Comparison of fatigue damage criteria for a CFRP aeronautical joint subjected to random fatigue load

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Abstract. The fatigue life prediction of components in CFRP subjected to random fatigue load was carried out considering different fatigue damage models. The selected component is a filled hole tension specimen, which is representative of the typical aeronautical riveted joint. The stress state of the riveted section was determined through a FEM model, created with CODE ASTER. Subsequently, the fatigue load history was introduced, calculating the stress field for the different load levels. Applying the constant life diagrams, fatigue cycles were counted and the damage was evaluated. Finally, the damage that occurs in the different ply of the specimen was calculated using different fatigue damage criteria present in literature. The creation of a parametric FEM model offers the possibility of optimizing the study and constitutes a useful tool in order to choose the most suitable damage criteria for the particular geometry and loading mode of the component. Moreover, different severity of the load history and different load sequence were introduced to show their effect in the fatigue failure.

Keywords: CFRP, damage, fatigue, FEM

1. Introduction

Within the aeronautical and aerospace industry, the use of composite materials is assuming increasingly important positions; the trend is to increase the percentage of composite materials used in the construction of an aircraft, exploiting the high mechanical characteristics that these materials offer to front with a lower specific weight than metallic materials; in fact, a composite material structure weighs less than a light alloy structure of equal strength [1, 2, 3]. The progressive replacement of the material used to make the structures and sub-structures of an aircraft has introduced, in addition to many advantages of a structural nature, various problems related to different aspects such as design and production. In particular, the use of a composite material introduces novelties regarding the failure modes and the fatigue life that differ considerably from what happens in metallic materials, mainly for two reasons: the different behaviour, given that the composite material is anisotropic, at the most orthotropic, while a metal is isotropic, and the inhomogeneity of the composite material with respect to the metal material. These two aspects introduce a whole series of structural problems different from metallic materials [4].

A very important aspect is that of the junctions: the different structures that make up an aircraft are joined together through junctions and are also made up of smaller parts joined together in different ways...
depending on the type of loads, of the form and function they must perform [1, 2]. Composite materials basically have two ways of joining: bonded joints and riveting and / or bolting joints, in which rivets or bolts are used, usually in titanium alloy, to mechanically join two or more parts together. The difference between the two types of joint is that the first type of joint cannot be dismantled except by damaging the parts connected between them, while the second type allows the joint to be disassembled without damaging the connected parts. These two types of connection between the parts introduce complications in the behaviour of a structure. In particular, the presence of holes, necessary for making a connection with rivets or bolts, introduces a concentration of stresses on the edge of the hole which tend to reduce the static and fatigue resistance of the component [1, 4, and 5]. This effect of reducing the resistance, due both to a reduction of the resistant section and to the cutting effect at the edges of the hole, interacts with the presence of the rivet inside the hole, which tends to modify the rigidity of the component due to the obstacle action that it carries out against the tendency of the hole to reduce its dimension in a transverse direction with respect to the load. Evaluations of this type are very important in the fatigue resistance, a fundamental aspect in the service life of the joint. In particular, the damage due to a fatigue stress in components of this type is substantially modified by the presence of a foreign body such as a rivet. Consequently, it is important to evaluate how the damage is calculated, which can have different values depending on the criterion used for its count.

In the bibliography there are some works that have dealt with similar issues. Payan et al. [6] developed a cumulative nonlinear damage model in order to evaluate laminated carbon/epoxy composites under static and fatigue loading. Instead, Subramanian et al. [7] have defined a new parameter in the evaluation of the fatigue damage that occurs at the interface of composite specimens subject to tensile fatigue, calling it “interface efficiency”, which evaluates the degradation of the interface between the sheets of a specimen subject to fatigue. Van Paepegem et al. [8] have introduced the skip-the-cycle approach to calculate the damage in fiberglass specimens to overcome the problem of redistribution of stresses within the specimen as the damage progresses and limit the computational cost of numerical simulations on fatigue. Also, Papanikos et al. [9] developed a numerical model with three-dimensional elements on ANSYS that evaluates the fatigue life of fiber-reinforced plastic components, using the Hashin damage criterion and the Ye delamination criterion. On the joints, Zhao et al. [10] have developed a numerical model to evaluate the degradation of material properties as the imposed fatigue cycles advance.

