PRELIMINARY PREDICTION OF SPECIMEN PROPERTIES
CLT and 1st order FEM analyses

first issue

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CHANGE RECORD

Issue/revision	date	pages	Summary of changes
draft	24-10-02	all	new document
1	15-11-02	4	correction of RF definition and added text on failure criteria

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1 INTRODUCTION

In this note, analysis results are given for the first analyses step in WP10. This involves predictions of the specimen strain patterns and reserve factor patterns for the Optimat Blades UD and MD specimens, using literature material data.
The properties have been predicted using a CLT program and a simple FEM package.

The following test cases are defined in [4]:

No.	type	loading		comments
		direction	value [N/mm]	
U1t	UD	tension longitudinal	40	
U1c	UD	compression longitudinal	40	
U2t	UD	tension transverse	40	
U2c	UD	compression transverse	40	
Ust	UD	shear tensile	tbd	still to be defined
M1t	MD	tension longitudinal	40	
M1c	MD	compression longitudinal	40	
M2t	MD	tension transverse	40	
M2c	MD	compression transverse	40	
Mst	MD	shear tensile	tbd	still to be defined

Table 1: Load cases for the specimen predictions

2 PREDICTION PACKAGES

2.1 Classical Laminated Plate package

The Classical Laminated Plate theory has been implemented in numerous software packages. Provided the packages have been tested thoroughly, these all should give the same results. There are some differences in the completeness of the user-interface and failure criteria offered but basically the results given are the ABD matrices, strains and stresses.
The package used in this report, is a demo version of 'The Laminator' [2], a relatively easy to use and cheap package. It offers possibilities of loading the (infinite) plate and calculate the strains, stresses and so-called 'Load Vector Scale Factors'. The latter gives the ratio of fracture load and applied load.
In parallel calculations have been performed with the 'Kolibri' package [1] on infinite plates. This package also has a simple finite element (see 2.2) and outputs strength results as the 'Reserve Factor' (RF) or the inverse thereof. This RF seems equivalent to the 'Load Vector Scale Factors' as used by 'The Laminator'. In this document RF will be used for both packages.

2.2 FEM package

The 'Kolibri' package offers the possibility of calculating the behaviour of a finite, rectangular plate when mechanically loaded. The plate can be constrained or loaded by a uniform pressure, or a point, area or edge load. For the purpose of this investigation, and edge force has been used. The package is limited in element types: only triangular elements are possible, probably with 3 nodes (no detailed information is given). The mesh can be generated automatically, or in a regular mesh.
Unfortunately it is not possible to constrain the loaded edge in such a way that global translation results. Therefore half-models are used (half of the specimen length) in which deformation of the cross section in the specimen middle plane is allowed although this would not occur in reality.
For these reasons, the package can not be seen as a high-quality FEM package like Nastran or MARC. Results can be used, however, as an illustration of the stress rise near the clamped edge.

In the 'Kolibri' package three failure criteria are possible: maximum strain, maximum stress and Tsai-Hill. In this document only the Tsai-Hill criterion will be reported on.

3 PREDICTION OF THE UD SPECIMEN PROPERTIES

3.1 Materials, lay-up and geometry

The material properties used for the analyses are as given for the Silenka E-glass/MY750 combination, as given in [3]. No tab material is used as there are no possibilities to model a specimen including tabs and grip constraints.
For some of the material properties, the complete stress-strain curve is given, since the behaviour is non-linear. The in-plane shear properties are given in Figure 1. The actual strain at failure is 4% instead of 1.25% (when using Hooke's law). This will have some consequences for the failure load predictions.
For both the CLT package applied as the FEM package, non-linar material properties are not possible. Therefore the initial moduli will be used and the failure stress as given in [3].

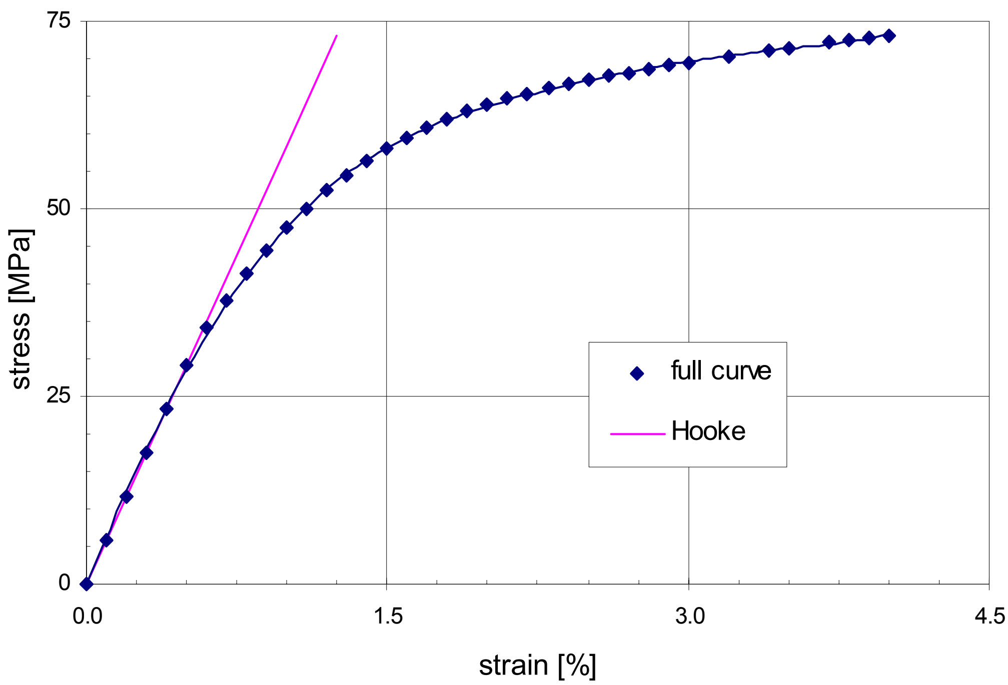


Figure 1: Stress-strain curve for in-plane shear

For the UD specimen a simple lay-up is used: 4 layers of 0° oriented layers with a thickness of 0.88 mm.

The geometry of the specimen is given in [3]: a straight specimen with width of 25 mm and free length of 35 mm. The nominal specimen thickness (4 layers of material) is 3.52 mm.

