Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 10 (2011) 1315–1320

Engineering Procedia

ICM11

Damage analysis and monitoring of composite materials and structures under cyclic loads

A. Muc, P. Kędziora, Z. Krawiec

Institute of Machine Design, Cracow University of Technology,ul. Warszawska 24, 31-155 Kraków, Poland

Abstract

The fatigue damage progress is analyzed both theoretically (FE modeling) and experimentally . Since the cyclic loading causes damage, reducing the strength until the material can no longer sustain even the service loading, the theoretical analysis is associated with the definition of the damage parameter corresponding to the stress criterion in the form proposed by Tsai and Wu. The detail analysis is mainly devoted to the consideration of two structural elements, i.e. rectangular plates with a centrally located circular hole (made of GFRP) and a square plate (made of Kevlar/epoxy resin) subjected to shear loading. The experiments demonstrate the scatter of results. The fuzzy set analysis have been proposed in order to estimate the uncertainty in the evaluation of critical number of cycles corresponding to the final fatigue damage.

Keywords : Fatigue damage; Fuzzy set approach; Composite plates; Fatigue life

1. Introduction

Currently a great number of monographs and review papers present the state-of-the-art understanding of damage mechanisms in composites under fatigue conditions. In this context it is worth mentioning the monographs [1-3] and the review paper [4]. Summaries of many ongoing research programmes, on the other hand, reveal that the current developments are still at the stage of explaining and interpreting experimental observations.

There is a variety of failure modes associated with static or fatigue damage, including: 1) matrix cracking, 2) interfacial debonding, 3) fibre breakage, and 4) delaminations. The first three mechanisms characterize the local (micromechanical) behavior of composites, whereas the last one can be described with the use of meso-modelling. Building a comprehensive, local model can only be accomplished by incorporating: (i) fiber mechanical properties and flaw statistics at the length scale of local fiber load

doi:10.1016/j.proeng.2011.04.219

transfer, including any stochastic stress-time dependency, (ii) matrix plasticity and creep in shear around fiber breaks, (iii) interface debonding and viscous frictional sliding in terms of local shear stress, (iv) local fiber and matrix packing geometry (2-D planar, 3-D hexagonal and random) and associated residual stresses from processing, (v) multiple matrix cracking as it affects penetration of the environment to the fiber surface. Reifsnider, Case [5], using micrographs, have evidently demonstrated microstructural randomness of manufacture-induced defects, microvoids, fibre rupture, kinks, etc. - so that the numerical analysis can always be conducted for a specific and individual construction but with a high computational cost. Therefore, the obvious trend would be the incorporation of various elements of randomness directly into the FE modeling schemes – through the meso-model.

2. Fatigue damage modeling

In this paper, a one-dimensional residual stiffness model is proposed. It aims at simulating the three stages of stiffness degradation, including final failure. To that purpose, the damage evolution law consists of two terms, separately accounting for damage initiation and propagation. The macroscopic damage variable *d* is a macroscopic measure for the fatigue damage, since the structural changes on the microscopic scale are characterized by a macroscopic reduction of the stiffness. To simulate the stage of final failure, the strength properties of the composite material must be included. Thereto, a new stress measure, the fatigue failure index, has been defined, based on a modified use of the classical Tsai–Wu static failure criterion:

$$RB = F_{xx}\sigma_1^2 + 2F_{xx}\sigma_1\sigma_2 + F_{yy}\sigma_2^2 + F_{ss}\sigma_6^2 + F_x\sigma_1 + F_y\sigma_2 - 1 \qquad (1)$$

where σ denotes the components of the stress tensor, and F the appropriate failure indices. The fatigue failure index, defined as: *d= 1/RB*, is particularly useful to model the stage of final failure. This is to be introduced with values between zero (virgin material state) and unity (final mode of failure).The damage parameter characterizes and simulates the three stages of stiffness degradation (sharp initial decline—gradual deterioration—final failure) [6]. The above approach will facilitate the damage (fracture) analyses to be conducted for individual plies in any arbitrarily laid-up the laminate. To put it differently, this novel approach will allow the applicants to utilize the meso-model whereby the existing FE modeling can be used .

