CHARACTERIZATION OF THE FRACTURE MECHANICAL BEHAVIOR OF C-SMC MATERIALS

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Abstract. The fracture mechanics of random discontinuous Carbon Fiber Sheet Molding Compound (C-SMC) materials compared to traditional carbon fiber composites are not well understood. An experimental study was carried out to characterize the fracture behavior of such C-SMC materials. Mode I tests, using double cantilever beam specimens, and mode II tests, adopting the four-point bend, end-notched flexure configuration, were performed. Results show high variations in the force-deflection responses and scatter in the fracture toughness properties G_{Ic} and G_{IIc}, due to the complex mesostructure defined by random oriented carbon fiber chips. To investigate the influence of the mesostructure, tensile tests with varying specimen width and thickness were assessed by stochastic measures to find the representative specimen size.

Keywords: C-SMC, Carbon Fiber Composites, Fracture Mechanics, Anisotropy.

1. Introduction

The exceptional strength to weight ratios presented by many advanced composite materials are desirable for industries (automotive, aerospace, . . .) that constantly fight to improve efficiency [1]. Random discontinuous C-SMC is a special type of SMC material, where a unidirectional carbon fiber prepreg is slit and chopped into chips, randomly distributed in a mold and finished in a single-stage compression and curing process. This material and process technology can be used to produce geometric complex, lightweight applications in an industrial (automated) and cost efficient way. The composition of the C-SMC material leads to a complex mesostructure, due to the random distribution and discontinuous nature of the chips. Research employing microscopical analysis of tensile, compressive and flexural tested specimens conducted by Feraboli et al. [2] showed that failure in random discontinuous C-SMC materials is a matrix-dominated event with two prevalent failure modes of intralaminar chip cracking and interlaminar chip delamination, with little or no fiber breakage. Further resin burn-off and de-plying of the tested specimens suggest that chip delamination is the main cause of structural failure. Also Nicoletto et al. [3] identified that final failure rather occurs due to chip debonding, than due to fiber fracture. The authors point out that delamination failure initiates in chips perpendicular to the load direction and propagates until delamination of other chips with higher alignment is involved. In another recently published work by Kravchenko et al. [4] the tensile failure behavior of discontinuous C-SMC with unidirectional aligned chips was investigated by numerical analysis. A critical length-to-thickness ratio

of the chips governing the failure mode was identified, above which chip tensile failure is observed due to the efficient load transfer between the chips. For smaller length-to-thickness ratios chip delamination is prevalent. However, in random discontinuous C-SMC materials, the effective load transfer between the chips is greatly reduced because of a wide distribution of overlapping lengths caused by the stochastic distribution of the chips.

Consequently, the main weakness of random discontinuous C-SMC materials was considered to be the interface between the matrix and the fiber chips. Therefore, fracture mechanical tests of mode I and II were carried out to characterize the fracture toughness of this material system and to study the failure behavior in the interface between the chips.

In Figure 1, the inhomogeneous strain field with high scatter is shown on the example of a tensile tested C-SMC specimen analyzed by Digital Image Correlation (DIC).

To get statistical significant values for the macroscopic mechanical behavior and to assess the influence of the mesostructure a experimental Representative Volume Element (RVE) study was conducted. RVE can be defined by:

- the RVE must include a large number of micro-heterogeneities (inclusions, grains, voids, fibers, etc.) [5];

- The RVE is a model of the material to be used to determine the corresponding effective properties for the homogenised macroscopic model. The RVE should be large enough to contain sufficient information about the microstructure in order to be representative, however it should be much smaller

than the macroscopic body. (This is known as the Micro-Meso-Macro principle) [5].

- The RVE is defined as the minimum volume of laboratory scale specimen, such that the results obtained from this specimen can still be regarded as representative for a continuum [5].

An experimental study of tensile tests with specimen dimensions varying in width and thickness was performed. Results were analyzed via Oneway-ANOVA.
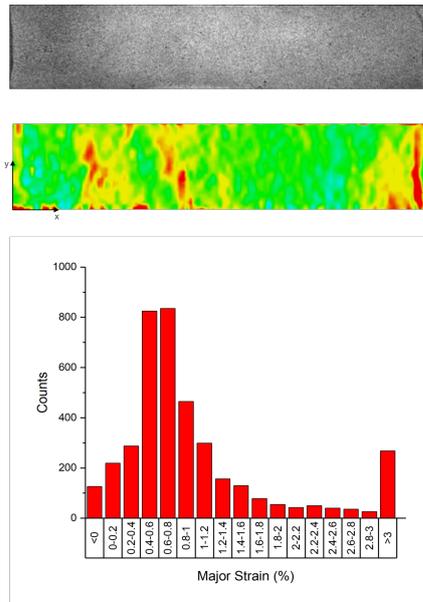
FIGURE 1. DIC analysis of a tensile test

