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Applicability of Displacement Controlled Fatigue Test Methods for Compliant Structures

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Abstract: Cyclically loaded components which reveal large compliances are wid ely used many industrial applications and are frequently exposed to co mplex combinations of mechanical loads. Both bulk and ela stomer composite components are used under cyclic loading conditions under high temperature gradients and in harsh environ ment. Current methodologies for describing elastomer fatigue behavior and to p redict the service life of rubber c omponents follow two general approaches [1]. One approach focuses on predicting crack nucleation life and makes use of continuum mechanics parameters such as stress and strain. The other is based on fracture mechanics concepts and focuses on the kinetics of crack growth using energy based fracture mechanics parameters. Furthermore, printed circuit boards (PCBs) reveal significant oscillations after drop tests and thus exposed to fa tigue loads on a lo cal scale. Fatigue experiments under displacement controlled cyclic loading for both of above approaches are described and discussed along with some examples in this paper.

Key words: *displacement controlled cyclic loading, elastomers and elastomer composites, printed circuit boards, local strain based Wöhler curves.*

1. Introduction

The characterization of the fatigue behaviour and the determination of adequate design parameters for compliant systems is not an easy task. Fatigue test are usually performed under force (nominal stress) controlled lo ading conditions and either conventional stress based Wöhler curves or fatigue crack growth kinetics curves using stress intensity factor (SIF) as a local crack tip parameter are determined. However, the app lication both of these methods is rather li mited for rubbers or other compliant structures. Due to the low modulus of elastomeric materials or due to low thickness of electronic components the test specimens reveal low stiffness. While the elastomers reveal an uniform low stiffness, the printed boards are weak in bending or in torsion. The accurate tuning (approaching the actual signal to the command signal and keeping it constant over the entire test duration) is rather difficult even for modern servohydraulic or electrodynamic testing machines which can apply sophisticated tuning algorithms

and possess fast controllers. Tuning, time delay at the start to reach constant amplitude (short term-problem) and keeping this amplitude constant over the entire test duration (long-term problem) are the main problems. For soft elastomers the accurate force controlled tuning with long term-stability is hardly possible and for stiffer elastomers it takes several 100 cycles even at low test frequencies (< 5 Hz). Furthermore, due to the large deformations and the highly non-linear behavior the determination of relevant stress values for these compliant systems is also difficult. It requires sophisticated experimental set-ups and the usage of finite element methods with complex material models.
To overcome several above mentioned difficulties various methods were proposed implemented and described in this paper.

2. Experimental

2.1. Test Methods

The following methods are described and discussed in this paper:

- Fatigue tests using Diabolo-type elastomer specimen under tensile loading. Cylindrical specimens with reduced cross section (smooth notch effect) along with suitable test devices for both single and multiple specimens were developed and used for elastomer tests.
- Further development of the De Mattia Tests for elastomers (also contains a well-defined smooth notch) under bending. The local strain around the notch was determined using additional optical strain measurements.
- Ring specimen tests of cross-ply elastomer laminates. Due to the stiffness difference of the layers and interlaminar crack initiation and growth is induced during the cyclic loading.
- Fracture mechanics test of elastomers using pure shear specimens (FWPS) with and without local crack tips strain measurements. While the conventional Tearing Energy method was used for the first experiments, the original definition of the J integral was used for the second in the data reduction.
- Bending fatigue tests of printed circuit boards (PCBs). The technical backgrounds and results are described in detail by Fuchs [2, 3].

