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Numerical tool with mean-stress correction for fatigue life estimation of composite plates

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ABSTRACT

In this paper a numerical fatigue assessment method is presented for the cyclic life estimate of composite plates via continuous strength and stiffness degradation calculation combined with mean stress correction and multiaxial fatigue failure criterion check. The most value-adding features of this methodology are the simultaneous monitoring of mean stress dependent strength and stiffness degradation over successive cycles using empirical interaction type degradation rules. The procedure has also been coded in a form of a complex automated workflow where the actual stress state for each ply is evaluated by appropriate Finite Element assessment and the residual strength and the ply-based stiffness analysis combined with failure check is executed in an external Python routine. The practical use of the automated workflow is presented via the virtual analysis of load- and strain-controlled tension-tension type fatigue tests of unidirectional specimens as well as a cross-ply open-hole test piece. Based on the results the expected damage mechanism is discussed.

1. Introduction

The ever-growing need in industry to improve efficiency and performance of products by preserving or even reducing the overall cost has led to a continuous development of materials with better strength to weight ratio than their conventional counterparts. The most relevant representatives of a new material generation nowadays are the continuous fiber reinforced plastics (FRPs). In highly demanding or exclusive industry sectors such as aerospace, race car or yacht manufacturing the introduction of these type of materials as the base material of structural parts had commenced decades ago even before fully robust characterization methods have been developed.

The faster spread of FRPs contrary to their exceptional structural performance per unit mass is delayed by numerous obstacles to cope with such as: less productive and in general more expensive and labor-intensive manufacturing methods, as well as high level of uncertainties on the static, dynamic and cyclic material properties which are the result of the inhomogeneous structure that couples very different constituents. The high variation in the material response and complex structure leads to a wide range of different interpretations and thus, a high number of – sometimes contradicting – material models especially in terms of static, cyclic strength and impact damage.

There are a number of comprehensive works providing a deep insight into the most important drivers of the fatigue assessment of composites such as: degradation of stiffness and strength, estimation of fatigue strength, effect of mean stress and statistical aspects etc. [1,2]. Due to the complexity and the continuously changing degradation phases it is also important to be aware of the main

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cracking mechanisms on a micro scale and to understand the relationship between the spatial distribution of those flaws and the global stiffness degradation as this is the basic assumption of some failure models [1–3]. Further basic inputs affecting the fatigue behavior of a composite ply are: fiber and matrix material, local heat emission due to the degradation process, strengthening fiber structure and orientation, fiber volume fraction etc. [2,3]. Based on the considerations above a huge variety of different fatigue life prediction methods have been elaborated in the last decades that are collected in [18]. Another review on the state-of-the-art on composite fatigue assessment techniques, fatigue phenomena, testing aspects and the relevance of damage assessment approaches is given in Alderliesten's work [32].

A fundamental feature of any fatigue model is the underlying approach to find the fatigue strength of material. There is a huge variety of approaches available in literature aiming to find that state when any characteristic of the composite reaches a limit that can be used as an indicator for fatigue failure. Chambers et al. [5] purely considers the stiffness degradation for this purpose. In the work of Yoshioka et al. [6] a shear-lag model was used to predict the modulus degradation as fatigue failure indicator as it was evaluated by Lee and Daniel [20]. In order to make this model work on fabrics it was extended by a Classical Laminate Theory (CLT) based crimp model as per [21] to consider the effect of yarn debonding. A very commonly used method to predict fatigue failure from stiffness degradation is the interaction law introduced by Adam et al. [30]. The most outstanding feature of this approach is the fact that since it provides a dimensionless relationship between cycles and stiffness it collapses all stiffness degradation curves at any stress level and fatigue life onto one master curve. It was further enhanced by Shokrieh et al. [29] by a combined stiffness degradation model for cross-ply laminates which changes method from the interaction rule to a sudden modulus decrease to zero if the sudden death behavior is anticipated to happen for the 90°plies. There are a number of stiffness degradation-based fatigue models available for woven structures such as Mao's work [7]. In the research of Laurin et al. [24] the stiffness degradation rule was derived upon thermodynamics-based principles.

Another class of fatigue models approach the degradation process from strength point of view. The difficulty in this is to find that strength level where the final failure can be assumed to happen. An early and simple example for this is the work of Broutman and Sahu [9]. Hashin and Rotem [12] managed to establish a correlation between static strength and fatigue strength as a function of mean stress, load frequency, number of cycles and fiber orientation. Naderi et al. [28] used an interaction type empirical degradation rule for strength reduction and the failure state was estimated using a modified 2D Hashin failure criterion which allows consideration of multiaxial stress states. Schaff et al. [8] introduced an R-ratio, stress and cycle dependent strength degradation equation in the form of a power law. A unique approach was introduced by Tittman et al. [25] by finding the fatigue life based on the comparison of the calculated strain energy density with Cuntze criterion. Draskovic [27] exploited the XFEM facility of ABAQUS FE software to estimate residual strength via crack propagation assessment.

