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# MODELING OF FATIGUE DAMAGE EVOLUTION IN COMPOSITE STRUCTURES

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## 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; delamination; composite plates; fatigue life.

## INTRODUCTION

Two types of damage mechanisms can be distinguishes in composites under fatigue conditions: interlaminar damage and delamination. Propagation of interlaminar cracks cause the degradation of material properties and overall failure of the laminate. There are several types interlaminar damage of composite structures such a transverse matrix cracking, fiber-matrix debonding and fiber ruptures. Thus, main source of structural failures in composites is loss of adhesion between two adjacent laminas – delamination. Delaminations can arise as the result of interlaminar stress concentration or manufacturing errors. Phenomenon of delamination may be analyzed in the context of fracture mechanics (failure modes) or damage mechanics (loss of contact between the laminas) (Carneiro, 2000).

In the state-of-the-art there are many analysis and models of different composite structures delaminations.

Existing fatigue models are presented in several reviews article (Degrieck, 2001). The authors distinguish three main categories of fatigue modeling:

1. models, which use s-N curves or Goodman-type diagrams and presented some kind of fatigue failure criterion but ignored the actual degradation mechanism
2. phenomenological models, which calculated residual stiffness/strength
3. progressive damage models which include damage variables included measurable manifestations of damage (f.e. delamination size).

Carneiro and Savi (Carneiro, 2000) developed model of delamination in composite material for two structures: antisimmetric laminated tube and laminated bar. Model of the laminate had a finite thickness interlayer and estimations of interlaminar stresses from modified lamination theory. Numerical results agreed with experimental data available in literature.

Fatigue delamination growth in composites structures is one of the most important topic in delamination research. Several authors used finite element method and cohesive elements to analysis different mode of loading.

Roe and Siegmund (Roe, 2003) presented fatigue damage growth with adding a damage evolution equation for cyclic loading to cohesive law. This article described separately unloading and reloading processes in form of hysteresis loop between unloading and reloading paths. Cohesive zone model for the simulation of delamination propagation under high-cycle fatigue loading was developed by Turon et al. (Turon, 2007). The damage evolution laws were combined with the law of damage evolution for quasi-static loads within a cohesive element. Results showed that this model of damage is suitable for both quasi-static and high-cycle fatigue delamination.

A fatigue degradation law for cohesive interface elements is developed by Harper and Hallet (Harper, 2010) using Ls-Dyna finite element software. Delamination crack propagation under cycling loading was analyzed by cohesive zone interface element degradation law and it is implemented using three-dimensional interface elements. Validation is done with composite material fatigue fracture toughness tests: Double Cantliever Beam (Mode I) and End Notched Flexure (mode II and mixed mode bending).

Computational modeling of delamination and delamination growth in composites was presented with using nonlinear finite elements (Shen, 2001). This work showed dependence the direction of delamination growth with maximum strain energy release rate. The main role sublaminate lay-up in the distribution of local strain energy release rate components along the delamination front is showed.

Bennati and Valvo (Bennati, 2006) presented model of delamination growth under compressive fatigue loads in composite plates. The composite structure is modeled as two sublaminates partly bonded by an elastic interface, represented by continuous distribution of linear elastic springs. Authors applied a mode-dependent fatigue growth law to easily predict the number of cycles needed for a delamination to extend to a given length or for complete failure, for any values of the minimum and maximum applied loads.

Hu et al. (Hu, 2008) developed cohesive model for simulating delamination propagation under transverse loads. They analyzed DCB problem with 3D hybrid finite element for evaluating the delamination propagations on interfaces of composites.

Two parameters monitoring damage evolution during fatigue test of composites: stiffness and dissipated energy per cycle were chosen in work of Giancane and al. (Giancane, 2010). This article is showed that this parameters are very important to describe the state of composite damage. Monitoring this parameters showed three stages for all testes. First and third stages are characterized by rapidly degrades of composites but on the other hand second stages of damage has more slowly and steadily progress. This paper presented a study of fatigue effects with long glass fiber under tension-tension fatigue load. Residual life evaluation is tested by experimental non-destructive method.

