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

M. Costa, G. Viana, L.F.M. da Silva, R.D.S.G. Campilho

September 8th, 2014

U.PORTO
FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO
idmec FEUP engenharia mecânica
FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA E DO ENSINO SUPERIOR
Nagase ChemteX
Sika
AdFEUP Adhesives Group Grupo de Adesivos

Contents

- Introduction
  - Motivation and objectives
- Degradation of the joint
  - Humidity
  - Humidity and Fatigue influence
- Experimental procedure and results
  - Specimens and adhesives
  - Fatigue and humidity results
- Numerical modelling
- Conclusions and future work

Contents

- Introduction
  - Motivation
  - Objectives
- Degradation of the joint
  - Humidity
  - Humidity and Fatigue influence
- Experimental procedure
- Experimental results
- Numerical modelling
- Conclusions and future work

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

Contents

- Introduction
  - Motivation
  - Objectives
- Degradation of the joint
  - Humidity
  - Humidity and Fatigue influence
- Experimental procedure
- Experimental results
- Numerical modelling
- Conclusions and future work

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

Contents

- Introduction
  - Motivation
  - Objectives
- Degradation of the joint
  - **Humidity**
  - Humidity and Fatigue influence
- Experimental procedure
- Experimental results
- Numerical modelling
- Conclusions and future work

Humidity

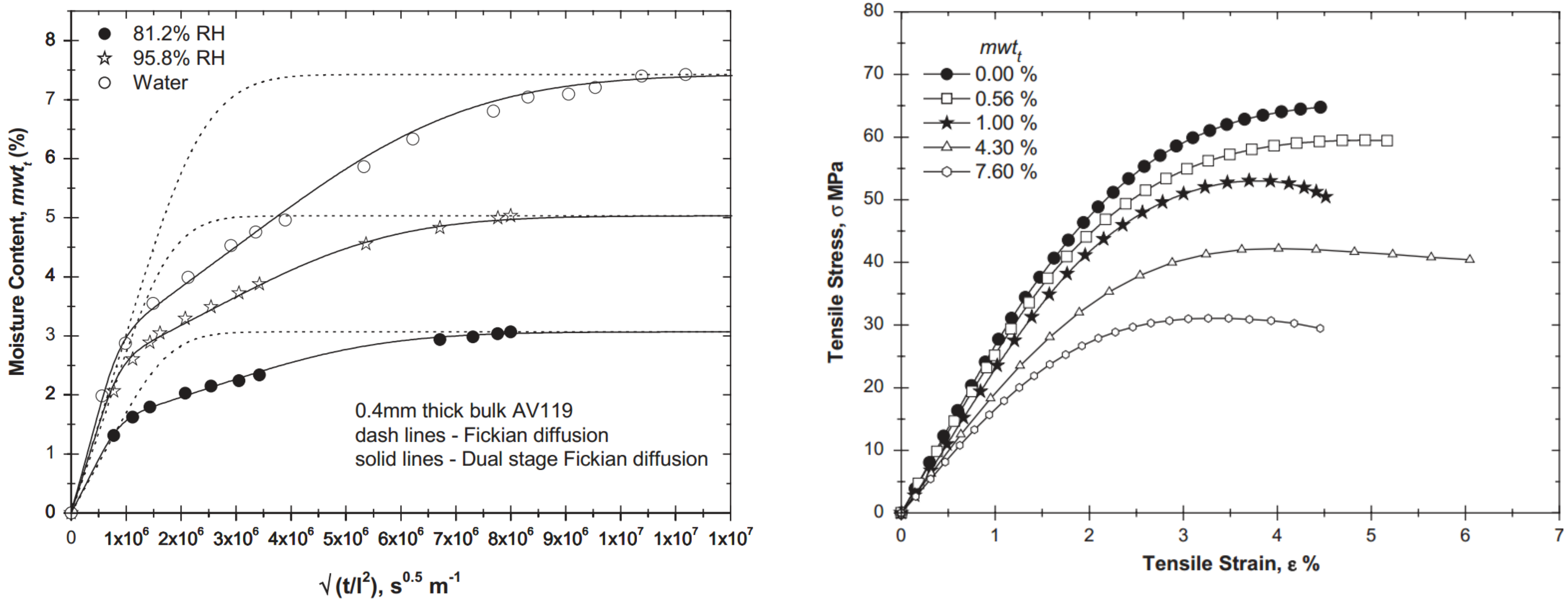


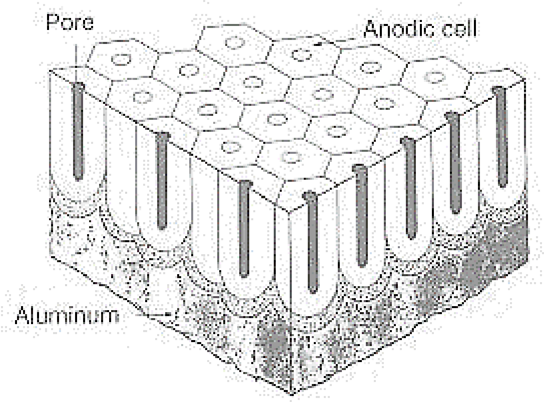
Fig. 1 – (left) Fickian diffusion plots, (right) Stress-strain curves for the same adhesive with different water concentrations. [W.K. Loh et al. (2005)]

Contents

- Introduction
  - Motivation
  - Objectives
- Degradation of the joint
  - Humidity
  - Humidity and Fatigue influence
- Experimental procedure
- Experimental results
- Numerical modelling
- Conclusions and future work

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)]



