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# Analytical and Experimental Determination of FML Stiffness and Strength Properties

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The paper presents application of analytical methods of determining the mechanical properties of Fibre Metal Laminates. Chosen micromechanical methods were employed to predict elastic moduli and strength of FML panels. Prediction was conducted on two levels i.e. micromechanics where properties of a single composite lamina (prepreg) were analyzed, and macro–mechanics to determine properties of a full FML hybrid material. The properties of a single GFR lamina were predicted by Rule of Mixture Method (ROM), inverse Rule of Mixture Method with correction factor, Halpin Tsai Method, Tsai Method and Wilczynski Method application. Properties of full 3–2 FML lay–up were determined using the Rule of Mixtures. Analytical results were verified by experimental tests. Tensile and bending test were performed on rectangular standard coupons of 3–2 FMLs.

*Keywords*: FML, hybrid laminate, mechanical properties, mechanical testing.

## 1. Introduction

Fibre Metal Laminates (FML) are a type of hybrid structural material consisting of alternating metal layers and layers of a fibre reinforced composite. At the beginning as a composite layer aramid epoxy prepreg (ARRAL) was used. However, the anisotropy of aramid made it unable to use ARALL as a component of plates. Nowadays, the most common solution is application of glass epoxy prepregs as a composite component of FML (GLARE) [18,28]. It allows to obtain higher material properties with lower manufacturing costs. The prevalent material for metal sheets is aluminium. The further FML development has brought CARALL - carbon fiber laminate with aluminium lay–ups and next class - titanium instead of aluminium.

This hybrid material system combines the advantages of metallic materials and fibre reinforced matrix. FML are a combination of high stiffness and strength of the composite layers and good impact strength aluminum alloy resulting in desired properties for aircraft structures [8]. One of the most important advantage of FML laminate is its resistance against crack propagation in aluminium. Their failure mechanisms are rather complex due to their inhomogeneous structures. Good fatigue strength makes lower thickness or higher stresses in FML possible. Thus thin–walled sections which are commonly used in industry, are prone to buckling [6, 23, 24].

Mechanical properties of particular material - here FML, could be obviously determined by experiment or Finite Element Method [3, 29]. These properties could be also predicted by analytical methods. Considerable research [1, 4, 10, 28] has focused on micromechanical behaviour of lamina and its dependence on applied components. Most studies were based on the Rule of Mixture [2, 11], where the usefulness of those method were investigated. One can find papers [4, 13, 26] which present a great compatibility of the Rule of Mixtures with experiment. Chawla [9] in his work noticed that analytical formulas gave higher results of FML mechanical properties. He pointed out some factors as residual stresses or the mode of deformation of two components which make that ROM is not valid for metal matrix composite. But other researches as Verolme [35], present in his work confirmation of a good agreement between analytical predictions by the Rule of Mixture and experiment. Nevertheless, they suggest more study to verify this concept. He highlights also that the mechanical properties of the FML singular components should be experimentally determined. Similar conclusion one can find in [1, 2, 26] where the analytical predictions were verified by numerical experiment with successful results. Lee at all [22] use the Rule of Mixture to determine in–plane mechanical properties of polypropelene sandwich FML. Authors got a good coherence between experiment, analytical and numerical model. Some discrepancies were observed above the yield limit in the elastic–plastic regime. Ginger at all [13] focused on transverse mechanical properties. He used micromechanical approach referring to reinforcement of factor $\xi$ applied in Halpin–Tsai Method. In the case of transverse properties some correction factors are required to come closer to the real values [15, 20, 21].

This brief literature survey proves that micromechanical model allows to determine mechanical properties of hybrid composite materials. In this study the usefulness of Rule of Mixture to predict mechanical properties of composite and FML structure is verified and highlighted.

## 2. Materials and method

The FML examined in this work was made of three layers of 2024 T3 aluminium alloy of 0.3 mm nominal thickness whereas two doubled prepreg layers were made of Hexcel R–glass with nominal cured thickness of 0.25–0.26 mm and 60% nominal fibre volume fraction. Four different stacking sequences given in Tab. 1 were considered.

In Tab. 1 ”Al” indicates aluminium sheets which ”0” orientation coincides with rolling direction. The orientations $0^{\circ}$, $25^{\circ}$, $90^{\circ}$ of the fibreglass laminae are also measured with respect to the rolling direction of metal layers. The GFR layer lay–ups correspond to commercial GLARE type versions as well as were chosen due to some specific composite futures. The hybrid composite was fabricated at

**Table 1** Arrangement of FML laminate

| Arrangement code | Lay - up |
|---|---|
| 1 | Al/0/90/Al/90/0/Al |
| 2 | Al/90/0/Al/0/90/Al |
| 5 | Al/0/0/Al/0/0/Al |
| 7 | Al/0/25/Al/25/0/Al |

Lublin University of Technology. FML panels were cured in autoclave process under vacuum [6, 7]. Nominal thickness of the entire cured laminate was 1.9 mm. However, the measurement of the thickness of the manufactured samples gave higher values of the total thickness. The actual thickness of FML samples was varying from 1.92 to 2.04 mm. These values were adopted in analytical calculations. The declared mechanical properties of both FML constituents given by LUT are outlinedin Tab. 2. Properties with subscript '3', usually required in FEM models were obtained due to assumed transversally isotropy of lamina cross section [3].