Wu and Yao (Wu, 2010) developed existing damage models (Epaarachchi, 2005, Mao, 2002), which defined strength degradation, stiffness degradation and energy dissipation and they compared its with experimental data. Model presented in this work is based on the stiffness degradation rule of composite materials under fatigue loading.

Nilsson et al. (Nilsson, 2001) showed model of slander composite panel loaded in compression with artificial delaminations at two different depths (shallow and deep delamination). The study presented change in delamination depth induced a transition in the direction of delamination growth along with a change in the basic fracture modes and stability. Developed model included contact zone between delaminated members, calculation of energy release rate with fracture mode separation by approximate as well as a reliable method for general layups and moving mesh scheme to account for delamination growth.

Andersons et al. (Andersons, 2004) showed empirical model for the stress ratio effect on the fatigue delamination growth rate under both mode I and mode II loading. Fatigue damage is estimated by linear cumulative assumption. Comparison of prediction based of this model with results for different type of fiber reinforcement composite give reasonable results.

Kawashita and Hallett (Kawashita, 2012) used software LS-Dyna to present crack tip tracking algorithm for cohesive interface element analysis of fatigue delamination propagation in composite materials. This method is used to analysis laminates with central cut plies as well as a circular benchmark under cyclic loading. Cohesive zone models with using Ls-Dyna was proposed also by Elmarakbi et al. (Elmarakbi, 2009). Finite element code ANSYS is used in model delamination growth (Landry, 2012) in composite under fatigue loadings of varying amplitudes. Nikishkov et al. (Nikishkov, 2013) developed fatigue failure simulation methods for multidirectional carbon/epoxy laminates with FEA. Their model used stress-based fatigue failure criteria and fatigue damage accumulation.

One of the most useful method to detect damages in composites with delamination is Structural Health Monitoring (SHM) method (Muc, 2012). Muc and Stawiarski presented the study of SHM using to test delamination and damage parameters. Diamanti et al. (Diamanti, 2007) presented tests of large composite structures with using SHM. In this work defects of critical size caused from low-velocity impact were successfully identified.

Presented article is also an extension of the analysis of design of composite plates under cyclic loading, made by Muc et al. (Muc, 2000, Muc, 2002, Muc, 2010, Muc, 2011).

## FINITE ELEMENT MODELLING OF FATIGUE DAMAGE

In this article, 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:

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

where:

σ - the components of the stress tensor,

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) (Muc, 2003). 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.

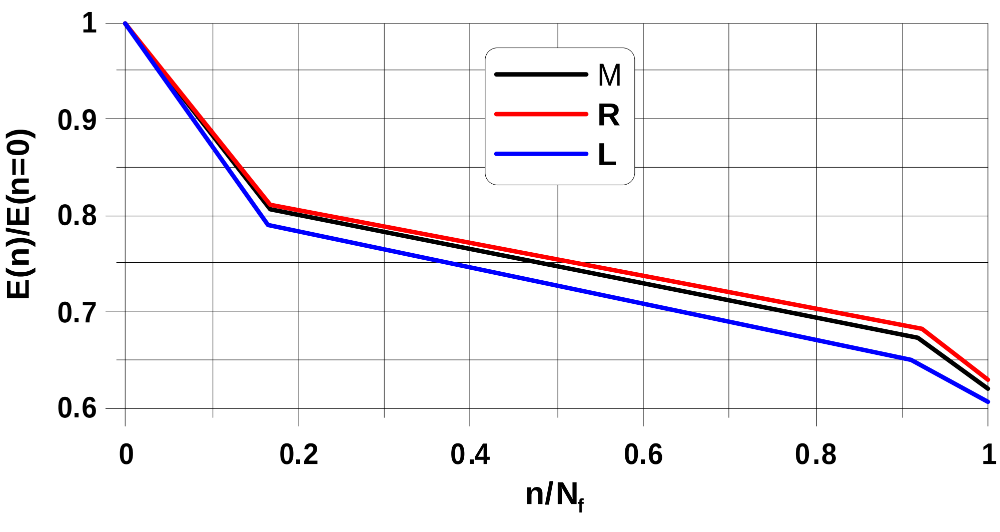


Fig.1 Stiffness degradation vs. number of cycles (mean–M, upper – R and lower – L values, respectively)

## FATIGUE LIFE PREDICTION

This article showed two models, which allows to estimate fatigue life prediction: rectangular plate with a centrally located hole and square plate subjected to an uniform shear.

