IDENTIFICATION OF LAYERS DISTRIBUTION IN THE COMPOSITE COUPON USING FINITE ELEMENT METHOD AND THREE POINT BENDING TEST

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Abstract: The main objective of the study is to develop experimentally validated FE model and perform numerical analysis of layered composites made by hand lay-up techniques during tension and bending test. The research object is glass - polyester laminate made of four unidirectional layers. In order to validate the numerical models experimental test were performed. Due to the very different stiffness modulus in tension and bending loading the material properties obtained from standard test are not suitable to apply in numerical model. Significantly different behaviour compared to experimental test was obtained for tree point bending where the numerical model becomes too stiff. Simple coupons, relatively easy to manufacture presented in the paper have very low quality. The differences in actual and theoretical bending stiffness (obtained from tension stiffness) exceed 70%. In order to represent the actual structure the layers of the composite were divided by resin layers and also additional resin layer at the top and bottom of the model were defined. Single stage optimization process was used to adjust the material layout. After layer set-up modification very significant improvement can be seen for flexural behaviour.

Key words: Fibre Reinforced Composite, FE Analysis, Hand Lay-Up Technique, Experimental Validation

1. INTRODUCTION

Composite materials, particularly fibre reinforced laminates, due to many advantages, are used as structural materials in many industries. They are characterized by high relative strength, high relative stiffness, weather resistance and quite low costs of production. However due to complex structure of such materials modelling of such structures is very difficult (Gama et al., 2011; Xiao et al. 2007; Mazurkiewicz et al., 2013).

The main objective of this study is to develop experimentally validated FE model and perform numerical analysis of layered composites made by hand lay-up techniques during tension and bending test. It has to be pointed out that those techniques are still the most popular method of composites elements production. On the other hand the hand lay-up composites are very sensitive to manufacture quality which is human factor dependent.

In the literature many authors discuss the problem of composite flexural stiffness. In the paper (Dong et al., 2013) authors presents study on the flexural behaviour of hybrid composites reinforced by S-2 glass and T700S carbon fibres, where different layout set-ups are tested in 3-point bending. The flexural strength is improved using numerical optimization. The good agreement of flexural moduli form FE analysis and experiments is a result of high-quality samples used in research. It also can be seen that the flexural modulus obtained experimentally is usually slightly lower than obtained from FE. In another publication (Nunes et al., 2012) a flexural behaviour of composite disc was studied. This time the difference between experimental and simulated values of the flexural stiffness was up to 13%. Also in (Khalid et al., 2005) where the glass/epoxy I-beams where subjected to three and four point bending, following dissimilarity can be seen between experimentally and numerically obtained flexural stiffness.

Our paper is focused on the problem of manufacture quality influence on decrease of structure bending stiffness and development of FE model with adequate flexural stiffness.

2. RESEARCH OBJECT

The research object is the glass fibre reinforced composite made of four unidirectional layers $[90]_4$. E-glass fabrics produced by Owens Corning Co., USA were used as reinforcement, i.e. D-610 (Weft 90°, uniaxial fabric, 607 g/m^2 – fibre set 595 g/m^2 and transverse stitching 12 g/m^2). The matrix constitutes Polimal 104 N-1 P/p-503 polyester resin, i.e. elasticized and incombustible Polimal 104 resin produced by Organika-Sarzyna Co., Poland.

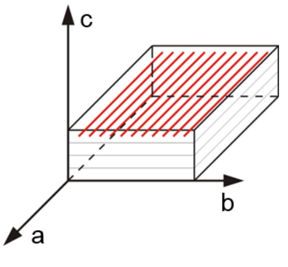

Fig. 1. Layer set-up of glass – polyester composite

3. STUDIED CASES

Two load cases were considered – tension and bending tests. The bending test is necessary to prepare more adequate multilayered plate model. The dimensions of the specimen used in those test and loading directions were presented in Fig. 2 and 3.

