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STRENGTH DETERMINATION AND PREDICTION OF DESTRUCTIVE PROCESSES OF COMPOSITES

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Abstract. This paper is devoted to issues related to strength determination and prediction of destructive processes of composites; these issues enable determining the limits of safe use of a product and to recognize when limits are reached. The model that was developed and is presented in this paper enables to describe not only the predictable strength of unidirectional composites, but also the character of the destruction, taking into account the fiber stress and/or ultimate strain distribution.

Keywords: strength, destructive processes, composite materials, destruction, diagnostics.

1. Introduction

Composites are increasingly being used in the aviation sector: for constructing the fuselage of fighter jets, sport and special use aircraft, as well as for building the fuselage of large and heavy passenger jets, such as "Boeing-777" and "A380-800", and especially "Boeing-787", for which the use of modern composites is vital for reducing weight and costs. To ensure the durability and safety of these aircraft, it is necessary to know precisely the relation of statistical strength and safe life characteristics, to predict how these values change if composite component characteristics are changed. By using composites in aircraft constructions rationally, it is possible not only to reduce weight, but also to lower the prime costs and obverall costs, and shorten the time of maintenance (Tsai, Hahn 1980). To do that models that can help to calculate material and final product strength and its changes regarding different factors should be developed. The basis of the authors' offered model is the development of a material collapse model, which takes thread breakage processes into account, assuming that these are the most informative processes and, at the same time, these processes reflect changes of the acoustic emission signal; therefore, the developed model could be used for non destructive diagnostics of composite material condition. The strength of laminates is usually predicted using the maximum tensions or their distributions of the laminate's fibers or threads. This study predicted the strength value changes and collapse nature differences of a laminate in cases when they are determined on the basis of fiber thread maximum extension distribution and/or when strength distribution is taken into account. Thus, it is possible to numerically evaluate, what role does one or another influencing factor play in material strength. The developed model was based on the works of H. Daniels (1986), V. Bolotin (1981), B. Rozen (1967) and others (Maymeister *et al.* 1980; Chatys *et al.* 2003; Daniel, Ishai 1994; Paramonov *et al.* 2010).

2. Description of destructive processes model

The model was based on a collapse pattern depicted in Figure 1 (Daniels 1986; Paramonov, Andersons 2008).

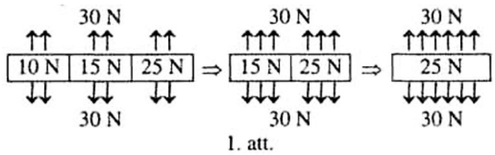

Fig. 1. A schematic illustration of the collapse process

In more complex structures strength decreases along with dispersion. Daniels proved that fiber strength distribution is a normal distribution with standard deviation, which is inversely proportional to $\sqrt{n}$. However, in practice, the normal distribution is substituted with logarithmical normal or Weibull distribution. The decrease predicted by standard deviation is also not accomplished and inversely proportional to $\sqrt{n}$. The deviations from Daniels' model can obviously be explained by the fact that the assumption about homogeneous distribution between elements is not true. In a composite, unlike an independent bundle of threads, the development of collapse does not occur homogeneously in all its cross section, but only in the proximity of damage. This collapse mechanism can be, therefore, viewed as a process, which starts with the collapse of a particular critical set of elements (located on the top of the sample). Then the collapse proceeds in the cross section of the sample, consequentially destroying it. Even "approximate homogeneity" can only be observed in a limited volume of the sample, which gradually changes its position.

The cross section collapse mathematical model can be described by formulas provided in (1), which determine the strength for i-th cross section and for the whole sample:

$$X_i^* = \max_t (x_t : n_C - K_{Ci}(t) > 0);$$
$$X_i^* = \min \min_{1 \le i \le n_L} \max_t (x_t : n_C - K_{Ci}(t) \ge 0);$$
$$X = \min_{1 \le i \le n_L}, \qquad (1)$$

where, in the first case, K_L cross section stages $0 < K_L < n_L$ damage appears K_{Ci} (t), $0 < K_{Ci}(t) < n_C$, $I = 1, ..., K_L$, n_L is the count of stages or elements within the whole length of the sample, n_C is the count of parallel elements, K_L – value of the case, K_{Ci} (t) – case time function, but in the second case the evolution of the collapse happens in one or more cross sections. The loading process is described as an increasing sequence $\{x_1, x_2, ...x_t, ...\}$.