**Table 2** Mechanical properties of FML constituents

| Al 2024-T3 | [ GPa ] | R-glassprepreg | [ GPa ] |
|---|---|---|---|
| E | 72 | $E_{L(1)}$ | 46.43 |
| $\nu$ | 0.33 | $E_{T(2)}$ | 14.92 |
| G | $E/2(1+\nu)$ | $E_{(3)}$ | 14.92 |
| | | $G_{12}$ | 5.233 |
| | | $G_{23}$ | 3.570 |
| $R_{0.2}$ | $359\times10^{-3}$ | $G_{13}$ | 5.233 |
| $E_{tang}$ | $E\times10^{-3}$ | $\nu_{12} = \nu_{13}$ | 0.269 |
| | | $\nu_{23}$ | 0.400 |

## 3. Analytical prediction of lamina mechanical properties

It may not always be practical to determine each material properties experimentally, therefore some methods have been developed to avoid this problem. Applicability of certain methods to FML structures was confirmed in several works [5, 19, 27, 35] and was verified in current paper as well. Due to conjunction of metal and composite layers the FML obtained its specific features and properties. Thus it should be not treated as metal nor composite but as true hybrid material. Particularly it is visible in a lack of FML direct test standards. However, the mechanical and utility FML attributes are governed directly by both its constituents. Consequently according to the level of study: micro–, meso– or macromechanics material model can be adopted and considered.

When at the micromechanical level to the analysis of unidirectional fiber composite one introduces some basic assumptions and approximations, and neglects the heterogeneous structure of a single lamina - it is smears the matrix and the fibers, and then will achieve the ability to determine mechanical properties of a lamina in terms of both constituent materials with comparatively simple formulas. Generally it is assumed that both materials are homogenous and elastic in this model. Additionally, when the two–dimensional arrangement of a lamina is accepted, a transversally isotropic composite can be considered. Within the cross–section of a lamina the requirement of statistical homogeneity is fulfilled while in its plane an orthotropy results. Both composite constituents participate in composite straining and stress transfer whereas potential voids (generally void volume fracture is less than 1%) are neglected. This approach lies at the basis of the Rule of Mixtures (ROM) and the inverse Rule of Mixtures (iROM) e.i. Voigt and Reuss models [1, 20]. Both models do not require the knowledge of exact stress and strain fields within the composite and neglect the interaction between constituents due to different Poisson ratio values simply adopting the spring system models. The experimental experience confirms that ROM is insensitive to this assumption yet some underestimation of transverse modulus and in–plane shear modulus is observed [1]. Then some empirical relation or correction factors are introduced [15].

In the subsequent study the mechanical properties of FML structure were predicted in analytical way at two levels – first for a single Glass Fiber Reinforced Epoxy lamina, next the technique was extended to multilayered FML panel. At the micro–level one assumes that a lamina consists of two components: fibres and epoxy matrix with known material properties and volume fraction of each of them. Next, at the macro–level each layer is treated as homogeneous, orthotropic and linearly elastic. To investigate the strength and stiffness characteristics at the first level the Rule of Mixtures [1, 20, 17], Wilczynski method [21, 33], Tsai [20] and the Halpin–Tsai equation [15, 32] were employed. The latter – the rule of Mixtures was applied for multilayered FML coupon. In introduced next formulas the indices $f$ refer to fibre and $m$ to matrix, respectively, whereas for elastic moduli classical notation of solid mechanics is introduced.

Employed in the current prediction analysis the Rule of Mixture, Wilczyński and Halpin–Tsai Method use the same formulas to determine the apparent (or effective) modulus in fiber direction and to predict in–plane Poisson's ratio. Specifying fibre volume fraction by $V_f$ and for matrix as $V_m$, these formulas are as follows:

- longitudinal modulus

$$E_1 = V_f E_{1f} + V_m E_m \tag{1}$$

- longitudinal Poisson's ratio

$$\nu_{12} = V_f \nu_{12f} + V_m \nu_m \tag{2}$$

Repeating the rule of mixtures the ultimate strength of composite material can be determined by the following equation:

$$\sigma_{c\max} = V_f \sigma_{f\max} + V_m \sigma_{m_{cf}\max} \tag{3}$$

where: $\sigma_{f\max}$ – maximum fibre tensile strength, $\sigma_{m_{cf}\max}$ – matrix stress at a matrix strain equals the maximum tensile strain in the fibres [20].

To determine transverse lamina properties each applied method use different approach. So called in literature "inverse" ROM assumes equality of stresses in fibres and matrix what allows to calculate elastic properties according to following formulas:

- transverse modulus

$$\frac{1}{E_2} = \frac{V_m}{E_m} + \frac{V_f}{E_f} \tag{4}$$

- shear modulus

$$\frac{1}{G_2} = \frac{V_m}{G_m} + \frac{V_f}{G_f} \tag{5}$$

The theoretical assumptions of the "inverse" ROM method lead however to inconsistency with measured results [2]. Numerous experimental tests showed that matrix has significantly higher influence on the transverse properties than it arises from iROM formulas. Tsai introduced $\nu_{cor}$ correction factor to formulas (4) and (5) to decrease incompliance with experiment, including matrix softness, fibers misalignment and nonuniform stress distribution within the matrix and fibers [32]. Value of a correction factor could vary from 0 to 1 and should be determined by the fit curve technique. From Tsai analysis for $E_2$ and $G_{12}$ modulus better estimation than from iROM was provided when $\nu_{cor} = 0.5$ [32].

$$\frac{1}{E_2} = \frac{\frac{V_f}{E_f} + \frac{\upsilon_{cor} * V_m}{E_m}}{\upsilon_{cor} * V_m + V_f} \tag{6}$$

$$\frac{1}{G_{12}} = \frac{\frac{V_f}{G_f} + \frac{\upsilon_{cor} * V_m}{G_m}}{\upsilon_{cor} * V_m + V_f} \tag{7}$$

For the range of considered in current analysis material properties this correction factor was assumed as equal to $\nu_{cor} = 0.4$.

