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NUMERICAL ANALYSIS FIBER METAL LAMINATES AS ADHESIVELY BONDED STRUCTURES

Jan Godzimirski, Agata Pietras

Military University of Technology
Department Mechatronics and Aeronautical
Gen. Sylwestra Kaliskiego Street 2, 00-908 Warsaw, Poland
tel.: +48 22 6839575, +48 505177494
e-mail: jgodzimirski@wat.edu.pl, apietras@wat.edu.pl

Abstract

FML composites are laminates made of adhesively bonded thin metal layers and reinforced with fibbers polymers composites layers. Destruction of hybrid laminar composites can be caused by exceeding of emergency strength in one of FML component or by destruction of their adhesive joints – delamination. Aim of conducted research was to estimate method of loading on strength of FML adhesive joints. Experimental tests and numerical calculations were basic to evaluate tensile strength and shear strength of adhesive. Material constants of FML components made of aluminum alloy 2024T3 and polymer composites made of glass fabric E81 and impregnate resin L410/H418 were determined. Composite specimens were made of 6 metal layers and 5 glass fabric layers. The numerical calculations of FML subjected to tensile, shearing and torsion were conducted to estimate adhesive joints loading. Additionally the loading of FML composites in range of plastic strain of metal component was evaluated on possibility of destruction of adhesive joints. Research showed that the safe loading of FML could not exceed the yield point in metal component because plastic strain can destroy adhesive joints (to cause delamination) after material unloading. It was pointed that torsion loading can destroyed FML composites by delamination.

Keywords*: Hybrid laminar composites, adhesive joints, delamination*

1. Introduction

Hybrid laminar composites type Fiber Metal Laminates are materials made of adhesively bonded thin metal layers and polymer composites reinforced with fibbers made of: glass, carbon or aramid [1, 2]. These materials have indirect properties: between metals and reinforced, with fibbers polymer composites. In spite of numerous advantages (low mass density, large relative strength, large fatigue life, corrosion resistance, impact resistance, electrical discharge resistance, fire-resistance [1, 3, 4]) only one material of this type was applied in oversize scope – in construction of Airbas 380 plane fuselage.

Limited application of these new materials is caused by incomplete expertise relating their strength. The bonding of materials of essential different mechanical and physical properties (elastic-plastic isotropic metal and orthotropic composite) may cause unconventional material destruction (of either components or adhesive bonding components). Thermal stresses and possibility of plastic strain of metal component while composite is elastic, deform may be dangerous for FML.

The aim of conducted research was to estimate method-loading influence on destruction way of FML. Elastic-plastic properties of metal component, orthotropic properties of composite component and adhesive force between bonded components were considered in studies. The testing object was hybrid laminar composite type Glare made with aluminium alloy AW 2024T3 thin sheets (thickness 0.29 mm) and with E81, glass fabric impregnated with epoxy resin L418 cured H418 curing agent. The resin was also adhesive bonding components (metal and composite).

2. Experimental test

Experimental test was conducted to determine L418/H418 resin properties, adhesive force between glass-epoxy composite and aluminium alloy, mechanical properties of aluminium alloy sheet, properties of polymer composite made with E81 fabric and mechanical properties of hybrid laminar composite sort Glare.

2.1. Testing of L418 resin

Experimental test of L418 resin concerned determination of stress-strain curve, tensile strength and shear strength.

The cylindrical bulk specimen for L418 adhesive was 12 mm in diameter and 25 mm long. The specimen was cured according producer's recommendation. The specimen was compressed in the testing machine at 2 mm/min to generate stress-strain curves (Fig. 1). Based on the test the modulus of elasticity E = 1.74 GPa, yield point $R_{0.2}$ = 73.2 MPa and ultimate compressive strength R_m = 105.4 MPa were determined.

