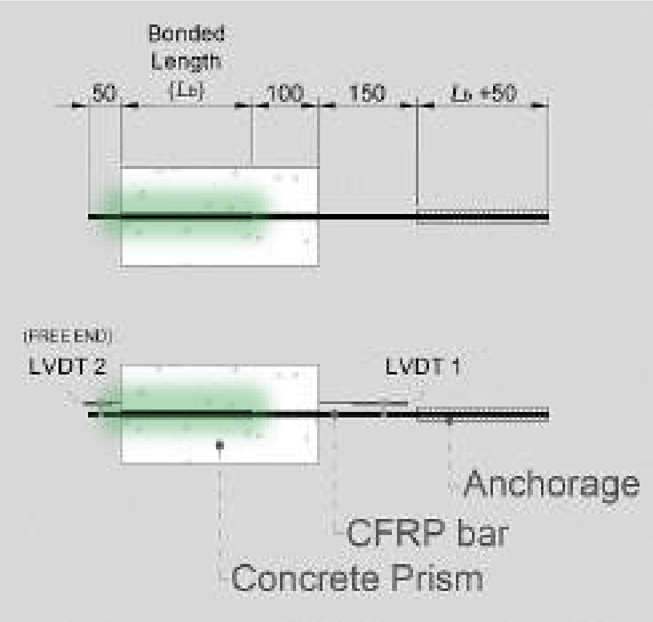


Materials

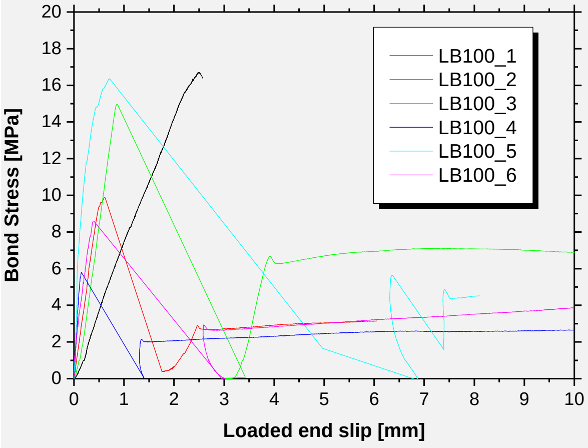
- Concrete (C30/37):
  f_{cm} = 31.0 MPa / E_{cm}=26.6 GPa
- CFRP (vacuum infusion):
  f_f=1462 MPa / E_f=145.8 Gpa
- Epoxy (S&P 55HP):
  $f_{a,t}$=15.9 Mpa / E_a=3.2 GPa

Direct pull-out tests
Experimental program

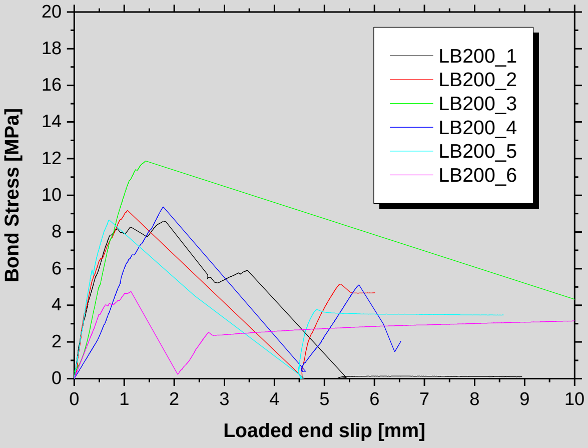
Direct pull-out tests
Experimental program

Direct pull-out tests:
Results and discussion

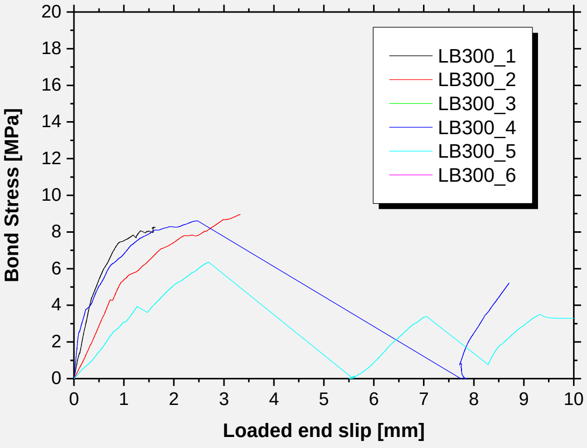
Series 1: L_b 100



Series 2: L_b 200



Series 3: L_b 300



Notes

[1] Average bond stress (force divided by {perimeter x bond length})

[2] Specimens 1-3 are with surface treatment, whereas 4-6 have no surface treatment

Direct pull-out tests:
Results and discussion

Series	Lable	F_{max} [kN]	τ_{max} [MPa]	$\tau_{max}{}^{b}$ [MPa]	$s_{m,le}$ [mm]	$s_{m,le}{}^{b}$ [mm]	$s_{m,ue}$ [mm]	$s_{m,ue}{}^{b}$ [mm]	$\tau_{max}{}^{*}$ [MPa]	*Failure Mode*
LB100	LB100_1	46.77	16.70	12.05	2.49	0.87	0.46	0.21	3.00	PO
	LB100_2	27.64	9.87		0.61		0.18		1.77	PO
	LB100_3	41.93	14.97		0.86		0.22		2.69	PO+FF
	LB100_4	16.25	5.80		0.14		0.00		1.04	PO
	LB100_5	45.80	16.36		0.71		0.29		2.94	PO
	LB100_6	23.98	8.57		0.40		0.10		1.54	PO
LB200	LB200_1	48.10	8.59	8.73	1.78	1.31	0.35	0.41	1.54	FF
	LB200_2	51.32	9.16		1.06		0.24		1.65	PO
	LB200_3	66.52	11.88		1.43		0.95		2.13	FF
	LB200_4	52.44	9.36		1.78		0.44		1.68	PO
	LB200_5	48.46	8.65		0.70		0.29		1.55	FF
	LB200_6	26.58	4.75		1.14		0.20		0.85	PO
LB300	LB300_1	69.40	8.26	8.05	1.60	2.02	0.69	0.61	1.48	FF
	LB300_2	75.25	8.96		3.33		(na)		1.61	FF
	LB300_3	(na)	(na)		(na)		(na)		(na)	(na)
	LB300_4	72.32	8.61		2.46		0.89		1.55	PO
	LB300_5	53.39	6.36		2.69		0.26		1.14	PO
	LB300_6	(na)	(na)		(na)		(na)		(na)	(na)

Notes: [b] Mean vaue for similar specimens; (na) specimen had to be disregarded due to thecnical problems in the acquisition system; Failure Mode: PO = Pullout, FF = FRP Failure

Direct pull-out tests:
Results and discussion

Series	Lable	F_{max} [kN]	τ_{max} [MPa]	$\tau_{max}{}^{b}$ [MPa]	$s_{m,le}$ [mm]	$s_{m,le}{}^{b}$ [mm]	$s_{m,ue}$ [mm]	$s_{m,ue}{}^{b}$ [mm]	$\tau_{max}{}^{*}$ [MPa]	*Failure Mode*
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Direct pull-out tests:
Results and discussion

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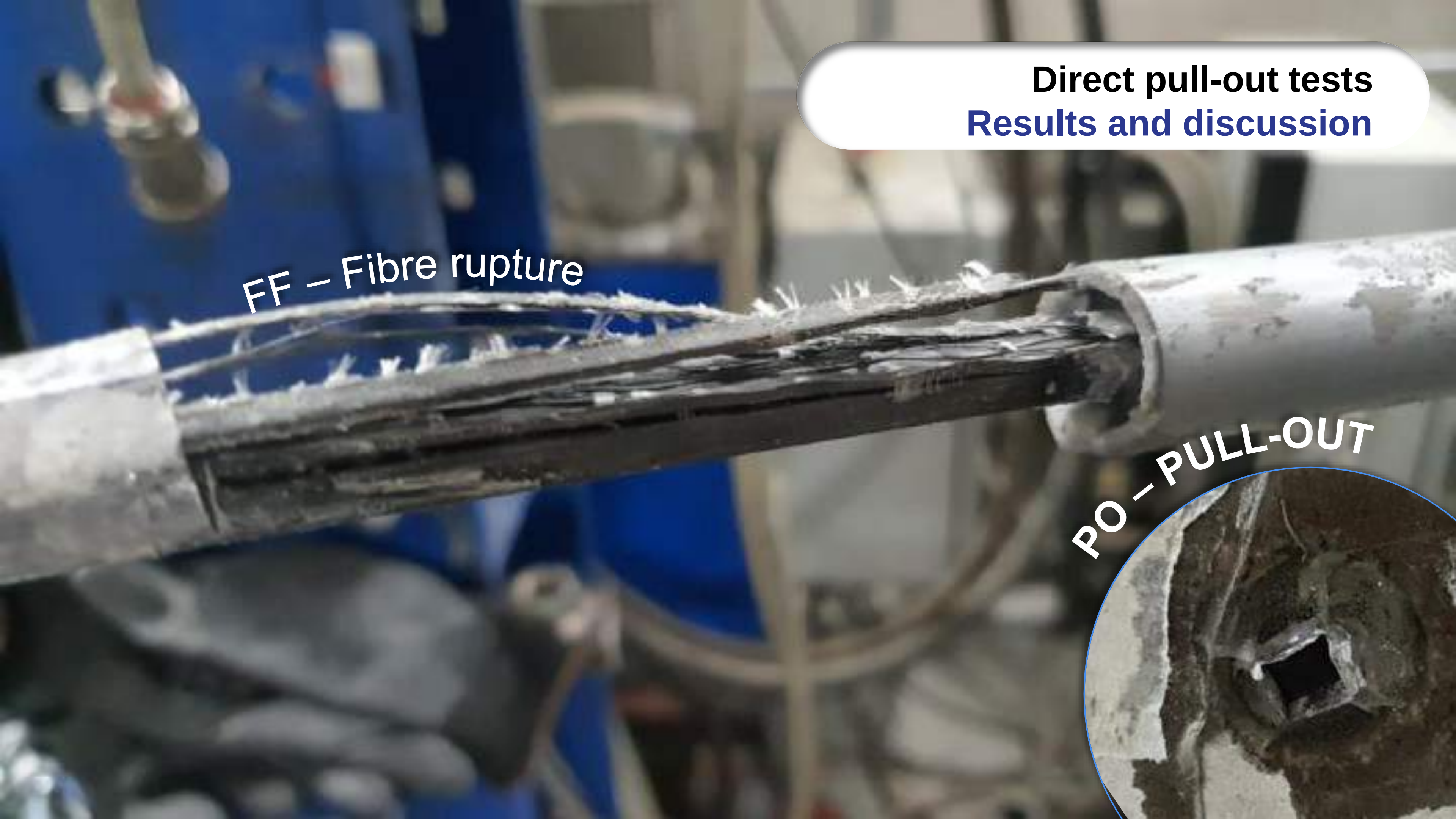
Direct pull-out tests
Results and discussion



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>> STUDY THE BOND BEHAVIOUR OF THIS SOLUTION <<

>> Study the interlaminar Shear strength of the composite <<<

Outline

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- Motivation
- Direct pull-out Tests
- Interlaminar shear tests
- Conclusions

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Interlaminar shear tests

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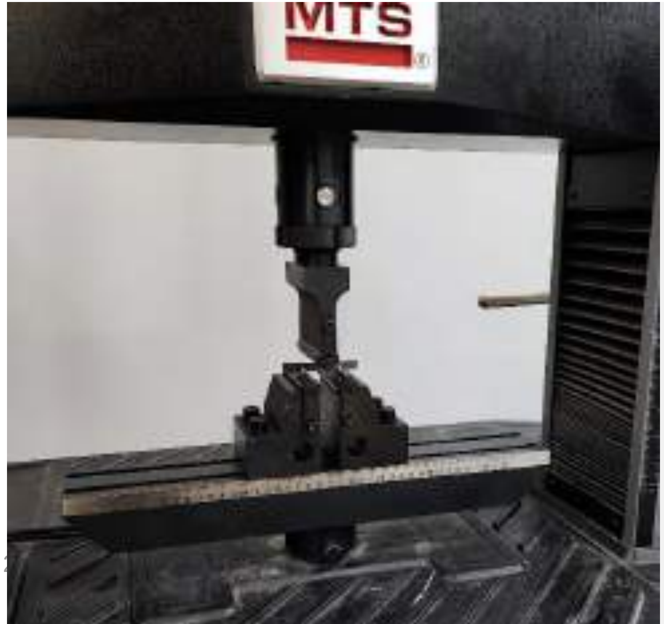
Interlaminar shear tests

Interlaminar shear tests:
Experimental program

- Twelve interlaminar shear tests were conducted to evaluate the interlaminar shear strength of the FRP composites.