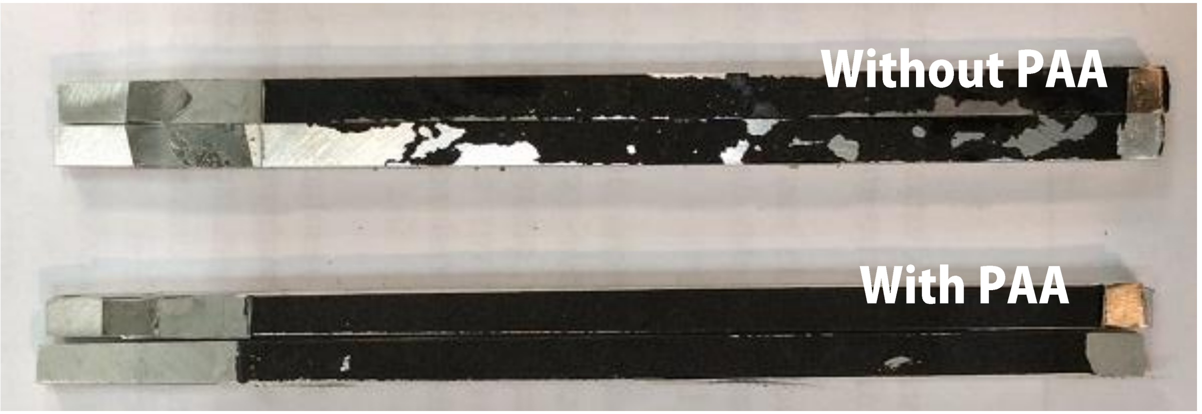


Fig. 2 – PAA microscopic structure (left), and diferences in testes joints due to PAA (right).

Contents

- Introduction
  - Motivation
  - Objectives
- Degradation of the joint
  - Humidity
  - Humidity and Fatigue influence
- Experimental procedure
- Experimental results
- Numerical modelling
- Conclusions and future work

Humidity and fatigue combined

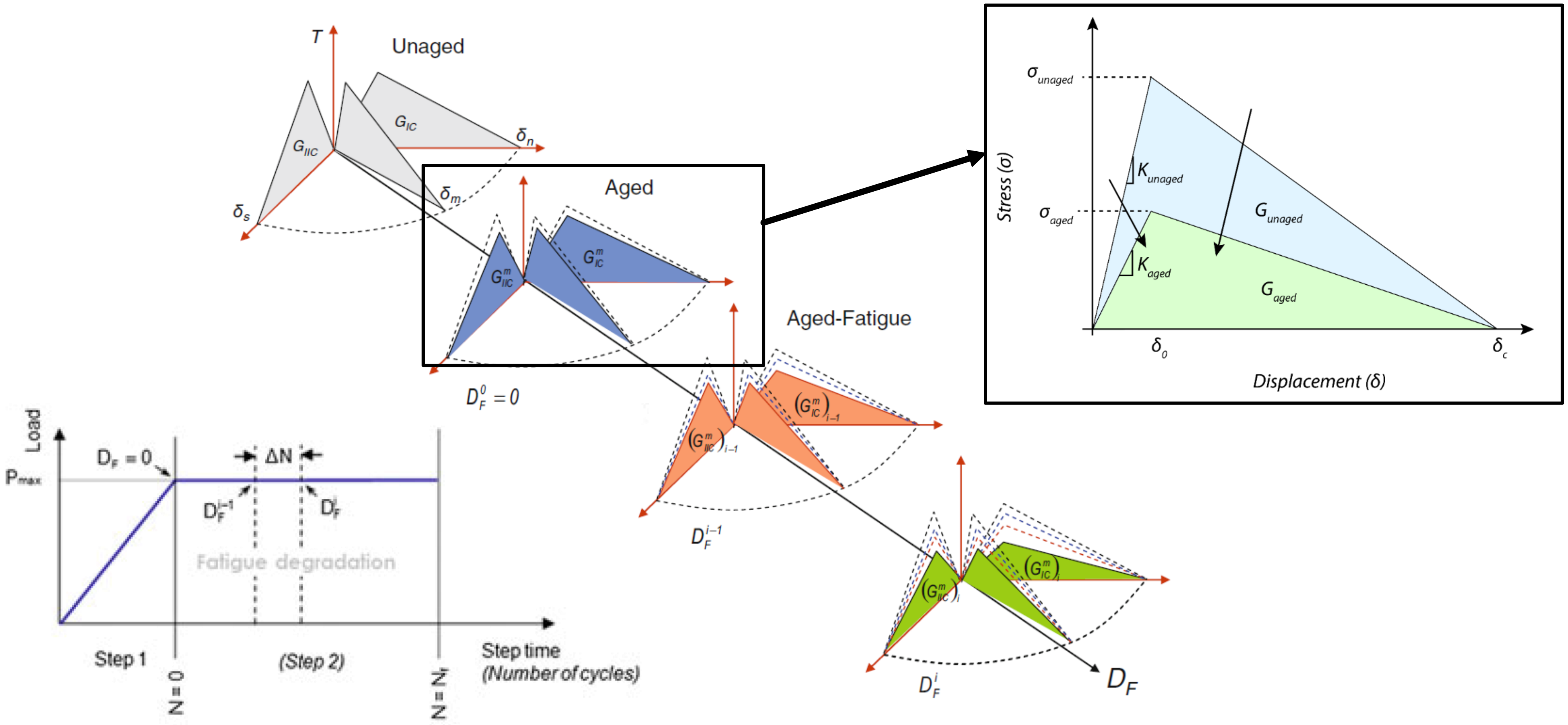


Fig. 3 – Degrading the CZM by both humidity and fatigue. [A.D. Crocombe et al. (2013)]

Experimental procedure

- Optimised specimens were used (needed due to humidity tests).

