A PROGRESSIVE DAMAGE APPROACH FOR COMPOSITE STRUCTURES UNDER FATIGUE LOADING CONDITIONS

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Keywords: fatigue, damage accumulation, FEM.

Abstract

In this paper a fatigue damage propagation numerical model based on gradual material degradation rules and Hashin fatigue failure criteria is formulated, implemented in a finite element platform and then used to simulate the intra-laminar fatigue damage evolution in composite structures. The model has been preliminary validated against literature experimental data in terms of s-n curves providing confirmation of its effectiveness in predicting pinned composite joints fatigue life. The simulation of the models fatigue life provided detailed information on the intra-laminar damage mechanisms on-set and evolution related to fatigue gradual degradation of material stiffness and strength for different values of the applied maximum stresses. Finally an application to a delaminated stiffened composite panel, loaded in compression-compression fatigue, is presented. The intra-laminar damage propagation in the delaminated area and in the rest of the panel has been simulated considering the material properties gradual degradation with the fatigue cycles and the sudden failure arising according to fatigue stress based criteria.

1 Introduction

Over the past years, most of the damage tolerant concepts experienced on metals have been straightforwardly applied to composites. However, the use of these concepts, due to the lack of robust numerical tools for composite structures fatigue damage tolerance and lifetime prediction, has led to over-conservative designs and extensive prototype testing, not allowing to exploit the full potential of composite materials in terms of costs and performances. The fatigue behaviour of fibre-reinforced plastic composites (CFRP), mainly due to their heterogeneous and anisotropic nature, is completely different. In the first stages of the deterioration induced by fatigue, which can start very early in the service life, the onset of more or less extended damaged areas is observable. These areas enclose a great number of microscopic cracks and other forms of damage (such as debonding, fracture of fibres, etc.). In a second phase, the deterioration of the material, characterized by a gradual growth of the damaged areas, takes place. More severe damages appear in the last phase, such as fibres breakages and delaminations, quickly leading to failure.

According to some authors [1], *empirical models* (based on extensive experimental data), *physical models* (based on predictable well-known physical phenomena) and *static and dynamic models* (considering respectively time-independent and time-dependent material properties) have been introduced. Anyway, two macro categories can be defined: models which take into account the damage mechanisms (phenomenological models), and models called in a general sense empirical models (or fatigue life models). Concerning the phenomenological models, a further sub-classification could be attempt by introducing models which account for the progressive cycle-dependent fatigue material properties (stiffness/strength) degradation and models based on evolution laws suitable for a specific type of damage.

Among the several "progressive cycle-dependent fatigue material properties (stiffness/strength) degradation based models", the Shokrieh and Lessard's "Generalized Residual Material Property Degradation Model" [3-4] can be considered as a good compromise in terms of generalization of progressive damage theories over amount of experimental tests needed.

In the present paper, the Shokrieh and Lessar "Generalized Residual Material Property Degradation Model" has been adopted in conjunction with Hashin stress based fatigue failure criteria [5] and proper sudden material degradation laws to formulate a fatigue progressive damage approach able to simulate the intra-laminar fatigue damage propagation in CFRP laminates. The introduced fatigue damage propagation model has been implemented in the ANSYS FEM code by adopting the ANSYS Parametric Design Language (APDL) and validated against the experimental results presented in [4]. Then, the model has been adopted to predicted the fatigue intra-laminar damage evolution in a delaminated stiffened panel under compression-compression fatigue loading conditions.

2 Theory and FEM implementation

Under fatigue loading conditions, during the first cycles, the material is usually subjected to a stress state considerably lower than the failure strength, therefore, generally, no or minimal static failure can be expected. However, by increasing the number of cycles, the material properties in terms of strength and stiffness degrade (gradual degradation) and eventually can lead to the occurrence of catastrophic failures.

It is worth noting that the change in material properties, induced by fatigue, depends on the maximum acting stress and on the stress ratio, which can be different at different locations within a structure, therefore the degradation is generally different in various locations and the stress consequently redistributes during the fatigue loading process.

