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Fracture mechanics test standards for fiber-reinforced polymer composites: Suggestions for adapting them to Industry 4.0 and the digital age

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Abstract

Fracture mechanics is expected to play an increasingly important role in design and development of components or structural elements made of fiber-reinforced polymer-matrix (FRP) composites, e.g., from carbon fiber epoxy. Test standard development in this sector has been slow. However, there are additional issues that impede implementation of the existing standards in Industry 4.0 and the digital age test facilities. Selected examples focus on recent developments in digital technologies, specifically imaging and image analysis and use of nondestructive test methods as well as handling of big data. Using these tools will reduce scatter (e.g., in determination of delamination lengths) and dependence on operator experience or qualification (i.e., the "human factor"). Further aspects discussed are automated data analysis and data fitting for evaluating materials properties, or for providing data for modelling and simulation of fracture behavior. It is argued that test set-ups with non-destructive delamination monitoring combined with automated analysis will efficiently provide reliable data for fracture mechanics based FRP structural design. Such data can also be compiled in data bases, e.g., for suppliers' data sheets or for comparing different FRP composites for use in structural applications. This is expected to have effects on the quality of data and on the test requirements as well as the related cost.

Keywords: fiber-reinforced polymer-matrix composites; fracture mechanics test standards; digital imaging; image analysis; big data; scatter in data;

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1. Introduction

Industry 4.0 is a term that is frequently used today, but digitalization and implementation of digital technologies that are at the core of this have roots that go back to the last century (see, e.g., Aceto et al., 2019). The development of fracture test standards for fiber-reinforced polymer-matrix (FRP) composites started in the 1980ies and is continuing today. However, up to now, the standard and draft test procedure documents dealing with these tests seem to have largely ignored digitalization. Overviews of the active, published standards and standards under development for FRP laminates are given, e.g., by Brunner et al. (2008) or, more recently, by Brunner (2019). The toughness or delamination resistance of FRP laminates under quasi-static or cyclic fatigue loads is typically determined for one of the basic loading modes. These are mode I (tensile opening), mode II (in-plane shear) or mode III (out-of-plane twist) or combinations thereof. The standards also specify the fiber orientation or lay-up for the fracture tests. Even though very few applications use so-called unidirectionally fiber-reinforced laminates with all fibers aligned in one direction, it is the choice for essentially all standards to date. This specific fiber lay-up implies that, on one hand, data from the tests are to some extent affected by so-called fiber bridging. This is most pronounced in tensile opening loading (mode I), and somewhat less in other modes, but avoids difficulties, such as crack branching and multiple delaminations that have been observed in testing multidirectional laminates (see, e.g., Brunner 2019). Fiber-bridging clearly occurs much less in laminates with woven reinforcement (see, e.g., Banks-Sills et al. 2019). On the other hand, the observation of large-scale fiber bridging in the standard tests raises the question of how such data can safely be used in FRP structural design (see, e.g., Yao et al. 2018a) where most fiber lay-ups are multidirectional or even quasi-isotropic (see, e.g., Yao et al. 2018b).

Nomenclature

AE	Acoustic Emission
CFRP	Carbon Fiber-Reinforced Polymer-Matrix (composite)
CZM	Cohesive Zone Model
DCB	Double Cantilever Beam (specimen)
ELS	End Loaded Split (specimen)
ENF	End Notched Flexure (specimen)
FBG	Fiber Bragg Grating
Gc	critical energy release rate
GFRP	Glass Fiber-Reinforced Polymer-Matrix (composite)
MD	Multidirectional (fiber lay-up)
MMB	Mixed Mode Bending (specimen)
m	exponential coefficient of the Paris equation (for fitting fatigue fracture data)
NDT	Non-Destructive Test
PEEK	poly-ether-ether-ketone (thermoplastic polymer)
UD	Unidirectional (fiber lay-up)
X-ray μCT	X-ray micro-computed tomography

