Development of a Cohesive Zone Model for Adhesive Joints that Includes Humidity and Fatigue Degradation

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Motivation

Accurate and easy to implement

Development of a **Cohesive Zone Model** for Adhesive Joints that Includes **Humidity** and **Fatigue** Degradation

Degradation of the adhesive's mechanical properties

Cyclic effects must be understood

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Objectives

- Study the effects of humidity ageing in two different adhesives
  - Obtain Fick's law and diffusion coefficients
- Study the effect of fatigue of aged and unaged adhesives
  - Obtain Paris Laws for all situations
- Model those results numerically through the use of a custom Cohesive Zone Model
  - Development of an ABAQUS® user element routine

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Humidity

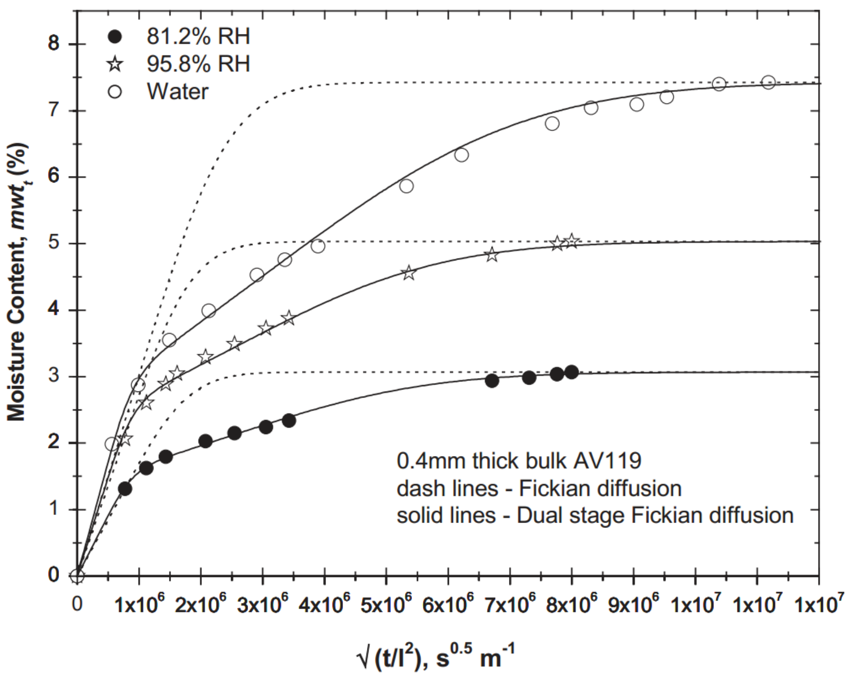

Fig. 1 – Fickian diffusion plots. [W.K. Loh et al. (2005)]

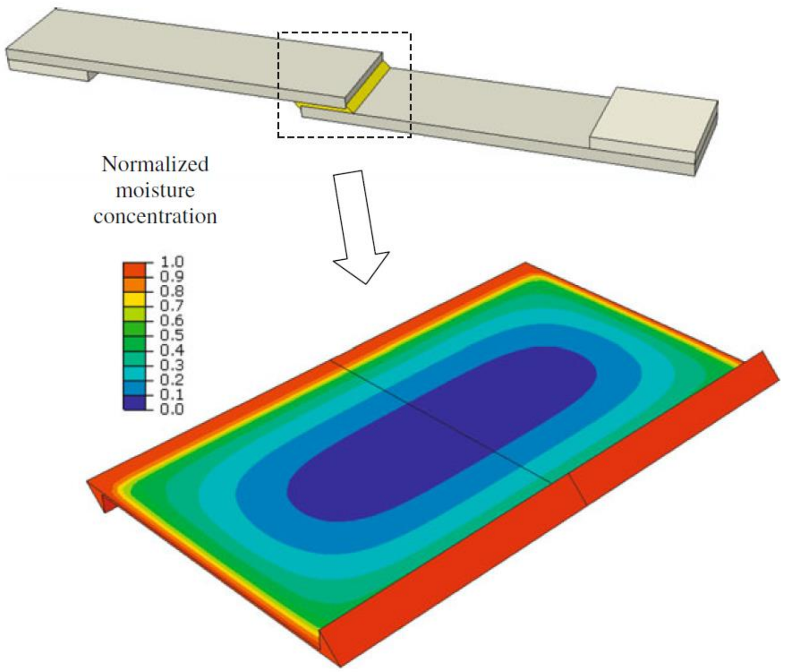

Fig. 2 – Diffusion in an adhesive joint. [I.A. Ashcroft et al. (2013)]

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Humidity

Table 1 – Effect of humidity in the adhesive's mechanical properties. [Adapted from S. Sugiman et al. (2013)]

Adhesive					
Condition	E (MPa)	T_n (MPa)	$T_s = T_t$ (MPa)	G_{IC} (kJ/m^2)	$G_{IIC} = G_{IIIC}$ (kJ/m^2)
Dry	2300	53	30.5	2.5	5
1 year	1960	39.1	23	2.1	4.2
2 year	1862	35.8	21	1.98	3.96