In order to take into account the "gradual degradation" of the material properties, induced by fatigue, the Shokrieh and Lessard approach [3-4] has been adopted, which integrates the residual strength and stiffness theory for different damage mechanisms and the constant life analysis. According to [3-4], the gradual degradation rules are determined as curve fitting of experimental data performed at coupon level. Indeed, one of the main objectives of the proposed numerical model is to adopt fatigue experimental data obtained at coupon level for uniaxial loading conditions to simulate the fatigue behaviour of complex structures under multi-axial loading conditions.

As a first step, the fatigue life, as number of cycles to failure N_f, at lamina level in each location of the structure, is evaluated by using the normalised fatigue life equation (1) developed by Adam [2].

$$u = \frac{\ln(a/f)}{\ln[(1-m)(c+m)]} = A + B\log N_f \tag{1}$$

Where, $m = \sigma_m / \sigma_t$, $c = \sigma_c / \sigma_t$, $a = \sigma_{alt} / \sigma_t$. σ_t is the tensile strength, σ_c is the compressive strength, $\sigma_m = (\sigma_{MAX} + \sigma_{min})/2$ is the mean stress and $\sigma_{alt} = (\sigma_{MAX} - \sigma_{min})/2$ is the alternating stress. The quantities f, A and B are curve fitting parameters which can be experimentally

obtained. By using Equation (1) and knowing f, A and B, it is possible to achieve a measure of the fatigue life at lamina level for each location starting from the knowledge of the stress components acting at that location in the lamina of interest.
The residual strength R and the residual stiffness E, after n cycles for a stress ratio k, are computed, according to [3], at lamina level for a particular location by using the Equation (2) and (3).

$$R(n,\sigma,k)=\left[1-\left(\frac{\log(n)-\log(.25)}{\log(N_f)-\log(.25)}\right)^{\beta}\right]^{1/\alpha}\left(R_S-\sigma\right)+\sigma \tag{2}$$

$$E(n,\sigma,k)=\left[1-\left(\frac{\log(n)-\log(.25)}{\log(N_f)-\log(.25)}\right)^{\lambda}\right]^{1/\gamma}\left(E_S-\frac{\sigma}{\varepsilon_f}\right)+\frac{\sigma}{\varepsilon_f} \tag{3}$$

Where R_s is the material static strength, E_s is the material static stiffness, σ is the magnitude of applied maximum stress, α, β, λ, γ and ε_f (average strain to failure) are additional experimental fitting curve parameters.
Equation (1), (2) and (3) can be written for each stress direction (longitudinal, transverse and shear directions) and, where applicable, both for tensile and compression loading conditions with appropriate stress components, number of cycle to failure, static strength, maximum stress components, static stiffness and experimental parameters f, A, B, α, β, λ, γ and ε_f. These data can be extrapolated by the experimental results reported in [4].
In order to check for the occurrence of failures, the fatigue failure criteria proposed by Hashin's [5] and proper material degradation rules [4] have been chosen.
The gradual material properties degradation, the failure criteria and the sudden properties degradation rules has been integrated into a progressive damage procedure able to simulate the residual strength, the fatigue life and the final failure mechanisms of composite laminates with an arbitrary geometry, stress ratio and stacking sequence under multi-axial fatigue loading conditions. The procedure has been implemented in ANSYS© by means of user subroutines in APDL. A flow chart representing the FEM implementation is shown in Figure 1. As a first step, the finite element model is defined.