In the proposed research, the spatial non-uniformity of material's properties at the microscopic level is to be taken into account from experimental data obtained during fatigue tests conducted for plies oriented at 0^0, 45^0 and 90^0 in tension and compression. When processed, this information will be represented by the lower and upper bounds of the stiffness degradation, i.e., as stiffness E(n) versus the number of cycles n relationships. These sets of lower and upper bounds will be available independently for 0^0, 45^0 and 90^0 orientations and Figure 1 illustrates the form of diagrams obtained for fibres oriented at 0^0 for specimens subjected to tension.

Using the arbitrary FE package it is possible to compute the stress distribution for given material constants and further it is possible to find the appropriate values of the failure index d – eq. (1). With the aid of fatigue diagrams characterizing the stiffness degradation for each number of cycles n it is possible to find the distributions of failure indices with number of cycles, i.e. d(n) and determine the fatigue life N_f as the failure index reaches the value 1 (the final damage). The numerical calculations are conducted for the mean, upper and lower values of stiffnesses and for the chosen increments of the cycles. It is worth to emphasize also that the numerical analysis is not limited to laminates made of plies oriented at 0^0, 45^0 and 90^0 since stiffnesses for other orientations can be computed with the help of the classical transformation law from local to global system of coordinates, assuming the validity of the linear, elastic Hook relations for orthotropic materials.

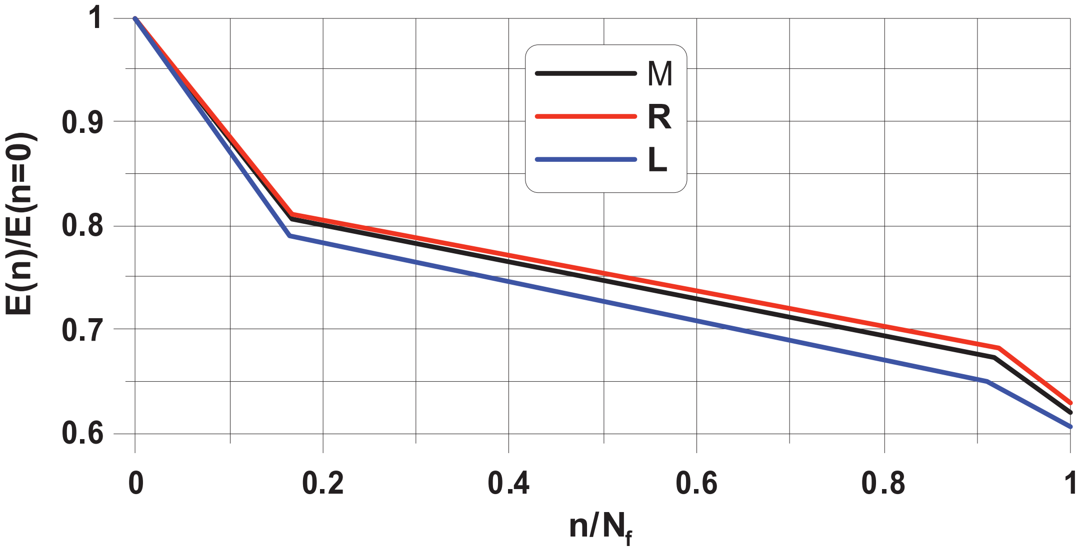


Fig. 1. Stiffness degradation vs. number of cycles (mean–M, upper – R and lower – L values, respectively)

3. Estimations of fatigue life

3.1. Rectangular plate with a centrally located hole

Let us consider a rectangular plate with a centrally located hole. The plate is made of glass fibre/epoxy resin and the laminates consist of five layers. Each layer was discretized with the use of 3D FE having orthotropic properties and the corresponding values of the stresses are demonstrated in Fig.3.

