THE UNIVERSITY of EDINBURGH
School of Engineering

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

OFR FIRE + RISK CONSULTANTS

UKRI Engineering and Physical Sciences Research Council

Hold the (bond) line

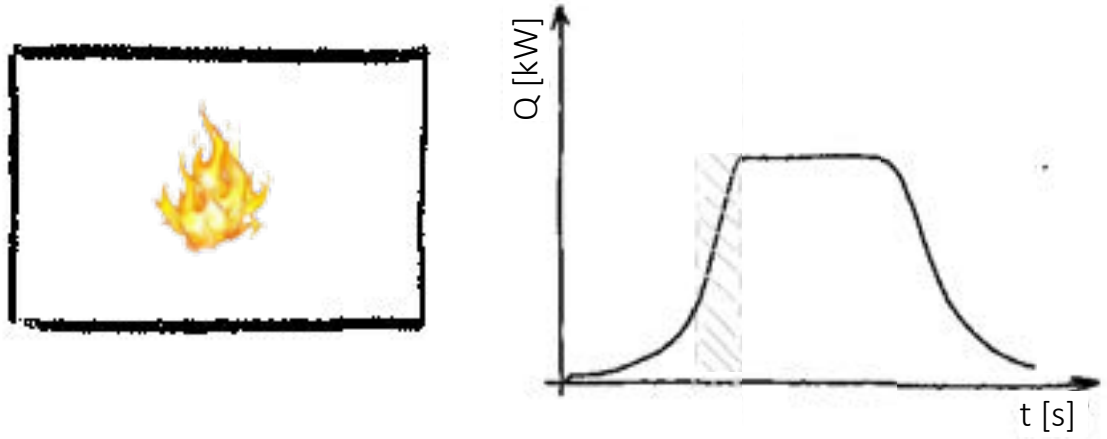
PhD student **Antonela Čolić**
Structural and Fire Safety Engineering

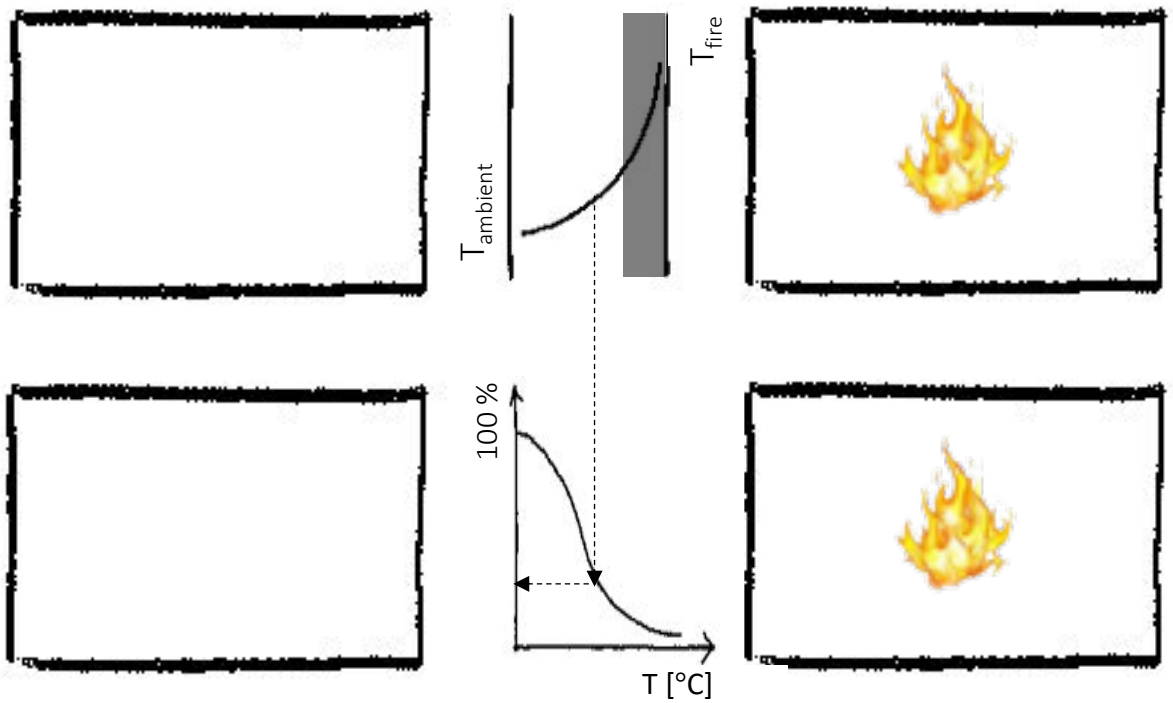
Supervisor(s)
Prof **Luke Bisby**

(Dr **Felix Wiesner** I Dr **Danny Hopkin** I Dr **Michael Spearpoint** I Dr **Angus Law**)

fire safety strategy (?)

crash course





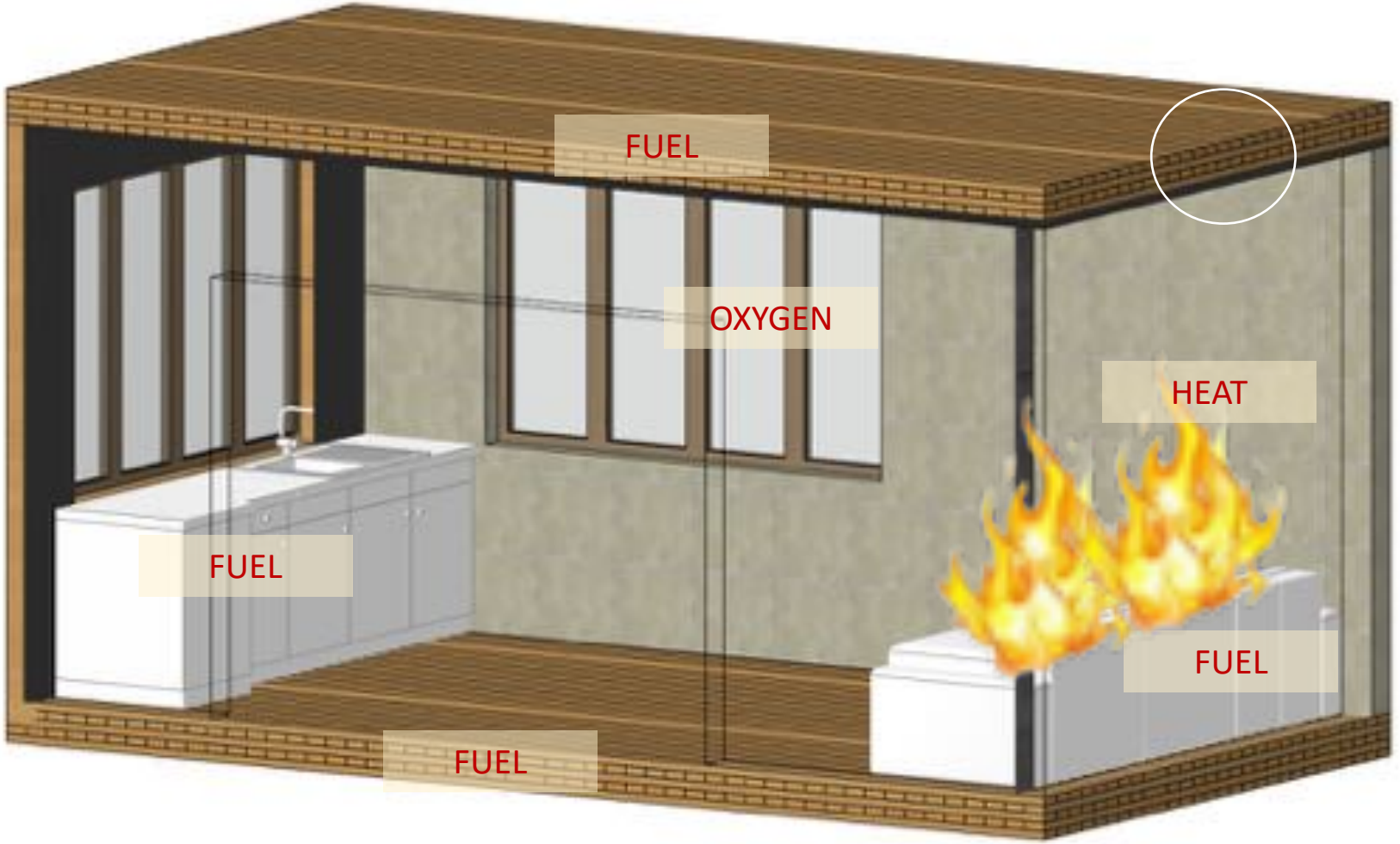
Thermal penetration

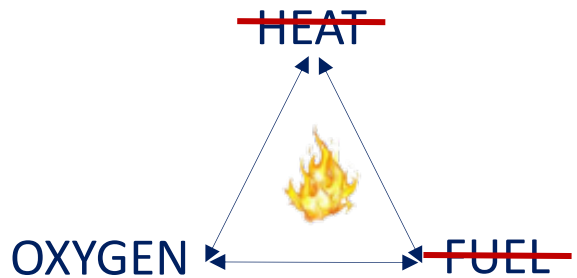
Residual capacity

Both affected by cross section loss

energy balance

$Q_{total} = \cancel{Q_{fuel\ load\ (furniture)}} - Q_{loss(construction)} - Q_{loss(openings)} + \cancel{Q_{fuel\ load(construction)}}$



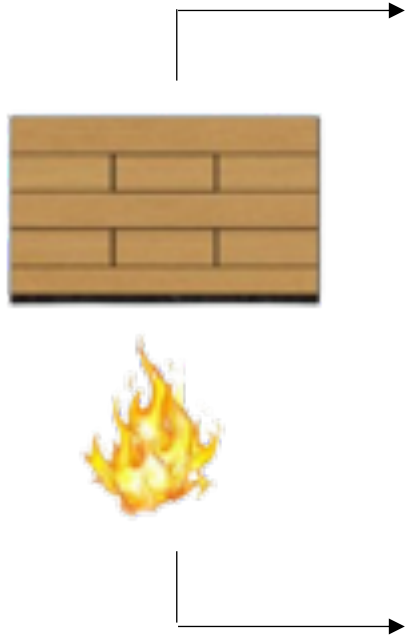


SELF EXTINCTION


GREAT SUCCESS!

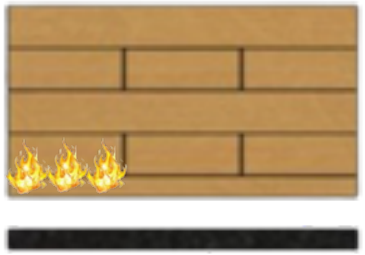
terminology

crash course



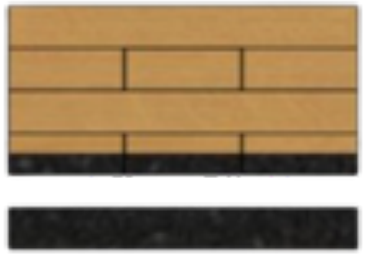
Char fall-off: just char

Before the adhesive line

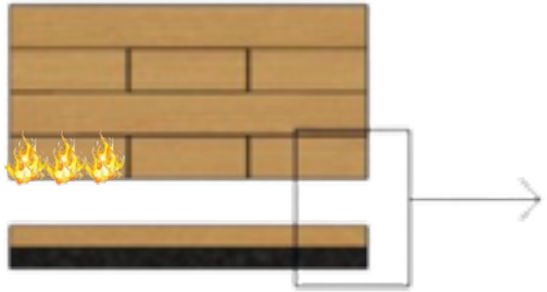


At the adhesive line

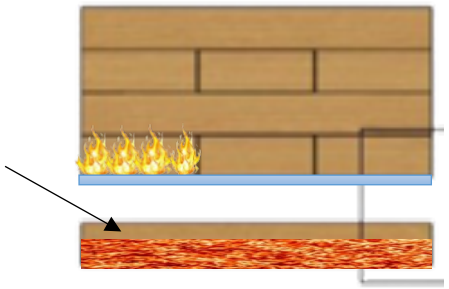
After the adhesive line



Fire induced delamination: partially charred lamella



Fire induced delamination



Char fall-off
At the adhesive line

Fire dynamics

Structural capacity

Bond line temperatures

- 70-220°C [1,2,3]

Bond line temperatures

- 200-300°C [4,5,6]

[1] R. Emberley, A. Nicolaidis, D. Fernando, J.L. Torero, "Changing Failure Modes of Cross-Laminated Timber" . In: *9th Int. Conf. Struct. Fire*. (2016) , pp.643–649.

[2] M. Klippel, A. Frangi, M. Fontana, "Influence of the adhesive on the load carrying capacity of GLT Members in fire" . In: *Fire Saf. Sci.* (2011). https://doi.org/10.3801/IAFSS.FSS.10-1219.

[3] C. Dagenais, L. Ranger, Revisiting heat delamination characteristics of adhesives in cross-laminated timber, in: WCTE 2018 - World Conf. Timber Eng., 2018.