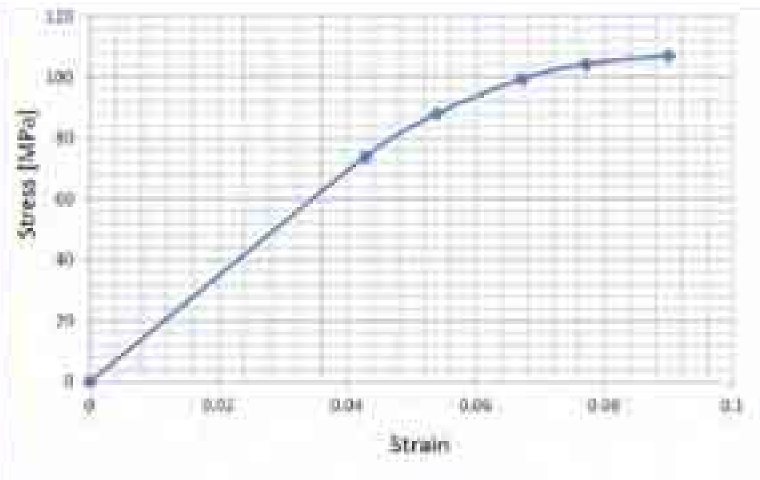

Fig. 1. Stress-strain curve for L418 plastic from compression test of bulk specimen

Butt specimens made of aluminium alloy AW 2017 (Fig. 2) were used to determine tensile strength of L418 adhesive. Sand-blast cleaning and acetone washing was applied for specimen surface preparation for bonding. To obtain similar adhesive thickness two wires were placed in not cured adhesive layers. The adhesive layers were cured at pressure about 0.1 MPa at temperature of 80^oC for 8 hours in heating chamber. The specimens were tested in ZD10 testing machine with used articulated grips. The test results were elaborated statically: Student-Fisher's method was applied to calculate the confidence interval for the level α = 0.95. The mean tensile strength of 6 specimens was R_o = 33.64±4.25 MPa. The mode of joint failure suggested adhesion destruction.

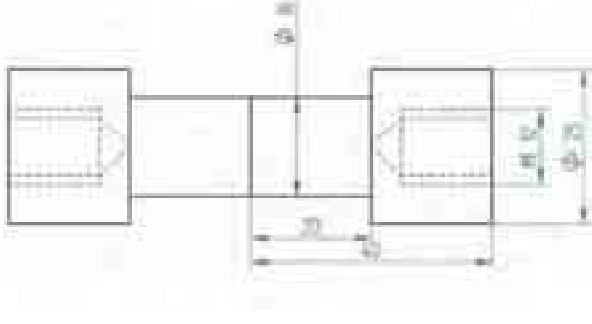

Fig. 2. Shape and dimensions of butt specimens

Single lap specimens made with aluminium alloy (AW 2024T3) sheets which was 2 mm thickness were used to determined shear strength of L418 adhesive. The lap length was 12.5 mm. Curing conditions and of the metal elements, surfaces preparing for bonding, were as those, used in butt specimens testing. 6 specimens were used in the strength test. Determined shear strength (mean shear stress) was R_t = 14.96±1.08 MPa.

For estimation of failure stress, the FEM numerical calculations were conducted in the Nastran for Windows program. 3D model of tested adhesive joint was build. The actual thickness of specimens' sheet, overlap length, thickness of the adhesive layer and the spacing of the testing machine handles were taken into account in numerical calculations. The adhesive layer was modelled by one layer of hexahedron finite elements according to [6]. The adhesive layer properties were described by $\sigma = \sigma(\varepsilon)$ function, modulus of elasticity E = 1.74 GPa and Poisson's ratio ν = 0.35. The linear-elastic properties of aluminium alloy sheet were assumed (E = 72 GPa, ν=0.35). The tested models of specimens were loaded with average forces according to experimental tests and displacement resulting from the fact that specimens were clamped in rigid holder of testing machine. Based on calculations the stresses distribution in adhesive layer was determined (Fig. 3) and value of maximal principal stress ~ 85 MPa.

