Deutscher Luft- und Raumfahrtkongress 2013
DocumentID: 301246

FFS – FE-ANALYSIS OF ADHESIVELY BONDED SCARF JOINTS USING P-FEM

M. Calomfirescu, Cassidian, Military Air Systems Centre, Manching, Germany
R. Zwinderman, Cassidian, Military Air Systems Centre, Manching, Germany

Abstract

The use of composite materials, such as carbon–fiber reinforced plastic (CFRP) composites, in aerostructures has led to an increased need of advanced assembly joining and repair technologies. Adhesively bonded joints provide an alternative to mechanically fastened composite structures, which often introduce undesirable stress concentrations. The objective of this paper is to evaluate the P-FEM method implemented in the commercial software tool StressCheck for failure prediction of adhesively bonded composite joints. The validation of the (geometrical and material) non-linear Finite Element Analysis was performed on bonded scarf joints. Bonded scarf joints are relevant for repairs of composite structures. A main focus within the analysis was to consider all relevant failure modes such as cohesive failure in the bondline and failures in the composite adherends (delamination, matrix and fiber failure). The validation has been performed on coupon level in tensile tests conducted at room temperature as well as at hot wet condition. The failure modes as well as the failure loads could be predicted within a satisfactory degree of agreement between analysis and testing.

1. INTRODUCTION

The use of composite materials, such as carbon–fiber reinforced plastic (CFRP) composites, in aerostructures has led to an increased need of advanced assembly joining and repair technologies. Adhesively bonded joints provide an alternative to mechanically fastened composite structures, which often introduce undesirable stress concentrations. The introduction of structural bonding into primary (composite) structures requires many different aspects to be considered, such as certification requirements, robust manufacturing processes, reliable nondestructive testing methods and design approaches, but also reliable analysis methods, which is the aspect addressed in this paper.

The objective of this paper is to evaluate the P-FEM method [1] implemented in the commercial software tool StressCheck for failure prediction of adhesively bonded composite joints. The validation of the (geometrical and material) non-linear Finite Element Analysis was performed on bonded scarf joints. Bonded scarf joints are relevant for repairs of composite structures. A main focus within the analysis was to consider all relevant failure modes such as cohesive failure in the bondline and failures in the composite adherends (delamination, matrix and fiber failure). The validation has been performed on coupon level in tensile tests conducted at room temperature as well as at hot wet condition. The failure modes as well as the failure loads could be predicted within a satisfactory degree of agreement between analysis and testing.

2. THEORETICAL BACKGROUND OF P-FEM

As mentioned before, to be able to effectively implement adhesive bonding for laminated composite structures, robust and reliable strength analysis for the design and repair of these structures is required. In classical finite element analysis (FEA) H-finite element methods (H-FEM), are used. H-FEM makes use of decreasing the size of the elements to improve the accuracy of analysis and increase the degree of freedom (DOF). In such a FEA the so-called shape functions, which calculate the stresses and strains in the elements, are fixed to a polynomial level (P-level), of either 1 (linear) or 2 (quadratic). As best practice, H-FEM programs state that the ratio of the dimensions of the elements should not be larger than 10:1 and their size transitions should not be greater than 3:1 [2]. This restriction means that analyzing thin bondlines and plies will introduce very large numbers of elements in the model.

An alternative type of analysis program called P-FEM improves the accuracy of the solution by increasing the polynomial level of the shape functions while keeping the element size unchanged [1]. Being responsible for the evaluation of the stresses and strains in the element, these shape functions with increased polynomial levels can represent more complex shapes with a higher degree of freedom as illustrated in BILD 1.