Local strain based Wöhler curves (LSWC) have been proposed for characterizing the fatigue behavior of materials in above loading conditions. There are two options for determining proper local strain values. The deformation is measured by optical device and the digital image correlation technique (DIC) can be used for deriving local displacement and strain values [4, 5]. Furthermore, finite element simulations are performed and the local strain is determined.
This methodology with slight adoption for the specific situation was used after the Diabolo tests, De Mattia tests, PCB tests.
The common steps of the determination of local strain based Wöhler curves by displacement controlled method are:

- Global displacement controlled test are performed at constant test amplitude at several amplitude level.
- Determination of cycles-to-failure, N_f values based on the changes of the global force, F_{max}/F_{min}. vs. cycle number curves, N.
- in addition to improve the reliability of the entire test, compared to single specimen testing, multiple specimen testing can be carried out (this is possible only in displacement control).
- Determination of local strains (ε_l) in the relevant section of the test specimen either by using

experimental full field strain analysis or finite element method
- derivation a g lobal displacement – local strain calibration curve and finally
- Construction of local strain based Wöhler curve (ε_l-N_f).

Furthermore, the faint waist pure shear specimen configuration allows for the application of fracture mechanics techniques. An interesting c ross-correlation of the deMattia tests and the FWPS tests can be est ablished based on the local strain values [6, 7]. Moreover, the ring test specimen of elastomer laminates has potential for both above mentioned techniques

2.2 Testing machine and test equipments

The fatigue tests were run on various servohydraulic test systems (MTS 831.59 Polymer Test Sy stem, MTS 858 Test System and MTS 839 A/T Test System, MTS Systems GmbH, Berlin, D) applying various test configurations in the Laboratory of the Institute of Material Science and Testing of Plastics at the Montanuniversität Leoben during the employment of the Author. The local strains were determined using an image correlation based optical measurement system (Aramis, GOM, Braunschweig, D). The FE simulations have b een performed using the various version s of Ab aqus (Abaqus 6.9 to 6.12, Simulia, F).

3. Selected Results

3.1. Diabolo-type specimens

The Diabolo-type specimen was manufactured by injection molding and also by machining with differe nt surface quality. The geometry and the calculated strain distribution (FE) of the Diabolo-type specimen is shown in Fig. 1.

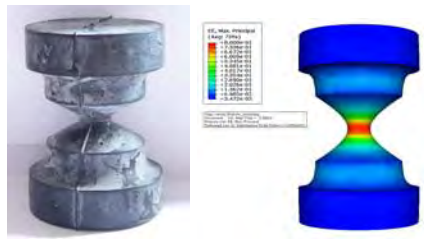


Fig. 1. *Diabolo-type specimen and its strain distribution (FE).*

Maximum and minimum force, F_{max}/F_{min} values were continuously recorded during the cyclic tests and example curve is plotted in Fig. 2. Based on these diagrams the cycle number-to-failure values, N_f were determined.

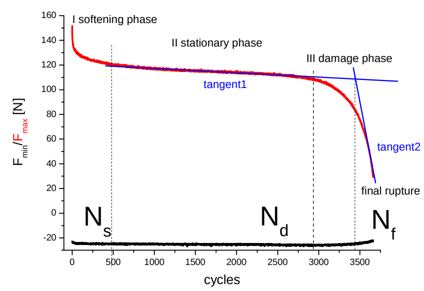


Fig. 2. *F_{max}/F_{min}-N curve.*

Furthermore, finite element simulations were performed and the local strain in the mid-section of t he specimen was determined and described in detail in [8]. Furthermore, a cali bration curve was created and it is shown in Fig. 3.

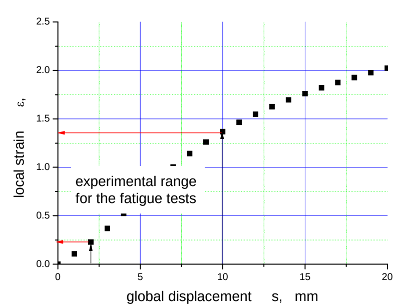


Fig. 3. *Global displacement-local strain calibration curve (FE).*

The accuracy of the local strain based Wöhler curve concept (LSWC) depends highly on the quality of the FE model. The LSWC was applied to v arious elastomer grades and several grades were characterized at elevated temperatures. The temperature dependence of the L SWC is shown for a selected grade in Fig. 4.

