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INFLUENCE OF VOIDS AND LAYERS NUMBER ON MECHANICAL PROPERTIES OF HAND LAY-UP BENDED LAMINATES

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Abstract

Composite materials are broadly used in industry. In maritime industry composite materials with great success supersede conventional materials as steel and wood. Engine foundations and power-transmitting shafts belong to the newest applications of composite materials in maritime industry. Composite shafts are fabricated predominantly by rowing method but for engine foundations hand lay-up method is still used. One of the greatest disadvantages of hand lay-up (contact) method is hazardous distribution of resin matrix and voids or air blisters that remain in bulk resin matrix or may stick to reinforcement fibres. This hazardous distribution of resin may cause inaccuracies in calculation of voids percentage in laminate. If an air blister sticks to a fibre its prejudicial influence on laminate resistance is greater than if it remains in bulk resin. Number of layers that constitute a laminate influences the maximum bending stress in specimen. This relation however is different from that in tensile tests.

Keywords: *composite materials, laminates, hand lay-up method, fibreglass reinforcement, voids percentage, layers number*

1. Introduction

Composite materials with layered structure are being used broadly in many branches of industry. Automotive, rail, maritime and aerospace industry are the most distinctive fields where composite materials continuously broaden their applications [1]. Laminates and sandwich composites offer to constructors technological latitude in planning wide scope of material properties and make possible fabricating parts of complex shape. Resistance to corrosion and amagnetic properties are also their significant trump cards. Sandwich composites with foam or honeycomb core due to their high stiffness to mass ratio are frequently used for building yacht and ship hulls. Ultimately composite materials are used for constructing engine foundations and shafts transmitting power from engine to propeller. Such shafts may transmit the power even of one megawatt. Composite shafts are not only about 80% lighter then steel ones, but also save on complexity. Steel shafts which may not distort in operation have limited length. Conventional transmission line is therefore made up of multiple shafts along with pedestal bearings and other elements. Composite shafts, because of their less mass, can be made longer, that results in fewer transmission arrangements. Composite shafts do not corrode and run more quietly.

The basic method used for mass-produced and reliable composite products is called Resin Transfer Moulding (RTM). This method consists in impregnating with resin a preform placed in rigid, hermetic mould. This method is applicable for products that must be characterized by significant smoothness on both sides and is restricted to elements of small and medium dimensions. The costs of moulds, especially the heated ones, costs of pressure-circuits and instrumentation used in this method are significant. Other, less expensive method, especially suitable for mass-produced elements of extensive surfaces e.g. plates and long profiles is called Resin Film Infusion (RFI) [2,3]. In this method one-sided mould is used for impregnating the preform with resin. The other side is hermetically protected with a flexible polymer cover. While extracting the air from beneath the cover, it presses the preform and the resin is being distributed evenly through the preform, ensuring very good impregnation of the preform and high percentage of reinforcing fibres in the product. This method is successfully used in production of aircraft wings, fuselages and boat hull sheathings.

Mayor part of composite products is still produced manually (contact method). This technology is applicable for fibre-reinforced laminates formed by process of applying alternately reinforcing layers and resin matrix. This paper presents influence of voids percentage and number of layers on mechanical properties of laminate subjected to bending.

2. Material characteristics of laminate matrices and reinforcements

Laminates under consideration were made of two kinds of polyester resins: orthophthalic and isophthalic one. The polyester orthophthalic resin used was a A105 - thixotropic and preaccelerated, unsaturated, general purpose resin, that is suitable for spray-up and hand lay-up methods for manufacturing numerous moldings and is especially recommended for manufacturing of boats. The polyester isophtalic resin we used was a K530 - thixotropic, preaccelerated, special purpose resin with good mechanical properties combined with high temperature resistance. K530 is a medium reactive polyester resin with relatively long geltime, suitable for spray-up and hand lay-up application for manufacturing different types of composites, exposed to a corrosive environment and/or composites where good mechanical properties are important e.g. tanks, pipes, silos, boats, etc. Comparison of mechanical properties of these two matrices is shown in Tab. 1.