To predict the tensile strength of a material in accordance with the characteristics of microsamples (here the term "microsamples" denotes a composite that is made from one fibrous thread and polymer), three variants will be analysed. The first variant consists of the strength calculation depending on the critical tensions of threads and the second provides the determination of material strength that depends on the criterion of reaching thread critical extension. The third variant is a combination of the first two, with the condition that each thread of the laminate can be torn only once after reaching one of the following criteria $\varepsilon_{i\,max} < \varepsilon$ or $\sigma_{i\,max} < E\varepsilon$, where $\varepsilon_{i\,max}$ is the maximum relative extension of the i-th thread and ε is the relative extension of the laminate, and $\sigma_{i\,max}$ is the maximum tension of the i-th thread. All the variants were considered using a simplified model with the assumption that a layer consists of threads of i fibers. These threads are mutually connected with the material of the matrix and the fiber volume relation to the matrix volume is the same as in the tested microsamples. All the threads and their fibers are perfectly linked and deform equally. Each fiber or thread together with the matrix takes up a particular area, and they have an equal relation of fiber and matrix volume. As a result, an orthotropic laminate with 4 elasticity constants is obtained. The laminate model is regarded as being composed of parallel, geometrically identical cells (fibers impregnated in the matrix). It is assumed that a thread, which is in the laminate, can be torn only once. Thread collapse is assumed to be approximately symmetrical; thus, when a thread breaks in tension, no torques form and only the tensile force is active in the laminate in direction 1 (there are no shifts towards y). This study does not examine the processes, which occur at compression, torsion or hack; similarly, tension in direction 2 (perpendicular to the direction of the tensile force) and shear processes during tension are not considered (Pipes, Dally 1972; Kamiński 2000; Wilczyński, Lewiński 1995).

The main idea of the carbon fiber laminate collapse simulation, which depends on the uniform displacement of the tension criterion, is that every fiber or thread breaks, when the critical tension, $\sigma_{i\ max,}$ is reached. The tensions formed by tensile force are distributed on all the fibers and threads equally: $\sigma_n = \sigma / i$, where i is the count of intact fibers or threads (Paramonov, Andersons 2008). Therefore, when an external force is added, the laminate faces tension, which will be equally distributed to all fibers and some of them will break if the tension will be equal to or will exceed the critical tension of the fiber. When the critical level of a fiber or thread is reached, it breaks, and the cross section area of the bundle loses one unit; therefore, its strength potential is decreased by a 1/i-th part.

Mathematically the model can be described by formula (2):

$$\sigma(\varepsilon) = \varepsilon \sum_{i=1}^{n_C} 1(\overline{\sigma}_i < X_i) E_i \varepsilon_i f_i \,, \tag{2}$$

where X_i is the critical tension of i-th cross section, f_1, ...f_n – cross section areas n and $E_1, E_2, \ldots E_n,$ – elasticity modules.

To simulate the collapse process, software was designed in the Matlab environment. The critical relative extensions of threads were not taken into account in the calculations. The calculated sample strength potential change curve is illustrated in Figure 2. Here the blue line represents the decrease of the strength potential of a sample at an evenly increasing disposition. The collapse character under the set conditions can be observed as well as the influence of each thread on the total strength potential, or, in other words, how much tension will the sample be able to withhold after the breakage of each weak thread.

The main idea of carbon fiber laminate collapse simulation, which depends on extension criterion for uniform displacement, is that every fiber or thread breaks, when the critical extension εi max is reached. The tension created by tensile forces is not taken into account. It is assumed that extensions of all the fibers are equal and they are equal to extension of the laminate. Therefore, when an external force is added, the laminate will be extended equally in all the fibers, and some of them will break, when the extension will be equal to or will exceed its critical value. When the critical level of a fiber or thread is reached, it breaks, and the cross section area of the bundle loses one unit; therefore, its strength potential is decreased by 1/i-th part. Mathematically it is described formulas in (3):

$$\sigma(\varepsilon) = \varepsilon \sum_{i=1}^{n_C} 1(\varepsilon \overline{\varepsilon}_i E_i < X_i) E_i \overline{\varepsilon}_i f_i \,, \tag{3}$$

where $\overline{\varepsilon}_i = \varepsilon_i / \varepsilon$ is the relative deformation for the i-th element at an average cross section deformation; ε is the distribution of the case value; $\overline{\varepsilon}_i$ is independent from ε.