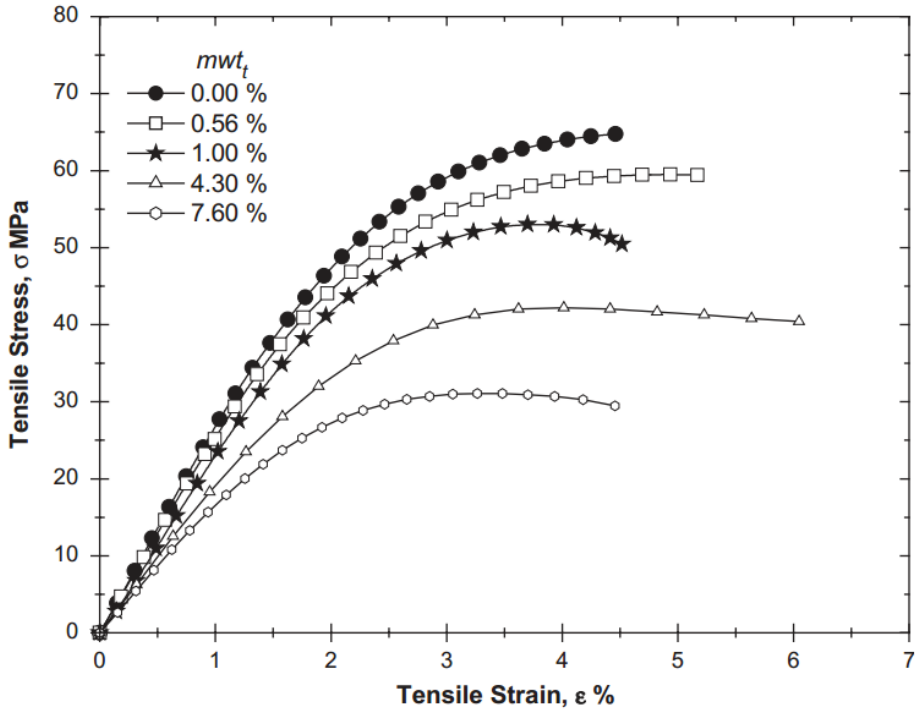

Fig. 3 – Stress-strain curves for the same adhesive with diferent water concentrations. [W.K. Loh et al. (2005)]

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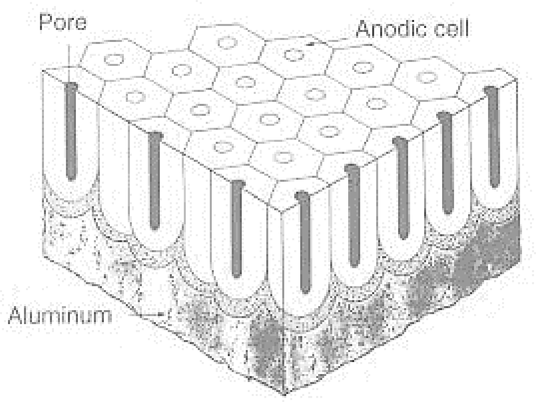
Humidity – Surface treatment

- Due to humidity, water can penetrate the interface between the adhesive and adherend – using a surface treatment improves the interface strength
- PAA (phosphoric acid anodizing) produces a very porous oxide coating, and highly adherent surface [G. Critchlow (2013)]



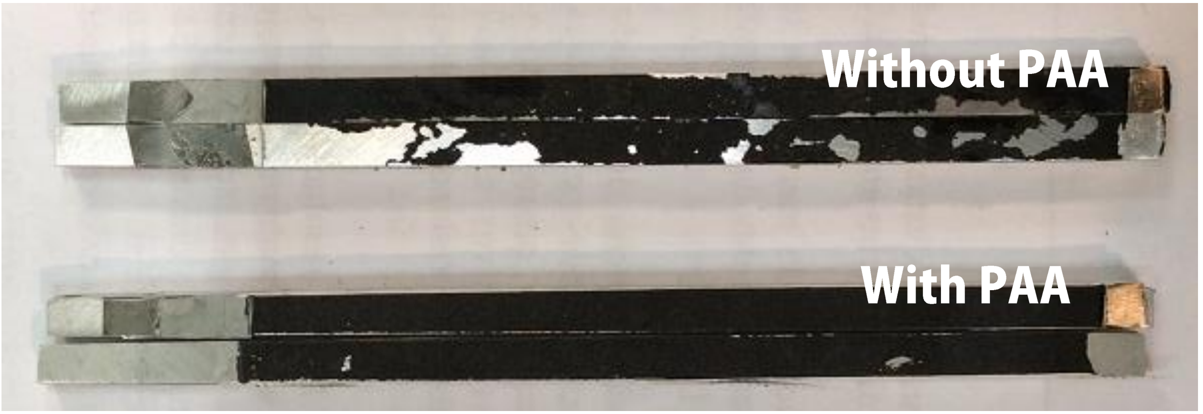


Fig. 4 – PAA microscopic structure (left), and diferences in testes joints due to PAA (right).

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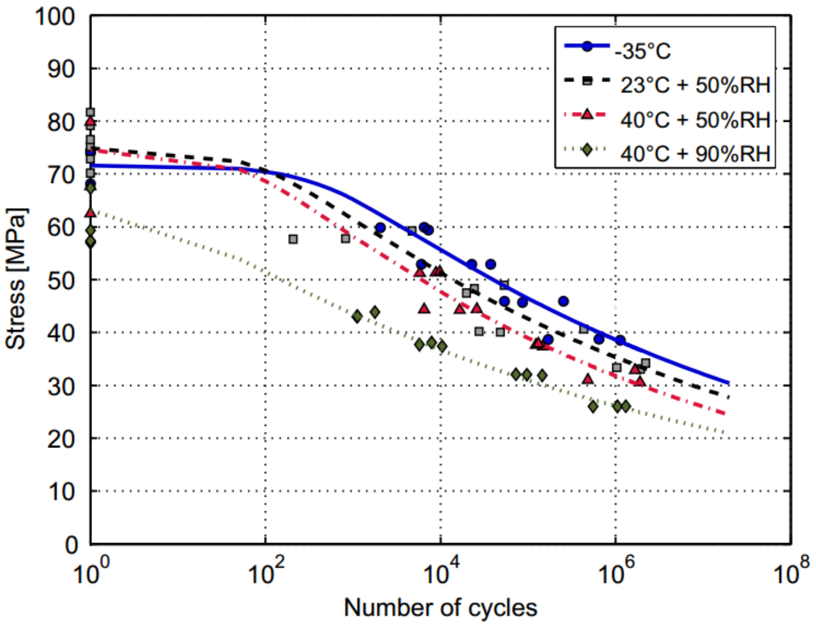
Fatigue

