10th International Conference on Composite Science and Technology
ICCST/10
A.L. Araújo, J.R. Correia, C.M. Mota Soares, et al. (Editors)

NUMERICAL SIMULATION OF IMPACT BEHAVIOUR OF CARBON COMPOSITE LAMINATE IN DEPENDANCE OF PLY THICKNESS

Peter Linde*, Francesca Mendolia†, Aniello Riccio†

* Airbus,
Kreetslag 10
21129 Hamburg, Germany
e-mail: peter.linde@airbus.com, web page: http://www.airbus.com

† Seconda Università degli Studi di Napoli
Via Roma, N° 29
81031 Aversa (CE), Italy
e-mail: aniello.riccio@unina2.it, web page: http://www.unina2.it

Key words: Impact, Carbon Composite, Finite Element Model, Delamination, Ply Thickness, Damage Behavior.

Abstract: The impact behavior of carbon fibre reinforced plastic laminates is investigated by numerical simulation in dependence of ply thickness.

The influence of ply thickness on the damage behavior of composite laminates has been subject of increased interest in recent years. Positive influence has been reported with decreasing ply thickness on different mechanical properties. Studies are however dispersed and mostly small so that clear conclusions are largely missing until date.

Impact behavior in dependence of ply thickness has essentially only been studied experimentally so far. The indications were favorable for decreasing ply thickness, but systematic evidence is missing. In this study numerical models of a laminate are built up, keeping a constant laminate thickness, with variation in ply thickness. As reference a 1,65 mm thick laminate consisting of 13 plies is chosen. The modelling is carried out in ABAQUS, using continuum shells for each ply, with cohesive elements between all plies, to enable simulation of delamination. In-ply damage is accounted for by the Hashin damage model.

Variations from the reference laminate are modelled, with 17 and 21 plies. Simulation of impact, taken as part of a Compression after Impact test procedure, is carried out using explicit integration. Delamination location and size is compared for all variations, as well as in-ply damage. It is concluded that the ply thickness has an effect on the distribution and size of damage.

Summary, conclusions and recommendations for future research are given.

1. INTRODUCTION

1.1 General

In carbon composite structures, it is known that the mechanical behavior is influenced by the ply thickness, shown in early research by Sin and Tsai [1] and has since been the subject of several investigations. This early research has focused on strength and fatigue behavior, and favourable effect of thin plies was indicated. The effect on damage by ply thickness under impact loading has however been relative sparsely studied. Initial investigations at the Kanazawa Institute of Technology [2] indicate different sequences of damage mechanisms for composite laminates built of thin plies compared with those built of thicker plies.

1.2 Scope

A numerical modelling of composite laminates built by different ply thicknesses, and simulation of impact loading is the main purpose of this paper. The scope is as follows:

In Chapter 2 an introduction to thin ply composites is followed by a summary of relevant recent research, identification of needs, followed by a task formulation

In Chapter 3 a numerical model of composite plates built of different ply thicknesses is shown, followed by a description of damage models and numerical results of impact simulation.

In Chapter 4 a summary with conclusions and recommendations for future research are provided.

2. THIN PLY COMPOSITES

2.1 Introduction

Ply thicknesses below the standard low grade plies, commonly 134 grams per square meters, gsm, are increasingly available, manufactured by tow spreading technology. By this it is possible, starting with a heavy tow, to spread the fibers into a wide and thin ply. Figure 1 shows the principle of a pneumatic tow spreading machine. On the left is the machine shown, and on the right a principal sketch of the gradual increased spreading of the fibers.

Some suppliers have specialized in developing tow spread products in recent years, in form of tapes and fabrics, and these often are as thin as 50 gsm, but can be down to 20 gsm.