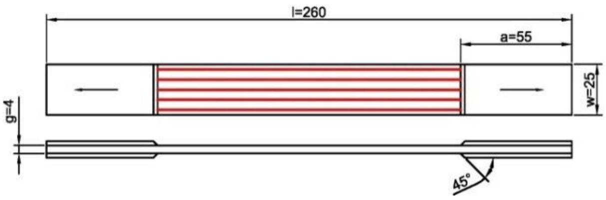

Fig. 2. Nominal dimensions of specimens and defined load for tension tests

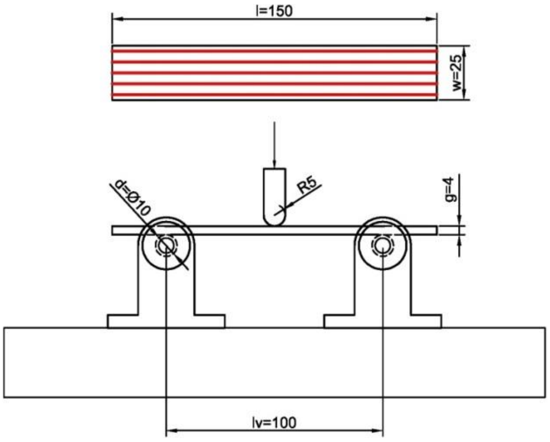

Fig. 3. Nominal dimensions of specimens and defined load for three point bending tests

4. EXPERIMENTAL TESTS

4.1. Properties identification

The material properties of FRC composite (Tab. 1) was obtained from the following experimental tests:

- tension test in fibre direction;
- tension test in cross-fibre direction;
- compression test in fibre direction;
- compression test in cross-fibre direction;
- shear test in plane *"ab"*;
- shear test in plane *"ba"*;
- shear test in plane "*cb*";

It should be mentioned that hand lay-up made composite can have relatively high thickness changes over the element, which can introduce additional error in stiffness parameters.

Tab. 1. Results of experimental test of FRC

E_{aa}^t [GPa]	E_{bb}^t [GPa]	E_{aa}^c [GPa]	E_{bb}^c [GPa]
21.7	6.05	22.4	7.48
v_{ab} [-]	v_{ba} [-]	v_{bc} [-]	G_{ab} [GPa]
0.19	0.099	0.40	3.20
G_{ba} [GPa]	G_{cb} [GPa]	R_{aa}^t [MPa]	R_{bb}^t [MPa]
2.24	1.67	402	34.4
R_{aa}^c [MPa]	R_{bb}^c [MPa]	S_{ab} [MPa]	S_{ba} [MPa]
375	110	45.8	47.7
S_{ca} [MPa]	e_{aa}^t [-]		
33.7	0.02		

Data provided by M. Klasztorny, P. Gotowicki, D. Nycz, Military University of Technology, Department of Mechanics and Applied Computer Science

where: E_{aa}^t, E_{bb}^t, E_{aa}^c, E_{bb}^c – Young modulus in direction "*a*" or "*b*" for tension (***t***) and compression (***c***); v_{ab}, v_{ba}, v_{bc} – Poisson ratio in plane *ab*, *ba* and *bc*; G_{ab}, G_{ba}, G_{cb} – shear modulus in plane "*ab*", "*ba*" and "*cb*"; R_{aa}^t, R_{bb}^t, R_{aa}^c, R_{bb}^c – tensile (***t***) and compressive (***c***) strength in direction "*a*" and "*b*"; S_{ab}, S_{ba}, S_{ca} – shear strength in plane *"ab"*, *"ba"* and *"ca"*, e_{aa}^t – tensile failure strain in direction *"a"*.

Additionally the material properties of matrix resin Polimal 104 N-1 (Tab. 2) were obtained from experimental tests:

- tension test;
- compression;
- shear test;

Tab. 2. Results of experimental test of polyester resin

E^t [GPa]	E^c [GPa]	v [-]	G [GPa]
3.21	3.31	0.17	1.58
R^t [MPa]	R^c [MPa]	S [MPa]	e^t [-]
60.6	189	46.9	0.026
e^c [-]			
0.39			

Data provided by M. Klasztorny, P. Gotowicki, D. Nycz, Military University of Technology, Department of Mechanics and Applied Computer Science

where: E^t, E^c – Young modulus for tension *(**t**)* and compression (***c***); ***v*** – Poisson ratio; ***G*** – shear modulus; R^t, R^c – tensile *(**t**)* and compressive *(**c**)* strength; ***S*** – shear strength; e^t, e^c – tensile *(**t**)* and compressive *(**c**)* failure strain.