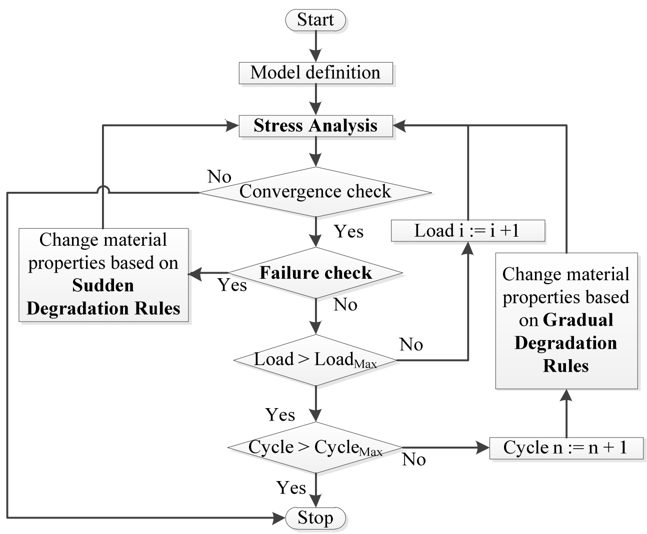


Figure 1. Graphical representation of the fatigue progressive failure procedure implemented in ANSYS.

The stress analysis is then performed by applying the load incrementally in each cycle to follow the evolution of “sudden failures”, in specific elements at lamina level, due to the satisfaction of criteria during the static application of the load within each fatigue cycle. Once the maximum load has been attained, within a cycle, the next cycle is selected and the proper gradual material degradation rules are applied to all the elements at lamina level. Then a new stress analysis is performed with the degraded material properties. A database with all the information about the fatigue life, the damage and the residual material properties of each lamina for all the elements are stored for every cycle and load step.

3 Numerical application to a pin hole joint: model validation and sensitivity analysis

In this section a first numerical application is introduced, where, for preliminary validation purposes, comparisons between the obtained numerical results (in terms of fatigue life curves and damage distribution) and experimental data available in literature [4] are shown for pinned composite joints under tensile-tensile fatigue loading conditions. The analyzed pinned joint configuration is schematically described in figure 2

MATERIAL PROPERTIES AS4/3501-6

E_{xx}	147.0 GPa
$E_{yy} = E_{zz}$	9.0 GPa
$E_{xy} = E_{xz}$	5.0 GPa
E_{yz}	3.0 GPa
$\nu_{xy} = \nu_{xz}$	0.3
ν_{yz}	0.42
X_t	2004 MPa
X_c	1197 MPa
$Y_t = Z_t$	53 MPa
$Y_c = Z_c$	204 MPa
$S_{xy} = S_{xz}$	137 MPa
S_{yz}	42 MPa
α	1.015e-8 MPa^{-3}
Ply thickness t	0.146 mm

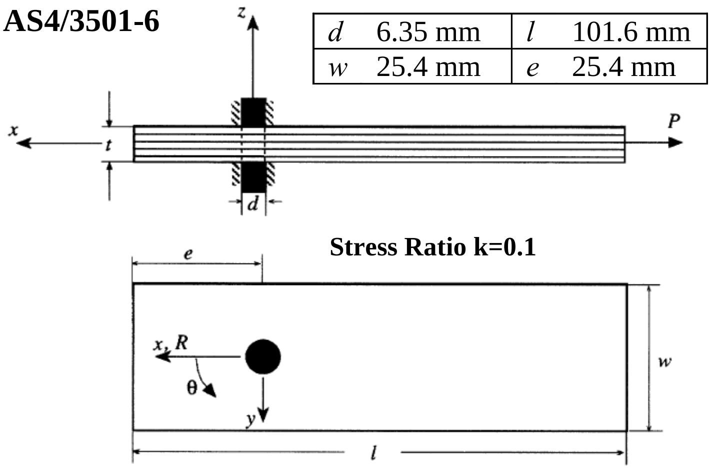


Figure 2. Material properties, geometry and stress ratio of the pinned joint.

The finite element model, built by adopting 8 node layered shell elements, is shown in figure 3.

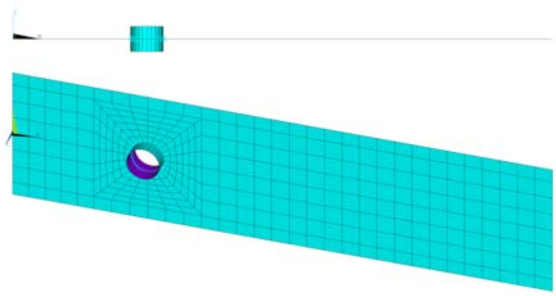


Figure 3. Finite element model of the pinned joint adopted for the computations.