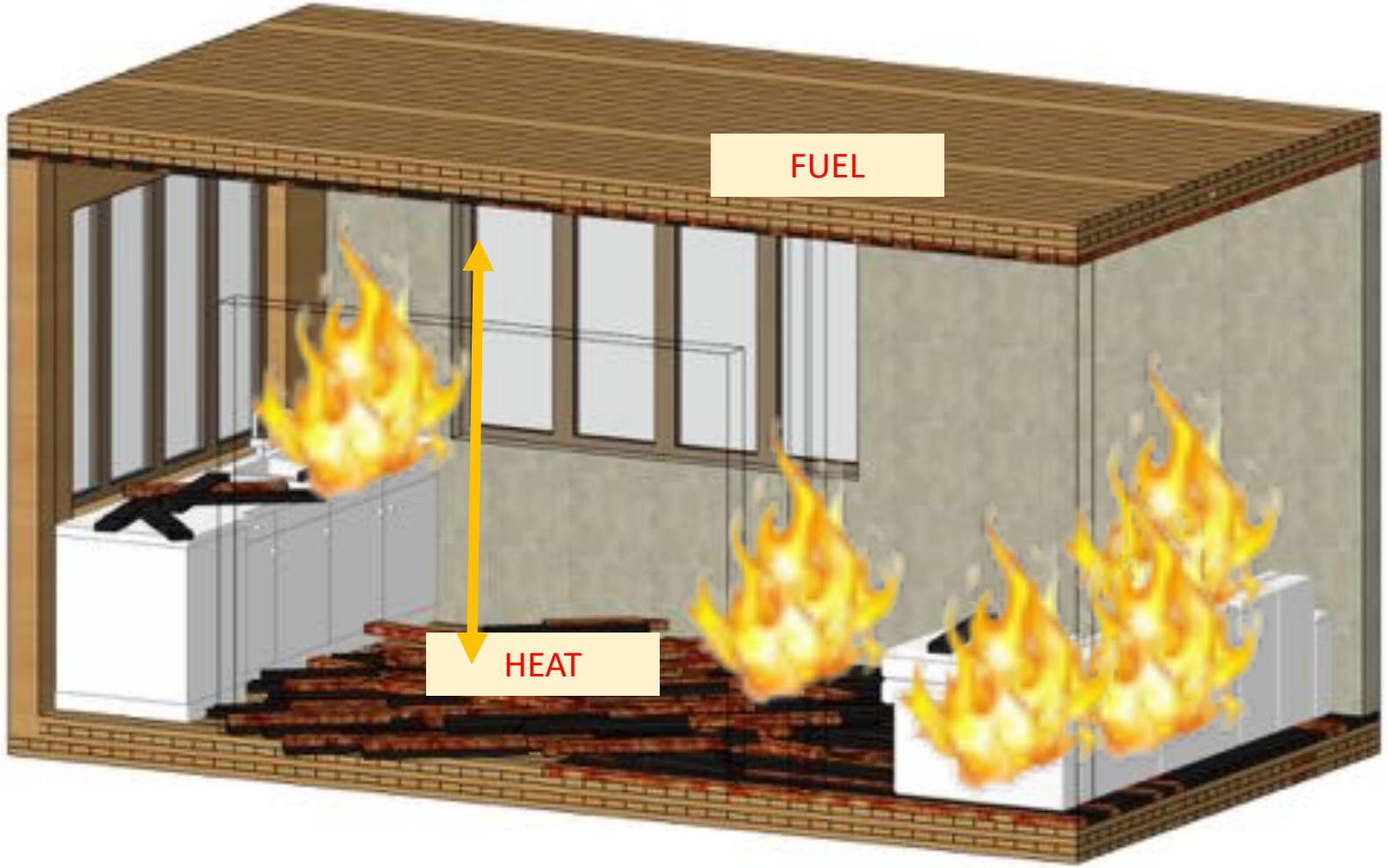
[4] S. Clauß, M. Joscak, P. Niemz, "Thermal stability of glued wood joints measured by shear tests" . In: *Eur. J. Wood Wood Prod.* 69 (2011) , pp.101–111. https://doi.org/10.1007/s00107-010-0411-4

[5] L. Schmidt, Experimental study on the effect of char fall off on the heat transfer within loaded CLT columns exposed to radiant heating, The University of Edinburgh: College of Science and Engineering, 2020.

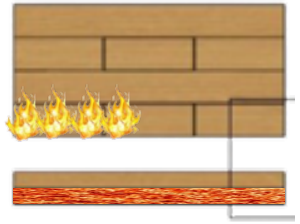
[6] A.I. Bartlett, R.M. Hadden, L.A. Bisby, "A Review of Factors Affecting the Burning Behaviour of Wood for Application to Tall Timber Construction" . In: *Fire Technol.* 55 (2019) , pp.1–49. https://doi.org/10.1007/s10694-018-0787-y.

back to energy balance

$Q_{total} = Q_{fuel\ load\ (furniture)} - Q_{loss\_construction} - Q_{loss\_openings} + Q_{construction} + Q_{reradiation\_floor}$

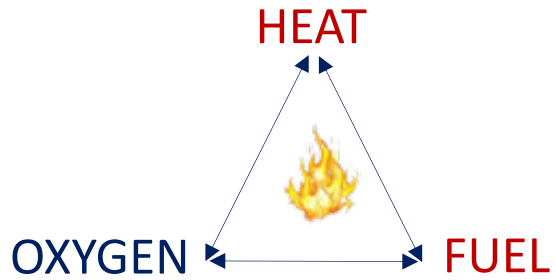


Char fall off
at the bond line



Delamination

CROSS- SECTION REDUCTION

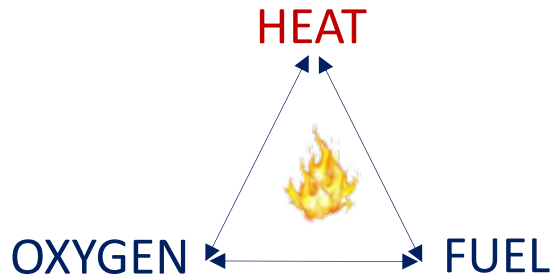


$$Q_{total} = Q_{fuel\ load\ (furniture)} - Q_{loss\_construction} - Q_{loss\_openings} + Q_{construction} + Q_{reradiation\_floor} + Q_{reradiation\_wall}$$

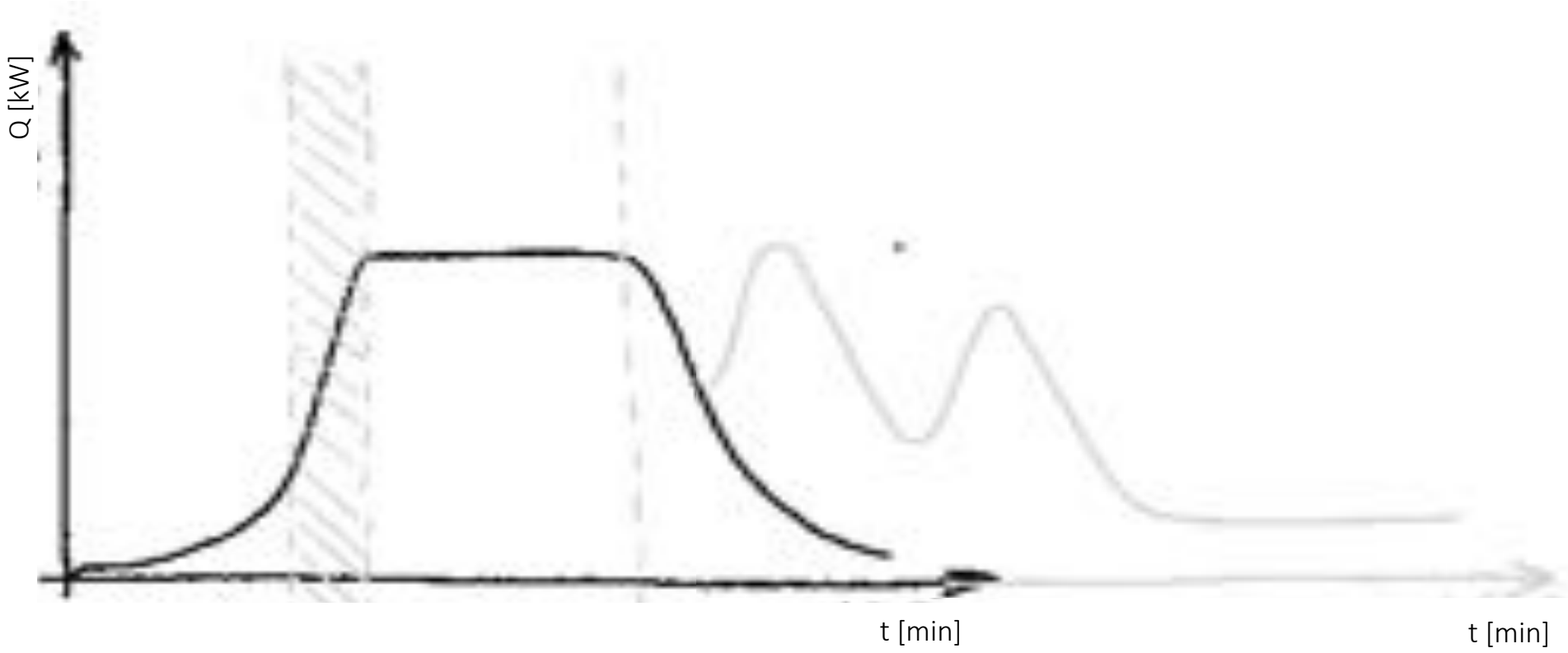
Char fall off
at the bond line

Delamination

RE-RADIATION



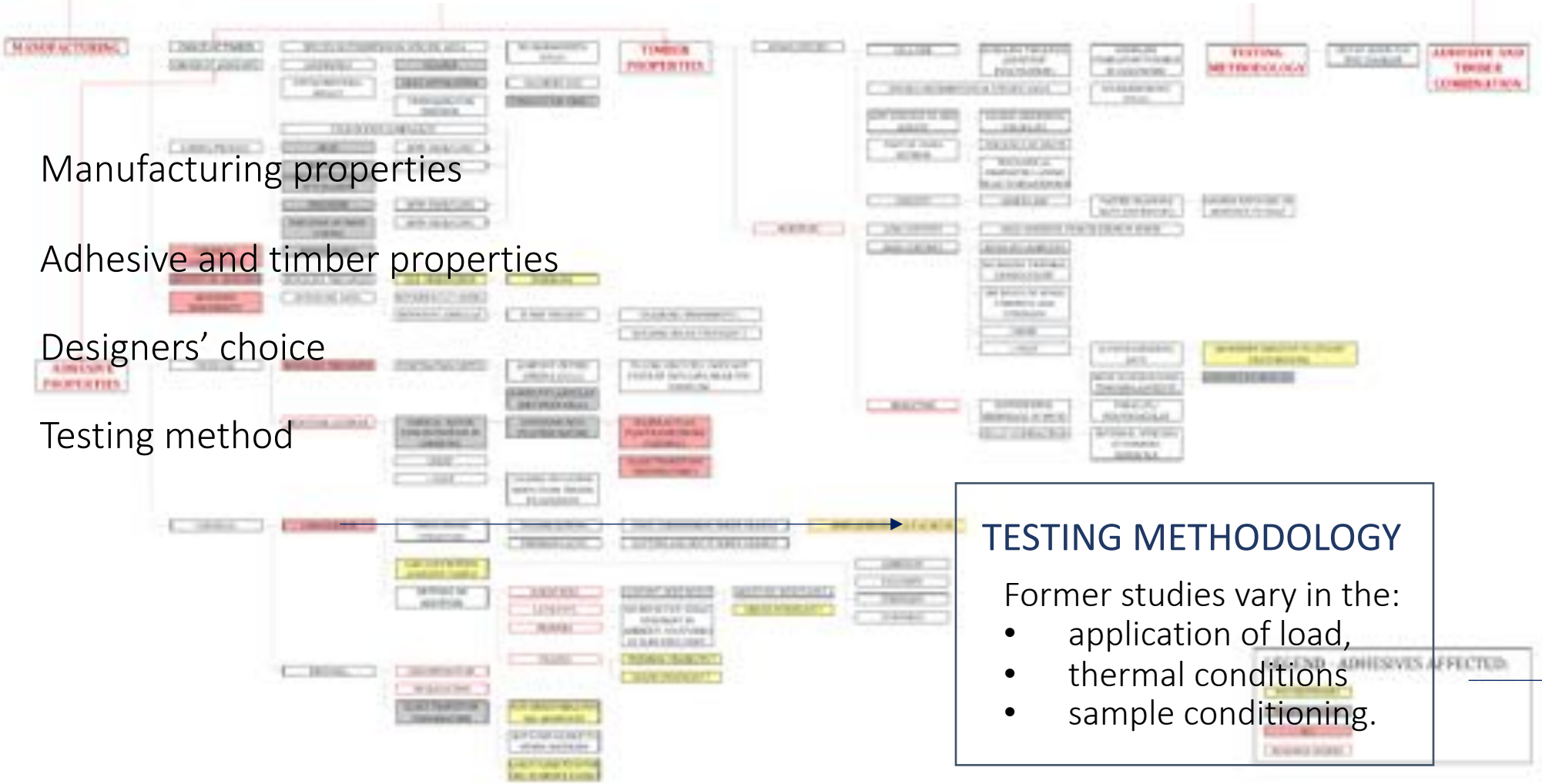
POTENTIAL STRUCTURAL COLLAPSE



$Q_{TOTAL} = Q_{fuel\ load\ (furniture)} + Q_{construction} + Q_{reradiation\_floor} + Q_{reradiation\_wall} - Q_{loss\_construction} - Q_{loss\_openings}$

