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Test method

# On the strain measurement and stiffness calculation of carbon fibre reinforced composites under quasi-static tensile and tension-tension fatigue loads

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The applicability of different strain measurement techniques for carbon/epoxy laminates under quasi-static tensile and tension-tension fatigue loads was studied. Strain gauges, mechanical extensometers, digital image correlation and 2 D camera systems were applied on laminates tested at angles of 0°, 45°, 60°, 90° and ±45°. In addition, displacements recorded by the servo-hydraulic piston were monitored and compared to local strain measurement techniques. Representative examples that illustrate characteristics and limits of each technique in quasi-static and fatigue tests are discussed. Influences of the respective method of strain measurement, the specimen surface, fibre direction and processes in the specimens during tests on the recorded stress-strain behaviour and on the calculated stiffness are presented. Recommendations for accurate strain measurement of anisotropic laminates based on the results are made.

## 1. Introduction

Carbon fibre reinforced plastics (CFRP) are, compared to metal materials, a relatively young material class. Consequently, comprehensive mechanical tests for assuring safe applications are even more important for these materials. Mechanical composite tests range from coupon level for material characterisation to component tests under realistic load profiles [1–3]. The highly anisotropic properties provide great opportunities for tailored components on the one hand. On the other hand, mechanical and thermal anisotropy issue new challenges to testing [4]. Regarding mechanical tests, material properties are mainly determined under quasi-static or fatigue loads. For both load cases, anisotropic material behaviour has to be considered for load application. Additionally, strains in composites are generally small compared to other materials. Under fatigue loads the associated strains in composites are even smaller [5]. Therefore, the recording of fatigue stress-strain behaviour requires attention to test techniques. A variety of methods for strain measurement under mechanical loads is available. However, studies about the choice of strain measurement technique or accurate strain measurement of composite materials are rarely available in literature.

In this work, the applicability of strain gauges, mechanical extensometer, digital image correlation (DIC) and 2 D camera systems for local strain measurement of carbon/epoxy laminates in quasi-static as well as fatigue tests is investigated. Machine piston displacement was also recorded in all tests to provide information about global strain behaviour. Stiffness of laminates tested at angles of 0°, 45°, 60°, 90° and ±45° was calculated according to different standards. Representative results measured with different techniques under quasi-static and fatigue loads are discussed. Limits, characteristics and influences on the measured stress-strain behaviour of each technique are illustrated. In preliminary tests, the tendency of different

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carbon/epoxy laminates for hysteretic heating in fatigue tests has been investigated, which is also presented. Recommendations for accurate mechanical testing, strain measurement and stiffness calculation under mechanical loads are given in conclusion.

### 1.1. Strain gauges

Strain gauges are one of the oldest and most accepted methods for measuring strains and were initially developed for use on specific metals. Measuring strains with strain gauges is based on changes in electrical resistance. Small resistance changes can be considered and are generally measured by using a Wheatstone bridge circuit [4]. When applying them to composite materials, inaccuracies can occur, mainly caused by the anisotropic nature of composite materials. Measuring accuracy can also be affected by strain gauge misalignment [6]. Beyond the need for calibration [4] and precise strain gauge alignment [6], the amount of time and money when many tests are required often limits the application of strain gauges.

### 1.2. Mechanical extensometers

Extensometers are, like strain gauges, a well-known and established technique for measuring strains originally developed for metal testing. Extensometers are easy to apply and available in different sizes and with different grips, depending on the type of test specimen, to assure good contact. Hodgkinson [4] points out one recommendation when using extensometers for strain measurement of composites: since failure in composites can occur suddenly or almost explosively, removing the extensometers prior to failure to avoid damaging of the extensometers is recommended. Another aspect which prevents strain measurement to final failure has been investigated by [7], [8] and [9]. In these three works, unidirectional and braided carbon/epoxy composites were tested under fatigue loads. In all fatigue tests, extensometers lost surface contact with the surfaces of CFRP specimens in the range of $10^4$ to $10^5$ cycles because of slipping and delamination prior to composite failure.

### 1.3. Digital image correlation

Digital Image Correlation (DIC) systems have been developed since the 1980's and have seen continuous improvement to very high levels since then. The main requirement of these systems is a pattern attached to the surface of the specimen to track local deformations. During loading, grey scale images of an object are compared with image correlation software. As a first step, the displacement field is calculated tangential to the displacement gradients. Secondly, strains are derived from the displacement gradients [10]. DIC systems provide great opportunities of accurate measurement of strains and strain fields. Longitudinal as well as transversal strains can be evaluated which provides advantage in comparison to other techniques. These systems are popular for different types of mechanical test with very different materials, such as high strain rate tests with glass-polypropylene weaves [11], biaxial tension and shear tests with unidirectional carbon-epoxy [10] or tests with polyoxymethylene [12].

### 1.4. Piston displacement

Piston displacement of test machines can also be used to interpret fatigue tests. In contrast to the local strain measurement techniques of strain gauges, extensometers and optical systems, piston displacement records not only the strain behaviour of the specimen but of the entire specimen–test machine–system. Consequently, data from piston displacement may vary from locally recorded data. Nevertheless, if the global character of the data measured via piston displacement is kept in mind, it can offer useful information about material fatigue behaviour in addition to local techniques.

## 2. Experimental work

Laminates made of carbon fibre and epoxy resin were studied in quasi-static tensile and tension-tension fatigue tests. EPIKOTE™ Resin MGS® RIMR135 (approved by German Lloyd) with the curing system EPIKURE™ Curing Agent MGS® RIMH1366 by Momentive (Esslingen am Neckar, Germany) and carbon fibres HS 15-50/250 by G. Angeloni srl (Quarto d'Altino, Italy) were used to produce plates in a vacuum assisted resin transfer moulding process. Glass transition temperature $T_g$ of the cured epoxy resin was about 93 °C (measured with differential scanning calorimetry). All carbon/epoxy plates were cured at 80 °C for 5 h. The curing process of the carbon/epoxy plates was monitored by dielectric analysis to assure fully cured plates for further specimen production. Carbon fibre volume content was 55% (measured with thermo gravimetric analysis). Unidirectional (UD) specimens were cut from the plates with diamond blades at angles of 0°, 45°, 60° and 90°. Balanced ±45° specimens were also produced. Geometry was 200 × 10 × 1 mm (length × width × thickness) for UD 0° and 200 × 20 × 2 mm for all other specimens. Aluminium tabs with 1 mm thickness were glued on both sides of all specimens.

Quasi-static as well as fatigue tests were performed on a servo-hydraulic test machine MTS 810 equipped with a load frame and load cell for 100 kN by MTS Systems Corporations (Minnesota, USA). Gauge length for all specimens was 100 mm. Hydraulic wedge grip pressure of 5 MPa was chosen in order to prevent slipping without damaging the specimen. Quasi-static tensile tests were performed with a test speed of 0.5 mm/min to failure. Tensile moduli of specimens tested at different angles were calculated between 0.0005 and 0.0025 absolute strain according to ISO 527-4 [13] and ISO 527-5 [14] and between 0.001 and 0.003 absolute strain according to ASTM D3039 [15]. Only unidirectional specimens in the fibre direction were evaluated between 10% and 50% of the maximum tensile load according to aircraft standards in addition [16]. Fatigue tests were performed at four different stress levels. A minimum of three specimens was tested at each stress level. All fatigue tests were performed with the *R*-value (= minimum force/maximum force) of 0.1 and constant load amplitude. Test frequency was chosen between 3 and 10 Hz depending