2. C-SMC Material

The Hexcel prepreg tape (HexMC-i/C/2000/M77 + HexPly M77CS/38%) consists of high strength carbon fibers with 62% fiber weight content and the HexPly® M77 resin system [6]. HexMC® M77 is produced as shown in Figure 2: the prepreg is slit and chopped into chips (50×8 mm^2), randomly distributed and pressed into mats with a width of 460 mm and a thickness of 2 mm (uncured) [6]. The material is delivered in semifinished (uncured) rolls which is cut into shape and finished in a (single compression molding) curing step. Plates with dimensions of 350 mm × 350 mm × varying thickness (2,4 or 6 layers) for tensile testing (see Figure 4) were produced by Hexcel Holding GmbH, Pasching. Additional plates were manufactured for fracture mechanical tests with dimensions of 245 mm × 245 mm × 2 Layers thickness containing an adhesive tape, with a width of 50 mm, in the midplane (see Figure 3).

3. Methodology

All mechanical tests were performed with the servo-hydraulic testing machine MTS 852 combined using the Digital Image Correlation (DIC) system ARAMIS, except a few tensile tests (see Table 1) which were

FIGURE 2. C-SMC production process (reprinted from [6])
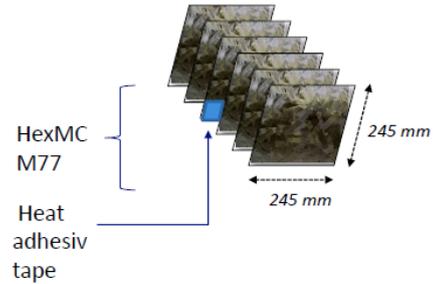
FIGURE 3. Composition of plate for fracture mechanical tests

carried out with a Zwick/Roell Z150 at TCKT in Wels due to loading limits of the MTS load cell.

3.1. Experimental RVE study

In order to assess the RVE size of the used HexMC® M77, an experimental study was carried out: Performed tensile tests with specimen dimensions varying in width and thickness (see Table 1) were statistically analyzed using Oneway ANOVA of the results. ANOVA consists of a comparison of two or more sample groups by testing if their expected values are different and if the variance between the groups is bigger than the variance within a group.

Assumptions of ANOVA:

- Variances of population, treatment and errors are normally distributed

- Error variances are equal between the groups

- Values are independent

The tensile test specimens were milled out of C-SMC plates (350×350 mm^2) with a diamond coated cutter according to the dimensions (see Figure 4). Specimens were modified through Aluminum tabs (25 mm ×Width×2 mm) glued to specimen in grip area in order to prevent failure. Tensile tests were carried out at 1 mm/min, room temperature and a humidity of 71 %.

Tensile test specimen dimensions

width	thickness
mm	mm
$200{\times}15{\times}2L$	$200{\times}30{\times}2L^{*}$
$200{\times}20{\times}2L$	$200{\times}30{\times}4L^{*}$
$200{\times}25{\times}2L$	$200{\times}30{\times}6L^{*}$
$200{\times}30{\times}2L$	
$200{\times}40{\times}4L^{*}$	
$200{\times}50{\times}2L^{*}$	

TABLE 1. Tensile test study: varying specimen dimensions; L=Layers; *tests performed on Zwick/Roell Z150
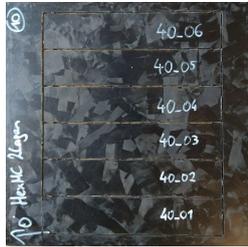
FIGURE 4. C-SMC plate: milled specimen pattern

3.2. MODE I

Mode I tests were performed using five Double Cantilever Beam (DCB) specimens with end blocks ($180{\times}40{\times}6.5$ and an initial crack length of 50 mm). Test setup is shown in Figure 5. Specimens were tested with an unloading/loading procedure according to [7] starting with loading until reaching an axial displacement of 6 mm, where the specimen was first unloaded by 2 mm and then loaded by 4 mm. These steps where repeated until reaching 20 mm. Mode I tests were carried out at room temperature and at 1 mm/min loading rate and at 5 mm/min unloading rate [7].
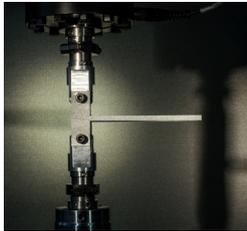
FIGURE 5. Mode I testing setup

Mode I fracture toughness (G_{Ic}) was calculated via Corrected Beam Theory (CBT) [8]:

$$G_{Ic} = \frac{3P\delta}{2B(a + |\Delta|)} \frac{F}{N} \quad , \quad (1)$$

where P is the applied load, δ the axial displacement, B the specimen width, F the correction factor for large

displacement (see Equation 2) and N the correction for loading blocks (see Equation 3). Δ may be determined experimentally by plotting the cube root of compliance, $C^{\frac{1}{3}}$, as a function of the delamination length a [8].

