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Mathematical Model on Flexural Properties of Composite Laminates

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Abstract— **Aim of this study is to investigate the impact of number of layers, applied pressure and fiber direction on flexural properties of laminated composite materials. For that purpose, E-glass/epoxy resin prepreg has been fabricated and used in the production of laminated composite samples with help of press technology. Produced samples have been tested on three-point-bending test according to ASTM D790. In order to present the relationship between technological parameters of production and flexural behavior of manufactured samples, factorial design of experiment (DOE) 2^3 was used. With help of DOE influence of technological factors and their relationship on mechanical properties of manufactured samples was quantitative calculated. Received results shown that number of layers, applied pressure and fiber direction used to manufacture the samples significantly affect sample's flexural strength. With help of scanning electron microscopy (SEM) analysis was used to analyze the gaps the interfacial behavior and breaking the fibers.**

This study demonstrate technological parameters which lead to optimal flexural properties of laminated composite samples, where maximal flexural strength of 474,9 MPa was reached. According to them, fiber direction has direct influence on flexural behavior of manufactured samples, whereas number of layers and applied pressure performed similar effect.

Keywords: DOE, flexural strength, three point bending

I. INTRODUCTION

A composite laminate is a structural plate consisting of multiple layers of fiber reinforcement encased in cured resin. The number of layers, the type of fiber (carbon, glass, or other), the fabric configuration (e.g. woven, stitched mat, unidirectional), the type of resin, and other factors can be varied to design a structural element that is suitable for a particular need.

In [1] flexural tests on composite samples with two different thicknesses were conducted, where it was found that the increase in thickness decreases the flexural properties of manufactured samples, such as flexural strength and flexural modulus. Also, it was concluded that the load carry capacity of the specimen increases with increase of specimen thickness. Contrary to this, in [2] it is stated that slight increase in thickness is recommended in order to increase the flexural properties of composite samples. Similar results have been reported in [3-5], where it was reported that thickness can play a vital role in mechanical properties.

Lassila et al. [6] investigated the influence of position of fiber rich layer on flexural properties of fiber-reinforced composite (FRC) construction. In [6] was found that specimens with FRC positioned on the compression side show flexural strength of approximately 250 MPa, while FRC positioned on the tension side show strength ranging from 500-600 MPa.

Influence of volume fraction on tensile and flexural strength of E-glass/epoxy laminated composites where studied in [7] were it is reported that volume fraction of 65:35 is optimal for composite's tensile and flexural strength. The effect of different fiber volume fractions on flexural behavior at hybrid composites was reported in [8]. Flexural behavior of hybrid composites was investigated in [9-12].

Quasi-isotropic and unbalanced stacking sequences of carbon fiber/epoxy laminated structures were tested on three-point bending test, where it was stated that quasi-isotropic composite samples exhibit higher flexural stress and brittle behavior in comparison to unbalanced composite sample with flexural stress of around 780 MPa and progressive failure mode consisting of fiber failure, debonding and delamination [13].

Microstructure of voids and their influence on mechanical properties of composite samples have been studied in [14, 15]. In these studies it is reported that tensile strengths decrease with increase of void content and cracks emanate from voids when void content in manufactured samples is 8.0% - 9.0% after tensile strength test.

The aim of this research is to study the effects of fiber orientation, number of layers and applied pressure on flexural behavior on plain E-glass/epoxy composites. For that purpose three-point-bending test were performed on manufactured composite samples. With help of factorial design of experiment (DOE) the influence between technological parameters used in sample production was presented.

II. EASE OF USE

A. Specimen Preparation

In this study is used preimpregnated composite material (prepreg), which was produced on vertical impregnation machine manufactured by Mikrosam AD. For the production of prepreg material plain E-glass fabric EW300-2000mm by Sinoma Science and Technology Co., & Ltd was impregnated in a solution of brominated epoxy resin CHS-EPOXY B200 M80 by Spolchemie. In table 1 and table 2 are given the properties of used E-glass fabric and epoxy resin, whereas table 3 gives the properties of produced prepreg material.

Total of fifteen and twenty plies of manufactured E-glass/epoxy fabric prepreg with dimensions 700mm x 500mm were used in the production of composite laminates. The plies were stacked in press machine where final curing of the preforms was performed at constant temperature of 145^0C and variable compressive pressure of 18 kg/cm^2 and 14 kg/cm^2. With help of machine five rectangular forms of MD direction and five rectangular forms of CD direction were cut from finished composite laminates according to ASTM D790 [16]. Dimensions and thickness of prepared specimens were measured with micrometer.