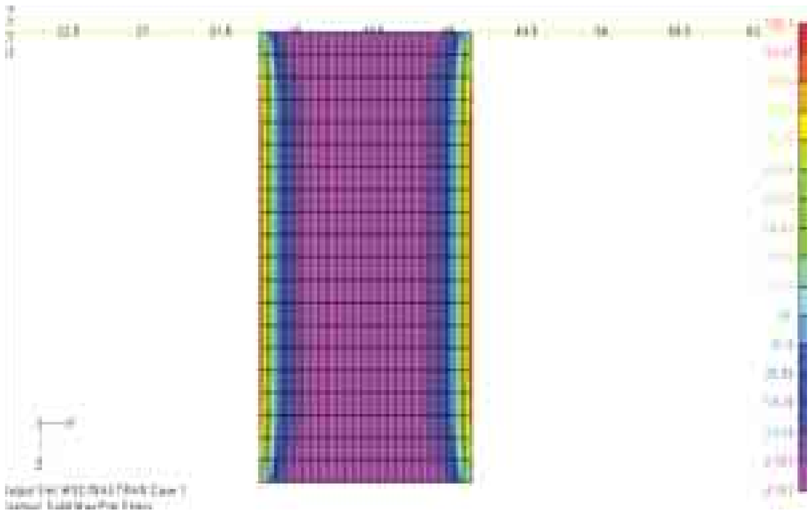

Fig. 3. Distribution of maximal principal stresses at breaking load in the adhesive layer of single lap specimens made of alloy 2024

The maximum positive principal stress hypotheses may be applied for determination of adhesive layer effort [7, 8]. According to these hypotheses, the failure of material subjected to shearing happens if maximal shear stress is equal reduced stress [9].

The tests of tensile strength of butt joints bonded with one layer of E81 fabric impregnated by L418 resin were conducted extra. Three batches of specimens were tested whose surface preparation for bonding was differed:

– acetone washing,
– sand-blasting and acetone washing,
– abrasive cloth grinding and acetone washing.

The results of test are shown in Tab. 1.

Tab. 1. Strength of butt specimens for different surface preparation method

Surface pretreatment	P [kN]	σ [MPa]
Acetone washing	5.79± 0.71	28.81± 3.50
Sand blasting	6.8± 0.95	33.83 ± 4.70
Abrasive cloth grinding	9.09±0.88	45.23± 4.38

The best effective surface preparation of adherents was abrasive cloth grinding and such procedure was applied for surface preparation of sheet used in hybrid laminar composite production. The main conclusions from this test are the following:

– composite may be failure due to delamination if normal positive perpendicular to surface stresses exceed 45 MPa,
– composite may be failure due to interlayer shearing if stresses exceed 85 MPa.

2.2. Testing of glass-polymer composite

The seven-layer and twenty-layer glass-polymer composites were made of E81 fabric and L418 resin. The lamination was conducted manually on wet. The composites were cured at pressure 1.3 MPa, at temperature of 80°C for 8 hours. Dimensions and masses of specimens are shown in Tab. 2. Glass properties and resin properties are shown in Tab. 3.

Tab. 2. Mass and dimension of specimens made of glass-epoxy composite

Material	Mass [g]	Length [mm]	Width [mm]	Thickness [mm]	A_t [m^2]
Laminate 7	41.1	213.5	147.5	1.012	0.22
Laminate 20	138.9	241	152	2.632	0.733

where: A_t – total area of glass fabric.

Tab. 3. Properties of components of glass-epoxy composite [10, 11]

Component of composite	Density ρ [g/cm³]	Young's modulus E [GPa]	Poisson's ratio ν
Glass	2.5	72	0.23
Resin	1.13	3.5	0.35

Getting to know the basis weight of E81 fabric 101g/m² [10], the area of composite specimens, number of fabric layers, glass density ρw and matrix density ρo , the mass fractions and volume fractions were calculated for glass and matrix (Tab. 4).

The material constants (shown in Tab. 5) were estimated on the basis of experimental tests [13] and data from literature [10].

The tensile strength of composite (thickness about 2 mm) did not exceed 180 MPa. The tensile strength of one-layer composite (thickness about 0.23 mm) was 196 MPa.

Tab. 4. Mass fraction (m) and volume fraction (f) of glass fiber and matrix in glass-epoxy composite

Kind of specimen	Mass and volume fraction			
	m_w	m_o	f_w	f_o
Laminate 7	0.540	0.460	0.35	0.65
Laminate 20	0.533	0.467	0.34	0.66

Tab. 5. Material constants of glass-epoxy composite

E_1	11000	MPa
E_2	11000	MPa
E_3	4050	MPa
G_1	1400	MPa
G_2	1690	MPa
G_3	1690	MPa
ν_1	0.16	-
ν_2	0.33	-
ν_3	0.33	-

2.3. Testing of 2024 alloy sheet

The curve stress-strain of metal component used to make of hybrid laminar composite is need for numerical calculations witch consider non-linear properties of this component. The curve $\sigma = \sigma(\varepsilon)$ was determined in tensile test of oar specimen made of sheet (thickness 0.52 mm, width 12.84 mm). The strains were determined by means of extensometer with measurement range 50 mm. The result of test is shown in Fig. 4).