- Loads above a certain threshold initiate microscopic cracks
- With each cycle the crack grows, until catastrophic failure is reached



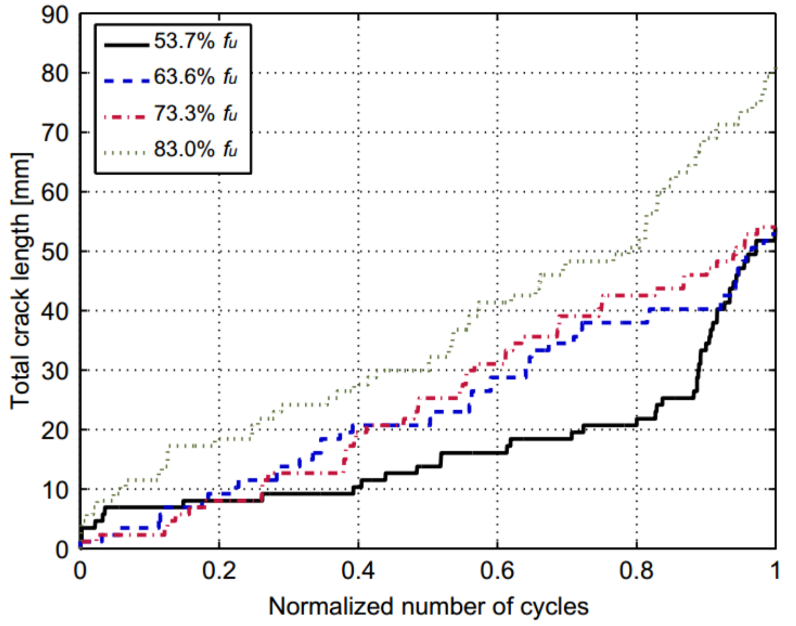


Fig. 5 – Moisture degraded load-life fatigue data for an adhesively bonded joint (left), crack propagation against normalized life for propagation (right). [Y. Zhang et al. (2009)]

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Cohesive Zone Model

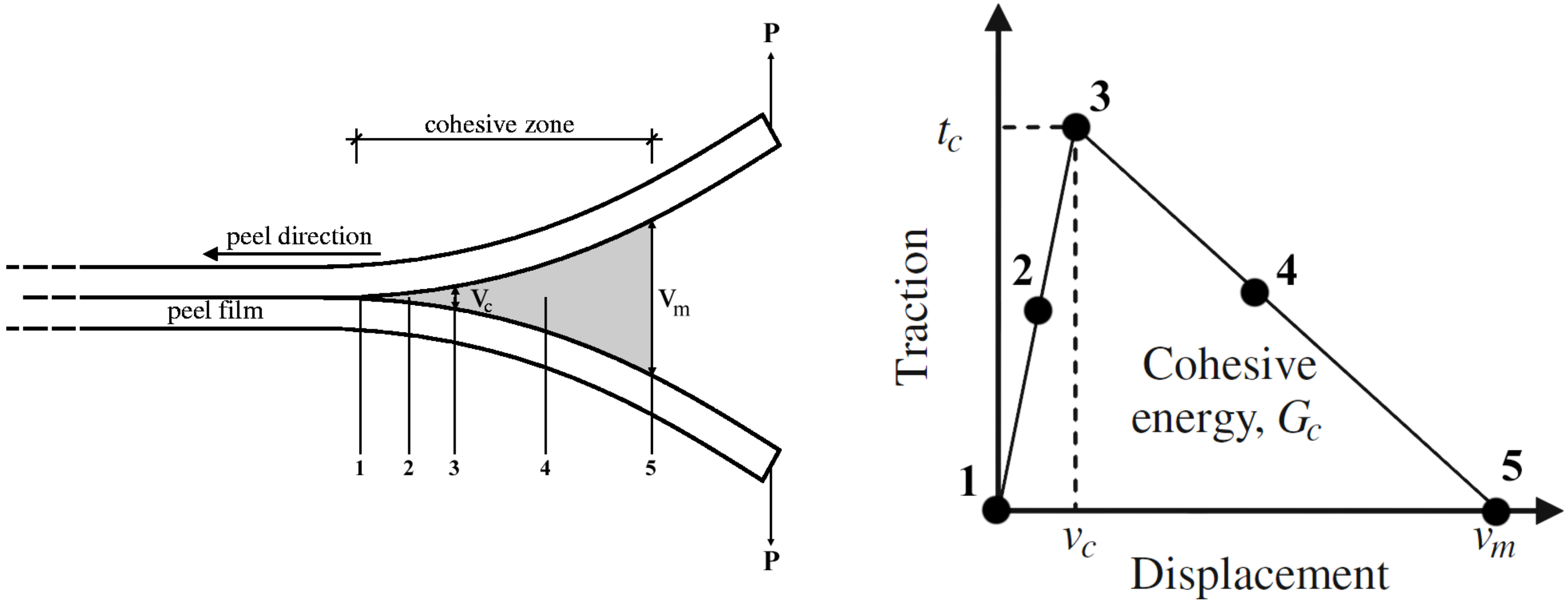

Fig. 6 – Cohesive zone in a loaded adhesive (left), and a bilinear traction-separation law (right).
[Adapted from G. Geißler et al. (2007)]

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Humidity

Adhesive		Cohesive					
Condition	E (MPa)	K_n (N/mm^3)	$K_s = K_t$ (N/mm^3)	T_n (MPa)	$T_s = T_t$ (MPa)	G_{IC} (kJ/m^2)	$G_{IIC} = G_{IIIC}$ (kJ/m^2)
Dry	2300	100,000	35,750	53	30.5	2.5	5
1 year	1960	80,000	28,550	39.1	23	2.1	4.2
2 year	1862	79,250	28,350	35.8	21	1.98	3.96