In his approach Wilczynski (further designated as WM method) assumed the periodic microstructure effect of fibers distribution and focused on a single cell (RVE) with unit dimensions and known volume fraction $V_f$, to set formulas for apparent moduli [21, 33]. His formulas are as follows:

- transverse modulus

$$E_2 = E_m \frac{E_m(1 - \sqrt{V_f}) + E_f\sqrt{V_f}}{E_m(1 - \sqrt{V_f}(1 - \sqrt{V_f})) + E_f(1 - \sqrt{V_f}(1 - \sqrt{V_f}))} \tag{8}$$

- shear modulus

$$G_2 = G_m \frac{G_m(1-\sqrt{V_f}) + G_f\sqrt{V_f}}{G_m(1-\sqrt{V_f}(1-\sqrt{V_f})) + G_f(1-\sqrt{V_f}(1-\sqrt{V_f}))} \tag{9}$$

Halpin and Tsai took into consideration fibres and packing geometry by introducing parameter $\xi$ as a measure of fiber reinforcement efficiency for transverse loading of a composite. For circular fibers (as glass fibers are) distributed in a square array $\xi = 2$ for calculation of $E_2$ and $\xi = 1$ for $G_{12}$ computation. In [13] the choice of parameter $\xi$ is discussed and "a better estimation" for the usual volume fractions found in practice for a unidirectional lamina of fiber reinforced composites is suggested. Thus effective transversal and shear elastic moduli of the composite according to Halpin–Tsai formulation are given by:

- transverse modulus

$$E_2 = \frac{E_m(1+\xi\chi V_f)}{1-\chi V_f} \tag{10}$$

where the coefficient

$$\chi = \left(\frac{E_f}{E_m} - 1\right) \Big/ \left(\frac{E_f}{E_m} + \xi\right)$$

- shear modulus

$$G_{12} = \frac{G_m(1+\xi\chi V_f)}{1-\chi V_f} \tag{11}$$

where similarly

$$\chi = \left(\frac{G_f}{G_m} - 1\right) \Big/ \left(\frac{G_f}{G_m} + \xi\right)$$

The last chosen analytical method – Tsai method takes into account some inaccuracies of manufacturing process. He noticed that for composite - mainly with high value of volume fraction, fibres couldn't be fully isolated. Therefore the misalignment factor $k$ and continuity factor $C$ were introduced. Both factors are highly dependent on manufacturing process. The parameter $k$ changes from 0.9 to 1 when $C$ could vary from 0 to 1. The lower values correspond to isolated fibers and upper to a perfect contiguity. In our analysis it was assumed that $C = 0.3$ and $k = 0.93$. The corresponding expressions take the form:

- longitudinal modulus

$$E_1 = k * (V_f E_{1f} + V_m E_m) \tag{12}$$

- transverse modulus

$$E_2 = 2[\nu_{12f} + (\nu_{12f} - \nu_{12m})V_m] \cdot \left[(1-C)\frac{K_f(2K_m+G_m) - G_m(K_f-K_m)V_m}{(2K_m+G_m)+2(K_f-K_m)V_m}\right] \quad (13)$$

where:

$$K_f = \frac{E_f}{2(1-v_f)} \quad (14)$$

$$K_m = \frac{E_m}{2(1-v_m)} \quad (15)$$

- longitudinal Poisson's ratio

$$v_{12} = (1-C)\frac{K_f\nu_f(2K_m+G_m)V_f + K_m\nu_m(2K_f+G_m)V_m}{K_f(2K_m+G_m) - G_m(K_f-K_m)V_m} + C\frac{K_m\nu_m(2K_f+G_f)V_m + K_f\nu_f(2K_m+G_f)V_f}{K_f(2K_m+G_m)+G_m(K_m-K_f)V_m} \quad (16)$$

- shear modulus

$$G_{12} = (1-C)G_m\frac{2G_f-(G_f-G_m)V_m}{2G_m+(G_f-G_m)V_m} + CG_f\frac{(G_f+G_m)-(G_f-G_m)V_m}{(G_f+G_m)+(G_f-G_m)V_m} \quad (17)$$

To compare in further discussion the glass lamina elastic modulus values determined with application of aforementioned formulas with nominal properties given by the manufacturer, some material data was required. But, mechanical properties for this kind of glass fibers given in different sources differ significantly. Due to a lack of compliance in fiber properties data, few different datasets were selected to perform calculations. These properties for matrix and fibres are given in Tab. 3 with the reference source. For both constituent an isotropic material model was established. The extreme dataset I and V were taken as bound values in further calculations. The dataset V is based on the R–fiber manufacturer official information [36]. Comparing nominal values of I dataset, the lowest modulus can rather be associated with E–glass fibers. However, a variety of data in literature is misleading.