3.2 CLT results

Specimen stiffness and FPF strength can be predicted by the CLT package. The results are easy to describe: the specimen has the stiffness and strength properties of the UD layer itself. No layers are included with different material properties or orientation, therefore the FPF strength also is the final failure strength.
The failure loads are given as running loads: force by unit width.

E_x	[MPa]	45600
E_y	[MPa]	16200
G_{xy}	[MPa]	5830
ν_{xy}		0.278
ν_{yx}		0.0988
N_{xt}	[N/mm]	4505.6
N_{xc}	[N/mm]	2816
N_{yt}	[N/mm]	140.8
N_{yc}	[N/mm]	510.4
N_{xy}	[N/mm]	257.0

Table 2: CLT results for the UD specimen lay-up (Tsai-Hill criterion)

3.3 FEM results

For the FEM analyses a half model has been used, see Figure 2, of the free part of the specimen outside the grips. Although the distribution of the triangular elements is not regular, this has no significant effect on the strain distributions.

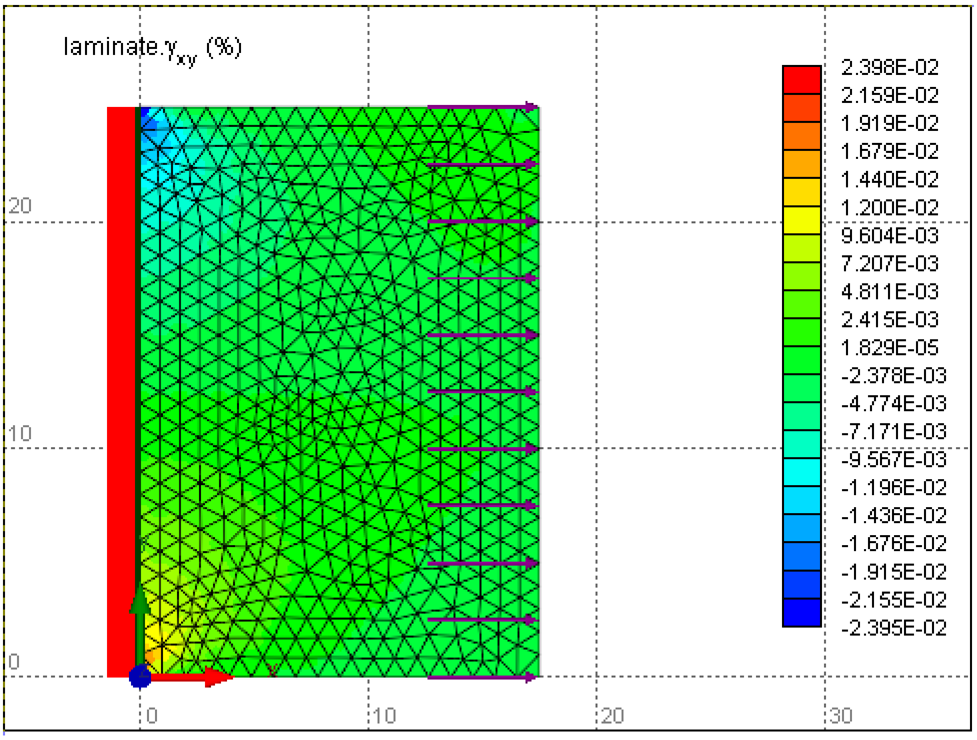


Figure 2: Mesh for the UD specimen, generated automatically by the Kolibri package

The rectangular plate is clamped at the left side, free at the other edges and loaded by an edge loading of 40 N/mm at the right side. Due to package limitations, no constraints on the right end are applied.
The FEM package has the option to rotate the laminate. This has been used to calculate the distributions when loading the laminate in the transverse direction.

As can be seen from the strain distributions in Figure 4, at the loaded end the specimen is not strained homogenously. This is a consequence of the short free length of the specimen. For a specimen with doubled length strains are homogeneous at the loaded end, as can be seen in Figure 3. It should be noted that the strain distributions over the first 17.5mm from the clamped side are not the same for both models.

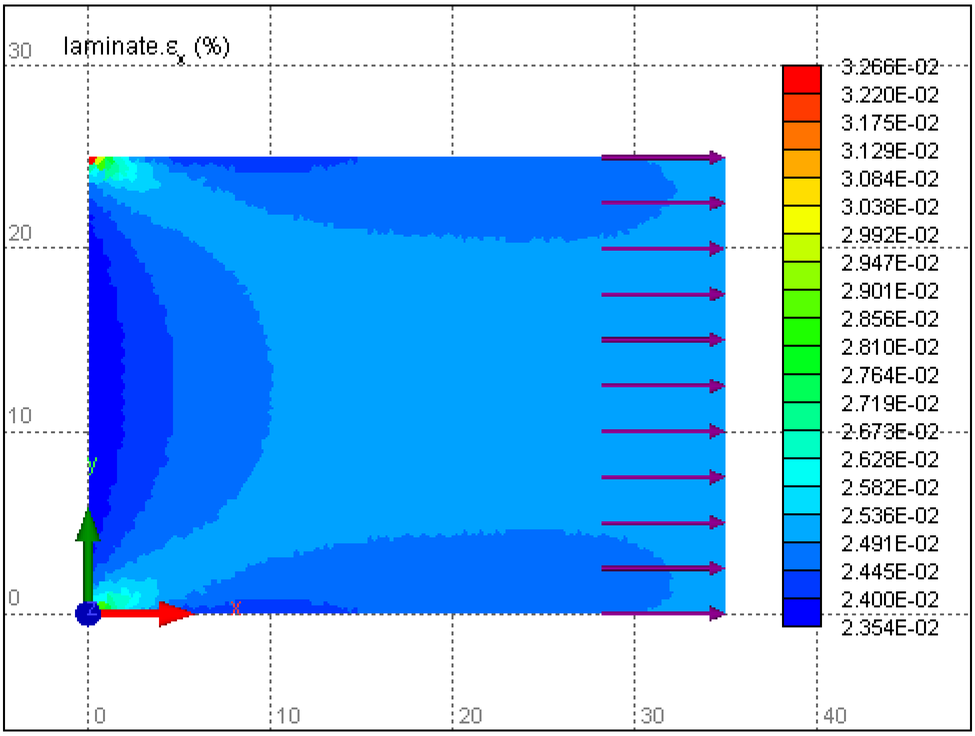


Figure 3: Longitudinal strain distribution for double length (load case U1t)

