MŰEGYETEM 1782

Budapest University of Technology and Economics
Department of Polymer Engineering

ANALYZING THE FLEXURAL BEHAVIOR AND FAILURE PROCESS OF UNIDIRECTIONAL COMPOSITES BEAMS

PhD Theses

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Thesis 1

I developed standard DIN 65 071:1992 further, and as a result I introduced a new manufacturing process and designed the necessary devices (impregnation system, molding tool) with the help of which unidirectional (UD) carbon/epoxy composite specimens can be prepared the from the roving (1D) structure in laboratory conditions. The new method is suitable for preparing rectangular cross section (2…10 mm thick, 10 mm width, long = 300 mm) UD composite beams which have well repeatable properties (fiber content = 62 ± 2 vol%, void content = max. 2%, dimension variation = h ± 0,15 mm, b ± 0,1 mm), and meet all requirements of the standard above.

Thesis 2

I verified the following statements for three- (3PBT) and four-point bending (4PBT) tests of UD carbon/epoxy composite beams (h = 2, 4, 6, 8 and 10 mm, b = 10 mm): The variation of the normal- (σ_x) and shear stress (τ_{xz}), which depend on the applied geometry ratio and the thickness of specimen, could be determined by these equations in the full domain (3PBT: 0 x = L/h < , 4PBT: 0 z = L_2/L 1). I determined the normal- and shear stresses from the force value of the first fracture with the classical beam theory (CBT).

3PBT *(z = 0)*:

$$\sigma_{3PBT}(x,z) = \frac{3}{2\cdot b}\cdot x\cdot\frac{F(x,z)}{h} \quad \rightarrow \begin{cases} c_{asy}, & x - \propto \\ 0, & x - 0 \end{cases} \tag{T1}$$

$$\tau_{3PBT}(x,z) = \frac{3}{4\cdot b}\cdot\frac{F(x,z)}{h} \quad \rightarrow \begin{cases} 0, & x - \propto \\ \tau_{theo}, & x - 0 \end{cases} \tag{T2}$$

4PBT:

$$\sigma_{4PBT}(x,z) = \frac{3}{2\cdot b}\cdot x\cdot(1-z)\cdot\frac{F(x,z)}{h} \quad \rightarrow \begin{cases} c_{3PBT}(x,z), & z - 0 \\ 0, & z - 1 \end{cases} \tag{T3}$$

$$\tau_{4PBT}(x,z) = \frac{3}{4\cdot b}\cdot\frac{F(x,z)}{h} \quad \rightarrow \begin{cases} \tau_{3PBT}(x,z), & z - 0 \\ \tau_{theo}, & z - 1 \end{cases} \tag{T4}$$

where:

$$f(x,z) = \frac{F(x,z)}{h} = \frac{a_0}{b_0 + b_1\cdot x\cdot(1-z)} \quad \left[\frac{N}{mm}\right] \tag{T5}$$

where in case of UD material the constants of *f(x,z)* function are:

$$a_0 = 1$$

$$b_0 = 4.8740\cdot 10^{-4}\ \text{[mm/N]},\quad b_1 = 9.0465\cdot 10^{-6}\cdot h + 6.0144\cdot 10^{-5}\ \text{[mm/N]}. \tag{T6}$$

I obtained the following asymptotic material characteristics with the help of these equations, independently of L/h and L_2/L ratios:, $_{asy}$ = 1917…996 MPa and $_{theo}$ = 153.87 MPa (in case of h = 2…10 mm, b = 10 mm).

Thesis 3

I proved the following statement for three-point bending tests (3PBT) (geometry parameters: R_1 = 5 mm, R_2 = 2 mm) of UD carbon/epoxy composite beams (b = 10 mm, h = 2, 4, 6, 8 and 10 mm):
The significant changes of apparent flexural modulus (E_{app}), which depends on the L/h ratio – almost independent of width to thickness ratio (b/h) –, could be determined with these equations in the full domain (0 x = L/h <). The apparent flexural modulus was determined from the recorded deflection-load characteristics (measurement settings: L/h = 5, 10, 15, 20 and 25) as a chord-modulus.

$$E_{3PBT}(x) = \frac{1}{4 \cdot b} \cdot x^3 \cdot \frac{\Delta F}{\Delta f}(x) \quad \rightarrow \begin{cases} E_f, & x - \propto \\ 0, & x - 0 \end{cases} \qquad \text{(T7)}$$

where:

$$g(x) = \frac{\Delta F}{\Delta f}(x) = \left[\frac{a_0 + a_1 \cdot x}{b_0 + b_1 \cdot x + b_2 \cdot x^2} \right]^3 \quad \left[\frac{N}{mm} \right] \qquad \text{(T8)}$$

where the constants of *g(x)* are:

$$a_0 = 0.788, \qquad a_1 = 1,$$

$$b_0 = 1.437 \left[\frac{mm}{N} \right]^{\frac{1}{3}}, \quad b_1 = 0.080 \left[\frac{mm}{N} \right]^{\frac{1}{3}}, \quad b_2 = 0.056 \left[\frac{mm}{N} \right]^{\frac{1}{3}}. \qquad \text{(T9)}$$

I obtained the following asymptotic material characteristics, independent of L/h and b/h ratios, with these equations: E_f = 136,4 MPa.

