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Assessment Methods of Mechanical Properties of Composite Materials

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The paper deals with a specific kind of imperfection in multilayered composite structures as thickness deviation. During manufacturing process the layers are laminated together with resin. Lack of accuracy or some errors during autoclaving process could contribute to thickness deviation when thin layer of resin remains between plies. This is particularly important in the case of hybrid laminates as Fibre Metal Laminates (FML). Therefore, the aim of this work is to determine the impact of thickness imperfection on the variation of effective mechanical properties of FML thin-walled panels. Two methods have been considered in the study: assumption of additional resin/matrix layer in a stacking sequence and a correction of fibre volume fraction in composite layers. A full 3-2 FML lay-up has been analyzed using Classical Lamination Plate Theory with connection to two micromechanical approaches: analytical (Rule of Mixture) and numerical (Finite Element Method). Results of calculations were verified by conducted experimental tests.

Keywords: Fiber Metal Laminate, mechanical properties, FEM, micromechanics, thickness imperfection.

1. Introduction

Nowadays the aerospace industry seeks in constructions to cost efficiency which could be obtain by applying strength and simultaneously lightweight materials. In connection to the weight reduction, composite materials characterised by high strength to weight ratio are commonly used. Rutan Voyager is an example entirely built of those materials. Relatively new hybrid structure - Fiber Metal Laminates, find also an application in aircrafts as wing skin panels, cargo doors, stringers as well as fuselage skin [1]. An example could be Airbus A380, in which FML's were introduced as the upper fuselage materials. Interest in the aerospace industry in those structures is strictly connected with its numerous advantages. FMLs combine all features which are crucial in design and maintain area: high strength to weight ratio, excellent fatigue and corrosion resistance. Moreover, alternating arrangement of composite and aluminium layers makes those structures very resistant to impact [2]. Nevertheless, Fibre Metal Laminates are being implemented to industry with a great caution. This is caused by manufacturing process which in case of composites is undoubtedly more difficult in comparison to metallic structures. The manufacturing process for FMLs consists of few steps: preparation of components - layers of prepreg and metal, bonding of individual layers and laminate curing using autoclave. Obviously, in each step high accuracy have to be gained and special conditions have to be guaranteed. However, it is a common situation when despite ensuring all required parameters and conditions of manufacturing process, the final structure differs a little from ideal one. In literature overview some works investigating the influence of autoclave process on the behavior of composite structures could be found [3, 4]. This operation can lead to thickness imperfection - when individual layers of prepreg and aluminum sheets are bonded together, a thin layer of resin could remain in laminates [3, 6]. It may have got an influence on the behavior of whole structure and on a change of its effective mechanical properties. The aim of this work is to investigate the effect of additional thin layer remained after bonding, on mechanical parameters of FMLs using two different methods. In the first approach thickness imperfection is taken into account by introducing additional layer of resin/matrix, while in the second one by implementing additional resin/matrix into prepreg by correction a nominal fibre volume fraction.

2. Subject of the study

GLARE like FML's rectangle samples produced by the autoclave method at the Lublin University of Technology (LUT) [7] were used to predict the effect of thickness imperfection on effective mechanical properties. Three different 3/2 FML stacking sequences with symmetrical lay-up presented in (Tab. 1) were chosen for the study [6].

Table 1 Analyzed FML layer sequences

Arrangement code	Lay-up
1	Al/0/90/Al/90/0/Al
5	Al/0/0/Al/0/0/Al
7	Al/0/25/Al/25/0/Al

Each considered sample consists of three layers made of aluminum alloy 2024-T3 and two double layers of R-glass-epoxy unidirectional fiber reinforced prepreg (Hexcel TVR 380 600 M12 26% R-glass) with fibre volume fraction equal to 60%. Nominal thickness of aluminum layers was 0.3 mm when prepreg sheet 0.25 mm. Mechanical properties of FML's components are presented in Tab. 2. Two samples of each considered stacking sequences were examined in the laboratory tests. Their dimensions are listed in Table 3.