The predicted patterns of the strain and the inverse of the reserve factor are given in Figure 4 to Figure 9.
Peak strains always occur at the corners of the clamped side of the specimen, as can be expected. The strain values itself are also influenced by the number of elements used in the mesh. Smaller elements apparently lead to higher peak strain values.
For tensile loaded cases, the inverse of the reserve factor per layer is dominated by the strain transverse to the fibre. For compression loaded cases, domination is less simple.

	strains [%]				1/RF	
	ε_x		ε_y			
	CLT	max	CLT	max	CLT	max
M1t	0.02492	0.03266	-0.00693	-0.00791	0.00888	0.0371
M1c	-0.02492	-0.03266	0.00693	0.00791	0.0142	0.0277
M2t	-0.00693	0.00888	0.07015	-0.00841	0.2841	0.3682
M2c	0.00693	-0.00888	-0.07015	0.00841	0.0784	0.1048

Table 3: Strains and strength aspects of UD specimen

Values for the strains and the inverse of the reserve factors, for a loading of 40 N/mm, are given in Table 3 for an infinite plate (designated 'CLT') and the extreme values for the FEM models. As can be seen from the table, the peak strains in the specimen are predicted considerably higher than for an infinite pate. As a consequence, the margin to failure is much smaller.

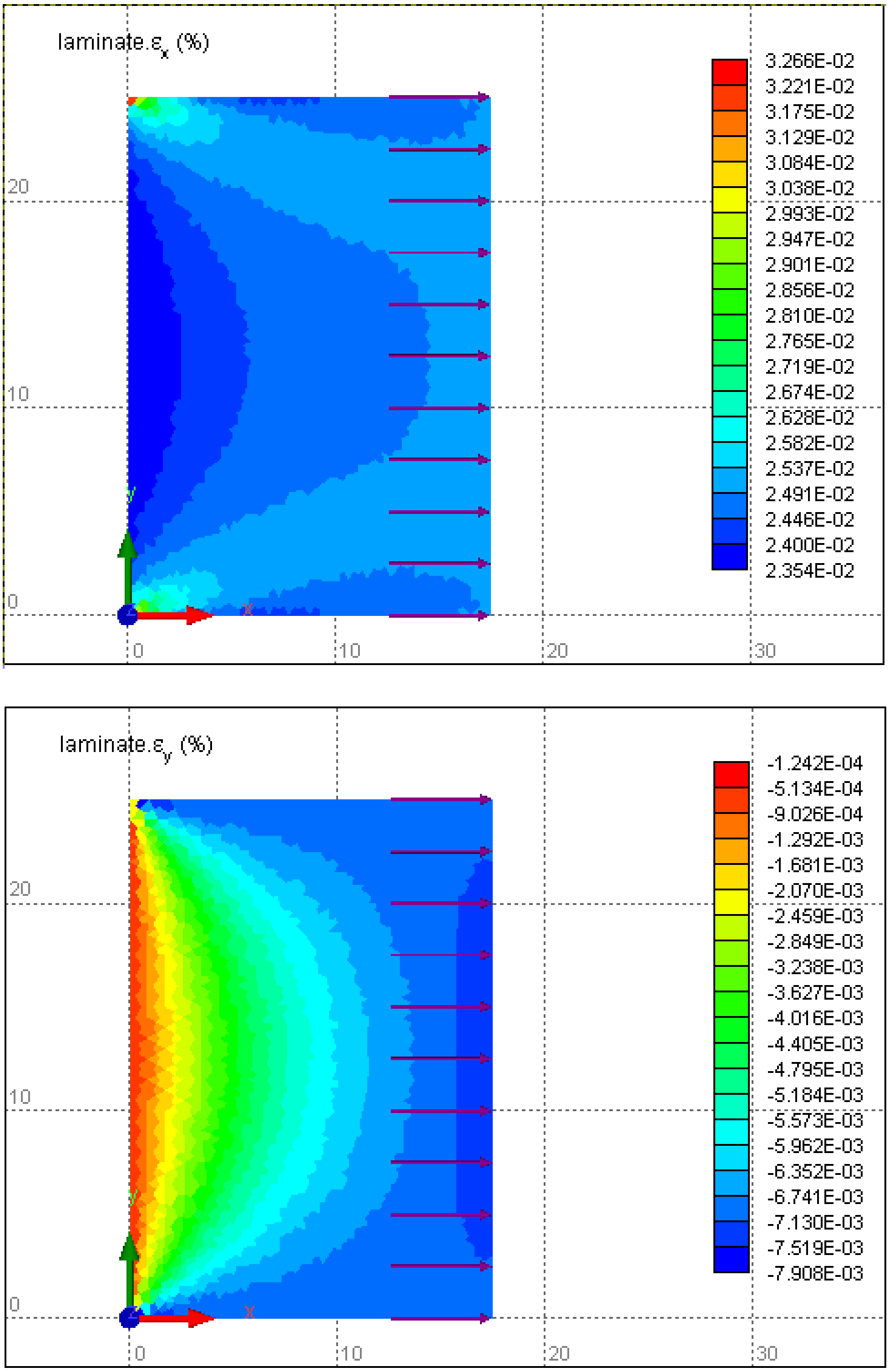


Figure 4: Laminate strain distributions at load case U1t (Fx = 40 N/mm)