It is evident that it is necessary to be able to numerically evaluate the damage that occurs in components subjected to fatigue loads. The present work comes from this consideration: the numerical results given by the application of different criteria for the calculation of the damage due to the application of random fatigue loads are compared, in order to evaluate which of them is more appropriate in estimating the damage and how this is affected by the load history sequence. The applied load history is derived from a load spectrum multiplied by a load constant. In this way it is also possible to define the absolute level of the load history needed to produce a unitary damage in the specimen. This document reports a preliminary work for the evaluation of the damage in a CFRP specimen that simulates a riveted joint.

2. Geometry and material

The specimen consisted of 16 plies in CFRP with a stacking sequence [45/0/45/0/0/45/0/45]. In the centre there is a hole with a conical part, in which a titanium alloy Ti6Al4V rivet is housed, in order to evaluate the interaction of composite and rivet of an aeronautical joint. The rivet has some clearance inside the hole. In addition, the specimens are equipped with tabs at the ends for gripping the test machine (Figure 1 and Figure 2).
Figure 1. Top view (a) and bottom view (b) of the specimen with the rivet

![Axonometric view of the riveted specimen](image)

Figure 2. Axonometric view of the riveted specimen

The mechanical characteristics of CFRP material are shown in Table 1, indicating the ones that have been hypothesized assuming they are similar to the mechanical characteristics of other similar materials.

| Table 1. Mechanical characteristics of specimen material |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| **E_{11}** & 60535.97 MPa & available |
| **E_{22}** & 58398.59 MPa & available |
| **E_{33}** & 8756 MPa & unavailable |
| **G_{12}** & 4378.17 MPa & available |
| **G_{13}** & 2700 MPa & unavailable |
| **G_{23}** & 2700 MPa & unavailable |
| **v_{12}** & 0.34 & unavailable |
| **v_{13}** & 0.545 & unavailable |
| **v_{23}** & 0.545 & unavailable |
| **UTS_{1}** & 743.53 MPa & available |
| **UCS_{1}** & 739.66 MPa & available |
| **E_{c,1}** & 58881.22 MPa & available |
| **UTS_{2}** & 625.35 MPa & available |
| **UCS_{2}** & 694.99 MPa & available |
| **E_{c,22}** & 55847.53 MPa & available |

3. Numerical model
The numerical model of the central area of the specimen has been built, as damage occurs in this area due to the stress concentration induced by hole. The useful length reported in the numerical model is 60
mm in total, with the hole positioned at the centre of this length. The numerical model was developed with the FEM Code Aster, which uses Salome - Meca as a pre-processing environment and Paravis as a post-processing environment.

Modeling is based on the use of 3D elements to reproduce each lamina and the rivet. The elements for composite material have a quadratic form function, while linear elements have been used for the rivet. Two different meshes were performed: mesh mapped for the laminas that make up the composite material and tetrahedral free mesh for the rivet. This choice was made because the results related to the rivet in terms of stress and strain are not relevant, while a mapped mesh for the edges allows to obtain more robust results and to better manage the post processing phase. The model thus produced has a total number of nodes equal to 11177 and a total number of three-dimensional elements equal to 2818, of which 574 tetrahedral elements relating to the rivet and 2244 hexahedral elements relating to the CFRP specimen (Figure 3). The numbering of the plies start from above, with the ply 1 corresponding to the rivet head.

![Figure 3. Numerical model](image1)

3.1. Constraints and load history
The specimen was fully constrained to one end blocking all DOFs. On the load application side, transverse displacements with respect to the direction of application of the load have been blocked and the relative motions between the nodes of the load application face. Furthermore, the motion of the rivet in the z direction (parallel to the axis of the rivet) and the transverse motion have been blocked, in order to have congruence in the simulation of the contact between the internal surface of the hole and the rivet (Figure 4).

![Figure 4. Constraints and load for the numerical model](image2)

The load was applied on the opposite end to the constrained one, using a surface force. The load consists of a load history that simulates the actual stress state that the component would receive during its service. There are several load histories used in the literature to evaluate the random fatigue life of
CFRP components. Schön et al. [11] used a load history with different R load ratios, modifying the load history based on the damage that was achieved in representative bolted joint specimens. In the aeronautical field, especially military, the FALSTAFF spectrum [12] is widely used, which is a particular pseudo-random spectrum equivalent to 200 aircraft flights. In order to be general, it is a scalable load spectrum based on the application for which it is used.