*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. In the construction of finite element model it is used mesh adaptation. Each layer was discretized with the use of 3D FE having orthotropic properties and the corresponding values of the stresses are demonstrated in Table 1.

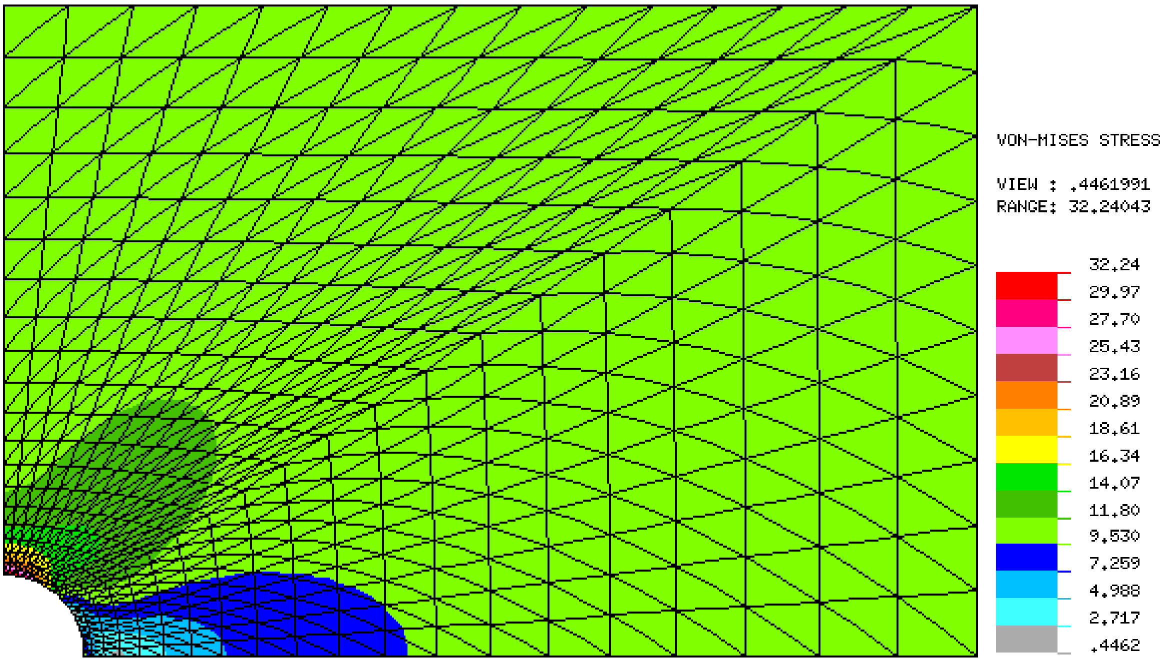


Fig.2 The example of the stress concentration

Table 1 The stresses at the hole edge and x=0, element id 33 (compare with Fig.2)

| **Layer Number** | $S_{xx}$ | $S_{yy}$ | $S_{zz}$ | $S_{xy}$ |
|---|---|---|---|---|
| **1** | 0,2145e+03 | 0,3336e+02 | 0,4208e+01 | 0,1900e+02 |
| **2** | 0,2233e+03 | 0,3258e+02 | 0,7242e+01 | 0,1811e+02 |
| **3** | 0,2262e+03 | 0,3232e+02 | 0,8252e+01 | 0,1781e+02 |
| **4** | 0,2233e+03 | 0,3258e+02 | 0,7237e+01 | 0,1811e+02 |
| **5** | 0,2145e+03 | 0,3336e+02 | 0,4197e+01 | 0,1899e+02 |