The toughness or delamination resistance of the UD FRP laminates according to the standard procedures (and also for test procedures under development to date) is essentially calculated from load and displacement data recorded by the test equipment (usually a mechanical test machine), from visually observed delamination lengths, and the size (average thickness and width) of the beam-shaped test specimens. The respective equations are detailed in standard documents, e.g., ASTM D5528, ASTM D7905, ASTM D6671, ISO 15024, ISO 15114, or JIS K7083. In cases where load blocks are applied for mounting the specimens in the test rig or test machine, correction factors involving the size of the load blocks have to be included in the data analysis. Visual reading of delamination lengths on the edge of the test specimen with a so-called travelling microscope that can move with the propagating tip of the delamination is the "standard" method. One notable exception is ISO 15114, the quasi-static ELS mode II procedure, where changes in the specimen compliance are correlated with the delamination and used for determining its length. This requires a calibration on a composite beam without delamination. The quasi-static ENF mode II procedures (JIS K7083 and ASTM D7905) use visual observation. Due to shear deformation in the ENF-specimen it may be quite difficult to unambiguously identify the delamination tip by visual observation (Blackman and Williams, 2005). The accuracy of visual observation (e.g., at least ±0.5 mm as required in ASTM D5528) hence significantly depends on the alertness and experience of the operator performing the measurement. This so-called "human factor" may also affect round robin results calculated by different people and different institutes, respectively as discussed by Brunner et al. (1994). In this case, the effect was essentially due to different interpretation of the draft test procedures used in the initial round robins, for example, the application of corrections factors. Another "human factor" effect was studied and analyzed by Davies (1996), who distributed a paper chart record of one single load-displacement curve from a quasi-static mode I test to 36 people familiar with this test and asked for identification of the non-linear and 5% compliance increase points on this curve. Both points (average Gc values of 1.04 and 1.34 kJ/m^2, respectively) were determined with a standard deviation of around 0.05 kJ/m^2 or between 4-5%. This indicates that the determination of the "visual" initiation point would show at least the same scatter, but likely even more. With typical reproducibility of mode I fracture round robin data with standard deviations (coefficient of variation for repeatability and reproducibility, respectively) between 7 and 14% for repeatability, and 10-18% for reproducibility from round robin results summarized by O'Brien and Martin (1993) it is clear that the contribution of variability in human assessment is significant. Another illustration of the effect of operator experience is provided by round robin data on mode I fatigue fracture (Stelzer et al., 2014). The coefficient "m" of the exponential fitting function in the double logarithmic Paris plot for a CFRP-epoxy laminate is similar for all five participants, but two institutes performing the test for the first time yielded larger scatter in this value, whereas for a thermoplastic CFRP-PEEK laminate discussed in the same paper, also the average value "m" was higher for these two participants.

Testing up to 19 million cycles in mode I fatigue fracture by Brunner et al. (2009) would yield "large" data files, if e.g., maximum and minimum loads and displacements for each cycle, and even larger ones, if the full cycles with a given resolution and hence sampling rate, respectively, were recorded. Maximum and minimum load and displacement were hence recorded only every few thousand cycles, to keep the file size within limits for spreadsheet calculation. Fitting larger data files for analysis, e.g., to the data fitting described for mode II fatigue fracture of adhesively bonded wood joints (Clerc et al., 2019) by hand is hardly feasible, but is accomplished easily by programmed analysis routines.

In view of the rapid development of computational power and related technological advances, e.g., in digital imaging and image analysis, in handling of "big" data with efficient algorithms, and of increasing automation based on computer controlled equipment, the methods and procedures described in the test standards seem rather old-fashioned or even outdated. Nowadays "big" data sets are in the range of several Gigabytes to Terabytes, but possibly, in a not too distant future, these values might considered to be "typical" or even "small". At the time of the initial development of the test procedures, computers were used to control test machines, but data in some cases were still recorded by analogue chart-recorders (see, e.g., informative Annex B.9 "Recommendations for obtaining the NL point" of ISO 15024). Most analysis and computation of toughness values were performed by hand. Nevertheless, during the development of the standard test procedures, spreadsheets for automated data analysis were introduced in some round robin tests. The advantage, beside ease of calculation, was that possible differences in interpreting the data analysis described in the procedures was eliminated, as discussed by Brunner (1994, 2000). However, at that time, there were no attempts at properly validating spreadsheets, e.g., by comparing results for selected sets of data obtained by different spreadsheets that had been developed independently.