$$F = 1 - \frac{3}{10}\left(\frac{\delta}{a}\right)^2 - \frac{3}{2}\left(\frac{\delta l_1}{a^2}\right) \quad , \quad (2)$$

$$N = 1 - \left(\frac{l_2}{a}\right)^3 - \frac{9}{8}\frac{\delta l_1}{a^2}\left\{1 - \left(\frac{l_1}{a}\right)^2\right\} - \frac{39}{25}\left(\frac{\delta}{a}\right)^2 \quad . \quad (3)$$

For the definition of l_1 and l_2 see Figure 6.
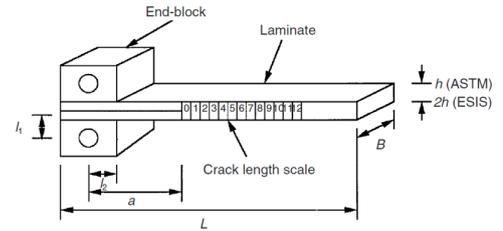
FIGURE 6. Mode I Double Cantilever Beam (DCB) specimen (reprinted from [8])

3.3. MODE II

Mode II tests were performed using five four point bending end notched flexure (4ENF) specimens ($180{\times}40{\times}6.5$ and an initial crack of 50 mm). Monotonic four point bending tests were carried out at room temperature and a loading rate of 1 mm/min until failure. Testing setup can be seen in Figure 7. Mode II fracture toughness was calculated via Experimental Compliance Method (ECM) [8]:

$$G_{IIc} = \frac{3P^2ma^2}{2B} \quad , \quad (4)$$

where P is the applied load, B is the specimen width and m is the slope from the compliance plotted versus the cube delamination length a^3.

FIGURE 7. Mode II testing setup

4. RESULTS AND DISCUSSION

4.1. EXPERIMENTAL RVE STUDY

In the Figures 8 and 9, results from the oneway-ANOVA of the tensile tests are presented, where the black points represent the measured values and the

green colored diamond shapes display the average mean (horizontal center line), the population size (width of the diamond) and the standard deviation values (height of the diamond). Results from specimens varying in both, width and thickness show high scattering with high standard deviation and error values. No clear trend could be observed by using ANOVA over the experimental window. The scattering of the values was too high and did not show a normal distribution (see right hand side of the Figures 8 and 9), thus it was not possible to determine the RVE by using ANOVA. One reason for the high scattering is the heterogeneous mesostructure due to the in-plane random orientation of the discontinuous chips. The experimental study performed in this work ended at a specimen width of 50 mm, which is also the length of the reinforcing fiber chips. This could be a reason for the high scattering of the values. The results of this study show, that the RVE might be found in larger specimen dimensions.
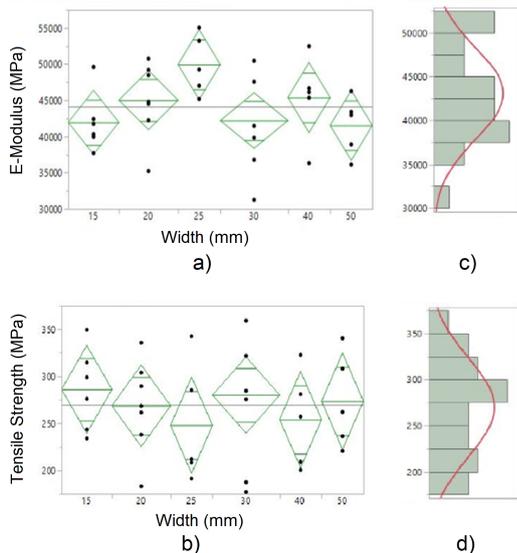
FIGURE 8. Oneway ANOVA: a) *E*-Modulus over width, b) Tensile strength over width, c) *E*-Modulus distribution, d) Tensile strength distribution
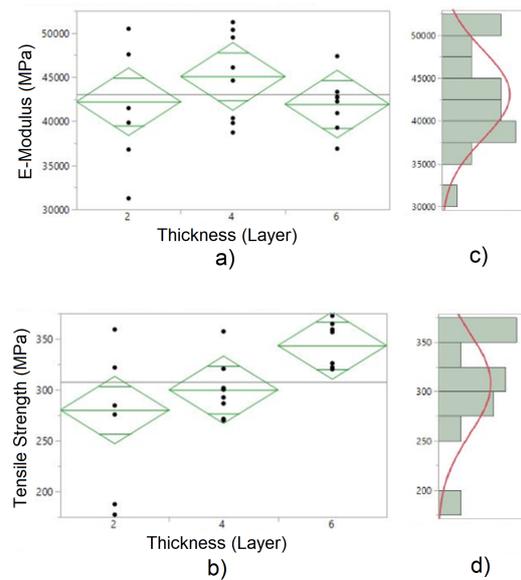
FIGURE 9. Oneway ANOVA: a) *E*-Modulus over thickness, b) Tensile strength over thickness, c) *E*-Modulus distribution, d) Tensile strength distribution

4.2. MODE I

In Figure 10, load-displacement curves and mode I fracture toughness are presented. High scattering of G_{Ic} values (from 1.53 to 2.69 mJ/mm^2; AVG = 1.83; Std = 0.542) compared to classical UD laminates was observed.