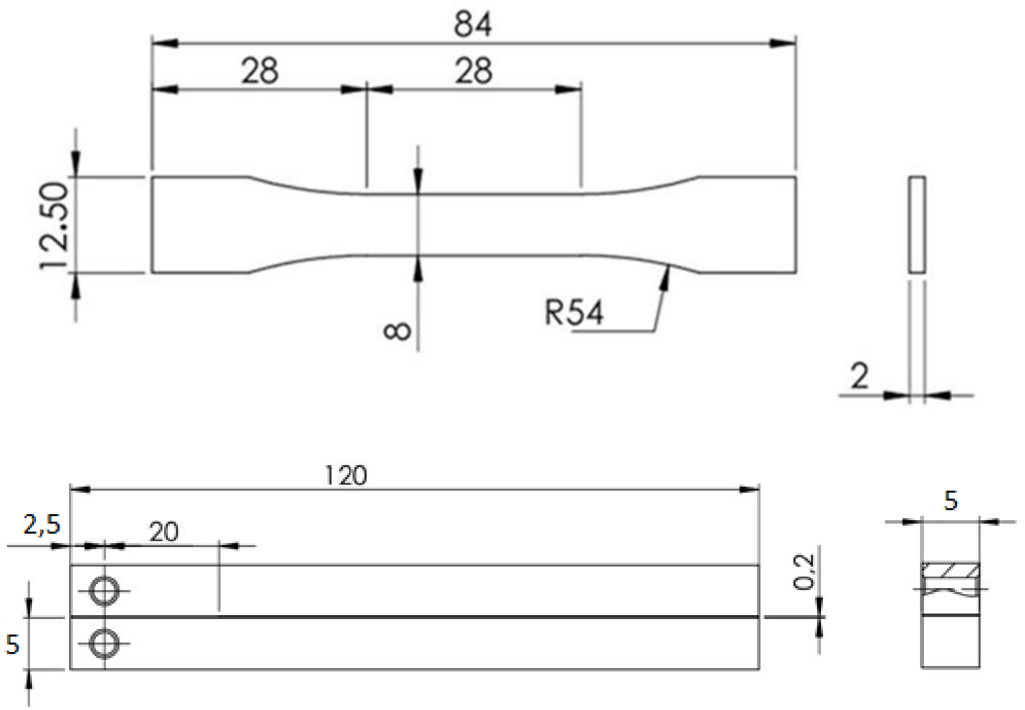


Fig. 4 – Optimised bulk specimens (top), optimised DCB specimens (bottom).

Contents

- Introduction
  - Motivation
  - Objectives
- Degradation of the joint
  - Humidity
  - Humidity and Fatigue influence
- Experimental procedure
- Experimental results
- Numerical modelling
- Conclusions and future work

Contents

- Introduction
  - Motivation
  - Objectives
- Degradation of the joint
  - Humidity
  - Humidity and Fatigue influence
- Experimental procedure
- Experimental results
- Numerical modelling
- Conclusions and future work

Experimental tests – adhesives

Table 1 – 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

Contents

- Introduction
  - Motivation
  - Objectives
- Degradation of the joint
  - Humidity
  - Humidity and Fatigue influence
- Experimental procedure
- Experimental results
- Numerical modelling
- Conclusions and future work

Experimental tests – fatigue

- Step 1 – Static test to find maximum load

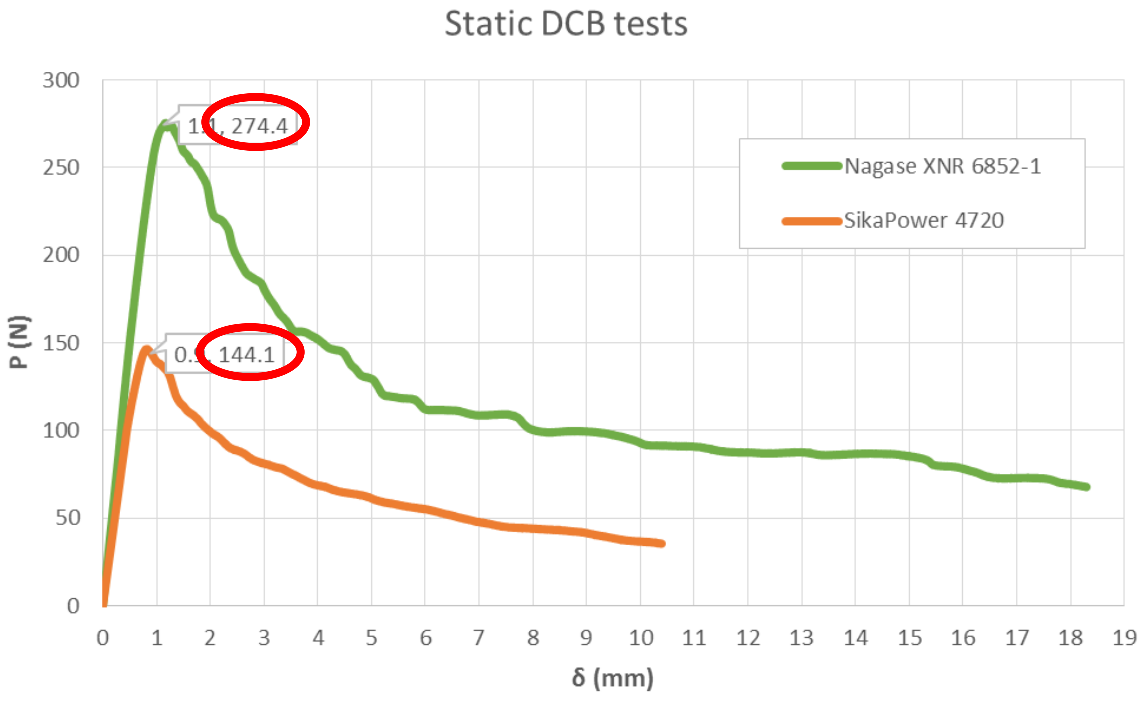


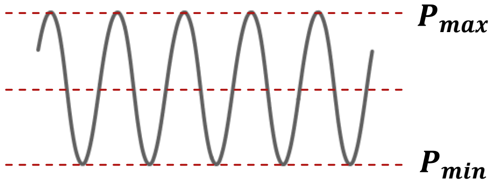
Fig. 4 – P-δ curves for both the tested adhesives, with the maximum load highlighted.