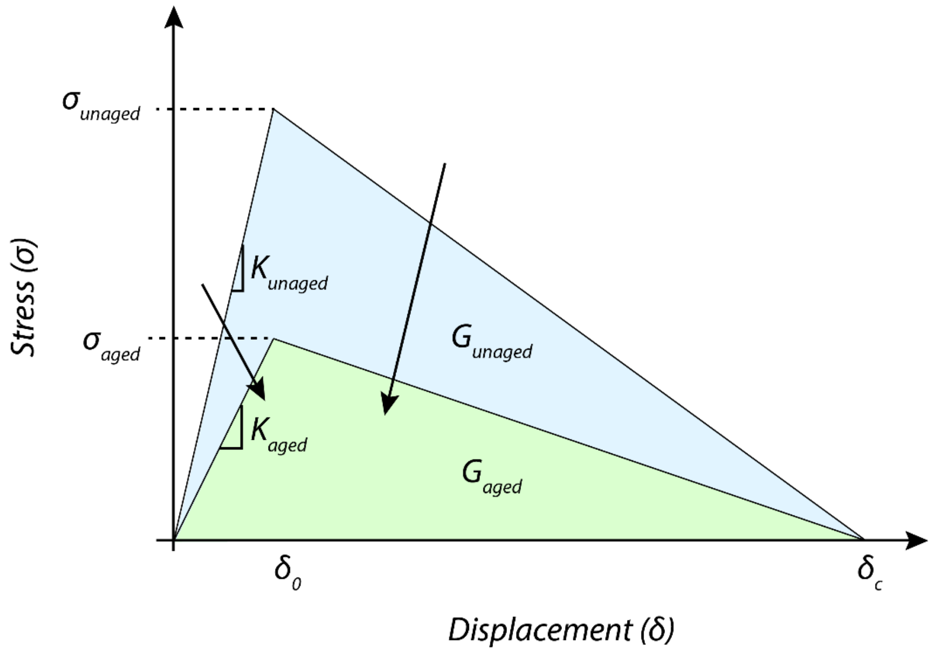

Fig. 7 – Cohesive zone model adapted to the humidity degradation.

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Humidity and fatigue combined

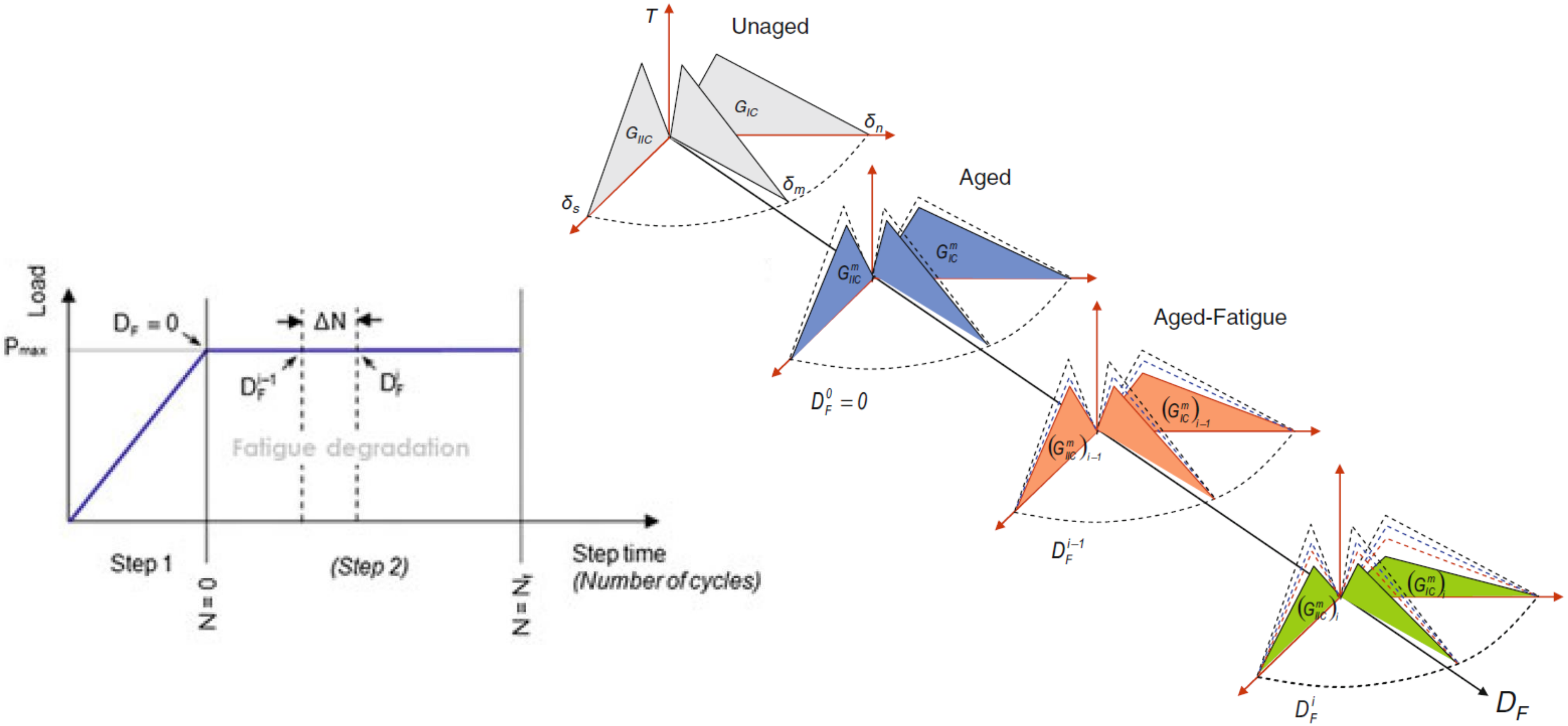

Fig. 8 – Degrading the CZM by both humidity and fatigue. [A.D. Crocombe et al. (2013)]

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Experimental tests – adhesives

Table 2 – Mechanical properties of both the adhesives used.