2. Materials and Methods

The materials, where noted, are FRP composites and described in detail in the cited references. The methods discussed in this paper are fracture test standards and test procedures under development for standardization. The standards discussed here are either published by the American Society for Testing and Materials (ASTM), the International Organization for Standardization (ISO), or the Japanese Standardization Association (JSA) publishing Japanese Industrial Standards (JIS). The same or similar standard test procedures are published by other national organizations or by industry, e.g., aircraft manufacturers, see Brunner (2019) for more details on these. For quasi-static mode I the standard procedures are JIS K7086 (published 1993), ASTM D5528 (first published 1994, last revision 2013), and ISO 15024 (published 2001). For quasi-static mode II the standard procedures are JIS K7086 (published 1993), ISO 15114 (published 2014) and ASTM D7905 (published 2019), and for quasi-static mixed mode I/II it is ASTM D6671 (first published 2001, last revision 2019). There is one standard on mode I fatigue delamination onset, ASTM D6115 (published 1997 and last reapproved 2019). Cyclic fatigue fracture test procedures on delamination propagation in mode I, mode II or mixed mode I/II are under development, but not yet ready for standardization. Activities aiming at standardization of a quasi-static mode III test were stopped, again see Brunner (2019) for details. However, the issues discussed below essentially apply to all types of fracture tests.

3. Issues, Approaches and Discussions

3.1. Test set-up and fracture test monitoring

Likely, the issue where digital tools are most useful and already applied in some laboratories, but not implemented in the standard procedures, is the determination of delamination length. The "standard" method for delamination length measurement is visual observation, usually with the help of a travelling microscope moving along with the propagation of the tip of the delamination on the edge of the specimen (Fig. 1). The main disadvantage of this method is the dependence on the operator, in particular on alertness and experience, and the difficulty of identifying the position of the delamination tip, especially in pure mode II or mixed modes involving mode II. Also, if a delamination length reading is missed for whatever reason, there is no way to go back, except estimating a value by interpolation between two observations assuming, e.g., a roughly constant propagation speed. An example of recording the specimen edge during a test with a digital camera is discussed by Chocron and Banks-Sills, (2019). The authors integrated the camera recording in the test set-up and through the interface with the test machine all data are properly synchronized and stored. These files are then easily transferred to a digital analysis routine.

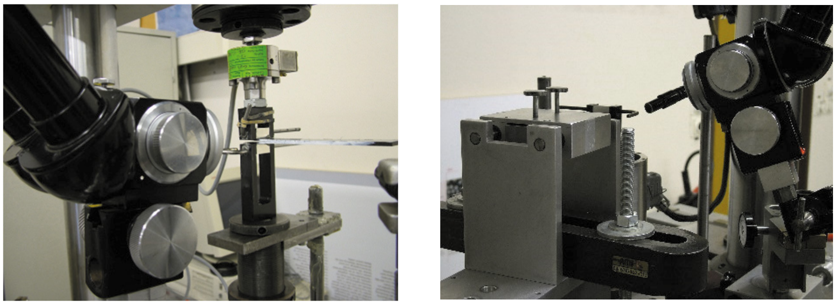


Fig. 1 (left) Mode I DCB delamination test set-up and (right) Mode II ELS set-up, both with travelling microscope for measuring the delamination length from the positon of its tip on the edge of the beam specimens.