In a number of research activities the classical S-N curve approaches have been introduced in connection with composites such as the research of Agarwal and Dally [13] or Hahn and Kim [14] as well as the work of Roundi et al. [34]. Kawai [15] proposed a methodology to identify master S-N relationship using the non-dimensional effective stress based on Tsai-Hill static failure criterion. There is also example in literature for the combination of orientation and mean stress dependence with relevant S-N curves resulting in orientation dependent Haigh-diagram for composite [33]. Hashin and Rotem [16] introduced a direct life vs. effective stress exponential damage relationship on a ply-by-ply basis. Later this model was further improved in [17] considering the change in load bearing capability of plies due to local failure and progressive growth of damage. This principle was also utilized in the work of Kawai et al. [4] to take into account the in-situ static strength of plies.

Besides the degradation and S-N curve models the literature contains several special approaches such as the micromechanical assumptions [26,36] or fracture mechanics-based methods to predict cyclic life [1,3,10,11]. Another promising attempt is to assess the cyclic behavior on a thermodynamics basis. These attempts have led to the unified fatigue life models [29,35] and to the use of the principle of conservation of energy [31]. Paepegem and Degrieck [19] proposed a highly physics-based model which is a combination of the approaches collected above.

Llobet et al. [22] developed an ABAQUS user defined VUMAT which approximates phase 1 of the cracking with a Continuum Damage Model combined with Paris type crack growth law. For the interlaminar cracking stage a Cohesive Zone Modelling (CZM) approach was used which is in line with practice. Similar procedure was developed by Carraro et al. [23] but assuming a mixed mode crack-propagation.

2. Proposed fatigue life assessment method

Current work presents an algorithm to predict cyclic response of continuous fiber reinforced plastics by utilizing the benefits of Finite Element (FE) based stress assessment. The workflow integrates FE stress assessment into a stiffness, strength degradation and failure assessment algorithm based on theories taken from literature.

In general, the fatigue mechanism of composites does not comprise such well-defined phases. It is a continuous microcracking and degradation process of the matrix as well as the fiber-matrix bond. It is further complicated by the fact that the plies have a very inhomogeneous structure on microscale and there is a strong interaction and load transfer between plies in case of a whole laminate. The basic damage procedure is well described in Fig. 1. On micro scale the final cracking of the composite ply is the result of a simultaneous crack initiation and propagation process including joining of cracks, delamination and fiber breakage at the end. On a global scale these changes in the matrix structure are manifested as degradation of the global stiffness as well as strength properties as shown in Fig. 1.

The key elements of the assessment method that are discussed in this section are: degradation law, mean stress correction and fatigue strength evaluation.

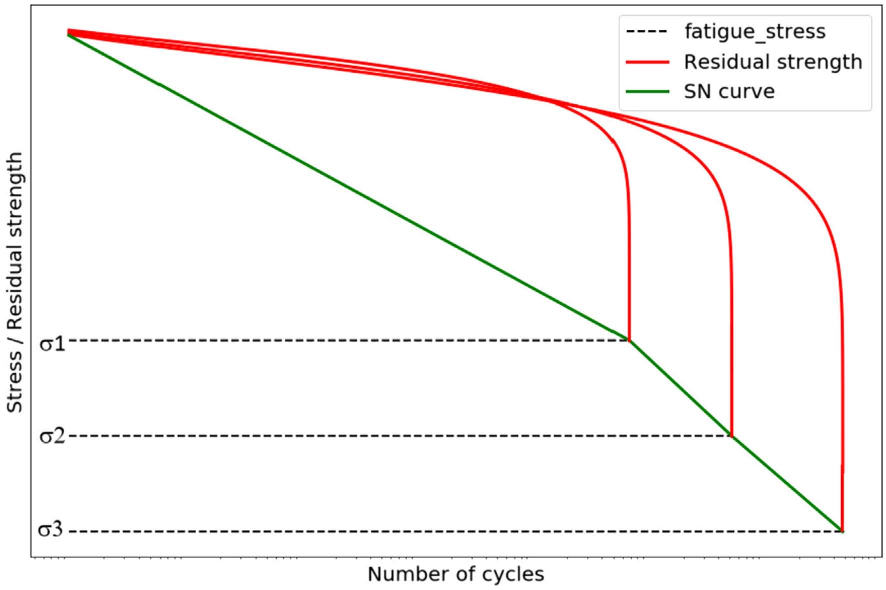

Fig. 1. Strength degradation of a laminate under constant uniaxial fatigue loading.

2.1. Fatigue damage law

To predict the damage state a global empirical approach was chosen by assuming the simultaneous degradation of stiffness and strength parameters. The reduction of static strength with cycles (e.g. fatigue strength) leads to final rupture once it matches the actual load level. However, for strain-controlled cases the degradation of stiffness also plays an important role. As cycles accumulate the reduced stiffness causes stress relaxation which prolongs cyclic life since the reduced stress level is associated with lower crack growth rates.

The dimensionless unified equation for any stiffness degradation from Adam et al. [30,2] was selected to describe the continuous reduction of stiffness and strength parameters. A graphical representation of the stiffness degradation process with the interaction model is highlighted in Fig. 2.

The model applied here considers stiffness and modulus degradation corresponding to each in-plane load types (longitudinal, transversal and shear). In addition, a similar equation has been proposed to take into account the gradual change of Poissons-ratio (if any) from the initial value to the one taken at the point of failure. For this, Adam's equation was modified in the following way:

$$\nu_{12}(n) = \left[1 - \left(\frac{\log(4n)}{\log(4N_f)}\right)^K\right]^{\frac{1}{L}} \nu_{12-s}(1-h) + h\cdot\nu_{12-s}, \tag{1}$$

where

$\nu_{12\text{-s}}$ – initial (static) in-plane major Poisson's ratio (PR),
K and L – fitting parameters,
h – ratio of PR at failure and initial PR.