Thesis 4

I proved in case of three point bending tests (3PBT) of UD carbon/epoxy composite beam specimens (b = 10 mm, h = 4 mm) that the characterizing failure mode and the total damage process are significantly influenced by the applied L/h ratio ($5 \leq L/h \leq 25$).

a. Based on the optical images and the recorded deflection-force charts, I proved for three-point bending tests that the primary failure mode that occur on the examined carbon fiber/epoxy UD material under the loading head (R_1 = 5 mm) can be divided into three types depending on the support distance (L/h ratio): $5 \leq L/h \leq 10$ – multilayer delamination, firstly shearing and after that compression failure; L/h = 15 – mixed mode failure, firstly crack at the compressed side, after that delamination; $20 \leq L/h \leq 25$ – failure at the compressed side of specimen (almost vertical crack) is the significant failure mode and delamination is only local damage.

b. I carried out simultaneous three-point bending tests (3PBT) and acoustic emission (AE) measurements on UD carbon/epoxy composite beams (L/h = 15, 20 and 25). Based on the results I found that irreversible micro failure already started when 50% of the load which causes the first macro damage was reached. I also revealed that the numbers of AE events were increasing constantly up to the occurrence of the first macro failure. I proved that the number of AE events from the unloaded state until the first macro failure, i.e. the cumulated number of events (∑E) in the different load intervals – $(0\text{-}0.5)\cdot F_{max}$, $(0.5\text{-}0.8)\cdot F_{max}$, $(0.8\text{-}1)\cdot F_{max}$ – can be described by this equation as a function of the support distance (L):

$$\Sigma E = a_i \cdot L^{2.6583} \tag{T10}$$

where:

$$(0-0.5)\cdot F_{max}: \quad a_1 = 3.090 \cdot 10^{-3}\ [\text{mm}^{-2.6583}] \tag{T11}$$

$$(0.5-0.8)\cdot F_{max}: \quad a_2 = 9.764 \cdot 10^{-3}\ [\text{mm}^{-2.6583}] \tag{T12}$$

$$(0.8-1)\cdot F_{max}: \quad a_3 = 8.963 \cdot 10^{-3}\ [\text{mm}^{-2.6583}] \tag{T13}$$

Thesis 5

In case of three point bending tests (3PBT) on UD carbon/epoxy composite beams (h = 4 mm) I proved that the E-bundle cell model – the parameters of the model are c_E, $c_{\varepsilon 0}$, $c_{\varepsilon 1}$ –, developed to describe the deflection-force relationship, which is a process characterizing the damage measurably, based on the breakage of the layers on the drawn side of the specimen is suitable for the phenomenological description of the total damage process and gives a good approximation for predicting the variation of the average bending load up to total failure at 95% confidence level.

Thesis 6

I examined the strength properties of UD carbon/epoxy composite specimens obtained from tensile tests and three-point bending tests (3PBT) with Weibull analysis.

a. Based on the results of statistical analysis of the tensile strength of the specimen at more structural levels – single carbon fibers, impregnated carbon roving, and UD composite specimens –, I proved that the Weibull theory can be applied to describe the tensile strength of brittle carbon fiber and carbon/epoxy composite material in case of tensile loading. I showed that the exploit age of the average theoretical tensile strength (σ_S) of single fibers and the Weibull scale parameter (σ_0) decrease, while the Weibull shape parameter (m) increases towards higher structural levels.

b. Based on the results of three-point bending tests (3PBT) (measurement settings: L/h = 5, 10, 15, 20 and 25) on UD carbon/epoxy composite beams (h = 4 mm, b = 10 mm), I proved that the Weibull scale parameter (σ_0) increases if the support distance (L) increases, while the Weibull shape parameter (m) remained approximately constant (m = 18.6). I proved with the Weibull analysis that the estimated theoretical flexural strength (σ_{fW}) approached with Weibull parameters is less by 23.5% than the flexural strength (σ_x) calculated at the moment of failure, therefore the Weibull theory cannot be applied without correction to estimate the change due to size effect in the flexural strength of the examined UD beams.

Thesis 7

For the tested UD carbon/epoxy composite specimens (h = 2, 4, 6, 8 and 10 mm, b = 10 mm) I showed with experiments how the acceptability of standards, which are used to determine the flexural (ASTM D790) and shear properties (ASTM D2344) of fiber reinforced composites, changes as a function of the standard investigation parameters (L/h ratio = 5, 10, 15, 20 and 25; b/h ratio = 1, 1.25, 1.67, 2.5 and 5).

a. I proved that standard ASTM D790 is suitable for determining the flexural strength of UD carbon/epoxy specimens tested only if $b/h \geq 5$ and $15 \leq L/h \leq 25$. If $1 \leq b/h \leq 2.5$, the measured flexural strength is only acceptable if a correction is applied.

b. I proved that the real interlaminar shear strength of UD carbon/epoxy specimens tested can be determined in interval $10 \leq L/h \leq 15$ if $1 \leq b/h \leq 5$.

c. Based on the analysis of deflection-load charts recorded during three-point bending tests, I proved that the flexural modulus – defined as a chord-modulus – of UD carbon/epoxy specimens tested is acceptable if $20 \leq L/h \leq 25$.

d. I proved with experiments that in case of the UD carbon/epoxy specimens tested (h = 4 mm, b = 10 mm) failure always starts on the compressed side – provided $5 \leq L/h \leq 25$ –, therefore the requirement of ASTM D790, i.e. damage starts on the tensile side, was not realized.

e. Based on results of three-point bending test (3PBT) and the developed fitting method, I suggest – as an addition to standard ASTM D790 – to extend results to interval $0 < L/h <$, and to determine the asymptotic parameters ($_{asy}$, $_{theo}$ and E_f), which are independent of L/h ratio, in order to obtain more information from the measurements.