Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 213 (2018) 17–24

Procedia Engineering

www.elsevier.com/locate/procedia

7th International Conference on Fatigue Design, Fatigue Design 2017, 29-30 November 2017, Senlis, France

Fatigue damage and stiffness evolution in composite laminates: a damage-based framework

Paolo A. Carraro, Marino Quaresimin*

Department of Management and Engineering - University of Padova, Stradella S.Nicola 3 - 36100 VICENZA – ITALY

Abstract

A damage-based design procedure has been developed by the authors to predict the damage evolution and the stiffness degradation in polymeric composite laminates under fatigue loading. For a safe and reliable design against fatigue degradation and failure, the initiation of the main damage mechanisms (off-axis cracks, delamination and fiber failure) as well as their evolution are considered and suitable models are proposed for the quantitative assessment of the lifetime associated to each mechanism. In parallel, the stiffness degradation deriving from the damage evolution over the fatigue life is properly described. After the illustration of the overall damage-based strategy, the paper discusses in details the analysis and modelling of the off-axis crack initiation and propagation. The initiation of cracks in the off axis plies has been proved to be the consequence of a damage process occurring at the microscopic scale since the early stages of fatigue. On this basis, crack initiation prediction is based on the use of local stress parameters: Local Hydrostatic Stress, LHS, and Local Maximum Principal Stress, LMPS, depending on the local degree of multiaxiality of the stress state and accounting for the statistical distribution of the local laminate strength. The propagation phase is then quantified by using a conventional fracture mechanics approach. The model has been implemented in a Matlab procedure for the quantitative evaluation of the crack density in each ply of a laminate during its entire fatigue life. The knowledge of the crack density trend allows the description of the laminate stiffness evolution taking advantage of another model recently developed by the authors, valid for a generic laminate configuration and accounting for the interaction between cracks in the neighbouring plies.

Keywords: Composites; Fatigue; Damage mechanisms; Stiffness degradation; Damage modelling

* Corresponding author. Tel.: +390444998723.
E-mail address: marino.quaresimin@unipd.it

10.1016/j.proeng.2018.02.003

1. Introduction

Composite materials are excellent candidates for the development of reliable lightweight components and structures complying, for instance, with the needs of decreasing fuel consumptions in the transportations field or increasing the specific energy production in the wind energy field.

Most of structural components manufactured with composite materials are subjected during their in-service life to cyclic loadings, which might lead to a progressive damage, a consequent loss of stiffness and residual strength and, eventually, to the final failure. The "design against fatigue" is therefore fundamental to improve the reliability of composite structural parts.

To meet the demand of fatigue design tools for composite structures, the Composite Group at DTG-University of Padova is working since several years to the development of a design framework suitable to predict the initiation of damage, its evolution and the final failure of composites under cyclic loadings [1-11].

As a starting point of the discussion, it is important to clarify the concept of "design against fatigue", which can be meant in different ways depending on the requirements of the part under design:

i) design against crack initiation (no damage);
ii) design against stiffness degradation (damage tolerant design);
iii) design against final failure.

In applications like fuel and pressure vessels, fuel rails or other, the onset of damage has to be avoided to satisfy the safety requirements. In this case, the capability to predict the life spent for the initiation of the first crack is essential. In other cases like automotive composite frames, turbine blades, bicycle cranks or composite rims, the global stiffness can be the design driver. Due to the several fatigue damage mechanisms, structural composite components can lose up to 30-40% of their initial stiffness (depending on lay-up and load conditions) much before the final failure. Therefore, for a more reliable and cost-effective design, it is important in these cases to estimate the stiffness degradation under the specific loading conditions [6].

When only the load bearing capability of the part is of interest, the final failure (separation into two or more pieces) is the design target.

In the authors' opinion, the only way to deal with such a complicated phenomenon and provide suitable and reliable design tools for the three targets above is to develop models and criteria based on the actual damage mechanisms occurring at the different scales.