Using h = 1 implies that no PR change is expected during the degradation process.

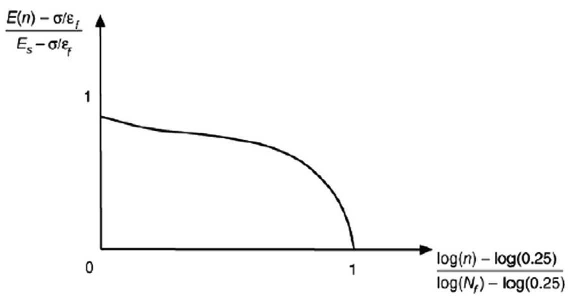

Fig. 2. Stiffness degradation of a composite ply under constant uniaxial fatigue loading [2].

2.2. Mean stress correction

As in case of fatigue experience with metals, the fatigue life of composites is also dependent on the mean stress level the alternating loading is operating at. The method followed in this work exploited the Haigh-diagram approach in a form suggested by Harris [2].

The proposed procedure defines a direct relationship for fatigue life from the Haigh-diagram which leads to a log-linear stress-life relationship:

$$N_f = 10^{\frac{\left[\frac{ln\left(\frac{a}{f}\right)}{ln(1-q)(c+q)}\right]^{-A}}{B}}. \quad (2)$$

The sought master parameters, A, B and f can be found via simultaneous fitting process on test data generated at different constant R-ratios and a, q and c stand for the stress amplitude, mean stress as well as compressive strength normalized by the tensile strength respectively.

In order to make the aforementioned Haigh-rule work for in-plane shear case, a slight modification was necessary. An extra scale parameter was added to the original equation in order to produce symmetric N = constant curves around the normalized amplitude axis. This is because under shear load there is only one strength value considered.

$$a = f\cdot[t\cdot(1-q)\cdot(c+q)]^{A+B\cdot log(N_f)}, \quad (3)$$

where: t – scale parameter. It shall take a value less than 1.0 if f is larger than one (historically 1.06).

Example for the symmetric normalized shear stress amplitude vs. mean shear stress is given in Fig. 3.

2.3. Fatigue strength evaluation

In the model introduced here the fatigue life is estimated in an iterative way. Instead of using an effective stress in conjunction with an S-N curve or monitoring stiffness degradation down to zero the stiffness and strength reduction with cycles is evaluated in parallel and after each cycle increment it is compared against the current strength limit. In order to take into account multiaxial stress at each cycle increment Puck's first ply failure criterion is invoked to decide whether failure state occurs or not. Puck's criterion is convenient to use as it is capable of distinguishing between relevant failure modes on the basis of the actual stress state of each individual ply. It also follows from this that the model assumes the same failure mechanism to take place at the point of cyclic failure in a given stress state as what normally would happen at the actual stiffness and strength values under instantaneous loading. Puck's criterion distinguishes between two major failure cases: fiber failure (FF) and inter-fiber failure (IFF) [37].

Based on Puck's criterion it is possible to predict a potential failure state in multiaxial stress state which is likely to occur in angle ply and multiaxial laminates. This approach is similar to the effective stress-based models. Since this approach couples degradation models with interactive static failure approaches it was necessary to decide which structural parameters to degrade in a given stress state. This is summarized in Table 1.

The model can be visualized by using the abstraction of the ply stress-state coordinate system. Assuming a multiaxial stress state within the ply under load control and R = 0 the maximum and minimum turning points of the load cycle correspond to two points in the σ_1-σ_2-τ_{12} coordinate system the minimum load being at the origin. The Puck envelope is manifested in a form of a surface in this stress space. Whilst the stress state of the ply alternates between these two points the failure surface shrinks on a cycle by cycle basis via the degradation of strength parameters. According to the theory fatigue life is reached when at any cycles the actual stress intersects the envelope. This can only happen at the maximum loading since the maximum point is always positioned closer to the failure envelope. A graphical representation of this is shown in Fig. 4. The static failure envelope (blue[1]) shrinks into a degraded state (red) whilst the biaxial tensile alternating load path represented by the black line stays the same (load-controlled situation).

2.4. Automated workflow for fatigue assessment method

An automated system was created to implement the theory described above. The algorithm is detailed in Fig. 5 and briefly described here. The actual laminate stresses in local ply coordinate system corresponding to the maximum and minimum turning points of constant amplitude loading history are evaluated in the appropriate FE model. The stress and strain results for pre-selected critical elements are read in by the external fatigue evaluation tool coded in Python. The code increments the cycles with a predefined number of cycles. In each cycle increment the fatigue life is evaluated with the Haigh-diagram approach at the stress amplitude and mean stress level read in from the FE assessment. It is followed by the stiffness and strength degradation computation at the accumulated number of cycles. The system allows treating varying stress states which is typically the case for features operating under strain control. When the stress changes, the degradation takes place on another curve. This necessitated to introduce an equivalent number of cycles calculation which defines the starting point for the actual degradation curve. The actual stress state is then checked against Puck's first ply failure criterion using the degraded strength values. If the Inverse Reserve Factor (IRF) in any element first

[1] For interpretation of color in Figs. 4, 11 and 15, the reader is referred to the web version of this article.