Understanding fire induced delamination

WHAT AFFECTS DELAMINATION



Manufacturing properties

Adhesive and timber properties

Designers' choice

Testing method

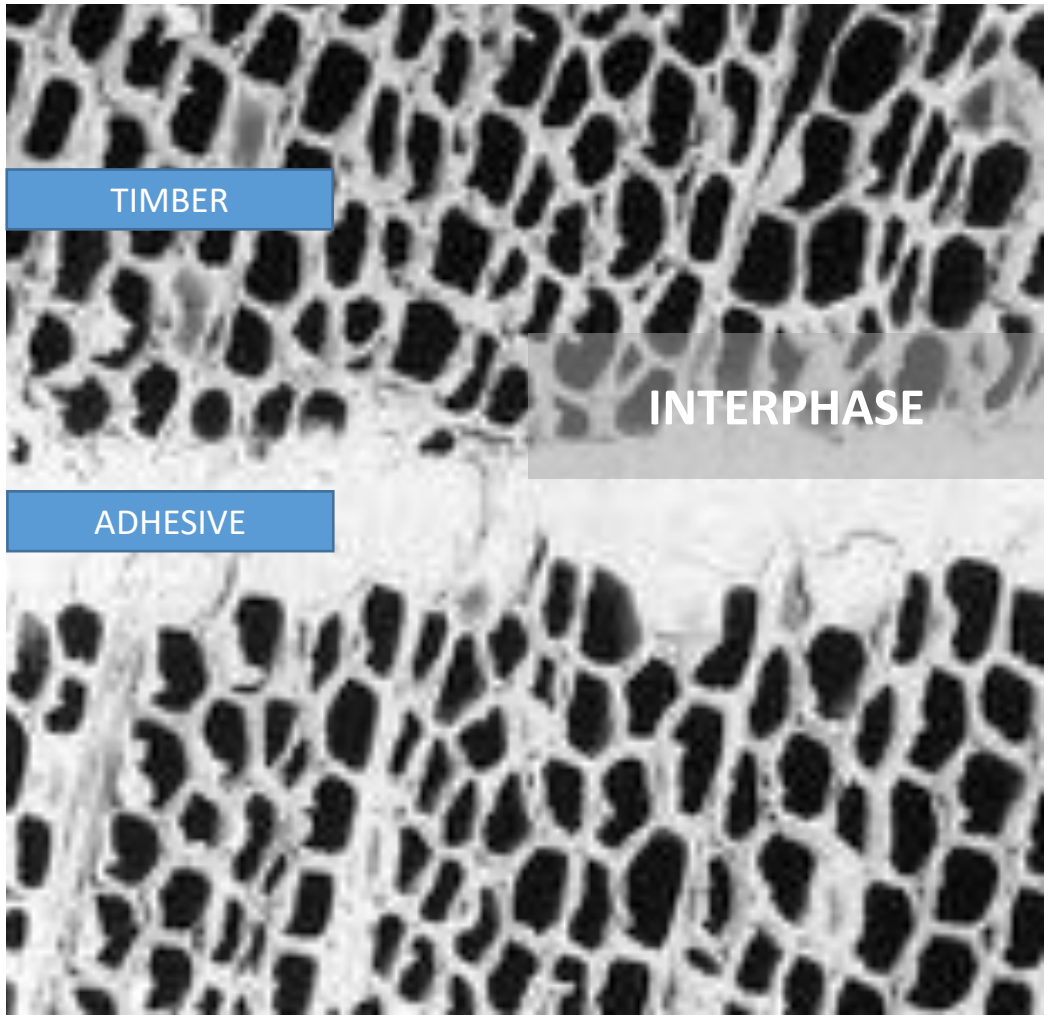
TESTING METHODOLOGY

Former studies vary in the:

- application of load,
- thermal conditions
- sample conditioning.

→ METHODOLOGY DRIVERS

WHAT IS BOND LINE?

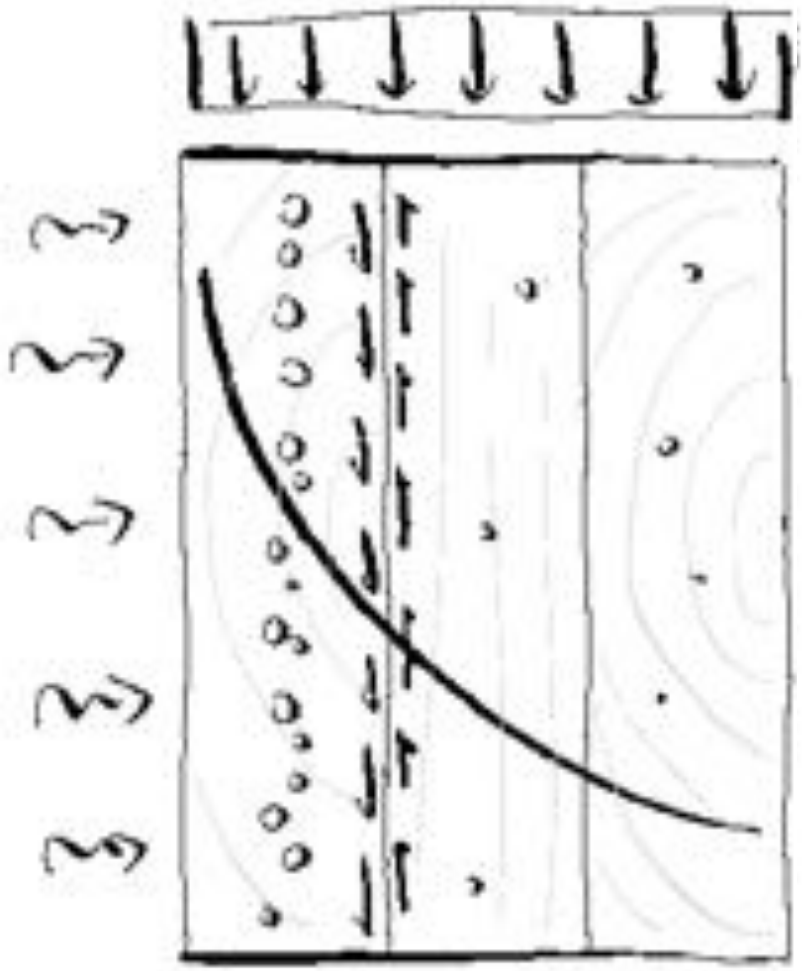


WHAT IS ATTACKING THE BOND LINE?

THERMAL

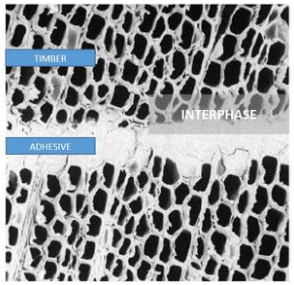
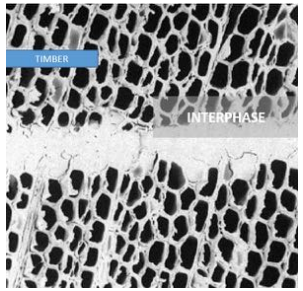
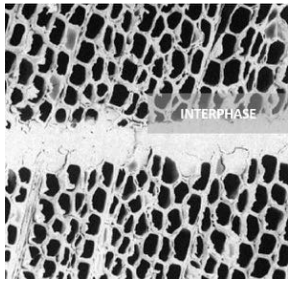
HYDRO

MECHANICAL

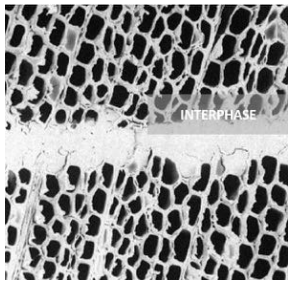


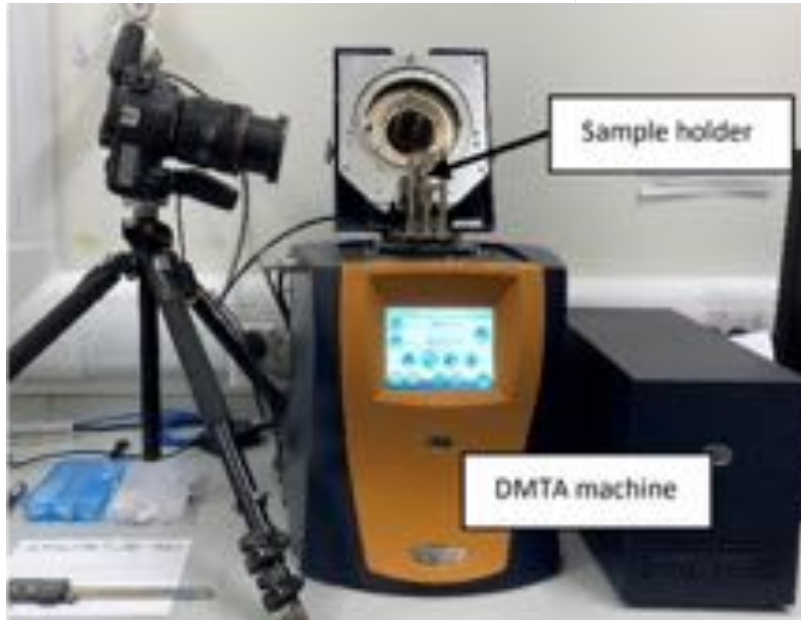
Optimistic project plan

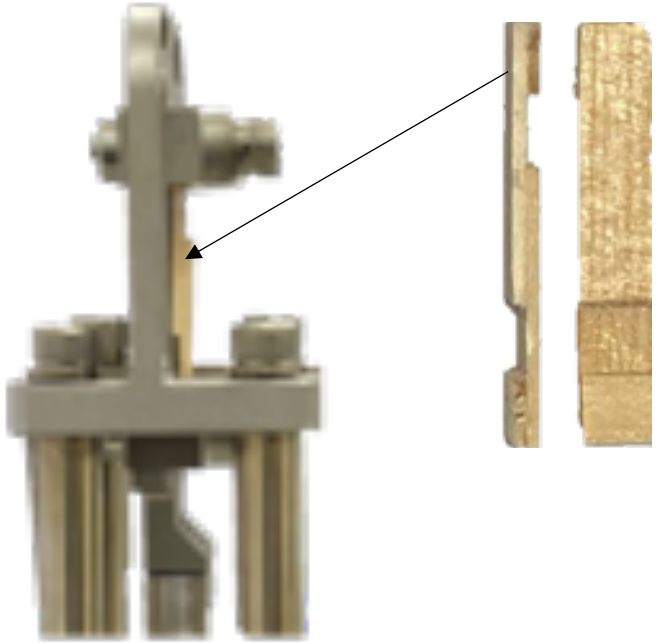
EXPERIMENTAL CAMPAIGN

SCALE	WHAT?	WHY?	HOW?
PHASE 1: MICRO?		Thermal behaviour Thermo-mechanical behaviour	TGA DSC DTMA
PHASE 2: BENCH		Hydro-thermal behaviour	NEUTRON RADIOGRAPHY
PHASE 3: INTERMEDIATE		Hydro-thermo-mechanical behaviour	HEAT FLUX SHEAR

EXPERIMENTAL CAMPAIGN

SCALE	WHAT?		WHY?	HOW?
PHASE 1: MICRO		Interphase: Shear lap	Thermal behaviour Thermo-mechanical behaviour	TGA DSC DTMA



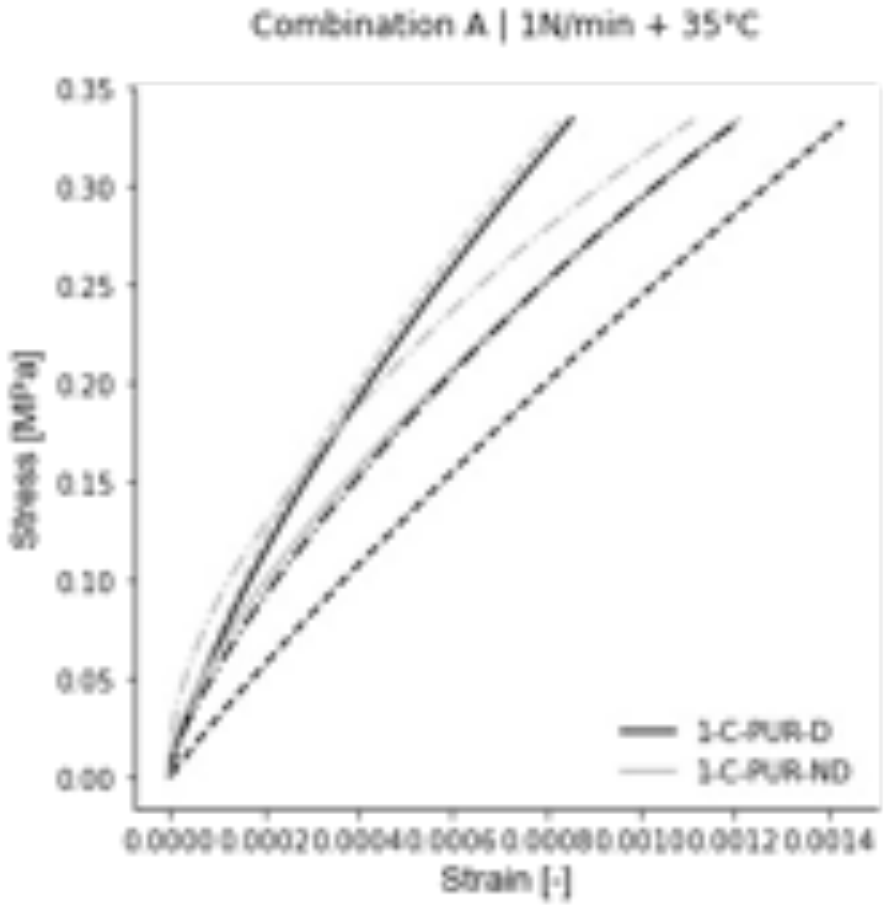


1-C-PUR D

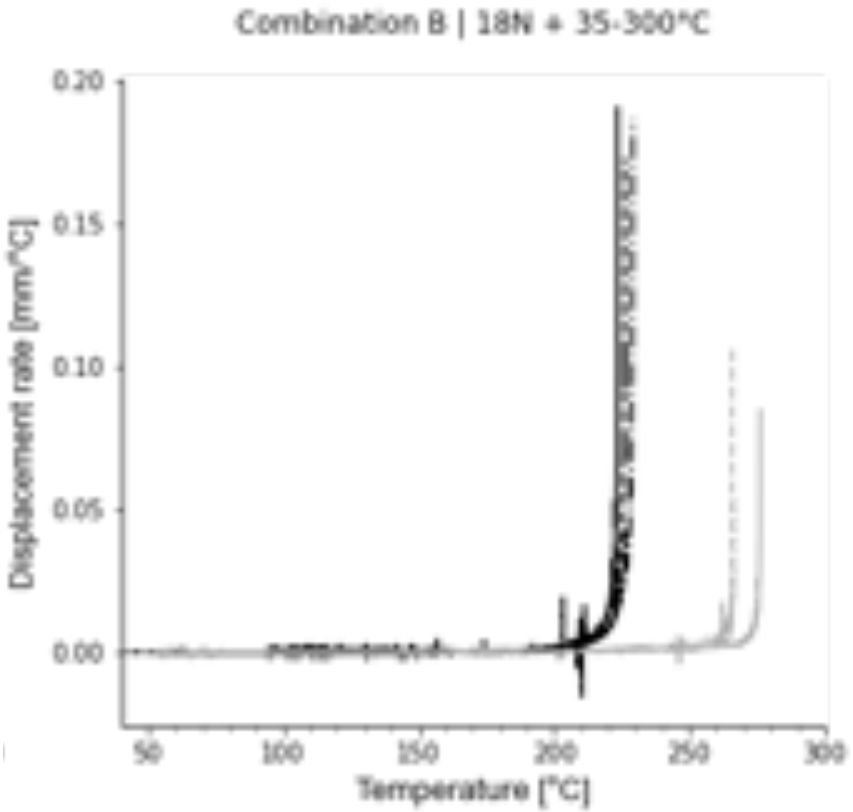
1-C-PUR ND

Why	Stress-strain ambient cond.	Stress-strain thermal cond.	Modulus Glass transition
	Is there a difference?		
	Is there a critical temperature?		
	Is glass transition a thing?		