Applying above presented micromechanical prediction formulas there were some numerical calculations performed. Results of them for appointed extreme dataset are summarized in the two tables with reference to both fibre properties dataset. The relative error placed in columns to the right of computed values– which refers to the data declared by FML manufacturer, is also presented for comparison and assessment.

**Table 3** Reference lamina material constituent properties

| | Matrix [1, 17] | Fibres | | | | |
|---|---|---|---|---|---|---|
| | | I Dataset [34] | II Dataset [14, 16] | III Dataset [8, 34] | IV Dataset [26] | V Dataset [36] |
| E [MPa] | 3 500 | 72 000 | 76 000 | 85 000 | 83 000 | 87 500 |
| PR | 0.40 | 0.14 | 0.22 | 0.23 | 0.30 | 0.20 |
| G [MPa] | 1821 | 31 579 | 31 000 | 34 553 | 31 923 | 36 458 |

**Table 4** Lamina apparent properties

| I Dataset | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | ROM | Relative error [%] | WM | Relative error [%] | H-T | Relative error [%] | Tsai | Relative error [%] |
| $E_1$ [MPa] | 44600 | -3.94 | 44600 | -3.94 | 44600 | -3.94 | 41478 | -10.67 |
| $E_2$ [MPa] | 8155 | -45.34 | 12805 | -14.18 | 14887 | -0.22 | 14694 | -1.51 |
| $PR_{12}$ | 0.244 | -9.29 | 0.244 | -9.29 | 0.244 | -9.29 | 0.225 | -16.36 |
| $G_{12}$ [MPa] | 2994 | -42.78 | 6456 | +23.37 | 4420 | -15.54 | 7460 | +42.56 |

**Table 5** Lamina apparent properties

| V Dataset | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | ROM | Relative error [%] | WM | Relative error [%] | H-T | Relative error [%] | Tsai | Relative error [%] |
| $E_1$ [MPa] | 53900 | +16.09 | 53900 | +16.09 | 53900 | +16.09 | 50127 | +7.96 |
| $E_2$ [MPa] | 8255 | -44.67 | 13210 | -11.46 | 15500 | +3.98 | 15069 | +1.00 |
| $PR_{12}$ | 0.280 | +4.09 | 0.280 | +4.09 | 0.280 | +4.09 | 0.273 | +1.49 |
| $G_{12}$ [MPa] | 4236 | -19.05 | 6632 | +26.73 | 4498 | -14.05 | 7461 | +42.58 |

Comparing calculated values of lamina effective mechanical properties with data obtained from manufacturer (Tab. 2) one can notice some discrepancies. Despite a relatively good agreement with longitudinal Young moduli values (Fig. 1) and Poisson's ratio values for dataset L, for all three employed methods, generally these results cannot be accepted. Coincidence in longitudinal Young's modulus values results obviously of identical or very similar (Tsai method) formulas applied in all methods. The scattered results of transverse elastic modulus and shear modulus confirmed that these mechanical property prediction requires methods where local stress and strain fields should be considered [1]. As suspected the inverse ROM gave serious underestimation of these moduli values with respect to experimental data – here nominal data. Consideration of some misalignment of manufacturing process in Tsai method gave significantly good results in case of transverse Young Modulus. However, this approach gave the greatest values of shear modulus. Moreover significantly discrepancy is visible in determining shear modulus- the Rule of Mixture and Halpin – Tsai method gave underestimation results when two other methods present greater values than nominal data. The next two figures (Figs 2–3) present comparison of all predictions with relative error referred to the property given by the fiber glass prepreg provider.