As shown in several works in the literature [2, 4, 7, 10, 12-16] the first observable damage event is the initiation and subsequent propagation of off-axis cracks. The crack density increases until reaching a sort of plateau that corresponds to the fading of the crack multiplication and the saturation of the crack density. In this phase, it is possible to observe a significant degradation of the laminate stiffness. The saturation is slightly preceded or followed by the initiation of delaminations triggered by the presence of the off-axis cracks. Delaminations propagate at the plies' interface causing a further stiffness degradation. These mechanisms are not directly responsible for the final failure, however they indeed promote the failure of the fibres until a critical condition is reached, in which the load bearing plies are not able anymore to carry the applied load. This corresponds to the final failure of the laminate.

According to this scenario, a reliable model for the prediction of the fatigue damage initiation and evolution should be able to describe (Figure 1):

- The cycles spent for the crack initiation;
- The crack density evolution (multiple crack initiation and propagation) until the saturation;
- The cycles spent for the delamination initiation and propagation;
- The cycles spent for the final failure, driven by the fibre breaks.

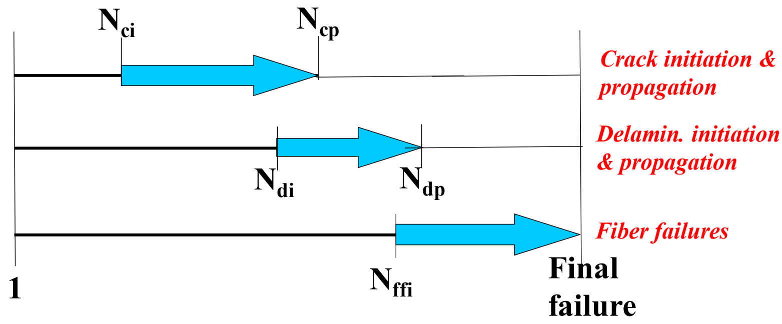


Fig. 1. Schematic of the damage evolution e modelling strategy for the life assessment of composite laminates

In the next sections, the modelling strategy recently proposed by the authors is presented, concerning the crack initiation, propagation and multiplication. Then the ongoing activity the authors are carrying out to assess the problem of delaminations is briefly illustrated.

2. Criteria for crack initiation and propagation

2.1. Criterion for crack initiation

A model for predicting the cycles spent for crack initiation in UD composites been presented by the authors [5]. As a starting point, it is important to remember that in the plies of a composite laminate the stress state is, in general, always multiaxial, either due to external loads in multiple directions or to the material anisotropy. The criterion proposed by the authors takes into account the local multiaxial stress state on the basis of experimental observations of the damage mechanisms occurring at the microscopic scale. It was observed that, if the shear stress in a ply is high enough with respect to the transverse stress, as for instance in a 45° ply, the initiation of an off-axis crack is due to the onset and coalescence of micro-cracks as shown in Figure 2 [3].

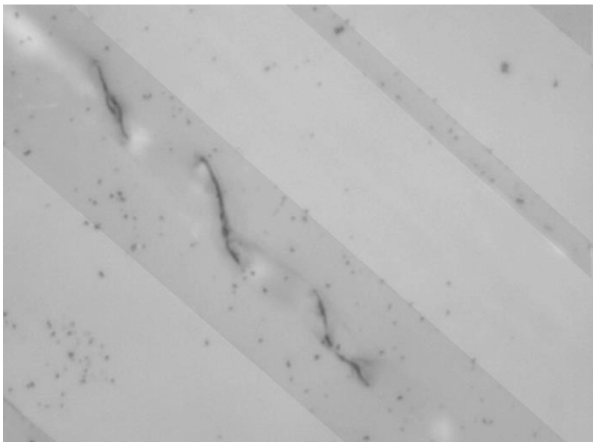


Fig. 2. Example of inclined inter-fiber micro-cracks in the matrix of a 45° ply [3]

It was also proved that the orientation of these micro-cracks, defined *local nucleation plane*, is normal to the Local Maximum Principal Stress (LMPS) in the matrix [3]. Accordingly, the authors proposed to use the LMPS as the driving parameter to predict the crack initiation under these conditions [5]. If the shear stress is much lower than the transverse stress, the micro-scale damage is instead driven by the Local Hydrostatic Stress (LHS), as shown by

Asp et al. under static loading [17]. Therefore, the LHS was proposed to predict the crack initiation when the shear to transverse stress ratio (λ_{12}) is lower than a certain threshold [5]. The LHS and LMPS are local parameters that can be calculated by means of Finite Element (FE) analyses of a fibre-matrix unit cell with proper boundary conditions as extensively illustrated in [5].