In order to preliminary validate the proposed progressive fatigue damage model, the tensile-tensile fatigue behaviour of the cross-ply pin-hole specimens $[0_4/90_4]_s$ and $[90_4/0_4]_s$ has been simulated and compared with the experimental data available in [4] for different values of the maximum tensile load acting on the specimen.

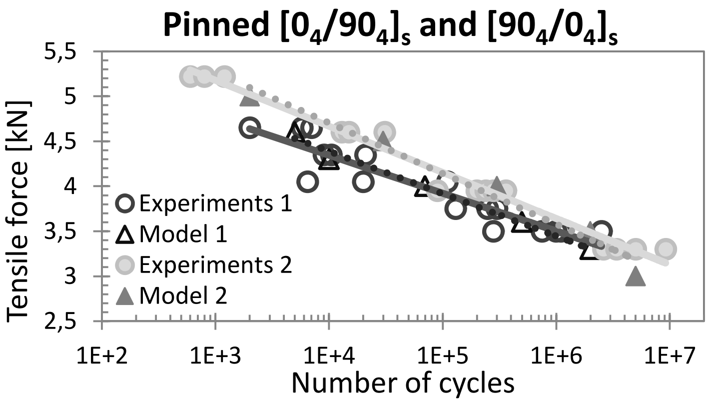


Figure 4. Fatigue life curve of the pinned joint – comparison between experimental data and numerical results for the $[0_4/90_4]_s$ (case 1) and $[90_4/0_4]_s$ (case 2) specimens configuration.

In figure 4, the comparison between numerical and experimental fatigue life of the two specimens, for different values of the maximum applied tensile load is shown. The agreement in terms of fatigue life between the experimental data and the numerical results is excellent throughout the analysed maximum applied tensile loads range. Actually, at 4 kN, the averaged experimentally measured fatigue life for $[0_4/90_4]_s$ specimens configuration [4] of about 65’000 cycles is in excellent agreement with the fatigue life predicted by the numerical model implemented in ANSYS ©, for that applied tensile load, which is about 70’000 cycles.
The numerical axial displacements distribution (fig 5.a) for the configuration $[0_4/90_4]_s$, with a maximum applied tensile load of 4kN, shows, at failure (70’000 cycles), a “sort” of rigid translation due to the ruptures in elements between the hole and the free edge of the specimen.

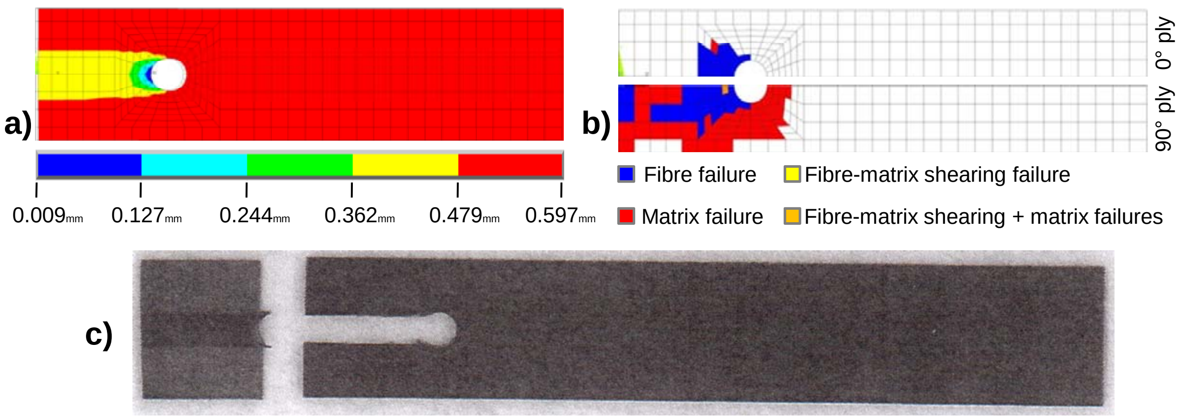


Figure 5. Comparison between numerical axial displacements (a), numerical damage distribution (b) and experimental specimen status at fatigue failure (c) - specimen configuration $[0_4/90_4]_s$.