As it could be noticed from presented in Table 3 measurements, the real thickness of each sample is higher than it results from simple addition of components' thickness (t_{nom} = 2 mm). A possible reason could be an existing in that multi-

Table 2 Mechanical properties of FML's components

Aluminum		TVR 380/26%		Epoxy		R-glass	
E_{al} [GPa]	77	E_1 [GPa]	54.5	E_m [GPa]	5.1	E_f [GPa]	87.5
ν_{al} [-]	0.3	E_2 [GPa]	18.8	ν_m [-]	0.4	ν_f [-]	0.269
G_{al} [GPa]	29.6	ν_{12}[-]	0.28	G_m [GPa]	1.8	G_f [GPa]	36.5
		G_{12} [GPa]	6.9				

Table 3 Dimensions of rectangle samples

Number of sample	Width [mm]	Thickness [mm]	Length [mm]
1A	25.00	2.10	150
1B	25.00	2.00	150
5A	19.97	1.99	200
5B	19.98	2.06	200
7A	25.00	1.94	150
7B	25.00	1.95	150

layered structure an addition amount of resin remaining between plies after curing process.

3. Methods of determining mechanical properties of FML structure

3.1. *Classical Lamination Plate Theory*

Mechanical properties of hybrid multi-layered structure could be determined according to Classical Laminate Theory [8] which is an equivalent single-layer theory and gives the reduction of a 3-D problem to a 2-D stress state problem. Thus CLT is frequently called Classical Laminated Plate Theory (CLPT). It allows to establish three constitutive stiffness matrices A, B and D which characterize composite structure properties and govern its in-plane, out-of-plane response due to applied load as well as coupling bending-extensional effects. The A extensional (or in-plane) stiffness matrix components A_{ij}, are defined as:

$$A_{ij} = \sum_{k=1}^{N} \left[\overline{Q_{ij}} \right] \; t_k \tag{1}$$

$\overline{Q_{ij}}$ is the lamina stiffness matrix and t_k is the thickness of a single layer [8]. The effective mechanical parameters of entire FML structure can be determined based on matrixA'_{ij} which is the inverse matrix of matrixA_{ij}. Thus one can obtain:

$$E_x = \frac{1}{A'_{11} t_c} \tag{2}$$

$$E_y = \frac{1}{A'_{22} t_c} \tag{3}$$

$$G_{xy} = \frac{1}{A'_{66} t_c} \tag{4}$$

$$\nu_{xy} = -A'_{12} t_c E_x \tag{5}$$

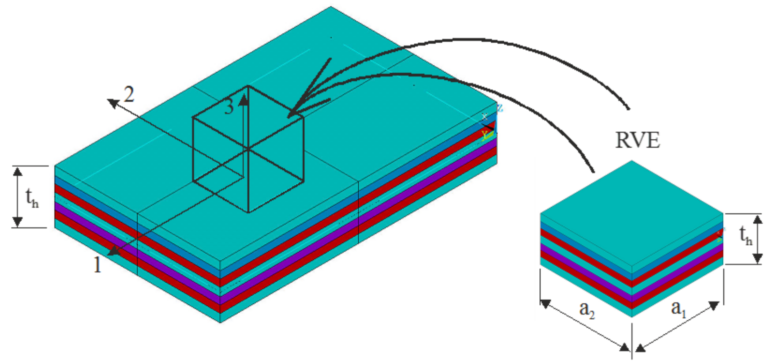

Figure 1 RVE of Fiber Metal Laminate

3.2. *Numerical model of Representative Volume Elements*

Due to the periodicity of composite structure its mechanical properties can be analyzed with reference to a representative cell or volume element cut out from a whole structure. This way of homogenization is applied to model composites at micromechanical level as well as at mesoscale. Similar procedure can be employed to model in the finite element analysis the three-dimensional representative volume element (RVE) of entire laminate [9]. Such a numerical model of FML panel (or thin walled plate) on meso-mechanical level is shown in Figure 1. This is a cell with unit in-plane dimensions and height corresponding to the laminate thickness.
The analysis was performed using FEM with the ANSYS commercial software [10]. Representative volume element (RVE) was modeled with three-dimensional SOLID186 element from ANSYS library. Due to FML symmetric stacking sequence in the numerical model a half of a structure was considered and thus the symmetry boundary conditions were applied. Subsequent boundary conditions were introduced to ensure cell periodicity and existing plate - plane stress state:

