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Original Contribution

EVALUATION OF DAMAGE LEVEL IN GLASS-FABRIC REINFORCED COMPOSITE

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A method is proposed for evaluating the extent of damage in fibre-reinforced polymer composites. The available methods for monitoring fatigue degradation in such materials are critically discussed. Reported are the results of actual tests on a glass-epoxy laminate under cyclic bending. The relative changes in the bending strength were several times higher than those of the dynamic stiffness, total elastic energy of a cycle and phase shift. A relationship is put forward for calculating the level of damage allowing for the mean value and the standard deviation of residual strength. The analysis is enhanced by presenting microscopic images of the material structure. The proposed model was shown to give reliable estimates of durability and can be especially useful to validate the damage parameter determined by other methods.

1. Introduction

Processes of mechanical degradation in polymer composites (PCs) reinforced with fibres [4, 28] result in structural phenomena on a global or local scale which appear chiefly as discontinuities of various types:

- debonding at the fibre–matrix interface,
- cracks in matrix and fibres,
- delamination.

Other effects observed are plastic deformation and changes in properties of laminate constituents (e.g. physical or chemical degradation of a polymer matrix). Structural changes may involve large volumes of material and thus reduce elasticity and strength indexes or increase internal friction (larger hysteresis loops and higher phase shift angles ($\tan\delta$)). The elastic and strength characteristics of PCs may get reduced sizeably (from a few to 50–60%). Sometimes, however, they are found to rise at first and then to drop gradually [26]. The residual strength of a composite material may assume a value lying somewhere between the initial static strength and the fatigue one [25]. BATHIAS [2] has reported the fatigue strength in GFRP composites to be about 40% of the static strength which may serve as a general estimate of the possible strength reduction magnitude. It should be noted that even higher drops have been found [11].

The strength values are affected the least in unidirectional (UD) composites loaded in the fibre direction. High resistance to mechanical degradation is typical of epoxy–carbon laminates. High strength drops have been reported in materials reinforced with woven fabric, mats and unfavourably oriented UD laminae. KNIAT [16] has found that glass–polyester pressure pipes formed by centrifugal casting may have their safety factors reduced by 50% throughout the service life of 50 years. The core structure of such pipes consists of a mat whose mechanical condition gets strongly affected with time.

It is seen that successful application of composites in pressure vessels and equipment requires that appropriate procedures for monitoring material condition be available. Such procedures must be based on a reliable measure of extent of damage present in a material [1, 18]. The measure must possess the following qualities:

- it has to admit explicitly the decreasing capacity of a material to carry service loads in terms of a drop in strength or remaining fatigue life,
- the measurements involved must be easy enough to carry out and have no effect on the material tested.

The presently available methods for assessing the extent of damage in PCs hardly satisfy all of the above requirements. The following approaches to the problem can be listed:

1. The extent of damage D (also: damage parameter) is directly linked to actual values of elastic constants, especially to the longitudinal one.
2. The value of D is derived from geometric or statistical characteristics of the dominant types of cracks.
3. The value of D is calculated from the residual strength and the fatigue life. The Palmgren–Miner linear model is an example [27].

The aim of the present study is to assess applicability of a few material characteristics (residual strength, dynamic modulus, total deformation energy of a cycle, phase shift angle) to monitor the extent of damage in a laminated composite.

2. SOME CONCEPTS OF THE DAMAGE EXTENT EVALUATION

Most of the composite material damage estimates in use are based on actual values of Young's modulus. The whole body of research centred around this principle and called *mechanics of damage* [15, 20] can be dated back to the Kachanov's theory of effective stress put forward in the late fifties. The underlying assumption is that degradation in a material is a gradual process of void formation. The voids dispersed throughout the component volume reduce the live cross-section (Fig. 1a), so the actual working stress exceeds the nominal one.

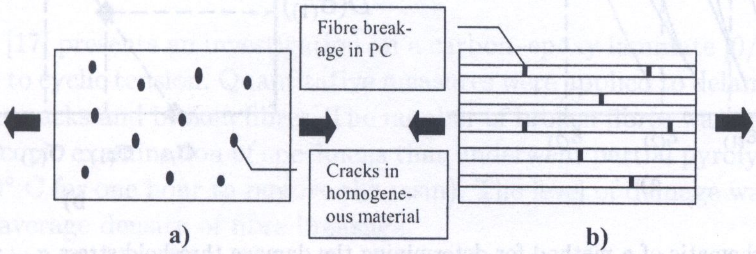


FIG. 1. Schematic representation of crack formation in homogeneous isotropic material (a) and UD composite (b).