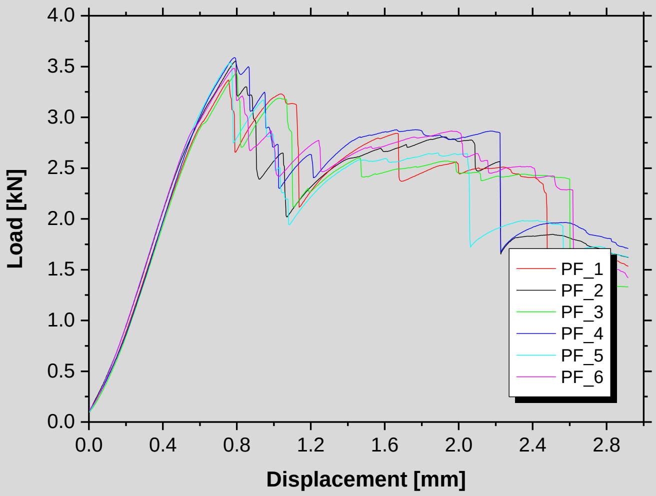


Geometry

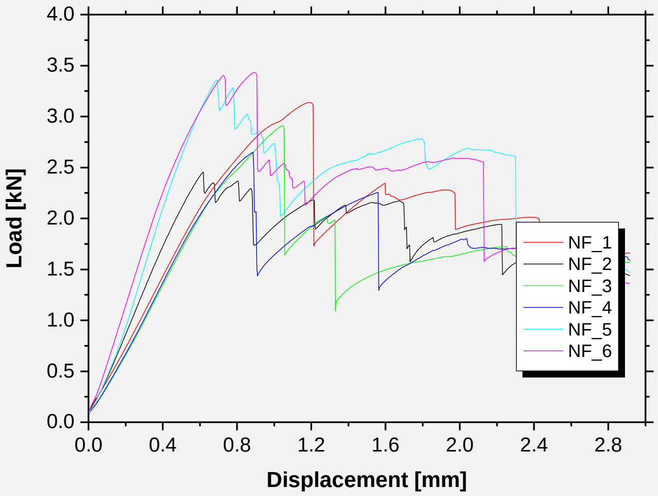
- Geometry and test configuration defined according to ISO 14130:1997 (three-point bending test)
- Same 2 types of CFRP bars, with 7mm of squared cross-section
- Length: 70 mm
- Span: 35 mm

Interlaminar shear tests:
Results and discussion

Series I: peel-off finish



Series II: without peel-off finish



Interlaminar shear tests:
Results and discussion

Interlaminar shear tests:
Results and discussion

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Surface	Specimen	F_{max} [kN]	δ_{max} [mm]	τ_{max} [MPa]	Failure Mode
With the Peel-off roughness Finish (PF series)	PF_1	3.52	0.81	53.95	MSF
	PF_2	3.55	0.79	54.41	MSF
	PF_3	3.37	0.76	51.55	MSF
	PF_4	3.44	0.80	52.63	MSF
	PF_5	3.59	0.79	54.93	MSF
	PF_6	3.54	0.77	54.16	MSF
	Mean	3.50	0.79	53.61	
	CoV	2.1%	2.2%	2.2%	
Without the peel-off roughness finish (NF Series)	NF_1	2.45	0.62	37.58	MSF
	NF_2	3.14	1.19	48.04	SSF
	NF_3	2.91	1.05	44.54	SSF
	NF_4	2.65	0.89	40.55	MSF
	NF_5	3.36	0.69	51.41	MSF
	NF_6	3.43	0.89	52.55	MSF
	Mean	2.99	0.89	45.78	
	CoV	12.0%	22.0%	11.9%	

Notes: Failure Mode: MSF = multiple shear failure, SSF = single shear failure

Interlaminar shear tests:
Results and discussion

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Conclusions

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Conclusions

- **Bond behavior and pull-out tests:** The pull-out tests demonstrated a non-linear relationship between bond stress and loaded end slip, with an initial increase followed by softening. Pull-out stress decreased as the bonded length increased.
- **Failure modes in pull-out tests:** Failure modes varied between pull-out and FRP failure, with interlaminar shear failure observed in some cases. Combined tensile and shear stresses in CFRP bars contributed to interlaminar shear failure.
- **Interlaminar shear tests:** Interlaminar shear tests provided valuable insights into composite material integrity. Multiple shear failure was the dominant mode, with the peel-off finish (PF) series showing higher interlaminar shear strength and lower result dispersion.

Conclusions

- **Influence of manufacturing process:** The manufacturing process with the peel-off finish yielded a better composite solution. Both series performed adequately, with results falling within the range available in the literature.

Acknowledgment

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This STSM was developed under the COST Action CA18120 (CERTBOND) and supported by COST (European Cooperation in Science and Technology).

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Funded by the Horizon 2020 Framework Programme of the European Union

This study is also a part of the project ‘‘Sticker –Innovative technique for the structural strengthening based on using CFRP laminates with multifunctional attributes and applied with advanced cement adhesives’’, with the reference POCI-01-0247-FEDER-039755.

Acknowledgment

This work was partly financed by FCT / MCTES through national funds (PIDDAC) under the R&D Unit Institute for Sustainability and Innovation in Structural Engineering (ISISE), under reference UIDB/04029/2020, and under the Associate Laboratory Advanced Production and Intelligent Systems ARISE under reference LA/P/0112/2020.

isise Institute for Sustainability and Innovation in Structural Engineering

ARISE

fct Fundação para a Ciência e a Tecnologia

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Multi-physics Numerical Modelling of EBR CFRP-concrete Bonded Joints under Water Immersion Exposure

Presenter:

Aloys Dushimimana

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Outline

- Opening
- What the work is about
- Main outcomes
- Conclusion

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Opening

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UMinho Team FRP Master ++

This work was conducted at EPFL


CCLab

CCLab Team

Science in Real World!

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What the work is about?

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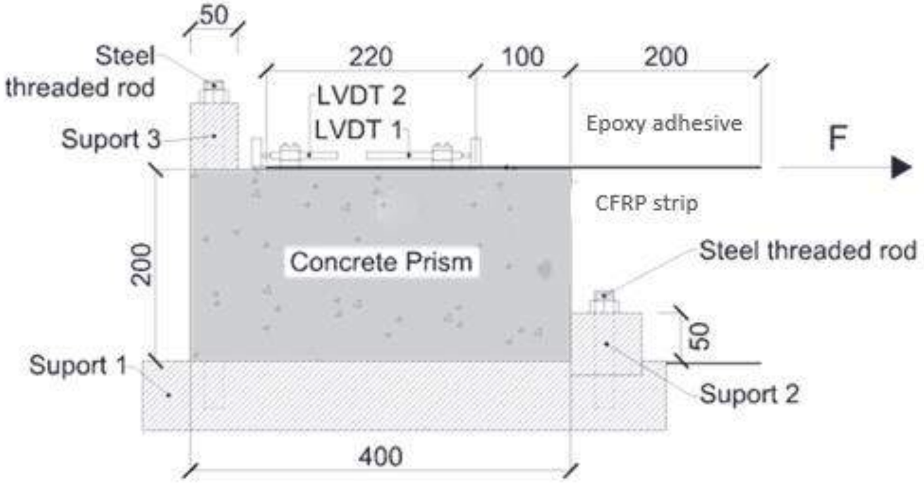
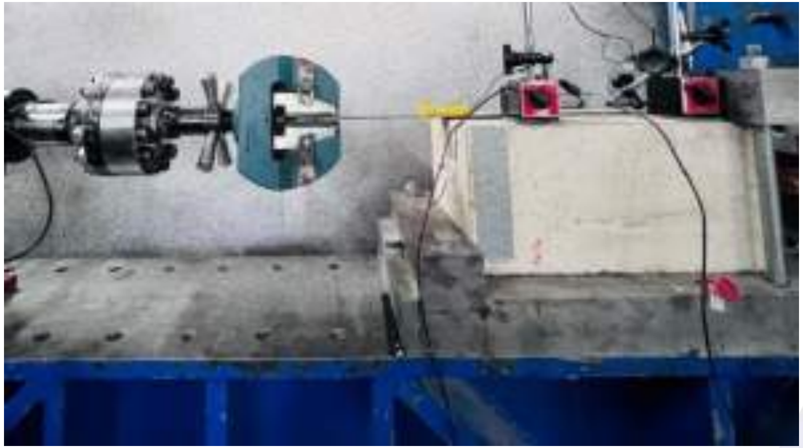
EXPERIMENT: PULL-OUT TEST

Dimensions [units in mm], Test set-up





WHY TESTING?

ANY ISSUE TO ADRESS?

ACCELERATED VS NATURAL AGING

SIMULATION PROCEDURE

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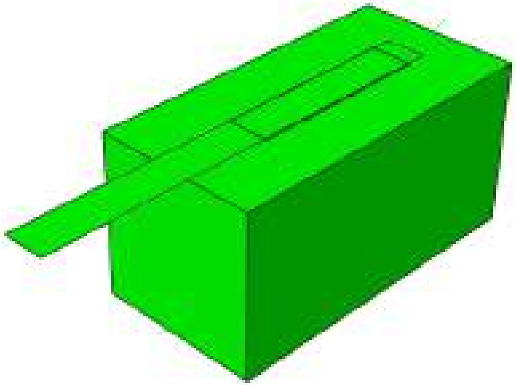


FEM Simulations [units in mm]:

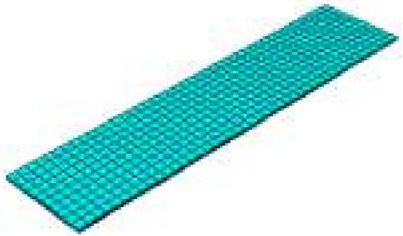
1) CFRP: 50x1.2x520, 3D, Deformable, Shell
2) Epoxy adhesive S&P: 50x1.5x220, 3D, Deformable, Solid
3) Concrete: 200x200x400, 3D, Deformable, Solid)

Element type:

1) CFRP: S4R

2) S&P adhesive: C3D8R

3) Concrete: C3D8R



SIMULATION PROCEDURE

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Concrete Properties: Density: 2.4e-9 ton/mm^3; E: 30280 MPa; poisson's ratio= 0.2;

Constitutive models:

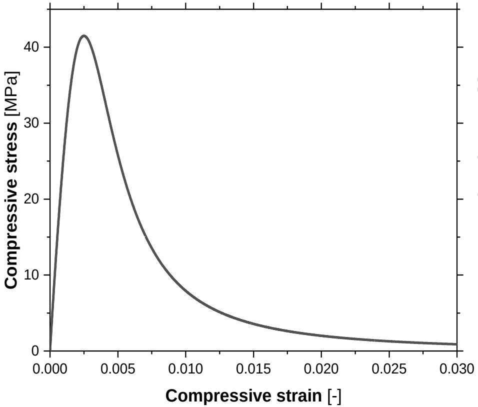
In Compression: Saenz (1964)

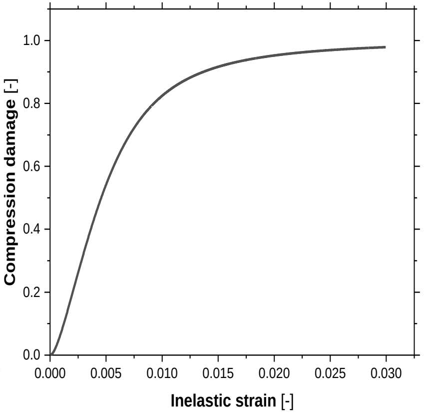
$$\sigma_c = \frac{E_c \varepsilon_c}{1 + (R + R_E - 2)\frac{\varepsilon_c}{\varepsilon_0} - (2R - 1)\left(\frac{\varepsilon_c}{\varepsilon_0}\right)^2 + R\left(\frac{\varepsilon_c}{\varepsilon_0}\right)^3}$$

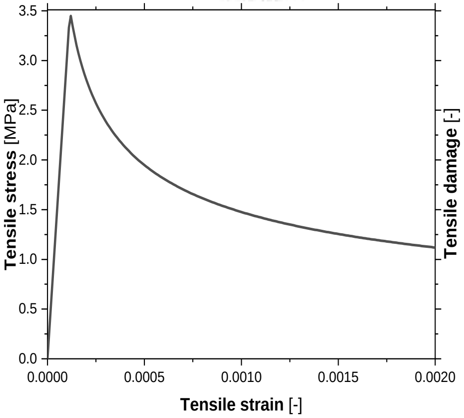
In Tension: Belarbi and Hsu (1994)

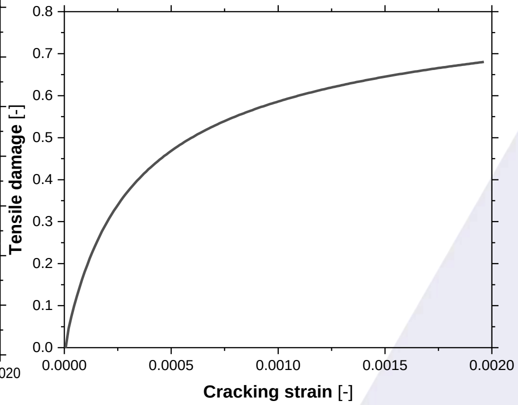
$$\varepsilon_t \le \varepsilon_{cr} \qquad \sigma_t = E_c \varepsilon_t$$

$$\varepsilon_t > \varepsilon_{cr} \qquad \sigma_t = f_{cr}\left(\frac{\varepsilon_{cr}}{\varepsilon_t}\right)^{0.4}$$









SIMULATION PROCEDURE

Epoxy Adhesive Properties: Density: 1.7e-9 ton/mm^3; E: 7176 MPa; poisson's ratio= 0.38;

Constitutive models:

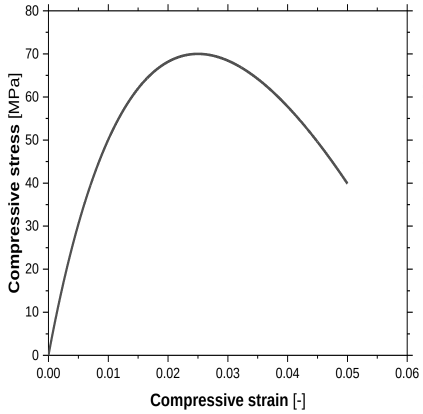
In Compression: Eurocode 2

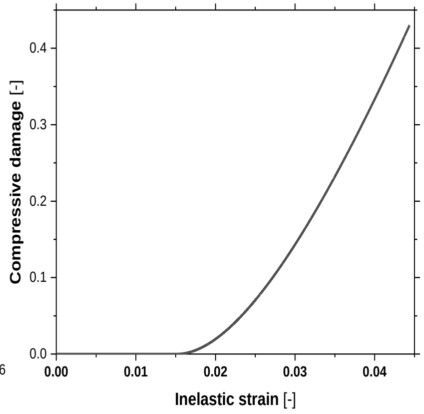
$$\frac{\sigma_c}{f_{cm}} = \frac{k\eta - \eta^2}{1 + (k-2)\eta}$$

