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# A new method to measure critical strain in composite materials – Combining the Euler–Fresnel spiral with acoustic emission to assess crack positions

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ABSTRACT

Critical strain is the strain level corresponding to the very first micro-crack in a composite layer. Current detection methods for such micro-cracks are limited to strain gage measurements, digital image correlation techniques or the Bergen ellipse [9]. With the Bergen ellipse a well-defined but non-linearly increasing strain can be applied to a strip of composite material to induce micro-cracks. In this paper a combined approach is described to measure the critical strain at which the first micro-crack occurs. The combined approach consists of 2 elements. First the Euler–Fresnel spiral is introduced as an elegant alternative to the Bergen ellipse to introduce a well-defined and *linearly* increasing strain to a strip of composite material secondly, since micro-cracks, caused by exceeding the critical strain values, are difficult to detect, multiple accelerometers on the composite strip are used to detect the micro-cracks by measuring the acoustic emission of the crack initiations. By measuring the time of arrival of the acoustic emission waves at the two ends of the strip, the positions of the micro-crack initiations can be determined. Using the geometrically defined relationship between strain and position on the Euler–Fresnel spiral, the strain-levels at crack initiations can be estimated. An important advantage of the approach described in this paper is that all micro-cracks are detected instantaneously during the measurement procedure. This includes the subsurface cracks that cannot be detected by the penetrant method. In this paper the proposed measuring method for critical strain in composites was successfully demonstrated.

## 1. Introduction to the critical strain and its relevance for composite materials

Most aircraft are covered by a nice furnish to protect their constructive materials. These protective layers have been improved during several decades to withstand environmental influences for longer time. Nowadays, aeroplanes are partly or fully made of composite materials. Even though the composite materials have been thoroughly characterized in terms of mechanical properties, some little, non-fatal damage, such as crazing followed by micro-cracking, may take place and show up on the outer layers of the composites at unexpected low strain levels. The micro-cracks are typically transverse cracks, i.e. in the thickness direction of the composite. Apart from esthetic degradation, these micro-cracks may function as notches from which fatigue cracks in the outer layers can start. The strain level at which these crazes and resulting irreversible micro-cracks occur in the material is referred to as 'critical strain'. At the critical strain no significant plastic deformation or breakage occurs. The critical strain is a material parameter that characterizes the onset of micro-cracks in composites, and is not depending on temperature if no phase transition is involved [1].

### 1.1. Micro-cracks

Former research has proven that transverse cracks reduce the stiffness, compressive and flexural strength of multidirectional laminates by less than 10% and are therefore not considered to be crucial in their effects on the structural performance [2,3]. This holds even at levels of saturated crack density. However, the

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process of micro-cracking is irreversible and initiated by crazing. The basic mechanism of craze initiation is starting with the formation of very small voids (<30 [nm]). These voids can then grow and finally become crazes. Crazing has been studied fundamentally by many researchers e.g. [4–6] and it is a well-known fact that crazes are no real cracks but thin spots in the material, just about to crack due to disentanglement and breakdown of the crazes. These microcracks will, if not arrested, propagate to the surface and function as a notch for the top layers which will eventually show visible cracks. Therefore crazing and micro-cracks must be considered as irreversible damage phenomena and a potential source of brittle fracture. They must be avoided in structural integrity critical applications [7].

### 1.2. Critical strain

Critical strain is often mentioned in the literature as "a strain limit for which problems might occur in several applications which were not expected on the basis of the specifications concerning the involved material properties". For example, solvent stress cracking of plastics due to solvent exposure has been a topic to General Motors in the late 1970s [8]. Normally, critical strain (as defined in this paper) is not an important design parameter (in the classical First Ply Failure detection procedure) because it does not immediately give any information about upcoming fatal failure of a material. However, materials like carbon/epoxy composites in combination with top layers (and their broad variety of applications) show a strong tendency to micro-cracking at unexpected low strain levels and therefore force us to reconsider critical strain as a meaningful design / damage parameter. The reason for this is that even the smallest craze or crack becomes immediately visible in the coating.