Indeed, fibres failures, as shown in figure 5.b, are located, in both 0° oriented and 90° oriented plies, around the pin-hole contact area between the hole and the specimen free edge. The displacements contour plot and the failure elements distribution recall somehow the experimentally observed bearing failure of the specimen (fig. 5.c).
Analyses on additional four pinned joint configuration have been performed in order to investigate the influence of the joints’ stacking sequence on their fatigue life. Hence six specimen configurations are considered to study the effects of material stacking sequence on the fatigue damage propagation in pinned composite joints (cross-ply $[0_4/90_4]_s$, $[(0/90)_4]_s$ and $[90_4/0_4]_s$, angle-ply $[45_4/\text{-}45_4]_s$, zero-dominated $[0/90/0/0]_s$ and quasi-isotropic $[0/90/45/\text{-}45]_s$).

The numerical tensile-tensile fatigue life of the six pin-hole specimens has been evaluated for different values of the maximum applied tensile load and compared in figure 6.

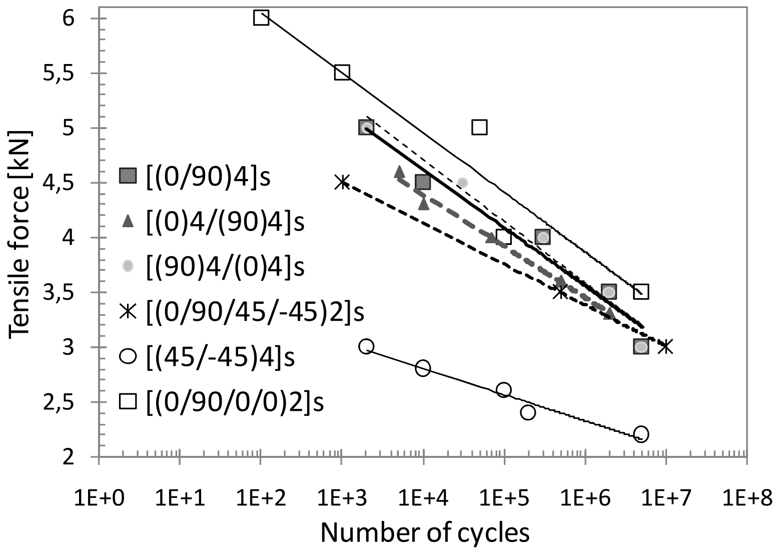


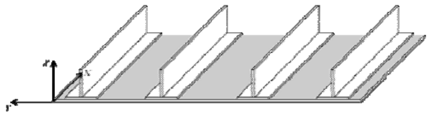
Figure 6. Numerical fatigue life curves of the pinned joints – comparison among configurations $[0_4/90_4]_s$, $[90_4/0_4]_s$, $[45_4/\text{-}45_4]_s$, $[0/90/0/0]_s$, $[0/90/45/\text{-}45]_s$ and $[(0/90)_4]_s$.

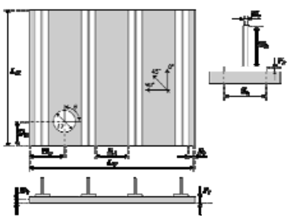
Figure 6 provides interesting information in terms of fatigue behaviour of pinned joints with various stacking sequences. As expected, the performances of the zero-dominated specimen configuration, in terms of fatigue life, is the best among all the others due to the presence of the highest number of 0° oriented plies. An opposite behaviour has been observed for the angle-ply configuration. Indeed this configuration seems to be the weakest one in terms of maximum sustainable tensile load and fatigue life. This is obviously due to the absence of 0° oriented plies which are the most performing plies from a fatigue perspective under tensile loading conditions.