- Step 2 – Determine fatigue parameters

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

Table 2 – 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



Contents

- Introduction
  - Motivation
  - Objectives
- Degradation of the joint
  - Humidity
  - Humidity and Fatigue influence
- Experimental procedure
- **Experimental results**
- Numerical modelling
- Conclusions and future work

Experimental tests – fatigue

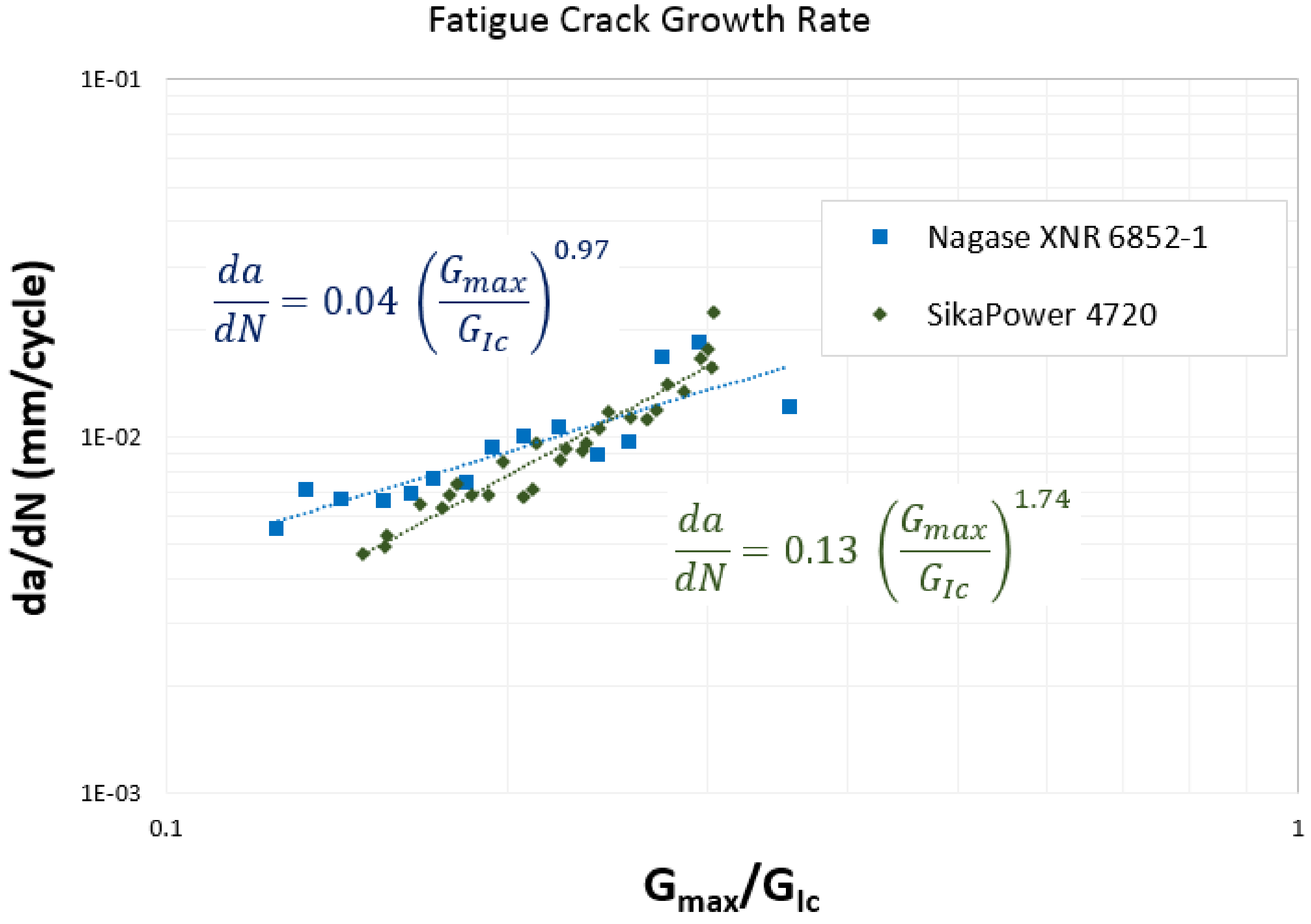


Fig. 5 – Paris Law curves and coefficients for both adhesives.