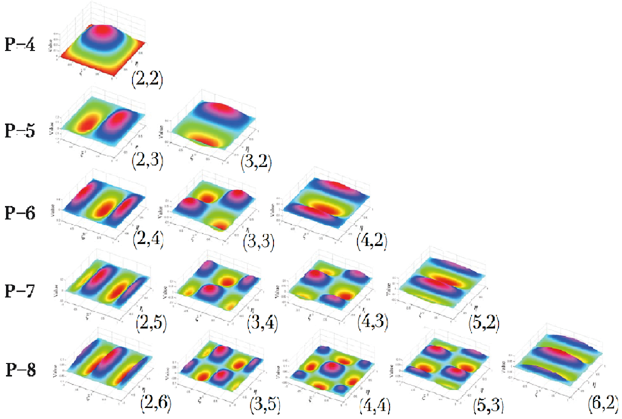


BILD 1. Visualization of the hierarchic shape functions for internal modes P = 4 to 8 [1]

This also implies that large aspect ratios of over 200:1 can be used and hence thin composite plies can be modeled efficiently [4-5]. Furthermore size transition ratios of over 7:1 can be implemented which makes it easy to contain stress singularities [2]. The commercial finite element analysis tool StressCheck from the Engineering Software Research and Development Company, ESRD, is such a P-FEM program. It is the first commercially available program to incorporate non-linearity analysis in combination with P-FEM [3]. Since StressCheck is able to automatically increase the order of the polynomial degree, an inherent discretization error minimization can be performed [5].

In the presented paper the potential of P-FEM over H-FEM and the non-linear analysis features in StressCheck are used to perform strength predictions of adhesively bonded scarf joints.

3. EXPERIMENTAL TESTING

A bonded scarf repair is a typical bonded repair for damaged composite structures. In this repair technique the damage is cut out from the composite panel in a circle or oval shape with a highly tapered edge with a certain scarf angle. The scarf bonded joints studied in this paper is presented in BILD 2.

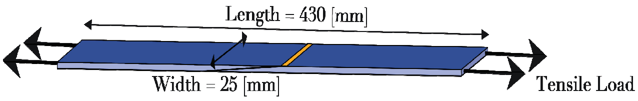


BILD 2. Dimensions of the scarf joint coupon specimens tested

Extensive experimental tests have been performed in which the strength of scarf joint coupons has been assessed using different composite layups, scarf angles and environmental conditions, as shown in TAB 1. Layup number 4 is a quasi-isotropic layup with 24 plies, layup 5 has a similar stacking sequence to layup 4 but is double symmetric and thus has 48 plies. The difference between layup 6 and layup 4 is the stacking sequence, as can be seen in TAB 1, the ply angle ratios are the same.

Laminate Layup			Room Temperature (T1)		Hot-Wet Conditions (T2)	
			Scarf Angle		Scarf Angle	
#	Stacking Sequence	Thickness	1/10	1/20	1/10	1/20
4	[45/90/135/0/45/90/135/0/45/90/135/0]s	3.0 [mm]	4-10-T1	4-20-T1	4-10-T2	4-20-T2
5	[45/90/135/0/45/90/135/0/45/90/135/0]2s	6.0 [mm]	5-10-T1	5-20-T1	-	5-20-T2
6	[45/0/135/0/0/135/90/90/45/135/90/45]s	3.0 [mm]	6-10-T1	6-20-T1	6-10-T2	-
7	[45/90/135/0/0/45/135/0/0/45/135/0]s	3.0 [mm]	7-10-T1	7-20-T1	7-10-T2	7-20-T2

TAB 1. Overview of scarf joint specimen used in this study

The two scarf angles used 1:10 and 1:20, result in respectively 5.71° and 2.86° angles. Two environmen tal testing conditions have been indicated in TAB 1, the room temperature and hot-wet conditions experimental tests. The hot-wet condition tests are first exposed to 70℃ and 85 % relative humidity, after which they have been tested at 100℃.

4. FINITE ELEMENT ANALYSIS

4.1. Finite Element Model

Although initially 3D models were evaluated, for the chosen failure extraction methods a comparable 2D model proved sufficient. The FE-model is shown in BILD 3. The change from 3D to 2D is justified by the fact that the stresses are nearly constant through the coupon width.

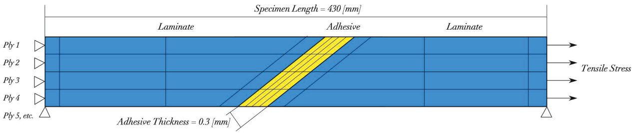


BILD 3. Schematic overview of the 2D StressCheck model used for the failure prediction of the scarf joints

As shown in BILD 3, the models are all loaded by a tensile force on the right hand side whereas the other boundary conditions represent the clamping forces of the test bench.

