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# FAILURE MODEL FOR UNIDIRECTIONAL COMPOSITE ELEMENT

**This paper is devoted to important issues of determining the strength and predicting the failure processes of composites. These issues enable determination of the limits of safe use of a product and the recognition of when limits are reached. It investigates the distribution function of the composite and its components. The developed model that is presented in this paper enables description of not only the predictable strength of unidirectional composites, but also the character of the failure, taking into account the fiber stress and/or ultimate strain distribution.**

Keyword: **failure, fibers, composite, strength, statistical model**

## MODEL ZNISZCZENIA ELEMENTU WYKONANEGO Z KOMPOZYTU JEDNOKIERUNKOWEGO

**Artykuł poświęcony jest ważnym zagadnieniom wyznaczania wytrzymałości i przewidywania procesów destrukcyjnych kompozytów. Kwestie te pozwalają na określenie granic bezpiecznego użytkowania produktu i rozpoznania, kiedy limity zostały osiągnięte. Zbadano dystrybuantę kompozytu i jego komponentów. Opracowany model przedstawiony w niniejszej pracy pozwala opisać nie tylko przewidywalną wytrzymałość kompozytów jednokierunkowych, ale także charakter zniszczenia, z uwzględnieniem naprężeń włókien i/lub rozkładu odkształceń końcowych.**

Keywords: **zniszczenie, włókno, kompozyt, wytrzymałość, statystyczny model**

## INTRODUCTION

Advanced composites may be described as layers, or plies, or high-strength fibers embedded in a matrix of plastic resin [1, 2]. The components of the composites materials in Boeing 757 and 767 airplanes consist mostly of graphite or aramid (Kevlar) fibers, woven into a fabric form and pre-impregnated with a partly-cured resin and finally cured in autoclaves [3-6]. Wing leading and trailing edge panels, control surfaces [7-12] and wing-to-body fairings are constructed in this way. Panel edge bands and control surface spar and rib chords are constructed from laminate materials with no core. The best-known technological innovation in Airbus A380 [13] is Glare (glass-fiber reinforced aluminum) composite material, which is used for much of the upper fuselage skins. Glare offers 15-30% weight savings over aluminum and boasts excellent fatigue properties. Altogether, the A380-800 incorporates 27 Glare panels covering a total area of 469 $m^2$. Although composite materials account for some 16% by weight of the A380 airframe, saving about 15 tons over the weight of an equivalent all-metal structure (the total empty aircraft weight is around 280 tons), the composite content could have been greater had the cost not been a limiting factor. It also needs to be noted that composites are commonly used in other areas of technology and engineering. They find application, for example, in civil and environmental engineering [14] as well as in heat exchanging devices [15].

## EXPERIMENTAL DATA PROCESSING

In order to study the distribution function of composite items, special tests were conducted. The values of 64 carbon-fiber strand strengths and 64 special 10-strand specimen strengths were obtained (Table 1 – every specimen was made of 10 strands). Then a test of 14 composite specimens was carried out.

At every step of the development of complex composite material (from fiber to strands, from strands to film and then to a multi-layer composite), we see a change in the two strength probability distribution function parameters: the mean strength decreases and the standard deviation decreases. In Figure 1 classic probability plots for the static strength of a composite and its components are shown. The main idea of the Daniels model is the uniform distribution of tension loads between parallel unbroken items (strands or fibers). Suppose that the initial items are strands. Before the test there are n parallel strands and at tension load $s$ (per one strand); the expected part of the failed strands will be equal to $F(s)$, where $F(s)$ is the cumulative distribution function of the strand strength. Then the expected strength of the bundle of $n$ strands, the failure load, is equal to:

$$s_b = \max_s n \cdot s\left(1 - F(s)\right) \tag{1}$$

TABLE 1. **Results of static strength tests**
TABELA 1. **Wyniki badań z wytrzymałości statycznej**