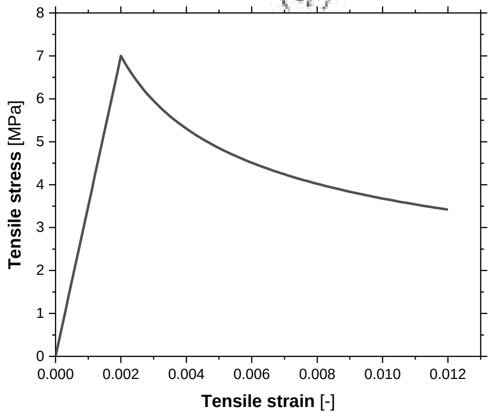
In Tension: Belarbi and Hsu (1994)

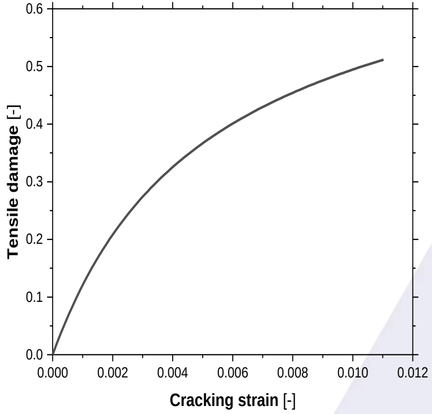
$$\varepsilon_t \le \varepsilon_{cr} \quad \sigma_t = E_c \varepsilon_t$$

$$\varepsilon_t > \varepsilon_{cr} \quad \sigma_t = f_{cr}\left(\frac{\varepsilon_{cr}}{\varepsilon_t}\right)^{0.4}$$









CFRP: Density: 1.6e-9 ton/mm^3; E= 190000 MPa; poisson's ratio= 0.3

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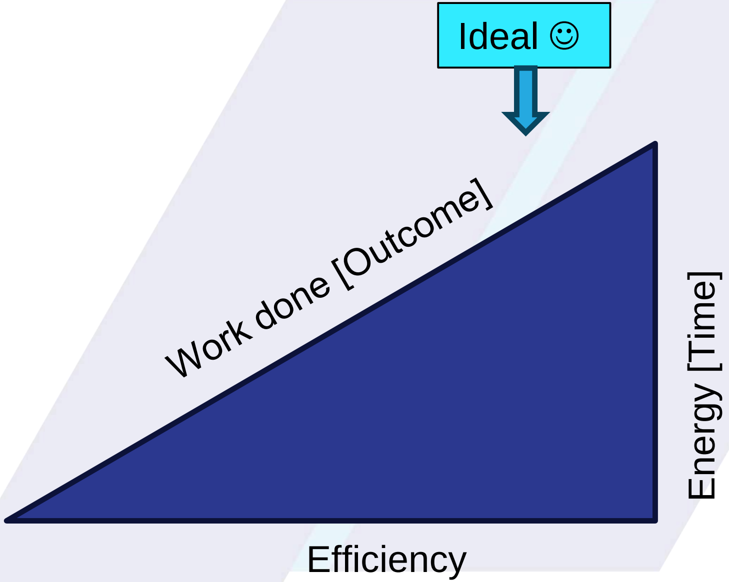
Main Outcomes

Work done $\gtreqless$ Energy lost ?



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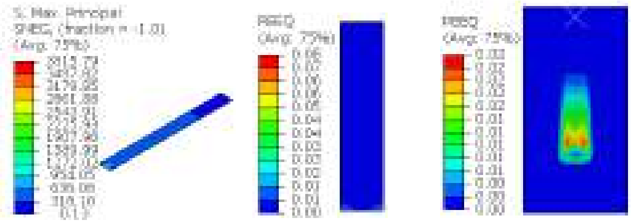
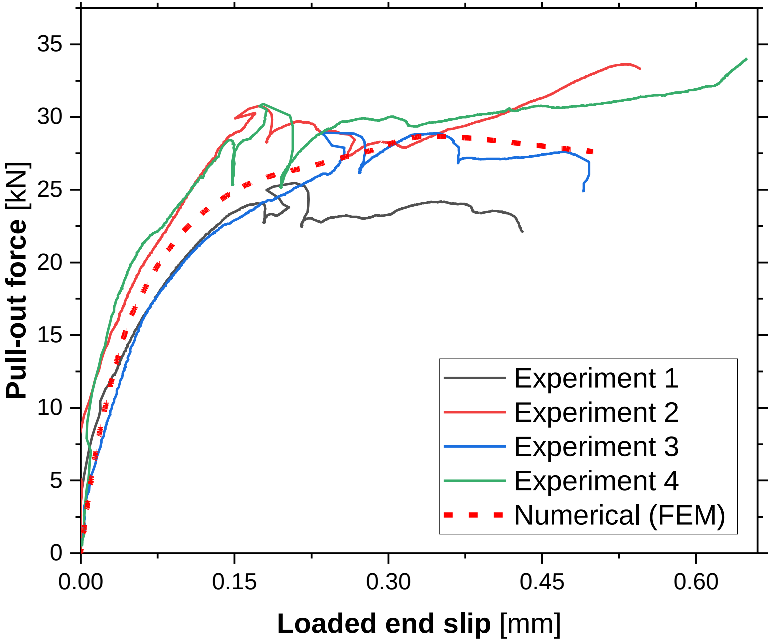
Funded by the Horizon 2020 Framework Programme of the European Union

MAIN OUTCOMES



Force vs slip relationship



MAIN OUTCOMES

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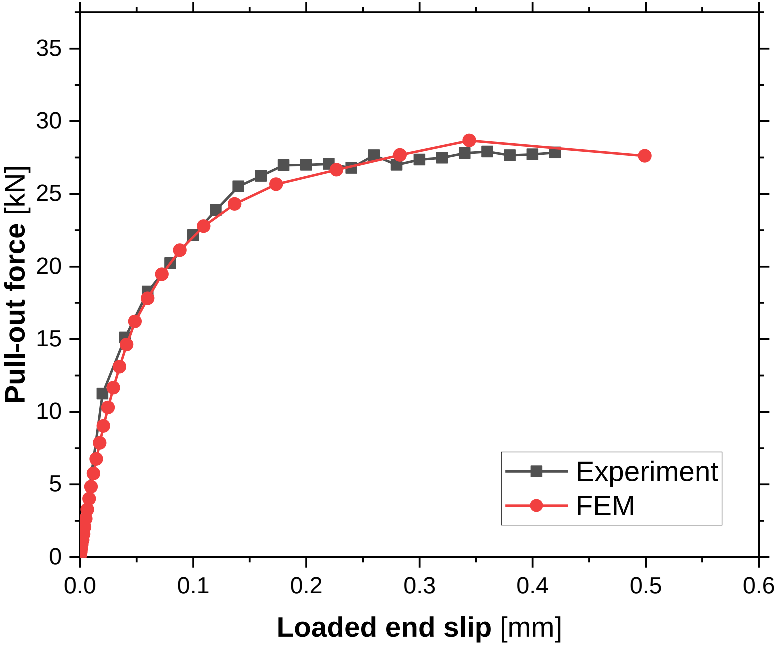
A good agreement between test and FEM results

Force vs slip relationship



MAIN OUTCOMES

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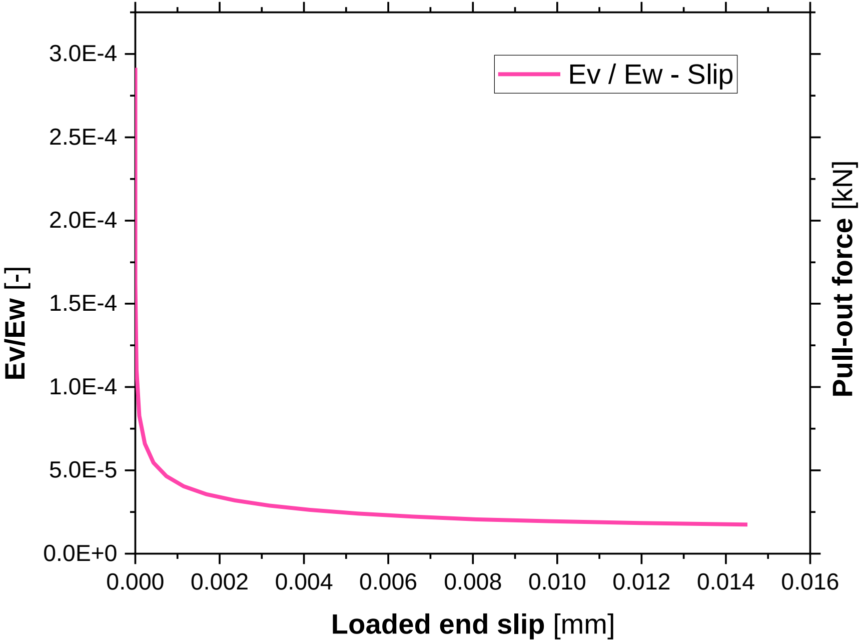
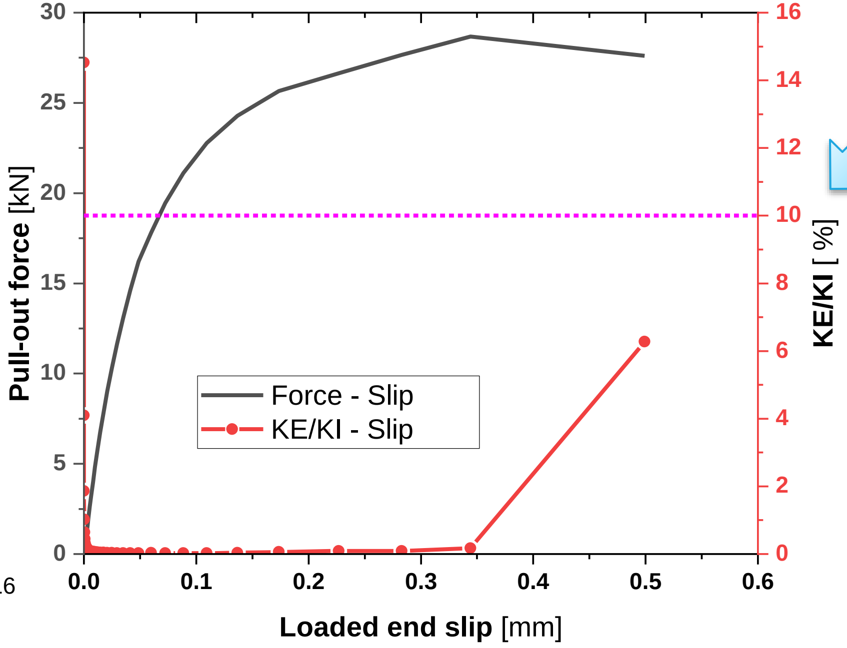
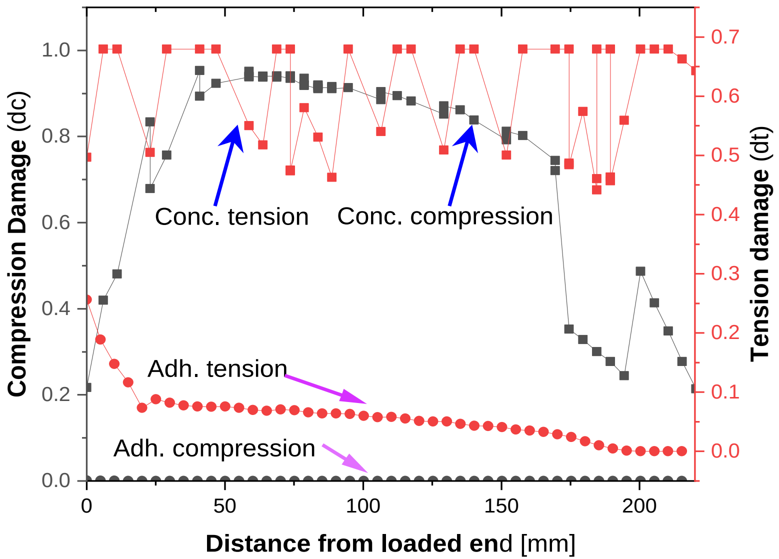
Model validity: refering to ABAQUS manual & existing literature