4.2. Validation tests

In order to validate the numerical models two experimental test tension and three point bending (Fig. 4) were taken into consideration. As authors stated before, bending test is necessary to prepare more adequate multi-layered plate model. Due to available equipment the three point bending test was performed, which is commonly used in flexural stiffness investigations (Dong et al., 2013).

In further research authors are planning to compare the presented results with those obtained from four point bending test which eliminates the shear influence and guarantees pure flexure mode. Such comparison of both test methods is presented in Khashaba et al., (2006) where better performance of 4-point bending tests is highlighted. It is also pointed out that in case of 3-point bending, the load concentration causes early micro cracking of the matrix as well as catastrophic failure. According to the authors, failure under bending is mainly caused by excessive delamination in the compression side of the specimen. However, in our experimental test this effect didn't appear and the failure was caused by damage in tension side.

Static experimental tests were performed on an INSTRON 8802 testing machine, with pressure force and punch displacement under registration (kinematic excitation at 2 mm/min velocity).

The validation tests revealed that the tensile and flexural stiffness moduli are very different from each other. In fact, this phenomenon is the main aim of the study.

Fig. 4. Tension and bending experimental tests set-ups respectively

5. PRELIMINARY ANALYSES

5.1. Discrete models

The discrete models were developed using Belytschko-Tsay shell elements (Fig. 5-6). The number of integration points through thickness was determined by a number of defined layers.

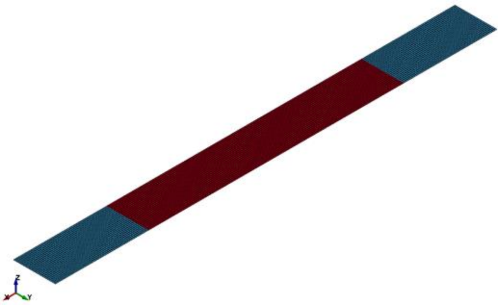

Fig. 5 Discrete models of FRC composite for tension test

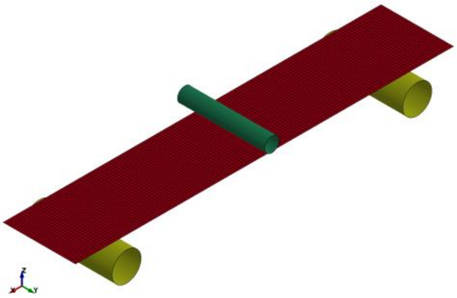

Fig. 6. Discrete models of FRC composite for bending test

Mesh sensitivity studies were performed with element sizes from 0.1 to 5 mm. As a result the simulation with element size of 1 mm revealed the best proportion between computational time and accuracy.

The models contain 1690 and 845 shell elements respectively for tension and bending tests. Additionally 9600 rigid shell elements were used to very accurately describe the rollers and the loading head and consequently to avoid unwanted contact problems.

The prescribed motion enforcement was applied to simulate the load. Selected nodes (corresponding to the place where crosshead was clamped and whole loading head part respectively in tension and bending test) were linearly displaced to final location. For the second load case (bending) the contact algorithm with penalty function was used. The contact stiffness is based on a minimum of master segment and slave node stiffness. The thickness of the shell elements is also considered in contact algorithm.

To reduce the computational time only the quarter of the models were analysed with symmetry boundary conditions applied.

5.2. Material model

From the number of composite materials models available in the LS-Dyna software, material model called Enhanced Composite Damage with failure criteria developed by Chang and Chang was chosen to describe the layered composite. This material model is specially designated to model failure mechanisms observed in composite materials. Besides usual static orthotropic properties, the various types of failure can be specified (LS-Dyna Keyword Manual):

