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Identification Method of Structural Defects in Glass Fiber Fabric/ Epoxy Resin Laminate

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Метод идентификации структурных дефектов в ламинате на основе стекловолокнистой ткани и эпоксидной смолы

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Описаны экспериментальные методы для идентификации структурных дефектов в 12-слойном ламинате на основе стекловолокнистой ткани и эпоксидной смолы. Для анализа основных структурных дефектов (локальная или глобальная дезориентация) использовались два метода. Один метод обеспечивает исследование (макроанализ) верхней и нижней поверхностей каждого слоя, другой – внутреннее исследование (микроанализ) каждого слоя после пиролиза матрицы (деламинации ламината).

Ключевые слова: структурный дефект, пластина, композитный материал.

Introduction. The greatest advantage of composite materials is strength and stiffness combined with lightness. Generally, a composite material is composed of reinforcement (fibers, particles and/or fillers) embedded in a matrix (polymers, metals or ceramics). The matrix holds the reinforcement to form the desired shape while the reinforcement improves the overall mechanical properties of the matrix [1]. According to the form of reinforcement, composite materials can be classified as follows: a) fibers as reinforcement (fibrous composites): random fiber- (short fiber-) reinforced composites and continuous fiber- (long fiber-) reinforced composites, b) particles as reinforcement (particulate composites), and c) fillers as reinforcement (filler composites).

The microstructural analysis describes the composition and structure (including defects) of the material that are significant for study of its properties. The analysis of manufacturing defects of a composite is necessary for the control of the material quality. Among widely used methods are: optical microscope (OM), transmission electron microscope (TEM) or scanning electron microscope (SEM). The non-destructive testing methods used to verify voids, delaminations and density are acoustic emission, radiography and ultrason. The investigations of the microstructure of fiber-reinforced polymer composite laminates can be visualized by means of optical or acoustic techniques [2, 3].

The structural strength of laminate is dependent on filament strength, matrix or resin strength, and fiber orientation. The mechanical strength of a composite is based on the interaction of fiber and matrix in a process that depends upon ply or layer thicknesses and percent of fiber volume. In the manufacturing process, filaments should be tested for tensile strength, elastic modulus, density, diameter, and stiffness. Matrix rheology must be characterized through chemical and physical testing. The preimpregnated material should be tested as to its satisfaction of chemical and thermal requirements. The laminate composites should be tested for mechanical strength (compression, flexion, and shear).

The mechanical behavior of this type of woven structure is very complex because of the particular problem involved in the geometry of the fiber network on which depend the structural properties. The significant question which arises for this type of configuration is the determination, according to each application, of the choice of the fibrous and resinous system, the nature of adhesion "renforcement/matrix," the technique of implementation, in order to obtain optimal characteristics. The system of reinforcement more commonly used for the development of the fabrics is the textile glass fiber because of is excellent ratio: mechanical performance/price.

The two principal parameters which guarantee the quality of the system of weaving are [4, 5]: surface density (size of yarns and type of armour) and counts (number of chain yarns and fill yarns).

The waving of the yarn in the woven is a parameter which characterizes the undulation of the yarn following the selected direction (warp and weft), it depends on the following principal factors: number of yarns and conditions of weaving.

The waving of the yarn in the woven (*K*) is the relation between the length of a fabric and the length of the yarn which is necessary to make weaving. Denser weaving, larger is the embuvage. It is defined by the following expression [6]:

$$K(\%) = \frac{L_f}{L_y} \cdot 100,$$

where L_f is length of fabric and L_y is length of yarn.

A fabric comprises yarns warp and yarns weft. It is characterized by four following elements [7]:

(i) the weave (armour): mode of intersection of yarns between them;

(ii) the account: number of warp yarns and weft yarns;

(iii) the nature of yarns: carbon, kevlar, aramid, and glass;

(iv) density of yarns before/during weaving.

This study presents the identification approach used for analysis of manufacture defects of laminate (glass fabric fiber/resin epoxy). The results obtained show the good detection of defects of composite studied. The structural properties of laminate depend strongly of fabrication process and the material microstructure.

Experimental Details. *Material Used*. The material used was a laminate constituted of 12 layers of glass fiber fabric at taffeta weave (the warp yarn and weft weaving alternatively) drowned in an epoxy resin. It is delivered in the form of plane plates (five plates) of average size: 350 (weft direction) × 340 (warp direction) × 3.2 mm (thickness). The fiber volume fraction of the woven fabric composite (glass fiber fabric/epoxy resin) was approximately 55% and the density was about 1.94 g/cm^3. The volume fraction of fibers was given according to the method of calcination and found equal to $V_f = 30\%$. The five studied plates carried numbers 1, 2, 3, 4, and 5 and have 12 layers each.

Analysis of Structural Defects. Initially, the visual observation of external surfaces was used to make a sketch of the orientation of the rovings of the chain (warp) and weft of the two external layers of the sheet (plate) on a tracing (Fig. 1).

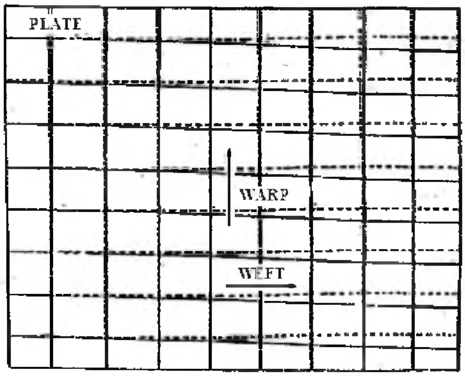

Fig. 1. Orientation defects of layers of the plate (solid lines correspond warp and weft directions of the superior layer, dashed lines – warp and weft directions of the lower layer).