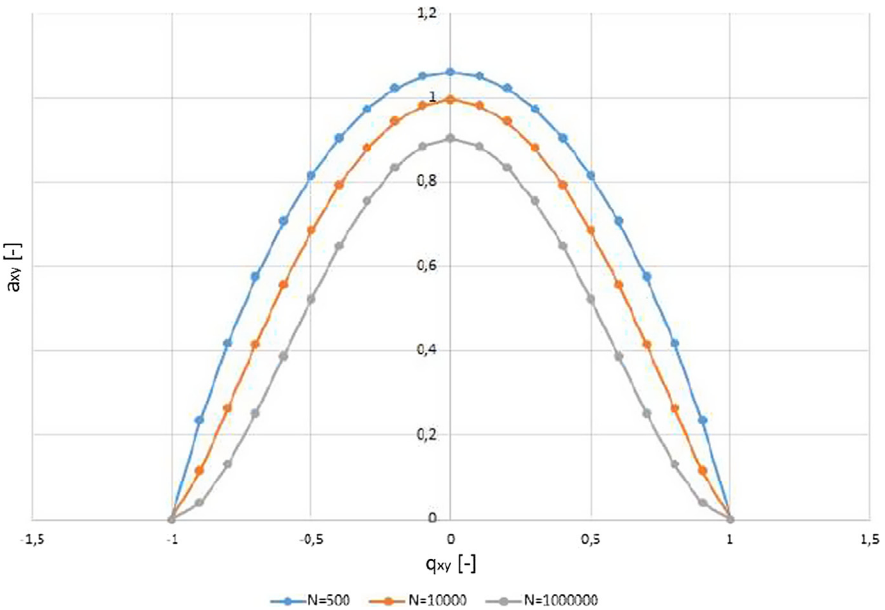

Fig. 3. Modified symmetric Haigh-diagram for alternating shear load.

Table 1
Relationship between acting stresses and stiffness / strength data to degrade.

Acting stress	σ_1		σ_2		
	> 0	< 0	> 0	< 0 & Mode B	< 0 & Mode C
Degrading stiffness parameter	E_{11}*	E_{11}*	E_{22}*, ν_{12}	G_{12}	E_{22}*, ν_{12}
Degrading strength parameter	X_t	X_c	Y_t	S_{12}	Y_c

* Identical modulus is assumed in tension and compression.

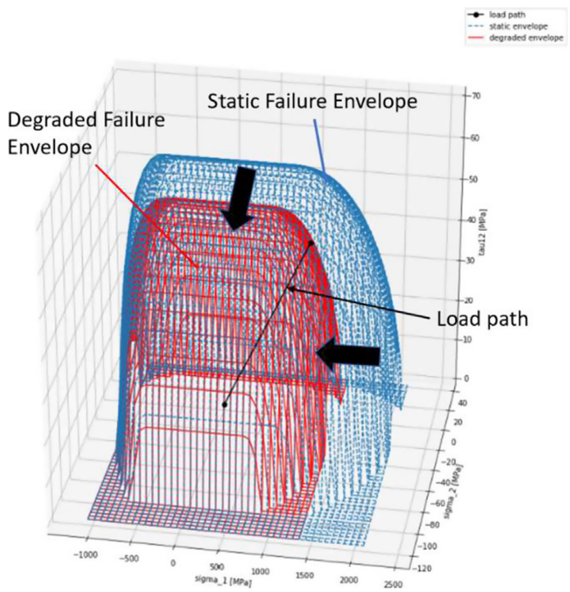

Fig. 4. Fatigue process under biaxial tensile alternating loading path in the coordinate system of the local ply stresses using Puck's failure criterion.

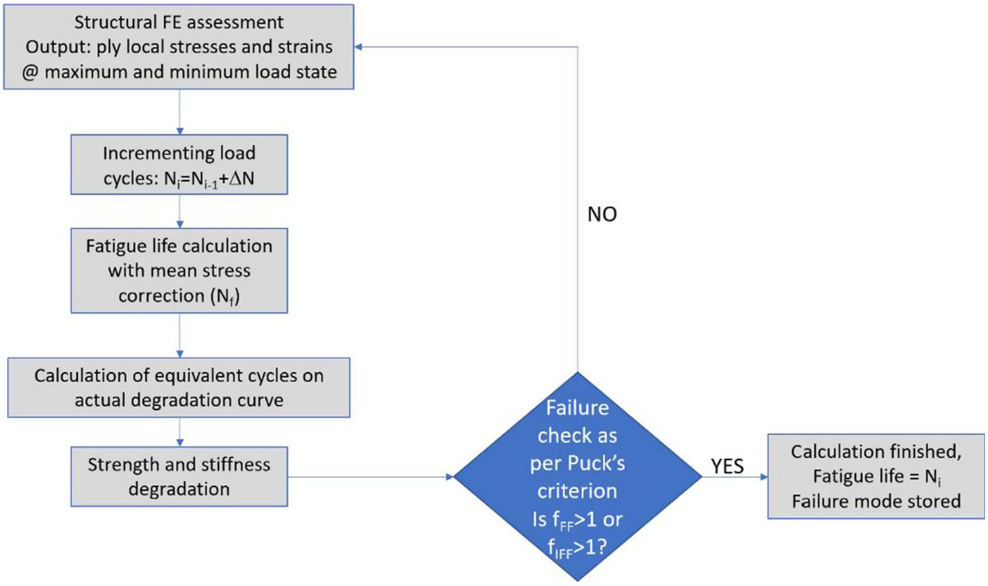

Fig. 5. The automated composite fatigue assessment workflow.

