PROGRESSIVE FAILURE OF COMPOSITE LAMINATES; ANALYSIS VS EXPERIMENTS

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ABSTRACT

The paper discusses different parameters affecting progressive failure analysis results of laminates. Experimental and numerical results are given for both glass fibre laminates (GFRP) and carbon fibre laminates (CFRP). Numerical results have been calculated with the commercial finite element software ABAQUS. The progressive failure has been added to the model with the use of a user subroutine and material dependencies. The numerical results are compared to the experimental results.

Introduction

It is a well known fact that composite laminates can carry considerable loads after initial failure. The ultimate load carrying capability can be predicted with progressive failure models. The models are also suitable for structural analysis when used with finite element analysis. The damaged areas are characterized with impaired material properties and the analysis is performed with multiple iterations. Therefore, progressive failure models provide tools to simulate damage progression in a structure and the ability to determine the damage tolerance of any kind of structure.

This work is focused on the use of progressive failure analysis models with simple loading conditions and simple structures. The emphasis is put on finding the parameters that affect the end result most. The purpose is not to find out the best progressive failure model. The evaluation of different failure criteria and post-failure analysis was done in the worldwide failure exercise [1]. In this work the different alternatives and parameters are systematically tested and the results are compared to the experimental test data.

Theory

Progressive failure models are a combination of ply-level failure criteria and post-failure degradation rules. The failure analysis is based on the calculation of the ply-level stresses. These stresses are calculated using the classical laminate theory. The stresses are then compared to the measured strength values by applying different failure criteria. The failure criteria indicate if failure has occurred and what is the mode of failure.

After a layer has experienced matrix failure, the material properties E_2 and G_{12} of the damaged layer are multiplied by a factor according to the degradation rules. The most simple degradation rule uses knockdown factors close to zero. This means that the damaged layer will not carry any transverse or shear loads after failure and the load is transferred to the remaining undamaged plies. This degradation rule is also known as the ply discount model. The constant stress model assumes that the damaged layer will carry its failure load but no additional loads. In real case the ply behavior is something between these two models. Therefore, models that use gradual unloading have been developed, for example [2]. A schematic presentation on the different degradation models and their influence on the ply level stress-strain curve is shown in Figure 1.

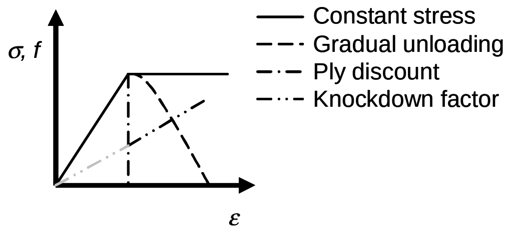


Figure 1. Ply behavior according to different degradation rules

The analysis is performed by increasing the load incrementally and updating ply properties when ply failure is detected. In laminate level, the failure occurs when the laminate experiences fiber fracture in any layer. In structural level, the analysis can be continued even after fiber failure has occurred in some elements. In such case, all material properties of the damaged ply are reduced close to zero. The analysis is then continued until final collapse of the structure. This can be observed from the load-response curve.

Analysis

The cases analyzed and tested are shown in Table 1. Both unnotched and noched laminates are considered. The cases 1-5 represent unnotched laminate loading. The lay-ups have been chosen such that the stress state in the angle-ply layers is multiaxial and the stiffness reduction would be noticeable in the laminate load-response curve. The laminates in cases 3 and 4 have equal in-plane stiffness but different stacking sequences. In case 4 laminate has thick layers meaning that the parallel layers are stacked together. In case 3 laminate is stacked according to the good design pratice i.e. parallel layers are distributed through the thickness. The cases 6 and 7 are tensile tests for laminates with a circular notch. The laminate lay-ups are the same as in the test cases 3 and 4.