In StressCheck material non-linearity of the adhesive is considered using the Von Mises material model [5]. The different StressCheck internal material models are fitted to experimental shear stress-strain data provided experimentally by the thick adherend test using aluminum adherends bonded using the corresponding film adhesive. For the room temperature tests a Ramberg-Osgood material model appears to fit in the best way to experiments, whereas for the hot-wet conditions a 5-parameter material model gave the best fit according to tests performed using the thick adherend specimen. BILD

4 and BILD 5 show the shear stress – strain behavior of the film adhesive used provided experimentally vs. the shear stress – strain behavior obtained using the most appropriate material model after fitting within StressCheck.

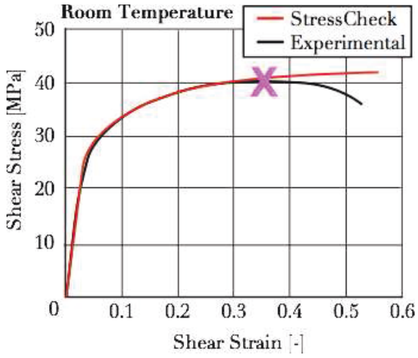


BILD 4. Room temperature adhesive equivalent stress-strain curve

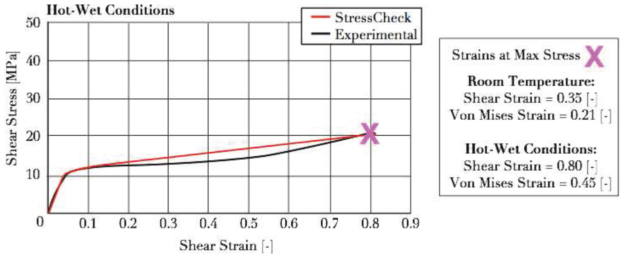


BILD 5. Hot-wet conditions adhesive equivalent stress-strain curve

Although both material models follow the initial linear part of the material shear stress-strain curve quite well, they are not able to follow the non-linear response of the material entirely. The model for the room temperature does not have a strain softening effect and for the hot-wet analysis the model is incorrectly linear between the yield stress and the failure shear stress-strain values. The material parameters are given in TAB 2.

Room Temperature			Hot-Wet Condition		
Material Model			Material Model		
Ramberg-Osgood			5-Parameter		
E-mod	1829	[MPa]	E-mod	329.8	[MPa]
v	0.39	[-]	v	0.39	[-]
S70E	53.5	[MPa]	S70E	20	[MPa]
n	9	[-]	e2	0.02	[-]
			E2-mod	32	[MPa]

TAB 2. Best fit material model parameters used in StressCheck for the approximation of the experimental shear stress-strain curves shown in BILD 4

4.2. Failure modes

In this study the focus was on modeling and considering all relevant failure modes in such bonded joints. From the design point of view the joint should be designed to ensure that the adherends fail before the bond layer, whenever possible, as illustrated in BILD 6 and noted as "stock-break failure". Usual failure modes are delaminations in parent composite as well as in the repair patch and cohesive failure in the bondline. Adhesive failure at the interface between the adherend and the bondline is not acceptable and is considered to be caused by non-optimal manufacturing and processing parameters, generally due to surface treatment issues.

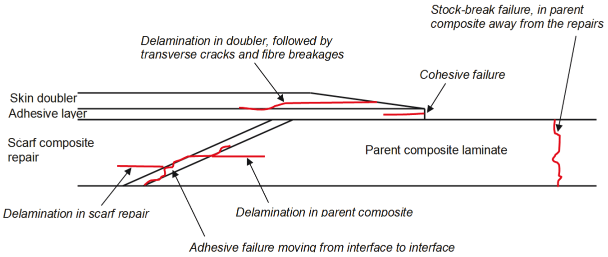


BILD 6. Failure modes in a composite bonded repair [7]