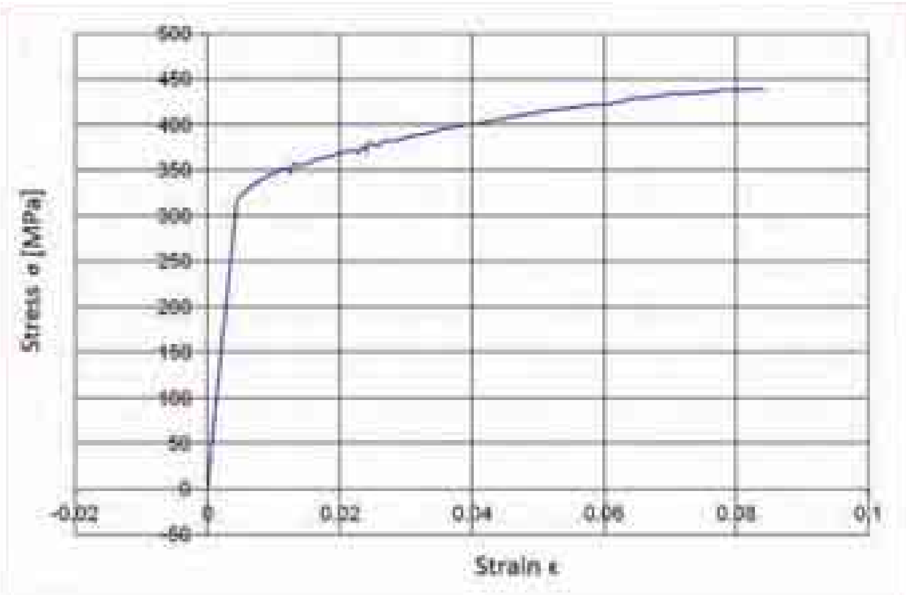

Fig. 4. Stress-strain curve for 2024 T3 aluminium alloy sheet

Determined values of modulus of elasticity E ≈ 72000 MPa, yield point $R_{0.2} \approx 330$ MPa and stress to failure $R_m \approx 440$ MPa were consistent with reported in the literature. On the basis of determined stress-strain curve, the nonlinear properties of tested material were put down in discrete form, which is useful for numerical calculation.

Testing laminar composite type Glare

The composite type Glare 5/6 was product. It consisted of 6 metal sheet layers (thickness about 0.29 mm each of them) and 5 E81 fabric layers impregnated with L418 resin (thickness about 0.142 mm each of them). Abrasive cloth grinding and acetone washing was applied for

the metal sheet surface preparation for bonding. The composite was cured at pressure 1.3 MPa, at temperature of 80^{o}C for 8 hours. The specimen in dimensions 200x40x2.45 mm was cut out of composite plate. The specimen was stretched in Instron testing machine to determine modulus of elasticity E = 49928, 50145, 49855 MPa. The tensile strength of Glare 5/6 was determined too. The specimen was clamped in testing machine grips via abrasive cloth for reduction of action affect of grips on tested specimen. The failure load was 32.6 kN. Calculated average failure stress was 332.65 MPa and was smaller than failure stress of alloy 2024T3. The destruction of material consisted in braking of outside facing and delamination.

Such destruction give evidence that composite specimen was not uniformly loaded in all cross-section.

3. Numerical calculations

The numerical calculations were conducted for Glare 5/6 composite corresponding with made of this material composite specimen in 10 mm width. 2D or 3D models were created depending on loading method. Each of composite layers was modelled by three rectangular or hexagonal elements. The orthotropic properties shown in Tab. 4 were granted for glass-polymer component and elastic-plastic properties presented by stress-strain curve (Fig. 4) for aluminium alloy sheet. The calculations were conducted with used ANSYS program.