To simulate the collapse process, software was designed in the Matlab environment. In the calculated variant, data of 25 microsamples from known experimental data were used. Therefore, it can be assumed that a virtual sample of 25 threads was created. To simulate

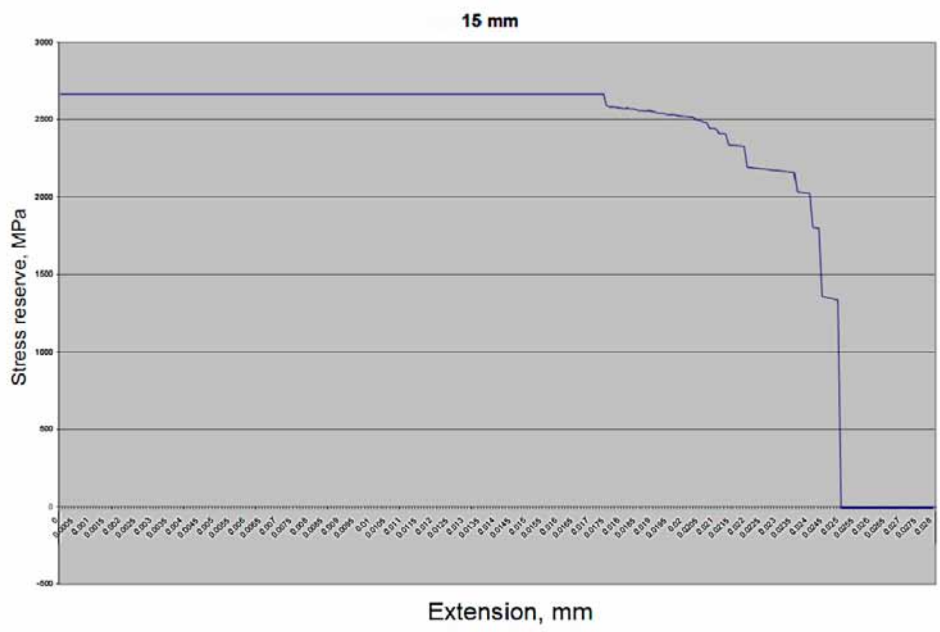

Fig. 2. Decrease of strength potential depending on the criterion of reaching critical tension for samples of 15 mm length

collapse, a series of predictable displacements were generated. These values were compared to the critical extension values of all the samples, after each step of the calculation. If the n-th calculated extension value is equal to or greater than the critical value of the i-th sample, the strength potential is decreased by 1/i-th part, where i is the count of intact threads. The critical tension value is not considered in the following calculation steps. All the fibers are,thus, broken in virtual reality and the fiber breakage places are determined. The curve of the calculated strength potential of the sample is illustrated in Figure 3. Here the blue line represents the decrease of the strength potential at an evenly increasing displacement.

The previous two cases exemplify the different nature of material collapse under different circumstances. Carbon fiber laminate simulation in accordance with both extension, and tension criterions without thepreviously mentioned assumptions and conditions must rely on the following procedures as well: a virtual sample, consisting of i fibers, is tested in virtual reality; the mechanical properties of these fibers are known; the sample is loaded with a tensile force with a steady pace; the tensions are applied to the intact fibers; each fiber can only be torn once, after one of the levels is exceeded; after each breakage, the tensions, which are applied to the intact fibers, increase due to the broken fiber; tensions are distributed evenly to all threads.