TABLE I. PROPERTIES OF E-GLASS FABRIC EW300-2000MM

Properties of E-glass fabric EW300-2000mm	
FAW (g/m^2)	300
Width (mm)	2000
Thickness (mm)	0.3
Count warp (ends/cm)	8±1
Count fill (ends/cm)	7±1
Type	plain

TABLE II. PROPERTIES OF EPOXY RESIN CHS-EPOXY B200 M80

Properties of epoxy resin CHS-EPOXY B200 M80	
Colour	gardner
Epoxide equivalent weight (g/mol)	435-556
Epoxide index (mol/kg)	1,8-2,3
Hydrolizable chlorine content (%)	Max. 0,1
Non-volatile substances by 140ºC for 2h (%)	78,5-81,5
Viscosity by 25ºC (mPa.s)	1100-2300

TABLE III. PROPERTIES OF MANUFACTURED PREPREG

Properties of manufactured prepreg	
Volatile content (%)	<2
Mass resin content (%)	30-35
PAW (g/m^2)	428-455

B. Flexural Test

Flexural properties of manufactured samples were determined with help of three-point bending test in accordance with the procedure described in [16]. For that purpose computer controlled universal testing machine (UTM) Hydraulic press, SCHENCK- Hidrauls PSB with maximal load of 250 kN, constant crosshead speed of 5 mm/min and span-to-depth ratio of 16:1 was used. Load and displacement were recorded by an automatic data acquisition system for each sample. Minimum five reproducible tests were conducted for each sample at room temperature. Samples ready for testing are presented on Fig. 1, whereas three-point-bending test is given on Fig. 2

Fig.1 Prepared composite samples ready for testing.

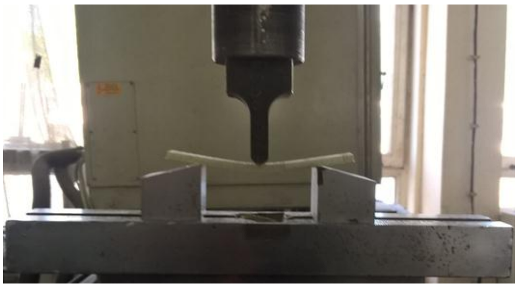

Fig. 2. Three-point-bending test on universal testing machine.

C. Design Of Experiment (DOE)

To optimize the production process of laminated composite samples and quantitatively to determine the influence of production parameter: number of layers (X_1), applied pressure (X_2) and fiber orientation (X_3), design of experiment (DOE) has been followed. DOE has been well known for its efficiency and allow gaining a maximum of information from a minimum amount of experiments.

For that aim factorial design of experiment with 2^3 permutations was used in the production of composite samples. Used technological parameters in two different levels with number of permutations 2^3 are presented in Table 4, whereas Table 5 represents manufacturing parameters of each laminated sample.

TABLE IV. LEVEL OF USED PARAMETERS

Symbol	Parameters	Parameter level	
		1	*2*
A (X_1)	Number of layers	15	20
B (X_2)	Pressure	14 kg/cm^2	18 kg/cm^2
C (X_3)	Direction of fiber	CD	MD

TABLE V. DESIGN OF EXPERIMENT (2^3) FOR LAMINATED SAMPLES

Sample Nº	X_1	X_2	X_3	A	B	C
1	A_1	B_1	C_1	15	14	CD
2	A_2	B_1	C_1	20	14	CD
3	A_1	B_2	C_1	15	18	CD
4	A_2	B_2	C_1	20	18	CD
5	A_1	B_1	C_2	15	14	MD
6	A_2	B_1	C_2	20	14	MD
7	A_1	B_2	C_2	15	18	MD
8	A_2	B_2	C_2	20	18	MD

D. Fractographic Analysis

Fractured surfaces obtained from performed three-point-bending tests were examined at different magnification with help of scanning electron microscope (SEM) from Tescan type Vega3 in order to observe fracture behavior of laminated specimens.

III. RESULTS AND DISSCUSSION

A. Flexural Strength

Manufactured composite samples were clamped and three-point-bending tests were performed. The tests were closely monitored and the load at which completed fracture of the specimen occurred has been accepted as breakage load.

Load-displacement curves were plotted for every sample and values for stress, strain and module of elasticity were calculated as average. The flexural stress (σ_f) in the outer surface of the test specimens occurred at the midpoint. These stresses were determined from the relation [16]:

$$\sigma_f = \frac{3FL}{2bh^2} \qquad (1)$$

Where, σ_f is the flexural stress (MPa), F is the load (N), L is the support span (mm), b is the width of the specimen (mm), and h is the thickness of the specimen (mm).

Flexural modulus of elasticity (E_f) and flexural strain (ε_f) of the composite specimens were determinate using equations (2) and (3) [16]:

$$E_f = \frac{L^3 m}{4bh^3} \qquad (2)$$

$$\varepsilon_f = \frac{6sh}{L^2} \qquad (3)$$

Where, m is the slope of the tangent to the initial straight-line portion of the load-deflection curve (N/mm) and s is maximum deflection of the center of the specimen (mm).