The effective stress σ is given as a function of the damage parameter D

$$\sigma = \sigma_0/(1 - D), \tag{2.1}$$

where σ_0 – the stress applied, and $0 \leq D \leq 1$.

The value of D can be determined from $D = 1 - (A/A_0)$, where A – actual cross-section value, i.e. allowing for the loss of section due to voids, and A_0 – initial cross-section value. For practical reasons D is frequently determined as

$$D = 1 - E/E_0, \tag{2.2}$$

where E – current value of the secant Young's modulus, E_0 – its initial value [15, 20].

Figure 2 shows after [24] how the damage threshold stress can be determined. The glass-epoxy and glass–vinyl ester laminate specimens were tested in tension with intermittent unloading (Fig. 2a). Values of the damage parameter D obtained from formula (2.2) for local maxima on the loading graph were extrapolated to determine the σ_{th} values. Also the acoustic emission (AE) method was used to obtain additional estimates of the σ_{th} quantity (Table 1). As it can be seen, extrapolation of function $D(\sigma)$ (Fig. 2b) is a more sensitive method than the AE one.

The σ_{th} values as determined above were used to evaluate working stresses in laminates intended for military purposes. Another damage criterion is used in constructing wind turbine blades where a 10% drop in stiffness renders a material incapable of further service [21]. Various examples of how changes in elastic constants values can be used in design analysis are presented in [18, 23].

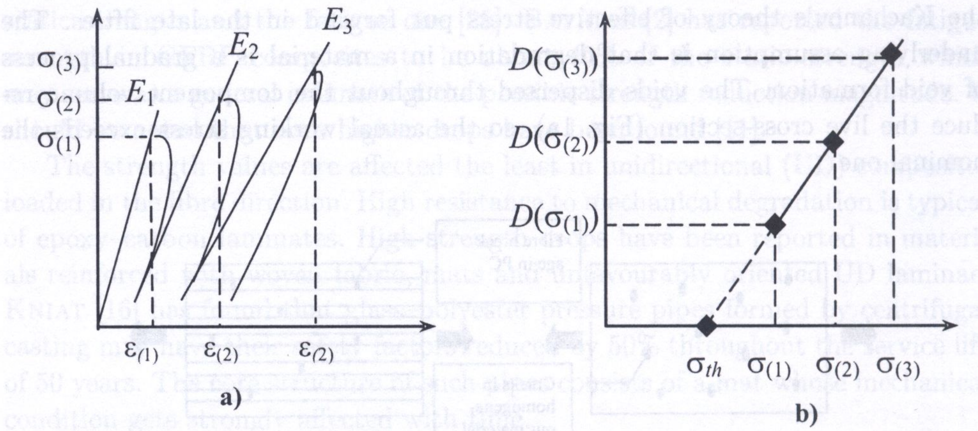


FIG. 2. Schematic of a method for determining the damage threshold stress $\sigma_{\rm th}$, after [24].

Table 1. The damage threshold stress $\sigma_{\rm th}$ values for two laminate types determined by different methods, MPa; after [24].

Material	Method of loading with intermittent unloading	Acoustic emission method
Glass–epoxy laminate	117	135
Vinyl–ester laminate	67	85

The level of damage in a composite material is determined by the type of cracks, their size and density. One approach in assessing the current level of damage consists in prescribing quantitative measures to density and size of cracks present in the material, their type being usually taken into account as an additional factor. Paper [3] presents a method for studying the damage growth in PCs by measuring the delamination area within the boundary effect zone.[1)] A carbon–epoxy laminate $[45/90/-45/0]_s$ was loaded in cyclic tension. On reaching the saturation density of transverse cracks in 90°, 45° and –45° plies, delamination at the 90°, 45° and –45° laminae started to grow. The longitudinal stiffness of samples decreased with the number of load cycles. The delamination area was determined with an ultrasonic technique. The damage parameter was found as

$$D = A/A_0, \tag{2.3}$$

[1)] The boundary effect (edge effect) in PCs consists in the formation of stresses that result in shearing or interlaminar tension [14]. The effect occurs in the vicinity of free edges and holes. The effect is due to differences in Poisson's ratio values of particular laminae and gives rise to delaminations growing according to the first or the second mode of linear elastic fracture mechanics.

where A is the actual delamination area and A_0 is the total area available for delamination.