To predict failure in the specimens, at multiple locations stresses and strains were extracted as visualized in BILD 7. Although from the experiments no fiber failure was found in the scarf joints, a maximum stress criterion in the fiber direction was incorporated in the FE-analysis to cover this failure mode. From the experiments it is found that the coupons tested at room temperature mostly failed in the composite adherend, in the fist plies, in the vicinity of the bondline. During the failure prediction iteration process, it was discovered that some 45° and 135° p lies had elevated J1 strains (where J1 strain is the sum of the principal strains) values when compared to the mean J1 strain of the rest of the 45° and 135° plies at the adhesive/adherend boundary. The J1 strain criterion has been implemented successfully in the prediction of laminate delamination failure by Tsai et al. [6] and proposed by Engelstadt et al. for matrix driven failure prediction [2]. Since the exact failure in the laminate is difficult to extract from the experiments, the failure prediction using the J1 strain is generalised in this paper as being a matrix/delamination failure. In the evaluation performed an optimum result was achieved when assessing the J1 strain for each individual ply by extracting it at 5 locations in the middle of the ply, see BILD 7, detail on right hand side. In this way the stress singularities at the ply terminations are avoided. For the cohesive failure in the adhesive, the Von Mises strain at maximum shear stress as shown in BILD 4 and BILD 5 was considered.

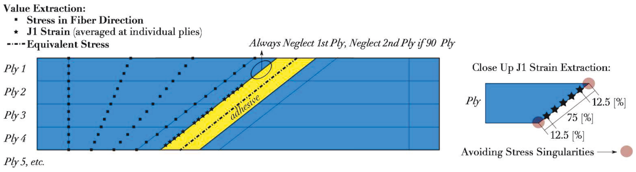
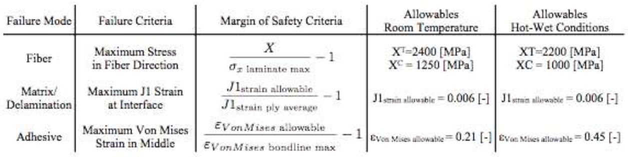


BILD 7. Extraction of local stresses and strains for failure evaluation

A summary of the different extraction locations and their accompanying failure criteria is given in TAB 3. Since the material strengths values are different for analysis of the room temperature conditions and the hot-wet conditions, two different sets of material allowables are given in this table.



Failure Mode	Failure Criteria	Margin of Safety Criteria	Allowables Room Temperature	Allowables Hot-Wet Conditions
Fiber	Maximum Stress in Fiber Direction	$\frac{X}{\sigma_{x\ \text{laminate max}}} - 1$	X^T=2400 [MPa] X^C = 1250 [MPa]	XT=2200 [MPa] XC = 1000 [MPa]
Matrix/ Delamination	Maximum J1 Strain at Interface	$\frac{J1_{\text{strain allowable}}}{J1_{\text{strain ply average}}} - 1$	$J1_{\text{strain allowable}} = 0.006$ [-]	$J1_{\text{strain allowable}} = 0.006$ [-]
Adhesive	Maximum Von Mises Strain in Middle	$\frac{\varepsilon_{VonMises\ \text{allowable}}}{\varepsilon_{VonMises\ \text{bondline max}}} - 1$	$\varepsilon_{\text{Von Mises allowable}} = 0.21$ [-]	$\varepsilon_{\text{Von Mises allowable}} = 0.45$ [-]

TAB 3. Summary of failure criteria used in the evaluation of the 2D scarf joint model, extraction locations illustrated in BILD 7

4.3. Validation

The 2D model is analyzed using StressChecks "Margin analysis tool" with an overall polynomial degree level of 8. In this tool the load is increased by user defined steps until one of the selected margins of safety becomes critical. The different coupons from TAB 1 were analyzed in this manner and their results are split in the room temperature and hot-wet condition experiments, BILD 8 and BILD 9 respectively.