Table 1. The test cases

Series	Laminate lay-up	Material	Loading and Numerical model
1	$[0/0/4(\pm 30)]_S$	E-glass and AS4	Tensile loading in one element
2	$[0/0/4(\pm 30)]_S$	E-glass and AS4	Compressive loading in one element
3	$[0/3(+45/-45/90)]_S$	E-glass and AS4	Tensile loading in one element
4	$[0/3(+45)/3(-45)/3(90)]_S$	E-glass and AS4	Tensile loading in one element
5	$[0/2(90)0/2(+60)/2(-60)0]_S$	E-glass and AS4	Tensile loading in one element
6	$[0/3(+45/-45/90)]_S$	E-glass	Quarter model with Ø6.35mm hole
7	$[0/3(+45)/3(-45)/3(90)]_S$	E-glass	Quarter model with Ø6.35mm hole

The numerical results were calculated with the commercial finite element software ABAQUS. The laminate was modeled with layered shell elements. Instead of modeling 20 layers separately, the parallel layers were stacked in thick layers. This can be done because shell elements assume a plane stress state and only in-plane loadings are considered. This also means that analysis results are the same for cases 3 and 4 and respectively for cases 6 and 7.

The progressive failure model was implemented to the code using user subroutines. The implemented failure criteria include maximum stress, Tsai-Wu and Hashin criteria. These failure criteria are selected because they do not include any special experimentally defined factors. In addition, they and can be considered as typically used in composite design work. After a matrix failure, the stiffness's E_2 and G_{12} of the damaged layer are degraded according to three different degradation models; a model that uses knockdown factor 0.2, ply discount model and constant stress model. The knockdown value 0.2 has been used for example in Ref [3]. The ply discount model should provide a conservative estimate for the ultimate strength and the constant stress model should provide the maximum. The software calls the subroutine (USDFLD) at each integration point in the beginning of each iteration step. The user subroutine uses layer stresses from the previous iteration which means that the progressive failure analysis is always one step behind. To minimize the error, the load increments must be kept small. However, if ply failures are not observed, the load increment is set equal to the reserve factor in order to speed up the calculation. After a failure has initiated in some integration point, the load increment for the next iteration is set to 1e-3 mm. In case no additional failures are observed the following load increment is defined again using the reserve factor. A fixed load increment was applied in the analysis using constant stress model since the failure criterion shows matrix failure for every iteration after first ply failure.

In cases 1-5 it is assumed that the stress state is uniform in the test specimen and the Poisson strain is enabled. Therefore, the analysis can be performed even with a single element. The cases 6-9 represent tensile loading of laminates with a circular notch. The results are strongly dependant on the element mesh. Thus, appropriate mesh refinement studies were conducted. The refinement study was performed with both linear and quadratic elements. The mesh is formulated using symmetry boundary conditions and the load is applied using displacement restraints. An example of the finite element mesh used and the applied boundary conditions are shown in Figure 2.

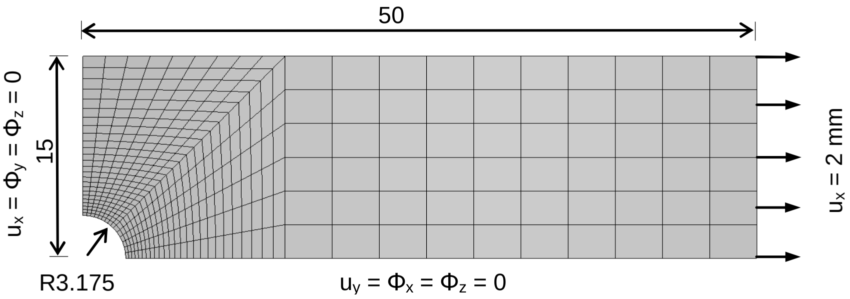


Figure 2. Finite element mesh used for test specimens with a circular notch

Experimental

The ply properties used in the analysis were tested for unidirectional laminates using standard methods. The measured ply properties are shown in Table 2.