approaches the failure state the system exists with the actual accumulated number of cycles as the fatigue life of the component. Strength and stiffness degradation data as well as IRF "evolution" over the cycles are also stored and can be highlighted in FE postprocessors as fringe plots or curves for further analysis.

3. Fatigue life calculation with the automated workflow

As a first attempt of verification we simulated a unidirectional carbon-epoxy composite with tension-tension loading with a stress-ratio of 0.1. This would be the simplest case of the practical usage of the workflow. The mechanical behavior of stress- and strain-controlled cases were compared. There was no need to use a numerical model here, the stresses and strains were calculated analytically. At the stress-controlled case the maximal applied stress was 1280 MPa, at the strain-controlled case the maximal applied strain was 0.8%. These two initial cases ensured the same initial stresses for both testing types. The used material parameters are summarized in the following tables. Table 2 describes the in-plane stiffness parameters. The used values refer to a general carbon fiber reinforced epoxy resin composite. Table 3 shows the different strength values. X and Y values mean the strength in fiber direction and cross-direction respectively, the indices t and c refer to tension and compression. The p-values are the Puck's constants described in Table 3. The fatigue parameters are shown in Table 4.

As a second verification step we performed a numerical simulation on a cross-ply composite using the automated workflow. The finite element solver was Ansys. We used a standard open-hole specimen with a length of 200 mm, a width of 36 mm and a hole-diameter of 6 mm. The laminate is a carbon-fiber reinforced epoxy resin composite with 4 unidirectional layers with a layer thickness of 0.4 mm. The stacking sequence is [0°/90°/90°/0°]. The same material parameters were used as in the analytical verification. The specimen geometry and the FE-mesh is shown in Fig. 6. The FE models consists of layered shell elements with an average element size of 3 mm. A local refinement was applied around the hole with an element size of 1.6 mm. We modeled a structured mesh with quadrilateral elements.

In the numerical simulation we investigated a load-controlled case. Fig. 7 shows the applied boundary conditions. The nodes on the one end of the specimen are fixed in all directions, the nodes on the other end are constrained together with a rigid constrained equation (CERIG). The master node of the constraint is loaded with a force of 3500 N. The load-ratio here is also 0.1, as it was in the analytical calculation.

Table 2
In-plane stiffness parameters of the investigated carbon-epoxy composite.

E_x [MPa]	E_y [MPa]	G_{xy} [MPa]	v_{xy} [–]
160 000	10 000	5 000	0.3

Table 3
Strength parameters of the investigated carbon-epoxy composite.

X_t [MPa]	X_c [MPa]	Y_t [MPa]	Y_c [MPa]	$p21_p$ [–]	$p21_m$ [–]
2000	1100	35	120	0.3	0.25

Table 4
Fatigue parameters of the investigated carbon-epoxy composite.

α [–]	β [–]	γ [–]	λ [–]	A [–]	B [–]	f [–]
8.867	0.545	11.0	0.4	0.01	0.5	1.06

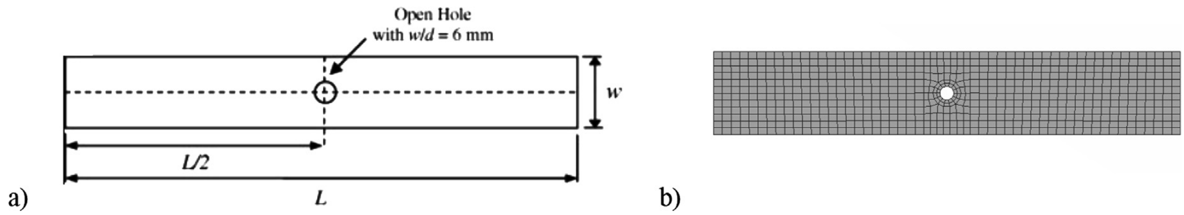

Fig. 6. (a) Specimen type and (b) FE-mesh.

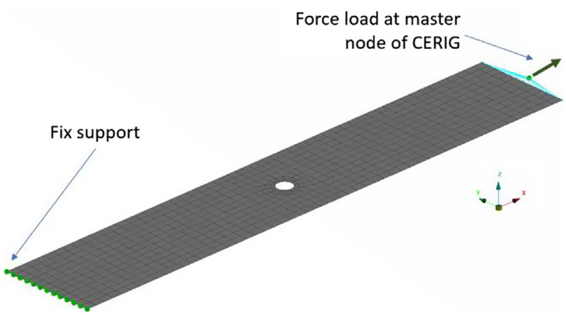

Fig. 7. Boundary conditions.