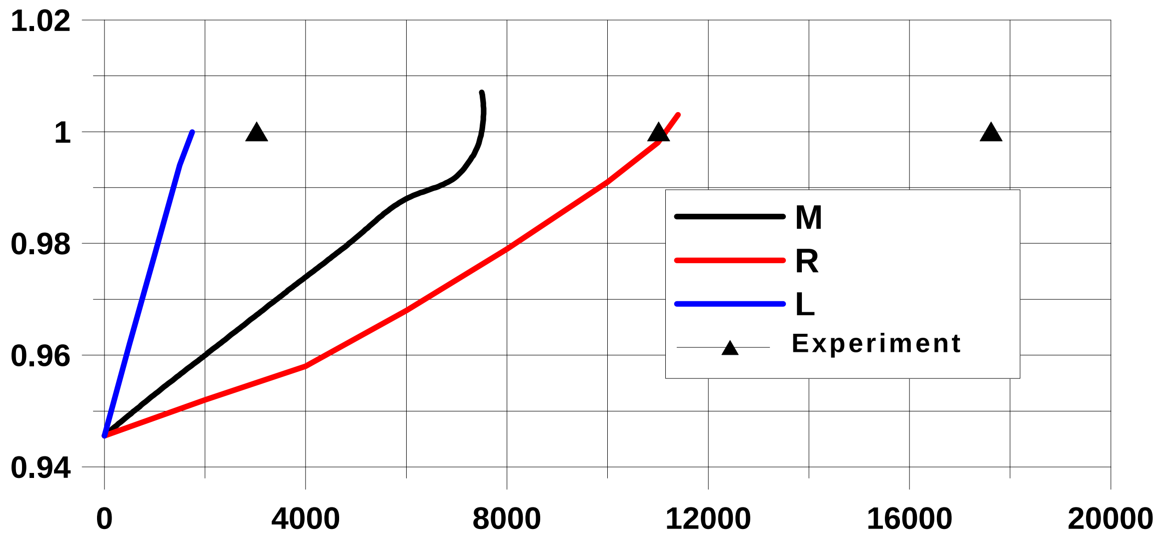


Fig.3 Comparison of theoretical and experimental values of the damage parameter d

Using the presented in the section 2 procedures the damage parameter d variations with the number of cycles are plotted in Fig. 3. They are compared also with experimental results. The scatter of the latter values is even higher than theoretically established higher bounds.

*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 analyzed structure this plate is made of five layers having identical thicknesses.

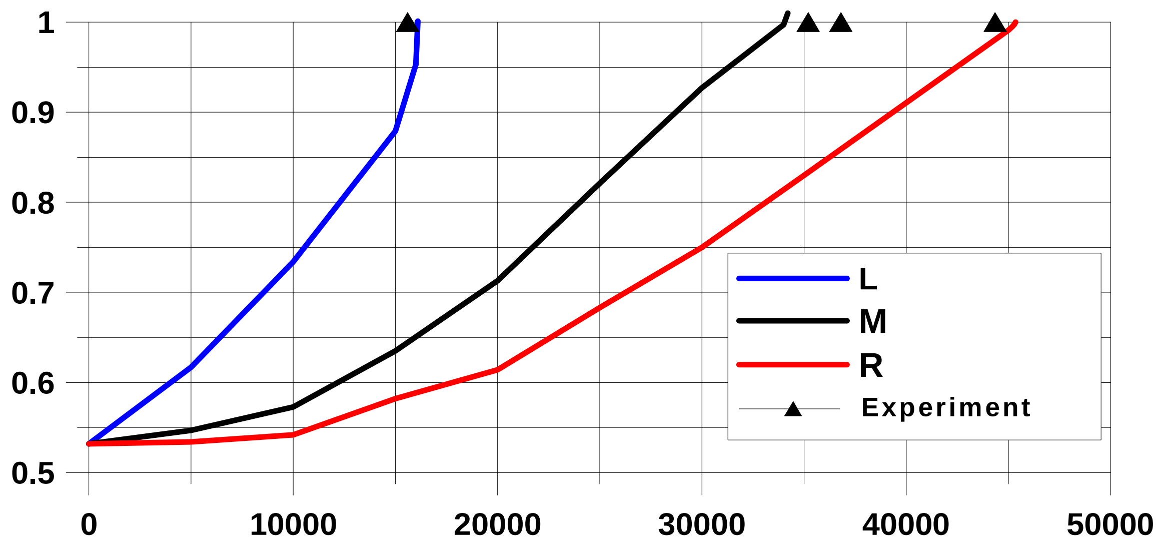


Fig.4 Comparison of theoretical and experimental values of the damage parameter d

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. 4. 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.