Combination	A	B	C
Structural load			
	1N/min, 1N-F_{max}	F_{max}	± 5µm, 1Hz
Thermal load			
	35°C	35 - 300°C	

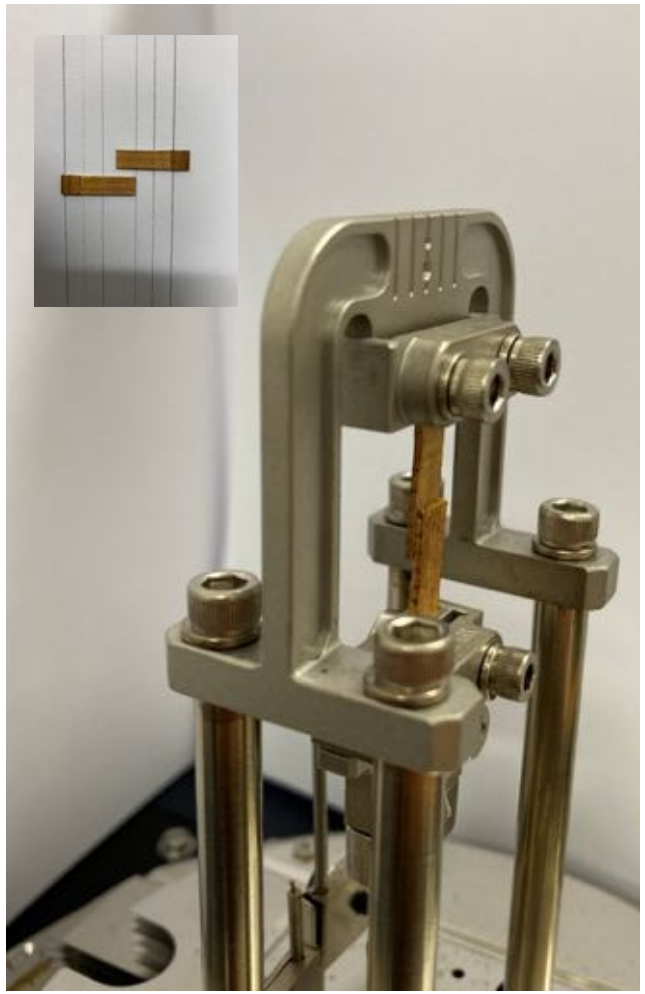


Is there a difference? I don't think so.

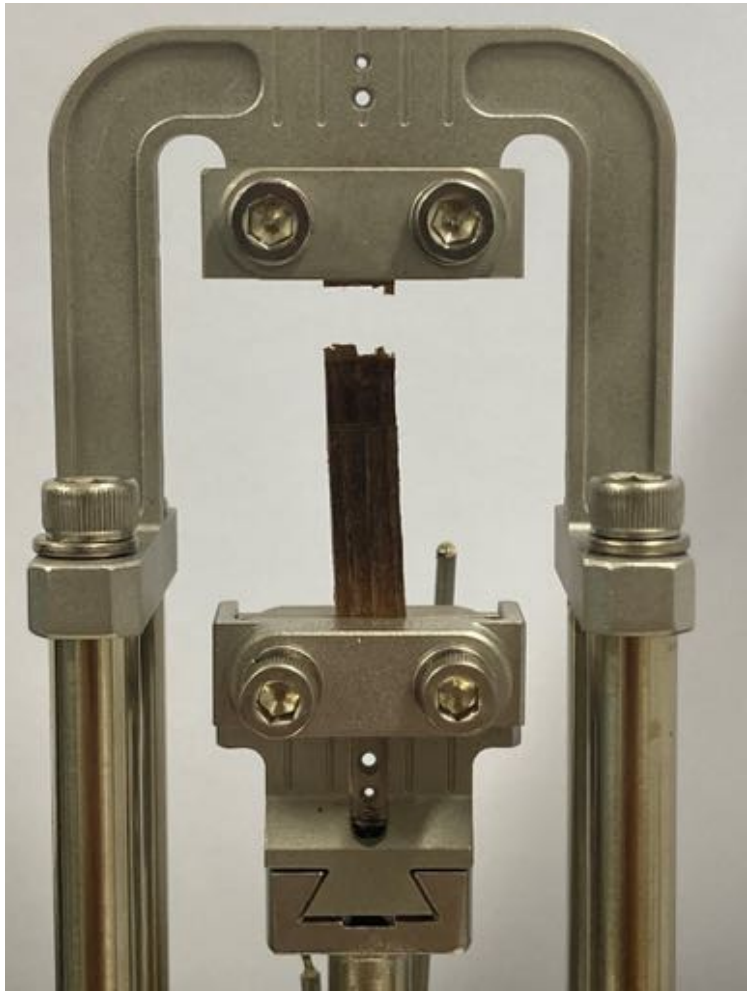


Is there a difference? Yes.

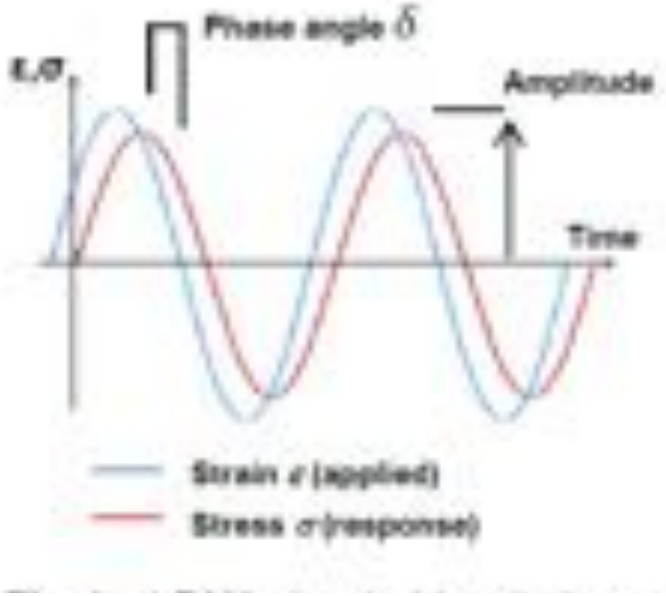
Is there a critical temperature? 220-230°C.

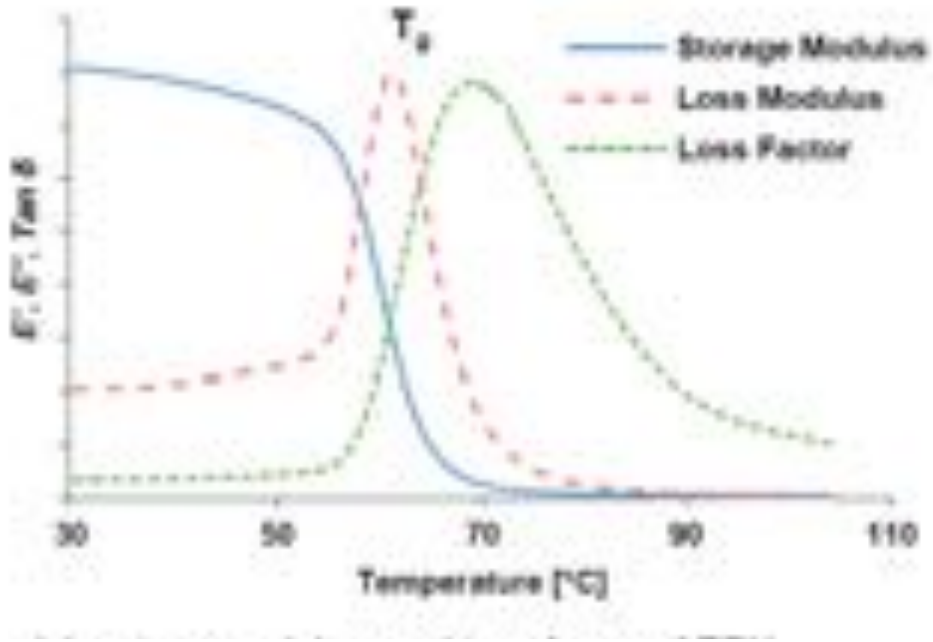


1-C-PUR-D



1-C-PUR-ND





$$\varepsilon = \varepsilon_0 \sin(t\omega)$$

$$\sigma = \sigma_0 \sin(t\omega + \delta)$$

$$E^* = \sigma_0/\varepsilon_0 \cdot \exp(i\delta)$$

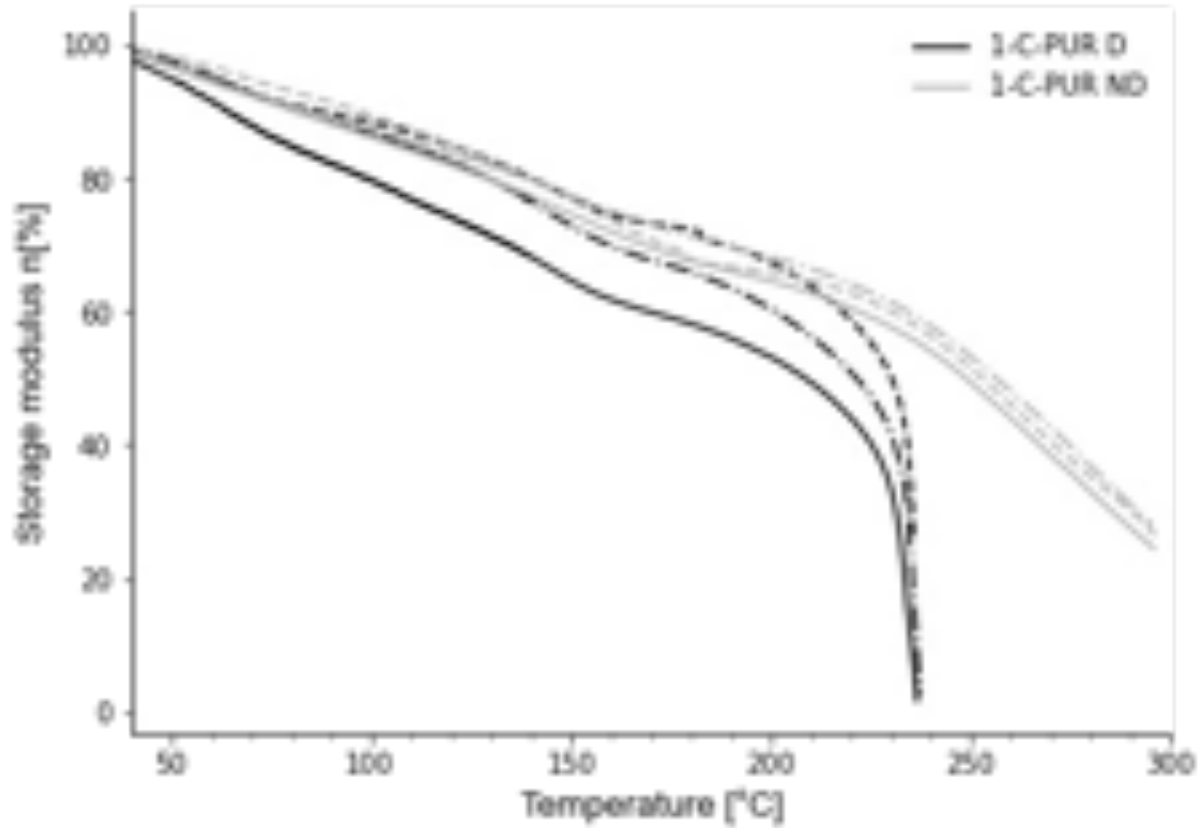
$$E^* = E' + i\,E''$$

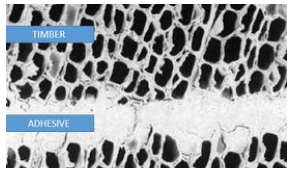
$$Tan\ \delta = E''/E'$$

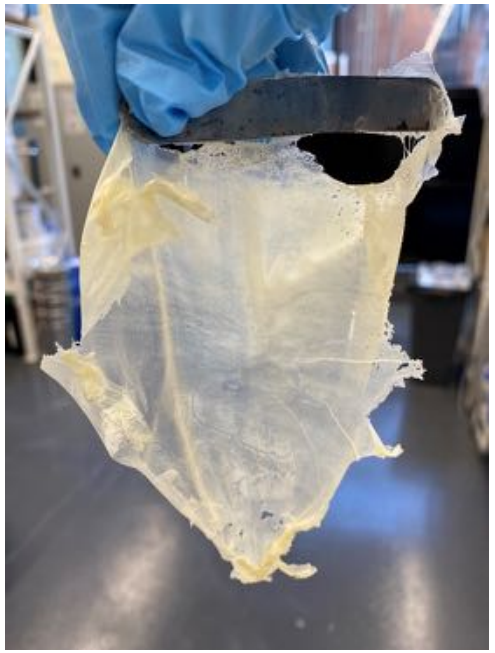
Storage – elastic
Loss - viscous
Tan delta – viscoelasticity