Table 2. Mechanical properties for the tested materials

	E-glass / MTM57	AS4 / 3501-6
Longitudinal modulus, E_1 (GPa)	47	140
Transverse modulus, E_2 (GPa)	15	10
In-plane shear modulus, G_{12} (GPa)	5	5,17
Major Poisson's ratio, ν_{12}	0,31	0,3
Longitudinale tensile strength, X_t (MPa)	1110	2080
Longitudinal compressive strength, X_c (MPa)	880	1560
Transverse tensile strength, Y_t (MPa)	77	59
Transverse compressive strength, Y_c (MPa)	178	203
In-plane shear strength, S (MPa)	120	93
Layer thickness, t (mm)	0,138	0,146

The test specimens listed in Table 1 were manufactured from unidirectional prepreg tape using press (GFRP) or autoclave (CFRP). The glass fiber prepreg was chosen such that the laminates were nearly transparent. In some cases it was possible to detect the damage progression visually during the test. Damage events for the carbon fiber laminates were detected using acoustic emission. The laminate stress-strain curves were measured with a 100mm extensometer. Typical damage progression started with matrix cracking of the 90º plies. This was clearly visible in test case 4 with thick plies. When 90º plies were saturated by cracks the edge delamination started to propagate from the free edges. The edge delamination propagated to nearly one third of the specimen width on both sides before final fiber breakage. The failure of the ±45º plies was not clearly observed. The damage progression is illustrated in Figure 3. Similar behavior was observed in notched laminates. In this case also the failure of the ±45º plies was observed before ultimate load as shown in Figure 4.

The test results are shown in Table 3. The measured strength for the laminate with thick layers (case 4) decreased 25% from the strength value measured for the GFRP laminate with distributed layers (case 3). The corresponding value for the CFRP laminate was 43%. The laminates with thick layers experienced a premature failure due to the edge delamination. This was observed for both notched and unnotched laminate tests. The standard deviation was within acceptable limits. The deviation was greater for CFRP laminates than for GFRP laminates.

Table 3. Test results for the test series

Series	Laminate lay-up	Measured	E-glass / MTM57		AS4 / 3501-6	
			Average	Deviation	Average	Deviation
1	$[0/0/4(\pm30)]_S$	Tensile strength (MPa)	594,2	10,4	432,6	7,2
2	$[0/0/4(\pm30)]_S$	Compressive strength (MPa)	396,9	15,9	705,6	42,4
3	$[0/3(+45/-45/90)]_S$	Tensile strength (MPa)	306,9	7,8	386,1	18,3
4	$[0/3(+45)/3(-45)/3(90)]_S$	Tensile strength (MPa)	229,6	6,3	218,7	15,0
5	$[0/2(90)0/2(+60)/2(-60)0]_S$	Tensile strength (MPa)	476,3	26,4	785,6	27,2
6	$[0/3(+45/-45/90)]_S$	Tensile strength (MPa)	199,8	9,8	-	
7	$[0/3(+45)/3(-45)/3(90)]_S$	Tensile strength (MPa)	151,2	7,4	-	