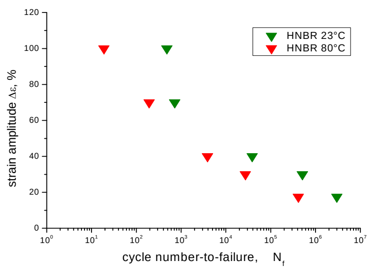


Fig. 4. *LSWC for a HNBR grade at 23 °C and at 80°C.*

As expected the curve at 80 °C was shifted to the right , indicating lower fatigue resistance.

3.2 The deMattia type specimen

The deMattia test specimen and the corresponding test method are widely used in the rubber industry for characterizing the fatigue behaviour of elastomers applying bending loading. To further develop this basic test in order to improve its informational value, the local strain distribution around the notch tip and the onset of a crack initiation on the notch root was measured by (DIC) method. Contr ary to the original method and sim ilar to the Diabolo method, displacement controlled tests were than performed at various displacement levels. The strain distribution of the specimen is shown in Fig. 5.

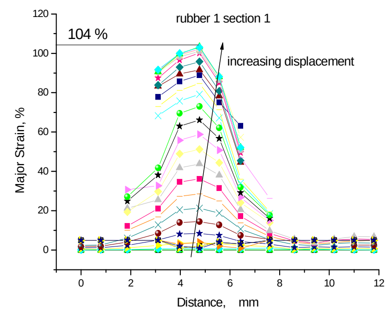


Fig. 5. *Strain distribution in the deMattia Specimen (DIC).*

At the standardized displacement amplitude (57 mm) the local strain lies above 100 % in the notch tip. An elliptical crack originates at the notch root and extends in all directions. The crack growth curve was determined by optical measurements and is shown in Fig. 6.

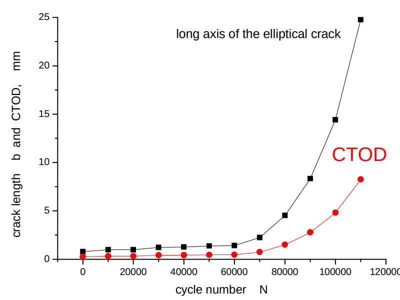
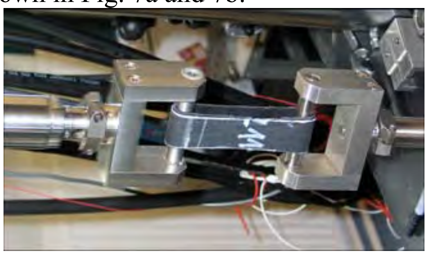


Fig. 6. *Crack growth curves of the de Mattia specimen.*

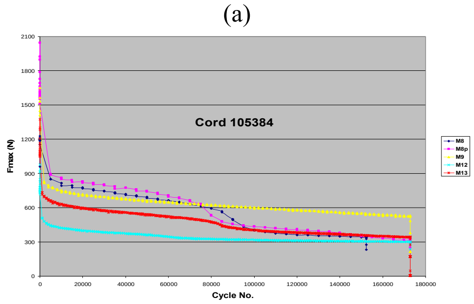
3.3 Ring type specimen-

To characterize the fatigue behaviour of elastomer composite components, ring type specimens were manu factured from cross-ply laminates including the real ply lay-up structure of the c omponents. The specimens were expos ed to cyclic axial loading and similar to the Diabolo both the force-displacement hysteretic curves as well as the F_{max}/F_{min} curves were plotted in order to characterize the failu re kinetics.

The test set-up and the F_{max}/F_{min} curves are shown in Fig. 7a and 7b.



(a)



(b)

Fig. 7. *(a) Test set-up and (b) F_{max}-N curves for various grades.*

These tests were carried out only at specific test amplitude, although, multiple level test would also easily be possible. The interply delamination of the ring specimen is shown in Fig. 8.