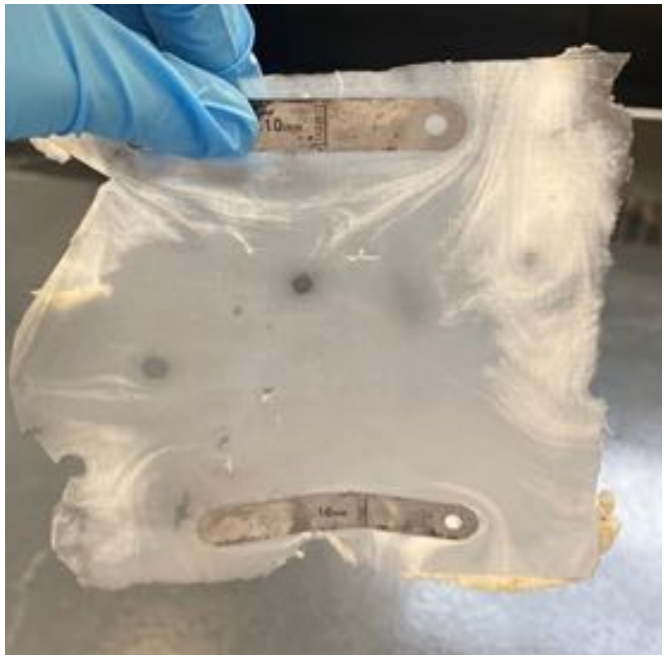
BUT! Tg not always easy to spot for polyurethanes

Verdet et al. 2016 Mechanical performance of polyurethane and epoxy adhesives in connections with glued-in rods at elevated temperatures


1-C-PUR D
1-C-PUR ND
Storage modulus η[%]
Temperature [°C]
100
80
60
40
20
0
50
100
150
200
250
300

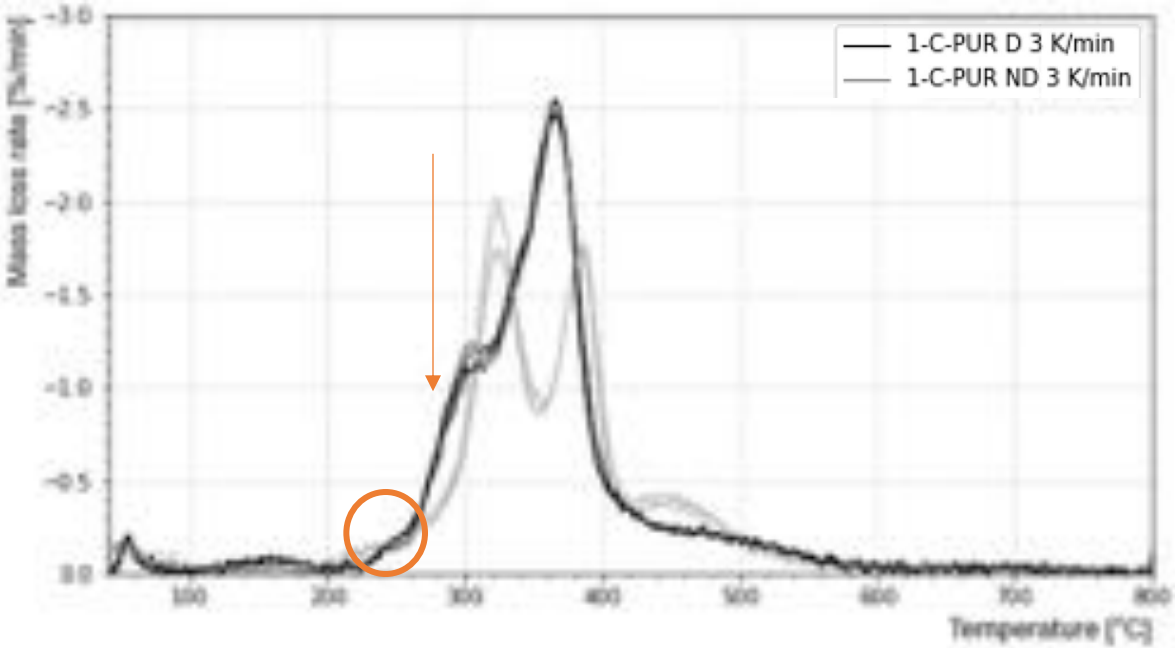
SCALE	WHAT?	WHY?	HOW?
PHASE 1: MICRO²		Thermal behaviour	**TGA** **DSC**

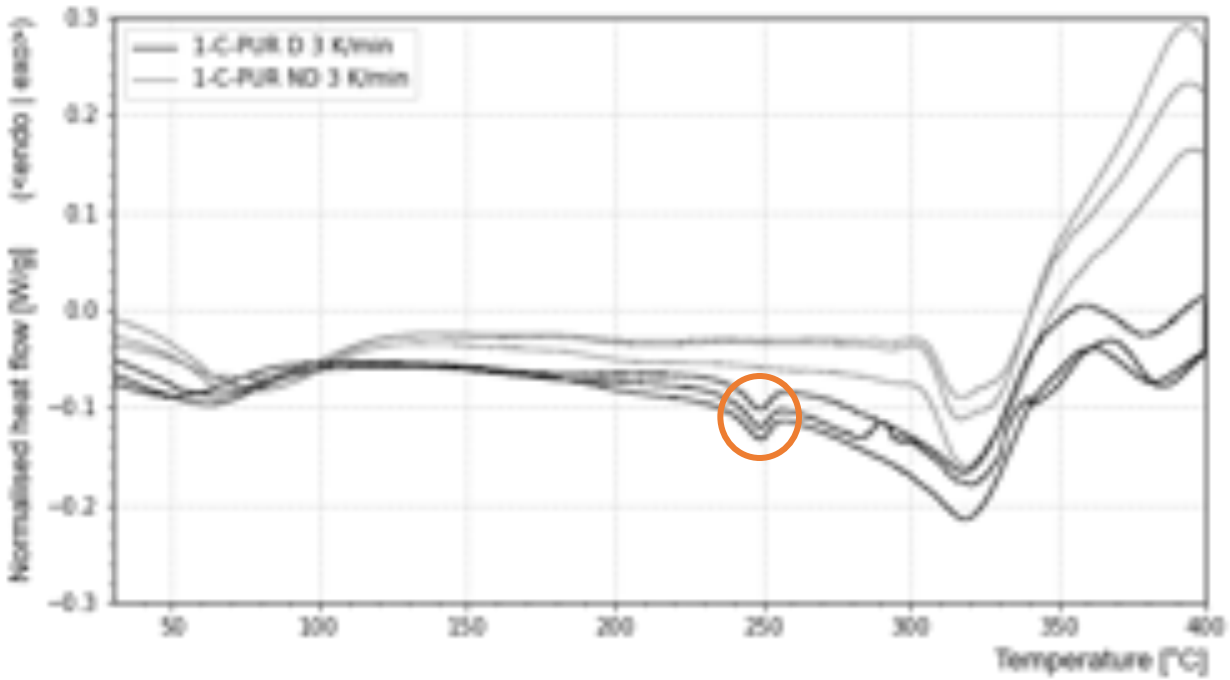




1-C-PUR D

1-C-PUR ND

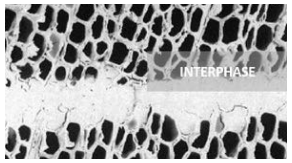

1-C-PUR D 3 K/min
1-C-PUR ND 3 K/min
Mass loss rate [%/min]
Temperature [°C]

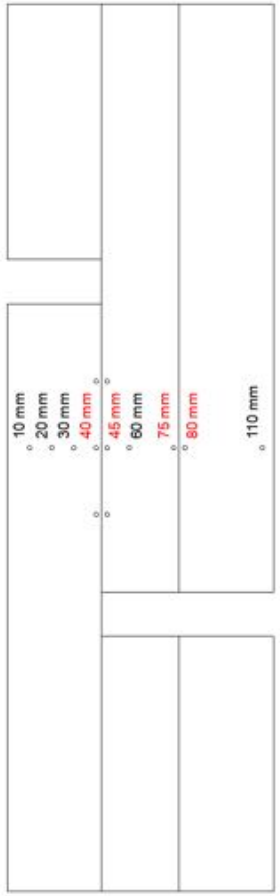

1-C-PUR D 3 K/min
1-C-PUR ND 3 K/min
Normalised heat flow [W/g]
Temperature [°C]

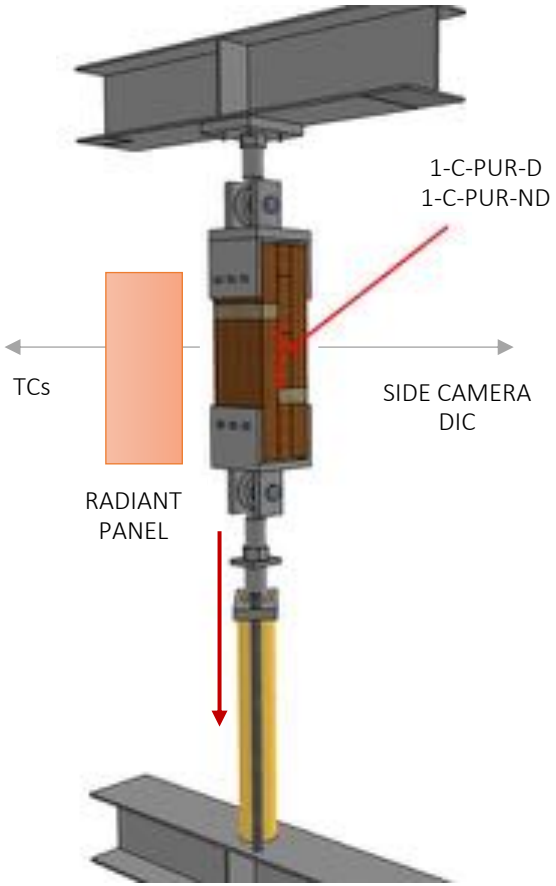
Thermo-mechanical - 1-C-PUR D interphase fails at 220°C
Thermal – 1-C-PUR D adhesive softens at 250°C

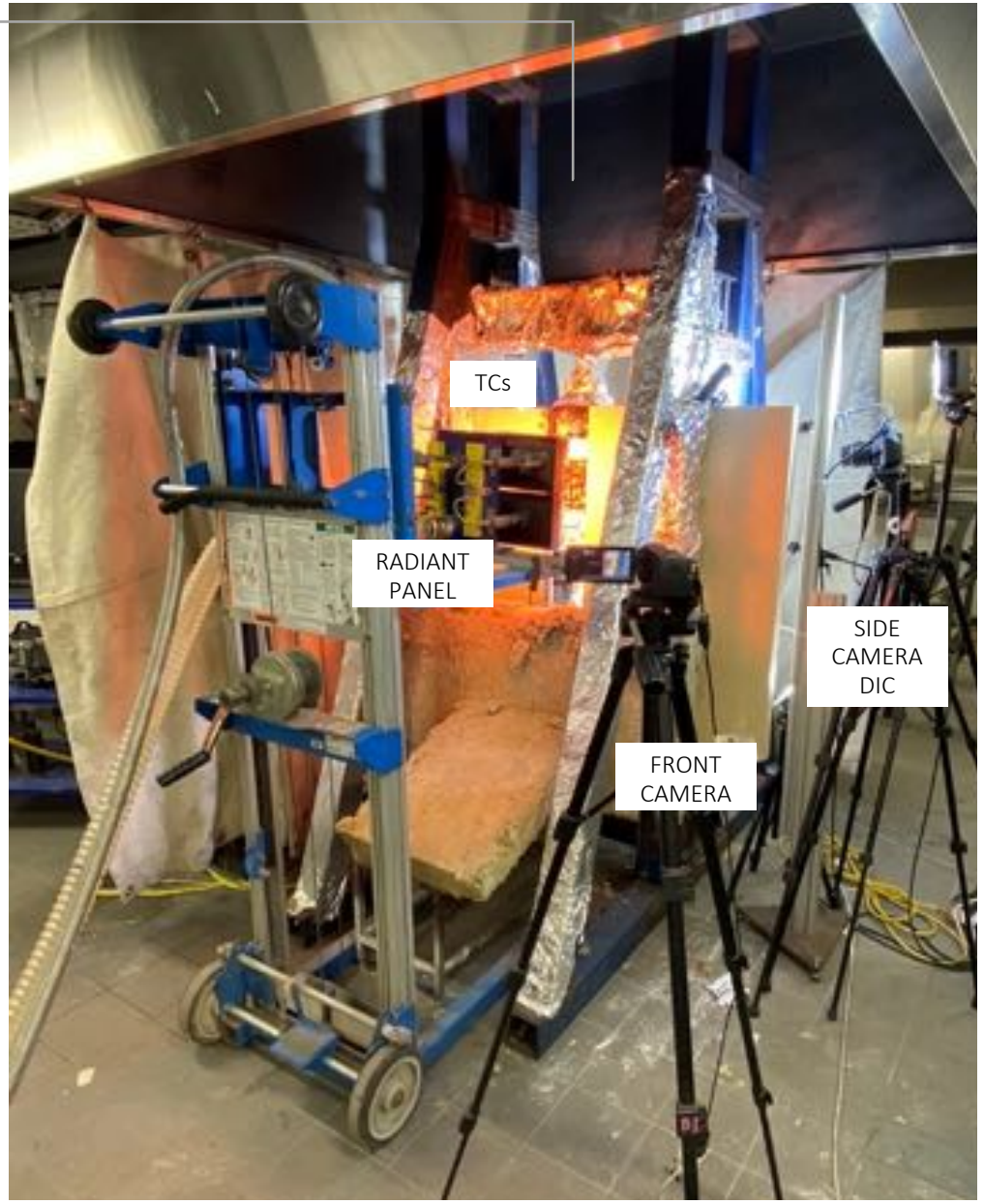
Chemistry matters

Can we upscale?

