MULTI-SITE DELAMINATION ANALYSIS USING VIRTUAL CRACK CLOSURE TECHNIQUE FOR A COMPOSITE AIRCRAFT WING FLAP

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Abstract

In this study, we investigate the application of virtual crack closure technique (VCCT) for a multi-site delamination damage in the F-18 Hornet fighter aircraft's wing flap. The work focuses on the interaction between multiple delamination sites at different ply interfaces. The effects of numerical analysis parameters, such as energy release rate tolerance, on the criticality of the delamination and on the delamination growth are also studied.

1 Introduction

Delamination is the most critical failure mode in advanced composite structures. Due to delamination, local stiffness deteriorates and the loss of laminate integrity leads to the re-distribution of load transfer paths. In order to analyse the damage tolerance of a structure, the applied analysis method must reliably and accurately determine the criticality of the observed delamination [1]. In the case of multiple delamination sites, the analysis of the criticality is challenging for any numerical method [2]. In this study, we investigate the applicability of virtual crack closure technique (VCCT) [3] for analysing the criticality of a multi-site delamination damage in a fighter aircraft's wing flap.

We have previously analysed the criticality of delaminations observed in the F-18 Hornet fighter aircraft's trailing edge wing flap (TEF) during typical operation [4]. The analysis was carried out using VCCT and respective energy release rates (ERRs) were determined for a selected flight condition (i.e. load condition). The criticality per delamination and a load condition can further be quantified by comparing the computed ERR values with experimentally determined fracture toughness values [5]. The challenge in the studied flap structure is that several delamination failures may occur simultaneously, and separate delamination sites affect the ERR calculated per delamination site. Moreover, the computation of further propagation of the occurring damage is dependent on numerical parameters typically set by the operator. An accurate analysis of the cross-effects is difficult due to several numerical as well as physical interacting parameters.

Explicit surveys have not been published about the effects of numerical analysis parameters [6] while the importance of the parameters has been clearly stated in the current literature [7]. Default parameter settings of a software may also lead to unsatisfactory results [8]. Parameters have shown to influence the beginning of the crack propagation – merely onset – and that could delay the subsequent crack propagation [9].

The target of this work is to analyse multiple delamination interaction. The ERR variation with different combinations of delamination sites and types is presented, which highlights the interaction effect on the delamination onset. The delamination "through-the-thickness" location, i.e. the related ply interface, is also considered using the case matrix created for delamination site combinations. The delamination onset is analysed while varying numerical parameters included as adjustment option in Abaqus®. The ERR tolerance (ERRT) level is studied in this work. Additionally, this study includes analysis of the incrementation control and so-called unstable option influence.

2 Finite element model

The finite element model computation was performed using Abaqus®/Standard (2017, Simulia). The application was a trailing edge flap (TEF) of F-18C/D Hornet (Fig. 1). The TEF is connected to the wing via a titanium lug, which is attached to the spar of the TEF using six rivets. The spar and rivet holes after the lug removal are shown in Fig. 2. The composite spar consists of 15 plies of carbon/epoxy prepreg AS/3501-6. The laminate stacking sequence is [45/-45/0/45/-45/45/-45/90/-45/45/-45/45/0/-45/45].

Our previous study was based on actual three delaminations observed in two existing TEFs. The delaminations studied in our previous work [4] were located around the rivet holes. All these delaminations were around rivet holes where the lug is connected. The analysis was performed using the submodel of the TEF (Fig. 3). The submodel included a selected load condition defined by Patria (Finland). All materials of the TEF were modelled using linear elastic properties. The geometric nonlinearity was included in analysis.

For modelling the composite spar delamination, the spar was divided based on the interface of the delamination. The spar was modelled using fully integrated shell elements (S4). The main target in this work was to compare different numerical parameters and multiple delaminations. The finite element mesh was kept constant thorough-out the analysis, which minimizes mesh influence on analysis. Delaminations were modelled between 11th and 12th plies (ply count started from the front) as a starting point.