By taking into account that the loss of modulus amounted to 65% of the initial value E_0, the damage parameter D was found to be

$$D = 2.857(1 - E/E_0). \tag{2.4}$$

Paper [17] presents an investigation on a carbon–epoxy laminate $[0/\pm45/90]_s$ subjected to cyclic tension. Quantitative measures were applied to delaminations, transverse cracks and broken fibres. The number of broken fibres was determined by microscopic examination of specimens that underwent partial pyrolysis (heating at 450° C for one hour to remove the resin). The level of damage was derived from the average density of fibre breakage.

It can be said that at present, the damage parameters derived from the intensity of occurrence of a certain type of cracks can hardly be considered as ripe enough alternatives in the analysis of structures. They suffer from major drawbacks. Changes in the elastic moduli give indirect measures of damage level since they reflect an average state of material structure while strength is principally related to the maximum size of defects. Methods involving direct measurement of defects are too complex to be used in engineering practice; furthermore, they are still at an early stage of development and the quantitative estimates they give leave much to be desired.

3. Changes in mechanical properties of laminates – an overview

Figure 3 presents a schematic of the fatigue S–N, residual strength and stiffness variation curves of a laminate. The S–N curves are the ones most frequently used by designers. The residual strength curves, while very useful, are seldom available. They are strongly dependent upon material properties and fatigue load parameters. They usually lie above the S–N curve (Fig. 3) [25]. At present there are no non-destructive techniques reliable enough to determine the strength of PCs, so the expenditure of work necessary to obtain curves of type 1 in Fig. 3 are comparable to that involved in the conventional fatigue test. Paper [7] gives an example of monitoring composite pipes by determining variation of residual strength with time.

In-service monitoring of structures is usually accomplished by measuring the loss in elastic moduli, especially – Young's modulus. The appropriate non-destructive testing techniques have long been available but there is a major inherent drawback to this approach – elastic constants reflect some average state of a material while its strength is primarily affected by defects built in during fabrication and those arising in service, i.e. local weak zones count the most.

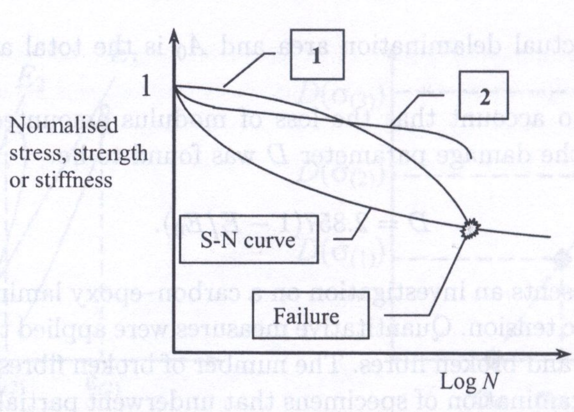


FIG. 3. Schematic representation of normalised S–N curve, residual strength (1) and Young's modulus variation (2) for plane laminate samples under cyclic load.

It can be said therefore that residual strength monitoring of a material is more reliable than that based on the elastic constant loss measurement.

Recent years have brought many papers dealing with fatigue degradation monitored with the help of energy characteristics such as dissipation energy and energy of elastic deformation [27]. The results have been promising and the energy approach is likely soon to become useful in the analysis of damage accumulation in PC structures.

4. INVESTIGATIONS ON DEGRADATION–RELATED CHANGES IN SELECTED MECHANICAL PROPERTIES OF A LAMINATE REINFORCED WITH GLASS FABRIC

The present author tested a glass-epoxy composite reinforced with glass fabric[2]. The laminate is commonly used as a constructional and an insulating material in high-voltage electrical applications. Fabric reinforcement[3] is frequently met in materials used in the construction of chemical equipment, wind turbine blades and vessel hulls. In a component, layers reinforced with fabric may be combined with UD plies or mats. As noted earlier, fabric reinforcement is liable to degradation caused by long-lasting constant or cyclic load. The effect is due to:

- wavy arrangement of fibre strands making up a fabric (Fig. 4),

[2] The tested laminate TSE-2 was manufactured by IZO-ERG S.A., Gliwice, Poland.

[3] The conventional textile glass reinforcement has the form of woven fabric [19] with wavy arrangement of particular fibres. The non-woven fabrics consist of a few UD laminae connected by stitching. Fibres in each lamina are straight and parallel but the two neighbouring laminae may have various angle orientations (e.g. 0°/90° or 0°/±45°/90°).

