

Study on Fatigue Performance of Composite Bolted Joints with Bolt-Hole Delamination

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Abstract. Fatigue performance of composite structure with imperfections is a challenging subject at present. Based on cohesive zone method and multi-continuum theory, delamination evolution response and fatigue life prediction of a 3D composite single-lap joint with a bolt-hole have been investigated through computer codes Abaqus and Fe-safe. Results from the comparison of a perfect composite bolted joint with another defect one indicates that a relatively small delamination damage around the bolt hole brings about significant degradation of local material performance. More notably, fatigue life of stress concentration region of composite bolted joints is highly sensitive to external loads, as an increase of 67% cyclic load amplitude leads to a decrease of 99.5% local fatigue life in this study. However, the numerical strategy for solving composite fatigue problems is meaningful to engineering works.

1. Introduction

Throughout the last four decades the application of composite materials in engineering structures has been steadily growing from sports equipment and high performance racing cars, to helicopters and commercial aeroplanes. These large-scale mechanical structures generally consist of thousands of small parts which are fastened together to create the final assembly. Different from metals, composite material features a pronounced notch sensitivity which especially develops under quasi-static loading. However, composite bolted joints stand out due to their excellent fatigue resistance and a residual strength as a consequence of inherent material softening mechanisms. What's more, bolted connection is efficient, reliable and economical. Thus bolted joints are one of the most common elements in construction and machine design using composite materials. Grinding and drilling holes are the most frequently employed operations of secondary machining for composite materials owing to the need for structure joining. One of the major problems during grinding and drilling is the delamination damage caused by the tool thrust. The delamination causes concentrated stresses and compromises the mechanical properties of the finished part but, more importantly, it may lead to reduced load-bearing capacity and fatigue failure.

The origin of this study lies within the framework of an industrial agreement to study the fatigue performance of composite bolted joints with delamination around its bolt hole. There are three kinds of approaches for the study of composite delamination under fatigue loading: phenomenological fatigue damage models, semiempirical models based on experiments and numerical simulation approach using finite element method (FEM). Phenomenological fatigue damage models predicts fatigue damage growth according to residual stiffness or residual strength whose evolution rules are based on experiment phenomenons.



Phenomenological models are commonly applied in Engineering, but they model the fatigue behavior of composite materials by a single continuum, occasionally anisotropic, whose constitutive constants are chosen in such a way that the behavior of the single continuum provides an approximation to the behavior which takes no consideration of inner damage mechanism of each constituent material and their interactions. There are a vast amount of literatures providing phenomenological fatigue damage models for many kinds of composite materials [1-5]. Semiempirical models study fatigue process using some parameters from experiment according to theory of continuum damage mechanics or microscopic damage mechanics. Semiempirical models based on continuum damage mechanics establish the damage evolution equation on the basis of the thermodynamic potential function and the dissipative potential energy function which is related to the generalized force. And the damage varies in accordance with the generalized force, which could be derived from the rate of change of the dissipative potential energy function [6-7]. Semiempirical models based on microscopic damage mechanics start from local stress state, combine the typical damage units, such as the micro-cavity, the micro-cracks and the shear band, and then give the rules of deforming and damage evolution for the combined typical damage units. Subsequently, we can reflect the macroscopic damage mechanism to meso mechanical behavior through the mechanical averaging methods, which makes it possible to predict directly the fatigue life and other characteristics of composite structures [8-10]. Numerical methods are always effective and convenient to give reasonable solutions for most engineering problems with various initial conditions and boundary conditions, among which FEM is most commonly used. Generally, the process of composite fatigue includes stiffness degeneration, Stress redistribution, damages accumulation, delamination growth and macroscopic failure. FEM relates variation of stiffness with fatigue process and then gives stress analysis, failure analysis and material performance degradation of structures [11-13]. Of all the three kinds of methods, Numerical methods are more cost-effective and time-consuming, thus present study makes an attempt to evaluate fatigue performance of composite bolted joints with bolt-hole delamination utilizing commercial codes.

2. Numerical approach

In this paper, commercial codes are used to analyze fatigue performance of composite bolted joints with bolt-hole delamination. Two parts are considered, the first part is the delamination initiation simulation of composite bolted joints by using commercial software abaqus, and the second part is fatigue analysis of the composite bolted joints with initial delamination damage by using commercial software fe-safe. Simulation of the first part utilized cohesive zone model approach and analysis of the second part is based on multicontinuum theory (MCT). Results of the first part are initial states of the second part.