The criterion was further validated against several crack initiation data from the literature, showing a very good agreement [5]. An example is shown in Figure 3, where crack initiation results in glass/epoxy tubes are presented in terms of the transverse stress (3a), the LHS (3b) and LMPS (3c) for different biaxiality ratios. All the data are clearly seen to collapse into two scatter bands, to be used for the crack initiation prediction when the biaxiality ratio is higher or smaller than a threshold equal to 0.5, for the material under analysis.

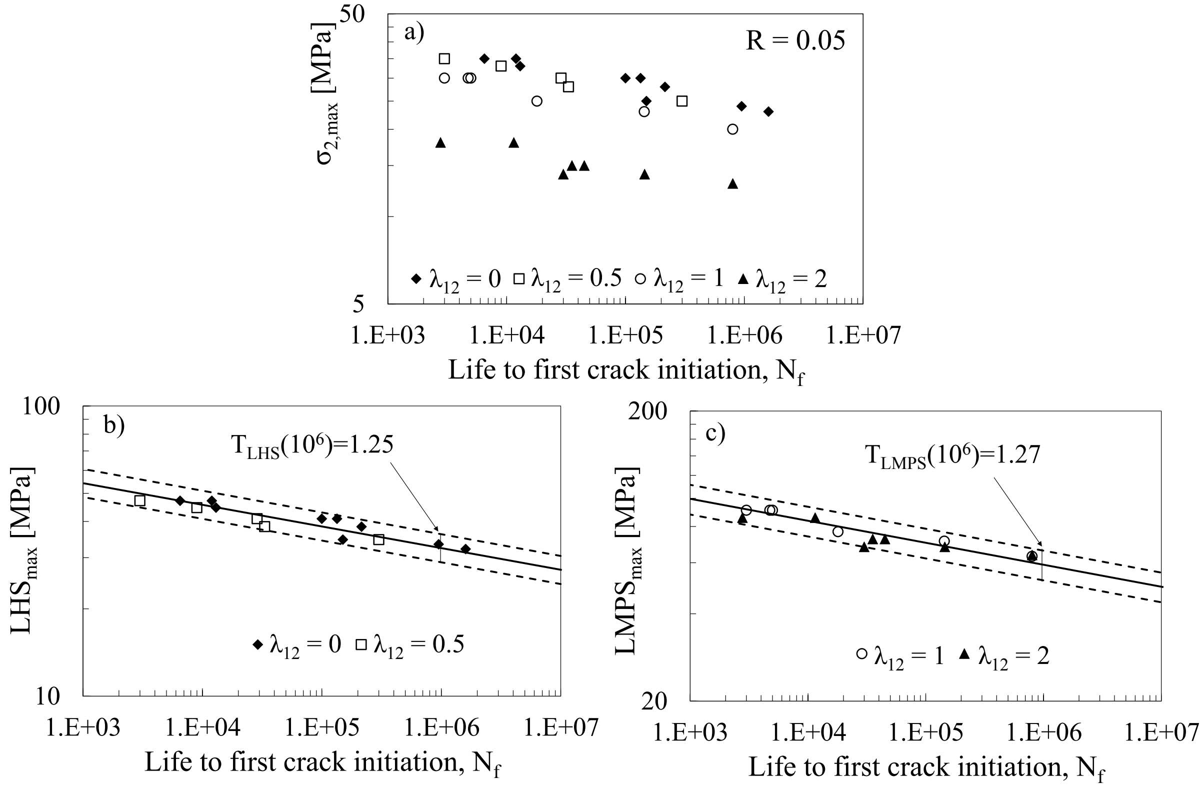


Fig. 3. First crack initiation results for glass/epoxy tubes [2]: maximum a) cyclic transverse stress, b) LHS and c) LMPS against the number of cycles for first crack