- unfavourable (e.g. perpendicular) orientation of some fibres wit respect to normal stresses induced by tension or bending which gives rise to early debonding at the resin/fibre interface.

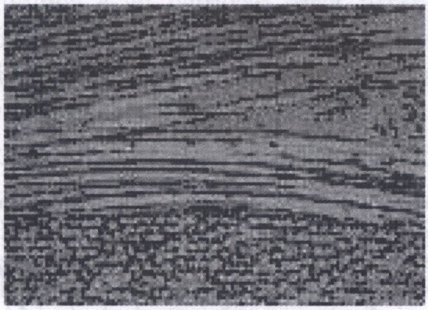


FIG. 4. Microstructure of the tested laminate. Wavy arrangement of fibres making up the fabric is clearly seen.

The aim of the tests was to determine the residual strength variation under cyclic three-point bending. The specimen span to height ratio was $l/h = 16$ (Fig. 5). For such geometries, failure can be almost solely attributed to the action of normal stresses. The specimens had a rectangular cross-section and were cut from a 4 mm thick plate.

The test procedure involved the following stages:

- application of a given number of load cycles ($10^{3.5}$, 10^4, $10^{4.5}$, 10^5) with a constant amplitude of force,
- bending test to failure of specimens with known numbers of accumulated load cycles.

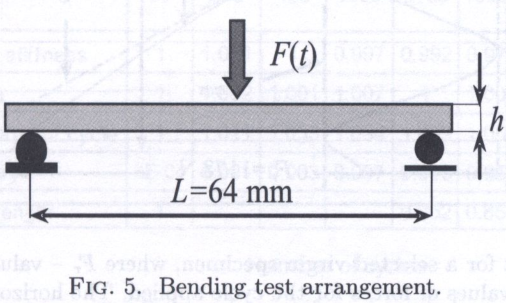


FIG. 5. Bending test arrangement.

The loading was accomplished on a hydraulic MTS 858 Minibionix testing machine. Frequency of loading was set to 12 Hz, the stress amplitude ratio was 0.13. The applied force $F(t)$ varied according to the pattern shown in Fig. 6. The maximum stress of a cycle was equal to 40% of the bending strength for virgin material and was lower than the knee point coordinate of the bending curve. The knee point value is commonly associated with the onset of microstructural damage (Fig. 7). Selected load cycles with numbers: 50, 190, 450, 1000, 3100 ($\approx 10^{3.5}$), 10^4, $10^{4.5}$ and 10^5 were recorded by a computer. The sequences of pairs: force–deflection were used to determine changes of the total elastic energy of a cycle (E_s), the phase shift angle between force and deflection ($\tan\delta$) and the dynamic (secant) modulus. The $\tan\delta$ quantity is a measure of internal friction of a material [8, 27].

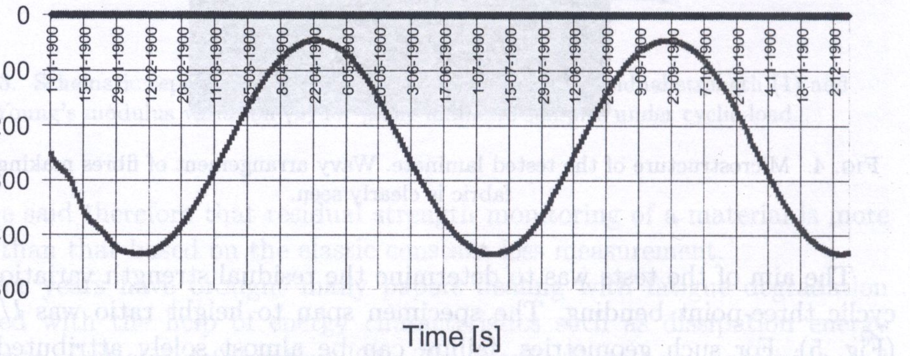


FIG. 6. Variation of loading force $F(t)$ with time.

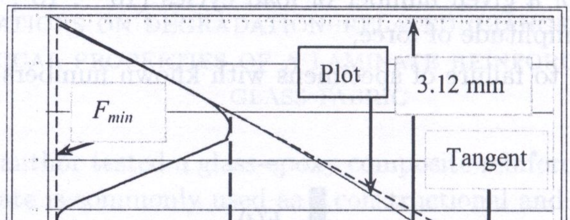


FIG. 7. Bending plot for a selected virgin specimen, where F_r – value of force at failure, $F_{\max/\min}$ – extreme values of forces for the cycle applied. The horizontal axis stands for force values, the vertical one – for deflection or time.