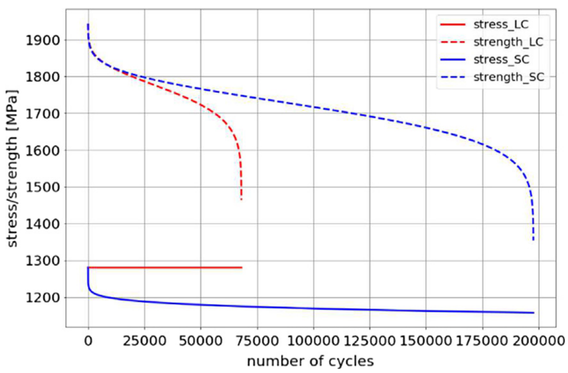

Fig. 8. Stresses and degraded strength values in stress- and strain-controlled cases.

4. Results and discussion

4.1. Fatigue test of UD

Fig. 8 shows the stress and strength values through the load cycles. LC refers to the load-controlled and SC refers to the strain-controlled case. In the load-controlled case due to the constant stress-level the system is hardly sensitive to the degradation of the modulus, the process follows one single strength degradation curve, therefore the fatigue life is shorter. This case gave a fatigue cycle number of ca. 60 000, while the strain-controlled case gave a fatigue life of ca. 200 000 cycles. The axial stress in the strain-controlled

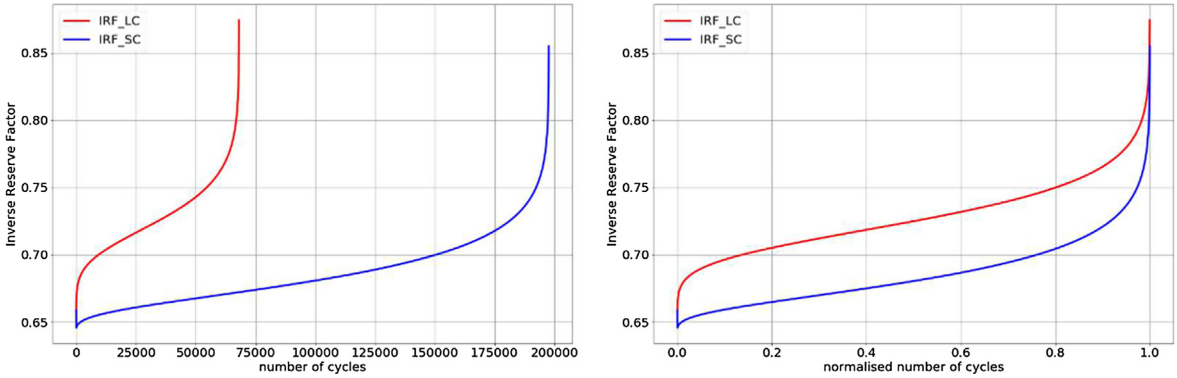

Fig. 9. Inverse reserve factors in stress- and strain-controlled cases – absolute/normalized cycles.

case relaxes as the cycles progress. This is the implication of the modulus degradation.

This lower fatigue life is also shown by the more progressive utilization accumulation as well. Fig. 9 shows the so-called inverse reserve factors (IRF) of each case. This factor is the ratio of the actual stress and the actual strength.

In the case of the strain-controlled test the degradation of the modulus leads to continuous stress relaxation since the stress is the product of the strain and the modulus. Thus, the slower IRF accumulation in that case is attributed to the more gradual modulus degradation in comparison with the strength reduction. Due to this effect the failure process is mostly driven by the progressive degradation of the strength. As soon as it turns up the stress and strength curves get very close to each other.

Fig. 10 shows the normalized strength and modulus curves versus the normalized number of cycles in the case of the strain-controlled loading. The normalized modulus degradation curve is flat, it has no progressively decreasing section as the stress get relaxed continuously, so the process follows a “flatter” degradation curve from cycle to cycle.

The curves show that all the parameters of the fatigue model should be obtained using load-controlled test. On one hand, they have a lower fatigue life, so the tests are shorter, furthermore, the stress-level is constant so the R-ratio is also constant through the process. Therefore, it follows the same modulus- and strength-degradation curve till reaching the fatigue life of the specimen. Strain-controlled tests are worth performing only for validation of the fitted model. On the other hand, as there is no ply with fibers in crosswise direction, it needs a much higher stress-level to reach finite fatigue life as the failure occurs in fiber direction. This also results in a much faster failure process for UD than for cross-ply.

4.2. Fatigue test of the cross-ply composite

The results of the simulation of the open-hole specimen are summarized in this section. Result items of each element were wrote out by Ansys into text files and those files were processed by our Python-tool. The evaluated user-defined results were visualized in the commercial software HyperView. Fig. 11 shows the maximum inverse reserve factor in each element. Inverse reserve factor is a utilization-like quantity, if the value is over 1, then failure is expected. Results in the elements only around the hole are plotted in color. As expected, the failure appears on the two side edges of the hole signed with red color. These elements have the highest IRF values, which are slightly over 0.7 at a cycle number of 87,920. The reason why IRF does not reach 1.0 at fatigue life is the very high IRF gradient above IRF = 0.7 which leads to numerical instability.