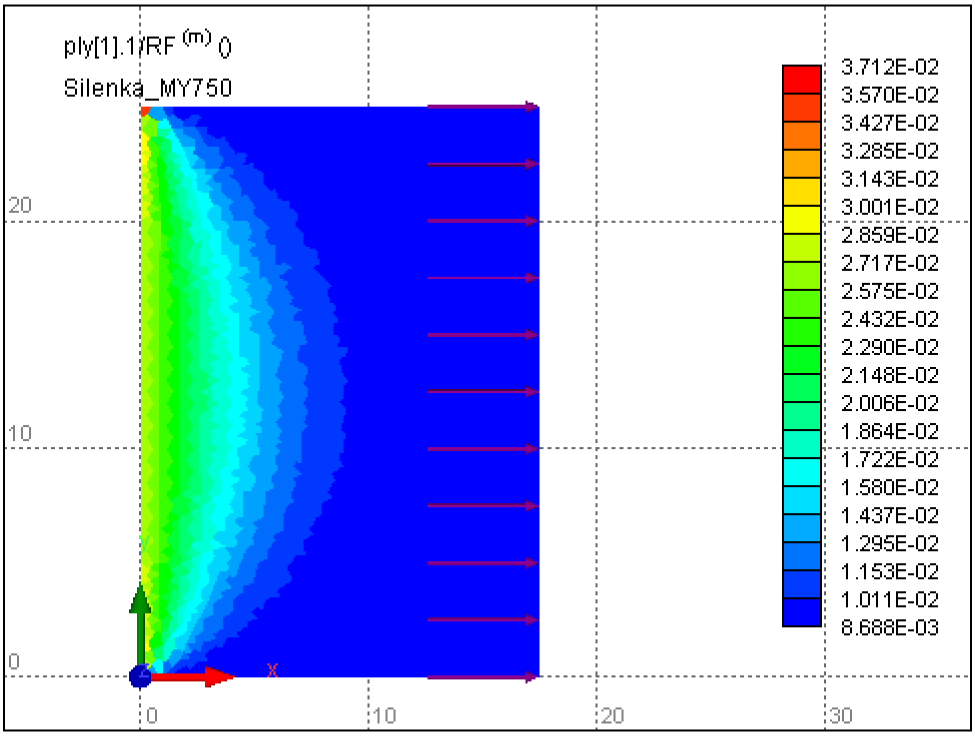


Figure 5: Reserve factor distributions for the 0° layer at load case U1t

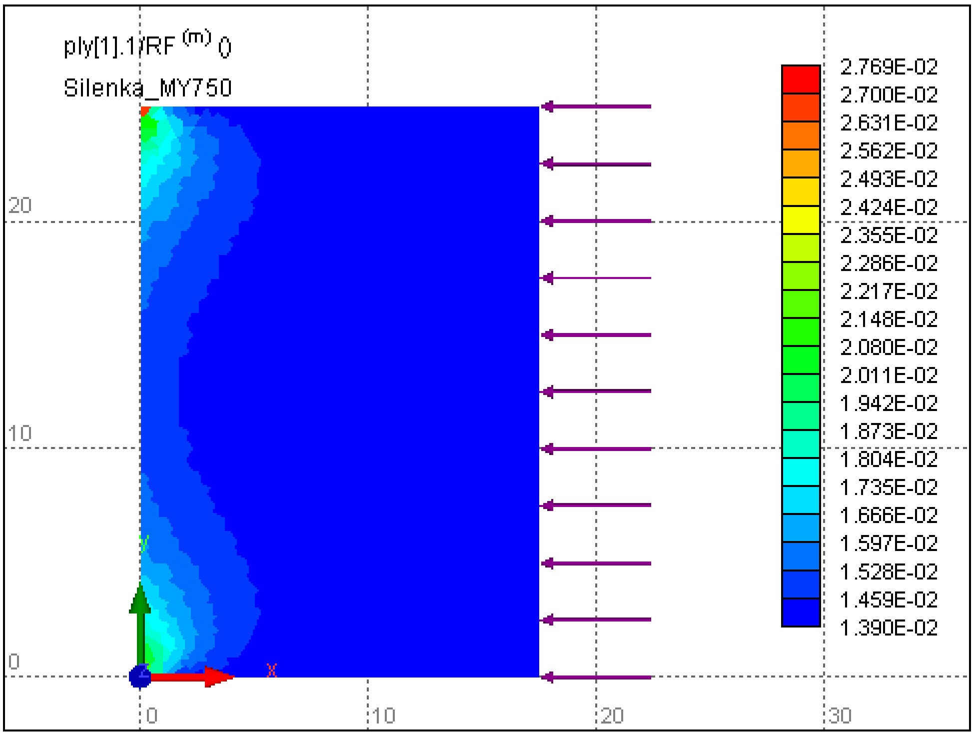
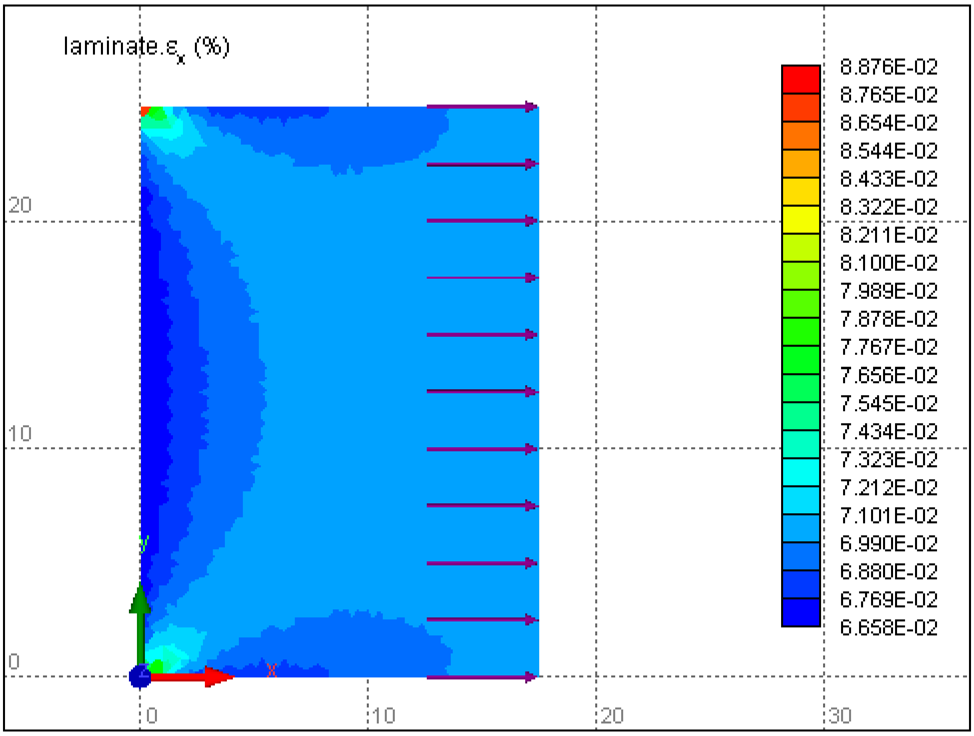


Figure 6: Reserve factor distributions for the 0° layer at load case U1c (Fx = -40 N/mm)