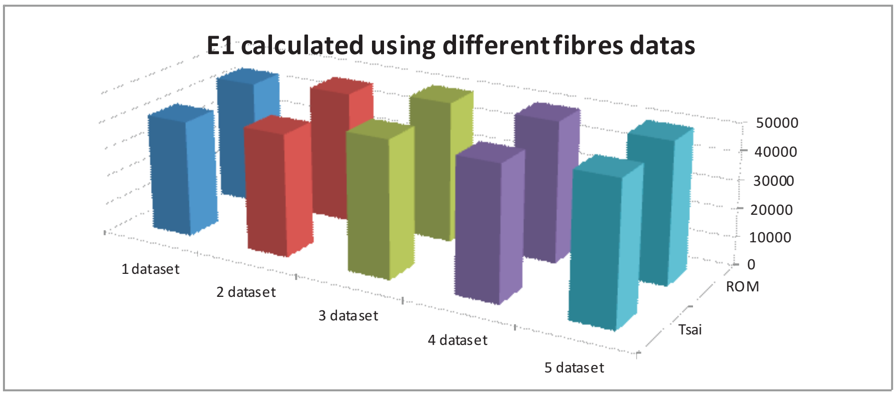


**Figure 1** Calculated $E_1$ lamina modulus

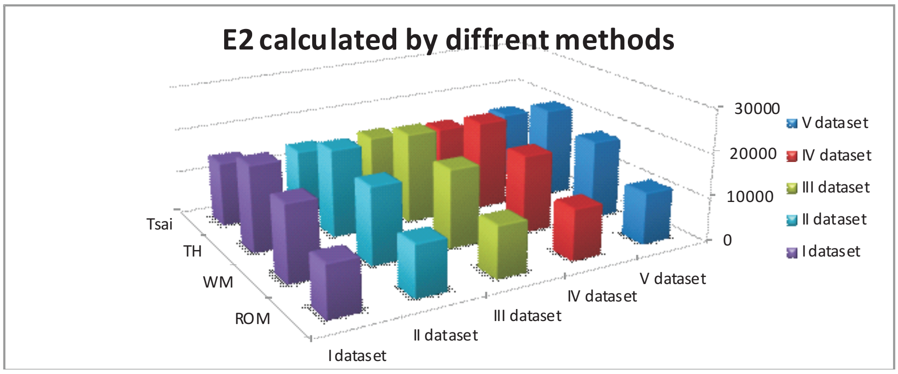


**Figure 2** Calculated $E_2$ lamina modulus

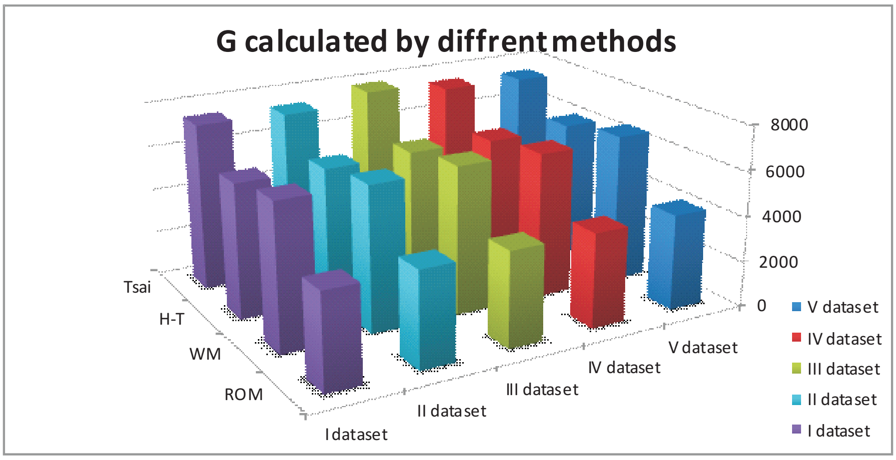


**Figure 3** Calculated $G_{12}$ lamina modulus

Employing Tsai formulas (6) and (7) with correction factor $\nu_{cor} = 0.4$ the prediction can be improved. The updated modulus values are given jet in Tab. 6. The difference between refined on values and nominal ones decreased significantly and this prediction gave fully satisfactory results placing them within acceptable engineering accuracy range.

**Table 6** Transverse and shear modulus with relative error in compersion data from manufacturer

| | I Dataset | | V Dataset | |
|---|---|---|---|---|
| $E_2$[MPa] | 14602 | -2.13% | 14924 | +0.02% |
| $G_{12}$[MPa] | 5412 | +3.42% | 5488 | +4.87% |

Concluding this part of the analysis updated results for a single lamina are put together in Fig. 4 for longitudinal elastic modulus $E_2$ and in Fig. 5 for in–plane shear modulus $G_{12}$. These results were determined for dataset I and dataset V and can be taken as a lower and upper bound of obtained lamina mechanical properties. The lowest values gave the inverse ROM method for both transverse and shear moduli, the next two methods predicted in opposite way both moduli nonetheless. The difference between extreme values is then ca 90% for $E_2$ and 120% for $G_{12}$, respectively. To emphasize this inconsistency the determined results for dataset I and V are compared in common plot below. Results for ROM with Tsai correction determined with I dataset are close to the reference elastic properties of prepreg (Tab. 2) whereas the data received based on V dataset convinced of "better" response possibility of applied GFR lamina. These two dataset results will be applied later for a whole FML plate effective elastic properties prediction.