$$u_1(a_1, a_2, x_3) - u_1(-a_1, -a_2, x_3) - 2a_1\varepsilon_{11} - 2a_2\varepsilon_{12} = 0 \tag{6}$$

$$u_2(a_1, a_2, x_3) - u_2(-a_1, -a_2, x_3) - 2a_1\varepsilon_{21} - 2a_2\varepsilon_{22} = 0 \tag{7}$$

$$u_3(a_1, a_2, x_3) - u_3(-a_1, -a_2, x_3) - 2a_3\varepsilon_{31} = 0 \tag{8}$$

$$u_1(a_1, -a_2, x_3) - u_1(-a_1, a_2, x_3) - 2a_1\varepsilon_{11} - 2a_2\varepsilon_{12} = 0 \tag{9}$$

$$u_2(a_1, -a_2, x_3) - u_2(-a_1, a_2, x_3) - 2a_1\varepsilon_{21} + 2a_2\varepsilon_{22} = 0 \tag{10}$$

$$u_3(a_1, -a_2, x_3) - u_3(-a_1, a_2, x_3) + 2a_3\varepsilon_{32} = 0 \tag{11}$$

To determine mechanical properties of FML, according to presented above boundary constrains equations respective unit deformations were applied to the numerical model in few steps. Based on obtained stresses and strains values, mechanical parameters were calculated using the following formulas:

$$\nu_{12} = -\frac{\varepsilon_2}{\varepsilon_1} \tag{12}$$

$$E_1 = \sigma_1 - \nu_{12}\sigma_2 \tag{13}$$

$$E_2 = \sigma_2 - \nu_{21}\sigma_1 \tag{14}$$

$$G_{12} = \tau_{21} \tag{15}$$

3.3. *Analytical model*

Among numerous micromechanical analytical models presented in literature only the simplest one i.e., the Rule of Mixture is being used in the case of hybrid multi-layer structures [9-14]. By the presence of two components (aluminum layers and GFRP plies) mechanical properties of entire FML laminate can be determined based on the following formulas:

$$E_1 = V_{al}E_{al} + (1 - V_{al})E_{1p} \tag{16}$$

$$\nu_{12} = V_{al}\nu_f + (1 - V_{al})\nu_p \tag{17}$$

$$E_2 = \frac{E_{al}E_{2p}}{(1 - V_{al})E_{al} + V_{al}E_{2p}} \tag{18}$$

$$G_{12} = \frac{G_{al}G_p}{(1 - V_{al})G_{al} + V_{al}G_p} \tag{19}$$

where *al* and *p* indices mean respectively properties of aluminum and prepreg.

4. Methods of implementing thickness imperfection to determining mechanical properties

5. Assumption of additional resin layer

Some imperfection in thickness of laminate composite structure could be included to the nominal model by its modification. A higher value of total thickness could be taken into account by implementing supplementary layer of resin/matrix in a entire structure (Figure 2). These additional layers were introduced between composite and metal sheets. Mechanical properties of FML model with three constituents were determined numerically and analytically - with ROM and CLTP method.

In analysis the thickness of additional layer–layer of resin/matrix was calculated for each tested sample directly from its measurements as presented in Tab. 4.