2.1. Cohesive zone model approach

For the production of composite structures, machining operations like drilling are frequently needed in composite structures, as the use of bolts, rivets or screws is required to join the parts. Generally, machined parts have poor surface appearance due to material anisotropy and low interlaminar shear strength. One of the most common problems is the elamination damages around the drilling holes, which can decrease the performance of the composite structure. For this issue in simulation works, abaqus applied a cohesive zone model (CZM) approach which has given satisfactory results for simulation of the initiation and propagation of delamination damage. Cohesive damage zone models relate tractions, τ , to displacement jumps, $\bar{\Delta}$, at an interface where a crack may occur. Damage initiation is related to the interfacial strength τ^0 . When the area under the traction-displacement jump relation is equal to the fracture toughness, G_c , the traction is reduced to zero and new crack surfaces are formed. If a linear softening law is used, the new crack surfaces are completely formed when the displacement jump is equal to, or greater than, the final displacement jumps $\bar{\Delta}^f$ (see Fig.1):

$$\begin{cases} \tau = (1-\bar{d})\tau^0 & \bar{\Delta} < \bar{\Delta}^f \\ \tau = 0 & \bar{\Delta} \geq \bar{\Delta}^f \end{cases} \quad (1)$$

In the cohesive damage model, the damage variable $\bar{d}$ describes the density of microcracks of representative element surface, when $\bar{d}=0$, the element has no damage, when $\bar{d}=1$, the whole element collapses. Then, the damage variable can be interpreted as the ratio of the damaged area, A_d , with respect to the area A^e associated with the local discretization. In the context of finite elements, the area A^e represents the area of the element (or that of an integration point). Using the linear softening law represented in Fig. 1, this ratio is a function of the energy dissipated during the damage process Ξ , and of the critical energy release rate G_c . The damage variable can be expressed as

$$\bar{d} = \frac{A_d}{A^e} = \frac{\Xi}{G_c} \quad (2)$$

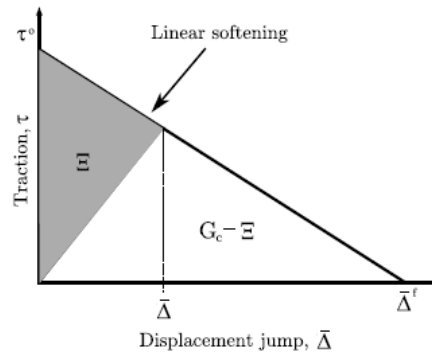


Figure 1. Linear softening law for a cohesive zone model approach.

2.2. Damage evolution criteria

Damage evolution criteria for none cohesive zones apply Hashin's failure criteria in which the failure modes are as follows.

- 1) Tensile fibre failure for $\sigma_{11} \geq 0$

$$\left(\frac{\sigma_{11}}{X_T} \right)^2 + \frac{\sigma_{12}^2 + \sigma_{13}^2}{S_{12}^2} = \begin{cases} \geq 1 & \text{failure} \\ < 1 & \text{no failure} \end{cases} \quad (3)$$

- 2) Compressive fiber failure for $\sigma_{11} < 0$

$$\left(\frac{\sigma_{11}}{X_C} \right)^2 = \begin{cases} \geq 1 & \text{failure} \\ < 1 & \text{no failure} \end{cases} \quad (4)$$

- 3) Tensile matrix failure for $\sigma_{22} + \sigma_{33} > 0$

$$\frac{(\sigma_{22} + \sigma_{33})^2}{Y_T^2} + \frac{\sigma_{23}^2 - \sigma_{22}\sigma_{33}}{S_{23}^2} + \frac{\sigma_{12}^2 + \sigma_{13}^2}{S_{12}^2} = \begin{cases} \geq 1 & \text{failure} \\ < 1 & \text{no failure} \end{cases} \quad (5)$$

- 4) Compressive matrix failure for $\sigma_{22} + \sigma_{33} < 0$

$$\left[\left(\frac{Y_C}{2S_{23}} \right)^2 - 1 \right] \left(\frac{\sigma_{22} + \sigma_{33}}{Y_C} \right) + \frac{(\sigma_{22} + \sigma_{33})^2}{4S_{23}^2} + \frac{\sigma_{23}^2 - \sigma_{22}\sigma_{33}}{S_{23}^2} + \frac{\sigma_{12}^2 + \sigma_{13}^2}{S_{12}^2} = \begin{cases} \geq 1 & \text{failure} \\ < 1 & \text{no failure} \end{cases} \quad (6)$$

Where, σ_{ij} denote the stress components and the tensile and compressive allowable strengths for lamina are denoted by subscripts T and C, respectively. X_T , Y_T , Z_T denotes the allowable tensile strengths in three respective material directions. S_{12} , S_{13} and S_{23} denote allowable shear strengths in the respective principal material directions.