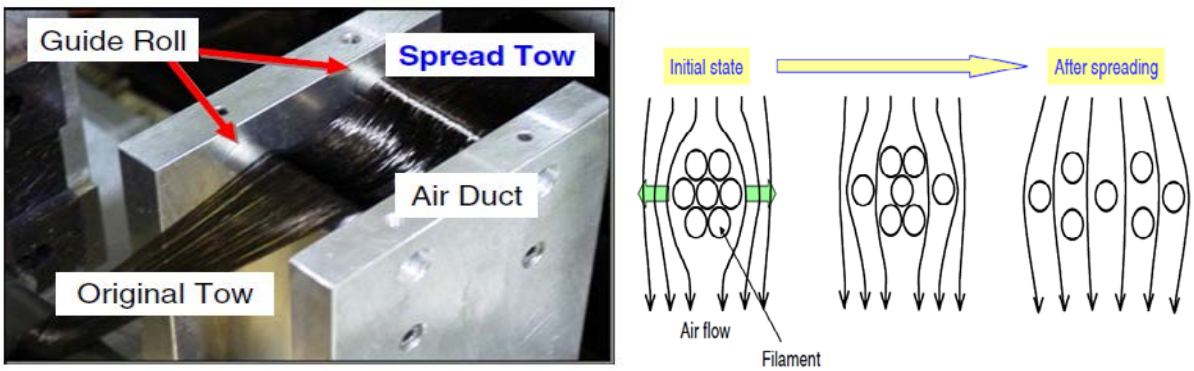

Figure 1: Pneumatic tow spreading machine (left); schematic representation of the spreading (right)

2.2 Recent research, needs and task formulation

In recent years an increase in research on mechanical behavior of thin ply composites has been noted. A systematic effort has been undertaken by a Swiss national program, with mechanical testing carried out at the EPFL [3]. Amongst test can be mentioned; plain strength, open hole compression and tension, and bearing strength, all of which benefitted from thinner ply thickness, except open hole tension static (however fatigue benefitted). At the University of Porto, experimental and numerical studies have focused on notched behavior [4], whereby no notch sensitivity was found, as well as on in-situ strength, which benefitted of thinner ply. At the Univ. of Girona research focused on delamination [5], including edge delamination, both of which benefitted with decreasing ply thickness.

Experimental research was carried out in a NASA-Stanford cooperation on damage tolerance behavior of thin ply composites involving specimens built of differently stacked thin ply fabric from Chomarat, whereby smaller mismatch angles in general appeared to result in higher CAI-values [6]. The variation in specimens were however not very large, and effects of ply thickness and mismatch angles not easy to separate. Thus a need is identified to study the influence of ply thickness on damage for impact loading in a more systematic way. A complete study would involve both numerical modelling and experimental tests, and several parameters, making it an extensive task. This cannot be accomplished with the frame of the work presented here, however, a relevant start can be performed as a first step.

The task of this study is a the creation of numerical models of composite plates built of differently thick plies, and to carry out a numerical simulation of impact loading of these plates.

3. NUMERICAL MODELLING OF IMPACT

3.1 Model of Impact specimen

The numerical model built in ABAQUS [7] of the composite plate with the impactor is shown in Figure 2. The specimen geometry is given in Table 1.

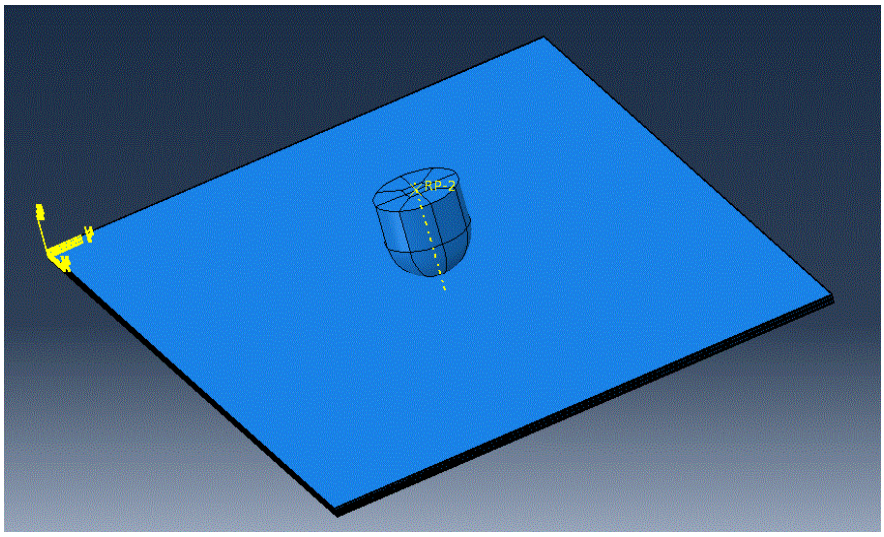

Figure 2: Numerical model of composite plate with impactor

Laminate	
Size	150x100
Thickness	1.65
Cohesive thickness	0.01

Table 1: Geometrical dimensions of plate in mm

The material is Hexply IMA/M21E and the properties including strength and fracture data used here are given in Table 2. Impactor properties are given in Table 3.