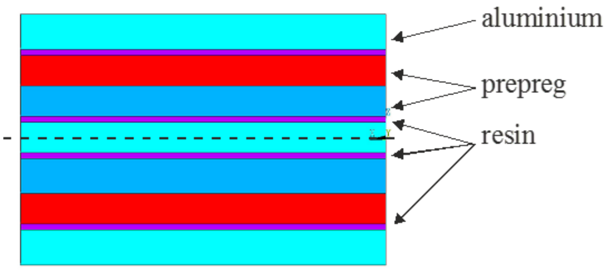

Figure 2 Model of FML with implementing additional layer of matrix

Table 4 Thickness of matrix layers in each sample

Number of sample	t_{real} [mm]	$t_{average}$ [mm]	$t_{nominal}$ [mm]	$t_{matrix} = 0.25(t_{real}\text{-}t_{nominal})$ [mm]
1A	2.10	2.00	1.90	0.05
1B	2.00			0.03
5A	1.99			0.02
5B	2.06			0.04
7A	1.94			0.01
7B	1.95			0.01

5.1. *Correction of fibre volume fraction in prepreg*

Another method which includes thickness variation was presented by Khakimova et al. [15] is only limited to prepreg layers. In the real model, the differences in its thickness is closely linked with variation of fiber volume fraction (FVF). When actually thickness of structure is higher than nominal one, more amount of matrix is probably introduced whereas the amount of fiber remains unchanged. Therefore, in result actual fiber volume fraction is lower than nominal one. Thus actual fibre volume fraction could be calculated based on nominal fibre volume fraction V_{fnom}, nominal thickness t_{nom} of structure and the actual thickness t.

$$V_f = \frac{V_{fnom}\, t_{nom}}{t} \tag{20}$$

Actual values of FVF for all analyzed FML samples are listed in Tab. 5.

In this approach mechanical properties of fiber-reinforced composite were calculated using micromechanical model proposed by Chamis [16]:

$$E_1 = V_f E_f + (1 - V_f) E_m \tag{21}$$

$$\nu_{12} = V_f \nu_f + (1 - V_f) \nu_m \tag{22}$$

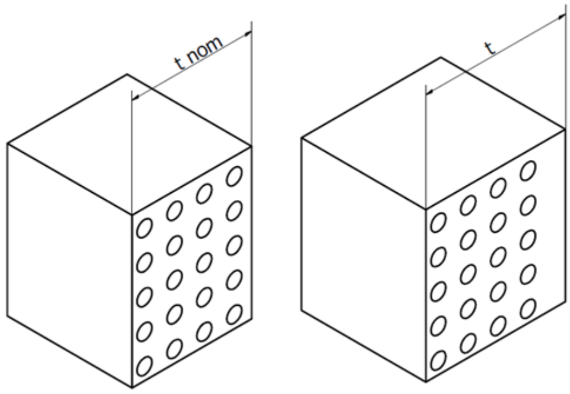

Figure 3 Imperfection of the structure thickness

Table 5 Recalculated fiber volume fraction of prepreg in each sample

Number of sample	t_{real} [mm]	V_{fnom}	V_f	$V_{average}$
1A	2.1	0.6	0.54	0.57
1B	2		0.57	
5A	1.99		0.57	
5B	2.06		0.55	
7A	1.94		0.59	
7B	1.95		0.58	

$$E_2 = \frac{E_m}{1 - \sqrt{V_f}(1 - \frac{E_m}{E_f})} \tag{23}$$

$$G_{12} = \frac{G_m}{1 - \sqrt{V_f}(1 - \frac{G_m}{G_f})} \tag{24}$$

where f and m refers to fiber and matrix, respectively.

Results of calculations where corrections of FVF were applied are presented in Tab. 6.

Table 6 Mechanical properties of unidirectional fiber-reinforced composite calculated with Chamis formulas

	Sample 1A	Sample 1B, 2A, 5A	Sample 5B	Sample 7A	Sample 7B
E_1 [MPa]	49831	52068	50700	53521	53272
E_2 [MPa]	16658	17646	17031	18338	18217
ν_{12} [-]	0.291	0.286	0.289	0.282	0.283
G_{12} [MPa]	6071	6442	6211	6703	6657

6. Experimental test

To verify results of numerical and analytical calculations, a static tensile test was performed using universal strength testing machine of Instron 4485 (Fig. 4). The test was conducted according to D 3039/D 3039M-00 standard [16]. The precise value of strains was measured with mechanical extensometer and also with strain gauge bridge. Two samples from each considered stacking sequence were subjected to laboratory test.