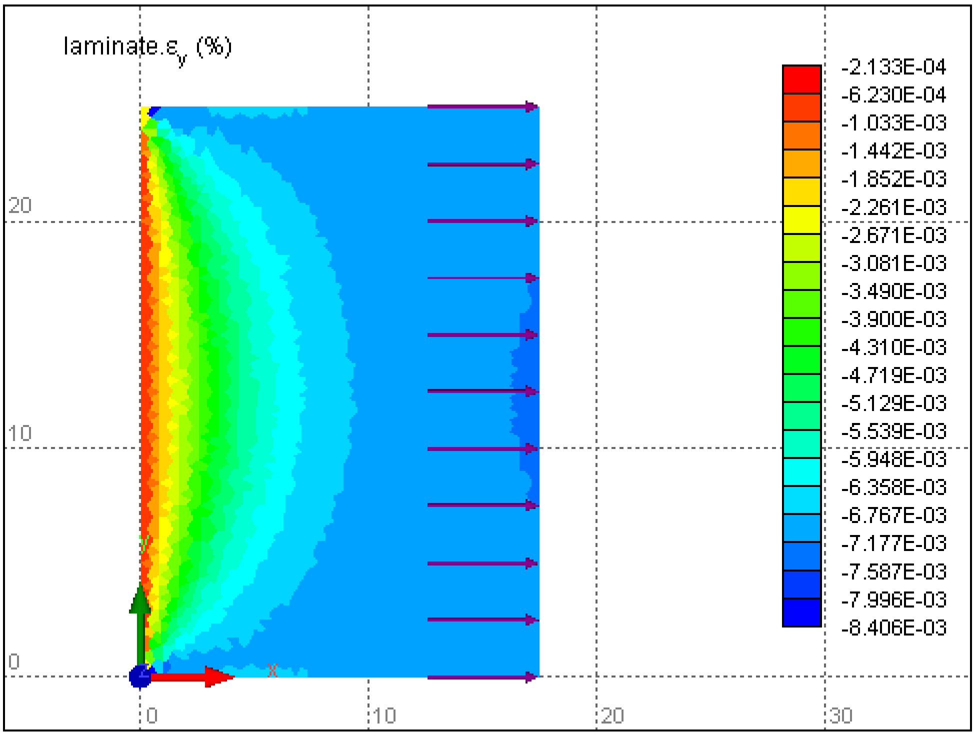


Figure 7: Laminate strain distributions at load case U2t (Fy = 40 N/mm)

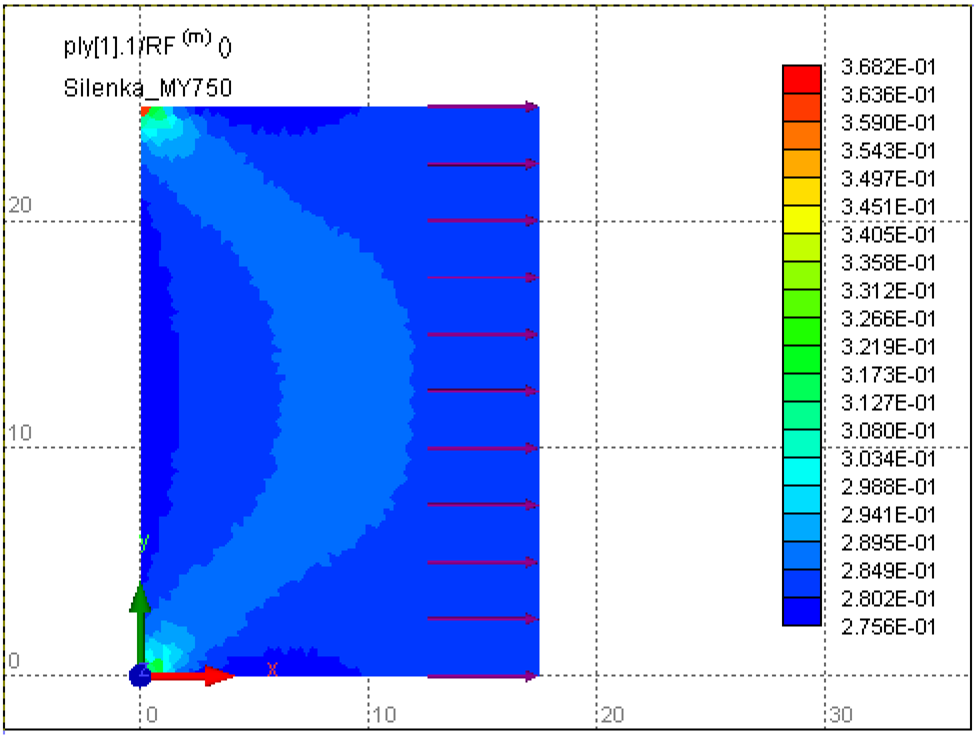


Figure 8: Reserve factor distributions for the 0° layer at load case U2t

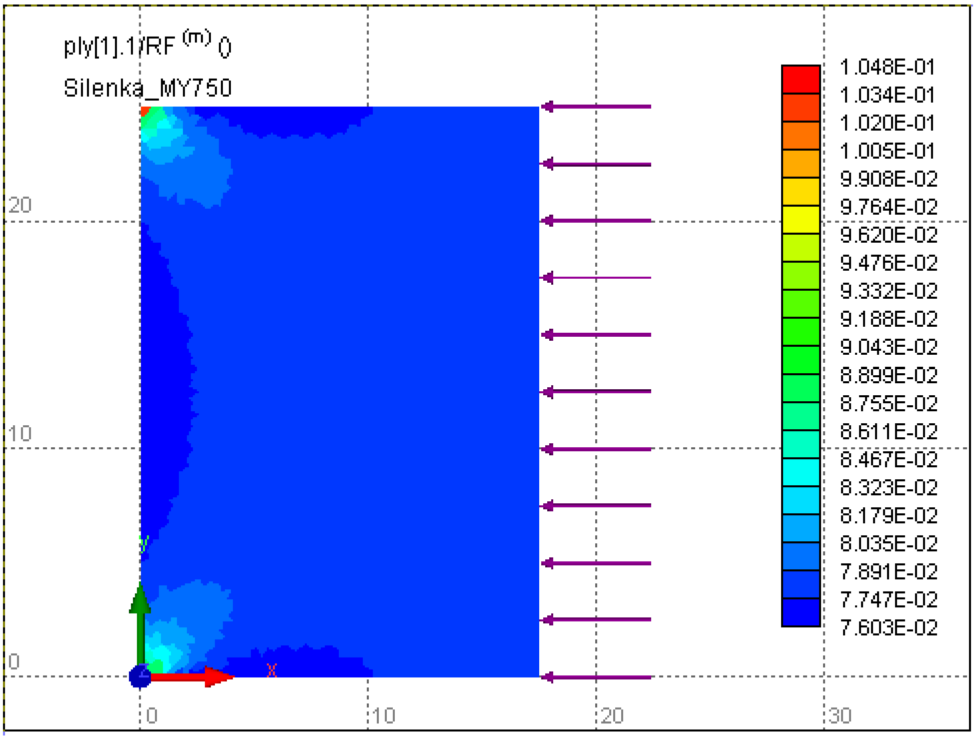


Figure 9: Reserve factor distributions for the 0° layer at load case U2c (Fy = -40 N/mm)