3.1. Tensile test

The plate model of Glare 5/6 composite was subjected to stretching (Fig. 5). All the degree of freedom was collected of nodes at one edge. The nodes of second edge were loaded with equal forces caused stretching in *x* direction.

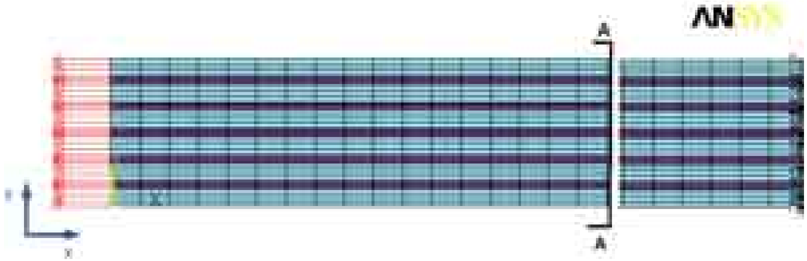

Fig. 5. Fixing and loading method of 2D model of Glare 5/6 composite

The calculations were conducted for several loadings. Uniformly stress pattern in different specimen cross-section was observed ignoring cross-sections being near to edges. According to expectation, the stress σ_x going in loading direction were prevalent. The dependence of stress in both composite components on loading is shown in Fig. 6.

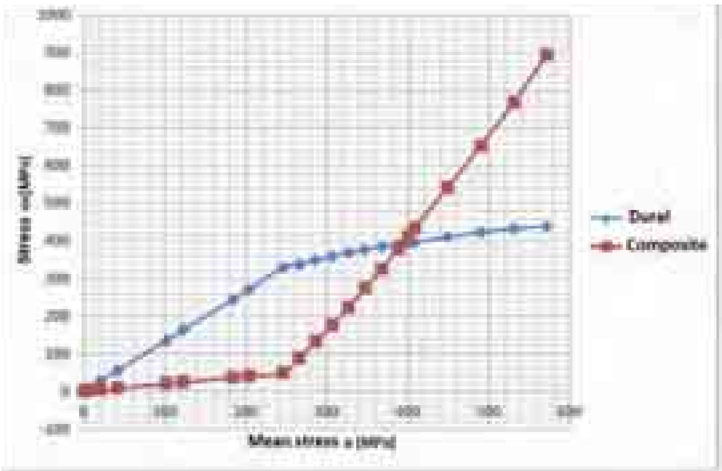

Fig. 6. Stress dependence on loading (average stresses) at stretching in laminar composite components

It was observed while the loading is smaller it is transmit in larger range by metal layers but while the yield point in metal is exceed the glass-polymer layers are more loaded. For failure loading (mean stress about 333 MPa), the stress in glass-polymer component was close to its strength determined in experimental test (about 200 MPa). Therefore, one may expect that the strength increase of composite component should cause the strength increase of the Glare 5/6 composite.

3.2. Bending test

2D model of Glare 5/6 composite was loaded by bending moment only (four-points loading of cuboid beam) to evade of contact stress in the best-loaded cross-section. The either support was fixed the second was shifting. The calculated model was loaded by two concentrated forces applied in symmetrically spaced to supports (Fig. 7). The force values were accepted to get the normal stress in outside metal layers equal yield point of alloy 2024.

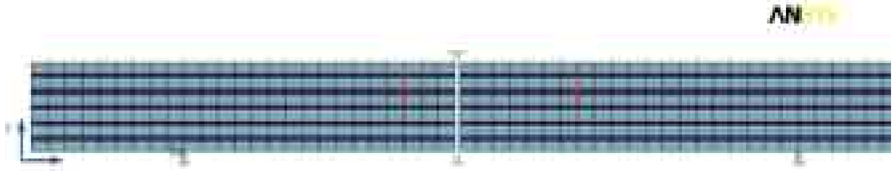

Fig. 7. Fixing and loading method of 2D model of Glare 5/6 composite subjected to bending

The normal stress perpendicular to composite layers and shearing stress between these layers, calculated in the best-loaded cross-section, was negligible small compared to normal stress σ_x. The σ_x stress was bigger in metal layers (Fig. 8).