Figure 3. The damage progression in the test case 4 laminates

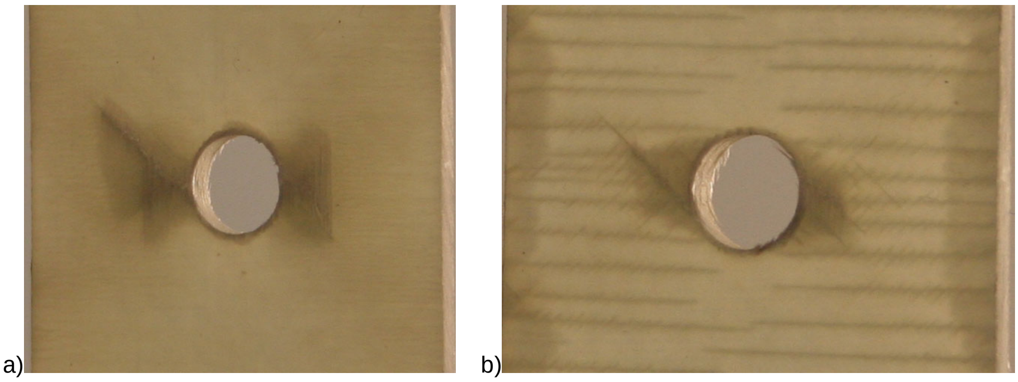
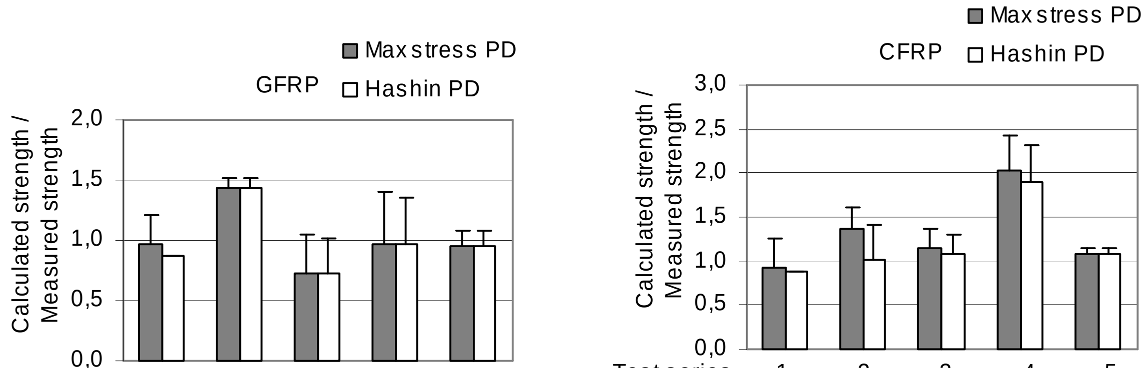


Figure 4. Tested laminates prior to failure for a) test case 6 and b) test case 7

Results for unnotched laminate

In the laminate analysis (cases 1-5) the laminate failure is determined by first fiber failure. Therefore, the failure strengths are mostly influenced by the selected failure criterion for fiber fracture. The normalized final failure stresses are shown in Figure 5. For each test case there are four results for failure strength. The lower bound is set by the conservative ply discount model (PD) and the upper bound is set by the constant stress model (CS). Maximum stress and Hashin criterion is used. The numerical results agree well with the test results for glass fiber laminates except for the compressive strength in test case 2. Most test results for the carbon fiber laminates are below the calculated values.

Applying different degradation rules changes the shape of the laminate stress-strain curve. The stress-strain curve using Hashin failure criteria and different degradation rules is shown in Figure 6. The stress-strain curve calculated with the constant stress model is smooth and gives ultimate loads closer to the measured value tested for the test case 3. The analysis gives same results for the test cases 3 and 4 since the analysis cannot take into account the effect of different stacking sequences. The analysis does not recognize free edge stresses and therefore cannot predict the strength degradation caused by edge delamination.



Test series	1	2	3	4	5
Maximum stress PD	570	570	175	175	454
CS	716	602	323	323	512
Hashin PD	521	570	152	152	454
CS	521	602	311	311	511
Measured (MPa)	594	397	307	230	476

Test series	1	2	3	4	5
Max stress PD	647	596	444	444	855
CS	888	698	529	529	905
Hashin PD	624	437	416	416	855
CS	625	608	505	505	337
Measured (MPa)	706	433	386	219	786