Tab. 1. Comparison of mechanical properties of K 530 and M 105 resin matrices

Property at 23 °C	K 530	A 105	Units	Method
Density	1,1	1,1	[kg/dm ^{3}]	ISO 2811
Tensile strength	65	55	[MPa]	ISO 527
Tensile modulus	4100	3600	[MPa]	ISO 527
Flexural strength	125	90	[MPa]	ISO 178
Flexural modulus	3700	4100	[MPa]	ISO 178

The aim of carried out tests was to find out relations between voids percentage, number of layers that constitute certain laminate and its mechanical properties in bending. Each laminate consist of a certain sequence of layers. Its structure is described by the following relation:

$$Wch + x(M\,450 + R600) + M\,450 + V\,30\,, \quad (1)$$

where:

Wch – chemo-resistant layer: V30+M300+2(M450),
x – number of coupled layers (M450+R600),
M450 - E-glass mat of 450 [g/m^2] specific weight,
M300 – E-glass mat of 300 [g/m^2] specific weight,
R600 – E-glass woven rowing of 600 [g/m^2] specific weight,
V30 – E-glass veil of 30 [g/m^2] specific weight.

So we deal with a laminate of asymmetric layer sequence. The mats M300 and M450 are of the same type of chopped strand mats for hand lay-up which homogeneity doesn't exceeds the range of ± 10%. The mat's glass fibres combine the electrical and mechanical properties of traditional E-glass with the acid corrosion resistance of E-CR glass. It is made of randomly oriented chopped glass strands bonded together using an emulsion binder. The emulsion binder uniquely bonds the mat so that it conforms rapidly to highly contoured moulds. The emulsion binder produces superior handling properties compared to powder bonded mats. The typical laminate properties of applied mats in an orthophthalic polyester resin with 31% weight glass content, moulded by hand lay-up method shows Tab. 2. The veil V30 is a type of very thin mat of 30 [g/m^2] specific weight, so we assume that its mechanical properties in a laminate layer are that of given in Tab. 2.

Tab. 2. Mechanical properties of M300, 450 mats in orthophtalic polyester resin with 31% weight glass content

Tensile Strength	Tensile Elongation	Tensile Modulus	Flexural Modulus	Flexural Strength	Flexural Elongation
108 [MPa]	1.8 [%]	7800 [MPa]	6770 [MPa]	204 [MPa]	3.4 [%]

In another Type Approval Certificate we find similar values for laminas made of M 300 and M 450 mats with less weight glass content (Tab. 3):

Tab. 3. Mechanical properties of M300, 450 and 600 mats in orthophtalic polyester resin

Property	300 [g/m^2]	450 [g/m^2]	600 [g/m^2]	Units	Method	
Glass content	29	28	29	[%]	ISO 1172	mean
Tensile strength	105/88	112/88	105/83	[MPa]	ISO 3268	mean/msmv
Tensile modulus	7404	7182	7045	[MPa]	ISO 3268	msv (mean)
Flexural strength	166/155	206/128	179/128	[MPa]	ISO 178	mean/msmv
Flexural modulus	6195	6095	6425	[MPa]	ISO 178	msv (mean)

where:

mean – mean of type test results,
msv – manufacturer's specified value, verified to be within ± 10% of mean of type test results,
msmv – manufacturer's specified minimum value, verified to be below mean – 2 × standard deviation of type test results.

We notice that the strength characteristics of the mats in laminas are specific weight dependent. The ultimate glass reinforcement type utilized in specimens preparation was R600 i.e. E-glass woven roving in the form of plain weave fabric which specifications according to a quality certificate are given in Tab. 4.

Tab. 4. Selected properties of R600 E-glass woven roving

Property	Value	Units	Method
Density (warp x weft)	2.6 x 2.25	[ends/cm]	GB/T 18370-2001
Tex (warp x weft)	1200 x 1200	[g/km]	ISO 1889
Weight	585	[g/m^2]	ISO 3374

Specimens were cut out of laminates prepared by contact method using rollers. Fabrication process was carried out conserving weight proportions of reinforcement to matrix as 3 to 4. Assuming that E-glass density equals 2.58 [g/cm^3] and utilizing data given in Tab. 1. we calculate a volumetric enforcement ratio of laminates [4]:

$$f_f = \frac{V_f}{V_m + V_f}, \tag{2}$$

where:

f_f – volumetric enforcement ratio,
V_f – volume of reinforcement material,
V_m – volume of matrix material.

Subsequently we calculate theoretical density of specimen according to the given formula [5]:

$$\rho_{ct} = \rho_f \cdot f_f + \rho_m (1 - f_f), \tag{3}$$

where:

ρ_{ct} – theoretical density of laminate,
ρ_f – density of reinforcement,
ρ_m – density of matrix.