The first ply failure appears in the layers with 90° orientation, where the fibers stand in crosswise direction, as the load is perpendicular here to the fiber direction and the strength of the matrix material is much lower than the strength of the fiber. Fig. 12

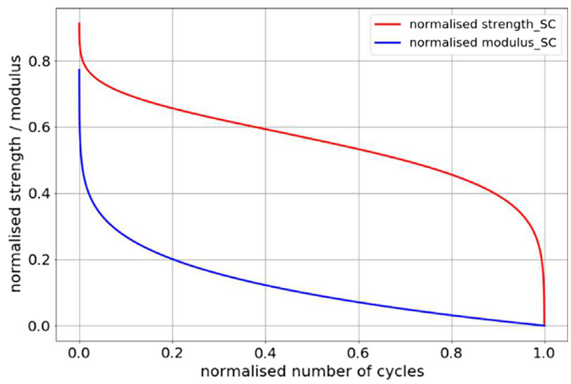

Fig. 10. Normalized strength/modulus vs. normalized number of cycles – strain-controlled case.

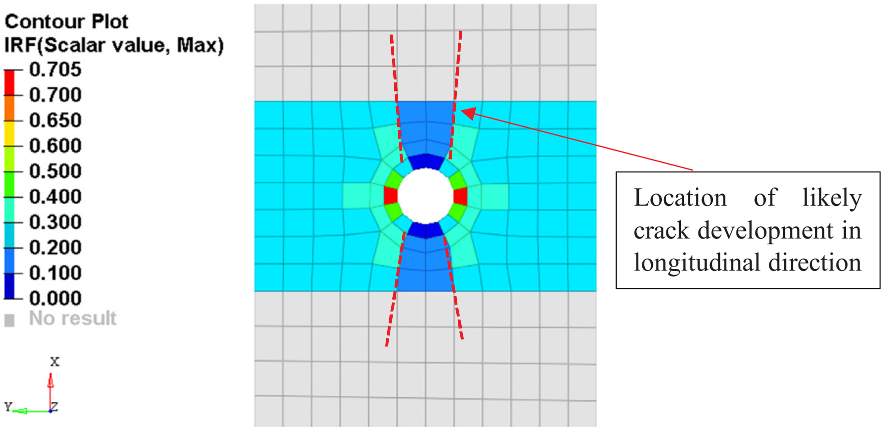

Fig. 11. Inverse reserve factor in worst layer.

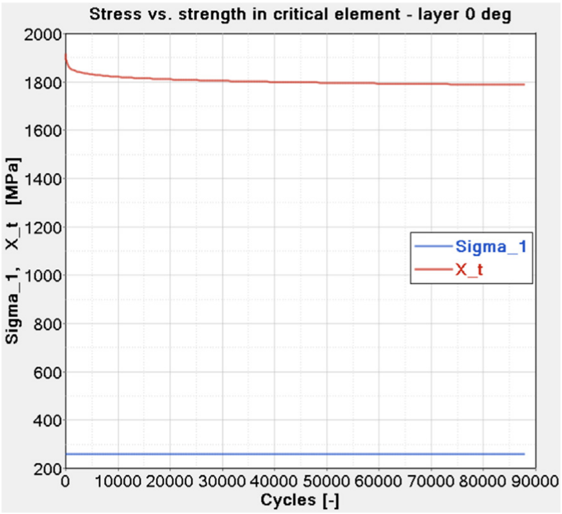

Fig. 12. Stress and strength in fiber direction in critical element.

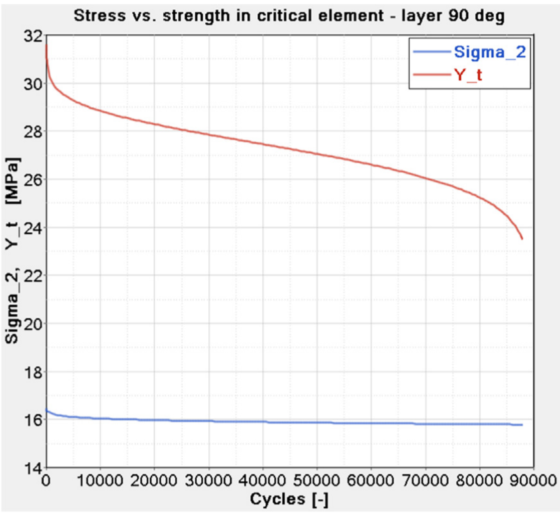

Fig. 13. Stress and strength perpendicular to fiber direction in critical element.

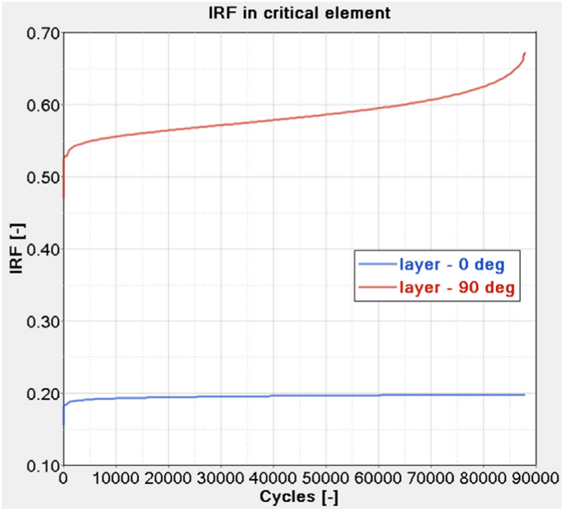

Fig. 14. Inverse reserve factor in critical element in layer 0° and layer 90°.