Contents

- Introduction
  - Motivation
  - Objectives
- Degradation of the joint
  - Humidity
  - Humidity and Fatigue influence
- Experimental procedure
- Experimental results
- Numerical modelling
- Conclusions and future work

Experimental tests – humidity

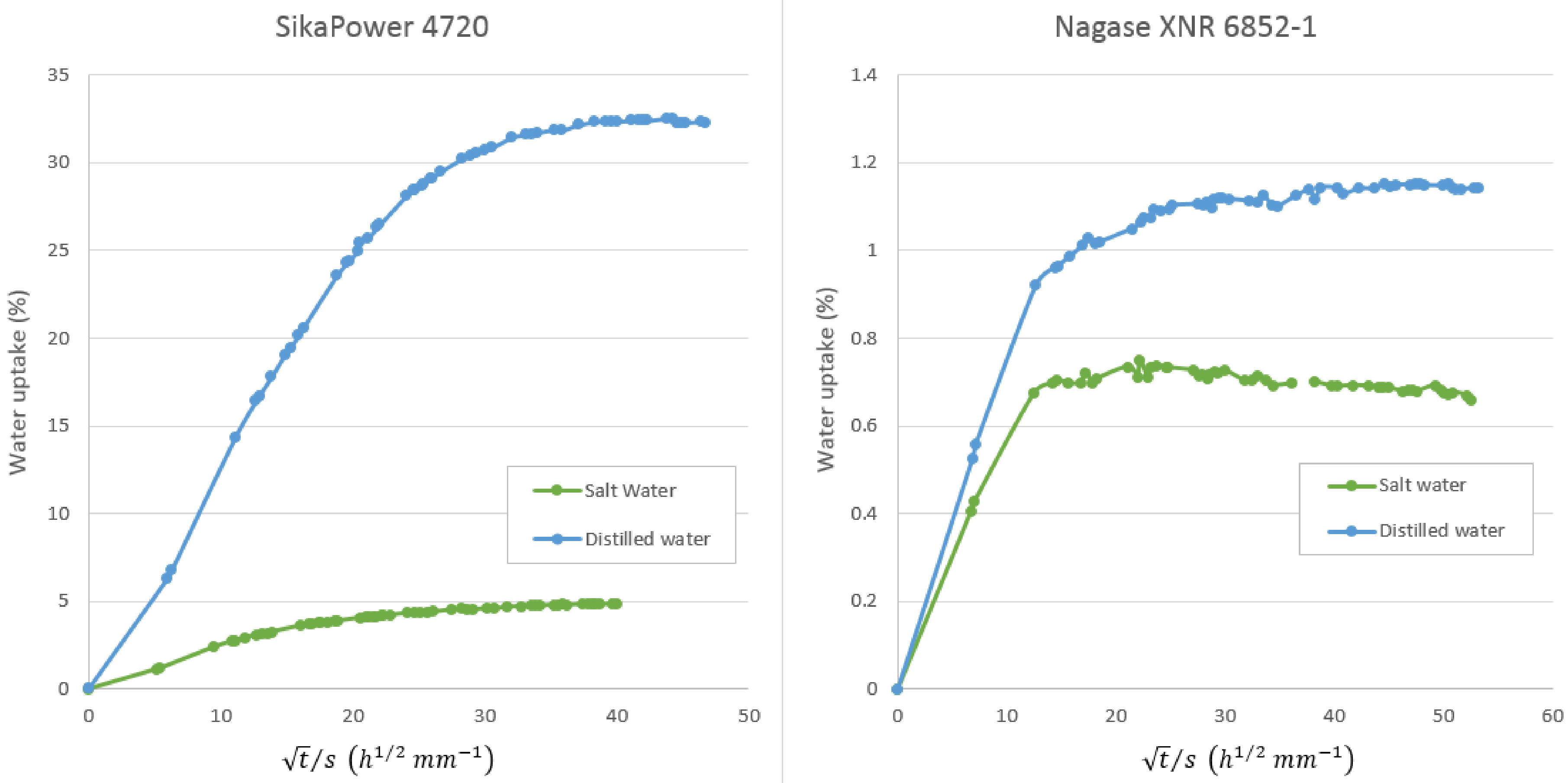


Fig. 6 – Diffusion plots for both tested adhesives.

Contents

- Introduction
  - Motivation
  - Objectives
- Degradation of the joint
  - Humidity
  - Humidity and Fatigue influence
- Experimental procedure
- Experimental results
- Numerical modelling
- Conclusions and future work

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

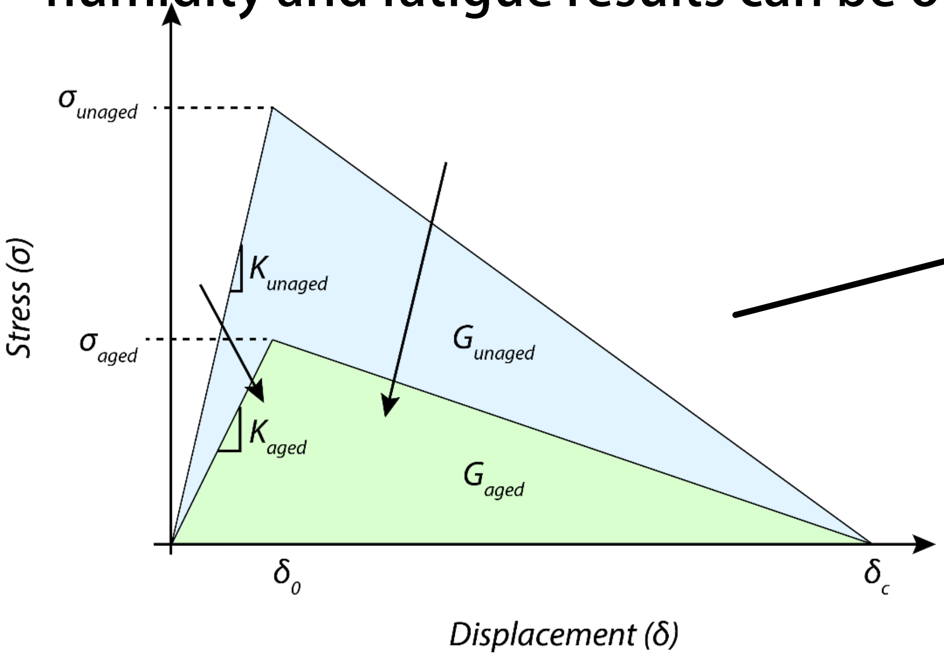


Fig. 7 – Cohesive zone model adapted to the humidity degradation.