Figure 1 – Finnish Air Force F-18 Hornet. [10]

Figure 2 – The composite spar of TEF. [4]

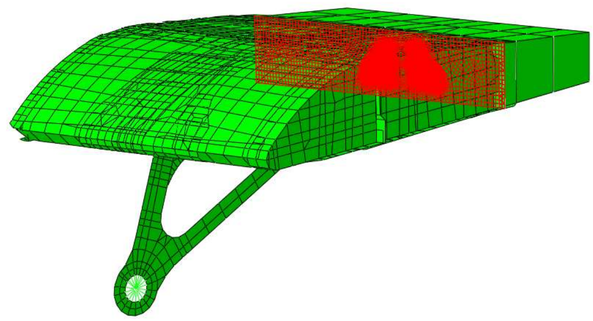

Figure 3 – The submodel of the TEF. The studied composite spar is highlighted.

The modelling included the definition of surfaces required for the VCCT. Rivets were modelled between the lug and the front surface of the spar, i.e., the rivets did not continue through the spar. This approach was chosen to be conservative in our previous study.

The target of the work in hand is to study the interaction between multiple delamination sites and the effect of numerical parameter values on crack onset. We modelled delaminations around the rivet holes. The delaminations and their naming conventions referred to later in this work are described in Fig. 4. The diameter of each delamination was 0.6 in.

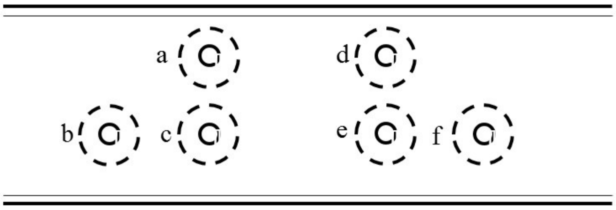

Figure 4 – Pattern of rivet locations and delaminations.

The modelled delamination pattern was modified during the analysis. This was done to show the effect of possible interaction between delaminations. The analyses were performed using seven different combinations of delaminations as given in Table 1. The first combination case included all delaminations for presenting the worst case. The case 6 had delaminations around same locations than in the real existing TEF. Other cases were randomly chosen.

Table 1 – Analysed delamination combinations.

	a	b	c	d	e	f
1	x	x	x	x	x	x
2				x	x	x
3	x	x	x			
4	x			x		
5				x		
6		x			x	x
7		x	x	x		

3 Delamination analysis

3.1 Virtual Crack Closure Technique (VCCT)

Virtual Crack Closure Technique (VCCT) is a numerical method mainly used for delamination analyses. The VCCT is based on Irwin's crack closure integral modifications made by Rybicki and Kanninen [11]. The theory and applications of the VCCT have been reviewed by Krueger [3].

The VCCT basic equation for the fracture mode I takes the form

$$G_I=F\delta u/(2Bda) \qquad (1)$$

where F and δu are the reaction force and separation, B and da are the element width and length, respectively. Eq. (1) can be derived for all three fracture modes. The reaction force and separation for a finite element crack tip are characterized in Figure 5.

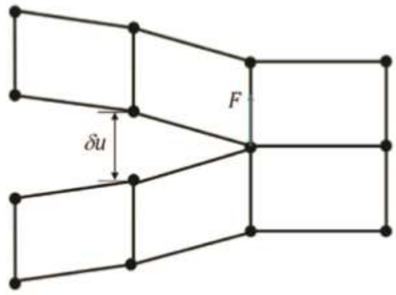

Figure 5 – VCCT crack tip. [12]

3.2 Fracture criterion

The onset and propagation of the delamination can be analysed when ERRs provided by the VCCT are compared to critical ERR values provided by experiments. The critical ERR values for the applied material system are G_{Ic} = 72 J/m^2 and G_{IIc} = 779 J/m^2 [5]. Typically, several fracture modes exist simultaneously at the delamination crack-front and comparison of separate modes typically is not feasible. The common method is to combine different fracture modes into one fracture criterion, which defines the fracture onset. The applied fracture criterion for the AS4/3501-6 was based on mixed-mode experiments. The fracture criterion was defined as [13]:

$$f=(G_I/72)^{0.75}+(G_{II}/779)^{0.69}. \qquad (2)$$

The studied delamination cases in this work did not result in the crack onset and propagation occurrence while our target was to study the interaction between delaminations and numerical parameters. We did not modify the loading of the structure but redefined the fracture criterion for achieving the crack onset. The redefinition was performed by setting G_{Ic} and G_{IIc} to the level of one percent of their original values.