There is a range of non-destructive test (NDT) methods for detecting delaminations in FRP composites and determining their size (see, e.g., Brunner et al. 2015 for details and discussion). Among the NDT methods, measurement of compliance (displacement divided by load) is one approach for which the data are readily available and only require a calibration (as detailed, e.g., in ISO 15114). There are also crack gauges for measuring delamination lengths (see, e.g., Shahverdi et al. 2012), but these are rarely used in practice. Disadvantages of crack gauges are their limited length range and the time required to mount them on the specimens and installing the measurement equipment. Ideally, the method for determining the delamination length independent of the visual observation by the operator should fulfill the following requirements: (1) provide at least the required resolution of length measurement (e.g., ±0.5 mm in ASTM D5528) throughout the test; (2) easy to integrate into the existing test set-up (not simply complementing it as an independent measurement to be synchronized later); (3) preferably non-contact method for eliminating potential interference during the test; (4) "simple" and "fast" set-up, calibration, and data analysis, and (5) equipment available at affordable cost and set-up and operation shall not require special qualification. There may be other criteria, but the above are considered the most important ones from an industrial perspective.

In addition to Chocron and Banks-Sills (2019), Kaushik et al. (2019) describe camera recording for delamination length measurements, with a lower level of integration into the test set-up, but specifying in detail the performance of the camera. Ekhtiyari et al. (2020) show that camera recording and image analysis with the open source program ImageJ are even applicable to high-rate delamination tests with J-integral analysis for toughness where visual observation is not possible. Contact-less, automated optical crack propagation monitoring with DIC is discussed by Khudiakova et al. (2020).

Some standards further require a check on the symmetry of the tip of the delamination (a difference of more than 2 mm in the position of the tip on either side after precracking and at the end of the test shall be noted in the report according to ASTM D5528 and ISO 15204). However, a set-up for continuously observing the delamination on both sides (edges) is rarely implemented. Verifying that delamination propagation does not result in strongly asymmetric shapes of the delamination tip, would make sense for interpreting the data, even if this is not prescribed by the current standards. If NDT methods are used for verifying the symmetry throughout the test (rather than at the end as required by the standards), this implies use of a second identical equipment (camera or other) with respective increase in experimental effort and testing cost, unless an arrangement with, e.g., a mirror and a single recording unit can be implemented. Other, more sophisticated NDT methods are reported in literature for delamination length determination, e.g., fiber optics with FBG (e.g., Farmand-Ashtiani et al., 2013), Acoustic Emission (AE, e.g., Mohammadi et al., 2015), or X-ray based methods, such as in-situ X-ray μCT (e.g., Sket et al., 2015). X-ray inspection is often used ex-situ, but this clearly is not suitable for monitoring delamination tests. Compared to the optical methods, their implementation in an industrial testing laboratory either requires much more elaborate equipment (e.g., AE, X-ray) or safety measures (e.g., for X-ray), more complex specimen preparation (e.g., fiber optics, whether embedded or surface mounted), or may not provide the required resolution (e.g., AE).

Digital data analysis and fitting is also used for the determination of materials values for modelling and simulation, and there is extensive literature on that. One example is the identification of CZM parameters and their uncertainty discussed by Jaillon et al. (2020).

An interesting question is whether test robots (typically advertised as "automated test systems") already do, or in the future, will achieve "better" quality of mounting of specimens in the test rigs and of setting up the associated measurement hardware than an experienced human operator. Test monitoring for any irregularity, also a task performed by the operator, may possibly be replaced by recording the test by video. It is expected that methods of artificial intelligence, such as machine learning, proposed for composite design and for predicting properties (see, e.g., Gu et al, 2018), if adapted and applied to data analysis may also be capable of identifying potential irregularities during testing, but this will require further development.

3.2. Data analysis

Computer aided data analysis has been introduced in the early stages of fracture test development by spreadsheet calculation. Fig. 2 shows an example of the spreadsheet described by Brunner et al. (1994) with data from a quasi-static mode I test performed on a CFRP epoxy laminate. The advantages of that have already been mentioned above.