Property	IMA/M21E
Ply Thickness	0.127
E_{11} (GPa)	164
E_{22}, E_{33} (GPa)	8.5
G_{12}, G_{13},	4.2
G_{23}	3.36
ν_{12}, ν_{13}	0.35
ν_{23}	0.265

Property	IMA/M21E
Interlaminar peel strength f3t	64.5 MPa
Interlaminar shear strength $f_{13s} = f_{23s}$	90 MPa
Fracture toughness mode I GIC	350 J/m²
Fracture toughness mode II GIIC	350 J/m²
Fracture toughness mode III GIIIC	2000 J/m²

Table 2: Material properties used in this study

Parameter	Value
Impact Energy [J]	7
Impactor Diameter [mm]	16
Impactor Young Modulus [GPa]	210
Impactor Poisson Ratio [-]	0.3

Table 3: Impactor properties

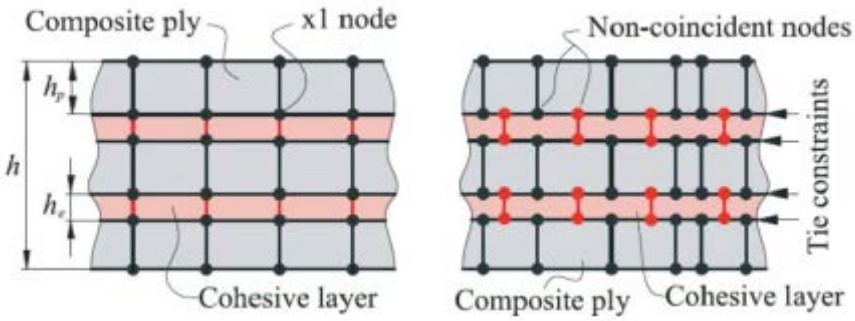

Figure 3: Inter ply damage modelling approaches; cohesive elements (left) and Tie constraints (right)

In Figure 3 different approaches of modelling inter ply damage considered are shown, To the left is the approach with cohesive layers shown. Between each ply exists a cohesive layer, each of which was modelled by cohesive elements in ABAQUS. An alternative approach, using tie constraints, also tested during the study, is shown to the right.

3.2 Damage models

For intra ply damage, the Hashin failure criteria, a set of criteria considering; fibre damage in tension and compression, as well as matrix cracking in tension and compression, that is implemented as a native damage model set in ABAQUS, was used. The constitutive model is shown in Figure 4. Undamaged response leads up damage onset, defined by the criteria, and denoted by Point A. From this point the damaged response is described by a damage degradation law, until zero stress has been reached. The criteria for the different failure mechanisms are summarized in Table 5.