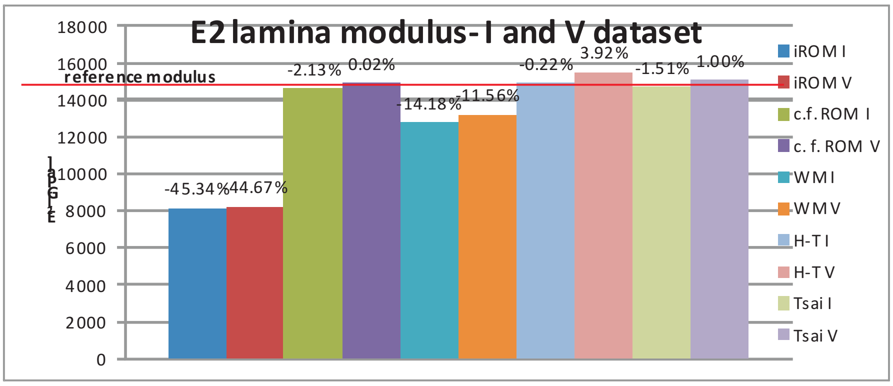


**Figure 4** $E_2$ determined by different methods for $I$ and $V$ dataset

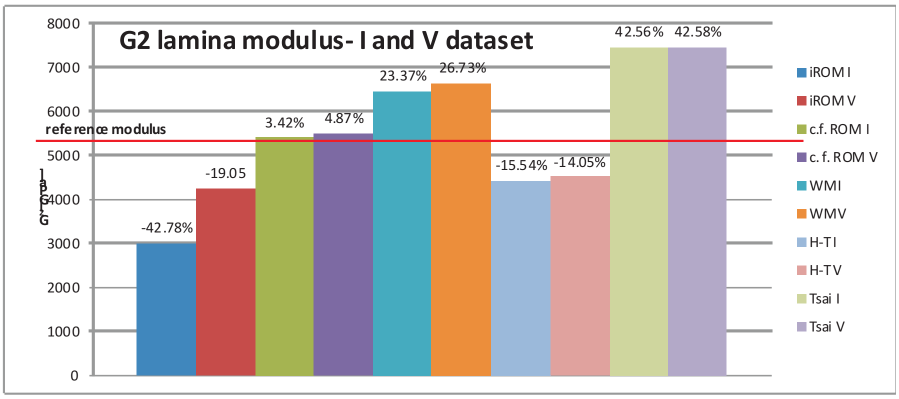


**Figure 5** $G$ determined by different methods for $I$ and for $V$ dataset

## 4. FML coupons properties prediction

The micromechanical formulas employed to determination of elastic moduli of composite lamina, could be applied directly to the whole multilayered FML structure. The volume fraction of metal and composite can be determined with relation to the thickness of both constituents within the specimen. Calculations were performed with assumption that the nominal single prepreg layer thickness $t_{com} = 0.25$ mm and aluminium nominal single layer thickness was $t_{alu} = 0.3$ mm. However, real dimensions of the specimen investigated during laboratory test differ from nominal one. Thus assumptions were made as taking into account possible aluminium sheet thickness tolerance and the presence of interlayer adhesive at the metal–composite interface introduced during gluing process. Moreover due to greater measured thickness of each tested coupon than the sum of all layers nominal thicknesses (according to manufacturer data) thus for further calculations it was assumed that FML coupon consists of three components – prepreg, aluminium layer and matrix layer (as remaining after bonding). Then due to some potential dimensional possibilities of layer thicknesses these variations were examined too. Few different mechanical properties of FML constituents were assumed – once according to nominal data (Tab. 2), second according to the determined in our tensile test aluminium properties, next with reference to the analytical predictions for R–glass fiber lamina (upper bound) and the last one according to the own aluminium data concerning the predictions for E–glass fiber lamina (lower bound). Detailed results of this 'numerical discussion' for lay–up 1 and 2are presented in Tab. 7. The stacking sequence [Al/0/90/Al/90/0/Al] and [Al/90/0/Al/0/90/Al] have no influence on tensile properties so the calculations are performed together. Other sequences have been calculated in analogous way and are presented in Tab. 8.

**Table 7** FML properties for different options [Al/0/90/Al/90/0/Al] and [Al/90/0/Al/0/90/Al]

| ' | al. 0.3 prepreg 0.25 | al. 0.3 prepreg 0.25 + matrix | al. 0.32 prepreg 0.25 + matrix | al. 0.28 prepreg 0.25 + matrix | Mean | STD |
|---|---|---|---|---|---|---|
| based on declared manufacturer data | | | | | | |
| $E_1$[MPa] | 49214 | 47582 | 45858 | 44420 | 46768 | 2081 |
| $E_2$[MPa] | 34166 | 22479 | 19673 | 24373 | 25173 | 6299 |
| $PR_{1-2}$ | 0.245 | 0.257 | 0.258 | 0.239 | 0.250 | 0.009 |
| G[MPa] | 8647 | 6399 | 5745 | 6847 | 6910 | 1244 |
| $R_m$[MPa] | 620 | 604 | 595 | 577 | 599 | 18 |
| $R_{02}$[MPa] | 244 | 230 | 221 | 215 | 228 | 13 |
| based on predicted data of V dataset | | | | | | |
| $E_1$[MPa] | 52836 | 51069 | 49220 | 47685 | 50203 | 2236 |
| $E_2$[MPa] | 33184 | 22065 | 19343 | 23883 | 24619 | 6007 |
| PR $_{1-2}$ | 0.229 | 0.242 | 0.244 | 0.225 | 0.235 | 0.009 |
| G[MPa] | 9374 | 6773 | 6044 | 7262 | 7363 | 1431 |
| $R_{02}$[MPa] | 203 | 218 | 196 | 191 | 202 | 12 |
| based on predicted data of I dataset | | | | | | |
| $E_1$[MPa] | 50388 | 48712 | 46845 | 45379 | 47831 | 2183 |
| $E_2$[MPa] | 31560 | 21362 | 18796 | 23078 | 23699 | 5528 |
| PR $_{1-2}$ | 0.219 | 0.233 | 0.234 | 0.216 | 0.225 | 0.009 |
| G[MPa] | 7850 | 5967 | 5390 | 6361 | 6392 | 1051 |
| $R_{02}$[MPa] | 203 | 218 | 187 | 181 | 197 | 16 |

From the obtained results it is clearly visible that using declared data from manufacturer FML mechanical properties have been decreased. Similar effect can be observed when taking into account thin adhesive plies. On the other hand assuming higher allowable tolerances especially for aluminium layers elastic moduli values increase. The standard deviation presented in the right side column is relatively high