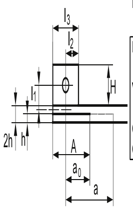
Limitations of the use of spreadsheets did not become clear until fatigue fracture test development started. Recording minimum and maximum load and displacement values for each cycle for averaging or fitting yields files with a size that cannot be handled by spreadsheets anymore, if tests are run up to several million cycles. Fig. 3 shows examples of fitting and extrapolating mode I fatigue fracture data for a CFRP epoxy composite. One graph shows the averaged Paris curve with upper and lower limit, the other an extrapolation of the experimental data to an assumed threshold at 10^{-7} mm/cycle. Statistical analysis of data, e.g., averages and scatter, determination of possible outliers, and of repeatability and reproducibility are also important, mainly for establishing precision statements for the standards, but also for materials data sheets, data banks and for use in simulation and modelling.

3.3. Required accuracy

Accuracy of the measurements is an important aspect in this discussion. ASTM D5528, for example, requires ±1% accuracy for load and displacement measurements relative to the indicated value over the load range of interest. In many fracture tests, typical loads are comparatively low, between a few N up to a few hundred N. and typical displacements on the order of a few mm to tens of mm. The load accuracy requirement hence corresponds to that of a class 1 test machine according to DIN EN ISO 7500-1 (2018). Assuming minimum recorded loads of 1-5 N for evaluating the toughness, the maximum range of the load cell, or the calibrated range used in the measurement, has to be limited. This is the reason why a calibrated load cell or load range around 200 to 250 N is recommended for mode I testing (Stelzer et al, 2012, 2014). For mode II and mixed mode I-II, this value shall be 1 kN maximum. The accuracy requirement for delamination length in ASTM D5528 is ±0.5 mm, i.e., ±(1-2)% of a typical delamination length between 50 and 100 mm. With digital image analysis, a higher accuracy of delamination length measurements seems feasible. However, the tip of the delamination is known to be curved, or sometimes showing an even more complex shape in the DCB specimens (see, e.g., de Kalbermatten et al. 1992) rather than straight as assumed in the schematic drawings shown in the standards. Therefore, the effective length of the delamination cannot be determined accurately from the position of the tip on the edges of the specimens. Any effort at determining fracture toughness or delamination resistance of FRP composites more accurately has to consider comparable accuracy for all relevant measurements. A crucial aspect in that is the scatter in the data, this is discussed in-depth by Alderliesten et al. (2018), distinguishing between intrinsic and extrinsic sources of scatter. Intrinsic scatter, e.g., typical material variability from processing and manufacture that would also exist in components and structures made from FRP has to be preserved (unless advances in processing and manufacturing technology provide higher reproducibility or repeatability), while extrinsic scatter, e.g., from test set-up and measurements has to be minimized.

Lab/Personnel:	Fiber/Matrix:	Test Date:
# of Specimens:	Manufacturer(s):	Stacking:

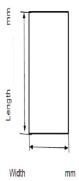
Specimen length	l [mm]	MISSING	Surf. prep./adhesive	[-]	MISSING		
Free length	L [mm]	MISSING	Block thickness / length	H / l_3 [mm]	6.50	/	12.85
Specimen thickness	2h [mm]	3.82	Max. cure / drying temp.	Tmc / Td [°C]	MISSING	/	71.00
Max. thickness variation	[mm]	0.06	Cure / drying duration	tc / td [h]	MISSING	/	1'103.00
Specimen width	B [mm]	20.37	Test temperature	T [°C]	23.00		
Starter foil material	[-]	MISSING	Relative humidity	r.h. [%]	50.00		
Starter foil thickness	[µm]	MISSING	Loading/unloading rate	[mm/min]	2.00	/	25.00
Starter foil length	A [mm]	61.50	Load introduction	[-]	Load blocks		
Precrack length	a_0 [mm]	51.50	Max.clamp displacement	dmax [mm]	MISSING		
% Change Compliance	Max / 5% [%]	MISSING	(Fiber volume fraction)	(Vf [Vol%])	MISSING		
			Distances l_1/l_2	[mm]	3.96	/	3.25



Regression

Method	Gcbt		Gecm		Gmcc	
Value	slope	Y-axis	slope	Y-axis	slope	Y-axis
	0.0107915	0.0372851	2.8317705	-5.525361	24.136358	-0.799825
Correction	Δ=	**-3.4551**	n=	**2.8318**	A1=	**24.1364**
Correl. coef	0.994982		0.994579		0.994982	