2.3. Multicontinuum theory

Fe-safe is a robust and computationally efficient tool for predicting fatigue life in composite structures. By utilizing an Multicontinuum theory (MCT), fe-safe helps to get access to constituent level fatigue behavior in a full-scale structural analysis, which is difficult for conventional structural analysis, see figure 2. The fundamental premise underlying continuum mechanics is that any physical quantity of interest can be evaluated at a material point by averaging the quantity over a representative volume element that surrounds the point of interest. The size of this representative volume element (RVE) must be very small compared to the overall physical dimensions of the material body, yet large enough to provide an accurate statistical representation of the quantity within the body's material microstructure. For typical unidirectional, fiber reinforced composites, the fibers tend to have a somewhat random spacing within the matrix material. Therefore, the RVE used to characterize a material point must be large enough to contain numerous fibers to provide an accurate statistical representation of any quantity averaged over the RVE. However, for the sake of computational expediency, it is common practice to assume a uniform fiber distribution that represents the actual random fiber distribution in some statistically meaningful sense. This assumption of uniform fiber spacing permits the RVE to economically be represented by a single unit cell with periodic boundary conditions. [14].

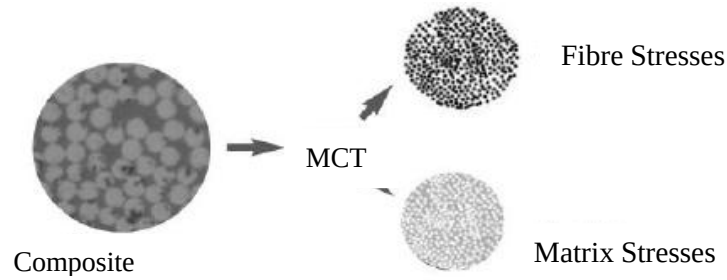


Figure 2. Composite lamina as a multicontinuum.

2.4. Fatigue failure criterion

The current constituent level failure criteria are based on revised failure criteria originally proposed by Mayes [15]. He developed a simple quadratic stress-based failure criteria to predict constituent failure within a composite lamina.

$$\pm A_1^f (I_2^f)^2 + A_4^f I_4^f = 1 \quad (7)$$

$$\pm A_1^m (I_1^m)^2 - \pm A_2^m (I_2^m)^2 + A_3^m I_3^m + A_4^m I_4^m - \pm A_5^m I_1^m I_2^m = 1 \quad (8)$$

Where

$$\begin{aligned} I_1 &= \sigma_{11} \\ I_2 &= \sigma_{22} + \sigma_{33} \\ I_3 &= (\sigma_{22})^2 + (\sigma_{33})^2 + 2(\sigma_{23})^2 \\ I_4 &= (\sigma_{12})^2 + (\sigma_{13})^2 \end{aligned} \quad (9)$$

In above equation, the quantities I_j^α ($j = 1, 2, 3, 4, 5$) are transversely isotropic invariants of the matrix average stress state. $\alpha = f$ for fiber, $\alpha = m$ for matrix. The coefficients A_j^m and A_j^f , leading the invariants, are constituent failure parameters, generally derived from experimentally determined composite ultimate strength data through correlation with the MCT decomposition. The $\pm$ signs in these equations indicate a dependence of the parameter on tensile versus compressive stress. Details on the computation of these parameters for the analyses presented

here-in may be found in Kenik [16].

3. Finite element model

Consider a half piece of a composite(T800H-2500-RT) single lap joint with a bolt hole in the center, see figure3. $L=240\text{mm}$, $W=36\text{mm}$, $H=3\text{mm}$. Radius of the hole is 3mm. The layer construction of the plate from top to bottom is $[45^\circ/0^\circ/-45^\circ/0^\circ/90^\circ/0^\circ/45^\circ/0^\circ/-45^\circ/0^\circ]_s$. Construct the initial delamination damage around the bolted hole by cutting off two elliptical defects, see figure 4. The two defects are located respectively at the bottom of the first layer and the second layer with a depth of 0.01mm. Their major radius and minor radius are 6mm and 4.5mm. As delamination damage degrades material property of the top two laminar layer, mainly on adhesive layers, two 0.01mm thin geometry layers with the same level of the elliptical defects were spilt from the plate. This two geometry zones were assigned as cohesive zone. Thus this two thin layers were applied with mesh category of COH3D8. The rest zones of the plate were applied with mesh category of SC8R. The left side of the plate is clamped, the right side is exerted with a linear displacement loading which is 2mm. A dynamic explicit method was used to compute the field variables with the time period of 0.001s. Material properties are listed in table 1 and table 2.