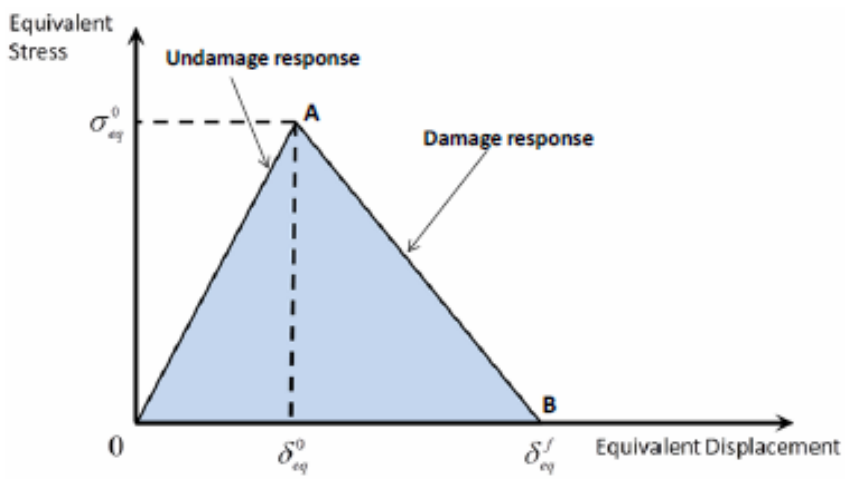

Figure 4: Constitutive model used in the Hashin failure criteria

FAILURE CRITERIA	FAILURE MODES
$\left(\frac{\sigma_{11}}{X_t}\right)^2 + \alpha\left(\frac{\tau_{12}}{S_l}\right)^2 = 1$	Fiber Tensile failure
$\left(\frac{\sigma_{11}}{X_c}\right)^2 = 1$	Fiber Compressive failure
$\left(\frac{\sigma_{22}}{Y_t}\right)^2 + \left(\frac{\tau_{12}}{S_l}\right)^2 = 1$	Matrix Tensile failure
$\left(\frac{\sigma_{22}}{2S_t}\right)^2 + \left[\left(\frac{Y_c}{2S_l}\right)^2 - 1\right]\left(\frac{\sigma_{22}}{Y_c}\right) + \left(\frac{\tau_{12}}{S_l}\right)^2 = 1$	Matrix Compressive failure

Table 5: Hashin damage criteria, implemented in ABAQUS, used in this study

Three laminates were modelled, as follows:

A laminate, consisting of 13 standard (low grade) plies, of 134 gsm, with thickness 0.127 mm each, forming a laminate of 1.65 mm, is used as base line. The stacking sequence is:

[45,-45, -45, 45, 90, 0, 90, 45, -45, -45, 45]

The first variant with thinner plies has 17 plies, in total the same 1.65 mm laminate thickness, 102 gsm and 0.097 mm thickness, and has the stacking sequence:

[45, -45, -45, 45, 90, -45, 0, 45, 90, 45, 0, -45, 90, 45, -45, -45, 45]

The second variant consists of 21 plies together with the same 1.65 mm laminate thickness, 83 gsm and 0.078 mm thickness, and has the stacking sequence:

[45, -45, -45, 45, 90, -45, 0, 45, 90, -45, 0, -45, 90, 45, 0, -45, 90, 45, -45, -45, 45]

3.3 Numerical results of impact simulation

Numerical simulations of the nonlinear behavior including damage of the composite plates subjected to impact, were carried out with ABAQUS Explicit. The results are divided into intra-ply damage (here: matrix cracking) and inter-ply damage (here: delamination).

The results are shown grouped together, whereby the base line stacking is shown to the left, followed by the variant stackings with 17 plies and with 21 plies. Before the results, these stackings are shown graphically with arrows indicating the position of the results. Ply number (same direction) as well as cohesive layer number are counted from the bottom to the top.

In Figure 5 laminates are shown with indications for the top plies and their numbers (from bottom). Results for intra-ply damage (Hashin, matrix, tension) in top plies are shown in Figure 6, according to ply numbering in Figure 5. The damage is somewhat larger for the thin ply, which can be explained with its lesser thickness, being directly hit by the impactor. Figure 7 and 8 show the corresponding damage some plies further down, at the third 90 degree ply, from the bottom. Here, the situation has changed and the thin plies display smaller damage.