SCALE	WHAT?	WHY?	HOW?
PHASE 3: INTERMEDIATE		Hydro-thermo-mechanical behaviour	**HEAT FLUX SHEAR**



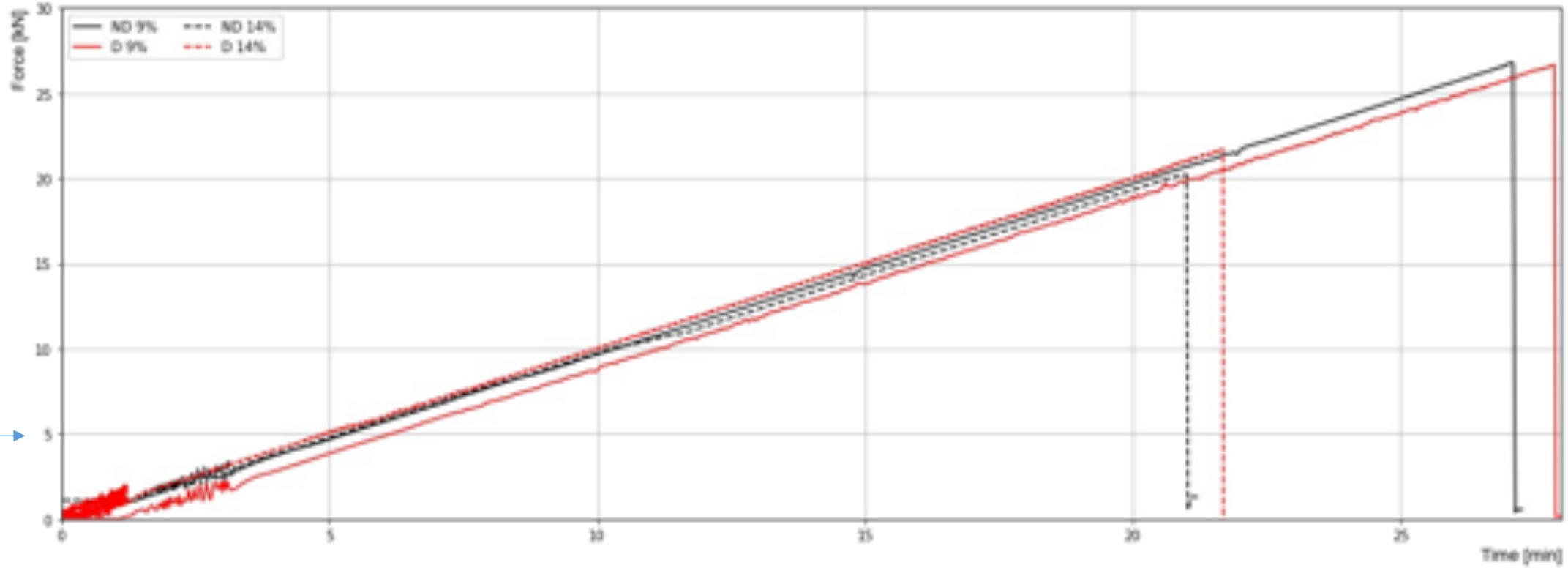




21C	25 kW/m^2	50 kW/m^2
MC 9%	D (5) | ND (3)	D (5) | ND (5)
MC 14%	D(5)	D (5) | ND (3)


25

Ambient results



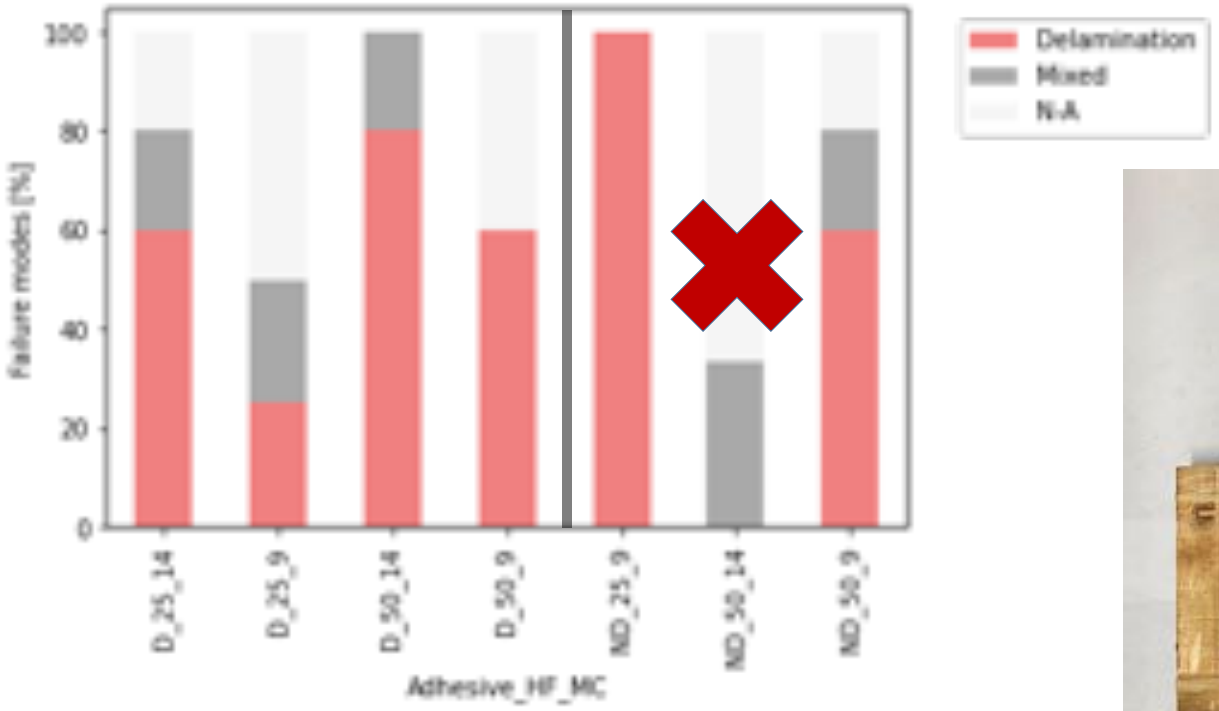
20%
SHEAR STRESS

Fire results

21C, 5kN	25 kW/m^2	50 kW/m^2
MC 9%	D (5) | ND (3)	D (5) | ND (5)
MC 14%	D(5)	D (5) | ND (3)

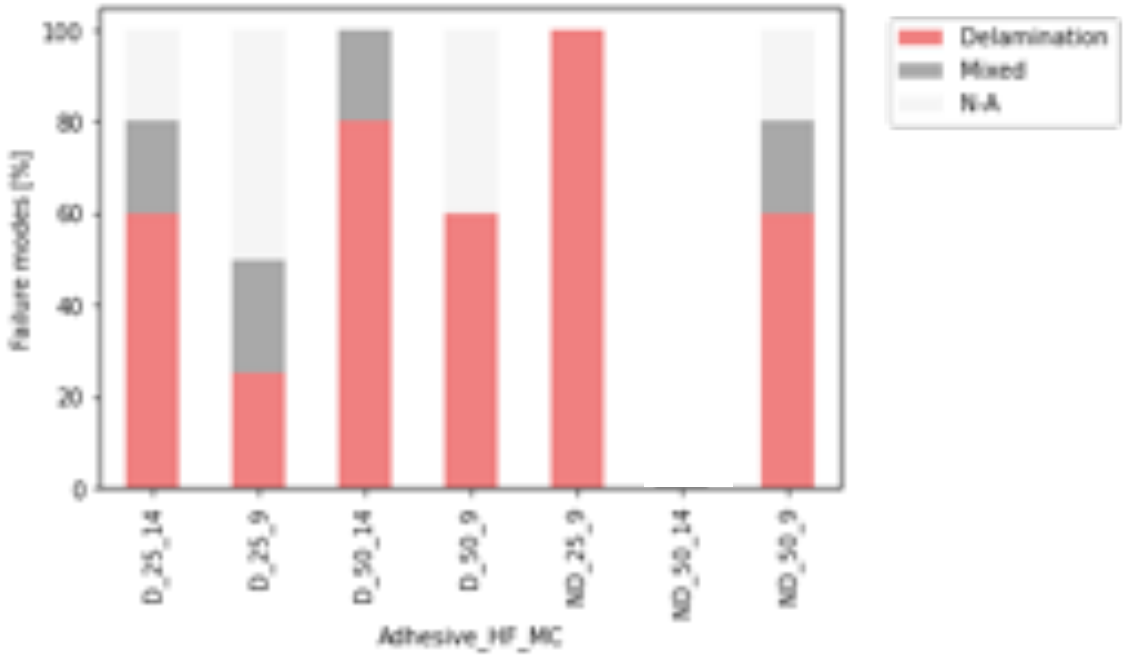
Why	Does MC matter? Heat flux constant, load constant
	Does the heat flux make a difference? MC constant, load constant
	Does it differ for the two adhesives?
	Failure mode? Failure time? Critical temperature? Displacement rate?

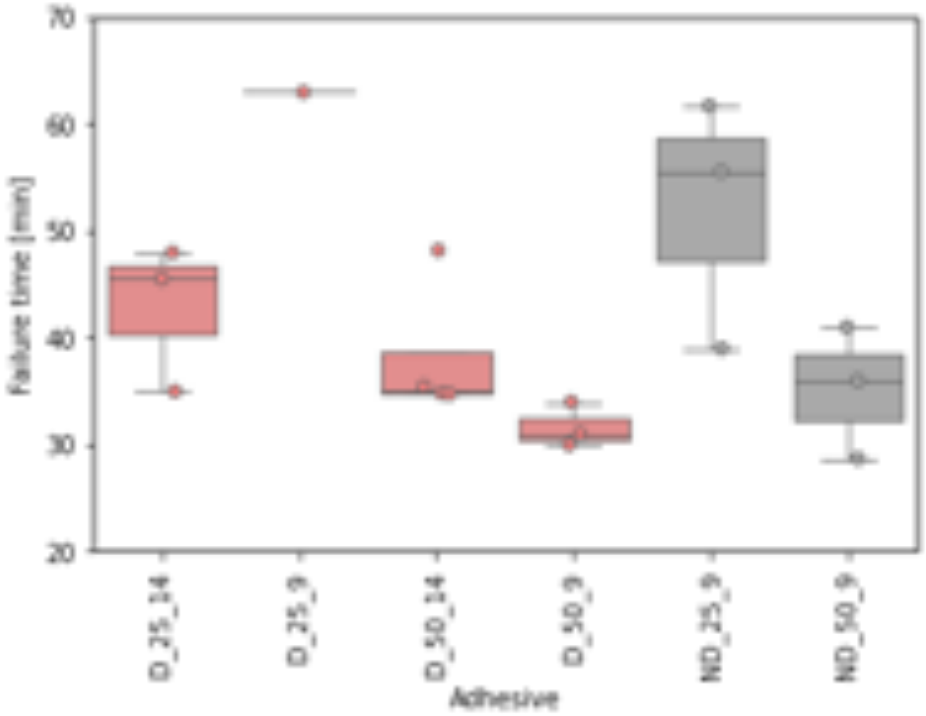
Failure mode



Delamination present for both adhesives
Higher moisture content not discussed for ND

