CMDWC 2021

Article

Predicting Environmental Ageing of Composites: Modular Approach & Multiscale Modelling

Andrey E. Krauklis

Institute for Mechanics of Materials, University of Latvia, Jelgavas Street 3, Riga, LV-1004, Latvia; andykrauklis@gmail.com; andrejs.krauklis@lu.lv; tel. +371 268 10 288

Abstract: Fibre-reinforced composite materials are used in structural applications in marine, offshore and oil & gas industries due to their light weight and excellent mechanical properties. However, an exposure of such materials to water leads to environmental ageing, weakening the composite over time. A typical design lifetime of offshore composite structures, being in direct contact with water and humid air, spans 25 years or more. Thus, prediction and modelling of the environmental ageing phenomena becomes highly important, especially for predicting the long-term environmental durability. In this work, a systematic and modular approach for quantitatively modelling such phenomena is provided. The modular methodology presented in this work can and should be further expanded – it is multiscale and scalable. In the state-of-the-art, the degradation framework is not complete, yet it is a systematic step towards the multiscale modelling paradigm for composite materials. The topic of environmental durability of composite materials is being actively developed and is expected to continue growing also in the future.

There are 3 constituents in a composite: matrix, fibres and an interphase. Each constituent degrades differently and may also affect the degradation behaviour of each other. Therefore, a modular multiscale approach is preferred. The modules are based on the physics, chemistry of individual constituents' interaction with the environment, including diffusion, molecular mechanisms and kinetics of environmental ageing.

The methodology is seen as a useful approach for both industry and academia, including such use cases as accelerated testing, prediction of lifetime of composite materials and structures, as well as improving understanding of the environmental ageing effects and the time-dependent properties of composites due to environmental ageing.

Keywords: composite materials; environmental ageing; multiscale modelling; accelerated ageing; lifetime prediction

---

Funding: This work was funded by the European Regional Development Fund within the Activity 1.1.1.2 "Post-doctoral Research Aid" of the Specific Aid Objective 1.1.1 of the Operational Programme "Growth and Employment" (Nr.1.1.1.2/VIAA/4/20/606, "Modelling Toolbox for Predicting Long-Term Performance of Structural Polymer Composites under Synergistic Environmental Ageing Conditions").

Acknowledgements: Andrey is especially grateful to Oksana V. Golubova for her support.

References

1. A. E. Krauklis, "Environmental Aging of Constituent Materials in Fiber-Reinforced Polymer Composites," *Ph.D. Thesis, NTNU, Trondheim, Norway*, pp 203, Aug 2019.
2. A. I. Gagani, "Environmental Effects on Fiber Reinforced Polymer Composites - Fluid and Temperature Effects on Mechanical Performance," *Ph.D. Thesis, NTNU, Trondheim, Norway*, May 2019.