- for the tensile fibre mode

$$\sigma_{aa} > 0 \ \text{then} \ e_f^2 = \left(\frac{\sigma_{aa}}{X_t}\right)^2 + \beta\left(\frac{\sigma_{ab}}{S_c}\right)^2 - 1 \begin{cases} \ge 0 \ \text{failed} \\ < 0 \ \text{elastic} \end{cases} \tag{1}$$

$$E_a = E_b = G_{ab} = \nu_{ba} = \nu_{ab} = 0$$

- for the compressive fibre mode

$$\sigma_{aa} < 0 \ \text{then} \ e_c^2 = \left(\frac{\sigma_{aa}}{X_c}\right)^2 - 1 \begin{cases} \ge 0 \ \text{failed} \\ < 0 \ \text{elastic} \end{cases} \tag{2}$$

$$E_a = \nu_{ba} = \nu_{ab} = 0$$

- for the tensile matrix mode

$$\sigma_{bb} > 0 \ \text{then} \ e_m^2 = \left(\frac{\sigma_{bb}}{Y_t}\right)^2 + \left(\frac{\sigma_{ab}}{S_c}\right) - 1 \begin{cases} \ge 0 \ \text{failed} \\ < 0 \ \text{elastic} \end{cases} \tag{3}$$

$$E_b = \nu_{ba} = 0 \rightarrow G_{ab} = 0$$

- for the compressive matrix mode

$$\sigma_{bb} < 0 \ \text{then} \ e_d^2 = \left(\frac{\sigma_{bb}}{2S_c}\right)^2 + \left[\left(\frac{Y_c}{2S_c}\right)^2 - 1\right]\frac{\sigma_{bb}}{Y_c} - 1 \begin{cases} \ge 0 \ \text{failed} \\ < 0 \ \text{elastic} \end{cases} \tag{4}$$

$$E_b = \nu_{ba} = \nu_{ab} = 0 \rightarrow G_{ab} = 0$$

$$X_c = 2Y_c \ \text{for 50\% fiber volume}$$

In the implemented constitutive model an erosion can occurs when:

- the tensile fibre strain is greater than ε_{max}^{+} or smaller than ε_{max},
- the effective strain is greater than ε_{fs}.

This means that, when a failure occurs in all of the composite layers (through-thickness integration points), the element is deleted.

In the preliminary analyses numerical models had four unidirectional composite layers with the properties defined based on experimental identification tests (Tab 1). Layers were uniformly distributed over the thickness and symmetrical with respect to neutral plane. Due to a small difference between compression (E_{aa}^{c}) and tension (E_{aa}^{t}) moduli (Tab. 1) average value was implemented in the numerical model. Authors assumed that application of model with separate stiffness properties for tension and compression would bring an insignificant improvement in obtained results for this particular composite material. Nevertheless for materials with higher differences between tension and compression modulus this approach should be used.

5.3. Numerical solution

The LS-Dyna software was used in our studies. Incremental static analysis was performed using full Newton-Rapshon algorithm. Equation solved in this stage had the following form (Hallquist, 2006):

$$K_i \Delta x_{i-1} = \Delta Q_i \tag{5}$$

where: K_i – stiffness matrix, Δx_{i-1} – displacement vector, ΔQ_i – external force vector.

The residual displacement and energy criteria were used to control the solution:

$$\frac{|\Delta u_i|}{u_{max}} < \varepsilon_d \quad \text{and} \quad \frac{|\Delta u_i Q_i|}{|\Delta u_0 Q_0|} < \varepsilon_e \tag{6}$$

where: Δu_i – increment in displacement in current step, u_{max} – maximum displacement, Δu_0 – desired increment in displacement, Q_0 – desired load, Q_i – load in current step.

5.4. Preliminary analysis results

The results of preliminary tests indicated that the model with four unidirectional layers defined and material properties obtained from standard tests behave correctly in tension test (Fig. 7).

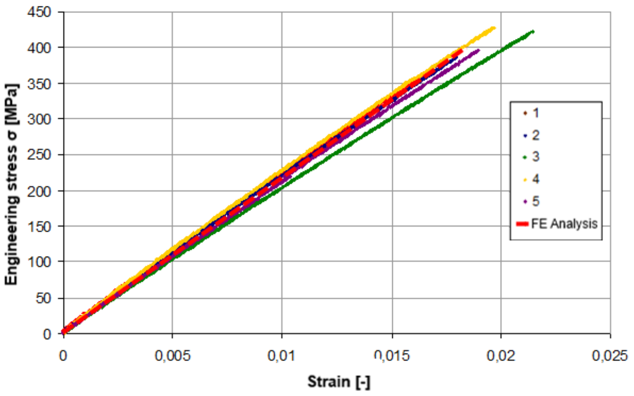

Fig. 7. Experimental (1-5) and numerical curves of engineering stress versus strain during tension test

Significantly different behaviour comparing to experimental tests results was obtained for three point bending tests, where the numerical model becomes too stiff (Fig. 8). The last point in FE analysis with a sudden decrease of a force indicates the numerical process of coupon failure occured.