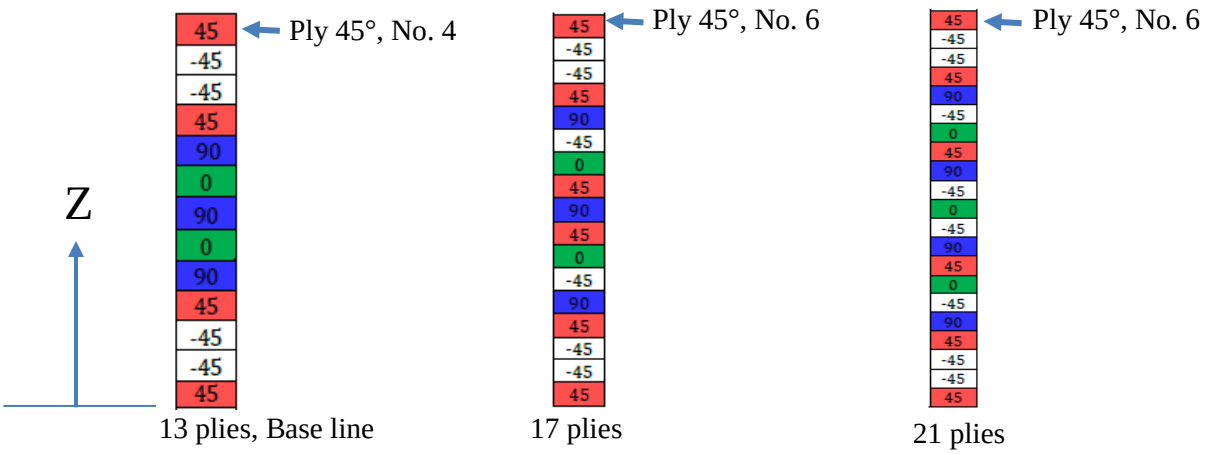

Figure 5: Laminate stackings for composite plate; 13 plies, base line (left), 17 plies (center), and 21 plies (right), denoting top ply numbers

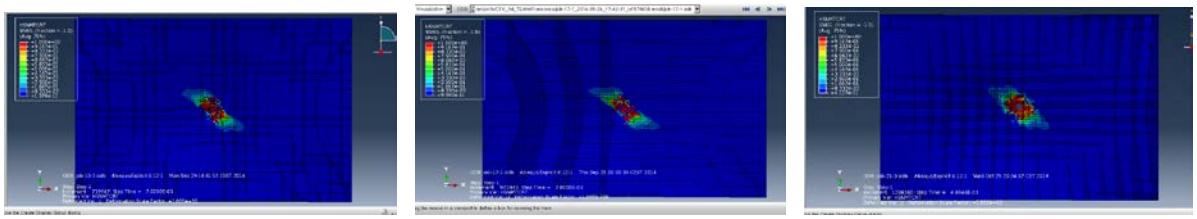

Figure 6: Intra-ply damage acc. to Hashin criterion; matrix cracking in tension; in top plies, numbered acc. to Figure 5.

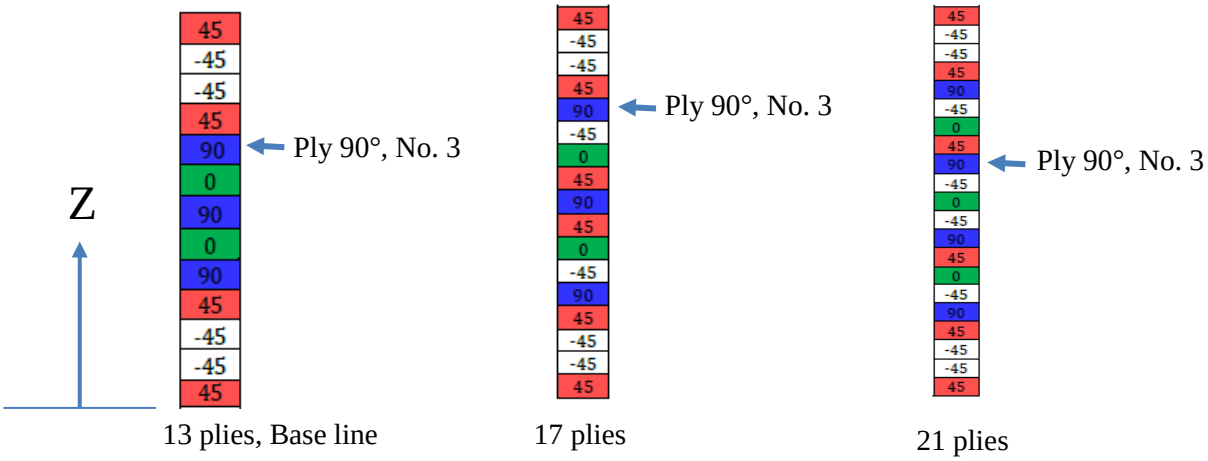

Figure 7: Laminate stackings for composite plate; 13 plies, base line (left), 17 plies (center), and 21 plies (right), denoting 3rd 90° ply numbers