2.2. Criterion for crack propagation

After initiation, off-axis crack start propagating along the fibres' direction. It was shown that the crack growth rate can be predicted from the Energy Release Rate (ERR) through a Paris-like law [2, 4, 7, 10]. It is important to mention that the ERR for tunnelling cracks does not depend on the crack length, so that their propagation is referred to as a steady state phenomenon [4]. Conversely, the ERR depends on the crack density. In fact, the higher the crack density, the lower is the ERR because of a local shielding effect at the crack tip [4].

The steady state value of the ERR can be easily calculated, as a function of the crack density, by means of analytical models (see Ref. [6] and the references quoted therein) or FE analyses.

In general, the off-axis crack propagation occurs in mixed I+II mode conditions, so that the Paris-like law should be expressed in terms of an "equivalent" ERR, G_{eq}, suitable to account for the mode mixity MM = G_{II}/G_{tot}. It is also known that the propagation of an interface crack in mixed mode conditions is driven by the mode I component only when the loading conditions are near to mode I. The equivalent ERR G_{eq} can therefore be assumed equal to G_I for mode mixity MM lower than a certain value (around 0.5) (see [2, 18] and the references quoted therein).

In the case of a mode II dominated scenario, the micro-scale mechanism of crack propagation changes, as reported in [3, 18]. The authors are currently working on the definition of a damage-based equivalent ERR to be used in these conditions. However, the use of the total ERR G_{tot} as equivalent ERR G_{eq} has also been proved to work satisfactorily [11] when MM is higher than 0.5 and lower than 1.

3. A model for the crack density evolution

The crack initiation criterion described in the previous section, combined with a simple stress analysis tool such as the classical lamination theory (CLT), can be used for predicting the first crack initiation within a ply in a laminate, once a certain probability of survival is given. The prediction of the crack density evolution is instead much more complicated and it was approached by the authors according to the following basic ideas [11]:

- The initiation of multiple cracks can be treated using S-N curves for crack initiation in terms of the local parameters LHS and LMPS. At this point, the statistical distribution of the fatigue strength to crack initiation has to be considered, this being the only explanation for having crack initiation at different number of cycles;
- The CLT is not suitable for the stress analysis of a laminate in the presence of cracks. To overcome this limitation, Carraro and Quaresimin developed a suitable stress re-distribution model [6] based on an *optimal shear lag* analysis;
- The off-axis crack growth rate can be predicted with a Paris-like curve as a function of the energy release rate, that can be calculated on the basis of the actual crack density.

The model for the crack density prediction consists in the simulation of the fatigue life by progressively increasing the number of cycles by steps ΔN.

For a given step of fatigue cycles ΔN, and for every off-axis layer, the following steps are taken:

1) Calculation of the stresses in each layer, considering the stress re-distribution due to the presence of cracks.

2) Calculation of local stresses by means of a fibre matrix unit cell subjected to periodic boundary conditions (see the stress concentration factors defined in Ref. [5]).

3) Calculation of the LHS and LMPS.

4) According to the multiaxial condition, calculation of the total density of nucleated cracks, by using the LHS of LMPS master curves and the associated statistical distribution of the fatigue strength for the material considered.

5) Analysis of the crack propagation phase to compute the length of all the nucleated cracks.

6) Increasing the number of cycles of a quantity ΔN and repeat steps 1)-6) until the required number of cycles or the crack density saturation is reached.

An example of the validation of the crack density prediction model is shown in Figure 4a, for a glass/epoxy laminate tested at different load levels [11].

