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A numerical parametric study on delamination influence on the fatigue behaviour of stiffened composite components

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Abstract. This paper investigates the fatigue phenomenon in Carbon Fibre Reinforced Plastic (CFRP) composite materials. Fatigue is a major problem in composite materials, due to their complex microstructures and inhomogeneous properties. In composite materials, fatigue is caused by cyclic loading, which leads to the accumulation of damage and eventually failure. This is related to several factors such as material properties, geometry, loading conditions, and environmental conditions. The fatigue life of composite materials is usually much lower than that of metals, and it is often catastrophic and unpredictable. Therefore, it is mandatory to understand behaviour of composite materials subjected to cyclic loading condition and to develop strategies to improve their fatigue performance. To this end, a Paris Law-based module has been implemented in the well-establish SMart-time XB (SMXB) procedure, being able to accurately numerically simulate the delamination growth caused by cyclic loads in complex composite structures. This process, which takes advantages of the mesh and load independency of the SMXB method in the evaluation of the delamination growth, has been implemented in the Ansys Parametric Design Language to create a highly versatile and parametric procedure. A numerical parametric study has been carried out to investigate the behaviour of a pre-existing circular delamination under cyclic loading, to assess the influence of delamination radius and thickness on the delamination growth. The results of this study will provide important insights into how delamination radius and thickness affect the delamination growth and the durability of composite structures. This study will help to inform the design of composite structures for various applications.

Introduction

Damage mechanisms in composite materials are the main reason behind the limited use of these materials for aircraft component construction. Delamination, in particular, is one of the most serious failure events that composites may experience, as it is undetectable and can therefore propagate, causing a rapid structural collapse. Fatigue phenomenon amplifies the weaknesses in terms of damage propagation in composite materials [1].

The study of interlaminar damage propagation has been extensively addressed in the literature, both experimentally and numerically. In particular, the Virtual Crack Closure Technique (VCCT) [2] and Cohesive Zone Models (CZM) are the most widely used computational methodologies for the investigation of delamination propagation in finite element (FE) environment. Among the others, the numerical procedure SMart time XB (SMXB) [2,3] is a FE tool based on the VCCT, which, however, has the unique feature to simulate delamination without dependence on the size of the elements used for the discretization of the model and independent from the load step size used in the numerical analyses. These characteristics are the basis for a further development of the SMXB, which is the possibility of simulating the evolution of delamination due to fatigue, i.e. a load acting on the structure in a cyclic fashion. The fatigue delamination simulation method integrated in SMXB has been implemented using the Ansys Parametric Design Language and is based on the Paris law relation. In [4], the mesh independence of the results obtained with the FaTigue SMXB (FT-SMXB) tool has been demonstrated in the case of a Double Cantilever Beam specimen.

In this work, a parametric study has been performed to investigate the behaviour of a CFRP typical stiffened panel with a pre-existing circular delamination, which aims to simulate an impact damage. The panel has been subjected to cyclic loads in order to assess the influence of the delamination radius and depth on the global compressive behaviour of the structure. The principal added value of this work is the use of the FT-SMXB, due to its inherent characteristics. Standard VCCT and CZM probably would affect the results due to their dependence on the mesh and time step of the finite element analysis.

Methodology

The SMart Time XB procedure has been introduced for the first time in [2] by Pietropaoli and Riccio in 2010. The tool has been improved over the years with different capabilities, for example the introduction of double delamination front in the case of skin-stringer debonding [3] or also the possibility to consider the R-curve. It is still being studied and enhanced today, in particular, by introducing the capability to simulate the fatigue driven delamination [4].

Fatigue in composite materials can be simulated considering the Paris Law equation, which has been developed for metals and then extended for composite materials. Equation (1) reports the Paris Law equation for composites, where a is the crack length, N is the number of cycles, G is the Energy Release Rate and n, c are experimentally derived constant parameters. This equation expresses the crack growth rate as a function of the number of fatigue cycles.

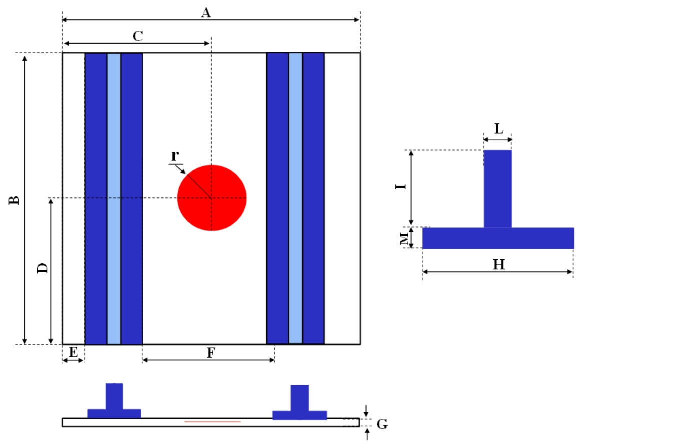
$$\frac{da}{dN} = cf(G)^n \tag{1}$$

The function of ERR, *f(G)*, may assume different expressions. In the FT-SMXB, *f(G)* can be selected among more than 4 expressions [], depending on the user needs.