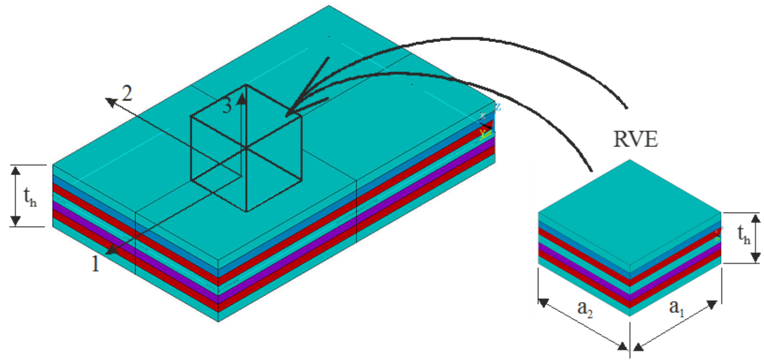

Figure 4 Specimen placed in the universal testing machine

Longitudinal effective Young Modulus obtained from stress - strain curves are presented in Tab. 7.

Table 7 Results of the tensile test

Number of sample	1A	1B	5A	5B	7A	7B
E_1 [GPa]	50.38	53.75	65.89	60.23	58.16	59.07

7. Results

Effective mechanical properties of multi-layer Fiber Metal Laminates were determined numerically and analytically. Firstly calculations were performed for perfect structure, it is with nominal thickness (Tab. 8). Secondly, two different ways of implementing thickness deviation were used: with the assumption of additional layer of prepreg and a correction of fibre volume fraction of composite layer. All results are presented for each considered stacking sequences in Tab. 9–11. In Fig. 5–7 mean value of calculated longitudinal Young Modulus and its standard deviation is compared with data obtained during experiment. By solid line results gained in tensile test are also distinguished. The most left columns refer to the approach where volume fraction of fibres in prepreg was recalculated (Method I). The right side columns of tables refer to Method II where additional layer of prepreg was introduced. Significantly good accuracy with experiment could be observed. However, in some cases - see Sample 5A, 7B - data gained from analysis are underestimated in comparison to those from stress-strain curves. It could be connected with some other inaccuracies as for example thickness imperfection could be result of thickness deviation of individual layers of aluminum sheets. To prove this hypothesis some more detailed studies would be required. Taking into consideration of transverse mechanical properties, significant difference between ROM and others methods was observed. Even thin layer of resin characterized by low stiffness introduced into a structure has significant impact on results of mechanical properties. It can be concluded that Rule of Mixture method underestimates transverse parameters. Similar observations and conclusions one can find in [**6**].

When two analyzed approaches of implementing thickness imperfection to a structure are investigated, high accuracy of results is observed. However, it should be emphasized that higher value of standard deviation was gained for approach were additional layer of matrix was applied. It means that addition even very thin layer of material with significantly different properties (as low stiffness matrix) increases the differences between used methods.

Table 8 Mechanical properties of FML for perfect samples

	Al/0/90/Al/90/0/Al		Al/0/0/Al/0/0/Al		Al/0/25/Al/25/0/Al	
	MEAN	STD	MEAN	STD	MEAN	STD
E_1 [MPa]	54309	1544	62791	2464	57862	1638
E_2 [MPa]	48842	7587	49566	11880	45503	4213
ν_{12} [-]	0.335	0.092	0.356	0.063	0.393	0.057
G_{12} [MPa]	15204	3795	15204	3795	16338	3659