3.3 Numerical parameters in VCCT analysis (Abaqus)

An increasing load applied to the FE model changes (increases) the ERR at the delamination tip. Based on the ERR value provided by the VCCT, the software evaluates the fracture criterion value after each analysis round. If the value does not reach the value of one, the nodal point will not fail and the load is increased. The exceedance of the critical value states that the nodal point fails. The default incrementation of Abaqus (Standard) tries to perform the whole loading at once. If the increment does not converge, a cutback follows. The cutback in VCCT analysis is most likely caused by delamination onset and propagation. However, issues related to faulty convergence criterion are also common. Abaqus allows the definition of an initial and maximum increment.

For a computation task, it is not effective to determine exact load level for the event of nodal point failing and delamination onset. For improving analysis efficiency, numerical parameters are typically applied. Abaqus provides tolerance (f_{tol}), which defines the allowed exceedance of the criterion. Default value is 20 percent, meaning that a nodal point fails when the failure criterion (f) reaches a value between 1 and 1.2. This can be presented as

$$1 \leq f \leq 1+f_{tol} \tag{3}$$

where f_{tol} is the tolerance. The tolerance has an effect on analysis results and on the analysis time. Abaqus decreases analysis time increment, which can be considerably low in VCCT analysis. This has a major effect on analysis time.

The improvement for the VCCT propagation phase was provided for Abaqus version 6.12 where the 'unstable growth tolerance' option was implemented. In case of a multiple nodal failure, the growth tolerance takes the form

$$1+f_{tol} \leq f \leq 1+f_{tol}^{u} \tag{4}$$

where f_{tol}^{u} is the unstable growth tolerance. The unstable growth option is beneficial when unstable delamination occurs and several nodal points fail approximately with the same load. The drawback of this feature is that the load state will not be updated frequently. Recently, the linear scaling upgrade has been implemented on Abaqus. Linear scaling assumes linear relation for a load, which can be scaled similarly as ERR.

Here, we focus on the delamination onset. Therefore, the analysis was aborted shortly after the delamination onset. The damage onset in our results is given in the form of analysis time (dbt). The 'time' states the portion of the entire loading, which was defined in the FE simulation in question. The delamination propagation was allowed but not of interest in our study.

3 Results

3.1 Multiple delamination effect on onset

The deformed shape (magnified) of the TEF is shown in Fig. 6. Delaminations were relatively small and did not have a significant influence on the global deformation.

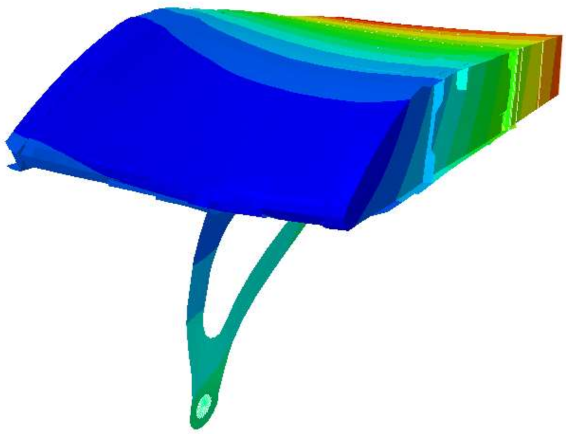

Figure 6 – Deformation of the TEF with the applied load (magnified deformation).

The study was initiated by computing the effects of multiple delaminations on the damage onset. These initial computations were performed using the default tolerance (20 %) and by applying the unstable growth option. The default incrementation of Abaqus was applied.

Figure 7 presents the damage onset in terms of analysis time (dbt). The comparison between analysis cases shows that the smallest dbt level is achieved when all delaminations exist. The cases including *d* and *f* delaminations are more critical than other combinations. Delaminations *a*, *b* and *c* are less critical, as indicated by the higher dbt value of case 3 in the figure. Otherwise, differences between the cases are small.

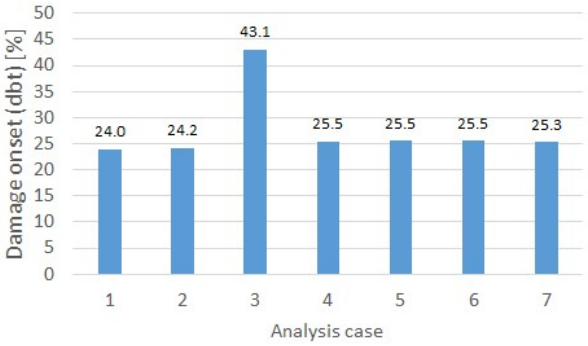

Figure 7 – Delamination onset when using default incrementation and tolerance.