The implemented tool considers the accumulation of damage on the crack front, so that the number of cycles at which the delamination propagates and the position of propagation on the crack front can be correctly assessed. Moreover, the procedure allows to take into account the load ratio and permits to evaluate the residual strength of the structure after a certain number of fatigue cycles.

Numerical application

The studied structure, shown in Figure 1, is a typical aeronautical component with two T-shaped stringers tied on a skin panel. It is characterized by a circular delamination, located in the middle of the bay, representing an example of typical impact damage. Two different configurations have been examined, both under cyclic loading conditions, which share all the geometrical properties except the radius of the delamination and its depth. Two radii have been considered, 30 mm and 40 mm, for each of them the delamination has been placed under 2 and 3 layers.



	A	B	C	D	E	F	G	H	I	L	M	r
CONF#1	400	300	200	150	63	146	2.64	64	400	5.28	3.96	30
CONF#2	400	300	200	150	63	146	2.64	64	32	5.28	3.96	40

All dimensions are in [mm]

Figure 1. Geometry of the analysed panel

The stacking sequence of the skin panel contains 16 layers with a layup of $(45°,0°,90°,-45°]_{2s}$, the foot stringer has 24 layers with a sequence of $(45°,0°,90°,-45°)_{3s}$, finally the web stringer has 32 layers with a layup of $(45°,0°,90°,-45°)_{4s}$.

The finite element model has been built in the Ansys Mechanical environment and a global-local approach has been used, whereby the structure has been discretised with a sparse mesh in the area not involved in the crack propagation phenomenon and a local area, characterised by the initial circular delamination and the propagation region, discretised on the contrary with a fine mesh. Both solid and shell parts have been considered, in order to reduce the computational cost of the analyses. The panel has been clamped on one side, while compressive cyclic load has been applied on a pilot node, linked to the other side nodes of the structure by means of rigid link elements.

Results

The panel has been analysed under cyclic loading conditions: 90% and 80% of the static onset load has been considered for the analyses. For each configuration static analysis has been performed in order to obtain the onset load on which the applied fatigue load is based. However, for the sake of brevity, only the results of fatigue simulations are reported in this section.

The results in terms of delaminated area as a function of the number of cycles are shown in Figure 2 for the configuration with 30 mm delamination radius. For simplicity, the configurations have been named CONF#1 for radius of 30 mm and CONF#2 for radius of 40 mm, in particular CONF#1-2 is the configuration with delamination radius of 30 mm under 2 plies.

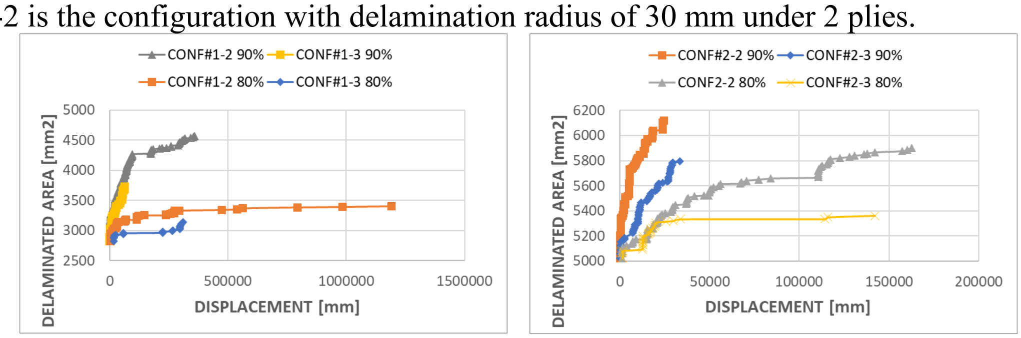


Figure 2. Delaminated area vs. Number of cycles

The analyses stop when propagation reaches the limit of propagation depending on the propagation region defined by the user (this is a numerical issue) or when the number of cycles overcome 1E6. According to Figure 2, in the selected configurations, only CONF#1-2 at 80% load exceeds one million cycles. The behaviour of the two configurations is similar: increasing the delamination depth reduces the delaminated area at the same number of cycles. Moreover, as expected, for a higher load the delamination is considerably unstable. Table 1 summarize the results in terms of delamination onset, buckling load and number of cycles to failure.

Table 1. Result summary

Configuration	Delamination buckling	Global panel buckling	Delamination onset load (static)	Number of cycles onset – 90%	Number of cycles failure – 90%	Number of cycle onset – 80%	Number of cycles failure – 80%
CONF#1-2	8264 N	207590 N	146117 N	148	358469	3174	>1E6
CONF#1-3	27325 N	207241 N	140209 N	385	64597	18000	309403
CONF#2-2	4696 N	206758 N	145539 N	92	24443	1208	162791
CONF#2-3	15610 N	205516 N	135655 N	69	33433	1650	144271

The local buckling load of delamination is different for all the configurations, it decreases by increasing the radius, while, at the same radius, it increases by increasing the delamination depth. The global buckling remains almost the same, between 205 and 207 kN.

Conclusions

In this paper the fatigue driven delamination has been studied in a composite stiffened panel with circular delamination. It has been found that the fatigue response of the panel depends on the delamination depth. Increasing the depth reduce the number of cycle to failure of the panel. the propagation trend remains similar as the delamination radius changes.

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