Received results from performed tests on laminated composite samples are given in table VI, where maximal flexural strength of 474,9 MPa for sample Nº8 and minimal flexural strength of 166,2 MPa for sample Nº3 can be observed. All technological parameters used in the production of sample Nº8 are at level 2. In comparison, specimen Nº3 had performed 65% lower flexural strength manufactured at highest pressure and level 1 of X_1 and X_3.

If comparison is made between three-point-bending results of samples manufactured with different number of layers and same technological parameters can be noticed an increase of up to 51% of flexural properties only by samples manufactured at X_2 at leevl 2. Main cause for this result is the high percent of voids, up to 4,6% by samples manufactured with smaller pressure (table VII). Same effect can be concluded for the influence of pressure as technological parameter on flexural properties on laminated composite samples. In this case, the influence of voids can be neglected.

(Pressure at level 2 used in the production of laminated composite sample together with bigger number of layers leads to an increase in flexural properties of tested samples. In this case, the influence of voids can be neglected.)

Comparison between results of specimens manufactured at same technological parameters, but different fiber orientation can give a notice that all samples tested at MD direction had performed better flexural properties in comparison to the samples tested at CD direction. This means that fiber direction directly affects flexural properties of laminated composite samples up to 30%.

TABLE VI. RESULTS FROM FLEXURAL TESTING FOR EACH DESIGN

Nº	Break force mean (N)	Flex. ($y_{exp.}$) (MPa)	Flex. Mean (MPa)	Nº	Break force mean (N)	Flex. ($y_{exp.}$) (MPa)	Flex. Mean (MPa)
1-1		325,97		5-1		427,15	
1-2		296,29		5-2		470,72	
1-3	704,24	330,99	317,74	5-3	970,2	477,51	454,65
1-4		326,27		5-4		450,34	
1-5		309,23		5-5		447,55	
2-1		317,23		6-1		323,77	
2-2		215,31		6-2		256,93	
2-3	960,4	254,08	272,62	6-3	1070	334,76	296,36
2-4		267,23		6-4		254,57	
2-5		309,21		6-5		311,77	
3-1		142,54		7-1		261,30	
3-2		178,89		7-2		259,33	
3-3	568,03	177,21	166,2	7-3	658,7	228,60	249,74
3-4		169,34		7-4		243,43	
3-5		163,07		7-5		256,06	
4-1		341,58		8-1		499,51	
4-2		322,36		8-2		464,32	
4-3	967,82	369,38	344,44	8-3	1404	460,86	474,90
4-4		340,11		8-4		469,93	
4-4		348,78		8-5		479,87	

Finally, average flexural strain at maximal stress has been estimated for each laminated sample (table VII). Calculated values are between 2,26% and 3,80%, whereas average module of elasticity had reached values between 4,41 GPa and 16.91 GPa for sample Nº 3 and sample Nº 8, respectively (table VII).

TABLE VII. DIMENSIONS OF THREE POUINT BENDING SPECIMENS

Nº	σ_f average (MPa)	ε_f average (%)	E_f Average (GPa)	*Void (%)*
Nº 1	317,74	2,87	11,40	1,6
Nº 2	272,62	2,85	9,74	/
Nº 3	166,20	3,80	4,41	0,7
Nº 4	344,44	2,72	12,75	0,1
Nº 5	454,65	3,10	14,82	1,5
Nº 6	296,36	2,26	13,34	4,6
Nº 7	249,74	3,61	6,69	0,8
Nº 8	474,90	2,81	16,91	0,2

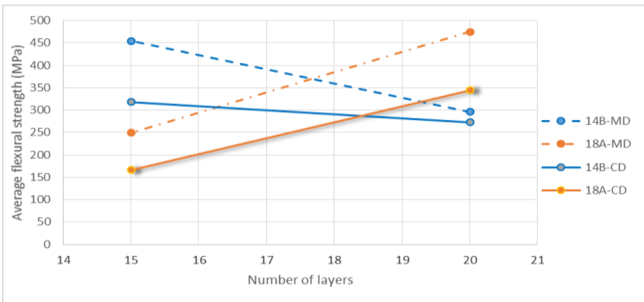

Fig. 3. Average flexural strength with number of layers, direction and pressure.