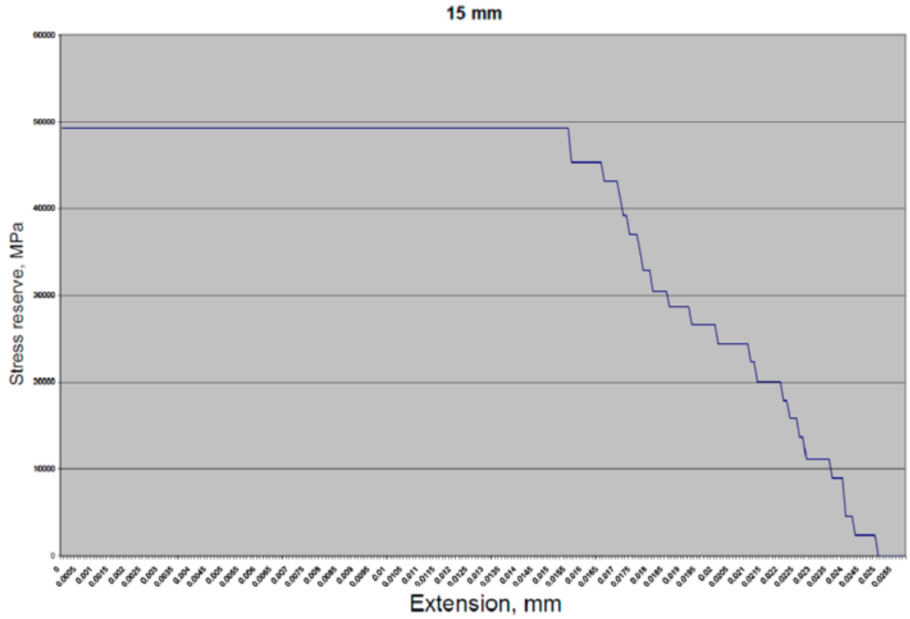

Fig. 3. Decrease of strength potential depending on the criterion of reaching critical tension for samples of 15 mm length

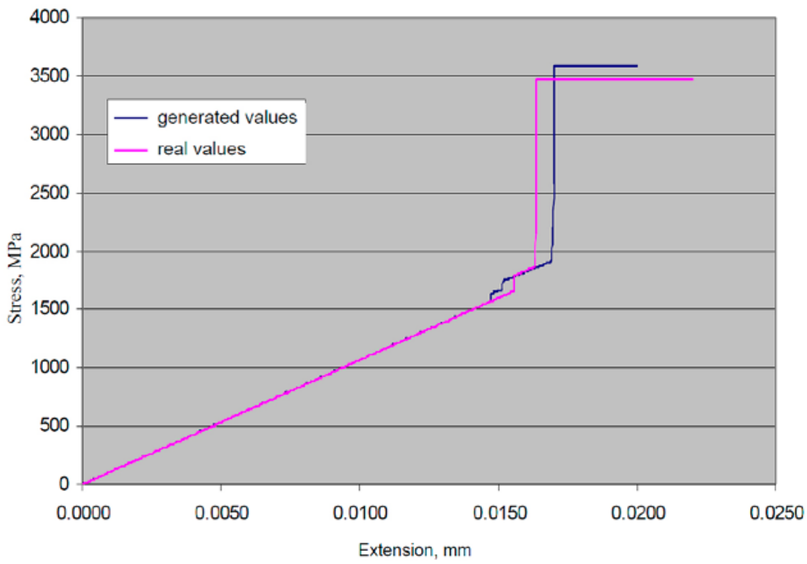

Fig. 4. Collapse simulation of carbon fiber samples

3. Results obtained by using the offered destruction model

Analyses of the generated and real values of reaching critical extension and tension conditions are presented in Figure 4. To simulate processes occurring in the material, it is necessary to know the predictable strength, critical extension and their standard offsets of thread microsamples, and, as noted before, the function of experimental data distribution is a normal distribution function. Figure 4 illustrates tension increase in a material with simulated data with a normal distribution function and 15 mm length sample offset and scale coefficients. As it can be observed, the comparison of curves of the simulated data and experimental data prediction shows a coincidence of both character, and critical values.

If we compare the critical values of the material with the average values, then, for example, for 15 mm length samples, the critical deformation is 0.021 and critical tension is 2181.7 MPa, but the calculated values are respectively 0.01633 and 1870 MPa. The critical deformation for 40 mm long samples is 0.012 and critical tension is 2202.4 MPa, but the calculated values are respectively 0.010 and 2190 MPa.

So, if we need to assess the strength of a composite laminate or to find the properties which would ensure the necessary conditions, it is vital to know the critical extension values and their dispersion, as well as the critical tension values and their dispersion of thread microsamples. The value distribution for a large number of threads inclines towards a normal distribution. The main advantage of assessing the critical parameters of a material in this way, is the possibility of evaluating the nature of collapse. The testing of manufactured composite laminate samples allows determining the critical tensions and extensions relatively simply, but it is hard to measure the brittleness or elasticity of a sample. Only using non-destructive methods of diagnostics, an overall view of the collapse can be obtained. The use of the developed model allows numerically determining the phase of collapse at a particular loading.

Sample collapse analysis enables not only to predict the maximum total strength and collapse rate of a material better, but also to understand the nature of acoustic emission signals.

4. Conclusions

- The developed fiber composite collapse model can be used to predict composite strength, according to the characteristics of its components. The model can be used in product design; it enables choosing the optimal material characteristics, which would ensure temporal recognition of collapse initiation, simultaneously ensuring maximum strength.
- The gained results can be practically applied, as well as supplemented and used for further calculation methodology improvement.

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