The main disadvantage of contact method constitute air blisters or voids that remain in the resin matrix when the rolling is not performed carefully. In this paper we demonstrate also the influence of voids in resin matrix on mechanical properties of fabricated laminates. Having measured the real specimen's density we calculate the voids percentage using following formula:

$$f_V = \frac{\rho_{ct} - \rho_{cp}}{\rho_{ct}} \cdot 100\%, \tag{4}$$

where:
f_V – voids percentage,
ρ_{cp} – real density of laminate.

Ultimately, four kinds of laminates were used for testing which properties are tabulated beneath:

Tab. 5. Properties of tested laminates

Symbol	Matrix	Number of coupled layers: x in (1)	Total number of layers	Theoretical density
C1	A105	1	8	1.46 [g/cm^3]
C2	A105	2	10	1.46 [g/cm^3]
D1	K530	1	8	1.46 [g/cm^3]
D2	K530	2	10	1.46 [g/cm^3]

3. Testing procedure, results and interpretation

Bending tests were carried out according to the procedures described in adequate standards: PN-EN ISO 14125 for three point bending on machine INSTRON 8774 with 0.5% precision range. Comparison of results is shown in Fig. 1. We notice predictable relation, that maximum bending stress increases alongside with decrease of voids percentage. Considering laminate types marked as C1 and C2 we see that the maximum bending stress is greater for laminate consisting of 10 layers then for that of 8 layers. Taking into account that laminates C1 and C2 are of similar quality, this relation is different from the relation between maximum tensile stress and number of layers published in [5]. The relation between maximum bending stress and number of layers is inverse in case of laminates D1 and D2. In this case the laminate made up of 8 layers reveals greater maximum bending stress then that of 10 layers. This fact has its reason in quality differences. Laminates under consideration were made by contact method, so comparing D1 and D2 laminates we discover that laminate D2 was defectively impregnated and demonstrates tendency to delamination.

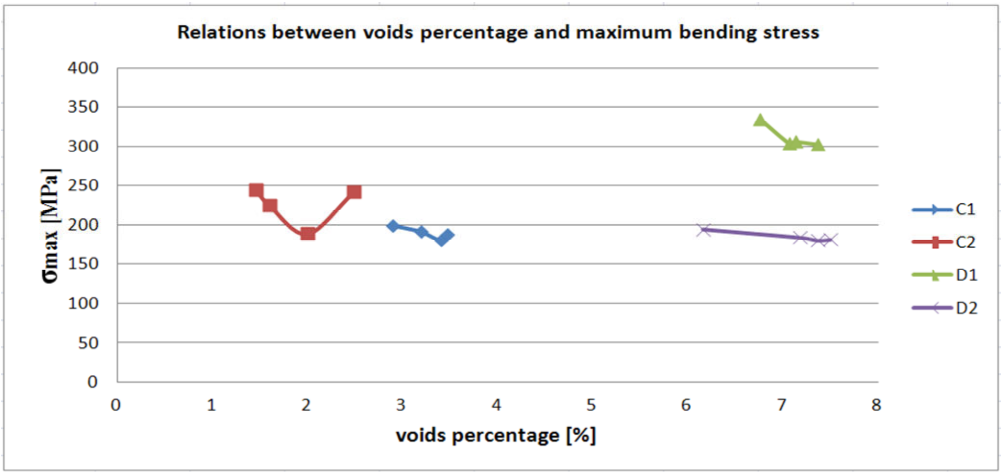

Fig. 1. The relation between voids percentage and maximum bending stress

The Fig. 2 and Fig. 3 reveal differences in fabrication quality of D1 and D2 laminates. Evaluating graphs of bending tests we notice that D1 laminate ruptures consistently in consequence of proper fabrication method while D2 laminate shows tendency to delamination.