3.2 Interface effect

Observed interaction between delaminations was small (Fig. 7) in general; the delamination sites in this case were located between 11th and 12th plies. Multiple delaminations (cases 1-7) were also analysed for interfaces 10&11 and 12&13 to understand ply interface related effects. The damage onset (dbt value) for these analyses was compared to the corresponding damage onset of the original interface and the results are shown in Fig. 8.

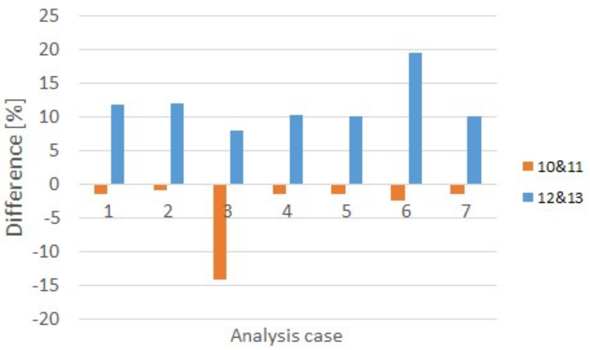

Figure 8 – Delamination interface effect on delamination onset.

The interaction between delaminations was observed when the results of the analysis cases were compared to the case 1 (all delaminations applied). Fig. 9 presents the comparison for all three delamination interfaces. Case 3 is clearly resulting in different behaviour compared to other cases, which can be explained by the fact that *d* and *f* delaminations were not included in the case 3. The comparison clearly shows that the interaction between multiple delaminations is also dependent on the ply interface.

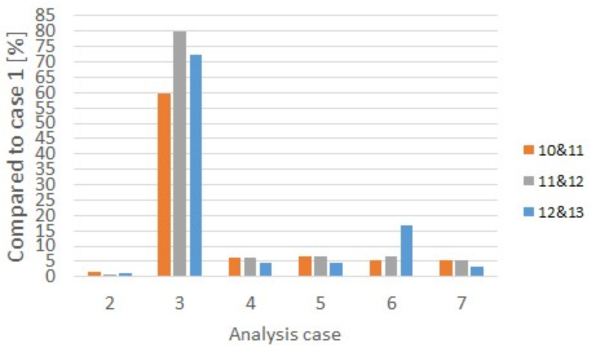

Figure 9 – Interaction between delaminations in different ply interfaces.

3.3 Tolerance effect on onset

The tolerance effect on onset was studied using three different tolerance values, which read 10, 20 and 40 percent. The incrementation controls were modified for these computations. The target of this modification was to remove cutback in the beginning of the analysis. Typically, Abaqus performs first increment (analysis round) using the full load as a default. If the crack onset occurs, the increment is decreased. Instead of using the default increment, the initial increment was modified to 0.05.

The influence of the modified increment is shown in Fig. 10, where the default tolerance 20 % and the results of Fig. 7 are used as a reference. It can be seen that the change in the incrementation has an effect on the damage onset. The onset time decreased in four simulation cases. However, the extent of the decrease is below 15 percent. The onset increased in the cases 1, 3 and 7, which refers crack to onset later than in the previous analysis (Fig. 7). The result of the case 1 is the most interesting one. Indeed, case 1 and 2 had almost equal damage onset (dbt) when using the default incrementation, but the case 1 onset was postponed while the case 2 damage onset occurred earlier after the change. This means that the case including all delaminations is not the most critical with the modified incrementation.

Figure 10 – Delamination onset when using default tolerance and an initial increment 0.05.

The tolerance effect on the delamination onset was further studied and the results are shown in Fig. 11. Fig. 11 shows the comparison of the results with 10 % and 40 % tolerance to the results with a default (20 %) tolerance. The tolerance of 40 % differs from the 20 % tolerance in terms of damage onset only for the simulation case 2, with almost five percent difference. The tolerance of 10 % resulted in a smaller difference for the cases 4 to 7.

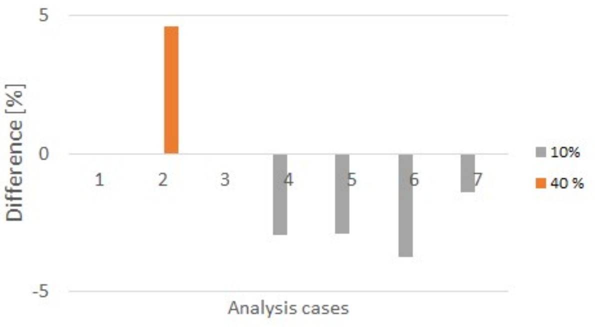

Figure 11 –Tolerance effect on delamination onset for tolerances 10 % and 40 % when compared to the default.