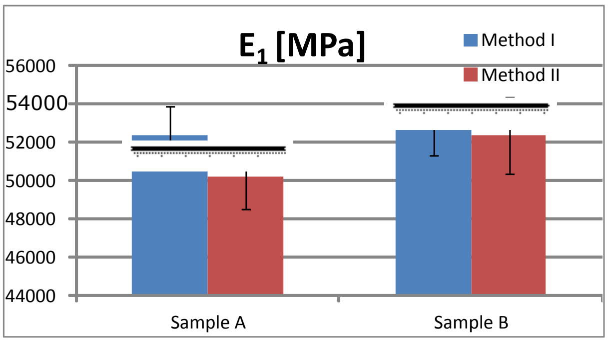

Figure 5 Longitudinal Young Modulus of FML with Al/90/0/Al/0/90/Al stacking sequence

Table 9 Mechanical properties of FML with Al/0/90/Al/90/0/Al stacking sequence

	Recalculating fibre volume fraction of prepreg				
	Sample A			MEAN	STD
	FEM	CLTP	ROM		
E_1 [MPa]	50811	52436	53821	52356	1507
E_2 [MPa]	50811	52436	37439	46895	8230
ν_{12} [-]	0.429	0.246	0.240	0.305	0.107
G_{12} [MPa]	16666	16161	9943	14257	3744
	Assuming additional layer				
	Sample B			MEAN	STD
	FEM	CLTP	ROM		
E_1 [MPa]	51697	54268	51997	52654	1406
E_2 [MPa]	51697	54268	35148	47038	10377
ν_{12} [-]	0.427	0.247	0.240	0.305	0.106
G_{12} [MPa]	16859	16870	9208	14312	4420
	Recalculating fibre volume fraction of prepreg				
	Sample A			MEAN	STD
	FEM	CLTP	ROM		
E_1 [MPa]	48210	51381	50960	50184	1722
E_2 [MPa]	48210	51381	24250	41280	14834
ν_{12} [-]	0.47	0.25	0.256	0.325	0.125
G_{12} [MPa]	16096	16150	7364	13203	5057
	Assuming additional layer				
	Sample B			MEAN	STD
	FEM	CLTP	ROM		
E_1 [MPa]	50018	53688	53253	52320	2005
E_2 [MPa]	50018	53688	29856	44521	12832
ν_{12} [-]	0.439	0.249	0.249	0.312	0.110
G_{12} [MPa]	16610	16866	8685	14054	4651

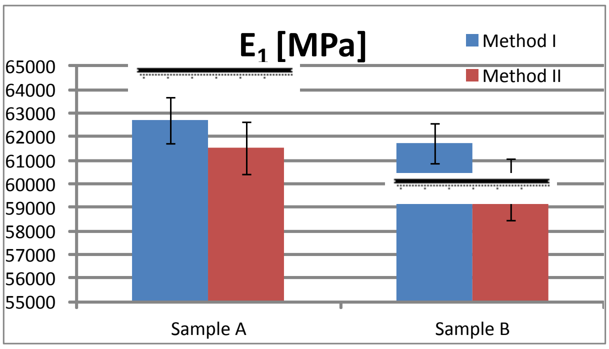

Figure 6 Longitudinal Young Modulus of FML with Al/0/0/Al/0/0/Al stacking sequence

Table 10 Mechanical properties of FML with Al/0/0/Al/0/0/Al stacking sequence

	Recalculating fibre volume fraction of prepreg				
	Sample A			MEAN	STD
	FEM	CLTP	ROM		
E_1[MPa]	58485	57877	57502	57955	496
E_2 [MPa]	42145	45724	42532	43467	1964
ν_{12}[-]	0.418	0.312	0.330	0.353	0.057
G_{12} [MPa]	18483	17955	10852	15764	4261
	Assuming additional layer				
	Sample B			MEAN	STD
	FEM	CLTP	ROM		
E_1[MPa]	58355	57594	57234	57727	573
E_2 [MPa]	42073	45380	40989	42814	2288
ν_{12}[-]	0.418	0.312	0.330	0.353	0.057
G_{12} [MPa]	18452	17824	10583	15620	4373
	Recalculating fibre volume fraction of prepreg				
	Sample A			MEAN	STD
	FEM	CLTP	ROM		
E_1[MPa]	58582	57047	57796	57808	768
E_2 [MPa]	43067	45303	49189	45853	3098
ν_{12}[-]	0.409	0.312	0.330	0.350	0.052
G_{12} [MPa]	18717	17780	11716	16071	3800
	Assuming additional layer				
	Sample B			MEAN	STD
	FEM	CLTP	ROM		
E_1 [MPa]	58246	56783	57597	57542	733
E_2 [MPa]	42811	45100	48918	45610	3085
ν_{12}[-]	0.413	0.312	0.330	0.351	0.054
G_{12}[MPa]	18628	17699	11621	15982	3806