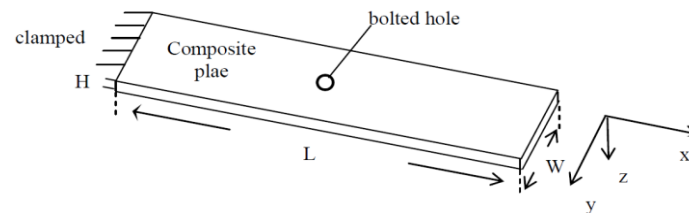


Figure 3. Composite plate with a bolted hole.



(a) delamination zone at top laminar layer. (b) delamination zones at 2nd laminar layer.

Figure 4. Shapes of delamination zones for composite plate with bolted hole.

Table 1. Material properties of composite plate with a bolted hole.

Material		T800H-2500-RT			
Elastic properties		Strength		Fracture toughness	
$E_1(\text{GPa})$	153	$X_t(\text{MPa})$	2537	$G_{1C}^T(\text{N/mm})$	91.6
$E_2=E_3(\text{GPa})$	10.3	$X_c(\text{MPa})$	1580	$G_{1C}^C(\text{N/mm})$	79.9
$\nu_{12} = \nu_{13}$	0.3	$Y_t(\text{MPa})$	82	$G_{2C}^T(\text{N/mm})$	0.22
ν_{23}	0.4	$Y_c(\text{MPa})$	236	$G_{2C}^C(\text{N/mm})$	1.1
$G_{12} = G_{13}(\text{GPa})$	6	$S_{12} = S_{13}(\text{MPa})$	90	$G_s(\text{N/mm})$	0.7
$G_{23}(\text{GPa})$	3.7	$S_{23}(\text{MPa})$	40		

Table 2. Properties of cohesive zones.

Properties of cohesive elements	Mode I	Mode II	ModeIII
Normalized elastic modulus (GPa)	120	43	43
Interlaminar strength (MPa)	30	80	80
Interlaminar fracture toughness (N/mm)	0.52	0.92	0.92

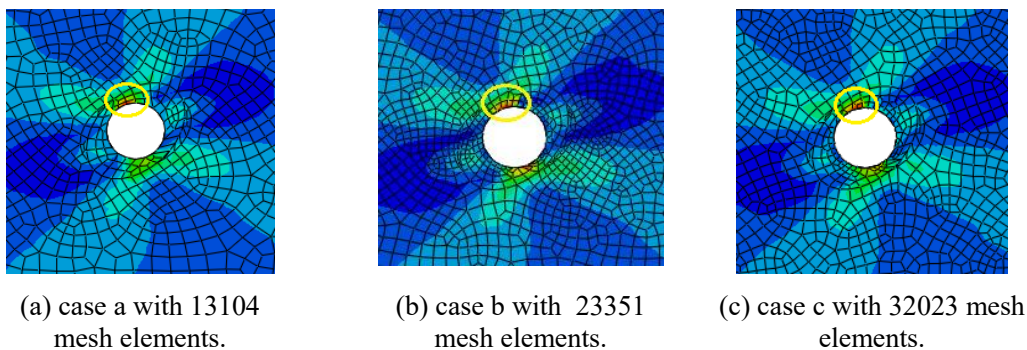
4. Results and discussion

A mesh convergence study was carried out to ensure that the results of FEA models are reliable, see table 3. As the results show, the max Mises stress varies little after the mesh number exceeding 10^4 . In the subsequent work, a model with 23351 meshes elements is adopted, comprehensively considering the computing efficiency and accuracy.

Table 3. Max Mises stress for cases with different amount of meshes.

sample	Number of meshes	Max Mises stress
1	13104	2421.44
2	23351	2435.06
3	32023	2438.38

To implement fatigue analysis, acquiring initial stress or strain distribution is of vast important, especially for stress concentration region near the bolted hole. In this study, fatigue based on cyclic stress is researched. As is shown in figure 5, three cases with different element density attained pretty much the same stress field results, and the highest-value point located at basically the same place. The reason why stress concentration areas are not uniformly distributed around the hole is that the arrange style of every ply is different making the property of material anisotropic. However, we can conclude that the adopted mesh strategy achieved stable solutions.

**Figure 5.** Top layer stress distribution for regions of interested.

Tensile fiber failure and tensile matrix failure of the most dangerous element, as seen in the yellow circle of figure 5, is investigated using normalized damage index with respect to the end displacement(or loading), see in figure 6. Damage occurs when tensile damage index is over 0, material collapse when tensile damage index reaches 1. It is observed that the delamination damage of composite structure evolves in an accumulative way with increasing of end loading, and the matrix is much earlier to lose bearing capacity than the fiber. What's more, the plate with delamination defects is much easier and much earlier to get failed than the perfect plate under the same loading conditions. The results are in accord well with physical fact.