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

$$G_{aged} = G_{unaged} * f_2(humidity, Paris\ Law\ parameters, cycles, \ldots)$$

More tests are needed to find out the exact relationships

Contents

- Introduction
  - Motivation
  - Objectives
- Degradation of the joint
  - Humidity
  - Humidity and Fatigue influence
- Experimental procedure
- Experimental results
- Numerical modelling
- Conclusions and future work

Numerical modelling

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

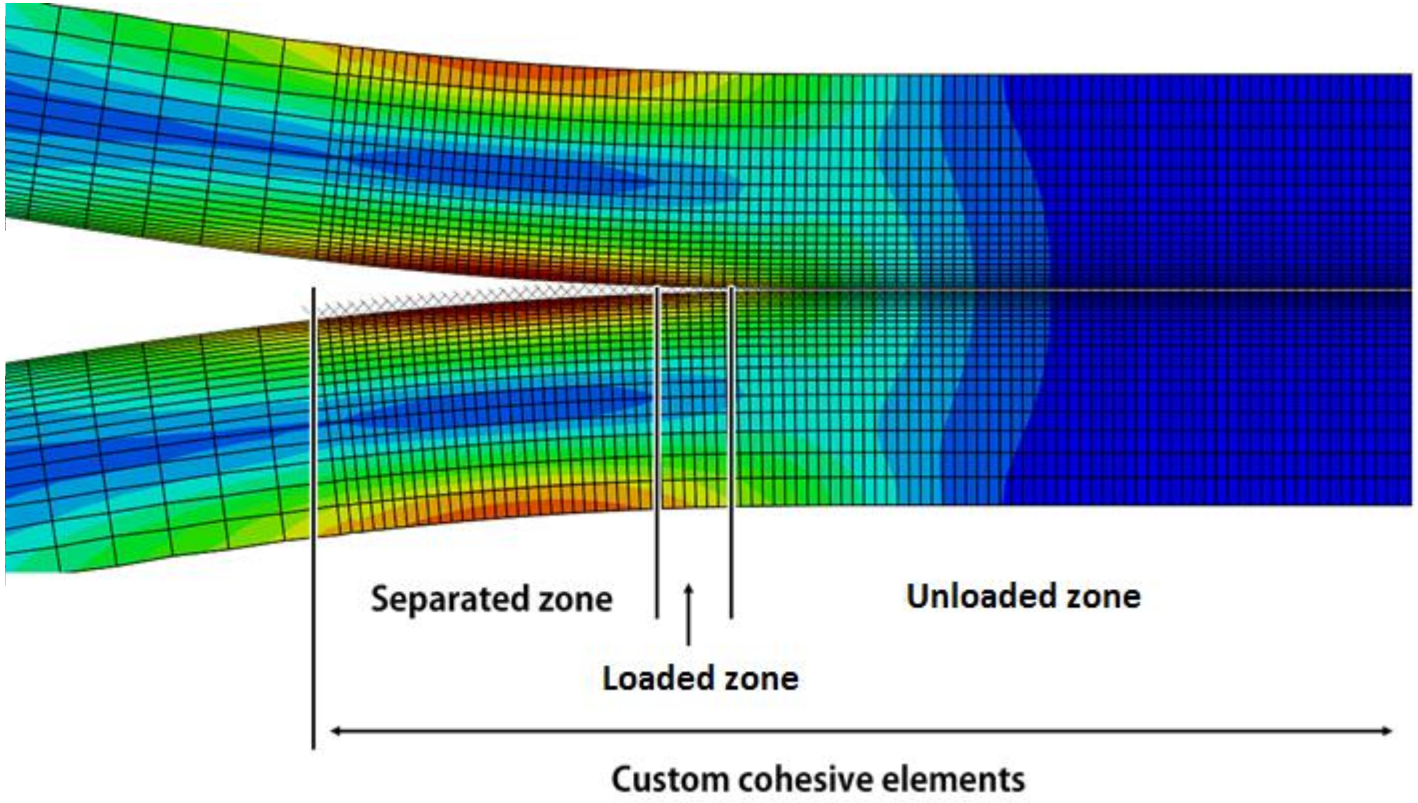


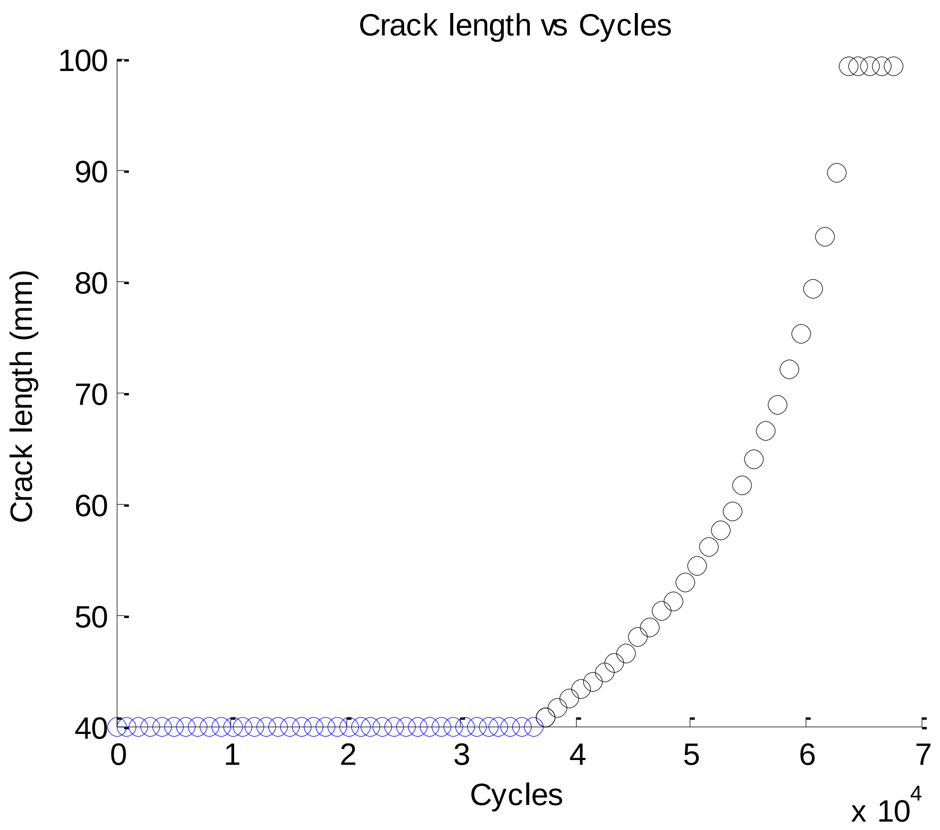
Fig. 8 – Resulting deformed configuration.

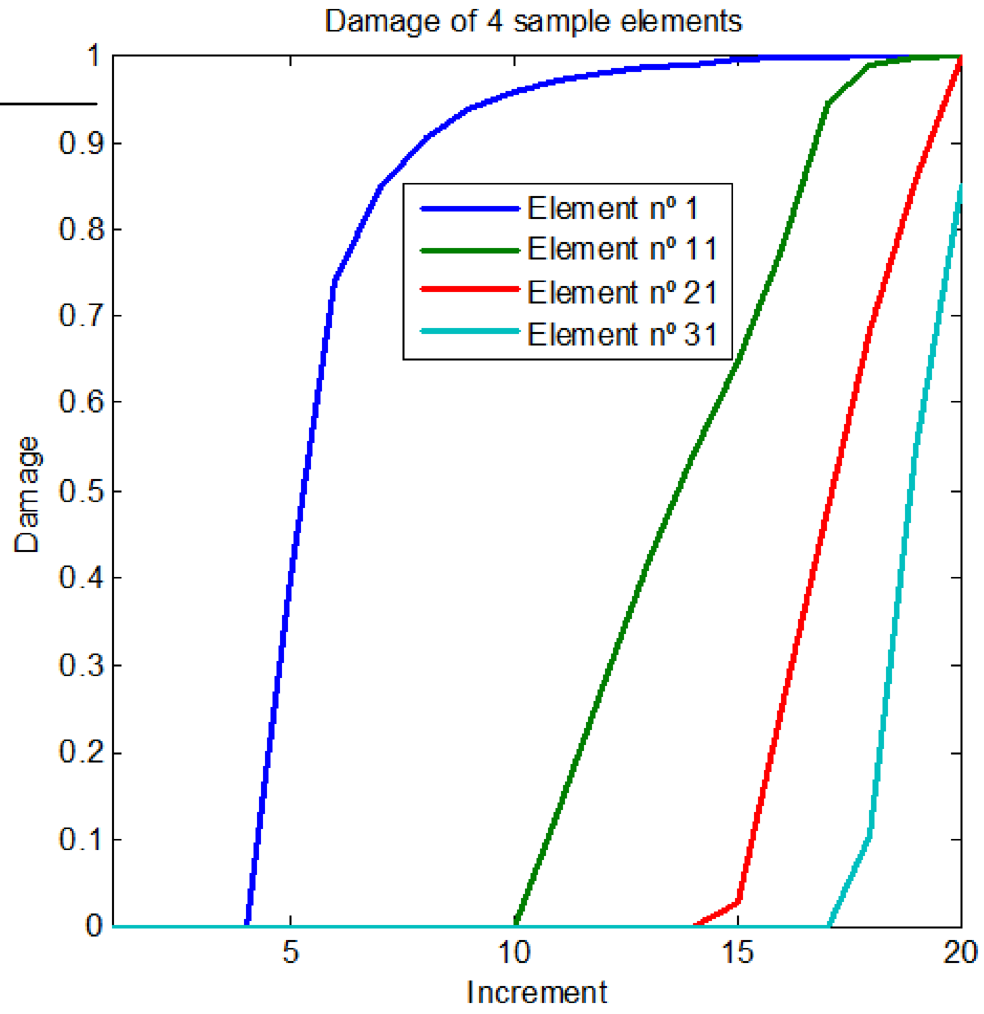
Contents

- Introduction
  - Motivation
  - Objectives
- Degradation of the joint
  - Humidity
  - Humidity and Fatigue influence
- Experimental procedure
- Experimental results
- Numerical modelling
- Conclusions and future work

Numerical modelling - methodology

If totally damaged, crack length is calculated. If partially damaged, it belongs in the FPZ.