The control method of the orientation defects of rovings used consisted in measuring the four representative angles of the defects observed in ten points distributed in each plate, then the average of the values obtained was assessed, whereas the following angles were measured:

α_{warp} is angle measured between the warps of the layers (superior/lower);

α_{weft} is angle measured between the wefts of the layers (superior/lower);

$\alpha_{1warp/weft}$ is angle measured between the rovings of the warp (chain) and the weft for the superior layer (1);

$\alpha_{12warp/weft}$ angle measured between the rovings of the warp and the weft for the lower layer (12).

Results and Discussion. From the results of the visual observations (Table 1) one can see that the variation of the angles α_{warp}, α_{weft}, $\alpha_{1warp/weft}$, and $\alpha_{12warp/weft}$ of the layers (superior/lower) is very low for the most plates (Nos. 1– 4), except for plate 5 for which the variation is very significant. In particular, the angles α_{warp} (angle measured between the warps of the layers: superior/lower) and α_{weft} (angle measured between the wefts of the layers: superior/lower) are definitely larger for plate 5 than for the other plates.

The variation of the weaving in the weft direction is, in general, much more significant than that observed in the warp direction. This variation is more reduced for plate 4.

The second phase of the study implied the analysis and identification with precision and a certain degree of confidence of the local orientation defects in the structure of the layers of each plate. This requires the pyrolysis of the matrix (epoxy resin). Two samples of 20 mm were studied (Fig. 2) in each plate in the sides left (small white square) and right (small black square).

Table 1

Results of the Representative Angles of the Defects Observed

Plates	α_{warp}, deg	α_{weft}, deg	$\alpha_{1 warp/weft}$, deg	$\alpha_{12 warp/weft}$, deg
1	0.6	1.5	91.5	89.0
2	0	1.5	90.5	89.5
3	0	1.6	90.5	89.5
4	0	1.0	91.5	88.5
5	1.0	4.0	93.5	88.5

Table 2

Results of the Principal Orientation Defects of the Plates

Plates	Samples	α'_{warp}, deg	α'_{weft}, deg	$\alpha'_{warp/weft}$, deg
1	Left side	0	0	90
	Right side	2.0	2.0	88 to 90
2	Left side	0	2.0	88 to 90
	Right side	0	0	88.5 to 90
3	Left side	0	0	90 to 91
	Right side	3.5	4.0	86 to 91
4	Left side	0	2.0	88 to 90
	Right side	0	2.0	88 to 90
5	Left side	2.0	1.5	87 to 89
	Right side	4.0	1.5	84 to 86

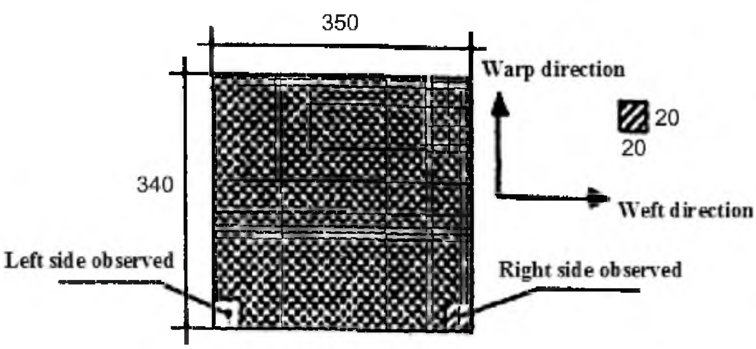

Fig. 2. Explanatory diagram of the two samples observed on each side (left and right) of the plate.

The study of visual observation of the various layers after pyrolysis of the matrix required the following steps:

(i) to carbonize the resin, in order to preserve only the separated layers of the laminate (taffeta of glass);

(ii) to photograph each layer on slide;

(iii) to project these slides, in order to obtain a schematic of the orientation of rovings of the warp and weft of each layer;

(iv) to superimpose the schematics obtained for the same sample of the layers in order to analyze the local orientation defects possibly observed.

For each layer one defines the following angles: α'_{warp} is maximum angle between the rovings of the warp relative to a reference, α'_{weft} is maximum angle between the rovings of the weft relative to a reference, and $\alpha'_{warp/weft}$ is angle between the rovings of the warp and the weft of the layer.

Table 2 shows for each plate the maximum values of the three defined angles, those clearly confirm notable confusions of plate 5 and a good quality of plates 1 and 2.

Conclusions. The above visual observation method (macroscopic and microscopic analysis) has permitted us to identify and classify the studied plates, starting from the results obtained, in three categories which are:

– plates 1 and 2 are a priori acceptable to realize tests (light variation of the undulation defects with a dispersion about 2°);

– plates 3 and 4 are of average quality but can be used;

– plate 5 is of poor quality.

Резюме

Описано експериментальні методи для ідентифікації структурних дефектів у 12-шаровому ламінаті на основі скловолокнистої тканини й епоксидної смоли. Для аналізу основних структурних дефектів (локальна або глобальна дезорієнтація) використовували два методи. Один метод забезпечує дослідження (макроаналіз) верхньої і нижньої поверхней кожного шару, інший – внутрішнє дослідження (мікроаналіз) кожного шару після піролізу матриці (деламінації ламінату).

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