Figure 5. Normalized final failure loads for test series 1-5

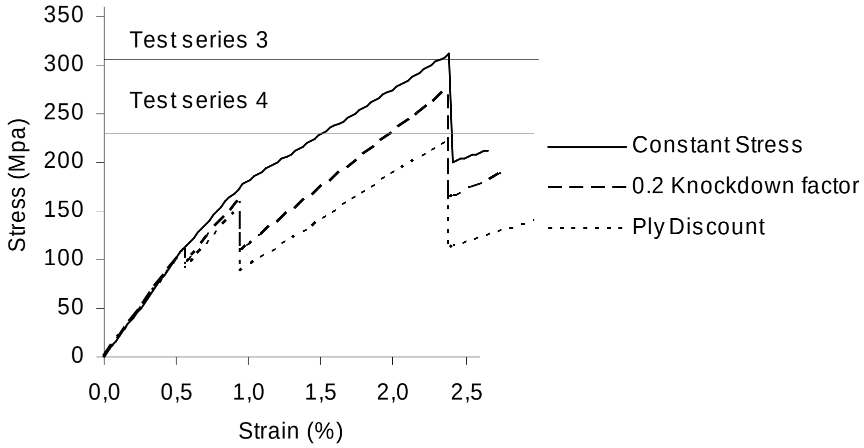


Figure 6. Stress-strain curve for the glass fiber $[0/3(+45/-45/90)]_S$-laminate using Hashin criterion

Results for notched laminate

In order to analyze the notched laminate, a mesh refinement study was performed. As the element mesh was made denser, the FPF-loads and the final failure loads was decreasing. This is due to the increase in peak stresses at the notch boundary. The value of the peak stress with respect to the element size is shown in Figure 7. The element type also had a significant effect on the peak stresses and the failure loads.

The element mesh was refined until the stress distribution from finite element solution provided the same results as analytical results based on complex potentials [3]. The analytical results were calculated using the ESAComp software [4]. The analytical results are derived for an infinite plate. The infinite plate solution was corrected with a finite width correction factor for isotropic plates [3]:

$$\sigma_{finite} = \sigma_{analytical} \frac{2 + \left(1 - 2R/W\right)^3}{3\left(1 - 2R/W\right)} = \sigma_{analytical} \cdot 1{,}053 \quad (1)$$

An appropriate mesh was accomplished with 380 elements and 0.271mm edge element width. As can be seen in Figure 7, the linear reduced integration element S4R cannot provide adequate results. Final results were obtained using the linear element S4 because the same accuracy with quadratic element (S8R) is obtained with less degrees of freedom.

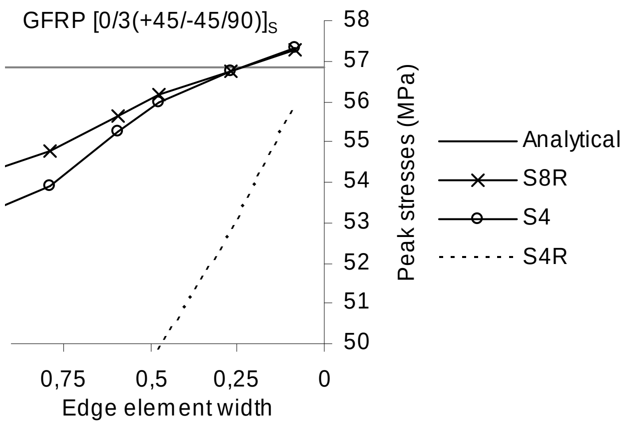
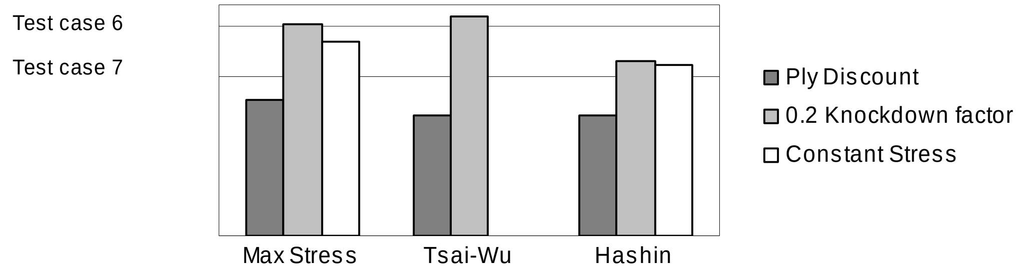