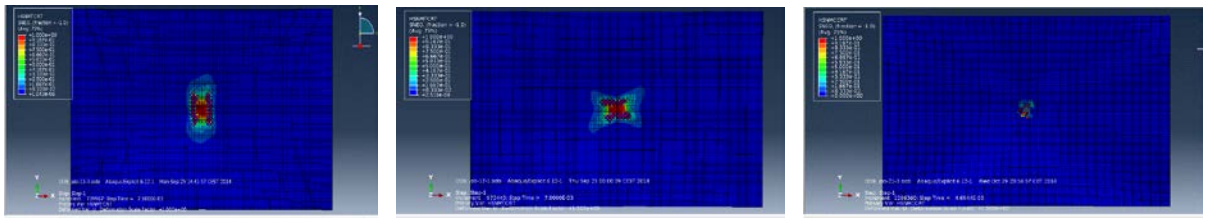

Figure 8: Intra-ply damage acc. to Hashin criterion; matrix cracking in tension; in 3rd 90° plies, numbered acc. to Figure 7.

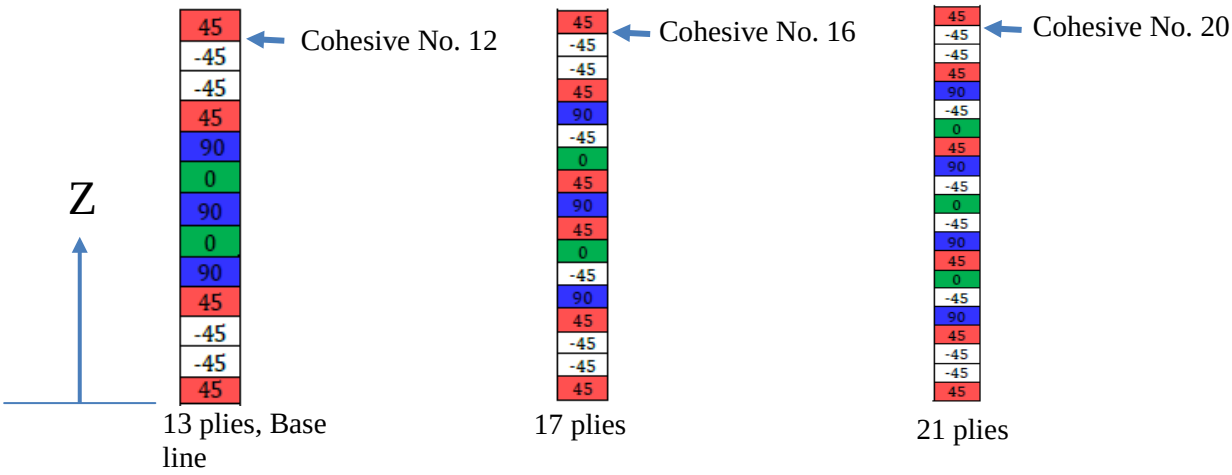

Figure 9: Laminate stackings for composite plate; 13 plies, base line (left), 17 plies (center), and 21 plies (right), denoting uppermost cohesive layers, numbered from the bottom.

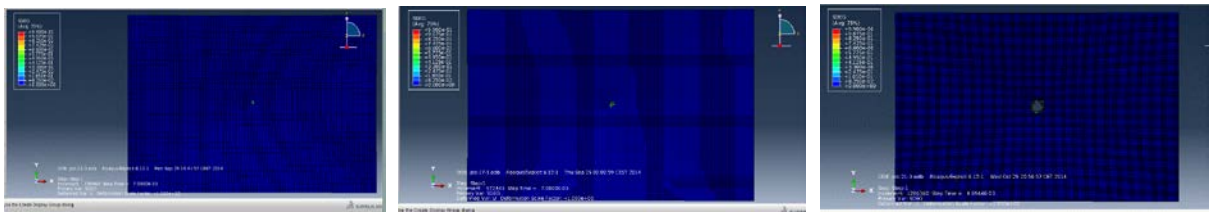

Figure 10: Inter-ply damage in cohesive elements; in cohesive layers; 12 (13 ply laminate), layer 16 (17 ply laminate), and in layer 20 (21 ply laminate) with numbering acc. to Figure 9.