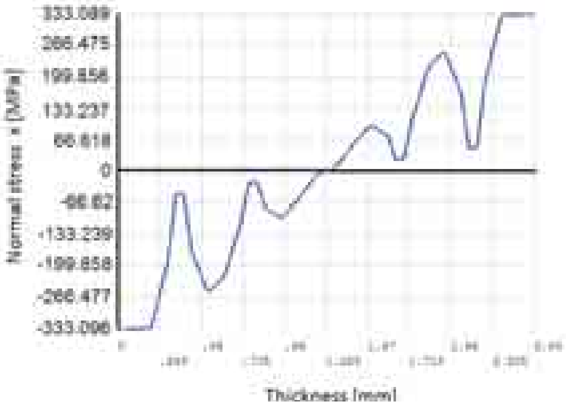

Fig. 8. Normal stresses in direction x in cross-section of laminar composite subjected to bending The little values of σy normal stress and τxy shearing stress show that there isn't danger of failure adhesive bonds between composite layers for considered loading method

3.3. Twisting test

3D model in dimension 50x10x2.46 mm was subjected to twisting. All degree of freedom were collected of nodes at the edge located in origin of coordinate system. The second edge was loaded by twisting moment trough node-to-surface contact element (Fig. 9). The possibility of displacement in direction *y* and *z* was made impossible for unbounded node of contact element. This node was loaded by 1000 Nm twisting moment. For this loading, the maximal value of von Misses reduced stress in outside metal layer was about 88 MPa and it was about quadruple smaller than yield point of alloy 2024T3.

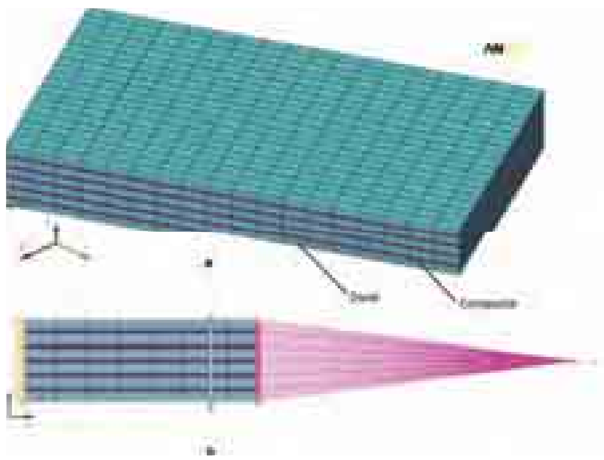

Fig. 9. 3D model of composite subjected to twisting

The calculation showed that, for assumed dimension of specimen and assumed loading method, the delamination caused by tensile of adhesive bonds would not occur due to small results from value of normal stress perpendicular to composite layers (σ_y). However, maximal searing stresses (Fig. 10) located between metal layer, glass-polymer layer are about 69 MPa, and they are relatively large comparing to searing strength of L418 adhesive.

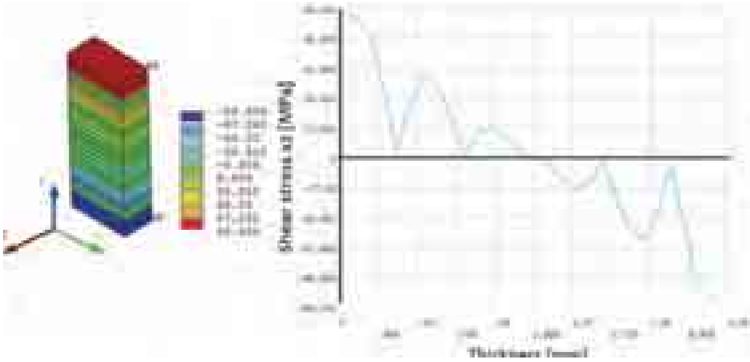

Fig. 10. Shear stresses τxy in composite layers at loading by twisting moment

The conclusion from this calculation is - there is great probability of failure adhesive bonds of tested material if it is subjected to twisting.

3.4 Stress analysis in Glare 5/6 after yield point overflow in metal component

The FML composite loading in such range that yield point is overflow in metal component causes after unloading coming into being stresses in material. The stress value should depend on plastic strain of metal layers. It results from stress-strain curve of 2024T3 alloy sheet (Fig. 4) that plastic true strain may be in the order of 0.06. The Glare 5/6 composite loading was modelled by displacement corresponding to true plastic strains in range 0.01–0.06. The stresses corresponding to plastic strains were calculated under loading and after unloading of material (Fig. 11, Tab. 6).