## 2. Development of Euler–Fresnel spiral as valid test method for critical strains

The determination of critical strain is usually carried out by tensile tests. With this method, the tensile strength is measured with a step-by-step increasing strain until the first damage appears. The strain is measured by strain gage, strain-o-meter, or digital image techniques. This method requires a significant number of samples and is time consuming. In the early 60s, Bergen introduced a method to measure critical strains of polymers using one test strip for the strain range up to 4%. The method consists of a curved rail into which a strip of composite material is pushed. The distance which the strip has traveled along the curved rail is measured constantly, see Fig. 1. For every location on the curved rail the curvature of the rail and the resulting strain in the strip is known. The Bergen ellipse has mainly been used to measure critical strains for environmental effects, stress cracking and solvent crazing of plastics under certain applied stress levels [9,10]. For composites, the Bergen ellipse is not suited due to the fact that composites will show critical strains far below the level of 4% strain. For the Bergen ellipse, the bending curvature (which is directly coupled to the strain level) is a strongly non-linear function of the contour length which causes its accuracy to be limited; it is over-sensitive to high strains and fairly insensitive tolow strains (for details on these statements we refer here to the next section). On the other hand, the curvature of the proposed Euler–Fresnel-curve is a perfectly linear function of the contour length and shows the same sensitivity to low and high strain levels without losing the advantage of using just one test strip, subjected to various strain levels. The following discussion is devoted to the development and comparison of the Bergen and Euler–Fresnel strain measurement methods.

### 2.1. Curvature description for Bergen–Ellipse and Euler–Fresnel Spiral

Let a two-dimensional curve **C** be given by:

$$\mathbf{C}(\theta) = \{\, x(\theta), \quad y(\theta)\,\}, \qquad \theta_0 \leqslant \theta \leqslant \theta_1 \tag{1}$$

The shape of the Bergen ellipse is described by:

$$\mathbf{C}_{\text{ell}}(\theta) = \{\, A\cos\theta, \quad B\sin\theta\,\} \tag{2}$$

where $A$ and $B$ are parameters (units [m]) of the ellipse. With standard goniometric relationships the curvature $\kappa$ (units [$\text{m}^{-1}$]) can be calculated as:

$$\kappa_{\text{ell}}(\theta) = \frac{AB}{\left(B^2\cos^2\theta + A^2\sin^2\theta\right)^{3/2}} \tag{3}$$

The Bergen ellipse from [9] is based on $A = 0.150$ [m] and $B = 0.06$ [m], as shown in Fig. 1.

The length of this Bergen elliptic curve, $s_{\max}$, is equal to 172.6 [mm]. The associated curvature as a function of the contour length (starting at the top of the curve, see Fig. 1a) is depicted in Fig. 1b. The curvature distribution [$\kappa_{\min}$, $\kappa_{\max}$] over the length [0, $s_{\max}$] is far from homogeneous. This strong non-linearity introduces significant measurement errors. At lower strain levels the sensitivity to length measuring inaccuracies is almost zero while at high strain levels the sensitivity to length measuring inaccuracies is too high.

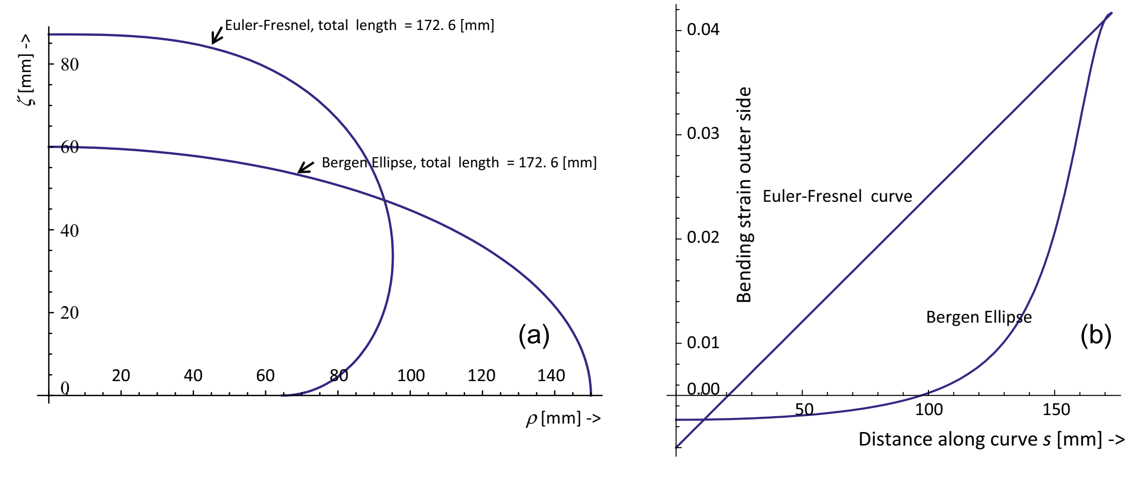

**Fig. 1.** (a) Euler–Fresnel curve: and Bergen ellipse curve; (b) Curvature as function of curve length for Bergen and Euler–Fresnel curve.