4 PREDICTION OF THE MD SPECIMEN PROPERTIES

4.1 Materials, lay-up and geometry

The material properties used for the analyses are as given for the Silenka E-glass/MY750 combination, as given in [3]. No tab material is used as there are no possibilities to model a specimen including tabs and grip constraints.

For the MD specimen [3] a 14-layer lay-up is used: 4 layers of 0° oriented layers with a thickness of 0.88 mm and 10 layers of 45° oriented layers with a thickness of 0.88 mm. The total lay-up is: (45/-45/0/45/-45/0/45/-45/0/45/-45/0/45/-45). The lay-up is therefore not symmetrical.

The geometry of the specimen is given in [3]: a straight specimen with width of 25 mm, free length of 40 mm and thickness of 6.57 mm.

4.2 CLT results

The evaluated laminate is non-symmetrical, therefore the strains in all layers with the same fibre orientation may differ. Non-zero values can be found in the B-matrix in positions B_{16} and B_{26}. The stiffness properties for the laminate and the laminate FPF uniaxial strengths, according to the Tsai-Hill failure criterion, are given in Table 4.

E_x	[MPa]	32906
E_y	[MPa]	18212
G_{xy}	[MPa]	9419
ν_{xy}		0.409
ν_{yx}		0.227
N_{xt}	[N/mm]	1097.7
N_{xc}	[N/mm]	1774.9
N_{yt}	[N/mm]	306.42
N_{yc}	[N/mm]	1036.9
N_{xy}	[N/mm]	385.27

Table 4: CLT results for the MD specimen lay-up (Tsai-Hill criterion)

For the load cases, as given in Table 1, different failure criteria can be compared. The results for the maximum stress, Tsai-Hill and Tsai-Wu criteria are given in Table 5. In general the differences are small for the plates in tension and shear loading. Larger differences occur for the compression loaded plates, especially for the 0 degree layer in transverse compression.
In view of the large differences between the reserve factors for the 0° and 45° layer in e.g. load case 'xt', the final failure can be expected to be at a much higher load. Even more so, since the stress-strain behaviour of the 45° layer is clearly non-linear at higher stress levels.

	Maximum stress		Tsai-Hill		Tsai-Wu	
layer	0°	45°	0°	45°	0°	45°
xt	153.76	**33.53**	138.38	**27.47**	133.85	**26.66**
xc	96.10	**48.02**	68.04	**44.38**	**53.47**	58.21
yt	**7.67**	14.17	**7.66**	12.84	**7.57**	12.95
yc	**27.79**	30.54	27.69	**25.93**	**27.31**	34.31
xy	19.37	**9.82**	19.31	**9.65**	18.84	**8.85**

Table 5: Reserve factors at 40 N/mm applied load (MD specimen lay-up)

4.3 FEM results

For the FEM analyses a half model has been used, see Figure 10. Although the distribution of the triangular elements is not regular, this has no significant effect on the strain distributions that will be shown later.

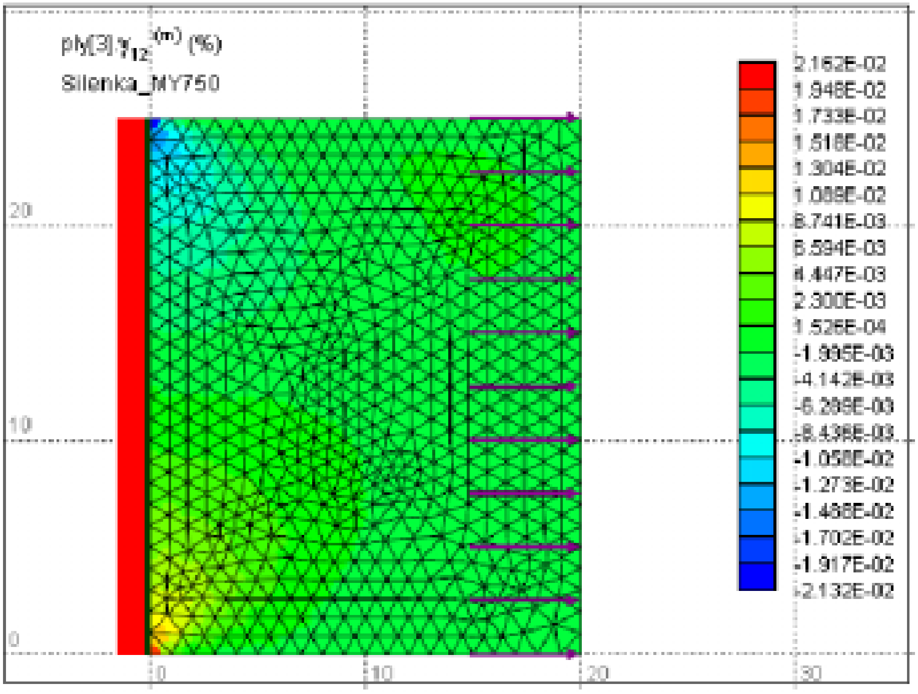


Figure 10: Mesh for the MD specimen, generated automatically by the Kolibri package

The rectangular plate is clamped at the left side and loaded by an edge loading of 40 N/mm at the right side. Due to package limitations, no constraints on the right end are applied. A quarter model gave slightly different results as a result of the non-symmetrical laminate.
The deformed shape for load case M1t is given in Figure 11. It clearly shows the effect of the non-symmetrical lay-up