3. A. T. Echtermeyer and A. I. Gagani and A. E. Krauklis and T. Mazan, "Multiscale Modelling of Environmental Degradation—First Steps," *Durability of Composites in a Marine Environment*, vol 2, pp 135-149, Jan 2018.
4. A. I. Gagani and Y. Fan and A. Muliana and A. T. Echtermeyer, "Micromechanical modeling of anisotropic water diffusion in glass fiber epoxy reinforced composites," *J Comp Mater*, vol 52, pp 2321-2335, Dec 2017.
5. A. I. Gagani and A. T. Echtermeyer, "Influence of delaminations on fluid diffusion in multidirectional composite laminates – Theory and experiments," *Int J Solids Struct*, vol 158, pp 232-242, Sep 2018.
6. A. I. Gagani and A. E. Krauklis and A. T. Echtermeyer, "Orthotropic fluid diffusion in composite marine structures. Experimental procedure, analytical and numerical modelling of plates, rods and pipes," *Comp Part A*, vol 115, pp 196-205, Sep 2018.
7. A. E. Krauklis and A. I. Gagani and A. T. Echtermeyer, "Near-Infrared Spectroscopic Method for Monitoring Water Content in Epoxy Resins and Fiber-Reinforced Composites," *Materials*, vol 11, pp 586-599, Apr 2018.
8. A. E. Krauklis and A. T. Echtermeyer, "Mechanism of Yellowing: Carbonyl Formation during Hygrothermal Aging in a Common Amine Epoxy," *Polymers*, vol 10, pp 1017-1031, Sep 2018.
9. A. E. Krauklis and A. I. Gagani and A. T. Echtermeyer, "Hygrothermal Aging of Amine Epoxy: Reversible Static and Fatigue Properties," *Open Eng*, vol 8, pp 447-454, Nov 2018.
10. A. E. Krauklis and A. I. Gagani and A. T. Echtermeyer, "Prediction of Orthotropic Hygroscopic Swelling of Fiber-Reinforced Composites from Isotropic Swelling of Matrix Polymer," *J Comp Sci*, vol 3, pp 10-23, Jan 2019.
11. A. E. Krauklis and A. T. Echtermeyer, "Long-Term Dissolution of Glass Fibers in Water Described by Dissolving Cylinder Zero-Order Kinetic Model: Mass Loss and Radius Reduction," *Open Chem*, vol 16, pp 1189-1199, Nov 2018.
12. A. E. Krauklis and A. I. Gagani and K. Vegere and I. Kalnina and M. Klavins and A. T. Echtermeyer, "Dissolution Kinetics of R-Glass Fibres: Influence of Water Acidity, Temperature, and Stress Corrosion," *Fibers*, vol 7, pp 22-39, Mar 2019.
13. A. E. Krauklis and A. I. Gagani and A. T. Echtermeyer, "Long-Term Hydrolytic Degradation of the Sizing-Rich Composite Interphase," *Coatings*, vol 9, pp 263-286, Apr 2019.
14. A. T. Echtermeyer and A. E. Krauklis and A. I. Gagani and E. Saeter, "Zero Stress Aging of Glass and Carbon Fibers in Water and Oil—Strength Reduction Explained by Dissolution Kinetics," *Fibers*, vol 7, pp 107-120, Dec 2019.
15. A. E. Krauklis and A. G. Akulichev and A. I. Gagani and A. T. Echtermeyer, "Time–Temperature–Plasticization Superposition Principle: Predicting Creep of a Plasticized Epoxy," *Polymers*, vol 11, pp 1848-1859, Nov 2019.
16. A. I. Gagani and A. E. Krauklis and A. T. Echtermeyer, "Anisotropic fluid diffusion in carbon fiber reinforced composite rods: Experimental, analytical and numerical study," *Mar Struct*, vol 59, pp 47-59, May 2018.
17. A. E. Krauklis and A.I. Gagani and A.T. Echtermeyer, "Hygrothermal aging of fiber-reinforced composites: Introduction to phenomenological perspective and mass balance approach," *21st International Conference on Composite Structures (ICCS21)*, Sep 2018.
18. A. E. Krauklis and A. T. Echtermeyer, "Dissolving Cylinder Zero-Order Kinetic Model for Predicting Hygrothermal Aging of Glass Fiber Bundles and Fiber-Reinforced Composites," *4th International Glass Fiber Symposium*, Oct 2018.
19. A. T. Echtermeyer and A. I. Gagani and A. E. Krauklis and R. Moslemian, "Long Term Fatigue Degradation - Superposition of Dry and Wet Properties," *22nd International Conference on Composite Materials (ICCM22)*, Aug 2019.
20. A. I. Gagani and A. E. Krauklis and E. Sæter and N. P. Vedvik and A. T. Echtermeyer, "A novel method for testing and determining ILSS for marine and offshore composites," *Comp Struct*, vol 220, pp 431-440, Jul 2019.
21. A. I. Gagani and A. B. Monsås and A. E. Krauklis and A. T. Echtermeyer, "The effect of temperature and water immersion on the interlaminar shear fatigue of glass fiber epoxy composites using the I-beam method," *Composites Science and Technology*, vol 181, pp 107703-107712, Sep 2019.
22. Y. Fan and A. E. Krauklis and A. Gagani and E. Sæter and A. T. Echtermeyer and A. Muliana, "Predicting Multi-axial Diffusion of Water in Laminated Composite Structural Components," *Comp Struct*, vol 261, pp 113551-113562, Apr 2021.
23. A. I. Gagani and E. P. V. Mialon and A. T. Echtermeyer, "Immersed interlaminar fatigue of glass fiber epoxy composites using the I-beam method," *Int J Fatigue*, vol 119, pp 302-310, Feb 2019.
24. A. I. Gagani and A. T. Echtermeyer, "Influence of delaminations on fluid diffusion in multidirectional composite laminates–theory and experiments," *Int J Solids Struct*, vol 158, pp 232-242, Feb 2019.
25. A. I. Gagani and A. T. Echtermeyer, "Fluid diffusion in cracked composite laminates–Analytical, numerical and experimental study," *Composites Science and Technology*, vol 160, pp 86-96, May 2018.

26. J. Bicerano, "Prediction of Polymer Properties, Ed. 3," *CRC Press*, pp 756, Aug 2002.
27. J. P. Foreman and S. Behzadi and S. A. Tsampas and D. Porter and P. T. Curtis and F. R. Jones, "Rate dependent multiscale modelling of fibre reinforced composites," *Plastics, Rubber and Composites*, vol 38, pp 67-71, Jul 2009.