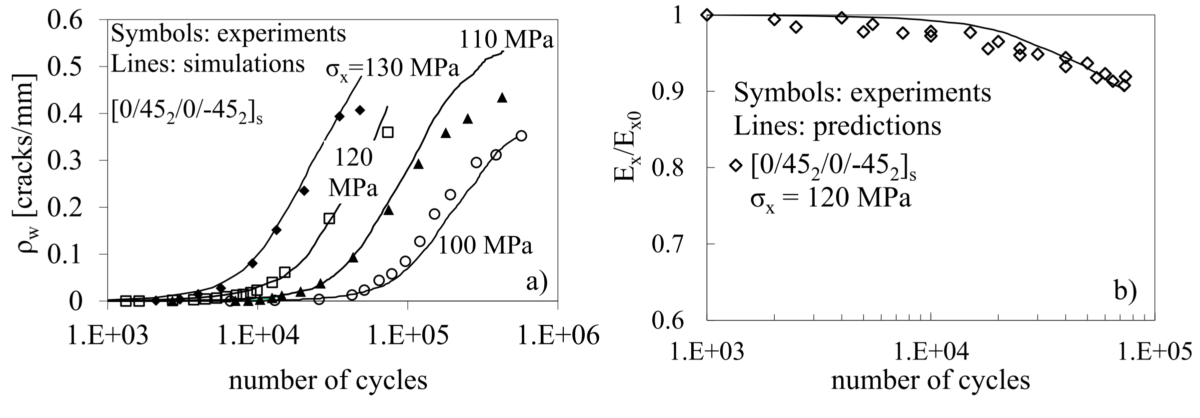


Fig. 4. Predicted and experimental trends of a) the crack density evolution and b) the stiffness degradation

Once the crack density is known in all the plies of a laminate, it can be used as input for a stiffness degradation model like, for instance, that recently developed by the authors [6]. This model was developed for generic laminates with cracks in one or more plies and it accounts for the interaction between cracks in different layers. An example of the application is given in Figure 4b, where, for the same laminate, the predicted stiffness degradation is compared to the experimental measurements, showing a very good agreement.

4. Analysis of the delamination onset and propagation

After crack initiation, delamination starts to grow from the crack tips causing a further, even if typically lower, stiffness degradation and playing an important role in the fibre failure process.

The authors have recently carried out a dedicated experimental program to investigate delamination initiation and propagation during fatigue tests on glass/epoxy cross-ply laminates. The Young modulus was measured throughout the fatigue tests, obtaining normalized trends as that shown in Figure 5. Optical observations and in situ imaging allowed the evolution of crack density and delamination ratio, meant as the ratio between the delaminated area and the total area of the gage length, to be measured. Typical trends are shown again in figure 5.

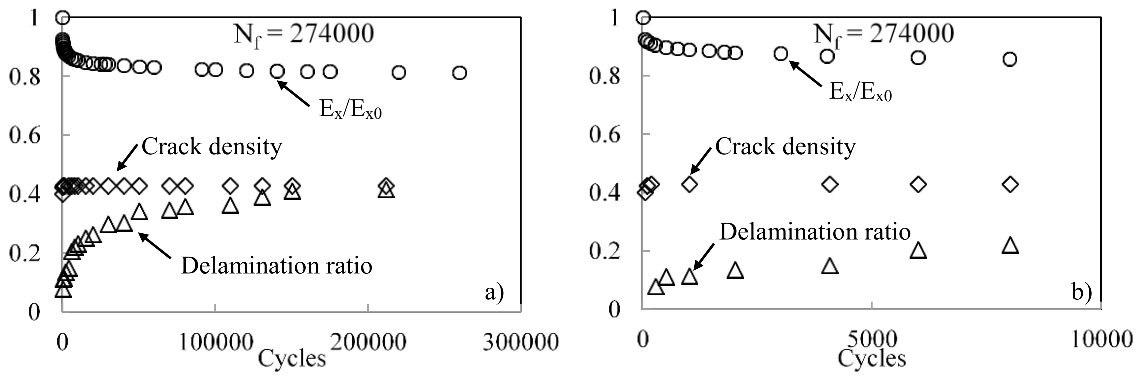
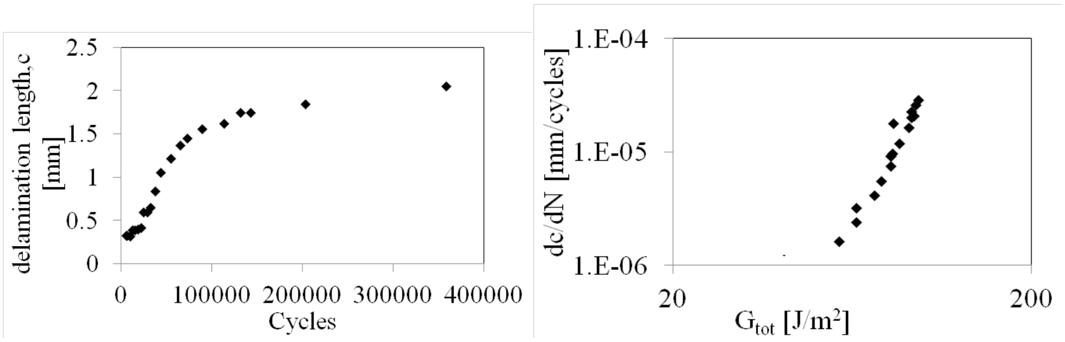