8. Conclusions

In the presented study two ways of implementing a thickness imperfection during determination of effective mechanical properties of Fibre Metal Laminate were considered. Properties were calculated using FE Method and analytically - with CLPT approach and Rule of Mixture equations. Results of numerical and analytical computations were verified experimentally by conducting tensile test. Comparison of E_1 modulus obtained from stress-strain diagram with those obtained analytically

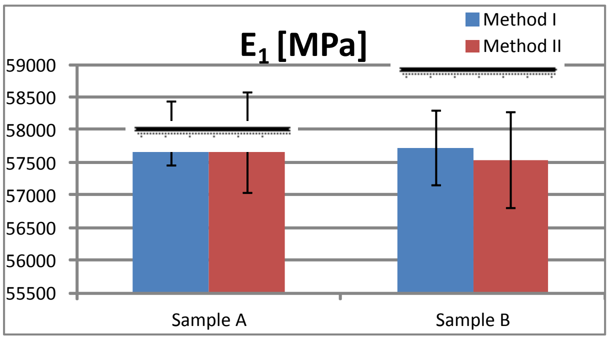

Figure 7 Longitudinal Young Modulus of FML with Al/0/25/Al/25/0/Al stacking sequence

Table 11 Results of calculation for layer sequences Al/0/25/Al/25/0/Al

	Recalculating fibre volume fraction of prepreg				
	Sample A			MEAN	STD
	FEM	CLTP	ROM		
E_1[MPa]	61543	63289	63287	62706	1007
E_2 [MPa]	42071	45040	60949	49353	10151
ν_{12}[-]	0.419	0.297	0.292	0.336	0.072
G_{12} [MPa]	16859	16870	9943	14557	3996
	Assuming additional layer				
	Sample B			MEAN	STD
	FEM	CLTP	ROM		
E_1[MPa]	60731	62191	62190	61704	843
E_2 [MPa]	41679	43904	59593	48392	9764
ν_{12}[-]	0.422	0.298	0.294	0.338	0.073
G_{12} [MPa]	16853	16436	9486	14258	4138
	Recalculating fibre volume fraction of prepreg				
	Sample A			MEAN	STD
	FEM	CLTP	ROM		
E_1[MPa]	60214	62181	62175	61523	1134
E_2 [MPa]	41892	45007	40297	42399	2396
ν_{12}[-]	0.364	0.297	0.295	0.319	0.039
G_{12} [MPa]	16838	16866	8685	14130	4715
	Assuming additional layer				
	Sample B			MEAN	STD
	FEM	CLTP	ROM		
E_1 [MPa]	58284	60521	60513	5977	1289
E_2 [MPa]	40496	43851	33553	39300	5252
ν_{12}[-]	0.448	0.297	0.298	0.348	0.087
G_{12}[MPa]	16384	16428	7826	13546	4954

for samples with nominal thickness (see Table 8), shows significance underestimation. It enhances the need to imply some kind of structure imperfection. When thickness imperfection is introduced, significantly higher accuracy was obtained. Both presented approaches applied to implement thickness deviation give similar outcomes of effective mechanical properties. However, using an approach where additional layer of resin/matrix is introduced to structure, a little bit higher deviation, mainly in transverse mechanical properties was observed. It could be a result of little underestimation of these parameters by Rule of Mixture method.

Presented analyses have shown that counting thickness imperfection allows to predict effective mechanical properties of multi-layered structure with better accuracy.

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