Figure 8 shows variation of the residual bending strength normalised with respect to the virgin material strength $R_g(n)/R_g(0)$. From seven to ten specimens were used to determine a single experimental point.

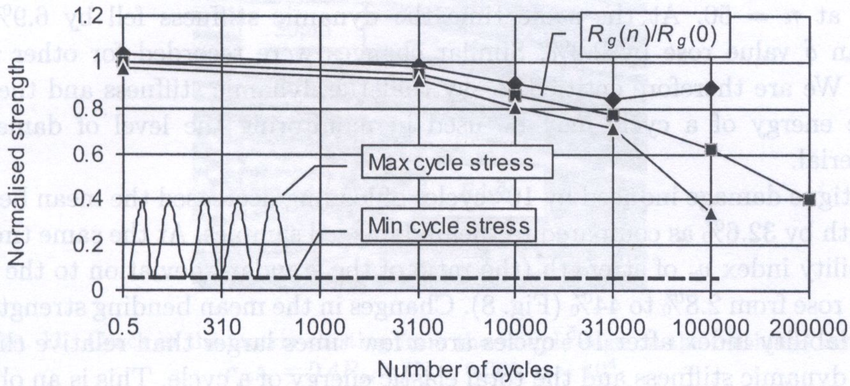
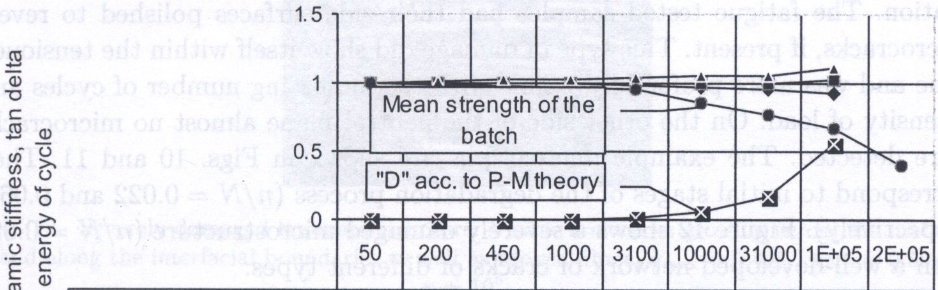


FIG. 8. Normalised bending strength shown with the scatter ±SD.

Figure 9 shows normalised variation of the dynamic stiffness, phase angle shift, total elastic energy of a cycle and level of damage (acc. to the Palmgren–Miner theory (P–M) [27]) as a function of the number of cycles for a given sample. The recorded changes were similar in character and intensity in the whole specimen batch. Plotted are also changes in the mean residual strength of the tested batch following the results from Fig. 8.



	50	200	450	1000	3100	10000	31000	1E+05	2E+05
Dynamic stiffness	1	1.001	1	0.997	0.992	0.978	0.963	0.931	
Tan delta	1	1.002	1.001	1.007	1	1.004	1.004	1.023	
Total energy of cycle	1	1.011	1.033	1.034	1.039	1.053	1.051	1.116	
P-M theory	3E-04	0.001	0.003	0.007	0.019	0.057	0.175	0.56	
Mean strength	1				0.952	0.858	0.776	0.674	0.4

Number of cycles

FIG. 9. Plots of the dynamic stiffness, phase shift and total elastic energy of a cycle as a function of the number of cycles. The quantities have been normalised with respect to the initial values.

It is seen from the table in Fig. 9 that on applying 10^5 cycles, the total elastic energy of a cycle rose by 11.6% as compared to the initial state assumed to be at $n = 50$. At the same time the dynamic stiffness fell by 6.9% and the tan δ value rose by 2.3%. Similar changes were recorded for other specimens. We are therefore entitled to say that the dynamic stiffness and the total elastic energy of a cycle may be used in monitoring the level of damage in a material.

Fatigue damage induced by 10^5 cycles of loading decreased the mean bending strength by 32.6% as compared to the undamaged samples. At the same time the variability index v_r of strength (the ratio of the standard deviation to the mean value) rose from 2.8% to 44% (Fig. 8). Changes in the mean bending strength and its variability index after 10^5 cycles are a few times larger than relative changes in the dynamic stiffness and the total elastic energy of a cycle. This is an obvious advantage when it comes to monitoring the damage level. Furthermore, the two named statistical quantities can be directly linked to reliability and service life of structural components [2, 29].