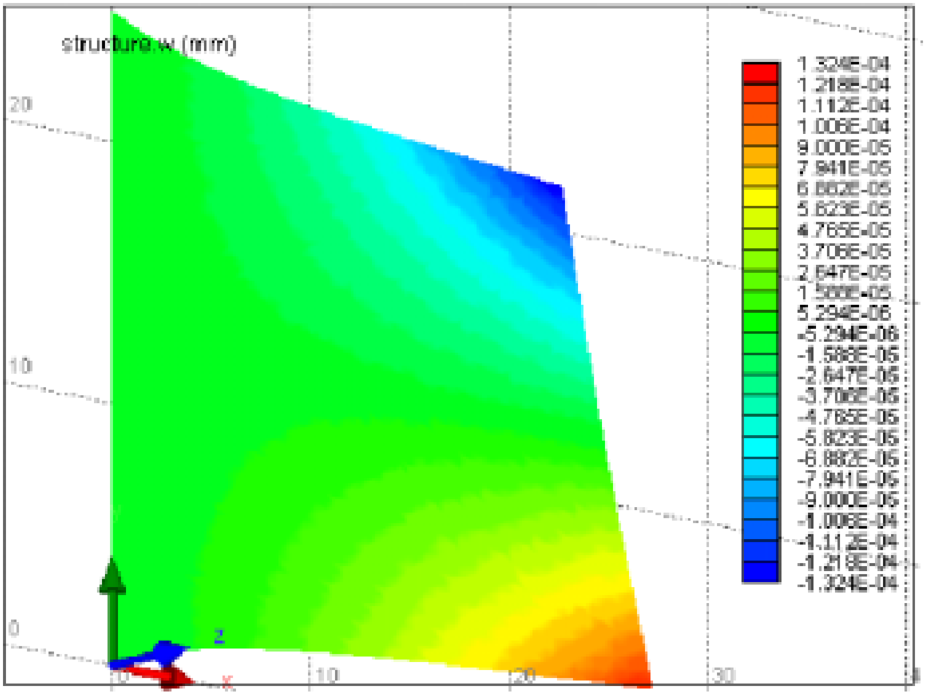


Figure 11: Deformed shape of the MD specimen for load case M1t

The predicted patterns of the strain and the inverse of the reserve factor are given in Figure 13 to Figure 18.
As can be seen in most of the transverse strain graphs (see e.g. lower graph of Figure 13) the strain at the specimen free end is not yet homogeneous. This is a result of the relative short specimen free length chosen in the project. For a specimen with twice the free length (i.e. 80 mm) the strain distribution at the middle section would be close to homogenous, see Figure 12 for load case M1t.

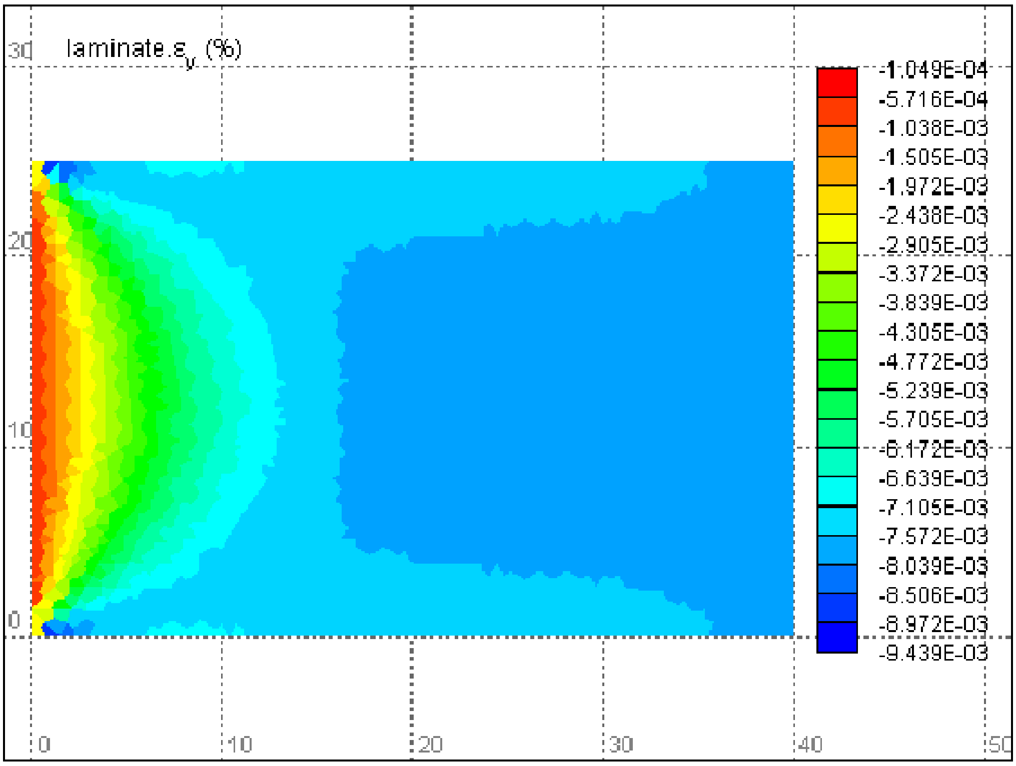


Figure 12: Transverse strain distribution for a model with double length

Peak strains always occur at the corners of the clamped side of the specimen, as can be expected. The strain values itself are also influenced by the number of elements used in the mesh. Smaller elements apparently lead to higher peak strain values.
As was the case for the UD specimen, for tensile loaded cases the inverse of the reserve factor per layer is clearly dominated by the strain transverse to the fibre. For compression loaded cases no simple relationship is possible between a strain component and the strength.

	strains [%]				1/RF			
	ε_x		ε_y		45° layer		0° layer	
	CLT	max	CLT	max	CLT	max	CLT	max
M1t	0.01850	0.02943	-0.00757	-0.00944	0.0364	0.1073	0.00723	0.0322
M1c	-0.01850	-0.02943	0.00757	0.00944	0.0225	0.0379	0.0147	0.0248
M2t	0.03343	0.05142	-0.00757	-0.00973	0.0780	0.1738	0.1305	0.2149
M2c	-0.03343	-0.05142	0.00757	0.00973	0.0386	0.0626	0.0361	0.0627

Table 6: Strains and strength aspects of MD specimen

Values for the strains and the inverse of the reserve factors, for a loading of 40 N/mm, are given in Table 6 for an infinite plate (designated 'CLT') and the extreme values for the FEM models. As can be seen from the table, the peak strains in the specimen are predicted considerably higher than for an infinite pate. As a consequence, the margin to failure is much smaller.