Figure 7. Peak stresses as a function of the edge element width

The analysis results for notched laminates are shown in Figure 8. The experimental results are provided for laminates with two different stacking sequences. The analysis results show that for notched laminates the effect of failure criteria is not that significant if ply discount model is used. The analysis results were close to the experimental values from test case 6 with the constant stress model and the 0.2 knockdown factor. It also seems that the calculated failure strength is dependant on the combination of failure criterion and degradation rules and these cannot be selected irrespective of one other. The degradation rules defines the behavior of the laminate after first ply failure and have more significant effect on the final failure strength than the chosen failure criteria for matrix failure.

The laminate stress-strain curve for the notched glass fiber laminates is shown in Figure 9. The Figure 9 shows the average strain across the specimen over 100 mm length. Again, the analysis does not take into account the different stacking sequences and gives the same result for both laminates. It can be seen from Figure 9 that the stiffness reduction for the laminate with thick layers (test case 7) is more significant than for the laminate with distributed parallel layers (test case 6). In test case 7 the nonlinear behavior started before edge delamination was detected. Therefore, edge delamination alone cannot explain the laminate stiffness loss. The layer thickness and the adjacent layer orientation most probably have an effect on the residual stiffness of the damaged layer.



	Max Stress	Tsai-Wu	Hashin
Ply Discount	129	114	115
0.2 Knockdown factor	201	209	166
Constant Stress	186		162
Test case 6	199,8		
Test case 7	151,2		

Figure 8. Final failure loads for notched glass fiber and carbon fiber laminates

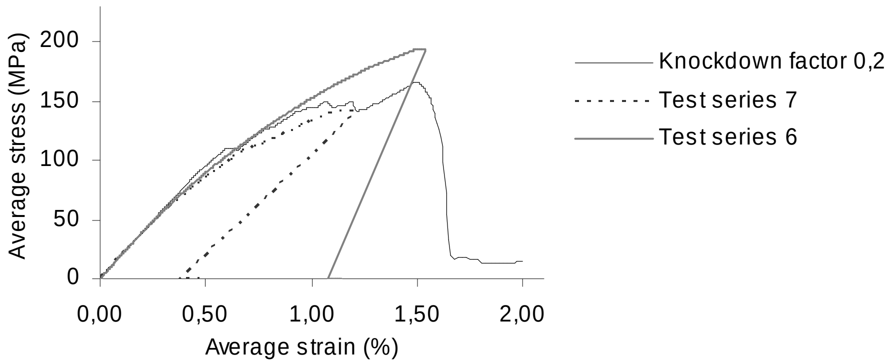


Figure 9. The stress-strain curve for the notched glass fiber laminated

Conclusions

The progressive failure models were applied with different failure criteria and different degradation rules. In the laminate strength analysis (cases 1-5) the failure strength results are mostly affected by the applied failure criteria for laminate failure. The applied degradation rules have a secondary role. In the analysis of notched laminates (cases 6-7) the choice of degradation rules had more effect on the final failure loads than the applied failure criteria.

In a structural analysis the results are always strongly dependant on the element mesh. A sufficiently fine mesh must be used in order to predict the stress distribution correctly. An alternative method to calculate the stresses should be used to compare with the FE results. If the stresses are not calculated correctly, the progressive models cannot be applied to the problem.

The experiments showed that laminate stacking sequence and ply thickness has a tremendous effect on the final strength of the laminate. Because of assumed plane stress state, the out-of-plane stresses are not included and therefore, the analysis does not describe the physical behavior and cannot estimate the failure load correctly.

References

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