Comments and Observations



Text	Measure a [mm]	Load [N]	δ [mm]	Plate Manufacturer:	Results Gcbt [J/m2]	Gecm [J/m2]	E-Mod. [GPa]	Gmcc [J/m2]	Comments	Text	F [-] (> 0.9 ?)	N [-]	F/N [-]	C/N [mm/N]	(C/N)^1/3 [mm/N]	log(C/N) [mm/N]	log(a) [mm]	δ/a (< 0.4 ?)	Check ok ? (yes or no)
NL	51.50	24.00	4.84	Specimen and Insert	155.2	156.3	45.9	157.7		NL	0.9865	0.9894	0.9971	0.2038	0.5885	-0.6907	1.7118	0.0940	yes
5%	52.00	25.47	5.58	Location on Plate	188.1	189.3	43.3	187.7		0.05	0.9843	0.9876	0.9966	0.2218	0.6053	-0.6540	1.7160	0.1073	yes
Prop.	53.00	25.73	5.98		200.0	201.1	43.1	199.2		Prop.	0.9835	0.9870	0.9964	0.2355	0.6175	-0.6281	1.7243	0.1128	yes
Prop.	54.00	25.98	6.45		214.0	214.9	42.5	212.1		Prop.	0.9826	0.9863	0.9962	0.2517	0.6314	-0.5991	1.7324	0.1194	yes
Prop.	56.50	25.88	6.71		212.5	212.9	46.2	216.7		Prop.	0.9833	0.9868	0.9964	0.2627	0.6405	-0.5805	1.7520	0.1188	yes
Prop.	57.50	27.69	7.98		265.8	266.0	43.6	266.0		Prop.	0.9799	0.9841	0.9957	0.2928	0.6641	-0.5334	1.7597	0.1388	yes
Prop.	58.50	27.57	8.44		275.3	275.2	43.1	274.5		Prop.	0.9791	0.9835	0.9955	0.3113	0.6777	-0.5069	1.7672	0.1443	yes
Prop.	59.50	28.02	9.20		300.1	299.7	42.1	297.0		Prop.	0.9774	0.9821	0.9952	0.3343	0.6940	-0.4759	1.7745	0.1546	yes
Prop.	61.50	28.28	9.83		313.6	312.6	43.6	314.2		Prop.	0.9769	0.9817	0.9951	0.3541	0.7074	-0.4509	1.7889	0.1598	yes
Prop.	63.00	28.65	10.83		342.0	340.5	42.9	340.9		Prop.	0.9749	0.9801	0.9947	0.3857	0.7279	-0.4138	1.7993	0.1719	yes
Prop.	65.50	28.47	11.43		345.7	343.5	45.1	350.4		Prop.	0.9750	0.9802	0.9947	0.4096	0.7426	-0.3877	1.8162	0.1745	yes
Prop.	67.50	28.46	12.25		359.9	357.1	45.8	366.8		Prop.	0.9741	0.9795	0.9946	0.4395	0.7603	-0.3571	1.8293	0.1815	yes
Prop.	69.00	28.99	13.42		393.1	389.6	45.3	399.3		Prop.	0.9719	0.9776	0.9941	0.4735	0.7794	-0.3247	1.8388	0.1945	yes
Prop.	71.50	29.00	14.27	unknown	404.2	399.9	47.1	416.2		Prop.	0.9715	0.9773	0.9941	0.5035	0.7956	-0.2980	1.8543	0.1996	yes