The method of evaluating the extent of damage through the remaining strength concept though inherently correct, is marred by technical difficulties. As it is known, the $R_g(n)$ curve requires a large number of specimens to be tested (30–40 or even more) since non-destructive techniques are helpless in this instance.

In addition to mechanical tests, the material underwent microscopic examination. The fatigue tested samples had their side surfaces polished to reveal microcracks, if present. This type of damage did show itself within the tensioned zone and was more profoundly visible with the increasing number of cycles and intensity of load. On the other side of the neutral plane almost no microcracks were detected. The example micrographs are shown in Figs. 10 and 11. They correspond to initial stages of the degradation process ($n/N = 0.022$ and 0.068, respectively). Figure 12 shows a severely damaged microstructure ($n/N = 0.59$) with a well-developed network of cracks of different types.

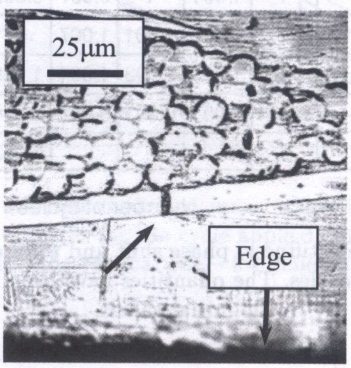


FIG. 10. Single broken fibre; $\sigma_{\max} = 0.4R_g$, $n/N = 0.022$, $n = 3100$.

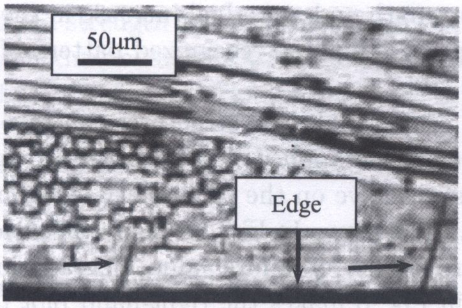


FIG. 11. Crack in the matrix starting from the sample edge on the tensioned side; $\sigma_{\max} = 0.4R_g$, $n/N = 0.068$, $n = 10^4$.

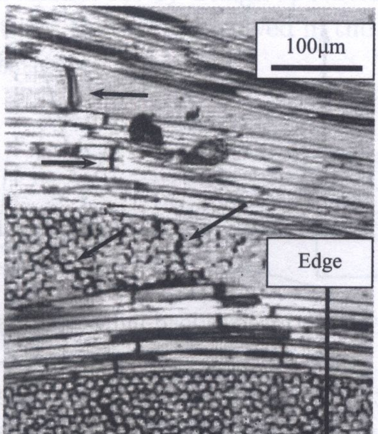


FIG. 12. Severely damaged laminate structure. Visible are cracks growing across the matrix and along the interfacial boundaries as well as broken fibres; $\sigma_{\max} = 0.4R_g$, $n/N = 0.59$, $n = 10^5$.

It should be noted that even small cracks marked in Fig. 11 are sufficient to consider the material condition as unsafe according to the FPF (first ply failure) criterion that is commonly used in designing chemically resistant equipment [13]. The extent of damage seen in Fig. 12 exceeds considerably the level established by the FPF criterion.

5. Evaluation of the damage level on the basis of changes in strength

The author's investigation has clearly shown that there are two main qualities characteristic of the degradation process in the tested material type: a gradual decrease of the mean strength and a gradual increase in the statistical scatter of the strength value (Fig. 8). This well recognized pattern of composite degradation is called *wear-out* [12].

Modern mechanics of materials and structures can take into account the effect the mean values of stress applied and material strength along with their statistical scatter measures have on the probability of failure [29]. The underlying concept is schematically shown in Fig. 13 where the shadowed portion of the graph stands for the probability of failure value. Degradation growing according to the pattern shown in Fig. 8 makes the right-hand plot (of strength distribution) to flatten and move to the left, i.e. the probability of failure becomes higher. The working relationships for determining the corresponding safety factors can be found in [29].

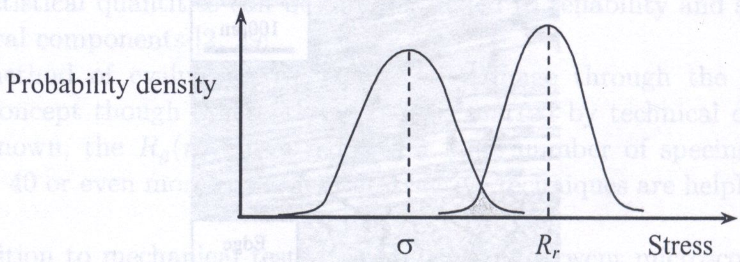


FIG. 13. Strength versus load-induced stress model.