MAIN OUTCOMES

Failure mode prediction



Concrete shows more damage than adhesive

Hence the failure might be initiated by concrete

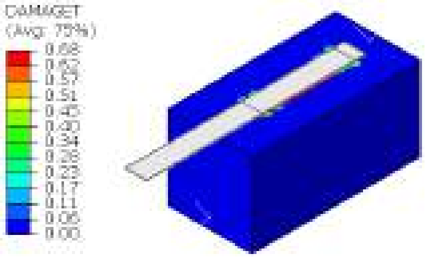
MAIN OUTCOMES

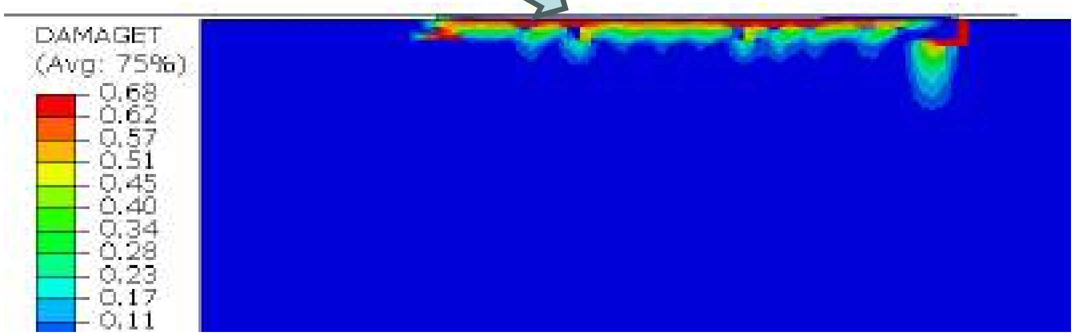
Damage Evolution

Failure mode prediction

Tensile damage

At failure stage:
Concrete shows
more damage than adhesive





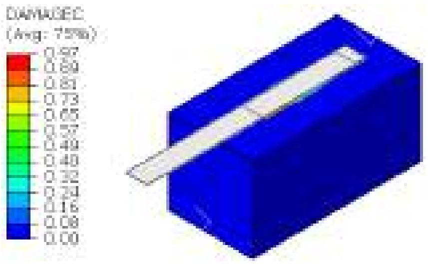
MAIN OUTCOMES

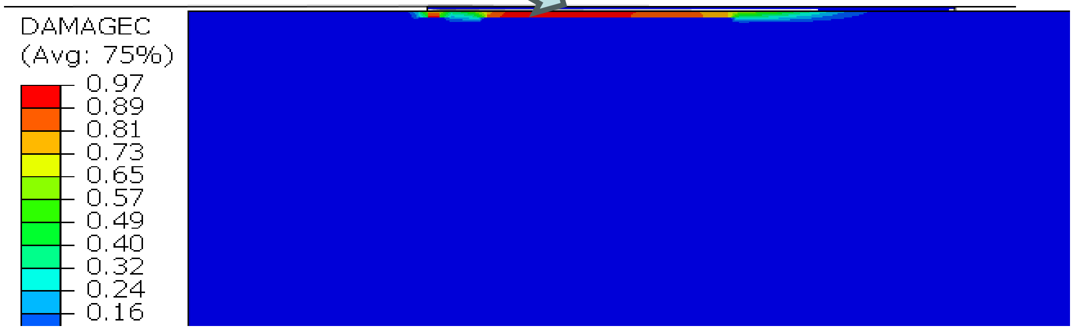
Damage Evolution

Failure mode prediction

Compression damage

At failure stage:
Concrete shows
more damage than adhesive





CONCLUSION

There is a good agreement between experimental and numerical results

The failure mode is well predicted: Concrete cohesive failure

The ratio of kinetic energy and internal inergy is always less than 10%

Modelling of water ingress and its effects on the bond strength: Work ongoing

ACKNOWLEDGEMENTS

CertBond
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- This work was also supported by **FCT - Portuguese Foundation for Science and Technology** under scope of the project FRPLongDur (POCI-01-0145-FEDER-016900), and the grant 2021.08403.BD provided by FCT.

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- The author would also like to acknowledge the support and contributions of the following companies:

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S&P Clever Reinforcement Ibérica, Lda

tecnipor

VIALAM

ARTECANTER

HILTI

Sika

Cachapuz
The best weigh

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Thank You!

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Contacts:
aloysdushimimana@yahoo.fr

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Machine learning in fatigue life of wind turbine blade adhesives

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Composite Construction Laboratory (CCLab),
Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland.

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Outline

- Introduction
- Research gap
- Proposed machine learning framework
- Results and discussion
- Conclusion
- Future scope

Introduction

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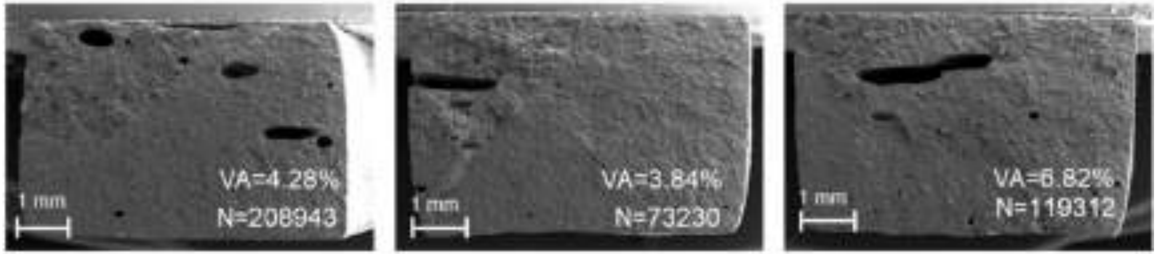
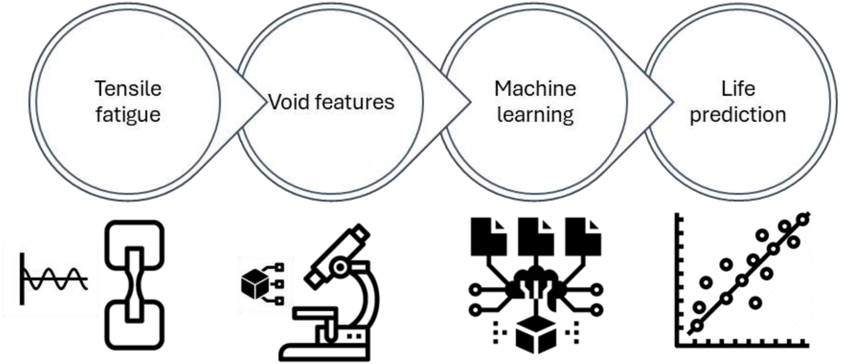


Fatigue failure surface of epoxy adhesive showing macro voids

- Structural epoxy adhesives are used in wind turbine rotor blade bonding.
- Characterizing the fatigue life of these adhesives is essential for joint design and analysis.
- Presence of voids influences the fatigue life substantially.
- Corelating the void characteristics such as shape, size, location and angle to the fatigue life is complex.

Research gap



- Machine learning framework <u>for minimal data set</u>
- Robust ML framework for a combination of <u>different material</u> fatigue datasets.

Proposed ML framework

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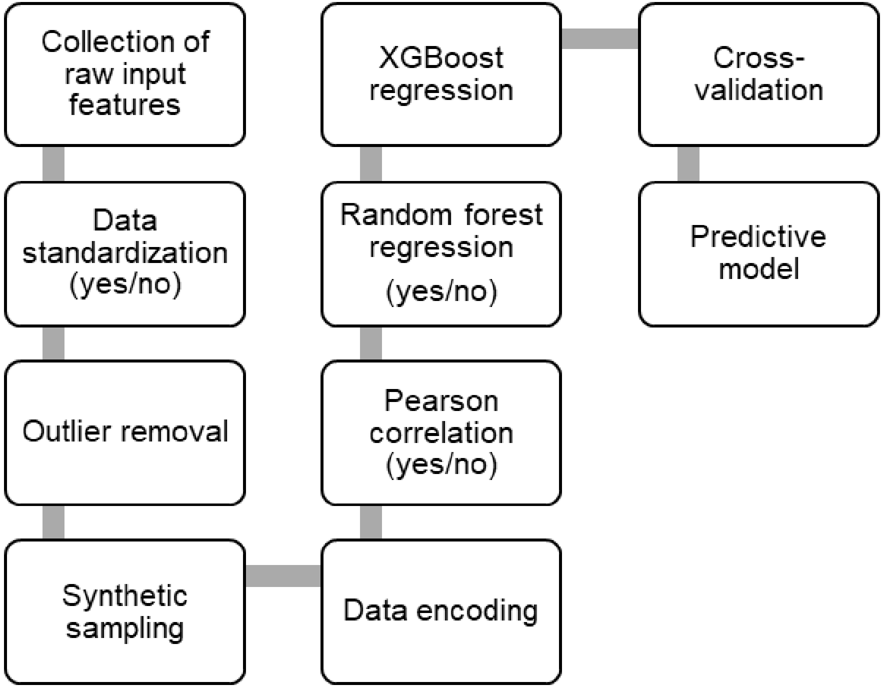
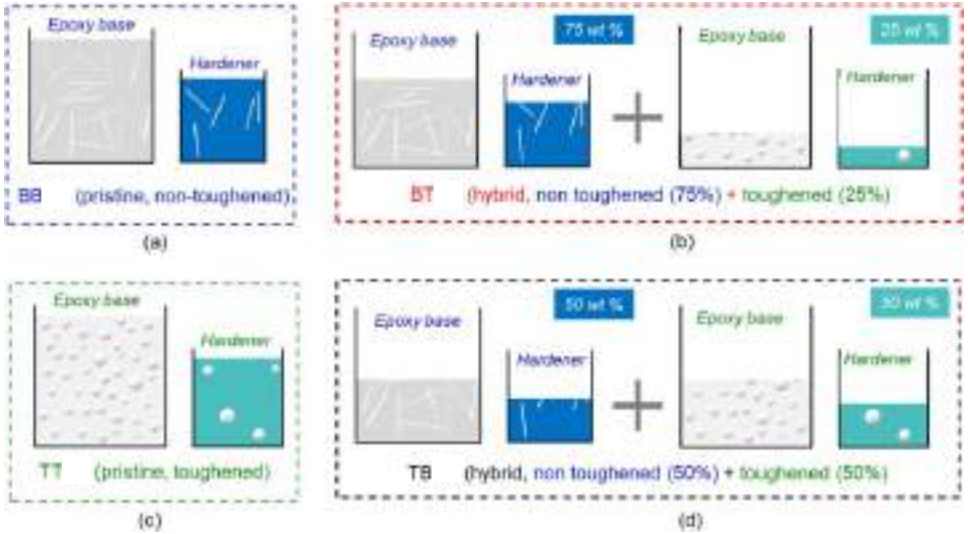


<u>Two different data sets</u>

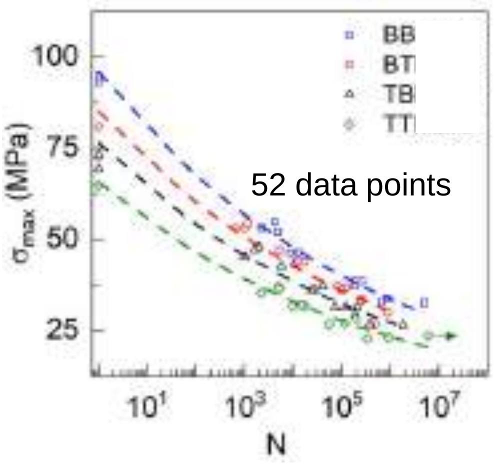
- Four epoxy adhesives
- Four epoxy adhesives + two AlSi10Mg alloys

Collection of Raw input features: Epoxy adhesives

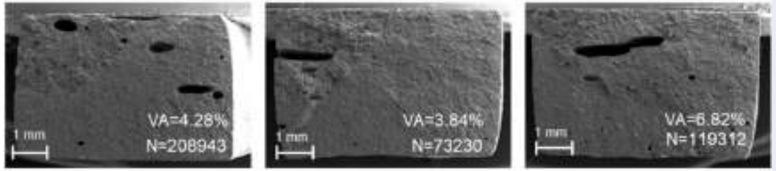


Illustrative diagram of adhesive materials: (a) BB (b) BT (c) TT and (d)TB

Srinivasan DV, Vassilopoulos AP. Fatigue performance of wind turbine rotor blade epoxy adhesives. Polym Test 2023;121:107975.



S-N diagram



Failure surface of TB specimes

Collection of Raw input features: Epoxy adhesives

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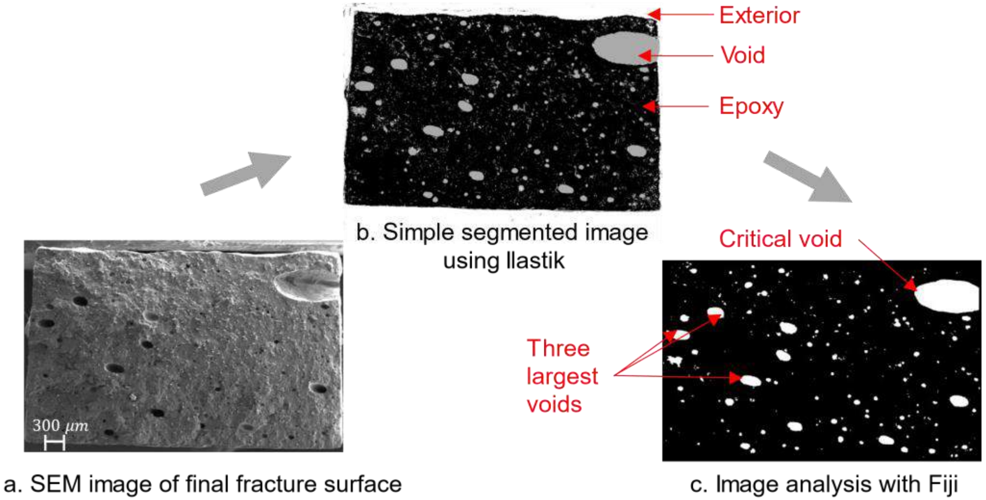
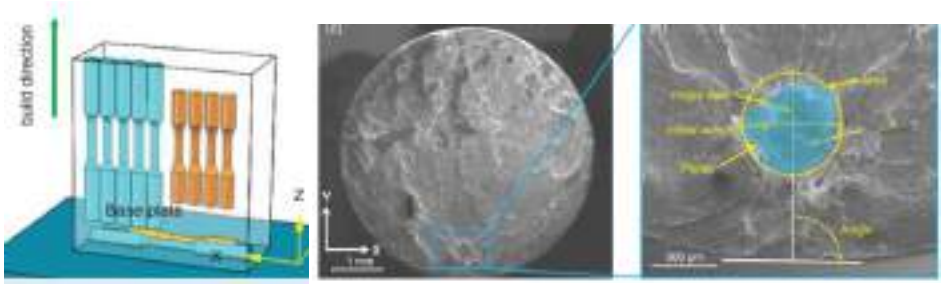


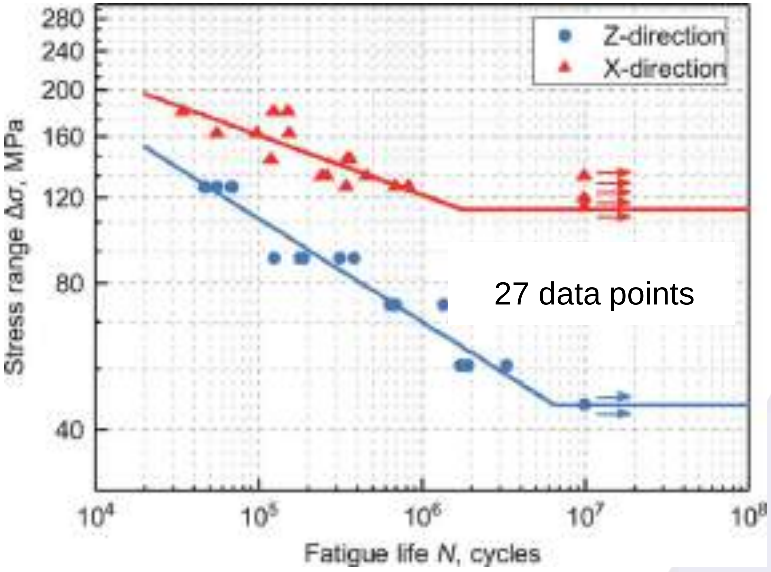
Digital image analysis and void data collection.