Hence the fatigue life curves associated to the zero dominated and to the angle-ply configurations represent respectively the upper and lower bounds for all the other configurations. The fatigue life curves, found for the cross-ply specimen configurations, are positioned very close to the zero-dominated one. As a matter of fact, the $[90_4/0_4]_s$ specimen configuration performs slightly better than the $[0_4/90_4]_s$ one from a fatigue life perspective. This behaviour is due, as remarked in [4], to the different distribution of contact stresses at pin-hole interface when the 0° or 90° oriented plies are positioned close to the middle plane. Indeed, the configuration with the 0° oriented plies positioned closer to the middle plane, is characterised by reduced global material properties degradation. The quasi-isotropic configuration is characterised by a fatigue life curve positioned between the cross-ply configurations and the angle-ply configuration due to the presence of four 0° oriented plies.

4 Numerical application: delaminated stiffened composite panel

The developed and validated progressive intra-laminar fatigue damage model has been applied to investigate the damage evolution in a stiffened panel with an embedded circular delamination, under compression-compression fatigue loading conditions. The geometrical description, the Finite Element model and the out-of-plane displacement contour plots at the local and global buckling load of the panel are shown in Figure 7. The stacking sequence of the panel's skin is $[(+45/0/90/\text{-}45)_3]_S$, while the stacking sequence of stringers foot and web are respectively [+45/-45/0/0/90]$_S$ and [+45/-45/0/0/90/90/0/0/-45/+45]$_S$. the delamination is placed between the 21st ply and the 22nd ply.





L_Y	Panel Width	*600 mm*
L_X	Panel Length	*500 mm*
S_l	Dist. btw. panel edge and stringer foot	*20.365 mm*
S_d	Dist. btw. Stringers	*116.73 mm*
S_b	Stringer foot Width	*52.27 mm*
P_t	Skin Thickness	*4.512 mm*
F_t	Stringer foot Thickness	*1.88 mm*
W_h	Stringer Web Height	*25.24 mm*
W_t	Stringer Web Thickness	*3.76 mm*
D_Y	Delamination position along *Y*	*131 mm*
D_X	Delamination position along *X*	*125 mm*
D_t	Delamination Depth	*3.948 mm*
D_D	Delamination Diameter	*40 mm*

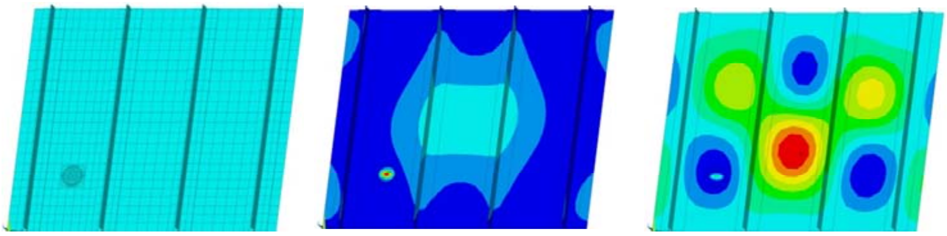


Figure 7. The FEM model of the stiffened panel analyzed (rectangular panel with a [(45,0,90,-45)$_3$]$_s$ layup, four stringers and a embedded circular delamination), with local and global buckling.

The residual properties of the elements depend on the stress ratio, the number of fatigue cycles and the applied compression force. Two numerical analyses are performed. The first simulation is carried out until the local buckling load for each cycle. The second simulation is carried out until the global buckling load for each cycle. In the frame of the first simulation, as expected, only the thin sub-laminate of delamination is subjected to a relevant material gradual degradation and experiences sudden failures. In Figure 8 the development of sudden failure in the delamination area is shown. The thick sub-laminate in the delamination area and the rest of the panel are not substantially affected by fatigue damage, in terms of sudden failure and gradual material properties degradation, due to the low level of applied load.