Fig. 5. a) Normalized Young modulus, crack density and delamination ratio for a glass/epoxy $[0/90_2]_s$ laminate tested with a global laminate stress of 120 MPa; b) zoom of the first 10000 cycles

The crack density saturation and the initiation of delaminations were seen to occur in very early stages of the fatigue life (1-2%), so that the cycles spent for these phenomena could be even neglected in the cases when the target of the analysis is the estimation of the total fatigue life. Also the largest part of the stiffness drop is concentrated in the early stages of fatigue life, being essentially related to the crack density evolution. On the other hand, the delamination growth is associated to a limited stiffness reduction only. In spite of this, the analysis and modelling of delamination initiation and propagation is of fundamental importance because of the effects of these mechanisms in terms of stress redistribution and fibre failure in the load bearing plies.

After the measure of the delamination length during the fatigue tests (figure 6a), the relevant values of the mode I and II Energy Release Rate (ERR) were computed with Finite Element analyses and the VCCT technique, and



eventually related to the delamination growth rate. It was thus possible to define a Paris-like curve (Figure 6b) relating the growth rate to the mode II energy release rate (the mode I contribution is very limited or absent, at least under tensile loadings). This approach allows the delamination length to be predicted as a function of the number of cycles.

Fig. 6. a) Example of delamination length evolution and b) relevant Paris-like curve

5. Conclusions

The fatigue behavior of composite laminates under fatigue loading is characterized by a progressive and multiscale damage evolution. It was shown by the authors that the first event of damage, in the presence of enough shear stress, is the initiation of micro-cracks in the matrix between the fibres. Their accumulation and coalescence lead to the initiation of off-axis crack, that propagate in a steady state manner along the fibres direction. It was proved that this kind of micro-scale damage evolution is driven by the Local Maximum Principal Stress (LMPS) in the matrix. Conversely, in nearly transverse tension conditions (when the shear stress is very low), the microscopic damage evolution is driven by the Local Hydrostatic Stress (LHS). Accordingly, a criterion was proposed by the authors, to predict the fatigue crack initiation under multiaxial stress states, based on the use of these two local parameters. This criterion can be used as well to predict the entire evolution of the crack density. In fact, an innovative model was proposed by the authors which accounts also for the statistical distribution of the fatigue strength and the stress re-distribution in the presence of cracks. The crack density predicted through this model can then be used as in input for a stiffness degradation model, to estimate the laminate stiffness degradation. The resulting tool is fundamental in a damage tolerant design against fatigue.

To predict the cycles spent for the final separation of a laminate, the mechanisms of the initiation ad propagation of delaminations, as well as the fibres' failure, must be addressed. An experimental campaign on cross-ply laminates was carried out for this purpose, revealing that the cycles spent for initiating the delaminations and saturating the crack density is about 1-2% of the total fatigue life. It was proved that a Paris-like can be adopted for predicting the propagation of delamination, which is another fundamental step for the estimation of the total life. To reach this final target, the influence of off-axis cracks and delamination on the development of fibre-related damage must be modelled. The authors are currently working in this direction, to provide a damage-based approach for the prediction of damage initiation, evolution and the final failure of industrial composite components.