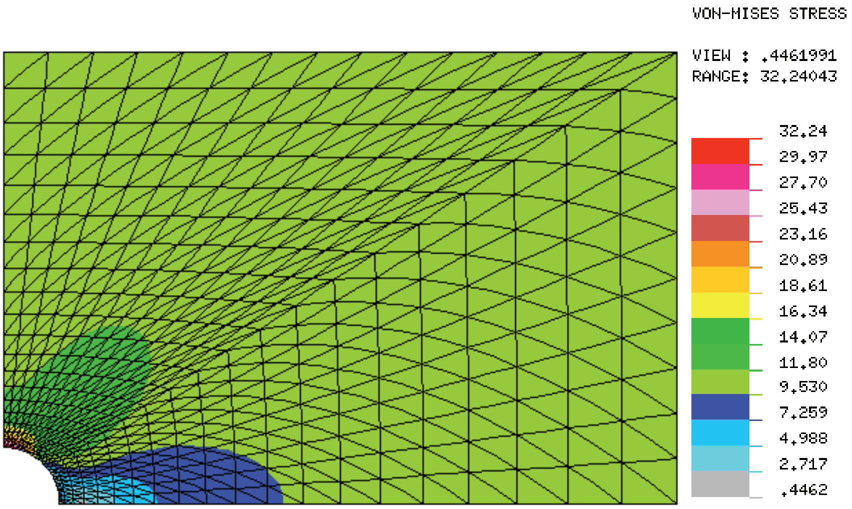
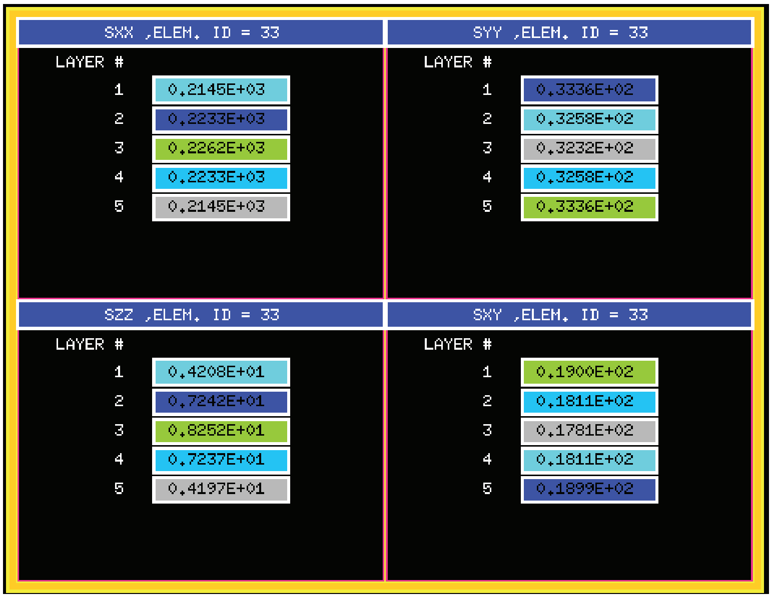


Fig. 2. The example of the stress concentration



```
SXX ,ELEM. ID = 33                 SYY ,ELEM. ID = 33
  LAYER #                            LAYER #
        1   0.2145E+03                     1   0.3336E+02
        2   0.2233E+03                     2   0.3258E+02
        3   0.2262E+03                     3   0.3232E+02
        4   0.2233E+03                     4   0.3258E+02
        5   0.2145E+03                     5   0.3336E+02

SZZ ,ELEM. ID = 33                 SXY ,ELEM. ID = 33
  LAYER #                            LAYER #
        1   0.4208E+01                     1   0.1900E+02
        2   0.7242E+01                     2   0.1811E+02
        3   0.8252E+01                     3   0.1781E+02
        4   0.7237E+01                     4   0.1811E+02
        5   0.4197E+01                     5   0.1899E+02
```

Fig. 3. The stresses at the hole edge and x=0 (compare with Fig.2).