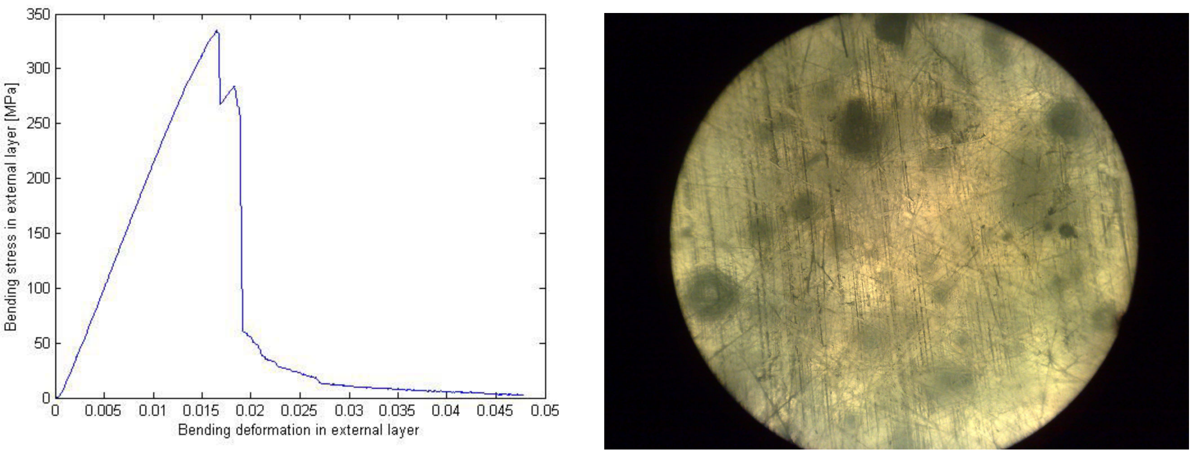

Fig. 2. The graph of bending test and structure of D1 laminate

The graph of bending test of D2 laminate (Fig. 3) shows clearly laminar form of crack. The quality of contact method of fabrication we may also evaluate comparing visible structure of laminate. We see that the D1 laminate has visible voids, but in structure of the D2 laminate we may see fibres of reinforcement. It reveals that impregnation of reinforcement is worse in D2 laminate than in D1 laminate.

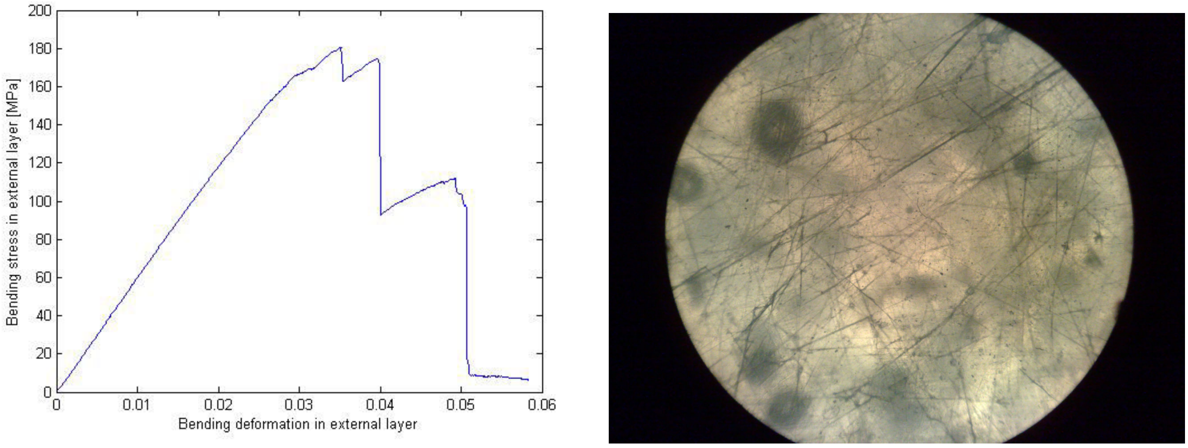

Fig. 3. The graph of bending test and structure of D2 laminate

Another case that needs an explanation is the increase of maximum bending stress in specimens having greater voids percentage. This is clearly visible in 4^{th} specimen of the C1 laminate. This phenomenon may have two reasons. First, the technique of calculating voids percentages consists in measuring real density of specimens. If the local weight proportion of reinforcement to matrix is other then 3 to 4 it will cause the change in real density. The other possibility is that the voids situated in proximity of reinforcement fibres are more harmful for mechanical properties of laminate than voids situated in bulk resin matrix.

5. Conclusions

Analyzing the influence of voids percentage on maximum bending stress we conclude that its influence is harmful and in case of contact method of fabrication the local weight proportion of reinforcement to matrix may differ that influences calculation of voids percentages.

Maximum bending stress depends on number of layers that constitute the laminate and this relation is different from that in tensile loading.

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