The load-displacement curves show several small force drops. These drops may occur when fiber chips, carrying the load, fully delaminate. However, load may increase further because the crack stops at the next chips. In C-SMC (Discontinuous Fiber Composite) the initial crack does not correlate to total failure. C-SMC material stop or at least greatly slow crack propagation. However, in Continuous Fiber Composites cracks propagate more easily. Initial failure is visible in load-displacement curves as a sudden load drop and often correlates to ultimate failure [9].

This crack stopping behavior is a result of the random distribution of the discontinuous fiber chips. A similar behavior was also found by Boursier et al.[9] by performing tensile tests with acoustic emission measurements. They found out that first cracks do not correlate with ultimate failure of the tensile specimens which supports further the crack stopping behavior of the C-SMC materials.

4.3. MODE II

In Figure 11 load-displacement curves and mode II fracture toughness are presented. High scattering of G_{IIc} values (from 2.21 to 3.69 mJ/mm^2; AVG = 3.13; Std = 0.551) compared to classical UD laminates was observed.

The load-displacement curves of mode II tested specimens show a crack stopping behavior similar to mode I. Values of mode II are less scattering compared
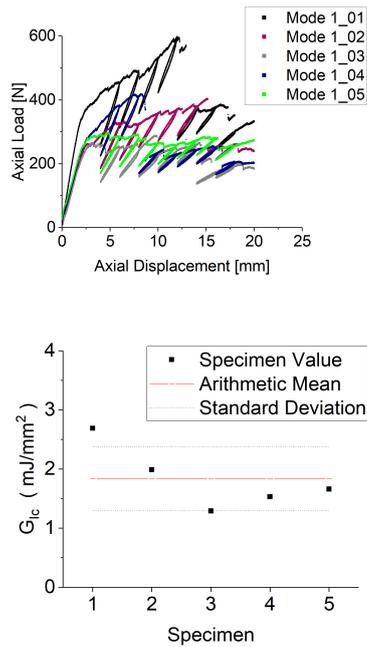
Figure 10. Results: load over displacement (top) and mode I fracture toughnesses comparison (bottom)
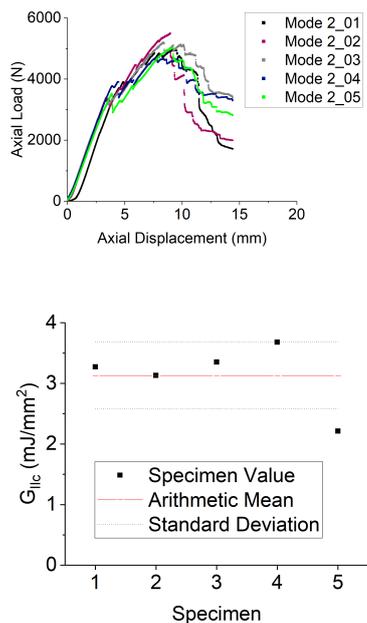
Figure 11. Results: load over displacement (top) and mode II fracture toughnesses comparison (bottom)

to mode I in the linear elastic region (see Figure 11) because specimens are loaded in shear mode.

5. Conclusion

Random discontinuous C-SMC is a special type of SMC material, where a unidirectional carbon fiber prepreg is slit and chopped into chips, randomly distributed in a mold and finished in a curing step. The production process leads to a heterogeneous mesostruc-

ture with high scattering. A representative specimen size could not be found in the investigated experimental window via ANOVA. However, the conducted experimental RVE study strongly suggests the use of statistical methods to account for the variability of the mechanical properties of C-SMC materials. Nominal values are not significant in the design process and modelling of such materials. The representative size is expected to be at bigger specimen dimensions.

Fracture mechanical test results showed higher scatter of G_{Ic}, G_{IIc} values of C-SMC material compared to traditional UD laminates. The crack propagation was found not continuous like in traditional UD laminates, but a crack stopping behavior was observed due to the random orientation of the discontinuous chips.

A combination of micromechanical simulations and experimental studies is proposed for a better understanding of the C-SMC fracture behavior, which will be part of future research.

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