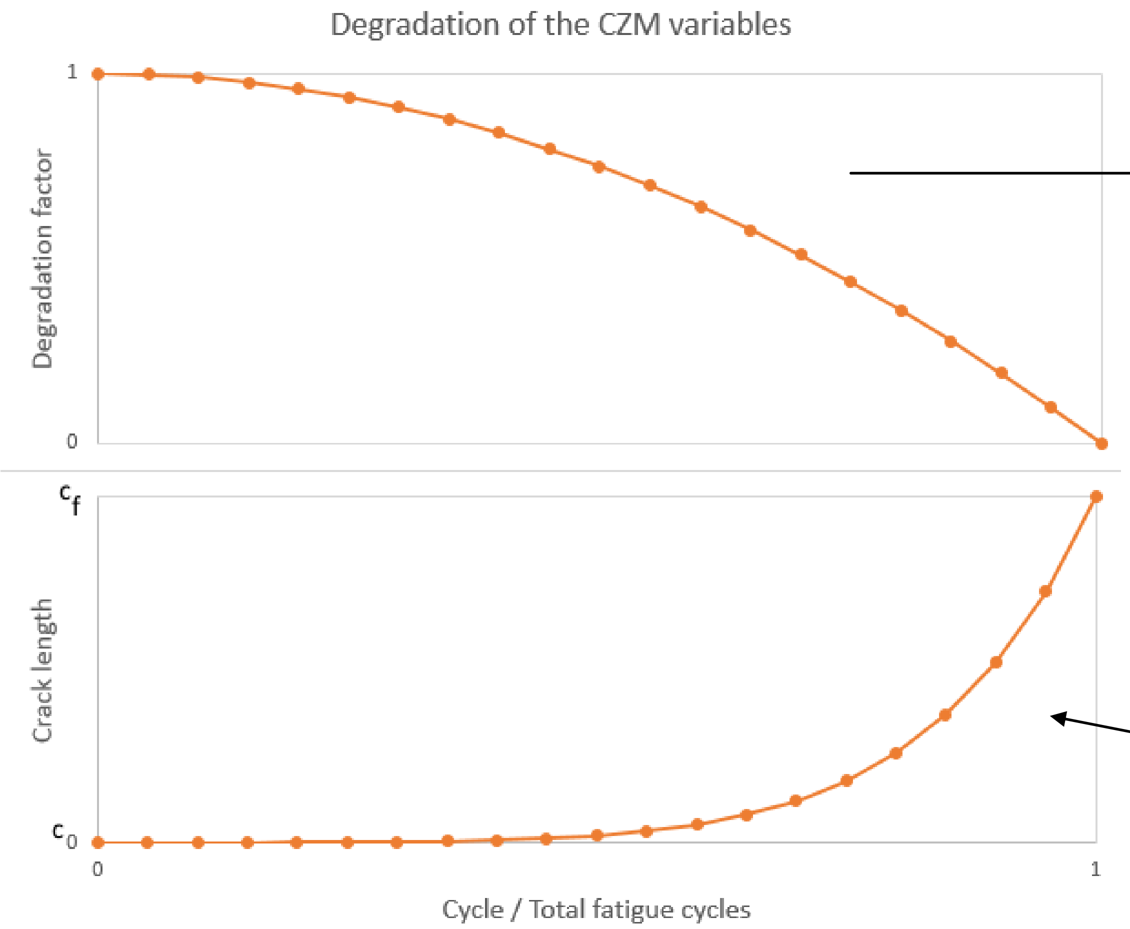




Contents

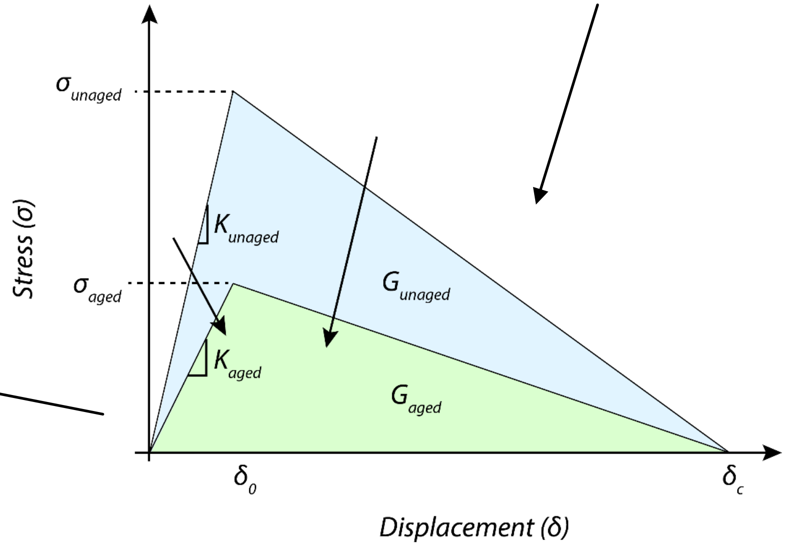
- Introduction
  - Motivation
  - Objectives
- Degradation of the joint
  - Humidity
  - Fatigue
- Cohesive Zone Model
  - Definition
  - Humidity and Fatigue influence
- Experimental results
- **Numerical modelling**
- Conclusions and future work

Numerical modelling - degradation



$$\sigma_{aged} = \sigma_{unaged} \cdot \left(1 - \frac{increment}{total\ increments}\right)^2$$

$$G_{aged} = G_{unaged} \cdot \left(1 - \frac{increment}{total\ increments}\right)^2$$



Contents

- Introduction
  - Motivation
  - Objectives
- Degradation of the joint
  - Humidity
  - Fatigue
- Cohesive Zone Model
  - Definition
  - Humidity and Fatigue influence
- Experimental results
- Numerical modelling
- Conclusions and future work

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 exact relationship between aged and unaged parameters;
- Implement the relationship in the UEL routine.

Acknowledgements

Fundação para a Ciência e a Tecnologia (FCT) for supporting this work through grant EXCL/EMS-PRO/0084/2012

Nagase Chemtex and Sika