Tab. 6. Stresses in laminar composite components loaded in plastic range of metal components and after unloading

No	True strain ε	Length of model	Extension Δl	Stresses in loaded material		Stresses in unloaded material	
				Al alloy	composite	Al alloy	composite
		[mm]	[mm]	[MPa]	[MPa]	[MPa]	[MPa]
1	0.01	50	0.5	342.7	110.3	-22.3	54.5
2	0.02		1	367.8	220.5	-63.1	154.6
3	0.04		2	398.5	440.7	-145.9	357.6
4	0.06		3	424.0	660.8	-229.0	561.1

Due to symmetry of calculated model, σ_y and τ_{xy} stresses were negligible small in comparison with σ_x stresses that is there is not danger of adhesive bonds failure. The Glare5/6 composite model which metal component was plastic deformed was next subjected to bending. The calculation was conducted for one-side fixed beam loaded by force uniformly distributed on nodes of second edge. The calculated stresses were compared with stresses in composite, which were not early loaded in plastic range of metal component. Naturally, the stress distributions for both cases were different (Fig. 12). The shearing stresses and normal perpendicular to bonded layers were relatively larger in material early loaded in plastic range of metal component (Fig. 13). This stresses may cause failure of adhesive bonds.

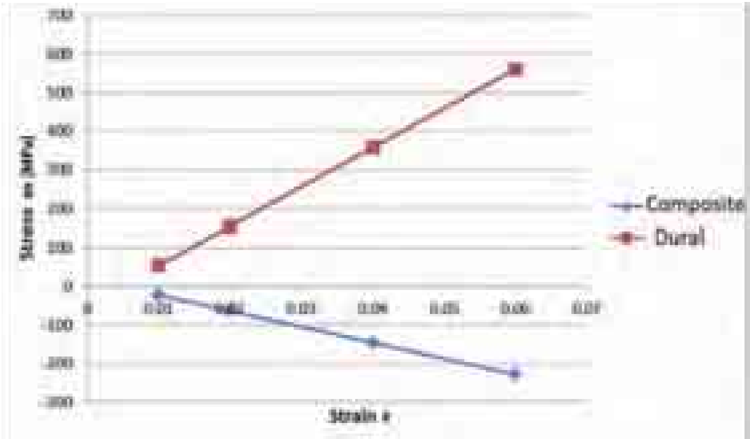

Fig. 11. Stress dependence on connected to preloading strain, in composite components, after unloading

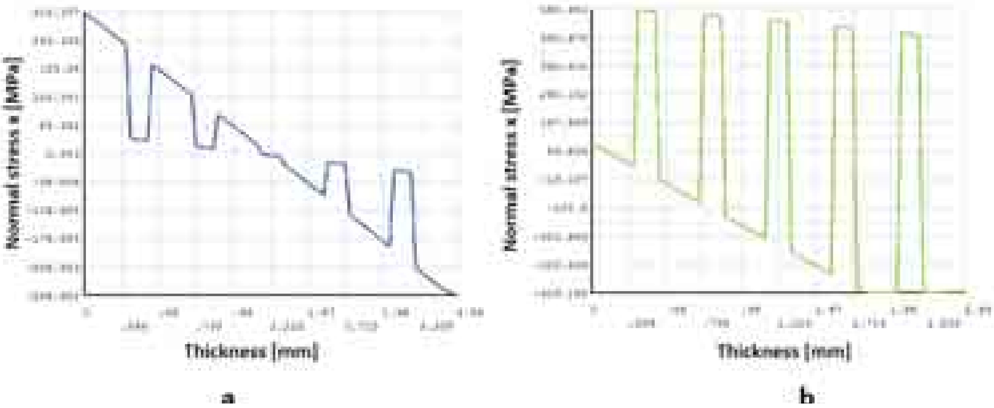

Fig. 12. Normal stresses σx in cross-section of laminar composite subjected to bending: a) don't preloaded material, b) preloaded material in plastic range of metal component