## RESULTS

Final fatigue damage is associated with fiber breaking in the fifth ply (Last-Ply-Failure) what is illustrated in Fig.5. 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 (Muc, 2002). The numerical computations demonstrates that the above condition is not satisfied.

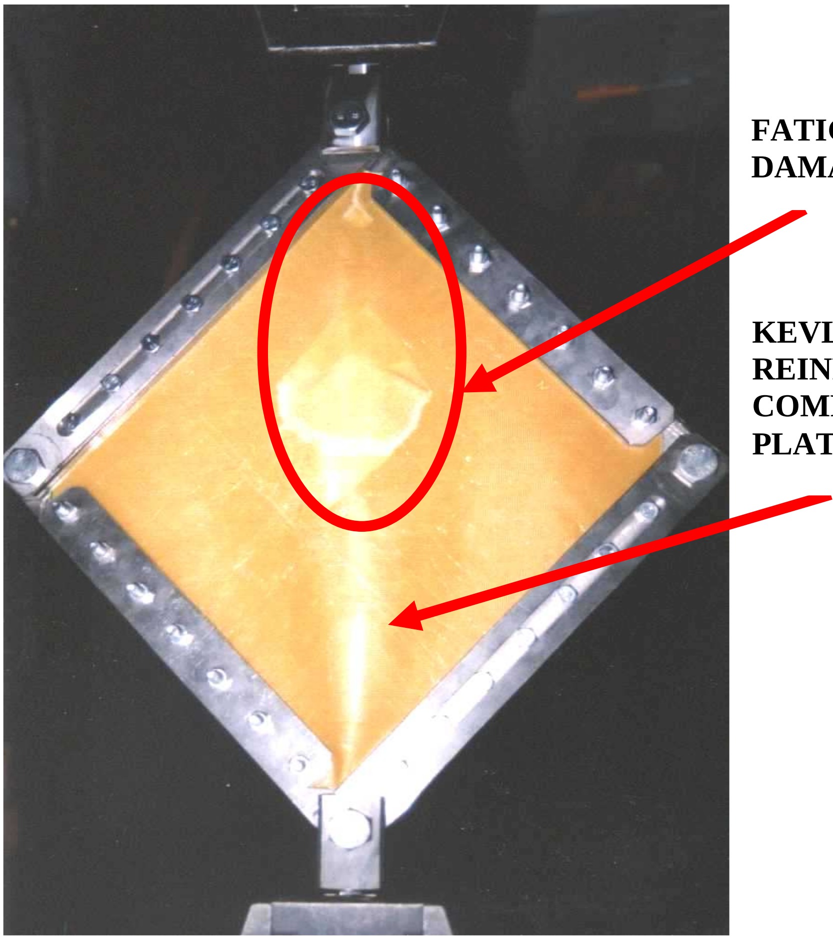


Fig.5 The photograph of damaged plate (the experiment No 3)

## CONCLUSIONS

The present study is a practical tool for the engineering calculations with the evaluation of fatigue life for real composite 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. It can be solved for each individual problem only because of a large variety of related problems.

## REFERENCES

Carneiro CAV, Savi MA, Modelling and simulation of the delamination in composite materials, Journal of Strain Analysis for Engineering Design, 35 (6), 2000, pp. 479-492.

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

Carneiro CAV, Savi MA, Modelling and simulation of the delamination in composite materials, Journal of Strain Analysis for Engineering Design, 35 (6), 2000, pp. 479-492.

Martinez X, Rastellini F, Oller S, Flores F, Oñate E, Computationally optimized formulation for the simulation of composite materials and delamination failures, Composites Part B: Engineering, Volume 42, Issue 2, 2011, Pages 134-144.

Roe KL, Siegmund T, An irreversible cohesive zone model for interface fatigue crack growth simulation, Engineering Fracture Mechanics, Volume 70, Issue 2, 2003, pp. 209-232.