Using Fe-safe to import results of above analysis as the basic data can generate S-N curve for the composite plate in study. Then define the material parameters and loading history, we can calculate the composite plate's fatigue life. In this case, loading history is set as $[n, 0, -n]_m$, where n is loading amplitude, $[n, 0, -n]$ is a basic period, m is cycle number.

Figure 7 draws that fatigue life of the composite plate with a bolt-hole drop rapidly with respect to the load amplitude increase, furthermore, an increase of 67% load amplitude leads to a decrease of 99.5% fatigue life. This demonstrates that fatigue life of composite bolted joints with bolt-hole delamination is highly sensitive to external loads. It also reveals the value and importance of studying the fatigue life for composite structures with defects.

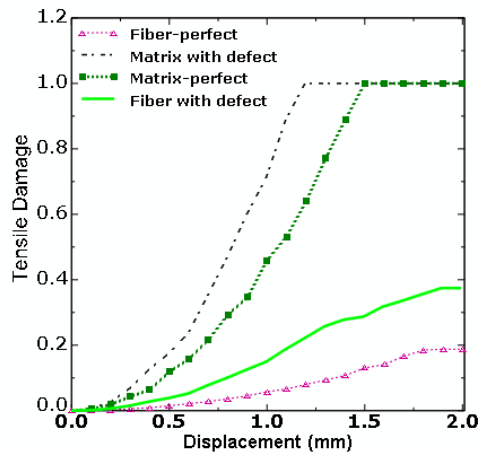


Figure 6. Fiber/matrix damage evolution in defect/perfect structures.

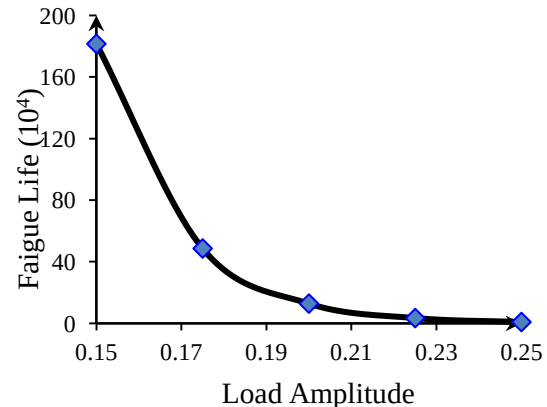


Figure 7. Load amplitude vs fatigue life.

Take the case with load history of $[2.5, 0, -2.5]_m$ for example to analyze fatigue results. Figure 8 illustrates fatigue life of every element on the top layer of the zone around the hole. Compared with figure 5, we can see that stress concentration areas possess the lowest cycle number, while low stress area is able to cycle millions of times remaining good service. This phenomenon results from the fact that high stress areas take possession of higher probability to accumulate irreversible plastic deformation which leads to fatigue failure. It is worth noting that this result only explained local composite fatigue, since most of the rest areas still hold load-bearing capacity. If the full-scale structure's fatigue performance is needed, one solution is to modify the above local fatigue region's property and recalculate the new model's fatigue life until the overall fatigue takes place.

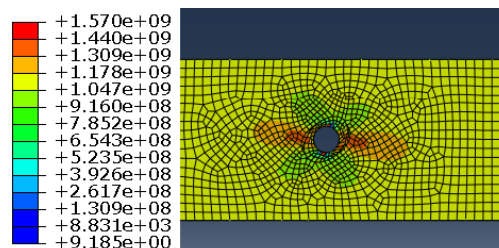


Figure 8. Fatigue life of top layer for the zone around the hole.

5. Conclusions

Bolt-hole delamination evolution of composite bolted joints is briefly investigated using CZM combined with Hashin's failure criteria, and the influence of delamination damage to composite material is discussed in virtue of commercial codes fe-safe. This numerical approach for studying fatigue life of composite structures with local delamination damage is quite suitable for engineering application. The below are the conclusions derived from the present study carried out on the composite bolted joints with bolt-hole delamination under cyclic symmetric tension-compression load.

(1) CZM is an effective way to simulate bolt-hole delamination evolution for composite structures, and slight degradation of material properties for local region with geometric singularity obviously accelerates local failure.

(2) Fatigue life of bolt-hole delamination area drastically decrease with the increase of end load, this is particularly evident at high stress area. For the composite plate in this study, an increase of 67% load amplitude leads to a decrease of 99.5% local fatigue life.

Acknowledgments

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