References

[1] M. Quaresimin, P.A Carraro, On the investigation of the biaxial fatigue behaviour of unidirectional composites, Compos. Part B 54 (2013) 200-208.

[2] M. Quaresimin, P.A. Carraro, Damage initiation and evolution in glass/epoxy tubes subjected to combined tension-torsion fatigue loading, Int. J. Fatigue 63 (2014) 25–35.
[3] M. Quaresimin, P.A. Carraro, L. Maragoni, Early stage damage in off-axis plies under fatigue loading, Compos. Sci. Technol. 128 (2016) 147-154.
[4] M. Quaresimin , P.A. Carraro, L. Pilgaard Mikkelsen, N. Lucato, L. Vivian, P. Brøndsted, B. F. Sørensen, J. Varna, R. Talreja, Damage evolution under internal and external multiaxial cyclic stress state: a comparative analysis, Compos. Part B 61 (2014) 282-290.
[5] P.A. Carraro, M. Quaresimin, A damage based model for crack initiation in unidirectional composites under multiaxial cyclic loading, Compos. Sci. Technol. 99 (2014) 154–163.
[6] P.A. Carraro, M. Quaresimin, A stiffness degradation model for cracked multidirectional laminates with cracks in multiple layers, Int. J. Solids Struct. 58 (2015) 34-51.
[7] P. A. Carraro, L. Maragoni, M. Quaresimin, Influence of load ratio on the biaxial fatigue behaviour and damage evolution in glass/epoxy tubes under tension-torsion loading, Composites Part A 78 (2015) 294–302.
[8] M. Quaresimin, Multiaxial fatigue testing of composites: from the pioneers to future directions, Strain 1 (2015) 16-29.
[9] M. Quaresimin , A damage-based strategy for fatigue design of composite structures, 37th international Risoe Symposium on Material Science- Understanding performance of composite, 5-8 September 2016 Roskilde (Denmark).
[10] L. Maragoni, P.A. Carraro, M. Peron, M. Quaresimin, Fatigue behaviour of glass/epoxy laminates in the presence of voids, Int. J. Fatigue 95 (2017) 18–28.
[11] P. A. Carraro, L. Maragoni, M. Quaresimin, Prediction of crack density evolution in multidirectional laminates under fatigue loading, Compos. Sci. Technol. 145 (2017) 24-39.
[12] J. Tong, F. J. Guild, S. L. Ogin, P. A. Smith, On matrix crack growth in quasi isotropic laminates-I. Experimental investigation, Compos. Sci. Technol. 57 (1997) 1527-1535.
[13] J. Bartley-Cho, S. G. Lim, H. T. Hahn, P. Shyprykevich, Damage accumulation in quasi-isotropic graphite/epoxy laminates under constant-amplitude fatigue and block loading, Compos. Sci. Technol. 58 (1998) 1535-1547.
[14] A.W. Wharmby, F. Ellyin, Damage growth in constrained angle-ply laminates under cyclic loading, Compos. Sci. Technol. 62 (2002) 1239- 1247.
[15] K. Tohgo, S. Nakagawa, K. Kageyama, Fatigue behaviour of CFRP cross-ply laminates under on-axis and off-axis cyclic loading, Int. J. Fatigue 28 (2006) 1254-1262.
[16] S. Adden, P. Horst, Stiffness degradation under fatigue in multiaxially loaded non-crimped-fabrics, Int. J. Fatigue 32 (2010) 108-122.
[17] L.E. Asp, L.A. Berglund, R. Talreja. Prediction of matrix initiated transverse failure in polymer composites. Compos. Sci. Technol. 56 (1996) 1089-1097.
[18] P.A. Carraro, G. Meneghetti, M. Quaresimin, M. Ricotta, Crack propagation analysis in composite bonded joints under mixed mode (I+II) static and fatigue loading: experimental investigation and phenomenological modelling, J. Adhesion Sci. Technol. 27 (2013) 1179-1196.