Observing the load spectrum reported in the work conducted by Schön et al. [11], a simple load spectrum was considered for the case in question, in order to highlight the influence that the sequence of application of the load levels has in the generation of fatigue damage. In particular, a load spectrum was designed consisting of five blocks formed by two load levels each, with a load ratio \( R = 0.1 \) and prevailing traction for all the blocks, as shown in Figure 5a. Taking up the distribution of loads in the spectrum reported in the same work, we have given a higher frequency of occurrence at low loads and a lower frequency of occurrence at higher loads (Figure 5b).

![Figure 5. Example of load spectrum levels (a) and cumulative load diagram (b)](image)

Being a spectrum, in order to have the load history to be applied and all the load levels, it is necessary to multiply the levels of the spectrum by a scale factor. In this way it is possible to evaluate for which combination of loads there is the unitary damage that marks the failure of the component.

The calculation of the fatigue damage was considered over a total number of cycles equal to \( 10^6 \) cycles. Knowing this data, three load histories have been constructed, with the characteristic of having a normal distribution of the intervention frequency of each single block constituting the load history itself. By identifying the blocks with the numbers 1, 2, 3, 4, 5, the following load histories were generated.

| Table 2. Load spectrum 1 |
|--------------------------|
| **Block ID** | 1 | 2 | 3 | 4 | 5 |
| **Number of repetitions** | 660000 | 120000 | 120000 | 60000 | 40000 |

| Table 3. Load spectrum 2 |
|--------------------------|
| **Block ID** | 5 | 4 | 3 | 2 | 1 |
| **Number of repetitions** | 40000 | 60000 | 120000 | 120000 | 660000 |

| Table 4. Load spectrum 3 * |
|--------------------------|
| **Block ID** | 1 | 2 | 3 | 4 | 5 | 4 | 2 | 3 | 1 | 5 | 2 | 4 | 1 |
| **Number of repetitions** | 220 | 60 | 60 | 20 | 10 | 20 | 40 | 60 | 300 | 30 | 20 | 20 | 140 |

* This load spectrum has a total of 1000 cycles. It will be repeated 1000 times to reach \( 10^6 \) expected cycles
3.2. Contact
The presence of the rivet provides for the simulation of the contact between the external surface of the rivet and the internal surface of the hole. This is because the rivet is not always in adherent contact with the internal surface of the sample hole, there is no type of adhesion between the surfaces. The presence of the rivet intervenes in the overall stiffness of the specimen since, depending on the type of stress to which the specimen is subjected, some areas of the rivet surface come into contact or not with the internal surface of the hole.

For example, in the case of traction, the rivet is in contact with the internal surface of the hole in a transverse direction with respect to the direction of application of the load while it has no contact in the longitudinal direction, as can be seen in Figure 6.

![Figure 6. Contact zone between specimen and rivet for tensile load](image)

The modelling of the contact introduced some geometric non-linearities which required the resolution of the problem in the non-linear field.

4. Damage criteria
The stress state resulting from the FE model was used to evaluate the fatigue damage induced by the three different load sequences. For this reason it is useful to calculate the damage that occurs after the application of a random load history for a total of $10^6$ cycles. Among the different criteria present in the literature, three criteria have been chosen for the evaluation of damage. The results of the chosen criteria will be compared, in order to evaluate which of them best approximates the calculation of the damage to the material. The choice of criteria was made on the basis of the data available on the material of the specimen.

The first criterion chosen is the classic Palmgren - Miner [13, 14], which expresses the damage as:

\[ D = \sum_i D(\sigma_{ai}) \]  

where $D$ indicates the cumulative damage given by the sum of the single damages that are generated for the cycles performed at a stress amplitude equal to $\sigma_{ai}$. The single damage due to these $n_i$ cycles compared to the total number of cycles $N_i$ executable for that load level can be evaluated according to the following equation:

\[ D(\sigma_{ai}) = \frac{n_i}{N_i} \]  

The second criterion chosen is that of Bond - Farrow [15], which is a generalization of the damage criterion of Owen - Howe [16]. The calculation model is expressed by the following equation:
\[ D = \sum_i \left[ A \left( \frac{n_i}{N_i} \right) + B \left( \frac{n_i}{N_i} \right)^C \right] \]  

Parameters \( A, B \) and \( C \) depend on the mechanical properties of the material, i.e. UTS, UTC and Young's modulus under compression \( E_c \) (Table 1). The terms for calculating the parameters change depending on whether you are in prevailing traction or prevailing compression conditions.