Collection of Raw input features: Epoxy adhesives

S.No	Input features	S.No	Input features
1	Youngs modulus	17	Void size Void critical
2	Tensile strength	18	Void size Void 1
3	Number of voids	19	Void size Void 2
4	Void area percentage	20	Void size Void 3
5	Void aspect ratio Void critical	21	Void Angle Void critical
6	Void aspect ratio Void 1	22	Void Angle Void 1
7	Void aspect ratio Void 2	23	Void Angle Void 2
8	Void aspect ratio Void 3	24	Void Angle Void 3
9	Void circlicity Void critical	25	Void Location Void critical
10	Void circlicity Void 1	26	Void Location Void 1
11	Void circlicity Void 2	27	Void Location Void 2
12	Void circlicity Void 3	28	Void Location Void 3
13	Void jaggedness Void critical		
14	Void jaggedness Void 1		
15	Void jaggedness Void 2		

Collection of Raw input features: AlSi10Mg alloy





Peng X, Wu S, Qian W, Bao J, Hu Y, Zhan Z, et al. The potency of defects on fatigue of additively manufactured metals. Int J Mech Sci 2022;221:107185. https://doi.org/10.1016/j.ijmecsci.2022.107185.

Exploratory data analysis

- Removal of outliers based on Z score 1.96
- Log transformation of fatigue life
- Data standardization

$$Standardized\ value = \frac{Observation - Mean}{Standrad\ deviation}$$

Synthetic minority over-sampling (SMOTE)

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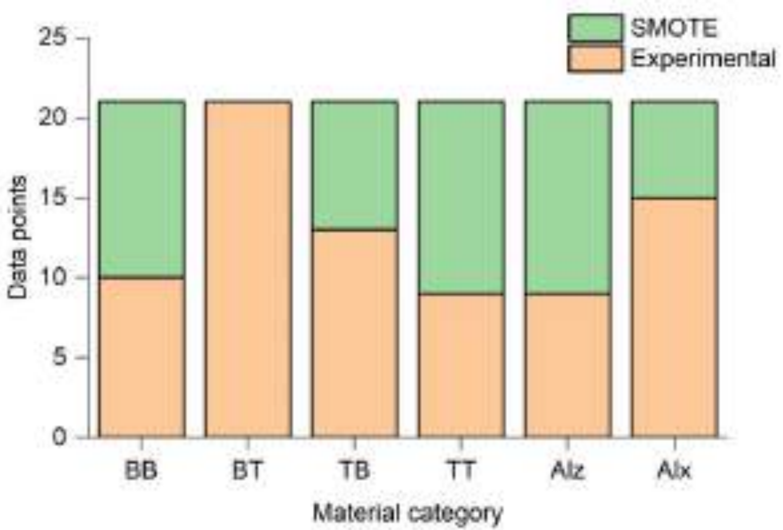

Balancing the data points among the materials using SMOTE technique

- Dataset imbalance can negatively impact machine learning algorithms' predictive accuracy.
- Algorithms tend to perform better on the majority dataset than on the minority class.
- Increasing the total data points from 81 to 126, with 21 data points for all materials

Pearson correlation coefficient (PCC)

- Pearson correlation coefficient between any two features (X1, X2) was identified utilizing their covariance (cov (X1, X2)) and standard deviations (σ_{X1}, σ_{X2}), as follows:

$$\rho\,(X1, X2) = \frac{cov\,(X1, X2)}{\sigma_{X1}\,\sigma_{X2}}$$

- Highly correlated features will reduce the model performance by assigning too much importance to the correlated features.
- There are 28 input features as of now for epoxy materials !

Categorical data encoding

- One-hot encoding

Categorical feature

Material
BB
BT
TB
TT

One-hot encoding →

Numerical data

BB	BT	TB	TT
1	0	0	0
0	1	0	0
0	0	1	0
0	0	0	1

One-hot encoding of epoxy polymer material categorical data.

- The categorical variable "Material" with four categories/cardinality: BB, BT, TB, and TT can be represented as a binary vector
- With these 4 additional features, the raw input features were increased from 28 to 32 features.

Categorical data encoding

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- Target encoding

Categorical feature

S.No	Material	Log of Cycles to failure
1	BB	1
2	BB	3
3	BB	5
4	BT	3
5	BT	4
6	BT	6
7	TB	4
8	TB	5
9	TB	6
10	TT	4
11	TT	5

→

Target encoding

Material	Log of Cycles to failure mean	Encoding
BB	3	3
BT	4.33	4.33
TB	5	5
TT	4.5	4.5

→

Numerical data

S.No	Material	Material
1	BB	3
2	BB	3
3	BB	3
4	BT	4.33
5	BT	4.33
6	BT	4.33
7	TB	5
8	TB	5
9	TB	5
10	TT	4.5
11	TT	4.5

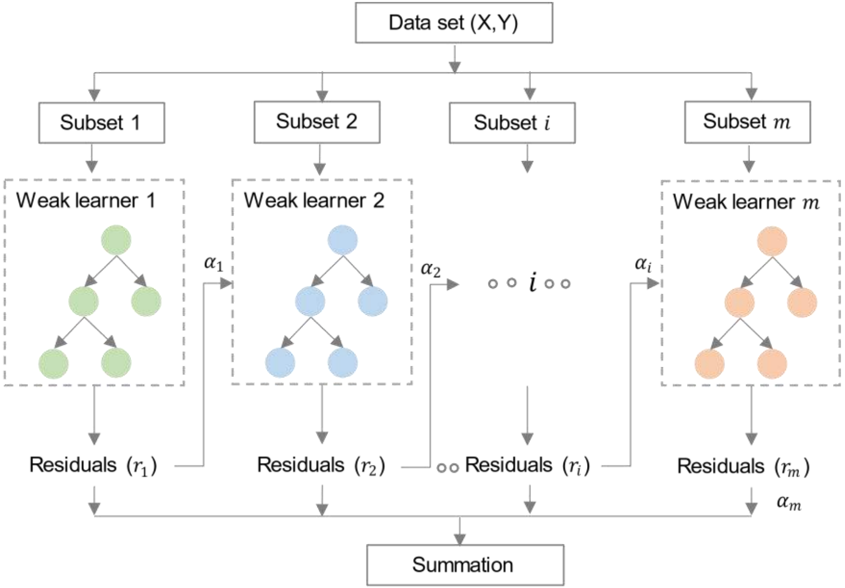
Working principle of target encoding method.

- Advantage: a low-dimensional feature space

Feature importance score

- Identifying the most key input features contributing to accuracy of the model is important.
- Random forest algorithm can be used deriving feature importance score
- It constructs multiple decision trees using randomly selected subsets of the data and features.
- Importance of each feature measured by how much the tree nodes that use the feature decrease the mean squared error in the target variable.
- Scores are averaged across the trees to obtain the final feature importance score

Extreme gradient boosting regression



General working flow of XGBoost algorithm

- Combines multiple weak learners to form a strong learner
- Iteratively building decision trees that correct the errors of the previous tree and can be regularized (α_i) to avoid overfitting

External loop cross-validation

- Outer loop: dividing dataset into a training set (further divided for k-fold cross validation) and a distinct test set (for validation).
- Inner loop: hyperparameters tuning (maximum depth, learning rate, sub-sample, and n estimators) for minimal root mean squared error, employing the Bayesian search technique.

Predictability of ML models based on epoxy adhesives

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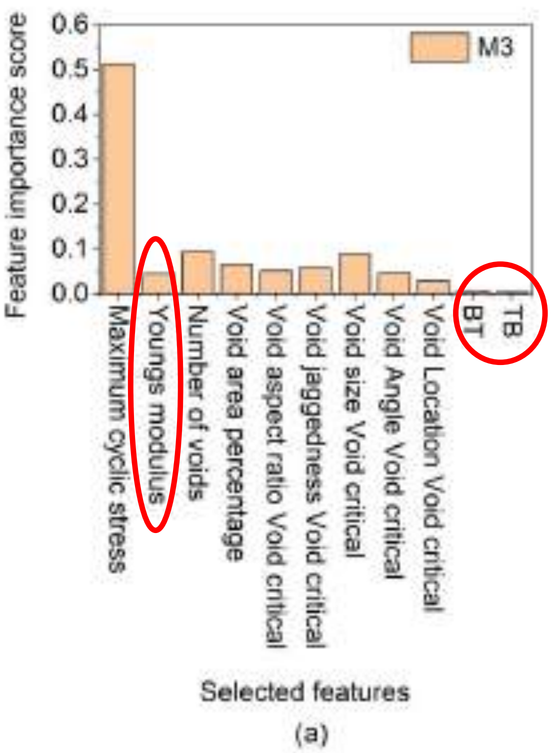
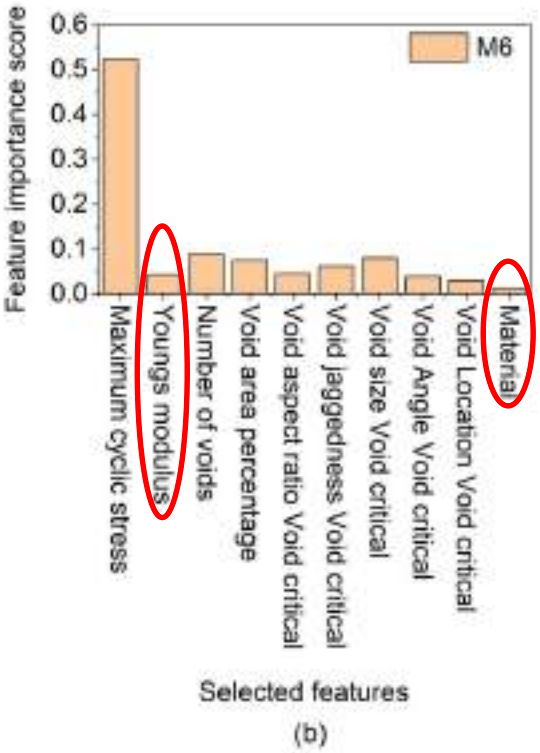
Model name	Standardization	Input features	Encoding	MSE	R^2
M1	no	all	Single-hot	0.394	0.60
M2	yes	all	Single-hot	0.255	0.74
M3	no	selective	Single-hot	0.068	0.93
M4	yes	selective	Single-hot	0.179	0.82
M5	no	selective	Target	0.089	0.91
M6	yes	selective	Target	0.064	0.93

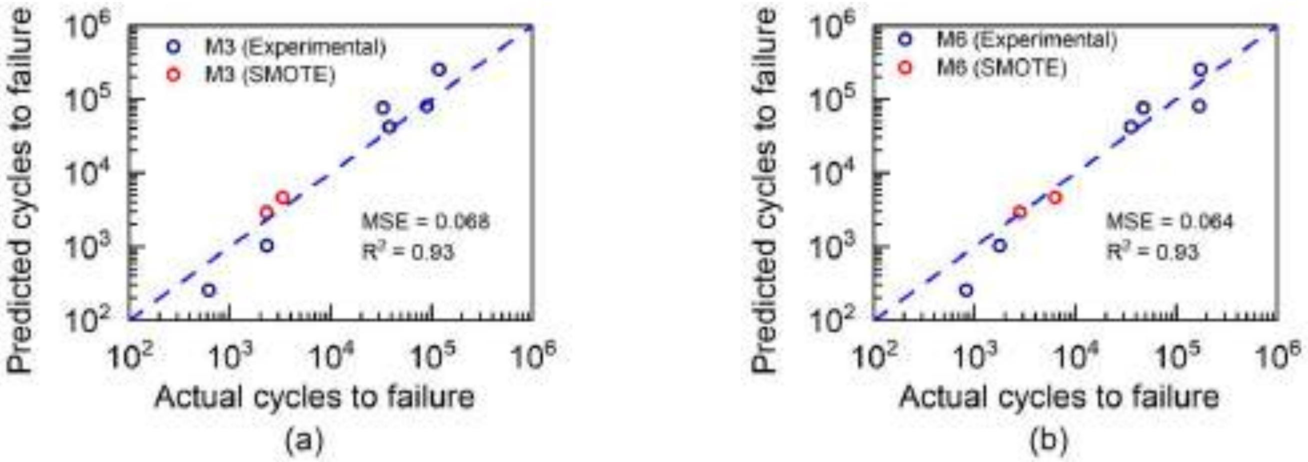
Predictability of ML models based on epoxy adhesives





Feature importance score: (a) M3 model and (b) M6 model

Predictability of ML models based on epoxy adhesives



Predicted versus actual cycles: (a) M3 model and (b) M4 model.