Adhesive	Tensile Strength (MPa)	Young's Modulus (MPa)	Strain to Failure (%)	G_{IC} (N/mm)
Nagase XNR 6852-1	56.4	2089.2	21.0	4.94
SikaPower 4720	25.0	2030	4.9	1.63

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Experimental tests – fatigue

- Step 1 – Static test to find maximum load

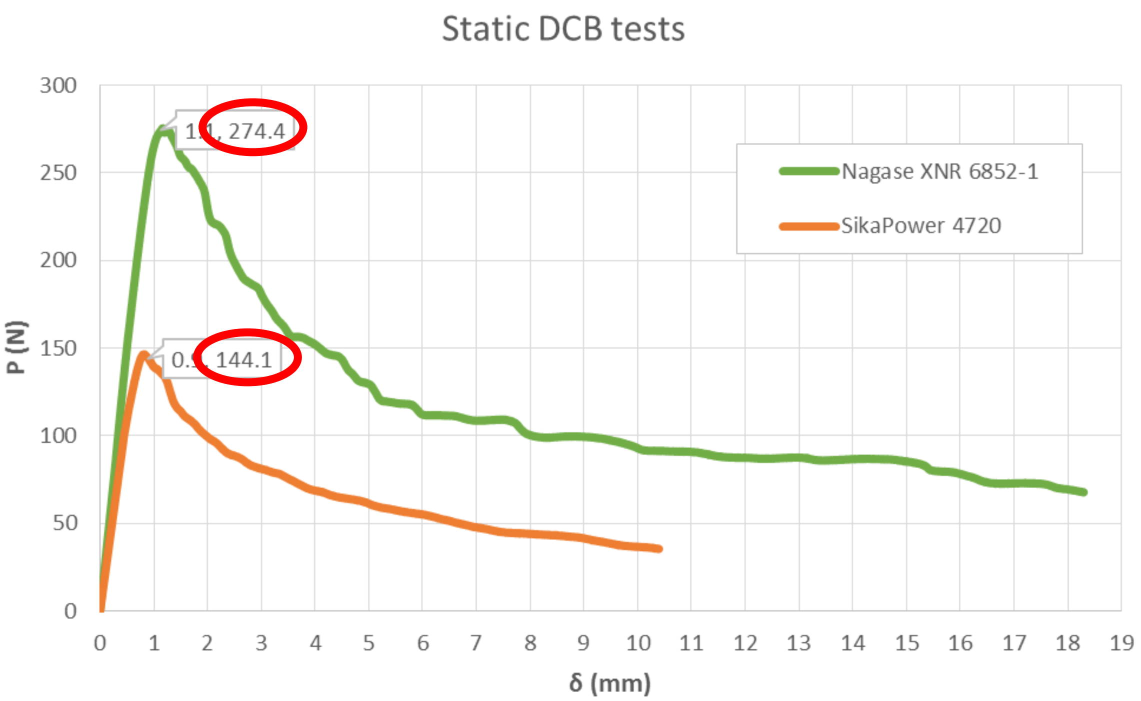


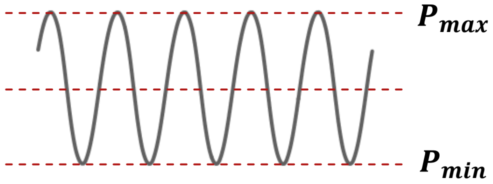
Fig. 9 – P-δ curves for both the tested adhesives, with the maximum load highlighted.

- Step 2 – Determine fatigue parameters

$$Fatigue \rightarrow \begin{cases} P_{max} = 60\% * P_{static} \\ P_{min} = 0.1 * P_{max} \end{cases}$$

Table 3 – Fatigue parameters.

Adhesive	P_{static} (N)	P_{max} (N)	P_{min} (N)
Nagase XNR 6852-1	274.4	165	16.5
SikaPower 4720	144.1	87	8.7



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Experimental tests – fatigue