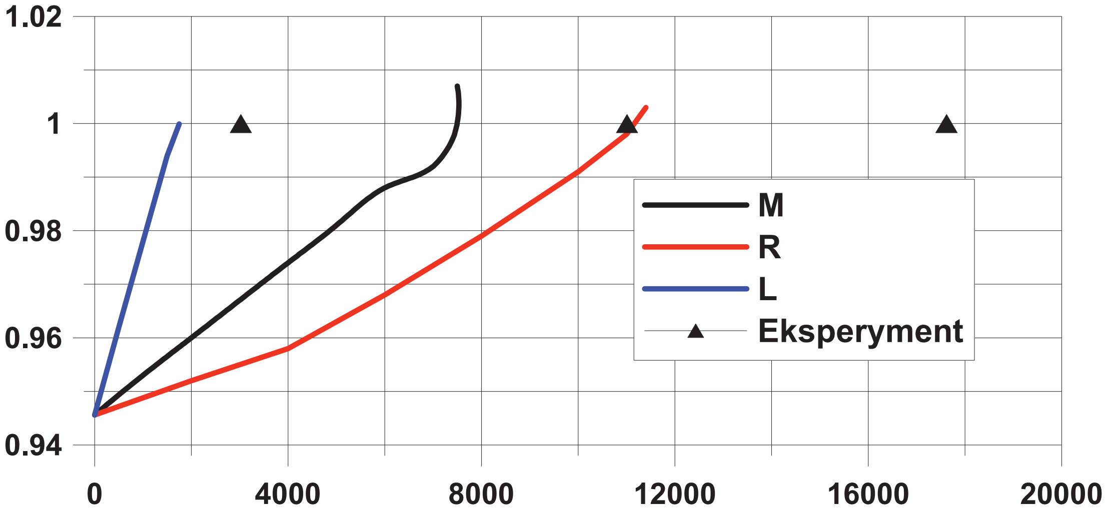


Fig. 4. Theoretical and experimental values of the damage parameter d

Using the presented in the section 2 procedures the damage parameter d variations with the number of cycles are plotted in Fig. 4. They are compared also with experimental results. The scatter of the latter values is even higher than theoretically established higher bounds.

3.2. Square plate subjected to an uniform shear

The next example deals with the analysis of fatigue behavior and damage of square plate made of aramid/epoxy resin. Similarly as previously the analyzed plate is made of five layers having identical thicknesses.

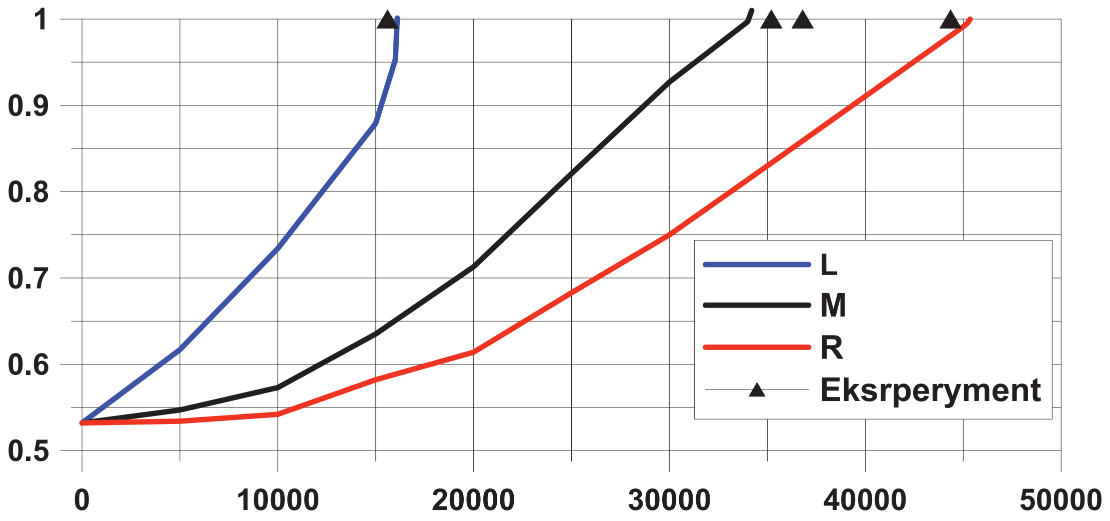


Fig. 5. Theoretical and experimental values of the damage parameter d

The damage (Last-Ply-Failure) occurs always in the upper ply. The slow (comparing with the previous example) development of fatigue damage demonstrates the existence of local delaminations and/or fibre debonding. The scatter of the fatigue life is quite high and varies from 16100 cycles to 45300 cycles. It is unsymmetric with respect to the mean (deterministic) value denoted by the letter M – see Fig. 5. The values of four experimental data lies almost exactly between upper and lower bounds. The better agreement can be achieved when the uncertainty of external loads would be taken into account since the uniformity of external shearing loads is an assumption only. In addition, boundary conditions do not reflect exactly the real experimental situation and set-up. However, the agreement between experiments and theory seems to be reasonably good.