Fig. 8. *Delamination in the ring specimen.*

The determination of the onset of the delamination is of prime practical importance in these tests. Various combinations of elastomer layers, fibers along with coatings reveal significantly different crack initiation and growth. The crack may first start either in the elastomer and move to the interface or contrary to this, starts at the interface and moves to the bulk. An example of the initiation site on the scanning electron microscopy image is shown in Fig. 9.

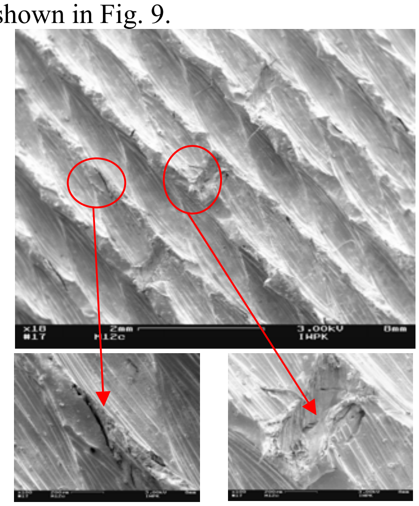


Fig. 9. *Scanning electron microscopy images of the fracture surface.*

3.4 Bending test of PCBs

To improve the characterization of printed circuit board panels along with insert and onsert functional elements and in addition to the well-known impact tests [9], bending tests of PCBs under cyclic loading conditions were performed at various displacement levels. An additional sensor was used to recognize the onset of the failure [3] and to determine appropriate N_f values. As the failure occurred in the solder joint, the relevant local failure parameter in terms of equivalent plastic strain, ε_p was determined by finite element simulations of the PCBs. Similar to the Diabolo method, local strain based Wöhler curves were constructed. The test set-up is shown in Fig. 10. It must be mentioned, however, that the method might be extended for the damage characterization of the glass fiber reinforced ply layers.

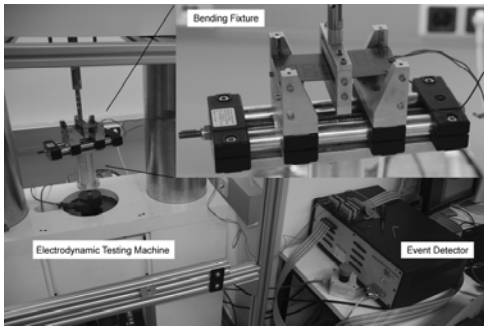


Fig. 10. *PCB test set-up[2].*

The crack initiation was observed in the solder point as it is shown in Fig. 11.

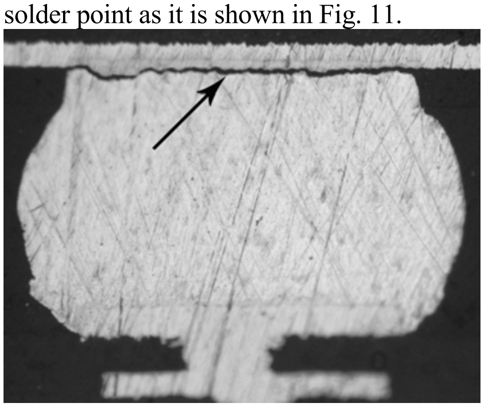


Fig. 11. *Solder point with crack.*

To apply the LSWC concept the local strain in this region was determined by FE simulation [3] and the strain distribution is shown in Fig. 12.

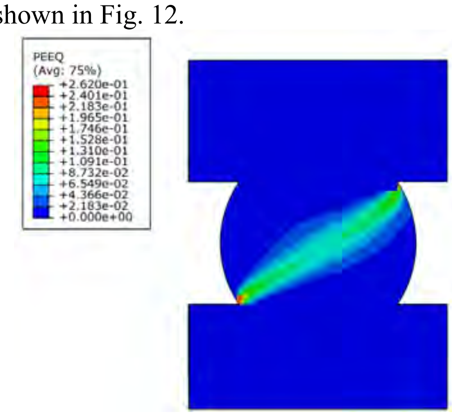


Fig. 12. *FE Simulation of the solder point.*

Finally, the LSWC curve was generated and in this case again fitted by a proper metal fatigue model (Manson and Coffin).