Prop.	73.50	29.20	15.14		420.5	415.5	48.4	436.8		Prop.	0.9706	0.9765	0.9939	0.5309	0.8097	-0.2749	1.8663	0.2060	yes
Prop.	75.00	29.70	16.40		454.2	448.5	48.0	471.1		Prop.	0.9683	0.9747	0.9935	0.5665	0.8275	-0.2468	1.8751	0.2187	yes
Prop.	76.50	29.07	16.94		450.6	444.5	48.2	467.8		Prop.	0.9681	0.9744	0.9935	0.5980	0.8425	-0.2233	1.8837	0.2214	yes
Prop.	78.50	28.47	18.25		463.6	456.9	47.1	478.0		Prop.	0.9662	0.9729	0.9931	0.6589	0.8702	-0.1812	1.8949	0.2325	yes
Prop.	80.50	27.99	20.25		493.4	485.7	44.7	500.5		Prop.	0.9625	0.9698	0.9925	0.7460	0.9070	-0.1272	1.9058	0.2516	yes
Prop.	81.50	27.58	20.59		488.5	480.7	44.9	496.2		Prop.	0.9624	0.9697	0.9925	0.7699	0.9165	-0.1136	1.9112	0.2526	yes
Prop.	83.50	26.78	21.90		492.8	484.4	43.9	497.0		Prop.	0.9607	0.9683	0.9922	0.8446	0.9452	-0.0734	1.9217	0.2623	yes
Prop.	86.50	26.79	22.65		492.9	483.9	47.0	508.6		Prop.	0.9614	0.9688	0.9924	0.8726	0.9556	-0.0592	1.9370	0.2618	yes
Prop.	88.50	26.00	24.17		499.2	489.6	45.6	510.1		Prop.	0.9593	0.9670	0.9920	0.9613	0.9869	-0.0171	1.9469	0.2731	yes
Prop.	91.50	25.09	25.34		489.1	479.1	46.2	502.0		Prop.	0.9590	0.9668	0.9920	1.0447	1.0147	0.0190	1.9614	0.2769	yes
Prop.	92.50	24.52	26.81		500.2	489.8	43.9	505.3		Prop.	0.9562	0.9644	0.9915	1.1337	1.0427	0.0545	1.9661	0.2898	yes
Prop.	94.00	23.98	28.36		509.3	498.4	42.4	509.0		Prop.	0.9536	0.9623	0.9910	1.2290	1.0712	0.0896	1.9731	0.3017	yes
Prop.	96.50	23.88	28.72		500.9	489.7	45.1	510.6		Prop.	0.9551	0.9635	0.9913	1.2483	1.0767	0.0963	1.9845	0.2976	yes
Prop.	97.50	24.10	31.17		542.7	530.4	43.0	545.4		Prop.	0.9499	0.9591	0.9904	1.3485	1.1048	0.1299	1.9890	0.3197	yes
Prop.	99.00	24.10	32.34		554.6	541.8	43.3	558.8		Prop.	0.9484	0.9578	0.9901	1.4010	1.1189	0.1464	1.9956	0.3267	yes
Prop.	101.50	23.97	33.88		564.0	550.5	44.1	572.1		Prop.	0.9470	0.9567	0.9899	1.4774	1.1389	0.1695	2.0065	0.3338	yes
					412.2	Average	44.8												
						Max. Variation	Check												