Predictability of ML models based on epoxy polymers and AlSi10Mg alloy

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Model name	Standardization	Input features	Encoding	MSE	R^2
M7	no	all	Single-hot	0.152	0.86
M8	yes	all	Single-hot	0.226	0.79
M9	no	selective	Single-hot	0.081	0.93
M10	yes	selective	Single-hot	0.064	0.94
M11	no	selective	Target	0.121	0.89
M12	yes	selective	Target	0.190	0.83

Predictability of ML models based on epoxy polymers and AlSi10Mg alloy

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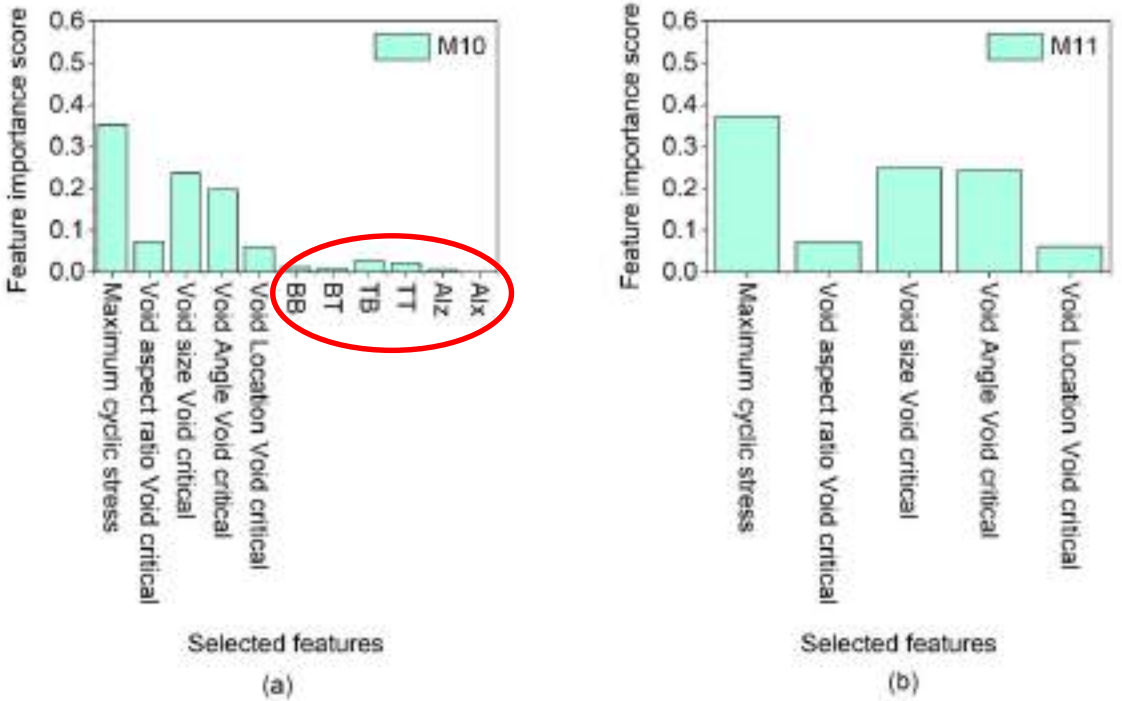
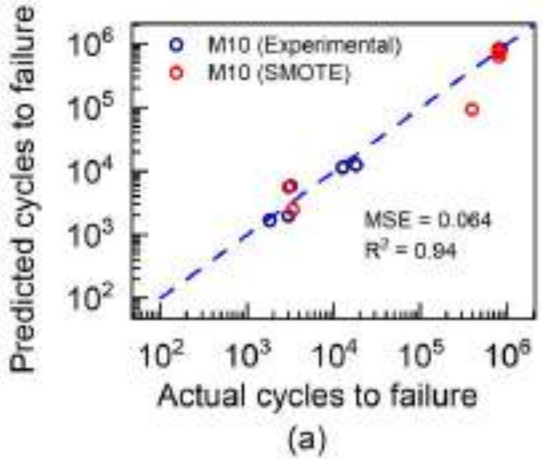
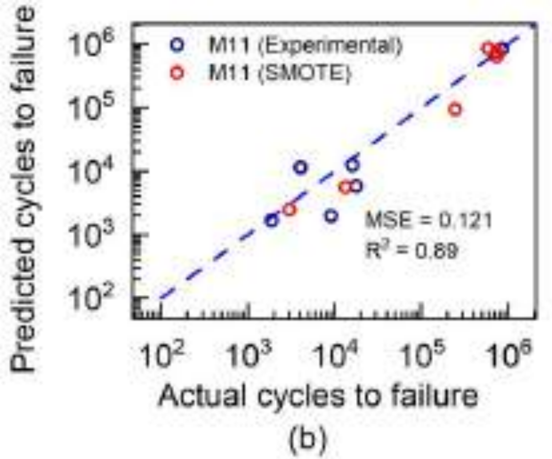


Feature importance score: (a) M10 model and (b) M11 model.

Predictability of ML models based on epoxy polymers and AlSi10Mg alloy





Predicted versus actual cycles: (a) M10 model and (b) M11 model.

Conclusion

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- A robust machine learning framework for predicting the fatigue life of different material systems with a minimal data set can be developed using extreme gradient boosting algorithms along with data encoding methods.
- While data standardization plays an insignificant role, feature reduction emerges as a critical factor for enhancing the model's overall performance.
- Single-hot encoding method works very well for both epoxy polymer data sets and combined data sets.
- This framework could be used for wide range of applications, especially involving multi-class, minimal material data set.

STSM insights

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STSM Host
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Center of Excellence in AI for Structures
TU Delft, The Netherlands.

STSM duration
01st March 2023 to 30th March 2023

STSM outcome
"A robust machine learning framework for fatigue life prediction with minimal data" manuscript under preparation.

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Swiss National
Science Foundation

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Performance of alternative models for predicting the shear capacity of CFRP-strengthened RC beams

Amirhossein Mohammadi

Supervisors: Prof. Joaquim A.O. Barros, and Prof. José Sena-Cruz

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Outline

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1 Introduction

2 Motivations and objectives

3 Assessment of models for contribution of FRP

4 Developement of design model for beam' shear resistance

5 Reliability Analysis

6 Validation

7 Conclusion

Shear failure and insufficient shear resistance

- Shear failure is abrupt and brittle that must be avoided.
- The insufficient beam's shear resistance can be caused by:
  - Corrosion of steel stirrups
  - Errors on design and/or construction
  - Increase in demand (upgraded design codes, seismic loads, change of use, …)
  - Introducing flexural strengthening

Brittle shear failure of a reinforced concrete beam. (YouTube)

Externally bonded FRP reinforcement

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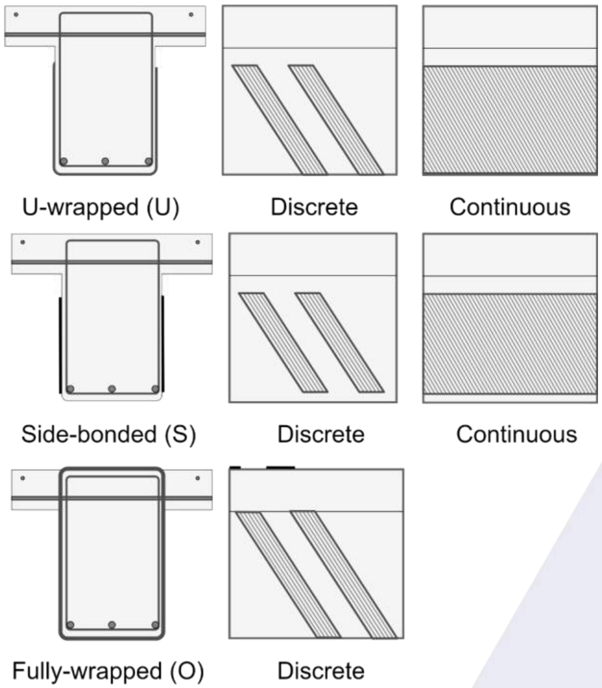
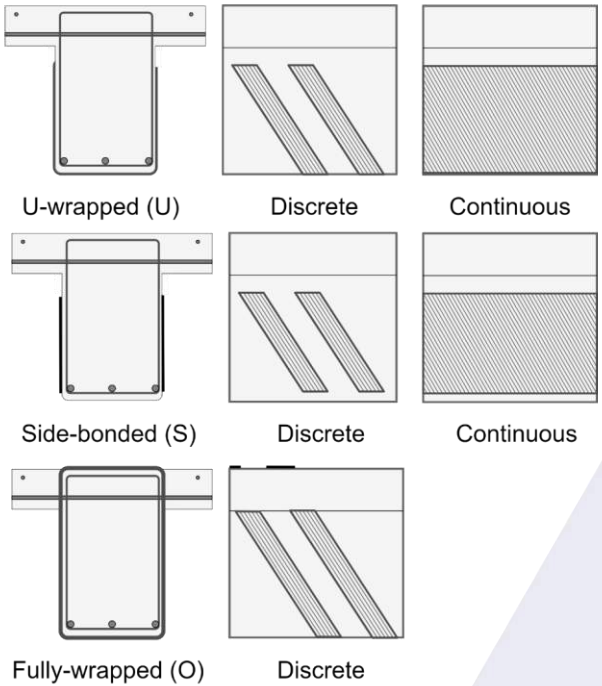
- Strengthening techniques utilizing FRP materials can outperform conventional techniques from economical, environmental, and architectural (aesthetic) standpoints.



Externally bonded FRP reinforcement

- Strengthening techniques utilizing FRP materials can outperform conventional techniques from economical, environmental, and architectural (aesthetic) standpoints.



Models for shear contribution of FRP

ACI 440-2R-17

fib bulletin 90

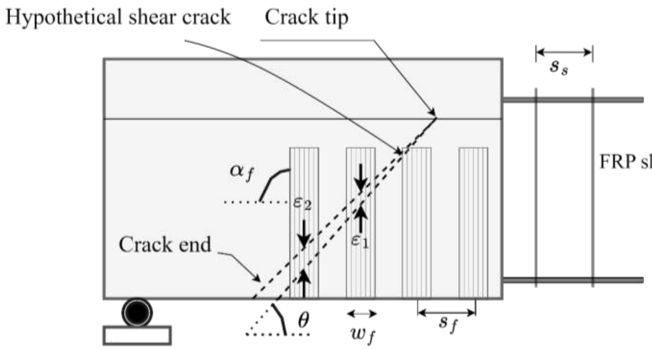
TR 55

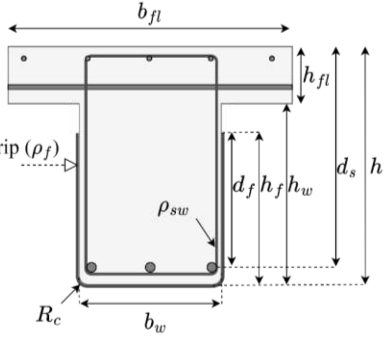
CNR-DT-200R1

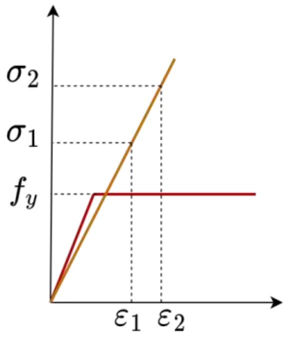
EN 1998-3

CIDAR

Effective strain for FRP reinforcements







$$V_c = \zeta \sqrt{f_c^{'}} b_w d_s$$

$$V_s = \rho_{sw} f_y \times b_w d \times (\cot\theta + \cot\alpha_s) \times \sin\alpha_s$$

$$V_f = A_{fwc} h_{fe} E_f \varepsilon_{fe} (\cot\theta + \cot\alpha_f) \sin\alpha_f$$

Objective and motivations

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- **Motivations:**
  - **Poor prediction performance of existing models:**

1- Models which are often fitted or validated with limited dataset.

2- Models which disregard the impact of influential parameters

  - **Nonapplicable or incompleteness of models:**

1- Some of the models are too complex and requires iterative procedure.

2- Some of the models require large number of parameters, which complicates the design process.

3- Some of the models are incomplete for design application.

Objective and motivations

- **Objectives:**
  - **To Develop a model with enhanced prediction performance:** reduced dispersion, reliable and consistent results.
  - **To include the influential variables on FRP contribution:** $\rho_{sw}, \rho_{sl}, R_c$ **,** and type of strengthening
  - **To consider a variant contribution for concrete and more accurate estimation of CDC angle.**
  - **Reliability Analysis for practical applicability**.