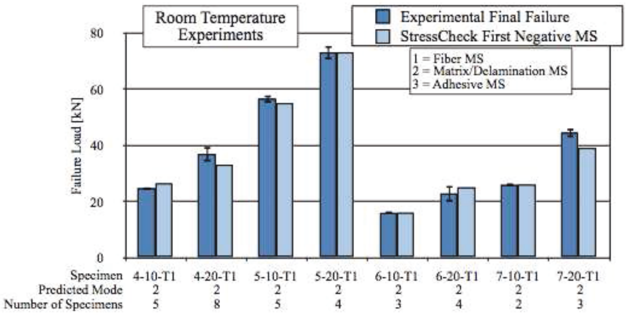


BILD 8. Comparison of final failure loads of the scarf coupons at room temperature

Comparing the predicted failure loads with the experimental values, an average difference of 5% is found for the room temperature tests. The highest differences between the actual failure loads and FEA results are found in the specimens 4-20-T1 and 7-20-T1, within the range of 8%. Furthermore the failure mode predicted by StressCheck is the matrix/delamination failure as observed during experimental testing.

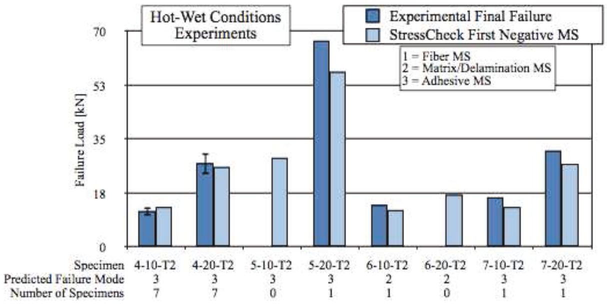


BILD 9. Comparison of final failure loads of the scarf coupons at hot-wet condition

When comparing the predicted failure load of the hot-wet condition specimens to the experimental test, an average of 9% difference is found. This average is higher than the one found using room temperature tests BILD 8. Especially the 5-20-T2 specimen shows a 12% higher experimental failure load than the StressCheck results. For the specimens with stacking sequence 6, see TAB 1, the predicted, predominant failure mode is matrix/delamination. This is different to the failure modes predicted for the other hot-wet specimens, which is predominantly adhesive failure.

5. SUMMARY AND OUTLOOK

Validated analysis methods and tools for predicting bonded joint strength is, among other issues, a crucial aspect urgently required for implementation of structural bonded composites as primary aerostructures. The p-FEM method, as studied within this paper, appears to be appropriate for the analysis. A satisfactory agreement between analysis and experimental results from the qualitative as well as from the quantitative point of view has been achieved. The qualitative point of view is considered to be the agreement with respect to failure mode, the quantitative agreement is referred to the predicted failure load.

For further evaluation of the P-FEM, validation on much more complex specimens on detail component and subcomponent level will be performed. Especially bonded T-Pull, T- Tension and T-Shear test will be performed and validate in the very next future. An automatic global-local approach will be developed in order to extract internal loads from Global Finite Element Models (GFEM) to perform detail analysis (DFEM) with StressCheck. Therefore the nodal displacements from GFEM will be extracted and interpolated to nodes within DFEM and additional geometry information will be imported from CAD data.

REFERENCES

[1] B. Szabo, A. Düster, and E. Rank: The p-version of finite element method, Encyclopedia of Computational Mechanics, Volume 1: Fundamentals, September 2004.

[2] S. Engelstadt: Composite bonded joint stress analysis. Powerpoint, Composite Affordability Initiative Technology Advances, Lockheed Martin Aeronautical Company, November 2006.

[3] A. Düster and E. Rank: The p-version of the finite element method compared to an adaptive h-version for the deformation theory of plasticity. Computer Methods in Applied Mechanics and Engineering, 190:1925–1935, 2001.

[4] S. Engelstadt and R. Actis: Development of p-version handbook solutions for analysis of composite bonded joints. Technical report, Lockheed Martin Aeronautics Company, Engineering Software Research and Development, 2003.

[5] Engineering Software Research and Development (ESRD): StressCheck Master Guide Release 9.2, 2012.

[6] H.C. Tsai, J. Alper, and D. Barnett: Failure analysis of composite bonded joints. Technical report, American Institute of Aeronautics and Astronautics, 2000.

[7] Donough, M et. al.: Review of Design and Analysis Methods Relevant to Bonded Composite Repairs of Aerospace Structures, CRC-ACS TR 11019, June 2011.