Fig. 2 Example of spreadsheet for calculating quasi-static mode I delamination resistance, the data are for a glass-fiber epoxy laminate, similar spreadsheet routines do exist for mode I fatigue fracture testing.

4. Conclusions and Outlook

Digital technology so far has not been explicitly introduced in fracture test standards or test procedures under development, in spite of selected examples reported in published research literature. These indicate that digital technology could support and facilitate the following aspects of fracture testing of FRP composites: (1) imaging, e.g., recording with digital cameras, and possibly digital image analysis applied to evaluating delamination lengths (instead of the subjective visual observation by the operator), in particular when eliminating the need to interrupt cyclic fatigue loading for visual identification of the delamination tip that may produce an offset in the data (see, e.g., Stelzer et al. 2014); (2) integrating this digital imaging such that delamination length data are synchronized with load and displacement data records; (3) digital fitting or extrapolation of data and digital analysis, including statistics; and (4) use of the data in modelling and simulation, and, even though not discussed here, digital data storage in data banks.

It is suggested to develop minimum requirements for implementing digital imaging for delamination length determination in quasi-static and cyclic fracture tests of FRP composites and to provide this information in an informative annex in the respective standard documents. These requirements shall include the minimum image resolution necessary to comply with the length resolution noted in the standards, minimum requirements for data synchronization between load and displacement values recorded by the test machine and the delamination length images. Further, minimum sampling rates for recording load and displacement data have to be defined that allow sufficiently accurate digital fitting of the load-displacement curves for determination of the non-linear and 5% increase in compliance load points for calculating the initiation values of the critical energy release rate Gc. Another issue in the determination of the non-linear or 5% compliance change loads, at least in quasi-static fracture testing, is the elimination of the initial play in the test set-up. For that, both, the accuracy of load and displacement measurements as well as the sampling rate of the data points, play a role and these may, in the end, determine the minimum requirements for data recording.

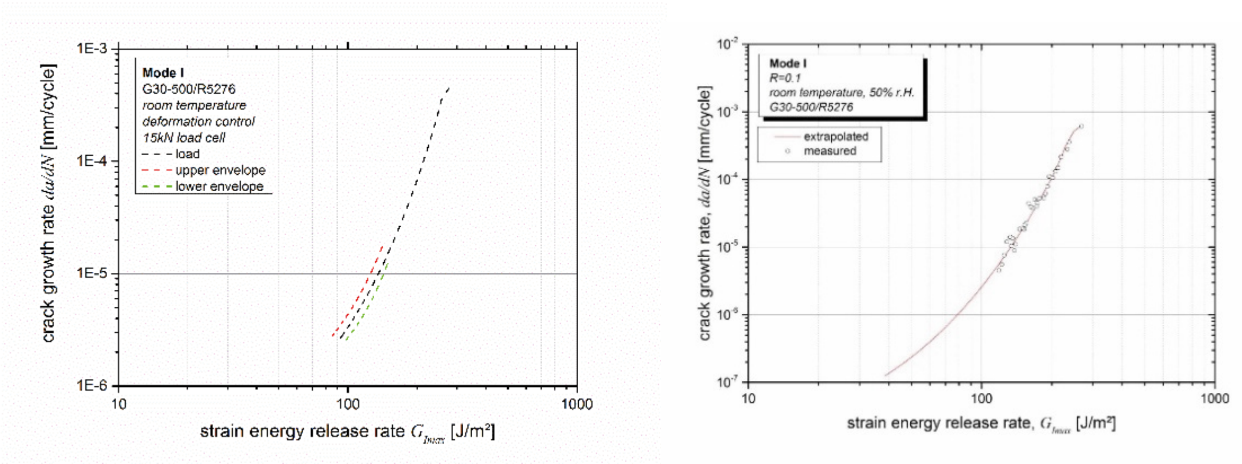


Fig. 3 Examples of data analysis of fatigue fracture tests on a CFRP epoxy laminate, (left) scatter in the Paris-plot, and (right) extrapolation of experimental data to a nominal threshold of 10^{-7} mm/cycle.

Data analysis of fracture tests on FRP composites has already been transformed to digital, at least in the form of programmed spreadsheets. The large data sets expected from fatigue fracture tests of FRP composites yielding the data necessary for fracture mechanics based design (Brunner et al., 2016) will benefit from algorithms with higher performance than standard spreadsheet programs. The tools for these developments as well as for more elaborate data fitting are available, and examples of applications have been cited above. One important issue, however, that has not received much attention yet is the validation of the spreadsheets or algorithms. Validation could be through round robin comparisons between different digital algorithms using the same sets of raw data. Determination of data for modelling or simulation from experiments and their related scatter also requires use of digital fitting and possibly extrapolation. This aspect is not discussed in detail here, but the increasing use of modelling and simulation in fracture research makes it likely that the importance of determining reliable input data and their scatter will increase.

From an industrial perspective, often the cost for qualified personnel is higher than cost for investing in digital technology and its integration into test machines. Therefore, it may well be that in the mid- and long-term cost reduction provides the better incentive for integrating digital technology in testing than the potential improvement in the accuracy of the data.

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