Failure time delamination





Wider spread in non delaminating results

Failure time is not proportionally higher for the lower heat flux

Non-delaminating adhesive can delaminate

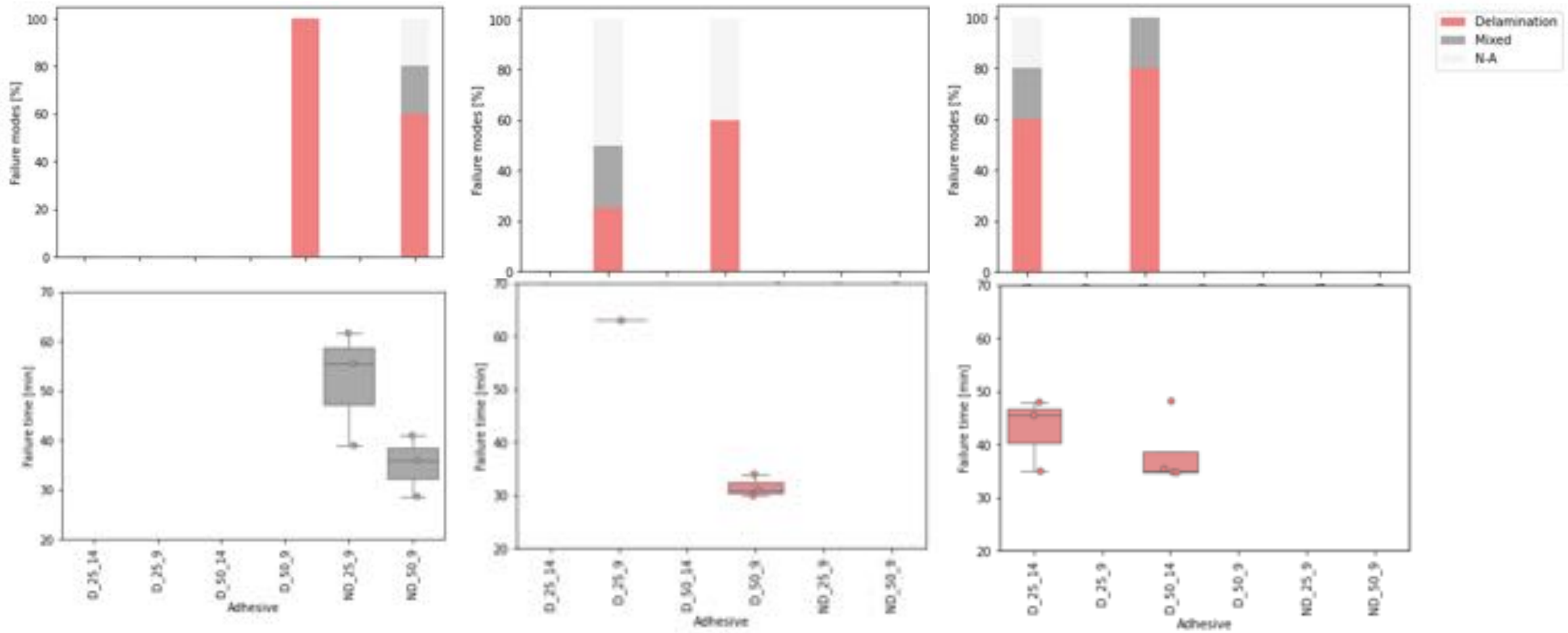
It is “just” the matter of force

Failure mode and time – Variable: Heat flux

1-C-PUR ND | MC 9%

1-C-PUR D | MC 9%

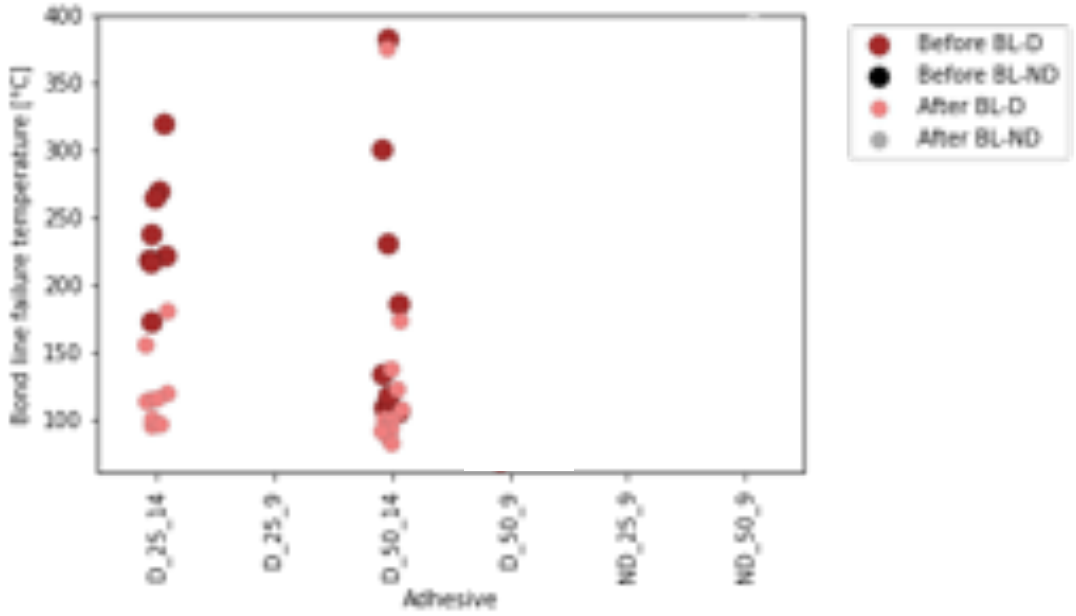
1-C-PUR D | MC 14%

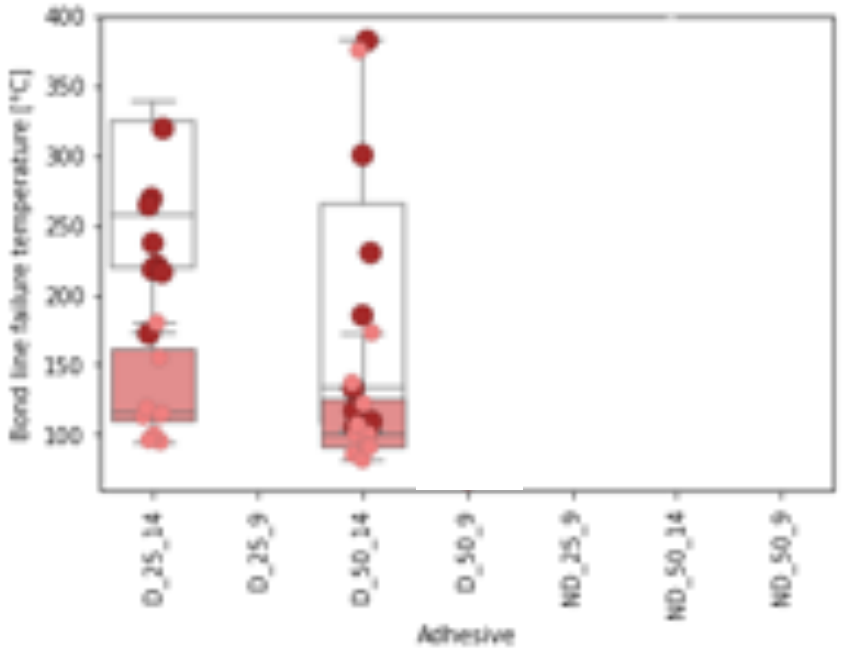


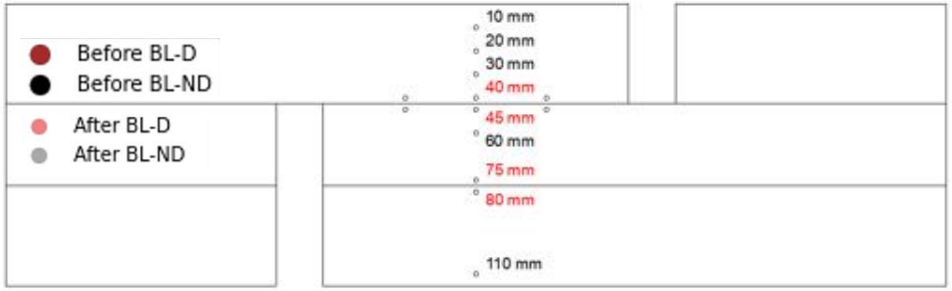
Failure time is not strongly/repetatively dependent on the heat flux

Higher moisture content seems to bring the results for the two heat fluxes together

Bond line temperature delamination

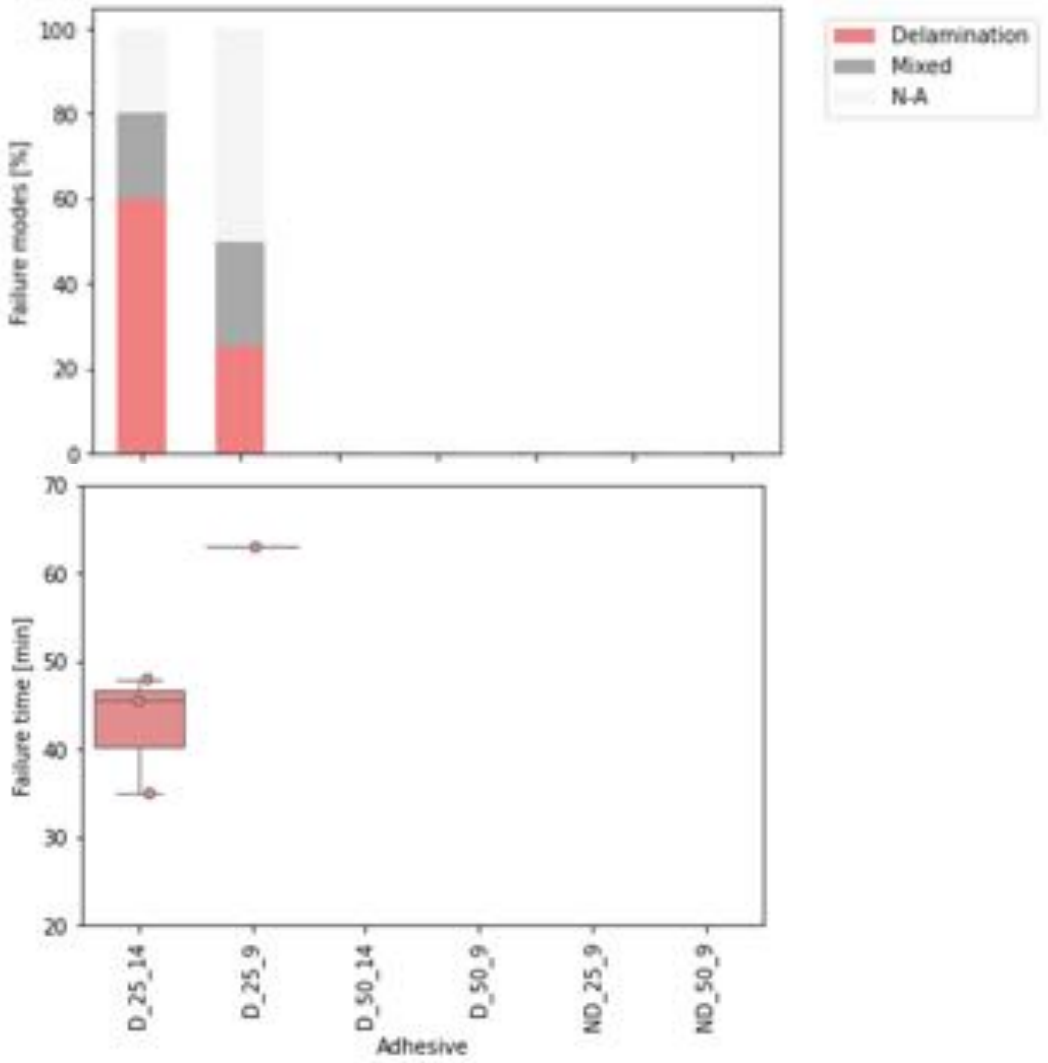




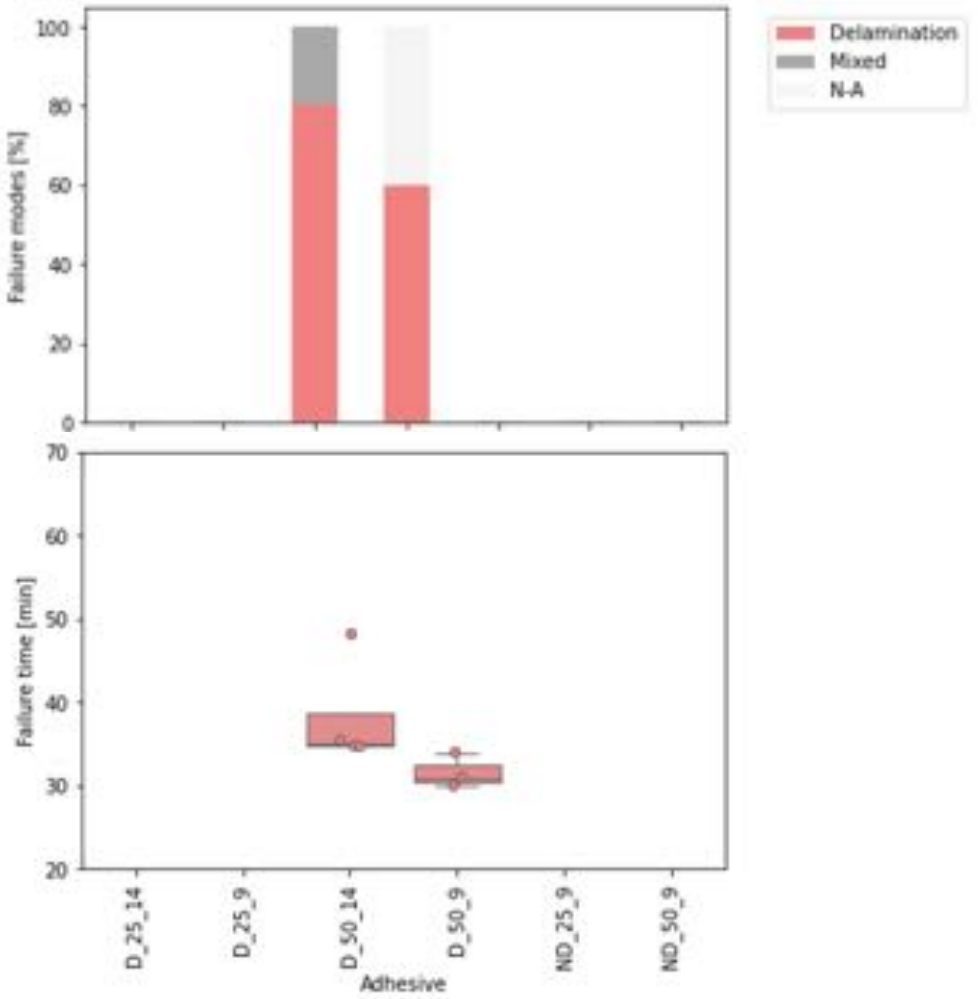


Failure mode and time – Variable: moisture content

1-C-PUR D | HF 25 kW/m^2



1-C-PUR D | HF 50 kW/m^2



Higher moisture content does not lead to earlier failure time

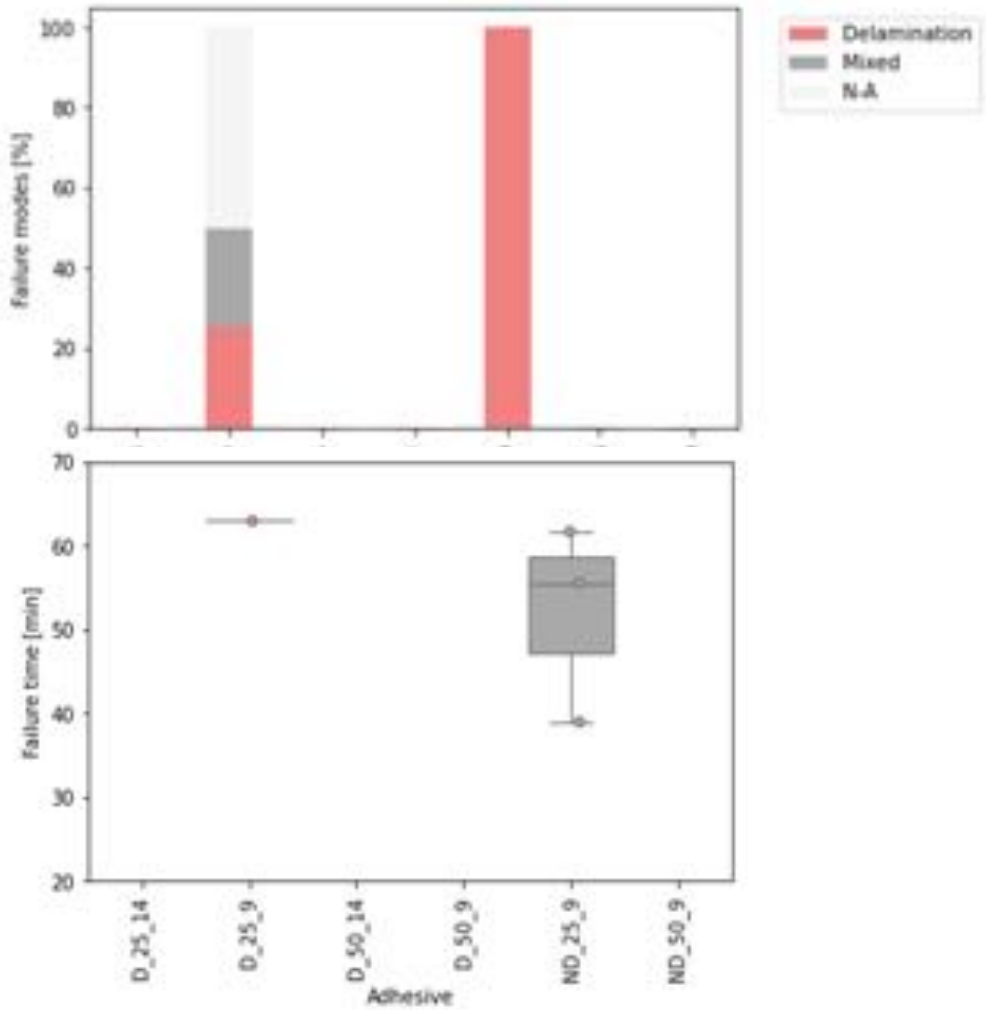

What's that got to do with the price of eggs?
ORGANIC
ORGANIC
7.99
6.99
DIF suppliers have increased
their prices on eggs, which
is causing higher prices
for our customers.