Both these criteria do not consider the effect of the sequence of application of the load levels.

The third criterion is that of Hashin - Rotem [17]. In this case, the authors approached the problem from a different point of view: in fact their method is based on the introduction of the concept of residual life time which, unlike the damage parameter \( D \), is a measurable quantity. The damage is evaluated later.

This approach can be summarized in the equation that expresses the damage \( D_i \) achieved at the end of the \( i \)-th loading step in a multi-step sequence:

\[ D_i = D_{i-1} \left( 1 - \frac{s_i}{S} \right) + \frac{n_i}{N_i} \]  

where \( s_i = \sigma_i / \sigma_s \), with \( \sigma_i \) is the \( i \)-th stress and \( \sigma_s \) the static failure stress.

The correct application of these criteria require the knowledge of the curves with constant life for each load ratio \( R \), which have been assumed on the basis of the non-dimensional constant life curves reported by Harris et al. [18]. Since these curves are dimensionless with respect to the maximum tensile and compressive failure stresses, they have been reconstructed numerically with a Python routine for the material in question. By plotting different lines for different \( R \), the necessary parameters were calculated to be able to evaluate the number of limit fatigue cycles \( N \) for each \( R \) needed to calculate the damage. Figure 7 shows the reconstruction of the constant life curves for the specimen material.

![Figure 7. Constant life curves for principal direction 1 of the specimen material rebuilt with Python](image-url)
5. Discussion of results

Numerical simulations of the static type and for the calculation of the damage were carried out. The first simulation was carried out with a static tensile load to determine which areas of the specimen were most stressed both in tension and in compression. Starting from the results obtained statically for a maximum load level, the stress values for the nodes belonging to each ply in the most stressed areas were extracted. These tensions, extracted for each load level constituting the load history, were used for the calculation of the damage developed through Python routines for each of the considered criteria.

5.1. Static numerical result

A numerical simulation with static load was performed to evaluate the stress state of the specimen and to evaluate the behavior of the contact in the interface between specimen and rivet. The load applied for the execution of the static simulation is approximately equal to 70% of the static resistance in tension.

![Figure 8](image8.png)

**Figure 8.** Stress field for first direction for 0° ply (a) and 45° plies (b)

![Figure 9](image9.png)

**Figure 9.** Detail view of the stress field for first direction around the hole for 0° plies (a) and 45° plies (b)

By observing the stress field of the specimen, it can be seen how this changes as a function of the orientation of the ply considered. In particular, in the case of 0° plies it was found that the areas with the highest stress values are in correspondence of the hole edges (Figure 8a and 9a), in transverse direction (along the y direction), with a symmetrical distribution of the stress field in the x direction, while in the case of the 45° plies the area with the greatest stresses are always at the edges of the hole but in a position rotated by about 45°(Figure 8b and 9b), with an anti-symmetrical distribution respect to what is observed for the 0° plies. This observation holds for both stresses in the x direction and for stresses in the y direction. These are the directions that have been considered for the subsequent fatigue damage calculation. These observations are independent of the ply considered, net of the calculated tension value, as they depend only by the fibres orientation. The following Figure 10 shows a detail view of the
stress field of the specimen near the hole, which highlights the different behaviour between the plies based on the orientation.

The static calculation shows that the highest stress is obtained in correspondence of ply 7, near the hole. This is attributable both to the stress concentration effect that occurs in abrupt changes in shape and to the fact that the hole has a countersunk part which determines, even in the cross section, a concentration of stresses due to the change in shape.

5.2. Comparison of the damage assessment
Starting from the calculated stress state, the damage for some plies have been calculated and reported in Table 5, considering as the area of interest that near the hole, which already statically present high levels of tension. Figure 11 shows the nodes around the hole for which the damage assessment was conducted according to the chosen criteria.

![Figure 10. Detail view of the specimen stress field in first direction near the hole](image)

![Figure 11. Nodes near the hole where the damage was calculated](image)
The calculation of the damage according to the three chosen criteria was performed with routines written in Python. The choice of plies to be considered was made by choosing those that presented a significant level of damage in tension and compression. Given the considerable amount of data produced, only the damages calculated for the gifts belonging to ply 7 and ply 8 are reported. The nodes considered are those most stressed both in tension and compression. Their position is shown in Figure 12.

