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NOVEL SERR-CONTROLLED ENVIRONMENTAL FATIGUE TEST METHODOLOGY FOR ADHESIVE-BONDED LAMINATES

Gabriel Riedl*, Robert Pugstaller, Gernot M. Wallner

Johannes Kepler University, Institute of Polymeric Materials and Testing, Linz, Austria
Christian Doppler Laboratory for Superimposed Mechanical-Environmental Ageing of Polymeric Hybrid Laminates, University of Linz, Austria
** Presenting Author email: gabriel.riedl@jku.at*

Abstract
In this paper a novel environmental fatigue test methodology is presented, in which the strain energy release rate (SERR) was controlled during the cyclic experiment at an elevated temperature in humid air. Therefore, an electrodynamic testing machine equipped with a custom-built environmental chamber along with a compatible calculation and controlling software package was used. To determine the crack length based on force and displacement data a compliance-based calibration method was implemented. SERR values were deduced for individual load cycles employing an user-defined control channel. The control channel allows for definition of a specific starting point (e.g., 10 J/m²) and an increase rate (e.g., +5 J/m² after 50,000 cycles). By holding the SERR constant over many cycles confidence bands were deduced for the measured crack propagation rates accounting for measurement uncertainties. To corroborate the novel methodology, experiments were conducted on double cantilever beam laminates bonded with soft adhesives in both, a SERR and a displacement controlled mode.

1. Introduction
Cyclic fatigue experiments of laminate structures are performed either in force or displacement controlled mode. Under force control, the set load has to be high enough to induce crack propagation in the pre-cracked laminate. The identification of adequate load values along with the achievement of a high number of load cycles ($N > 10^6$) is challenging and time-consuming. Displacement controlled fatigue tests overcome some of these issues. Initially, the forces are highest. The duration of the crack propagation regime is depending on the fixed displacement amplitude. Moreover, an adequate displacement amplitude allows for assessment of the threshold regime. Nevertheless, high initial forces may lead to wrong fatigue results, especially for soft, viscoelastic polymeric adhesives. This is related to excessive plastic deformation associated with void nucleation and fibrillation. In contrast, laminates fail in-service usually in a brittle manner, especially under harsh environmental conditions. So far, little research was done focusing on SERR controlled fatigue testing which would allow to overcome the problems described above. Hence, the main objective of this study was to implement and evaluate SERR controlled fatigue test procedures for hybrid laminates with a soft, polymeric adhesive layer.

2. Experimental
Double cantilever beam specimen based on glass laminates with weakly crosslinked ethylene-copolymer adhesive layer were investigated. An electrodynamic fatigue test machine (ElectroPuls E3000, Instron) along with the "Calculation Module" and "Advanced Control" (WaveMatrix™, Instron) software package were employed. To control the SERR value, the crack length was assessed for each load cycle. Therefore, the compliance of various double cantilever beam specimens with well-defined initial crack length was determined. By plotting the compliance data over the crack length in a double logarithmic diagram, a linear relationship was deduced. Adding the fitting parameters to user-defined functions within the WaveMatrix™ module allowed for calculation of the SERR value of a specific load cycle. The SERR values were adjusted according to a control function defining the starting SERR value, the step size and the step rates. Using the "Advanced Control" software package, the current applied strain energy release rate was automatically adjusted to the value of the user-defined control function. Furthermore, fluctuations of the crack propagation rate were evaluated by segmenting datasets at a constant SERR. To quantify the measurement

uncertainties, confidence bands were deduced with an implemented python script. The results of the SERR controlled fatigue tests were compared to already published data obtained under displacement control.

3. Results and Discussion

In Fig. 1 (left) fatigue crack growth curves are depicted for double glass DCB specimen tested under SERR and displacement control. Interestingly, an apparently higher delamination resistance was obtained in the displacement controlled experiment. The elastomeric adhesive revealed a pronounced plastic zone at the beginning of displacement controlled tests associated with void nucleation, growth and breakdown. This damage zone was less pronounced under SERR control. The resolution of SERR controlled tests is limited by the accuracy of crack length measurement and the test duration. It was difficult to analyze the threshold regime unambigously. Considering that crack length changes of 0.3 mm were detectable over 50,000 cycles by the compliance calibration method, the obtained crack propagation rate is limited to $6*10^{-6}$ mm/cycle. This is still exceeding the fatigue threshold regime. Nevertheless, the presented methodology is of high interest for development and monitoring of adhesives and derivation of constant crack propagation rates at user-defined SERR values. The progression of a SERR controlled fatigue test is illustrated in Fig. 1 (right). The SERR control was quite accurate. Just small deviations of ±0.1 J/m² from the set value were discernible. Moreover, the set values were reached at a frequency of 5 Hz within less than 200 cycles.

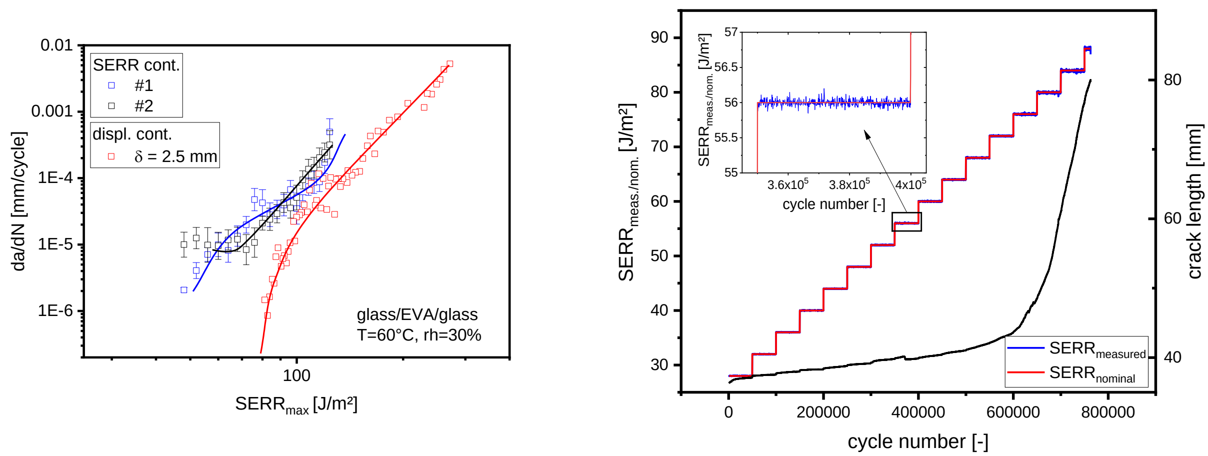

Fig.1 - left: Fatigue crack growth curve of a glass/EVA/glass laminate tested at 60°C and 30% rh under SERR (in black and blue) and displacement (in red) control. **right:** Illustration of nominal and measured, step-wise adjusted SERR values along with the measured crack length as a function of cycle number.

4. Summary and Conclusions

A novel fracture mechanics SERR controlled, environmental fatigue test approach was developed and implemented for double glass laminates with an elastomeric, semi-crystalline adhesive. Compared to displacement controlled experiments with pronounced plastics deformation of the soft adhesive a slightly lower fatigue delamination resistance was ascertained in SERR mode. At a test temperature within the melting range of the elastomeric, polar ethylene copolymer adhesive and defined SERR values, constant crack propagation rates were corroborated.

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