The available amount of experimental evidence that can be used for evaluating the two named statistics for particular PCs is small. One example can be another study by the present author [4] where a UD glass-epoxy composite was cyclically tested. It was found that the effect of changes in the standard deviation of strength on the safety factor value was by one order of magnitude higher than that of changes in the mean value of strength.

The line of reasoning adopted there was as follows:

- the ability of undamaged material to carry load corresponds to $D = 0$,
- at the strength value falling down to the allowable stress level adopted in the beginning by a designer, the whole strength reserve has been depleted and $D = 1$.

With the two above assumptions the following formula was put forward for evaluating the current level of damage D in a material

$$D = \frac{R_{r/P}(0) - R_{r/P}(n)}{R_{r/P}(0) - \sigma_{\max}}. \tag{5.1}$$

The terms $R_{r/P}(0)$ and $R_{r/P}(n)$ stand for the so-called certified strength of virgin material and for the actual strength determined after n cycles of loading, respectively. The certified strength is determined for a given confidence level P_u. The $\sigma_{\max}$ denotes the maximum value of stress in a cycle. The quantities $R_{r/P}(0)$ and $R_{r/P}(n)$ can be found from the formulas

$$R_{r/P}(0) = R_r(0) - (u_g \times SD), \tag{5.2}$$

$$R_{r/P}(n) = R_r(n) - (u_g \times SD), \tag{5.3}$$

where the safety characteristic u_g [29] has to be adjusted to the adopted confidence level. For example, for $P_u = 0.95$ we have $u_g = 1.65$ and for $P_u = 0.99$, $u_g = 2.33$ (acc. to the normal distribution tables). The standard deviation SD is determined from tests of the residual strength. The adopted value of P_u should be in accordance with requirements set by design specifications. Figure 14 presents schematically some quantities that were involved in the evaluation of the damage level of the laminate investigated.

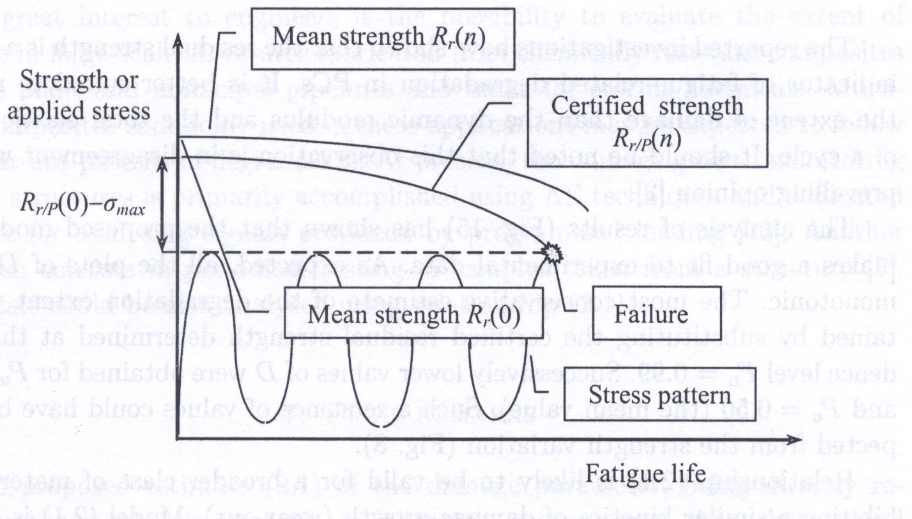


FIG. 14. Actions involved in determining D from formula (2.1).

Values of the residual strength and the standard deviation determined experimentally for various set levels of cyclic damage (Fig. 8) were used to determine the damage parameter value for the laminate tested from formula (2.1). The calculation was carried out for two values of the certified strength determined for the confidence levels of 95% and 99%. The damage parameter was also determined from the mean value ($P_u = 50$) and the Palmgren–Miner theory ($D = n/N$, where n–the number of cycles already executed, N–the number of cycles to failure at the stress level $\sigma_{\max}$). The results so obtained are shown in Fig. 15.