![Diagram of Ply 7 and Ply 8 with nodes and directions](image)

**Figure 12.** Location of the nodes whose damage values are reported

| Table 5. Damage values calculated according to the chosen criteria – Load History 1 |
|---|---|---|---|---|
| Ply | Node | Direction | Palmgren - Miner | Bond - Farrow | Hashin - Rotem |
| 7 | 1 | 1 | 3.0662927 e-52 | 4.6016950048 e-52 | 7.65221368 e-57 |
| 2 | 2 | 1.6364842 e-18 | 3.210328717 e-16 | 4.0824303644 e-23 | 0.259993539 |
| 3 | 1 | 1 | 0.26207761 | 0.505624788 | 7.652213678 e-57 |
| 2 | 2 | 1.214698356 e-37 | 1.956178897 e-33 | 3.030936211 e-42 |
| 4 | 1 | 1 | 0.2585824614 | 0.498864494117 | 0.2599934518 |
| 2 | 2 | 1.49219233 e-37 | 2.35378396 e-33 | 3.7237949436 e-42 |
| 5 | 1 | 1 | 8.165656835 e-34 | 1.328126355 e-33 | 2.0372336714 e-38 |
| 2 | 2 | 4.6172964965 e-35 | 4.098411942 e-31 | 1.152780466 e-39 |
| 6 | 1 | 1 | 6.92191788 e-11 | 1.261282077 e-10 | 1.72217459 e-15 |
| 2 | 2 | 6.30057584 e-19 | 1.3590426965 e-16 | 1.57218388 e-23 |
| 7 | 1 | 1 | 7.92911904 e-34 | 1.289576451 e-33 | 1.9781601 e-38 |
| 2 | 2 | 4.0815362406 e-35 | 3.66811335 e-31 | 1.0189561922 e-39 |
| 8 | 1 | 1 | 6.888041184 e-11 | 1.2587402238 e-10 | 1.718178515 e-15 |
| 2 | 2 | 6.027049168 e-19 | 1.305836585 e-16 | 1.503891228 e-23 |
By observing the data reported in the tables for ply 7 and ply 8, it can be observed that the damage is relevant only for some nodes. It is evident that the damage begins near the edge of the hole and then spreads to the rest of the section.
Finally, a comparison was made for different load history of the damage criteria considering the damage that occurs in node 4 belonging to layer 7, which is the node that presents the highest damage at the change in shape of the cross section and of the hole.

![Damage Comparison](image)

**Figure 13.** Comparison of damage levels calculated according to the criteria chosen for the three load histories

From the histograms shown in Figure 13a and 13b it can be seen that the damages calculated with the Palmgren - Miner and Bond - Farrow criteria always show the same values as the load application sequence varies. Instead, the Hashin - Rotem criterion (Figure 13c) highlights a damage value that is substantially affected by the load application sequence.

6. Conclusion

In the field of the study of the fatigue behavior of composites, it is of fundamental importance to be able to predict with a certain accuracy the damage that occurs when a component is stressed with a random load history. The calculation of the damage can be carried out according to criteria that evaluate the progress of the same as the load history advances, basing it on the sequence of stresses that the load history produces.

To evaluate the influence that the load application sequence has on the calculated damage, a numerical model of a CFRP specimen with a titanium alloy rivet, representative of an aeronautical joint, was created. Three load histories have been assigned with the same load levels but with a different load application sequence. From the static analysis of the specimen, it was found that the most stressed area is near the edge of the hole, due to the double change in shape of the section due to the presence of the hole itself and to the profile of the hole, which houses a rivet with head flared. The load level at which there was a maximum stress slightly lower than the ultimate tensile stress due to fatigue is equal to 26kN. The damage was then calculated according to three criteria found in the literature and chosen on the basis of the information available on the material of the specimen.
In conclusion, it was found that among the three criteria considered, that of Hashin - Rotem is the one that best evaluates the damage in the case of different load application sequence, allowing a better assessment of the damage. Furthermore, it must be remembered how this work was carried out without taking into account the damages that occur in the composites, such as delamination, and the redistribution of stresses in the case of damage in one point, which greatly affect the effective fatigue resistance.

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