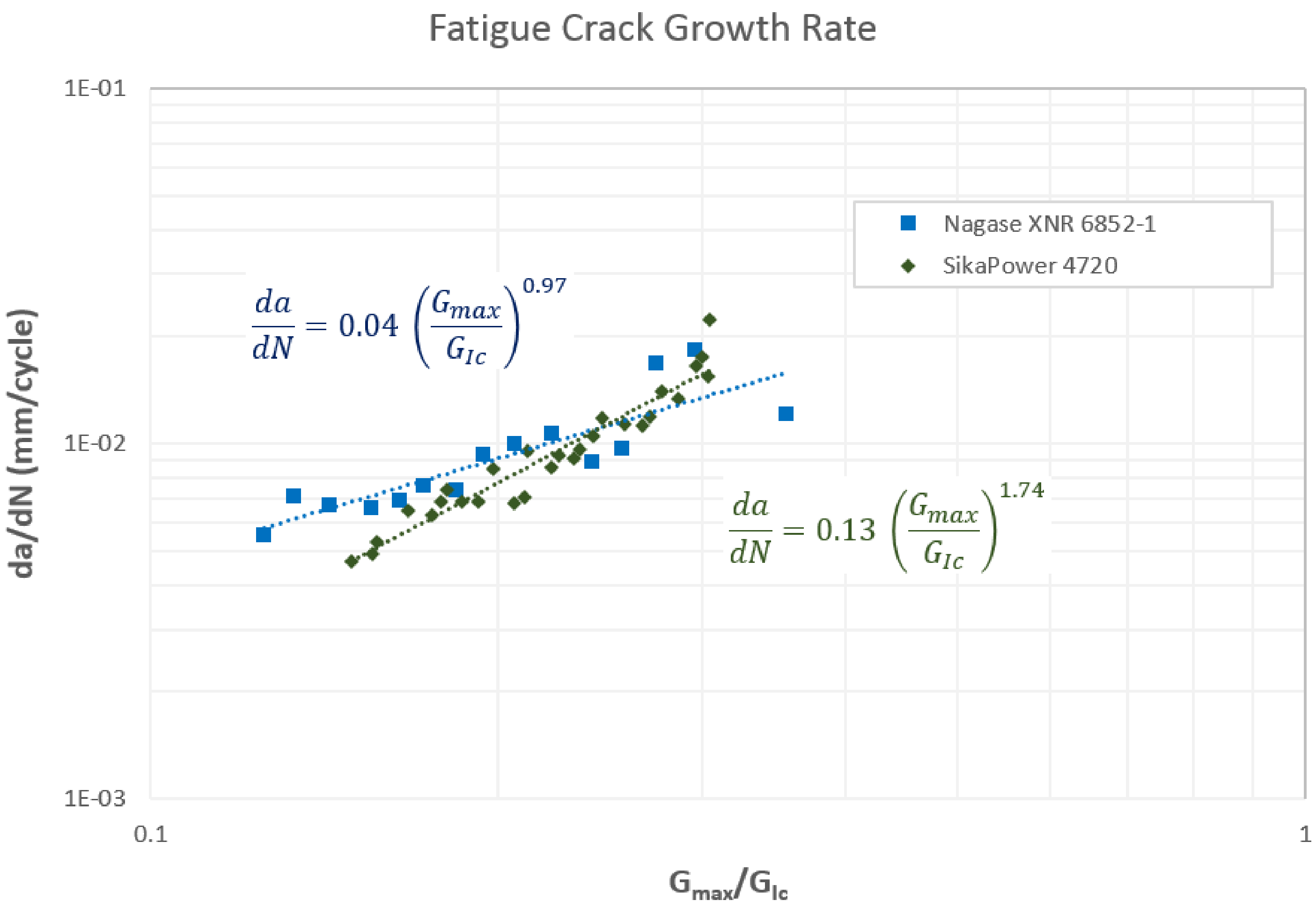

Fig. 10 – Paris Law curves and coefficients for both adhesives.

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Experimental tests – humidity

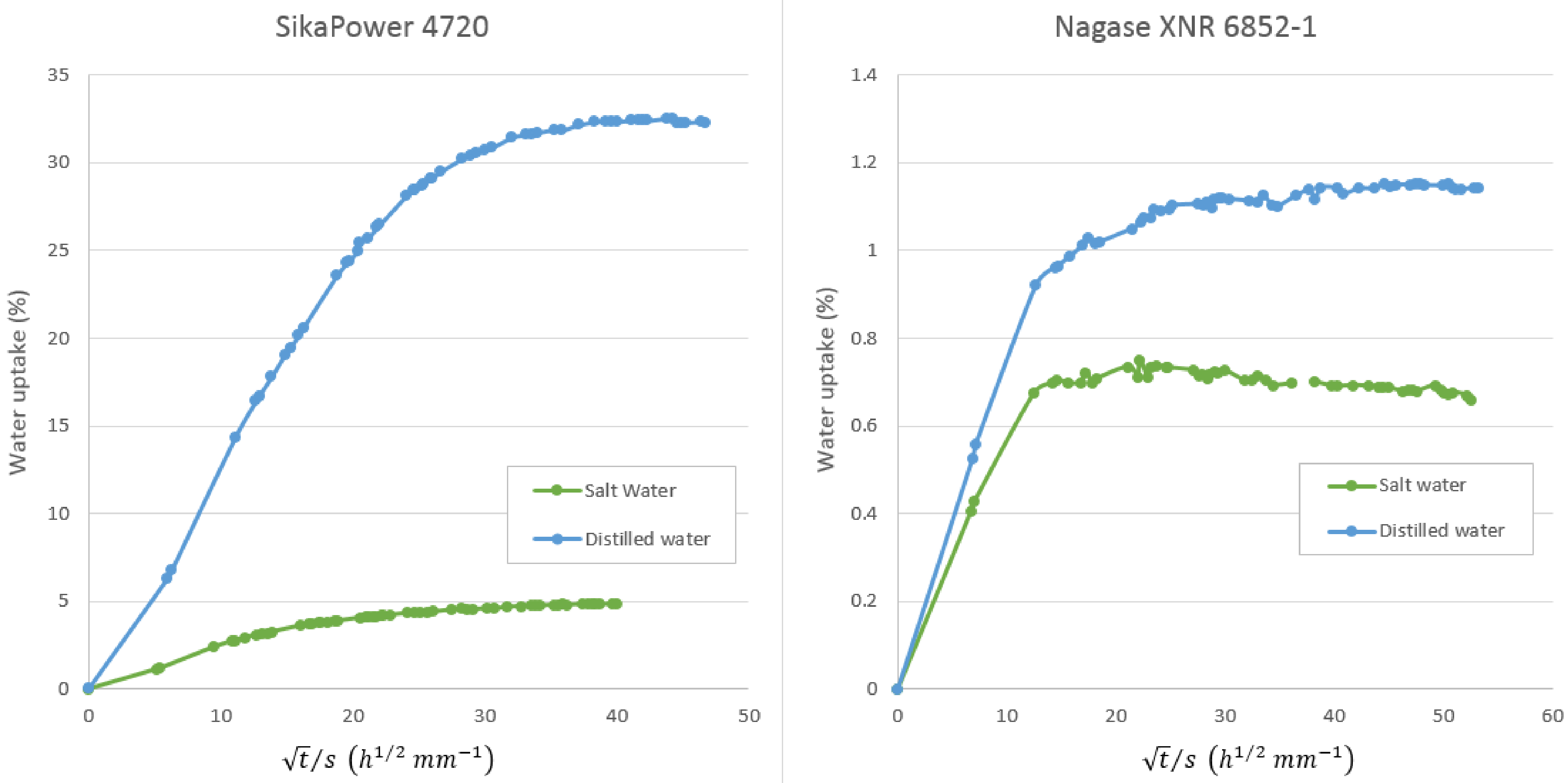

Fig. 11 – Diffusion plots for both tested adhesives.