For inter-ply damage, in a corresponding manner, we start at the top of the laminate, regarding the cohesive layer closest to the top ply. With a cohesive layer numbering starting from the bottom, as shown in Figure 9, we will regard, cohesive layer number 12 in the laminate with 13 plies, and cohesive layer number 16 in the laminate with 17 plies, and cohesive layer number 20 in the laminate with 21 plies.
In Figure 10 the cohesive damages, i.e. delaminations, are shown for the three laminates at the position right below the top plies. It can be seen that the thin ply laminate displays a somewhat larger delamination than the standard ply laminate. Given that the intra-ply damage is larger here, as was seen in Figure 6, this makes sense considering that matrix cracking usually will trigger delamination, termed MCID (matrix crack induced delamination).

In Figure 11 the cohesive layer locations for the last set of cohesive damage results are shown, in the lower half of the laminate; layer 5, for all the three laminates, counted again from the bottom. Figure 12 shows the corresponding cohesive damage for layer 5 in all laminates. Here it is seen that cohesive damage has decreased in all the three laminates, to practically zero, with a minor spot still visible in the thin ply laminate.

It should here be noted that in the results above, the simplifying assumption has been made to apply equivalent strength to all the plies in all three laminates. This is not correct, given known results from first mechanical tests, see e.g. [3], which displayed a clearly increased tensile as well as compressive strength for thinner plies. Therefore the results above for both intra-ply and inter-ply damage are not yet fully realistic, in as far as the higher strength, that should have been applied to the thinner plies, was intentionally not used. The goal was to study what effects may show when purely altering the ply thicknesses.

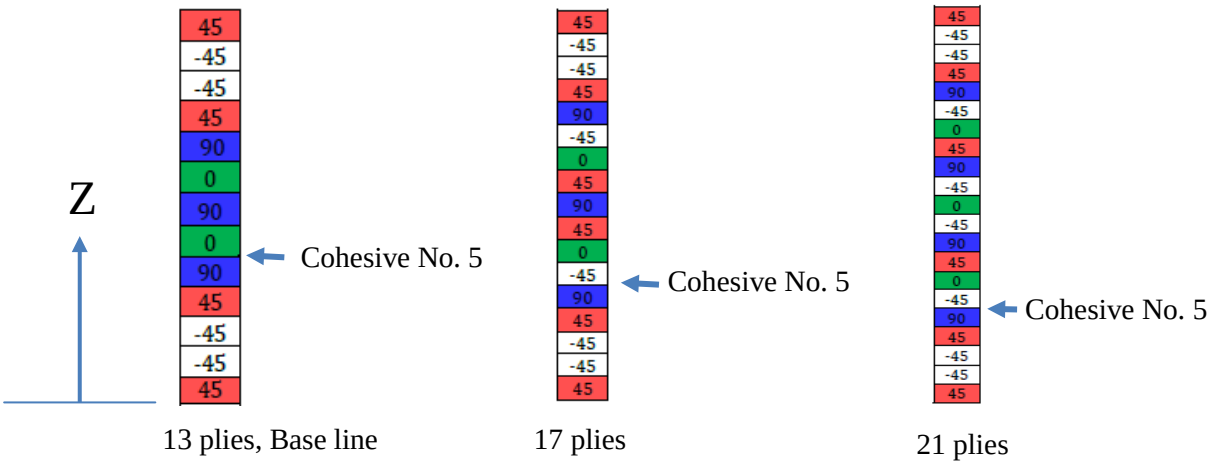

Figure 11: Laminate stackings for composite plate; 13 plies, base line (left), 17 plies (center), and 21 plies (right), denoting cohesive layer number 5 from the bottom.

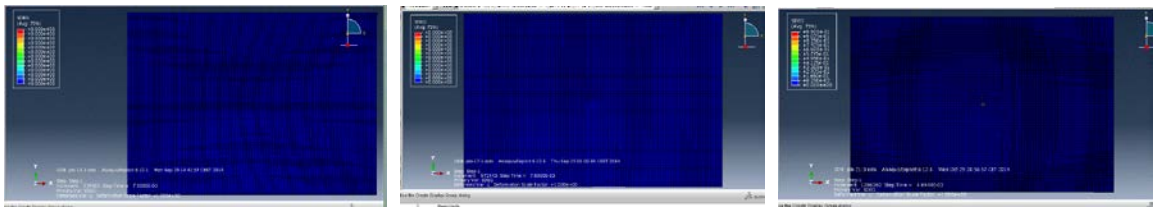

Figure 12: Inter-ply damage in cohesive layers; layer 5 (13 ply laminate), layer 5 (17 ply laminate), and in layer 5 (21 ply laminate) with numbering acc. to Figure 11.

4. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

4.1 Summary

For investigating the effect of the impact behavior of composite laminates with varying ply thickness, a numerical study was planned and carried out. A composite plate was chosen as a study object, taking its dimensions from standard CAI specimens; 100 x 150 mm. As base line was chosen a laminate consisting of 13 plies of 134 gsm each, amounting to a total laminate thickness of 1,65 mm. A standard stacking, optimized for damage tolerance, was chosen. Two alternative stackings were chosen, each with thinner plies than the standard stacking, but keeping the total laminate thickness constant. These stackings had 17, and 21 plies, respectively.

The modelling was carried out in ABAQUS, using continuum shell elements for the plies combined with the Hashin failure criteria, and a linear damage propagation. For the ply interfaces, cohesive elements were used, with elastic behavior up to failure, and followed correspondingly by a linear damage propagation. An impactor was modelled in ABAQUS and simulation of impact was carried out with explicit integration.

4.2 Conclusions

Damage was studied at certain locations, in the vicinity of the impactor and at some different levels over the laminate thickness.

For intra-ply damage, only matrix cracking was studied here, and it was concluded that at the top of the three laminates, the one with the thinner plies displayed somewhat larger matrix cracking. This can be explained by the smaller ply thickness affected directly by the impactor.

Further down in the laminate, this reversed, and the laminate with thinner plies displayed smaller matrix cracking area.
For the inter-ply damages delamination was studied in the cohesive elements and correspondingly, the laminate with the thinnest plies displayed a somewhat larger delamination right below the topmost plies, attributed to the matrix damages there. Further down in the laminate, all three laminates displayed decreased delamination.
Simplified assumptions, in particular using equivalent strength for all ply thicknesses, has had an effect on the above results.

4.3 Recommendations for future research

It is recommended that the studies in this paper be complemented with studies focusing on the following:

- Strength increases for thinner plies, taken from experimental results, such as [3], should be included in the numerical model, and will likely influence the results
- Complementary output in terms of fiber damages should be included
- Effect of the variation of the fibre angles between adjacent plies should also be studied, in particular more shallow angles than was used here
- Further sample points over the thickness of the laminate should be studied

ACKNOWLEDGEMENT

The studies in this paper were carried out during an internship of the second author at Airbus in Hamburg from April through September 2014. The assistance in ABAQUS related matters by Dr. Torsten Möcker of Simulia Dassault Systémes is gratefully acknowledged.

REFERENCES

[1] Sihn, S., Kim, R., Kawabe, K., Tsai, S.W., Experimental studies of thin-ply laminated composites, Compos. Sci. Techn., 67: 996-1008, 2006

[2] Mototsugu, T., Ohtsuki, Y., Morita, M., Ikemoto, T., et al, A Simulation on Impact Damage Process in Thin-ply FRP Laminates Based on In-situ Observation, Technical report, CDW 15, Kanazawa Inst. of Techn., 2011

[3] Amacher, R., Cugnoni, J., Botsis, J., Sorensen, L., Smith, W., et al, Thin ply composites: Experimental characterization and modelling of size-effects, Compos. Sci. Techn., 101: 121-132, 2014

[4] Arteiro, A., Catalanotti, G., Xavier, J., Camanho, P.P., Notched response of non-crimp fabric thin-ply laminates, Compos. Sci. Techn., 79: 97-114, 2013

[5] Guillamet, G., Turon, A., Costa, J., Linde, P., Mayugo, J.A., Damage occurence at edges of non-crimp-fabric thin-ply laminates under off-axis uniaxial loading, Compos. Sci. Techn., 98: 44-50, 2014

[6] Tsai, S.W., Multi-angle C-ply tapes for ATL – Design driven and enhanced by manufacturing, Proc. 1st Int. Symposium on Automated Composites Manufacturing, Concordia Univ., Montreal, 11.-12. April, 2013

[7] ABAQUS; V. 6.13, Reference manual, Simulia - Dassault Systémes, 2014