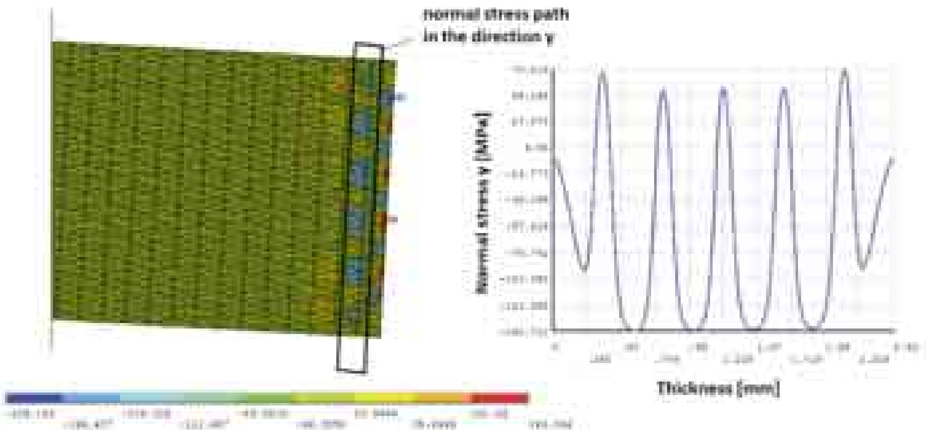

Fig. 13. Normal stresses σy in cross-section of preloaded material in plastic range of metal component next laded by bended moment

It results from the calculations that exceeding of yield point in metal components may cause failure of laminar composite after unloading. The experimental test was conducted to verify this possibility. Two laminar composite specimens consisted of 7 sheets of AW 5251 aluminium alloy thickness 0.3 mm and 6 layers of Kevlar fabric (basis weight 172 g/m^2) impregnated with Epidian53/Z1 epoxy resin were made. The dimension of specimen cross-section was 45x3.9 mm. The first specimen was subjected to tensile. The failure occurred at force of 47.5 kN. The second specimen was loaded by force of 38 kN to cause plastic strain in metal component and next it was unloaded. The specimen was delaminated during the taking out from testing machine grips (Fig. 14).

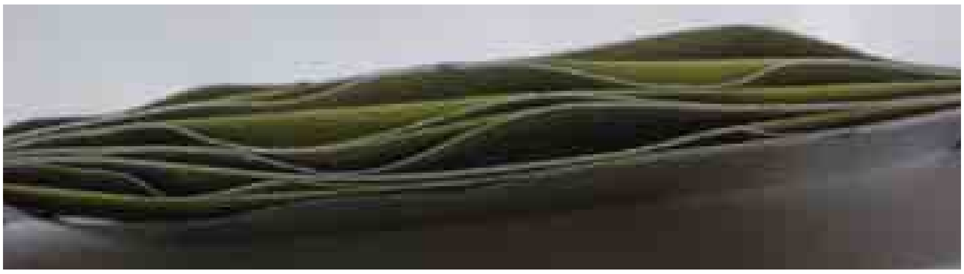

Fig. 14. Delaminated specimen of laminar composite

4. Conclusions

The main conclusions from this work are the following:

1. The strength analysis of elements made of FML composite should consider the destruction possibility as result of delamination caused by tensile or shearing of adhesive bonds. The numerical calculation of elements, which FML coating that is modelled by shell elements do not make possible to consider all possibilities of such type laminar composites destruction.
2. For obtaining optimal tensile strength of FML laminar composite the polymer, composite component should have larger strength then metal component, which shows elastic-plastic properties. Theoretically, both components should have identical failure strain values. However, the permissible loading of FML composite should not exceed of yield point of metal component because as a result of plastic strain may occur the failure of adhesive bonds after unloading of composite.
3. FML composites can transmit the large loading when they are subjected to tensile or bending. For such type of loading probability of delamination cased by tensile or interlayer shearing is small. However, the twisting of FML composite causes danger of delamination.
4. The value of adhesive forces bonding FML composite components limits the FML strength and their structural application. It seems that the progress of FML development will be connected with working out of new impregnant (resin) showing the better adhesive properties and more effective preparing of metal component surface for the adhesive bonding.

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