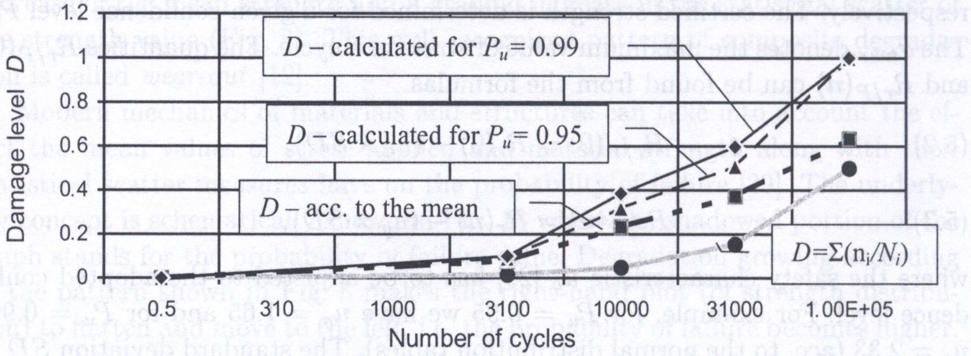


FIG. 15. Damage parameter D of the laminate as a function of the number of cycles determined from different formulas.

6. Analysis of the results

The reported investigations have shown that the residual strength is a reliable indicator of fatigue-related degradation in PCs. It is better suited to monitor the extent of damage than the dynamic modulus and the total elastic energy of a cycle. It should be noted that this observation is in disagreement with the prevailing opinion [2].

The analysis of results (Fig. 15) has shown that the proposed model (2.1) makes a good fit to experimental data. As expected, all the plots of $D(n)$ are monotonic. The most conservative estimate of the degradation extent was obtained by substituting the certified residual strength determined at the confidence level $P_u = 0.99$. Successively lower values of D were obtained for $P_u = 0.95$ and $P_u = 0.50$ (the mean value). Such a sequence of values could have been expected from the strength variation (Fig. 8).

Relationship (2.1) is likely to be valid for a broader class of materials exhibiting a similar kinetics of damage growth (wear-out). Model (2.1) is capable of allowing for variations in the standard deviation of strength which can be of practical interest in design [4].

The confidence level adopted in the determination of certified strength should be in accordance with reliability and safety requirements set by specifications for a given class of structures. The problem is discussed in more detail in references dealing with the application of composites in the aviation industry, where two types of the certified strength are defined: *A-allowable* and *B-allowable strength* [22].

Application of the P–M theory resulted in estimates for D that were 2–5 times lower as compared to those resulting from (2.1). This is in agreement with results obtained by many investigators who have found the P–M theory estimates to be even by one order of magnitude different from actual values of life. For example, for a composite tested in [27] $D_{\text{P-M}} = 0.1$ at failure instead of the stipulated $D = 1$. Paper [9] goes even further stating that comparison between fatigue lives calculated according to the P–M theory and experimental data revealed differences as high as hundredfold. Despite the weaknesses, the P–M theory is still widely used in design [9, 21].

It can be inferred from micrographs shown in Figs. 10 and 11 that the damage growth process occurred at stress levels below the knee point coordinate of the static test curve (Fig. 7). The disadvantageously early development of damage has been long known in laminates with reinforcement that is not closely aligned with the loading direction. It is seen from Fig. 12 that after 59% of the fatigue life determined according to the P–M theory has been depleted, serious damage could be detected within the most severely loaded portion of the specimen. Such experimental observations account for the recommendations met in some design codes where fatigue safety factors n may be equal to 20 (!) [30].

Of great interest to engineers is the possibility to evaluate the extent of damage in large-scale structures fabricated from chemically resistant composites such as plant and municipal pipelines and tanks for storing chemicals. Multi-layer composites commonly used in these applications may be expected to follow the wear-out pattern of degradation. At present, the damage growth monitoring in such structures is primarily accomplished using AE techniques and dedicated software for analysing signals produced by programmed loading [10]. Another approach consists in periodical testing of samples taken from a structure [7]. Such tests could be also analysed using relationship (2.1).

7. Final remarks

The proposed estimate (2.1) of the damage parameter, being directly related to the material's strength, is inherently more correct than those based on the elastic constant variation or the intensity of cracking. For that reason the D values determined from (2.1) may be used for validating indirect (non-destructive) methods of monitoring the material condition. Complete evaluation of the damage level must take account of changes in both strength and structure.

The presented results could be probably extended to the whole class of ply composites with various types of reinforcement undergoing the wear-out type of fatigue degradation. The process of damage accumulation in such materials is characterized by a steady decrease of strength with time of loading and the damage level can be then evaluated from (2.1). The results so obtained are more realistic than those predicted by the P–M theory.

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