**Table 8** FML properties for different variations [Al/0/0/Al/0/0/Al]

| | [Al/0/0/Al/0/0/Al] | | | | | |
|---|---|---|---|---|---|---|
| | declaredmanufacturer data | | calculated based on V dataset | | calculated based on VI dataset | |
| | Mean | STD | Mean | STD | Mean | STD |
| $E_1$[MPa] | 54635 | 2257 | 60080 | 2457 | 55518 | STD |
| $E_2$[MPa] | 28302 | 3632 | 29006 | 5667 | 27523 | 4939 |
| PR $_{1-2}$ | 0.295 | 0.009 | 0.287 | 0.009 | 0.267 | 0.009 |
| G[MPa] | 6910 | 1244 | 7363 | 1431 | 6392 | 1051 |
| $R_m$[MPa] | 724 | 185 | | | | |
| $R_{02}$[MPa] | 272 | 12 | 242 | 12 | 228 | 17 |
| | [Al/25/0/Al/0/25/Al] | | | | | |
| | declaredmanufacturer data | | calculated based on V dataset | | calculated based on I dataset | |
| | Mean | STD | Mean | STD | Mean | STD |
| $E_1$[MPa] | 48448 | 2118 | 53182 | 2302 | 49775 | 2226 |
| $E_2$[MPa] | 24693 | 2182 | 25755 | 3555 | 23912 | 2974 |
| PR $_{1-2}$ | 0.314 | 0.010 | 0.318 | 0.010 | 0.317 | 0.010 |
| G[MPa] | 7229 | 1372 | 8013 | 1721 | 7120 | 1330 |
| $R_m$[MPa] | 628 | 39 | | | | |
| $R_{02}$[MPa] | 229 | 29 | 214 | 12 | 205 | 17 |

[12]. So considered possible discrepancies of FML layer thicknesses influence the apparent elastic properties in limited way however should not be neglected. Different inaccuracy possible during manufacturing process could have similar influence [5, 25]. Without exact information concerning real thicknesses of component we got some boundaries where real value of mechanical properties could exist.

## 5. Experimental results

Analytical prediction was verified by experimental test where mechanical properties including yield limit and Young's modulus were investigated. All considered layer sequences were examined during tensile and bending test. Unfortunately only two specimens of each stacking sequence were available to each test. The overall dimensions of all investigated FML samples are given in Tab. 9.

### 5.1. *FML coupons tensile test*

Tensile tests were conducted according to D3039/D3039M-00 in a room temperature conditions [30]. Specimens were mounted in the grips of an universal strength testing machine Instron 4485, upgraded with Zwick/Roell control software (Fig. 6). The elongation was measured an attached strength machine mechanical extensometer. Axial and transverse strains were also measured with the application of two pairs of crossed strain gauges bonded back–to–back on each specimen. The single specimen was loaded until fracture with the loading control of 5 $N/mm^2$ $min^{-1}$.

**Table 9** Dimensions of FML samples

| [mm] | Tensile 1A | Tensile 1B | Tensile 2A | Tensile 2B | Tensile 5A | Tensile 5B | Tensile 7A | Tensile 7B |
|---|---|---|---|---|---|---|---|---|
| width | 25.00 | 25.00 | 24.90 | 24.97 | 19.99 | 19.98 | 25.00 | 25.00 |
| total length | 150 | 150 | 250 | 250 | 200 | 200 | 150 | 150 |
| actual thickness | 2.10 | 2.00 | 1.97 | 1.99 | 1.97 | 1.98 | 1.94 | 1.95 |

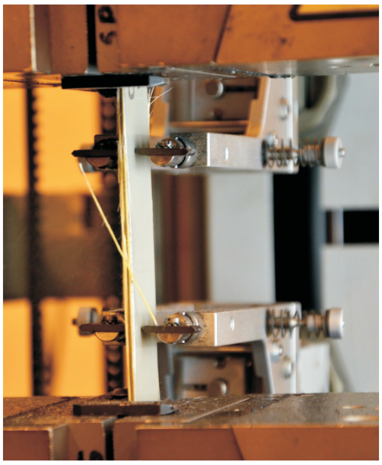

**Figure 6** Specimen placed in the universal testing machine

**Figure 7** FML specimen during three point bending test

Results of performed static tensile tests are presented in Tab. 10. It is visible that result of specimen 2B differs significantly from values of other samples what was be caused by some inaccuracy in specimen placing in the machine grips. Due to this the value of Young's modulus has been varied and couldn't be taken into consideration during further analyses.

**Table 10** Results of FML specimen tensile test

| Test | $a_0$ | $b_0$ | $S_0$ | $E_{axial}$ | $R_{p0.2}$ | $R_m$ | $F_{max}$ | $A_t$ |
|---|---|---|---|---|---|---|---|---|
| Sample | mm | mm | $mm^2$ | GPa | MPa | MPa | kN | % |
| 1A | 2.10 | 25.00 | 52.5 | 50.38 | 237 | 700 | 36.73 | 8.71 |
| 1B | 2.00 | 25.00 | 50.00 | 53.75 | 249 | 736 | 36.82 | 7.25 |
| 2A | 1.97 | 24.9 | 49.05 | 50.57 | 247 | 711 | 34.87 | 5.08 |
| 2B | 1.99 | 24.95 | 49.65 | 37.46 | 237 | 691 | 34.30 | 5.65 |
| 5A | 1.99 | 19.97 | 39.74 | 65.89 | 299 | 1185 | 47.08 | 5.14 |
| 5B | 2.06 | 19.98 | 41.16 | 60.23 | 298 | 1156 | 47.60 | 5.44 |
| 7A | 1.94 | 25.00 | 48.5 | 58.16 | 276 | 806 | 39.10 | 5.09 |
| 7B | 1.95 | 25.00 | 48.8 | 59.07 | 263 | 812 | 39.60 | 4.94 |

## 5.2. *FML coupons flexural test*

The flexure test was carried out according to the standard D790-00; procedure B [31], again using the strength machine Instron 4485. The three point bending flexural test allowed to determine the flexural stress-strain response of the FML material. Specimens were mounted over the special flexural fixture of the universal testing machine and gradually (5 mm/min) loaded in bending (Fig. 7). Two different spans of supports were set during the bending (120 and 150 mm). In the flexural test both pairs of 1 and 2 stacking sequences had to be analyzed separately what was not the case for tension.