shows the stresses and strength values of the layers with 0° orientation, while Fig. 13 shows these values of the layers with 90° orientation. In fiber direction we have much higher values, the initial strength is 2000 MPa. After a short degradation of about 200 MPa the slope of the curve is very low. In contrast the degradation curve and the stresses in the 90° layer has a much higher slope and after a cycle number of 80 000 it starts to fall down suddenly. This phenomenon implies that the fatigue process starts with the continuous fracture of 90° plies. As those loose their stiffness, a gradual load transfer takes place in the direction of 0° layers. However, due to the significant stiffness difference, this extra loading on 0° plies does not result in notable degradation in fiber direction. The transverse cracking as the first sign of fatigue is well-known from literature and experience [38]. Dense transverse cracks develop at the beginning of the fatigue process in the 90° oriented plies around the stress concentration zone of the hole. Once the 90° layers loose their load bearing capability the microcracks develop into the 0° plies resulting in long cracks in the loading direction at the border of the highly utilized and the intact region as shown by the red arrow in Fig. 11. These cracks lead to delamination and catastrophic burst of specimens at the end of fatigue life.

It is also worth mentioning, that due to the low level of load-bearing contribution of 90° plies the full fracture of laminate only takes place when the 0° plies exhibit failure. Based on the degradation curves plotted up to the estimated fatigue life one can expect a significantly longer damage accumulation period for 0° oriented layers until catastrophic failure. Thus, the cross-ply laminate has a long-life reserve after the 90° layers ruptured. However, it also has to be mentioned that the crack transition and propagation process between plies cannot be taken into account by this model which might lead to shorter than expected lives until full separation of specimen.

The difference in damage accumulation between layers can be seen on the IRF plots as well. Fig. 14 shows the IRF values in the two different layers. The curves show that a sudden degradation appears right after the first couple of cycles and then the utilization increases with a constant slope. This slope is very low for the layers where the fibers are in the load-direction and significantly higher in the cross-layers. After the cycle number of 80 000 the IRF value of the cross-layers starts to increase suddenly, predicting the failure of the specimen.

The distribution of the degraded moduli is shown in Fig. 15. The left figure shows the 0° layer and the right figure the 90° layer. The initial values were 160 000 MPa for the fiber-direction and 10 000 MPa for the cross-direction. It can be seen that the blue area in the middle is hardly degraded, because these are areas with a low stress-level. This is valid for both the layer orientations, which is also consistent with the experience.

The system introduced in this work is a good basis for safe cyclic life calculation of components under constant amplitude loading

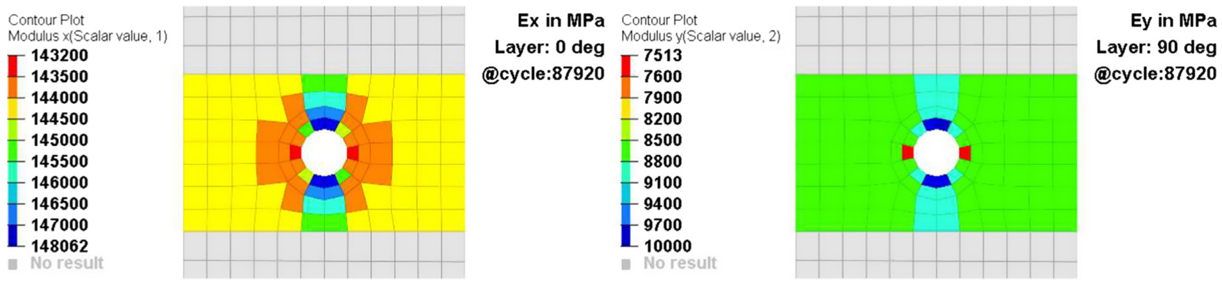

Fig. 15. Degraded moduli in in fiber- and in cross-direction.

history, however, needs extended functionalities if more lifelike, stochastic loading history acts on the component in question. These extended features shall include the separate consideration of sudden death and gradual degradation mechanisms, the treatment of varying amplitude loading block sequences as well as the statistical aspects associated with the uncertainty of fatigue life estimation. In addition, if the progressive degradation of damage of plies is in focus, the implemented first ply failure fatigue strength evaluation methodology will also need revision.

Further task is to validate the model with appropriate UD and multidirectional laminate fatigue test results which are under preparation.

5. Conclusion

The fatigue life estimation method proposed in this paper is a general approach that due to the exploitation of FE analysis is capable of predicting the stress evolution of any composite parts with any ply layups over successive loading cycles as a result of continuously monitored strength and stiffness degradation even under multiaxial state.

These capabilities have been demonstrated via virtual test specimen case studies. Firstly, simple plain unidirectional pieces were analyzed and compared under strain and load control. As next a cross-plied open hole test specimen was assessed under tension-tension type fatigue loading. The results are in line with expectations; however, the validation of the built-in degradation and strength model parameters is still to be done based on real fatigue test data.

Currently, as the incorporated damage model is based on first ply failure criterion, the progressive damage evolution over plies cannot be forecast. Thus, the proposed method is equipped with a certain level of safety with regards to estimated fatigue life of composite plates.

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Declaration of Competing Interest

None.

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