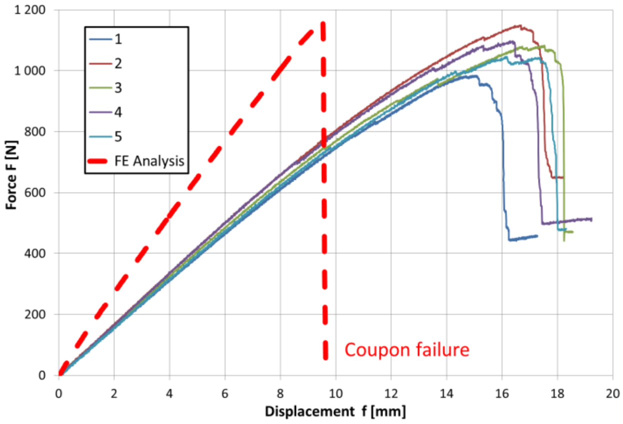

Fig. 8. Experimental (1-5) and numerical curves of force versus displacement during three point bending

6. LAYERS LAYOUT MODIFICATION

6.1. Method used

Due to the very different stiffness modulus in tension and bending loading the material properties obtained from standard test are not suitable to apply in numerical model. Authors assume that this is the result of the hand lay-up production and non-uniformly distributed layers of composite through thickness. Therefore a modified representation of composite structure is proposed. The reverse approach to a homogenisation was performed (Boczkowska et al., 2000). The layers of the composite were divided by resin layers and also an additional resin layers at the top and bottom of the model were defined. Resultant thickness of a the composite coupon remains unchanged.

The models were developed based on two parameters:

- composite volume fraction

$$V = \frac{n \cdot g_c}{g_{res}} \tag{7}$$

- external matrix volume fraction

$$V_z = \frac{2 \cdot g_e}{g_{res}\,(1-V)} \tag{8}$$

where: g_c – actual composite layer thickness, g_i – internal matrix layers thickness, g_e – external matrix layers thickness, g_{res} – resultant composite thickness, n – number of composite layers

The resultant layer set-up is presented in Fig. 9.

The material properties for matrix layers were defined based on resin experimental test, but to simplify the model linear elastic material was used. Therefore, to represent the actual matrix behaviour the reduced Young modulus equals to $E_m = R^t/e^t$ was used.

Reversing the simple plain stress homogenisation theory for laminar materials, the stiffness and strength properties for composite layers were obtained according to (Boczkowska et al., 2000):

$$E_{res} = E_c V + E_m(1-V) \rightarrow E_c = \frac{E_{res}-E_m(1-V)}{V} \qquad (9)$$

where: E_{res} – resultant stiffness modulus (obtained from experiments), E_m – matrix layer stiffness modulus (obtained from experiments), E_c – composite layer stiffness modulus, V – composites volume fraction.

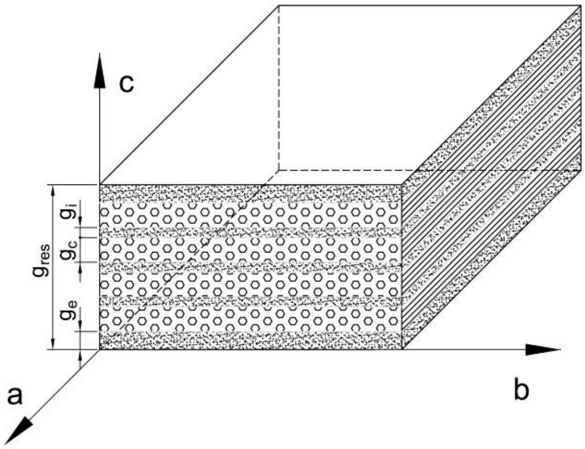

Fig. 9. Layers layout after model modification

6.2. Layout optimization

To explore the sensitivity of the model and to find the correct layer layout the model was submitted to a single stage optimization process (Stander et al., 2009). The LS-Opt software was used to run the optimization process for bending test. The following analysis parameters were defined:

variables:

- composite volume fraction $V = (0.3 \div 0.99)$
- external matrix volume fraction $V_Z = (0.4 \div 0.99)$

dependent variables:

- stiffness parameters,
- strength parameters,
- density,
- layers thickness

objectives:

- stiffness error $\Delta S = |S_{num}-S_{exp}|/S_{num}$ where $S = |F_{max}/f_{max}|$
- force error $\Delta F = |F_{num}-F_{exp}|/F_{num}$
- displacement error $\Delta f = |f_{num}-f_{exp}|/f_{num}$

constrains:

- resultant thickness g_{res}

The procedure was performed for 16 sampling points and the genetic algorithm implemented in LS-Opt software where used for optimization.

Optimized layer obtained from this procedure consist of following layers:

- layer 1 – polyester resin – $g_e = 0.7218$ mm
- layer 2 – composite – $g_c = 0.396$ mm
- layer 3 – polyester resin – $g_i = 0.3168$ mm
- layer 4 – composite – $g_c = 0.396$ mm
- layer 5 – polyester resin – $g_i = 0.3168$ mm
- layer 6 – composite – $g_c = 0.396$ mm
- layer 7 – polyester resin – $g_i = 0.3168$ mm
- layer 8 – composite – $g_c = 0.396$ mm
- layer 9 – polyester resin – $g_e = 0.7218$ mm

6.3. Results

The resultant model with layout obtained from optimization process was submitted to numerical tension and bending tests. Results for the tension test are the same as the one from preliminary results due to equivalent resultant Young modulus and strength parameters.

However, a significant improvement can be seen for flexural behaviour (Fig. 10). The model stiffness is nearly identical with the coupon stiffness. Also, the maximum force is comparable to the experimental one. The difference in stiffness and maximum force can be caused by a simplified linear elastic model of matrix, numerical representation of damage process and element erosion.

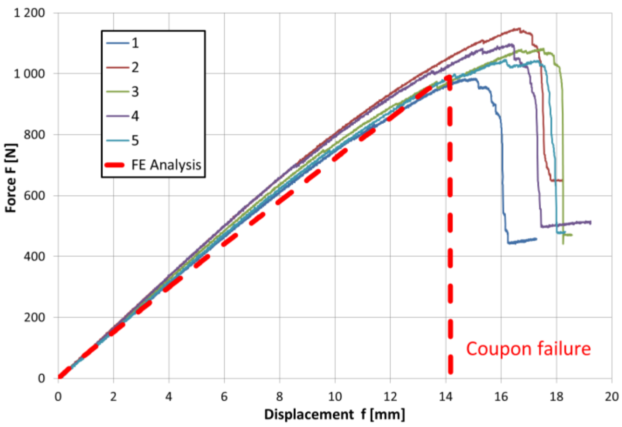

Fig. 10. Experimental (1-5) and numerical curves of force versus displacement during three point bending – modified numerical model with optimized layer layout

7. SUMMARY

The industrially made composite elements using hand lay-up techniques have very non-uniformly distributed layers. Presented in the paper simple rectangular coupons, which are relatively easy to manufacture, have very low quality. In effect the differences in actual and theoretical bending stiffness (obtained from tension stiffness) exceed 70%.

Results presented in this paper clearly show that the tensile test is not enough to validate the developed discrete model. To obtain the proper flexural stiffness the validation in tensile and bending test is required.

The method of fibre reinforcement composite FE model validation which takes the advantage of numerical optimization procedure of layers distribution adjustment is proposed. This method can be efficient way for composite model development where the structure layout is dependent on coupons quality.

The presented method can be extended to be applicable for the materials with large dissimilarities in tensional and compressive modulus by adopting a constitutive model with separate tension and compression stiffness parameters.

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