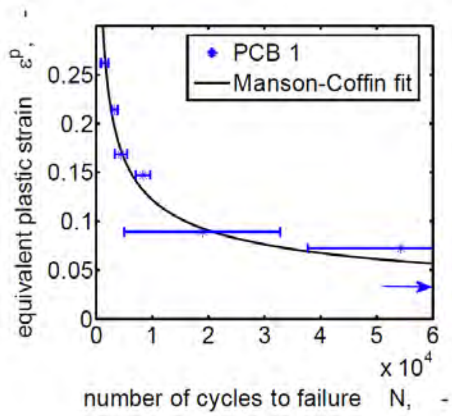
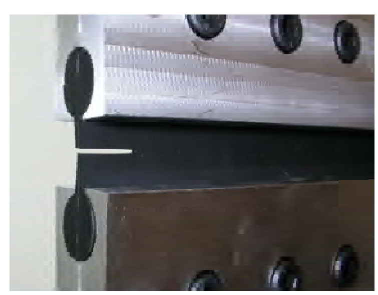


Fig. 13. *LSWC curve using equivalent plastic strain[3].*

While at high strain values a low data scatter, at low strain values a rather high data scatter was observed.

3.5 Fracture mechanics tests with FWPS specimens

Finally, for offering alternative concept for the data reduction, fracture mechanics type test have been performed. While above described local strain-based Wöhler curves provides information for the designers about the crack initiation, fracture mechanics methods are used for characterizing the crack growth behaviour of polymers [10] and Elastomers [6, 11]. The notched FWPS specimen along with the strain distribution is shown Fig. 14.



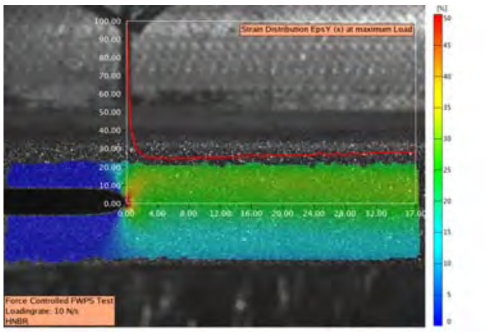


Fig. 14. *The pre-crack and the crack tip strain distribution of FWPS specimen.*

The FWPS tests were performed by applying a blockwise (10kcycles) increase of the loading amplitude. Selected crack growth curves for two elastomer grades illustrate the difference between the elastomers regarding fatigue crack growth resistance in Fig. 15.

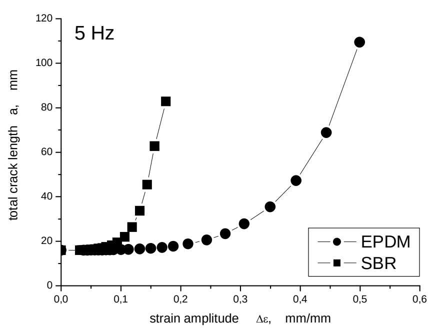


Fig. 15. *Crack growth curves of FWPS specimens for two elastomer grades.*

A summary of TE curves for various elastomer grades is shown in Fig. 16. While the threshold tearing energy values are significantly different for these elastomer grades, a minor variation of the slope of these curves was observed. That is, significantly different stress, strain or energy input is needed for initiating crack growth, but a growing crack is very similar for very different grades. Similar observation was done regarding the crack tip radius sensitivity [6, 11].