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B. Design Of Experiment (DOE)

The results for flexural strength, dispersion and minimal value of parameter’s final coefficients for factorial design 2^3 in this research are shown in table 8. According to table 8, minimal calculated value of parameter’s final coefficients is 10,13. Parameter’s function and their interaction with 5% mistake are represented with (4).

$$Y=322{,}08+25X_1-13{,}26\,X_2+46{,}83X_3+75{,}85X_1X_2+20{,}01X_1X_2X_3 \quad (4)$$

From design 2^3 were calculated Cochran criteria (G_{cal}) with value 0.391 and Fisher criteria (F_{cal}) with value 0.4, which fulfill the rule $G_{cal} < G_{tab}$ and $F_{cal} < F_{tab}$ [17, 18]. According to this, the hypothesis for model 2^3 is acceptable with 5% mistake.

TABLE VIII. RESULTS FROM DESIGN OF EXPERIMENT (DOE)

<table>
<tr><th>N^o</th><th>y_{exp}</th><th>y_{cal}</th><th>S_y^2</th><th>S_y^2sum</th><th>S_y^2mid</th><th>S^2b_i</th><th>Δb_i</th></tr>
<tr><td>1</td><td>317,75</td><td>319,35</td><td>212,14</td><td rowspan="8">4734,5</td><td rowspan="8">591,8</td><td rowspan="8">4,96</td><td rowspan="8">10,13</td></tr>
<tr><td>2</td><td>272,62</td><td>257,67</td><td>1746,46</td></tr>
<tr><td>3</td><td>166,21</td><td>181,15</td><td>215,42</td></tr>
<tr><td>4</td><td>344,45</td><td>342,83</td><td>288,76</td></tr>
<tr><td>5</td><td>454,65</td><td>453,03</td><td>401,54</td></tr>
<tr><td>6</td><td>296,36</td><td>311,31</td><td>1441,07</td></tr>
<tr><td>7</td><td>249,75</td><td>234,79</td><td>188,07</td></tr>
<tr><td>8</td><td>474,90</td><td>476,51</td><td>241,03</td></tr>
</table>

C. Scanning Electron Microscopy (SEM) Analysis

Scanning electron microscopy (SEM) analysis were performed in order impregnation quality of glass fibers into the epoxy resin during press process to be determined. In figure 4 are presented SEM analysis from already tested composite samples. However, voids with smaller dimensions can be observed on some places at samples manufactured with X_2 at level 1, which can lead to reduction of mechanical properties of laminated samples.

Also, optical analysys were obtaied to characterize da fracture surface of laminated sample, where dominant faliure mode was compressing failure.

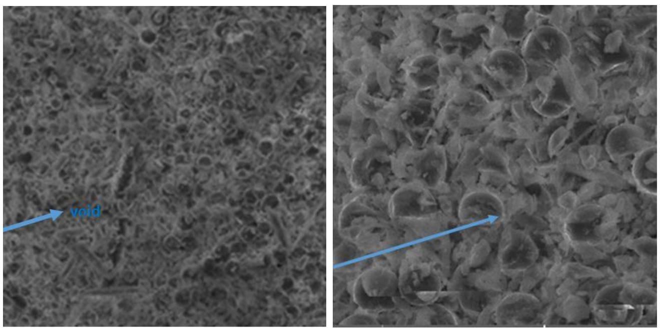

Fig. 4. SEM analysis of tested samples. a) Sample 6. 20c/14B-MD with “void” b) Sample 8. 20c/18A-MD without “void”

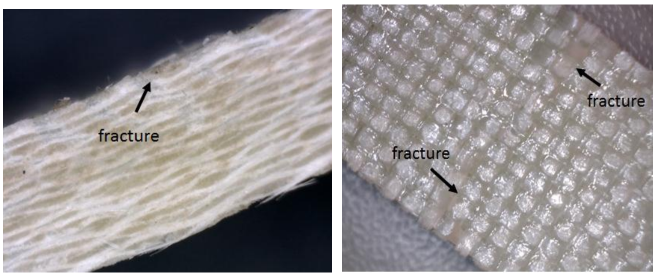

Fig. 5. Optical analysis of tested samples.

IV. CONCLUSION

From present study on flexural properties of laminated E-glass/epoxy resin composite samples can be concluded, that flexural strength and flexural modulus of elasticity increase in MD direction in comparison to CD direction. From these results, is concluded that fiber direction as production parameter influence directly on the flexural properties of laminated composite samples. Contrary, number of layers or more specific, thickness and applied pressure as technological parameters perform similar effect on flexural behaviour on laminated samples. Flexural properties of tested samples are increased when level 2 of parameters X_1 and X_2 are used, regardless fiber direction.

Performed factorial design of experiment quantitatively determined the influence of technological parameters and their interactions on flexural properties of laminated E-glass/epoxy resin composite samples. Calculated mistake in DOE is 5%.

Finally, sample manufactured with level 2 of all production parameters has shown best flexural properties with flexural strength of 474.90 MPa.

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