3.4 Unstable growth tolerance

The last numerical study was performed using the unstable growth tolerance option. The values for tolerance and unstable growth tolerance were 20 % and 40 %, respectively. The unstable option did basically not influence the damage onset behaviour. It should be noted, however, that the delamination propagation was stable in the current analysis. Figs. 12 and 13 present the delamination *d* propagation for load levels from 50 % to 100 % (dbt 50 % to 100 %). The figures indicate only some minor difference between the results obtained with the two tolerance options.

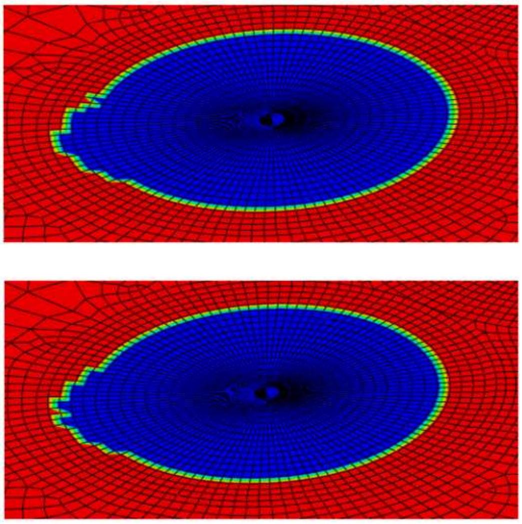

Figure 12 – Delamination propagation case 5 (load level 50 %); tolerance 20 % (upper) and tolerance 20 % & unstable growth tolerance 40 % (below). Red presents intact and blue open contact.

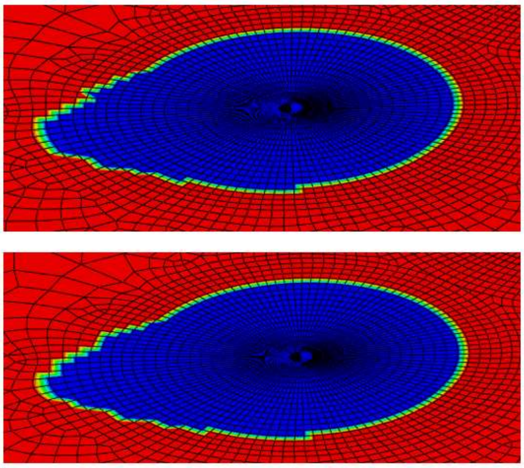

Figure 13 – Delamination propagation case 5 (load level 100 %); tolerance 20 % (upper) and tolerance 20 % & unstable growth tolerance 40 % (below). Red presents intact and blue open contact.

4 Discussion

Delamination is a challenging failure mode because normally it is not detected in a visual inspection and non-destructive inspection methods need to be used. The observation of a delamination may lead to repair activities and to the definition of inspection intervals. Our work here concentrated on numerical analyses of delaminations at the composite spar of a trailing edge flap. This spar is a typical example of a fighter aircraft structure for which inspection and repair are challenging. Availability of analysis approaches providing a conservative estimate on the effects of delaminations is essential to guarantee airworthiness of such structures.

Current analysis approaches for delamination studies are based on long-term development. The analysis methods for delamination studies have mainly been implemented on commercial software during the last decade. Standard methods for testing have been defined during the same time period. The only option for ensuring conservative results with the current approaches is the usage of a feasible margin. The margin should include all uncertainties existing in inspection methods, material properties and analysis procedures, for example. For better understanding analysis uncertainties, numerical parameter effects on analysis results should be covered in more detail in future studies.

5 Conclusion

In this study, the interaction of multiple delamination was quantified by computing the damage onset for a composite spar cap with selected delamination cases. The interaction was dependent on delamination locations. The delamination interface also influenced the interaction.

The effect of Abaqus analysis parameter values on the computed damage onset was further studied. ERR tolerance effect on delamination onset was relatively small. Mainly, differences occurred when comparing 10 % tolerance value to the default (20 %) tolerance value or a higher value. Our results showed that incrementation of the analysis case can also influence the results. The usage of unstable growth tolerance can also change delamination propagation while the studied delaminations were stable.

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