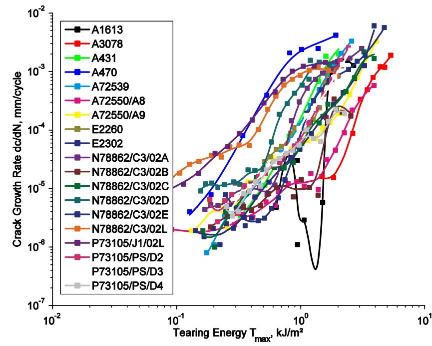


Fig. 16. *Tearing energy curves of FWPS specimens for many elastomer grades.*

As it was mentioned before, global tearing energy values may be calculated using global force-displacement curves. It is expected and it was proven, that in a pure shear stress state, the tearing energy is independent from the crack length and it may be calculated applying the strain energy density, W and the original height of the specimen, h_0 [6]. This method provides sufficient results for material characterization in the stable crack growth regime. However, the significant difference between elastomers lies not in the stable crack growth range, rather in the crack initiation (threshold) regime. Hence, the local crack tip strain and crack initiation behaviour was more closely investigated. To determine J-integral values based on the original definition by Rice [12], a hybrid experimental-numerical procedure was elaborated by Feichter [11]. J-integral values both under monotonic and under cyclic loading conditions have been determined and compared to global Tearing energy values for a number of elastomer grades. An example of this comparison is shown in Fig. 17.

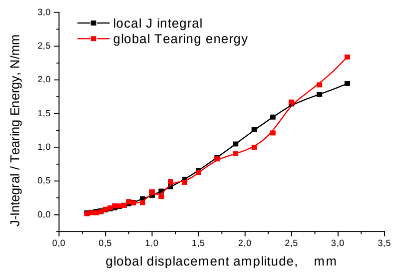


Fig. 17. *Crack growth curves of FWPS specimen for two elastomer grades.*

A good agreement between global TE and local J was found for this material. In general, the correspondence depends highly on the quality of the hyperelastic material models used and the quality of the DIC measurement. In addition to the J calculations, the directions of t he crack growth and the ro le of sh ear stress components was investigated.

4. Summary, Conclusions and Outlook

Global displacement controlled cyclic tests can easily be carried out using modern fatigue machines over a wide amplitude range. These experiments are simpler than force controlled ones and it was expected and was proven that they may reveal less data scatter. However, in polymeric materials stress relaxation occurs under constant displacement. In these tests 3 stages were observed, (1) Mullins-effect, (2) stable and (3) unstable damage. The hysteretic curves recorded provide reliable F_{max}/F_{min} values over the entire cycle number range and used for assigning proper cycle-to-failure, N_f values.

Furthermore, while the conventional Wöhler approach is based on engineering stress values, the application of the se values limited for polymers and for complex composite (elastomer laminates) or hybrid (PCB) structures. More relevant, local strain values can either be determined experimentally by DIC methods or by using FE simulations. The LSWC curves were generated by the combination of N_f and ε_l values. This technique was applied in different test configurations under tensile loading for elastom ers and for PCBs in bending.

It is not possible to describe and analyse all aspects and effects of these experiments within the lim itations of this paper. But several specific issues are dressed:

- To determine accurate LSWCs for elastomers adequate hyperelastic material models should be used
- Not only the LSWC method can be applied with deM attia set-up, but CTOA/CTOD values of the crack from the notch. This makes the establishment of a lin k between conventional and. fracture mechanics method
- In elastomer composite ring specimens interlaminar crack growth was observed. This makes the establishment of a lin k between conventional and. fracture mechanics method on both above tests.
- FWPS Specimens with global Tearing energy values were successfully used for comparison of the fatigue crack growth behaviour of many elastomers. For a focused analysis in the threshold regime and for design applications, local methods and the calculation of J integral is needed [13].
- Compliant structures under cy clic bending loading are t ested under displacement control and LSWC was successfully applied.

Future work is focusing on the num erical implementation of these methods and for the development of design procedures of elastomers components considering various fatigue mechanisms.

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