Turon A, Costa J, Camanho PP, Dávila CG, Simulation of delamination in composites under high-cycle fatigue, Composites Part A: Applied Science and Manufacturing, Volume 38, Issue 11, 2007, pp. 2270-2282.

Harper PW, Hallett SR, A fatigue degradation law for cohesive interface elements – Development and application to composite materials, International Journal of Fatigue, Volume 32, Issue 11, 2010, pp. 1774-1787.

Shen F, Lee KH, Tay TE, Modeling delamination growth in laminated composites, Composites Science and Technology, Volume 61, Issue 9, pp. 1239-1251.

Bennati S, Valvo PS 2006, Delamination growth in composite plates under compressive fatigue loads, Composites Science and Technology, Volume 66, Issue 2, 2001, pp. 248-254.

Hu N, Zemba Y, Okabe T, Yan C, Fukunaga H, Elmarakbi AM, A new cohesive model for simulating delamination propagation in composite laminates under transverse loads, Mechanics of Materials, Volume 40, Issue 11, 2008, pp. 920-935.

Giancane S, Panella FW, Dattoma V, Characterization of fatigue damage in long fiber epoxy composite laminates, International Journal of Fatigue, Volume 32, Issue 1, 2010, pp. 46-53.

Wu F, Yao W, A fatigue damage model of composite materials, International Journal of Fatigue, Volume 32, Issue 1, 2010, pp. 134-138.

Epaarachchi JA, Clausen PD, A new cumulative fatigue damage model for glass fibre reinforced plastic composites under step/discrete loading, Composites Part A: Applied Science and Manufacturing, Volume 36, Issue 9, 2005, pp. 1236-1245.

Mao H, Mahadevan S, Fatigue damage modelling of composite materials, Composite Structures, Volume 58, Issue 4, 2002, pp. 405-410.

Nilsson F, Asp LE, Sjögren A, On transition of delamination growth behaviour for compression loaded composite panels, International Journal of Solids and Structures, Volume 38, Issues 46–47, 2001, pp. 8407-8440.

Andersons J, Hojo M, Ochiai S, Empirical model for stress ratio effect on fatigue delamination growth rate in composite laminates, International Journal of Fatigue, Volume 26, Issue 6, 2004, pp. 597-604.

Kawashita LF, Hallett SR, A crack tip tracking algorithm for cohesive interface element analysis of fatigue delamination propagation in composite materials, International Journal of Solids and Structures, Volume 49, Issue 21, 2012, pp. 2898-2913.

Elmarakbi AM, Hu N, Fukunaga H, Finite element simulation of delamination growth in composite materials using LS-DYNA, Composites Science and Technology, Volume 69, Issue 14, 2009, pp. 2383-2391.

Landry B, LaPlante G, Modeling delamination growth in composites under fatigue loadings of varying amplitudes, Composites Part B: Engineering, Volume 43, Issue 2, 2012, pp. 533-541.

Nikishkov Y, Makeev A, Seon G, Progressive fatigue damage simulation method for composites, International Journal of Fatigue, Volume 48, 2013, pp. 266-279.

Muc A, Stawiarski A, Identification of damages in composite multilayered cylindrical panels with delaminations, Composite Structures, Volume 94, Issue 5, 2012, pp. 1871-1879.

Diamanti K, Soutis C, Hodgkinson JM, Piezoelectric transducer arrangement for the inspection of large composite structures, Composites Part A: Applied Science and Manufacturing, Volume 38, Issue 4, 2007, pp. 1121–1130.

Muc A, Design of composite structures under cyclic loads, Computers and Structures 76 (1), 2000, pp. 211-218.

Muc A, A fuzzy set approach to interlaminar cracks simulation problems, International Journal of Fatigue 24 (2-4), 2002, pp. 419-427.

Muc A, Kędziora P, Krawiec Z, Damage analysis and monitoring of composite materials and structures under cyclic loads, Procedia Engineering 10, 2011, pp. 1315-1320.

Muc A, Stawiarski A, Wave propagation in composite multilayered structures with delaminations, Mechanics of Composite Materials 48 (1), 2012, pp. 101-106.

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