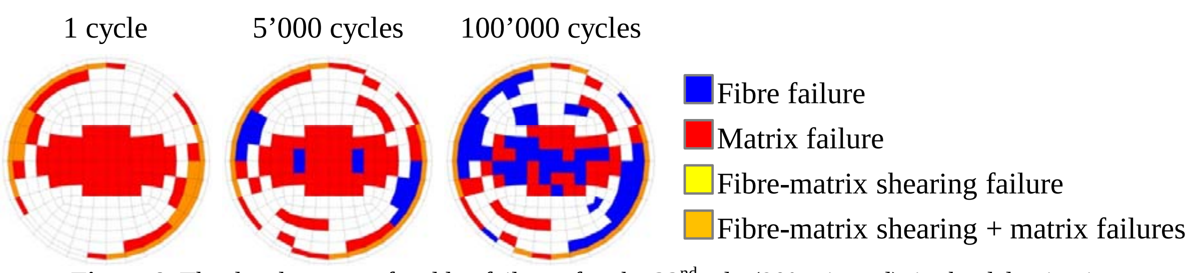


Figure 8. The development of sudden failure of a the 22nd ply (90° oriented), in the delamination area.

The second simulation shows substantially different results, the structure is not able to reach the same number of cycles as in the previous case, due to the higher level of applied load. Indeed, at 5’000 cycles the failure of the panel is reached. The development of sudden failures in the 1st ply (45° oriented) is shown in Figure 9.

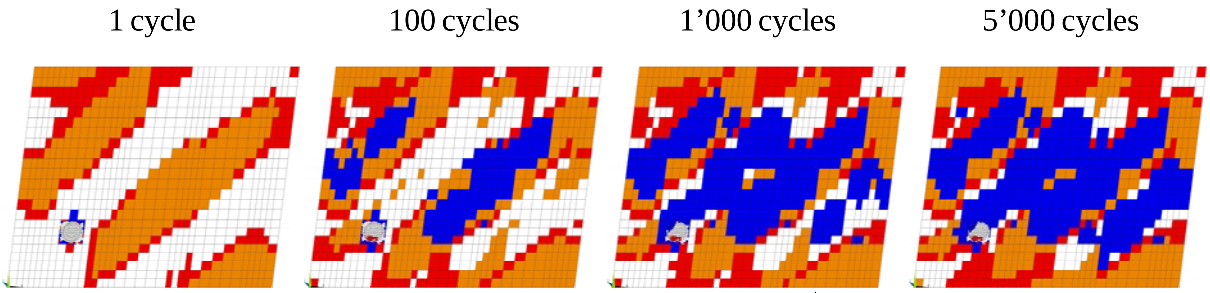


Figure 9. The development of sudden failure of the 1st ply (45° oriented)

5 Conclusions

In this paper, a fatigue damage propagation model based on gradual material degradation rules, Hashin fatigue failure criteria and sudden properties degradation rules has been introduced and implemented in ANSYS by means of the APDL based subroutines.

The developed numerical tool has been preliminary validated against literature experiomental results on pinned composite joints. The obtained numerical results and the experimental data taken from literature for these three configurations were found to be in excellent agreement for different values of the maximum applied tensile force. Moreover the fatigue damage distribution at failure obtained with the numerical model showed a good correlation with the experimental failure modes experimentally observed. A further sensitivity analysis on the influence of the stacking sequence on the lamina failure and on the material properties gradual degradation has been carried on six pinned joint configurations with different lay-up.

The developed model, which has been demonstrated capable to effectively and accurately predict the fatigue intra-laminar failure propagation in composite pinned joints, has been used to investigate the fatigue intra-laminar damage propagation in a delaminated stiffened panel. Two numerical simulations are performed. The first simulation is carried out up to the local buckling load for each cycle. The second simulation is carried out up to the global buckling load for each cycle. In the frame of the first simulation, as expected, only the thin sub-laminate of delamination is subjected to a relevant material gradual degradation and experiences sudden failures. While in the frame of the second simulation a global area affected by intra-laminar damage is appreciable and the computed fatigue life is 5000 cycles.

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