| | 1 strand | 10 strands | Specimens |
|---|---|---|---|
| 1 | 448.3 | 297.2 | 317.1 |
| 2 | 454.2 | 316.9 | 323.9 |
| 3 | 484.6 | 347.3 | 339.7 |
| 4 | 490.5 | 350.2 | 341.3 |
| 5 | 496.4 | 350.2 | 346.2 |
| 6 | 496.4 | 358.1 | 347 |
| 7 | 509.2 | 370.8 | 348.1 |
| 8 | 514 | 371.8 | 356.9 |
| 9 | 519.9 | 375.7 | 361.1 |
| 10 | 523.9 | 383.6 | 361.4 |
| 11 | 524.8 | 383.6 | 368.1 |
| 12 | 529.7 | 386.5 | 378.9 |
| 13 | 530.7 | 389.4 | 391 |
| 14 | 571.9 | 414.9 | 396.5 |
| 15 | 574.9 | 420.8 | |
| … | … | … | |
| 55 | 794.6 | 568.9 | |
| 56 | 799.5 | 577.8 | |
| 57 | 799.5 | 586.6 | |
| 58 | 802.5 | 596.4 | |
| 59 | 808.3 | 600.4 | |
| 60 | 860.3 | 655.7 | |
| 61 | 868.2 | 680.8 | |
| 62 | 877.9 | 688.7 | |
| 63 | 886.8 | 719 | |
| 64 | 869.2 | 774.0 | |

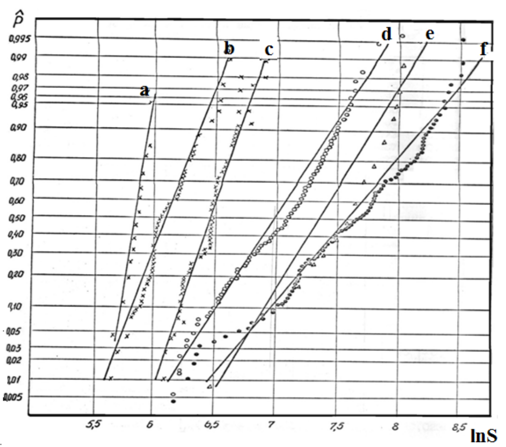


Fig. 1. Normal plot for static strength of: a – specimens (structure:0-6/+-45-4/90-3), b – 10 strands, c – 1 strand, d, e – PAN fibers, f – carbon fiber

Rys. 1. Normalny rozkład wytrzymałości statycznej: a – próbek (struktury 0-6/+-45-4/90-3), b – 10 pasm, c – 1 splot, d, e – włókien PAN, f – włókien węglowych

Later on, we put here $n = 1$, then we can consider value $s$ as the stress in parallel unbroken strands and $s_b$ as the mean breaking nominal strength. The main claim by Daniels is formulated in following way: "If all the fibers have the same load-tension curve and $b(s)$ is the probability of failure of one fiber under load $s$ and ($1$-$b(s)$) converges to 0 faster than $1/s$, then strength $s$ of a strand of a large enough number of fibers has normal distribution with an expected value."

$$S_r = n \cdot s_r \cdot [1 - b(s_r)] \tag{2}$$

Standard deviation

$$\sigma = s_r \cdot \sqrt{n \cdot b(s_r) \cdot [1 - b(s_r)]} \tag{3}$$

Where $s_r$ corresponds to the maximum of:

$$s \cdot [1 - b(s)] \tag{4}$$

Hence, the mean strength is defined by the formula:

$$\overline{S}_r = s_r \cdot [1 - b(s_r)] \tag{5}$$

and its standard deviation by the formula:

$$\overline{\sigma} = s_r \cdot \sqrt{b(s_r) \cdot [1 - b(s_r)]} \,/\, \sqrt{n} \tag{6}$$

In the previous section we chose the lognormal distribution as the most appropriate for the static strength distribution of composite components. In this case, we are interested in studying the function:

$$y(x) = x(1 - \Phi_0((\log(x) - \theta_0) / \theta_1)) \tag{7}$$

where $\Phi_0(\cdot)$ - normal standard distribution function.