**Table 11** Results of flexural tests

| TEST of | $t_{tot}$ | $b_0$ | $F_{max}$ | $R_g$ | $E_{flex}$ | $E_{a\_flex}$(13) |
|---|---|---|---|---|---|---|
| | mm | mm | N | MPa | GPa | GPa |
| 1A(0/90) | 1.92 | 25.00 | 197.1 | 481.2 | 59.88 | 59.53 |
| 1B | 1.92 | 25.00 | 192.6 | 470.3 | 61.39 | 60.16 |
| 2A(90/0) | 1.98 | 24.95 | 225.72 | 415.37 | 54.93 | 54.25 |
| 2B | 2.01 | 24.99 | 229.51 | 409.18 | 52.51 | 52.02 |
| 5A | 1.94 | 19.97 | 250.79 | 600.61 | 64.57 | 64.12 |
| 5B | 1.97 | 20.03 | 252.52 | 584.72 | 62.62 | 62.15 |
| 7A | 1.96 | 25.00 | 214.10 | 501.5 | 62.81 | 62.49 |
| 7B | 2.04 | 25.00 | 218.10 | 471.6 | 55.89 | 55.29 |

According to a three–point bending solution for a composite beam flexural moduli could be determined by the formula:

$$E_{a\_flex} = \frac{F_c}{w_c}\frac{L^3}{4t_{tot}^3 b_0} \tag{18}$$

where $L$ – span of specimen supports (thus $L/t_{tot} \approx 60 \ \vee 75$ and the shear effect was reduced in essential way), $w_c$ – measured deflection for $F_c$ applied actual bending force and $t_{tot}$ is a total thickness of actual specimen.

A good agreement between analytical and experimental results presented in Table 11 can be observed. It is also visible that flexural moduli are higher than those indicated during tensile tests what is a common feature.

In Tab. 12 theoretical calculations are compared with results of tensile tests. There the column headings indicate: ROM I results obtained based on manufacturer declared data of FML components (see Tab. 2), II and III results of predictions based on micromechanical approach where components properties were referred to V and I dataset, respectively (see Tab. 3).

**Table 12** Results of tensile test

| [Al/90/0/Al/0/90/Al] and [Al/0/90/Al/90/0/Al] | | | | | | | |
|---|---|---|---|---|---|---|---|
| | EXPERIMENT | | | | ROM | | |
| [MPa] | 1A | 1B | 2A | 2B | I | II | III |
| $E_1$ | 50380 | 53750 | 50570 | 37460 | 46768 | 50203 | 47831 |
| $R_{02}$ | 237 | 250 | 247 | 237 | 228 | 202 | 197 |
| [Al/0/0/Al/0/0/Al] | | | | | | | |
| | EXPERIMENT | | | | ROM | | |
| | 5A | | 5B | | I | II | III |
| $E_1$ | 65890 | | 60230 | | 54635 | 60080 | 55518 |
| $R_{02}$ | 299 | | 299 | | 272 | 242 | 228 |
| [Al/25/0/Al/0/25/Al] | | | | | | | |
| | 7A | | 7B | | I | II | III |
| $E_1$ | 58160 | | 59070 | | 48448 | 53182 | 49775 |
| $R_{02}$ | 277 | | 263 | | 229 | 214 | 205 |

The higher moduli values correspond better to R–glass prepreg properties than declared by FML manufacturer data what also S confirmed results of buckling experiments conducted on FML short columns of open cross-section profiles [25].

## 6. Conclusions

In the presented paper the micro- and macromechanicsmethods were applied at two levels. On micro- level longitudinal and transverse mechanical properties of GFRE were determined basing on Voigt/Reuss tenants, Wilczynski, Tsai method and Halpin–Tsai equations. Significant differences were observed between results determined with applied methods of predicted transverse properties. The highest discrepancies were observed for Tsai method and Halpin–Tsai, where the last method is sensitive to $\xi$ parameter estimation. Introduced correction factors to Rule of Mixture formulas gave finally satisfied results. For Fiber Metal Laminate hybrid material the longitudinal properties were indicated by Rule of Mixture. All analytical predictions were verified by experimental tests. It should be emphasise that the thickness of FML components as well as mechanical properties of prepreg and aluminium alloy are crucial factors to predict mechanical properties of FML hybrid material. Even small tolerance deviation gave visible discrepancies in results. Due to that it is impossible to determine exactly mechanical properties without exact component data. The effect of technology - autoclaving assembling, introduction of adhesive layers, decreases the stiffness of entire Fiber Metal Laminate as well as possible changes of fiber orientation. The problem of residual stress influence and rheological interaction of constituents was not considered in performed analysis.

The presented analyses confirmed that mechanical properties of fibreglass reinforced epoxy lamina as well as Fiber Metal Laminate hybrid material could be determined by simply micromechanical formulas.

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