Proposed model

$$v_f = \frac{A_{fwc} h_{fe} E_f \varepsilon_{fe}}{b_w d} \left(\cot\theta + \cot\alpha_f \right) \sin\alpha_f$$

$$\varepsilon_{fe} = m_F \times 0.038 \times \left(\boxed{E_f \rho_f / f_{cm}^{2/3}} \right)^{-0.765}$$

$$m_F = \kappa_{sw} \kappa_R \kappa_{O/U}$$

$$\kappa_{sw} = 1 - 24.1 \boxed{\rho_{sw}}$$

$$\kappa_R = 0.17 \left(\frac{\boxed{R_c}}{50} \right) + 0.93 \leq 1.1$$

$$\kappa_{O/U} = 0.92 + 0.28 \boxed{\kappa}$$

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Composite Structures

Volume 319, 1 September 2023, 117081

A new model for predicting the shear strength of RC beams strengthened with externally bonded FRP sheets

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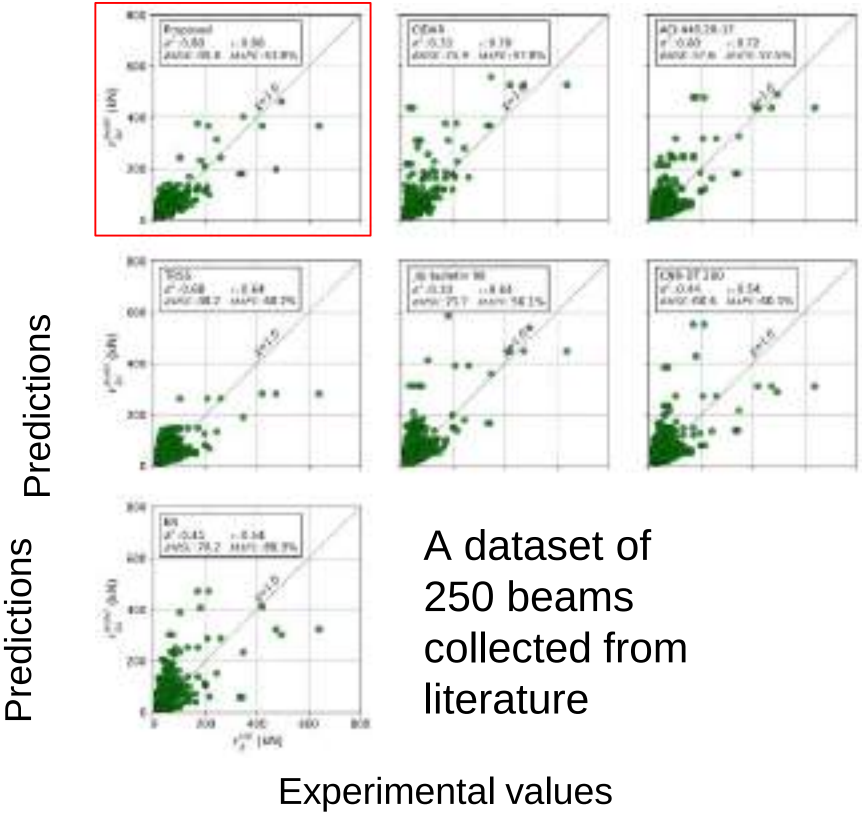
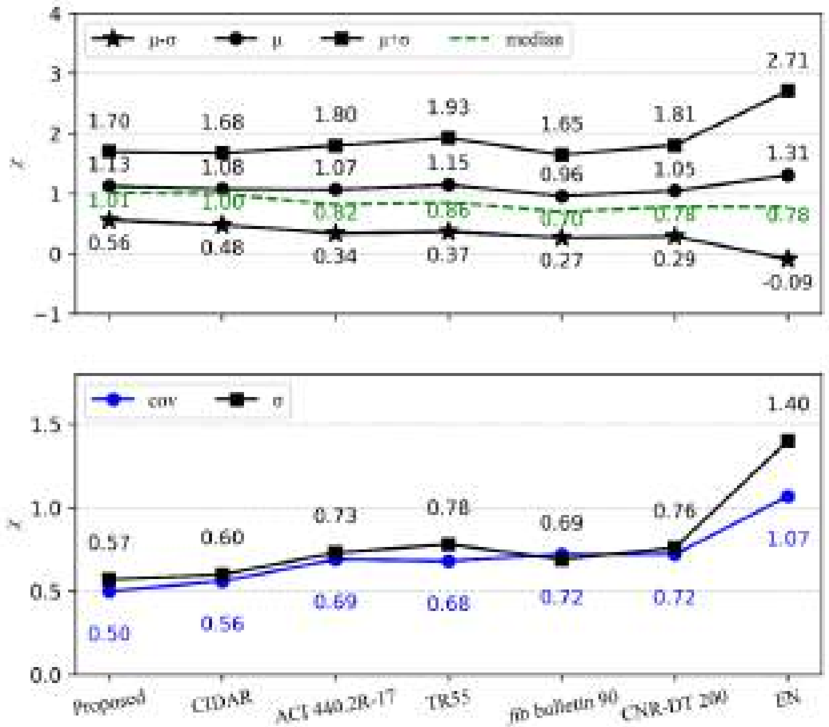
Assessment of models for contribution of FRP



A dataset of 250 beams collected from literature



Bias of models (FRP contribution)

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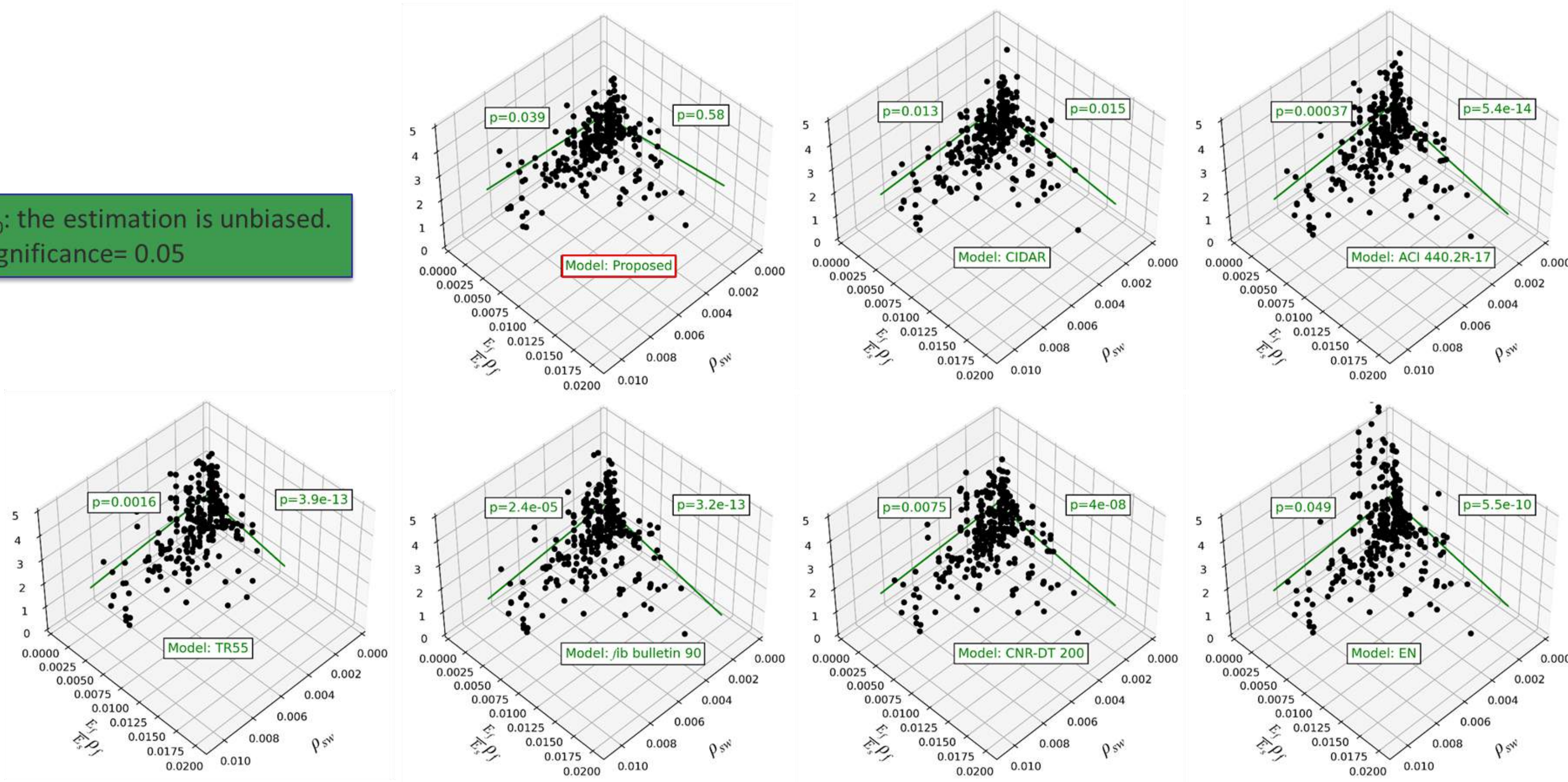
H_0: the estimation is unbiased.
Significance= 0.05



Comprehensive design model

$$V_{Rd}^{\text{model}} = \phi \nu b_w d_s$$
$$= \phi\left(\nu_c + \nu_s + \nu_f\right) b_w d_s \qquad (Eq.1)$$
$$= \phi\left(k_f \zeta \sqrt{f_{cm}} + \rho_{sw} f_{swy} \cot\theta + \nu_f\right) b_w d_s$$

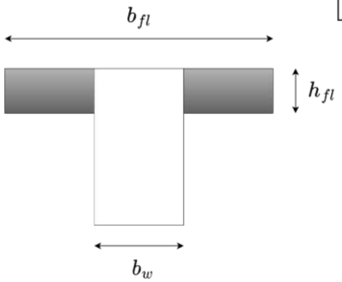
- To obtain the value of ε_x, and then ζ and θ, Simplified Modified Compression Field Theory (SMCFT) is utilized:

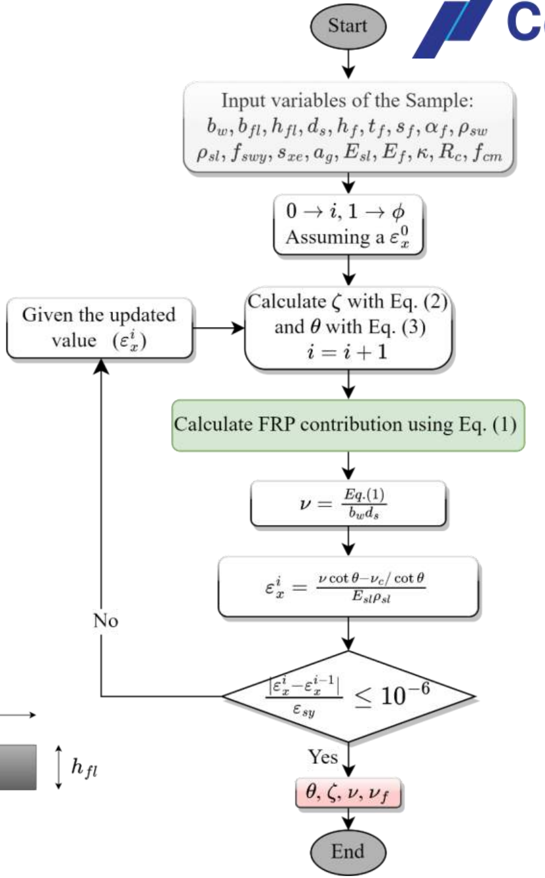
$$\zeta = \frac{0.4}{1+1500\varepsilon_x}\,\frac{1300}{1000+s_{xe}} \qquad (Eq.2)$$

$$\theta = \left(29 + 7000\varepsilon_x\right)\left(0.88 + \frac{s_{xe}}{2500}\right) \le 75^\circ \qquad (Eq.3)$$

- Recommended modification factor by RILEM TC162-TDF :

$$k_f = 1 + n\frac{h_{fl}^2}{b_w d_s} \le 1.5 \qquad n = \frac{b_{fl} - b_w}{h_{fl}} \le 3$$





Closed form equations for ζ and θ

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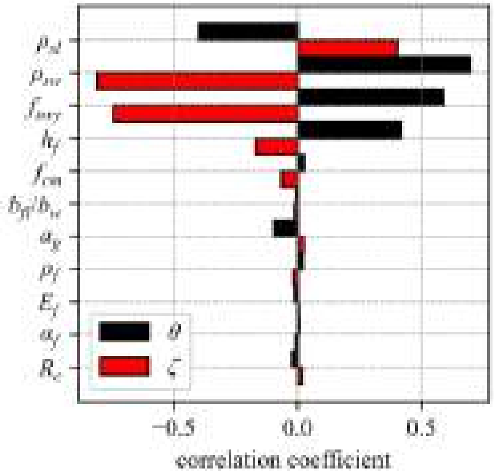

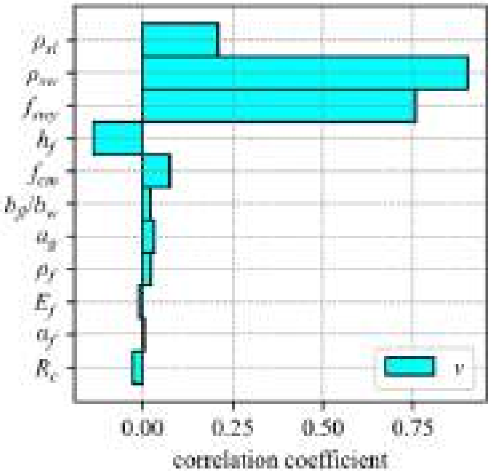

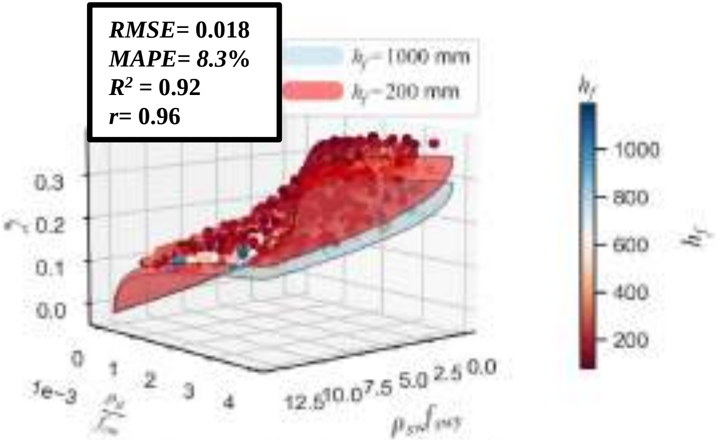

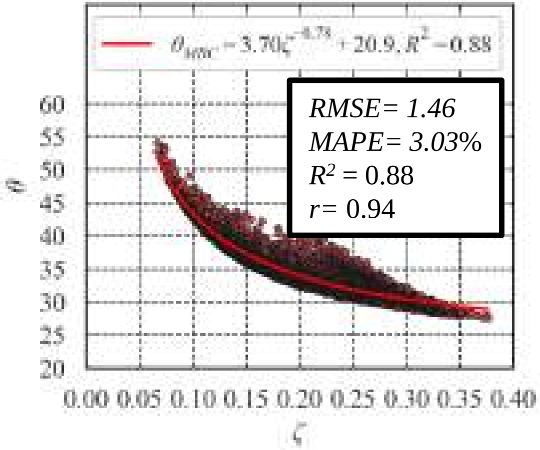

- ❑ Closed-form equations:

$$\zeta_{MBC},\ \theta_{MBC}$$

Reliability analysis

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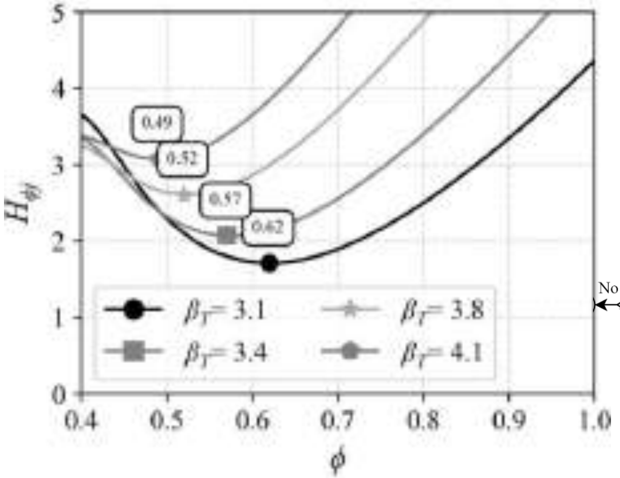
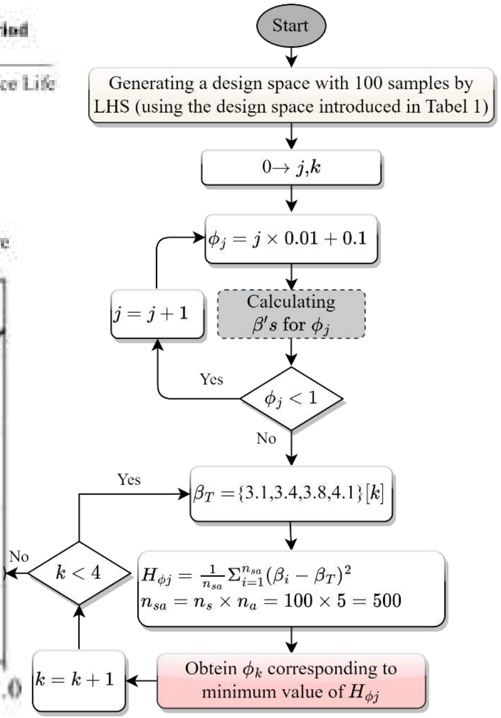
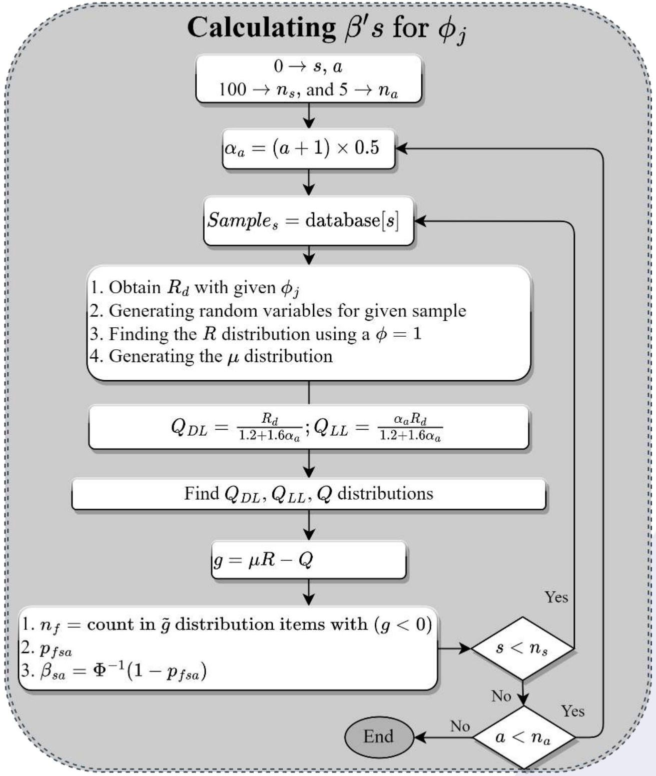
Table 3.3-6: Suggested range of target reliability indices β for existing structures, related to the specified reference periods.

Limit states	Target reliability index β	Reference period
Serviceability	1.5	Residual Service Life
Ultimate	in the range of 3.1 - 3.8*	50 years
	in the range of 3.4 - 4.1*	15 years
	in the range of 4.1 - 4.7*	1 year

* depending on costs of safety measures for upgrading the existing structure



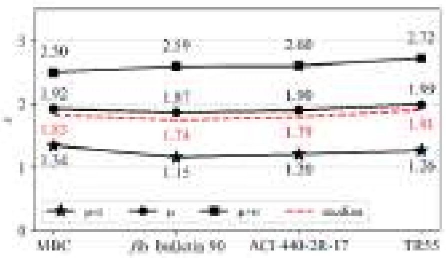


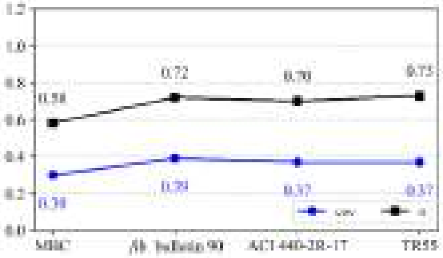


Comparison of results

- **Moderate consequence**
- **low cost**
- **50 years**

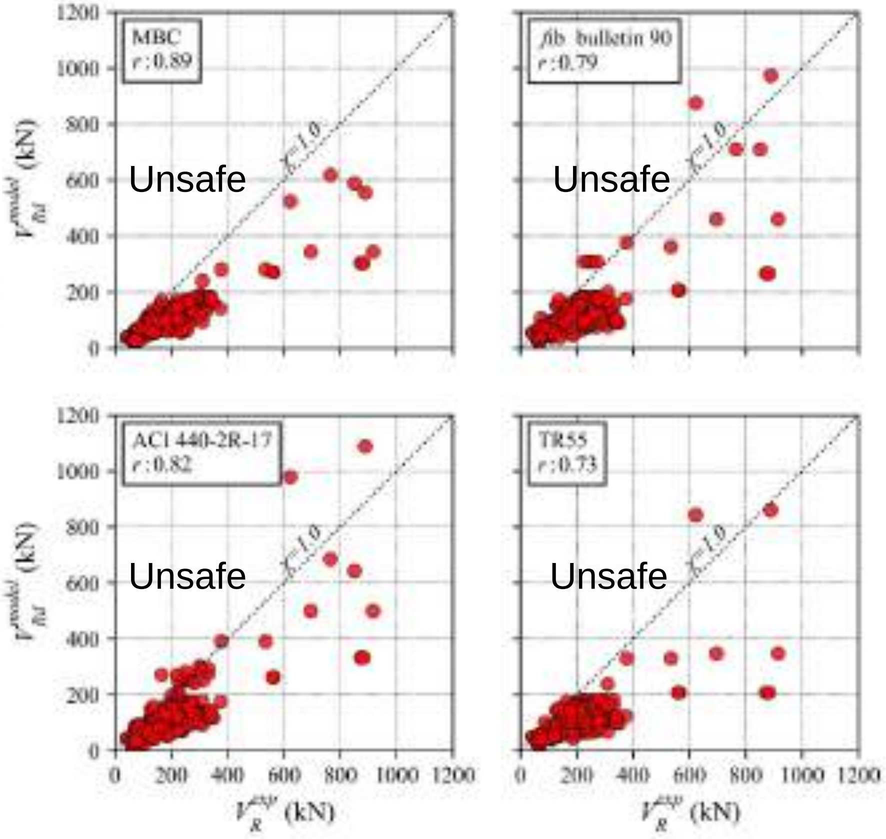
$$\beta_T = 3.8 \rightarrow \phi = 0.52$$





χ	Classification	Penalty	MBC	ACI	TR55	fib bulletin 90
<0.75	Extremely dangerous	10	0%[a]	1%	0%	2%
0.75-1.0	Dangerous	5	1%	7%	3%	5%
1.0-1.25	Low safety	0	8%	11%	7%	10%
1.25-1.75	Appropriate safety	1	35%	30%	31%	35%
1.75-3	Conservative	2	52%	46%	49%	38%
>3	Extremely conservative	4	4%	6%	9%	11%
Total demerits point score			1.6[b]	1.91	1.8	2.0

a: Percentage of specimens with χ laying in the range.
b: ((0×10)+(1×5)+(8×0)+(35×1)+(52×2)+(4×4))/100=1.6



Bias of models (total resistance)

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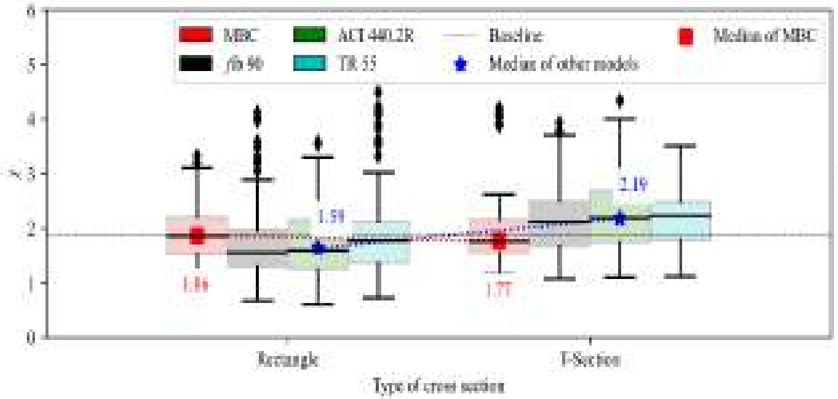

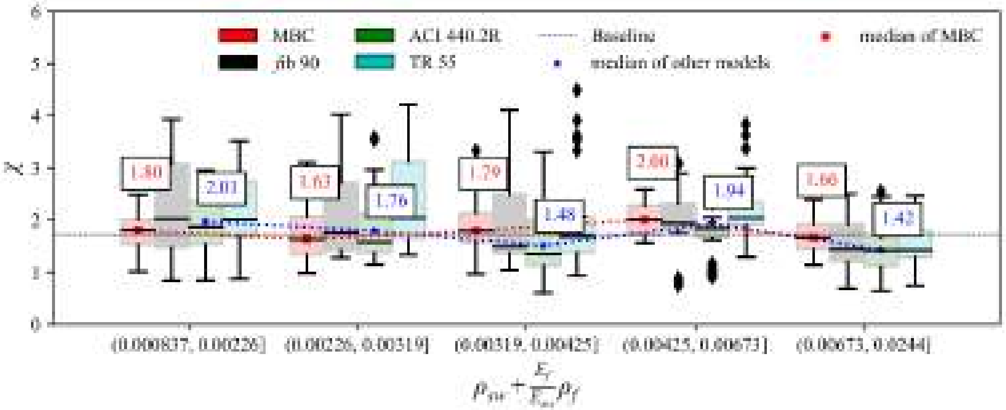

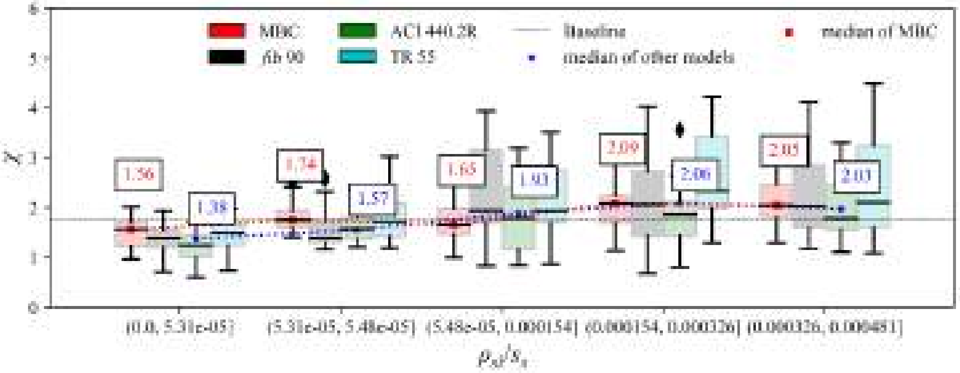

Conclusion

- Using the compiled dataset, some well-known design models were assessed.
- Simplified modified compression field theory was employed to obtain the resistance of RC beams strengthened by CFRP-EBR systems.
- Through sensitivity analysis, a novel closed form model was introduced for the tensile stress factor and CDC angle.
- Resistance reduction factor were found for different levels of safety according to reliability analysis.
- The compiled dataset was employed to validate the proposed model, showcasing superior performance compared to existing guideline models.
- These findings demonstrate the robustness and efficiency of the proposed approach, supporting its potential for practical applications.

Acknowledgment

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Snapshots from CertBond and project related ideas

Michal K. BUDZIK
Associate Professor

LIGHTWEIGHT MATERIALS AND STRUCTURES

AARHUS UNIVERSITY
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What was CertBond for us?

Meetings: Kick-off meeting in Delft **14-15 October 2019, Delft, The Netherlands**

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Traning Schools: 1st TS 20 to 22 September 2021, Trieste, Italy

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Traning Schools: 2nd TS 17 to 19 October 2022 Guimarães, Portugal

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STSMs

sting set-up - DCB quasi-static
tests.
Cohesive fai
Matrix crac
Figure 2: crack pr

- **But also more**

What happened with me during CertBond

- Met a lot of brilliant people
- Collaboratored within 3 STSMs
- Visited amazing places
- Moved from Aarhus to Billund
- Moved within Billund
- Moved to LEGO to become R&D AM Manager
- Moved back to academia
- Brought to my life a lot of friends
- and each time I have some idea I start with them
- ohh yes, got COVID...twice

Meetings: General/Working Group/Management Committee meeting 24-25 May 2022, Patras, Greece

What aspect of CertBond stood out to you as the most important or intriguing?

What aspect of CertBond stood out to you as the most important or intriguing?

Idea

- What is *green* adhesive and *green* bonding?

- Can we start an EU application, DN?
- Is it material for the EU COST?

Share your idea or thought incl. topic and framework (if known)

Nobody has responded yet.

Hang tight! Responses are coming in.

- Green and Circular Economy for Composites
- Sustainability
- Sustainability
- How to create and innovate in an environmentally-friendly way
- Sustainabilty
- Life cycle assessment
- Probabilistic design
- Toughned, recyclable, Green polymer
- Mechanical testing
- Disassembling
- Eco-design
- Natural derived materials

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