There is some interaction with adhesive and moisture

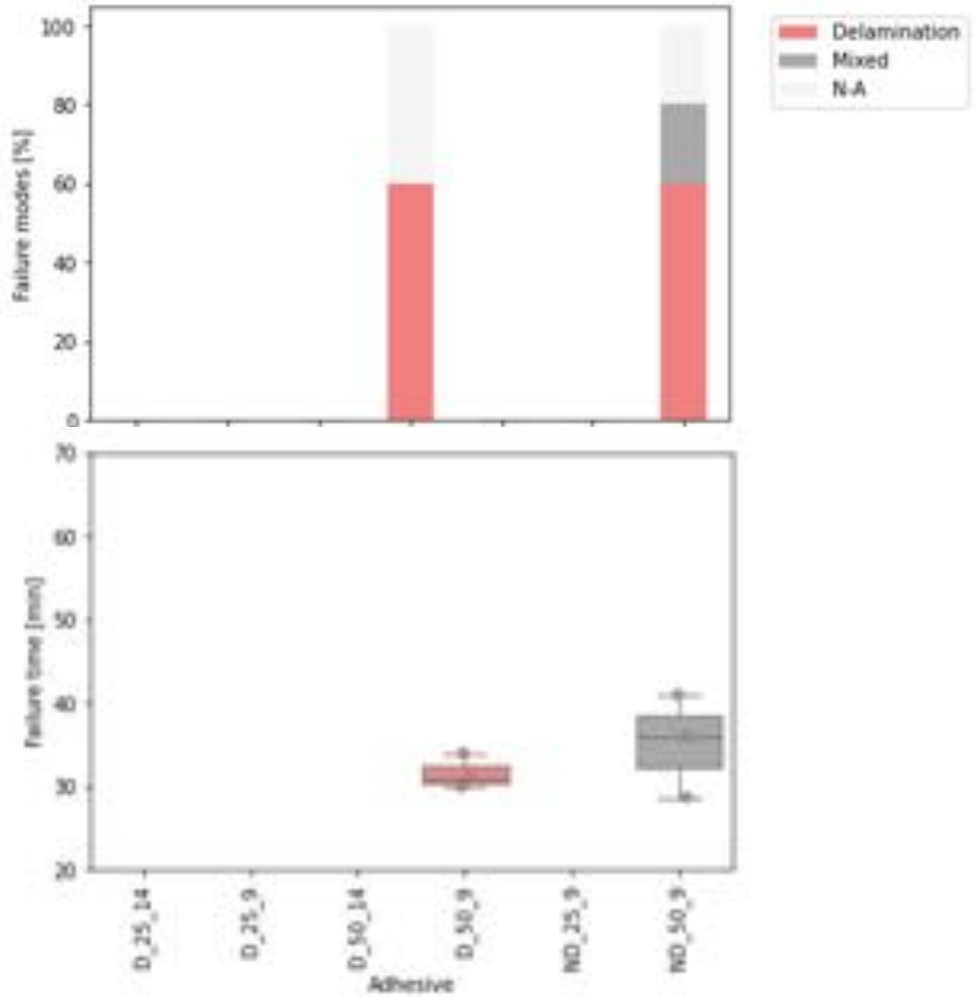
I just do not understand it yet

Failure mode and time – Variable: adhesive

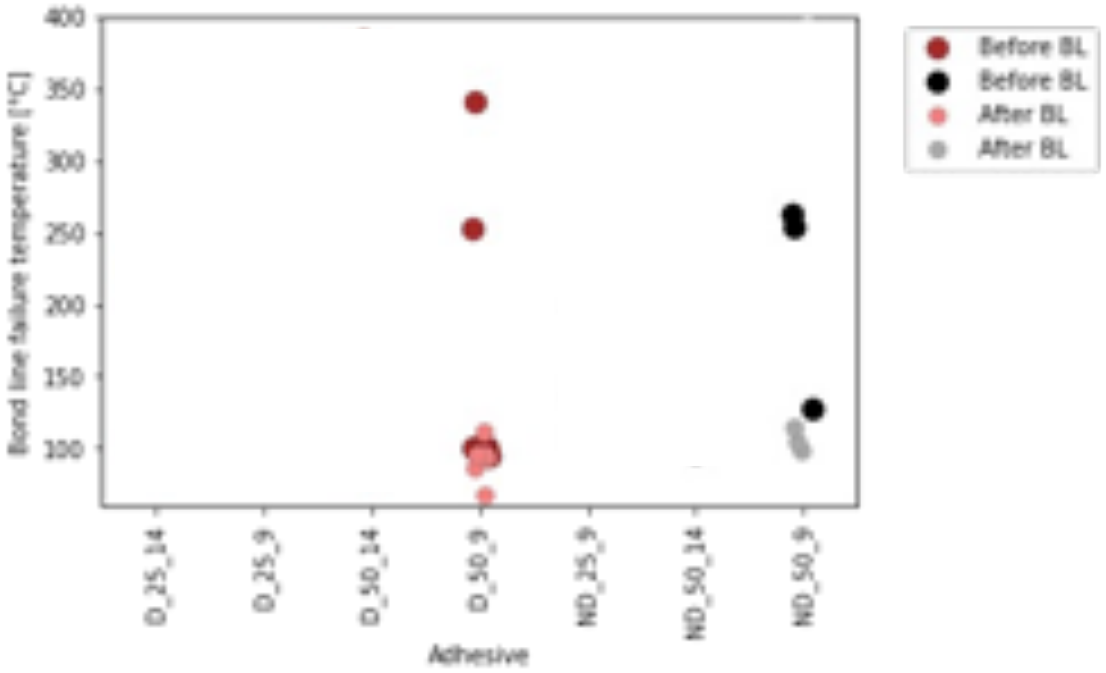
MC 9% | HF 25 kW/m^2

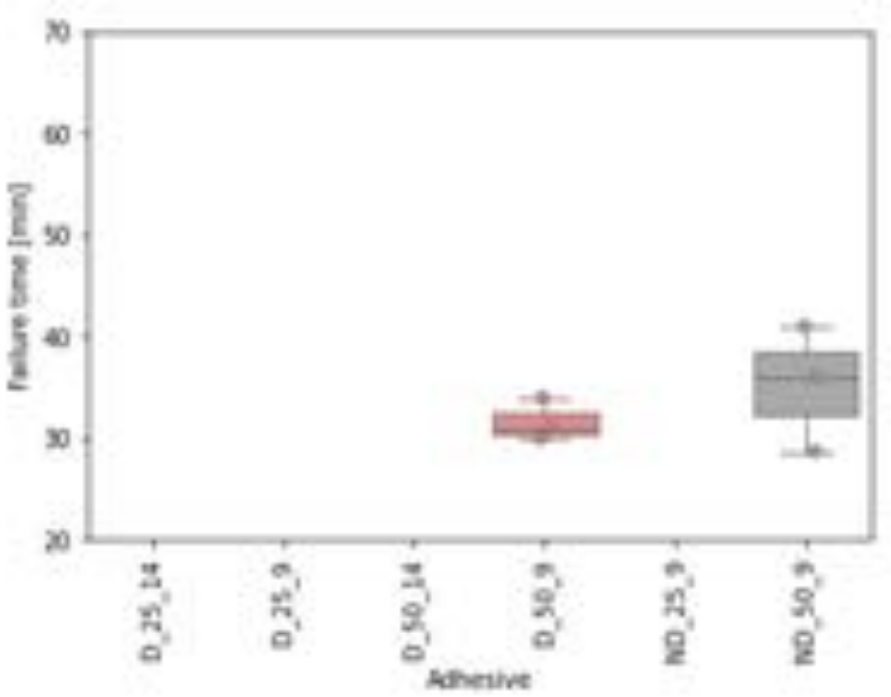


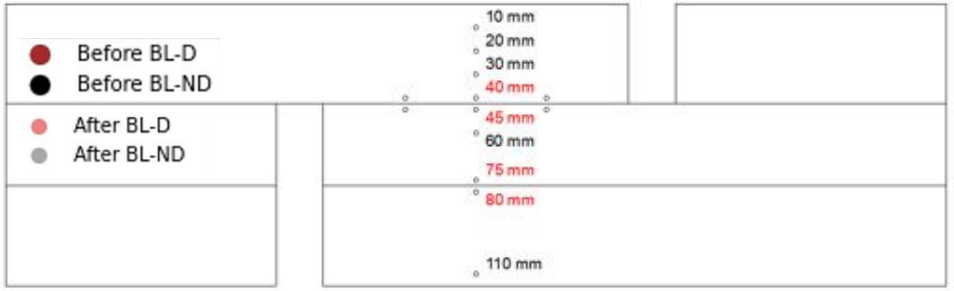
MC 9% | HF 50 kW/m^2



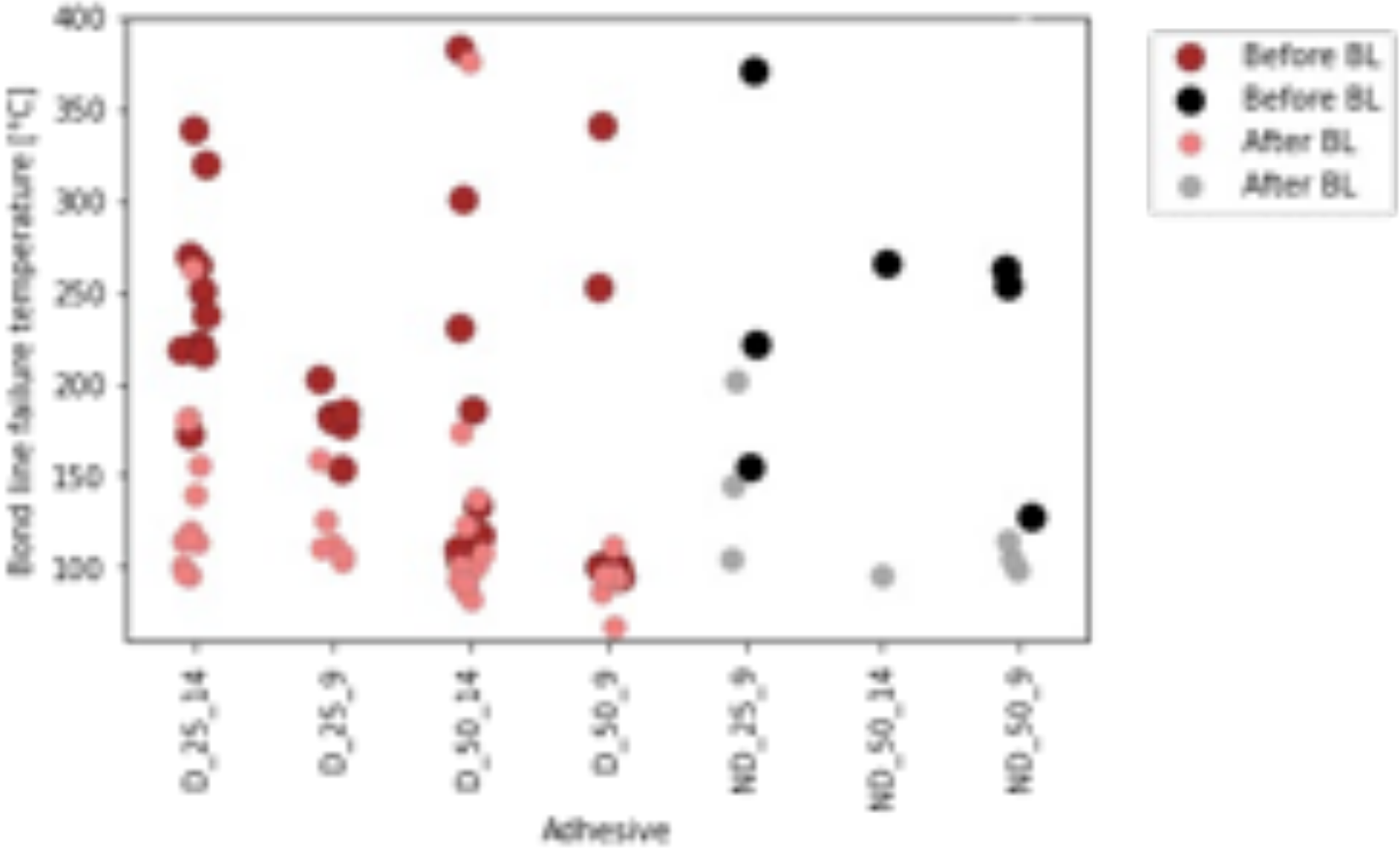
Bond line temperature delamination







Failure temperatures vary!



No conclusions

Future work

Shear stress distribution analysis
In-depth thermal penetration

Connection to microscale results

THE UNIVERSITY of EDINBURGH
School of Engineering

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

OFR FIRE + RISK CONSULTANTS

UKRI Engineering and Physical Sciences Research Council

No conclusions – no questions! :D

PhD student **Antonela Čolić**
Structural and Fire Safety Engineering

Supervisor(s)
Prof **Luke Bisby**

(Dr **Felix Wiesner** I Dr **Danny Hopkin** I Dr **Michael Spearpoint** I Dr **Angus Law**)