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Numerical modelling

- Using ABAQUS® it is possible to develop custom finite element formulation (using FORTRAN®), called UEL routines
- Adopted approach: degrade the cohesive zone parameters in such a way that humidity and fatigue results can be obtained

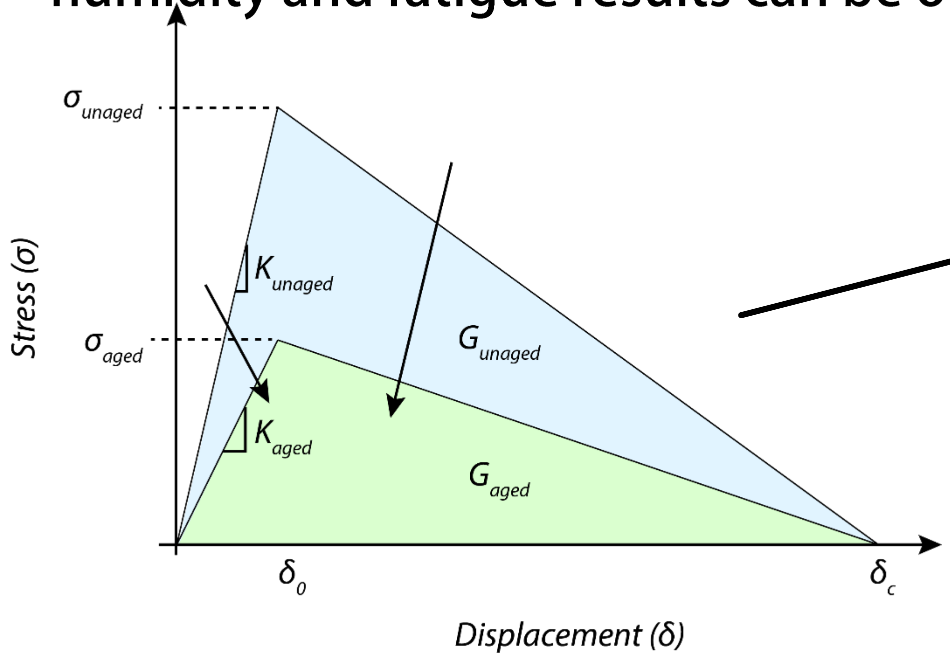

Fig. 12 – Cohesive zone model adapted to the humidity degradation.

$$\sigma_{aged} = \sigma_{unaged} * f_1(humidity, Paris\ Law\ parameters, cycles, \dots)$$

$$G_{aged} = G_{unaged} * f_2(humidity, Paris\ Lawparameters, cycles, \dots)$$

More tests are needed to find out the relationships

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Numerical modelling

- UEL is created and working (with sample degrading coefficients):