## STATISTICAL MODEL

The failure process of a composite under the influence of load and the influence of various operating factors is considered as a sequential accumulation of damage [15, 16]. At the very beginning, damage to the components inside the elementary volume (failure of individual fibers, bundles), cracking of the matrix and the development of a nidus of micro-failure to extensive development and the formation of macrocracks are observed. The model describes the phenomenon observed during the processing of experimental data that the strength of the fibers, fiber bundles, microplastics, and specimens, respectively, decreases with increasing complexity of the structure. A bundle of fibers immersed in resin acts as a microplastic, in which there is already some kind of form, redistribution of the load and joint work of the fibers. A microsample is understood as a limited number of strands in a matrix of a regular structure. It is accepted that:

$$E_f > E_{strand} > E_{microplastic} > E_{microspecimen} \tag{8}$$

$$\sigma_f > \sigma_{strand} > \sigma_{microplastic} > \sigma_{microspecimen}. \tag{9}$$

 

Based on the statistical characteristics of the physical and mechanical properties (PMP) of reinforcing fibers, it can be stated that the failure of a reinforced polymer matrix under tensile load occurs by successive fragmentation of the fibers (bundle) until the formation of a critical length that is not capable of transmitting normal stresses due to shear failure of the matrix. This phenomenon is described by individual model. The model assumes that:

1) The composite material consists of fibers processed into bundles (bundles of fibers) and matrices, monolithically interconnected.
2) The fibers (bundles) have random PMP, with randomly distributed defects.
3) The deformation in the section is the same in all the components; the stresses in the matrix are less than the stresses in the bundles and the shear deformations in the bundles are negligible in comparison with the shear deformations in the matrix.
4) Near the internal break of a fiber (bundle, bundles of fibers) in the composition, the axial load is transferred to the neighboring fibers (bundles) due to shear forces in the matrix.
5) The accumulation of accidental damage to the material leads to the emergence of a sufficient number of non-working sections of fibers (bundles) throughout the volume and the formation of a weak section, which leads to failure as a whole.
6) The concept of a critical elementary volume is used, which is responsible for the failure.
7) It is assumed that the failure process proceeds in the same way both in a bundle with resin and in a unidirectional composite consisting of bundles.

A diagram of the composite is presented in Figure 2. It consists of a large number of elementary cells, in which structural elements with individual PMP are located (Fig. 2).

In the bundle, the fibers also have different PMP, respectively, different loading, and their failure occurs randomly throughout the entire volume (Fig. 3).

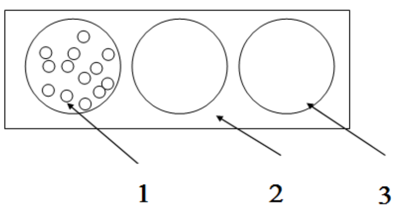


Fig. 2. Fiber bundle immersed in matrix: 1 – fibers, 2 – matrix, 3 – bundles

Rys. 2. Wiązki włókien zanurzone w matrycy: 1 – włókna, 2 – osnowa, 3 – wiązka

A zone is gradually formed in which, when the critical number of fibers fails, the elementary volume and, accordingly, the bundles as a whole fail. According to the individual characteristics of monofilaments obtained from experiments or modeled according to the statistical characteristics of the PMP, the strength of the bundle is calculated by the formula:

$$F(\sigma) = 1 - \exp(-\alpha L \sigma^{\beta}) \qquad (10)$$

where: $\alpha$ and $\beta$ are the parameters of the Weibull distribution; $L$ is the fiber length.

If there are experimental data on the strength of microplastics, then they are used to determine the strength of a bundle (microplastic), a unidirectional composite. When loaded, many failures can occur. The place of failure is allocated randomly in the place of the weakest elementary volume, which is defined as the critical zone of failure.

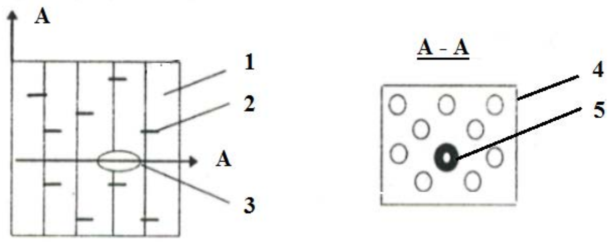


Fig. 3. Unidirectional layer composite: 1 – bundles, 2 – matrix, 3 – crack bundles, 4 – elementary failure volume, 5 – failed

Rys. 3. Jednokierunkowy kompozyt warstwowy: 1 – wiązka z włókien (elementarna), 2 – osnowa, 3 – pęknięcie wiązki, 4 – podstawowa objętość zniszczenia 5 – zniszczenie

In the event of a rupture, the redistribution of loads occurs at the critical length of the bundle. Figure 4 presents the diagrams of redistribution of the load through the shear stresses on the adjacent fiber (bundle), and the inclusion of the fiber in operation, on $L_{kr}$.