Final fatigue damage is associated with fiber breaking in the fifth ply (Last-Ply-Failure) what is illustrated in Fig.6. It is necessary to add that the observed local buckling of the ply joined with the local delamination of the ply is the secondary effect being, in our opinion, the result of the fibre breaking. Usually, the local buckling occurs if the delamination area exceeds the critical one – the detailed explanation of this effect can be found e.g. in the work [7]. The numerical computations demonstrates that the above condition is not satisfied.

4. Concluding remarks

The present study is a practical tool for the engineering purposes dealing with the evaluation of fatigue life for real constructions. On the other, the above model of fatigue damage simulation can be easily adopted in the optimization problems that concerns maximization of fatigue life with respect to laminate configuration (understood in the sense of design variables). The next, still open problem, is connected with the total number of uncertain parameters that should be considered in order to describe with an acceptable accuracy the real behavior of engineering structures. However. It can be solved for each individual problem only.

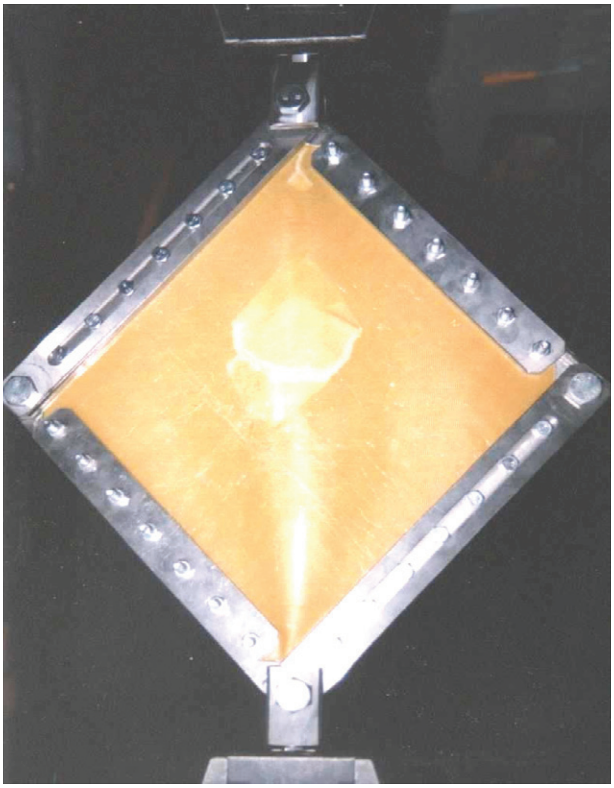


Fig. 6. The photograph of damaged plate (the experiment No 3).

References

[1] Reifsnider RL, Composite Materials Series: Fatigue of Composite Materials. Vol 4, Elsevier Science Publishing Company: New York; 1991.

[2] Talreja R, Fatigue of Fiber Composites, Materials Science and Technology: Structure and Properties of Composites, Vol 13, T.W. Chou, Ed., VCH Publishers, Weinheim, 1993.

[3] Composite Materials, Military Handbook 17, Materials Usage Design and Analysis, Vol 3, Department of Defense, Philadelphia, PA

[4] Degrieck, J, Van Paepegem, W., Fatigue damage modelling of fibre reinforced composite materials: review, Appl Mech Rev; 2001: 54 , 279–300.

[5] Reifsnider, K.L., Case, S.W., Damage Tolerance and Durability of Material Systems, Wiley-Interscience, 2002, New York.

[6] Muc A, Kędziora P., Application of Fuzzy Set Theory in Mechanics of Composite Materials, in Soft Computing in Textile Sciences (L.M.Sztandera and Ch.Pastore, eds), Physica-Verlag, Heidelberg, New York 2003, ss.16-50.

[7] Muc A., A fuzzy set approach to interlaminar cracks simulation problems, Int. J. Fatigue, 2002: 24; 419-427.

[8] Muc A., Nonlinear progressive delamination of composite plates under cyclic loadings, Proc. ICCM/12, Paris 1999.