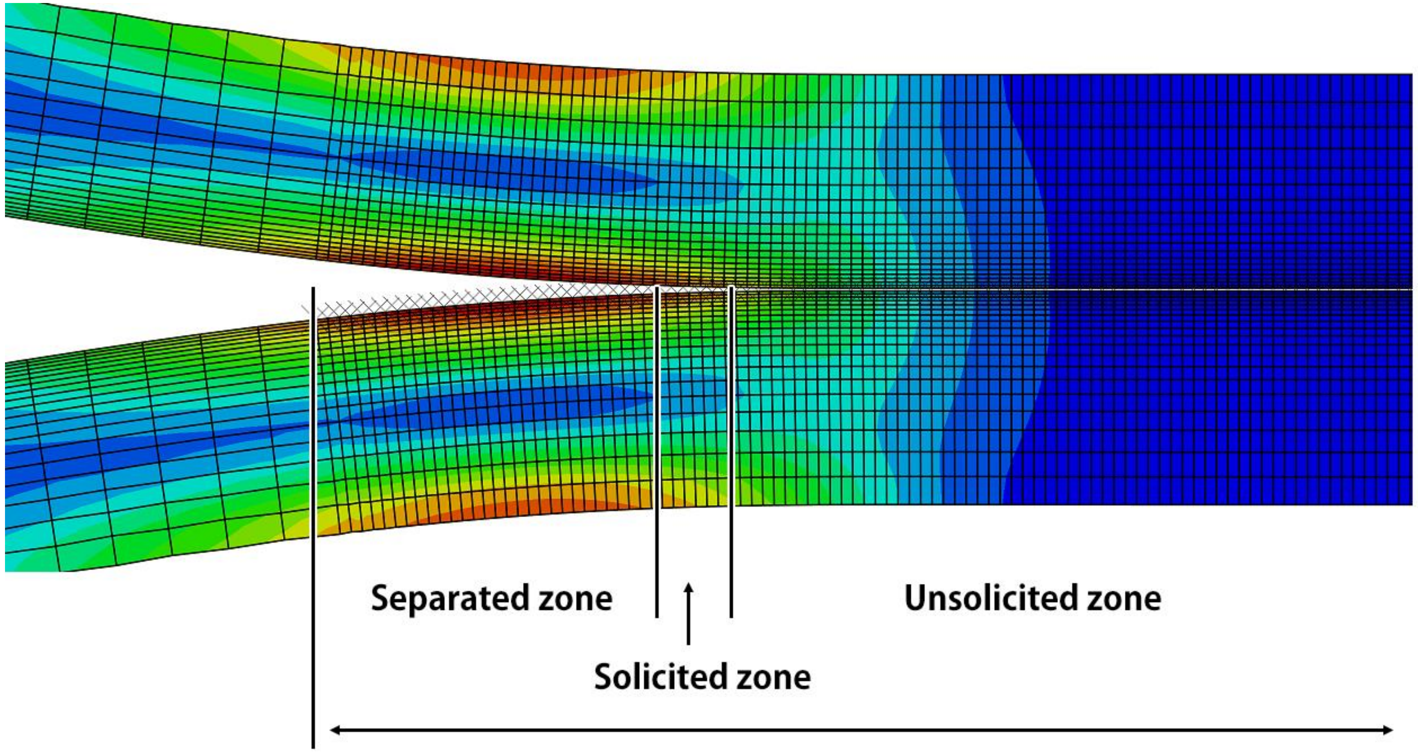

Fig. 13 – Resulting deformed configuration.

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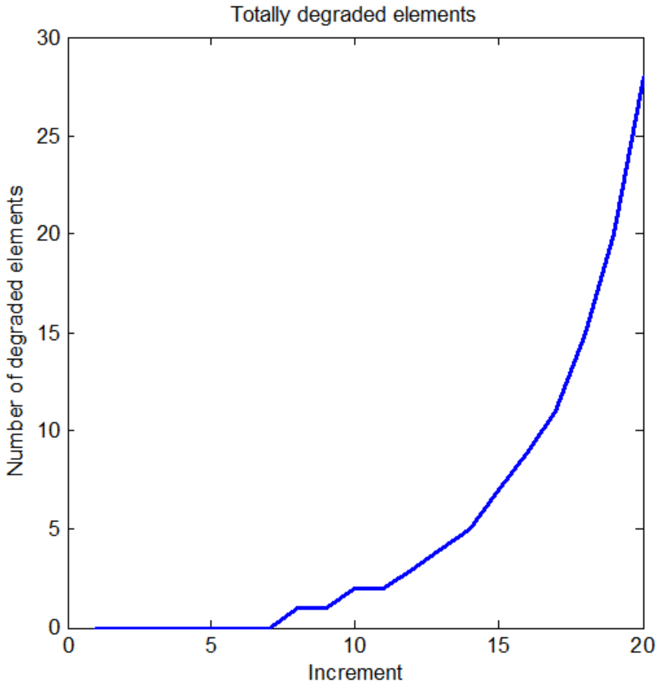
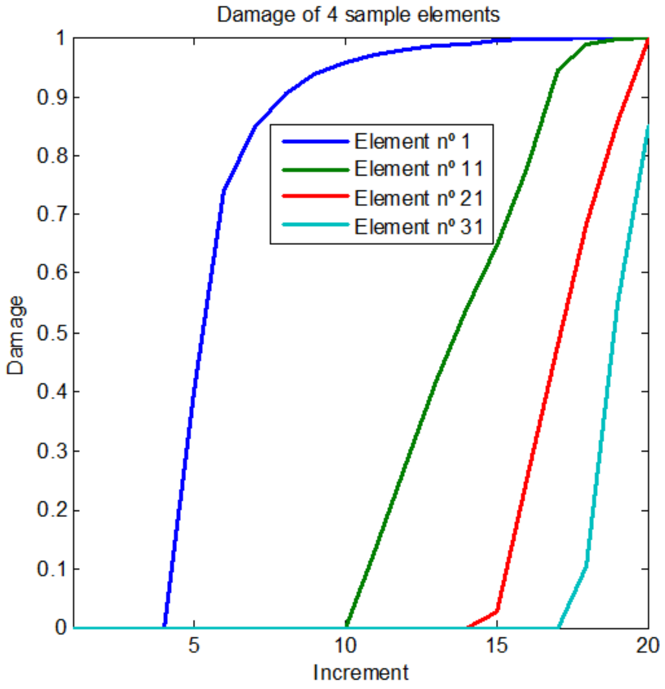
Numerical modelling

- Fatigue parameters are obtained from a crack-length vs cycles curve
  - Crack length can be inferred from the number of totally degraded elements
  - Cycles can be controlled through the degradation coefficient and iteration number





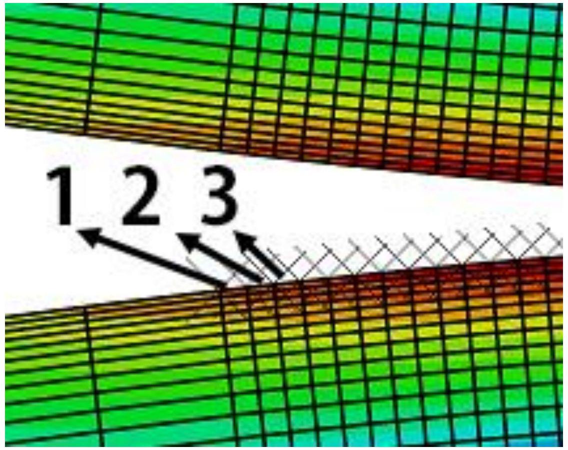


Fig. 14 – Number of degraded elements (left), damage of some elements on the overlap (middle), cohesive element numbering (right).

Conclusions

- Experimental data for humidity is a slow process;
- UEL routine is behaving like expected;
- Humidity + Fatigue will provide a robust tool for predicting the future effects on the adhesive joints.

Future work

- More experimental testing is needed (humidity at various stages, fatigue with humid joints, etc.);
- Using those results to find the relationship between aged and unaged parameters;
- Implement the relationship in the UEL routine.

Acknowledgements

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