The matrix redistributes the load between the fibers (bundles) at critical length $L_{kr}$, calculated using the Rosen model [15]:

$$L_{kr} = d_f \left[ \left( \frac{1 - V_f^{0.5}}{V_f^{0.5}} \right) \frac{E_f}{G_m} \right]^{0.5} arch \left[ \frac{1 - (1-\varphi)^2}{2(1-\varphi)} \right] \qquad (11)$$

where: $L_{kr}$ – critical ineffective length; $\varphi$ – relative loading level at which the fiber is considered included in the work (0.97); $D_f$ – fiber diameter; $E_f$ – elastic modulus of the fiber; $G_m$ – matrix shift modulus; $V_f$ – filling factor.

a) b)

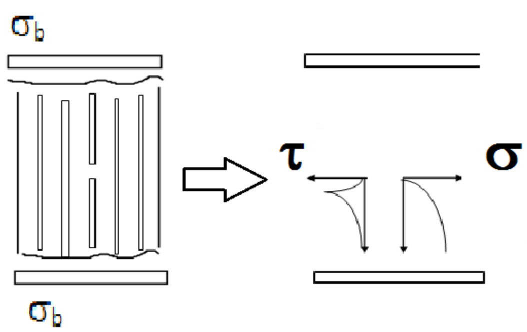


Fig. 4. Critical failure zone: a) failure of bundle, b) diagrams of changes in stresses $\tau$ and $\sigma$

Rys. 4. Krytyczna strefa zniszczenia: a) zniszczenie wiązki, b) wykresy zmiany naprężeń $\tau$ i $\sigma$

 

Critical length $L_{kr}$ is calculated taking into account the time and temperature patterns of deformation of the matrix and fiber, resin and bundle through the PMP components [16]. When the bundle or the fiber itself breaks in the bundle, in the composite, it does not fail completely, but only the ends closest to the rupture are unloaded. The remaining parts of the fiber or bundle are loaded again and can be split several times until the final fiber length reaches $L_{kr}$, on which the matrix can no longer load the adjacent fiber (bundle) by means of shear stresses.

In the calculations, it is possible to take into account the change in strength under the influence of temperature, moisture, time and other environmental factors, according to empirical formulas compiled on the basis of processing experimental data. If the maximum stress exceeds the limiting one, then the fracture process will not stop until the sample fails. If it is less than the limit, then the sample retains its bearing capacity. The process will continue with increasing load until the ultimate strength is exceeded in any bundle. When modeling the fracture process, a step-by-step increase in stress leads to repeated redistribution of local stresses in the bundle or fiber. If failure does not occur yet, then we increase the load again until failure of the weak elementary volume occurs [17]. If two or more bundles collapse side by side at the same time, then there is a high probability that catastrophic failure will begin. The concluded sequence of laminar composite failure confirms earlier findings concerning the initiation and development of the failure process in laminates [18, 19].

In the above-presented modeling of the physical-mechanical properties of the components of a unidirectional composite, the influence of the technological (manufacturing of the composites [20-22]) and operational parameters (i.e. temperature, humidity, aging time, etc.) of the material, respectively, were not taken into account.

## CONCLUSIONS

Based on the log-normal distribution of the physical and mechanical properties of the components in the model (i.e. bundle elemental strength, unidirectional composite sample), a critical beam length was used to estimate the composite strength. The model takes into account the changes in PMP as well as the failure of the components and the composite itself, along with an increase in the complexity of the structure with different loads. A fiber bundle immersed in a resin in which some kind of load, load redistribution and joint work of the fibers already exists, assumes that the failure process takes place in the same way both in the bundle with the resin and in a unidirectional composite consisting of bundles in a critical volume.

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