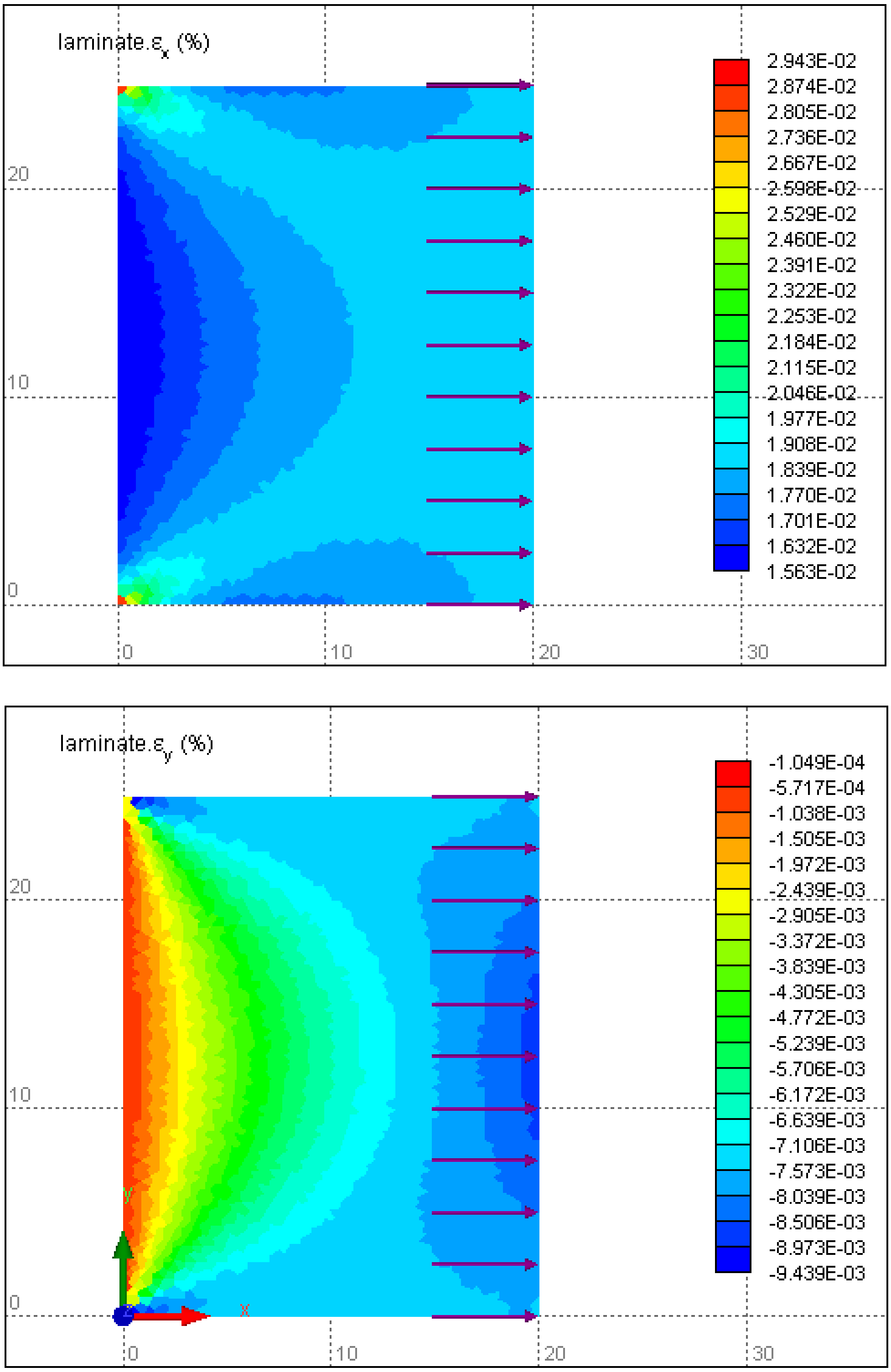
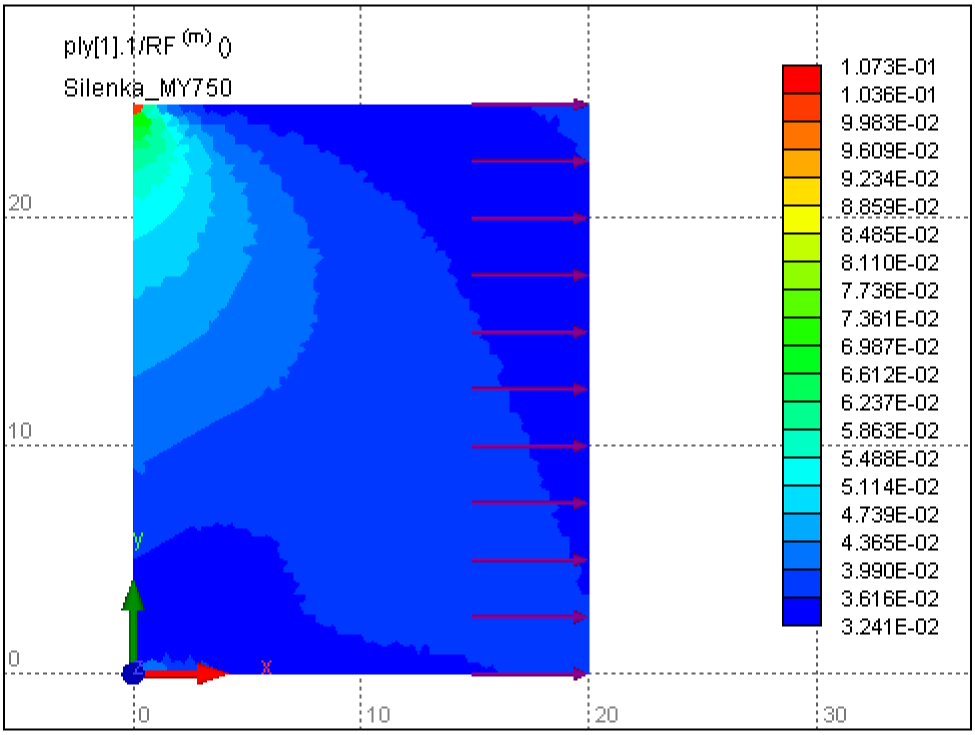


Figure 13: Laminate strain distributions at load case M1t (Fx = 40 N/mm)



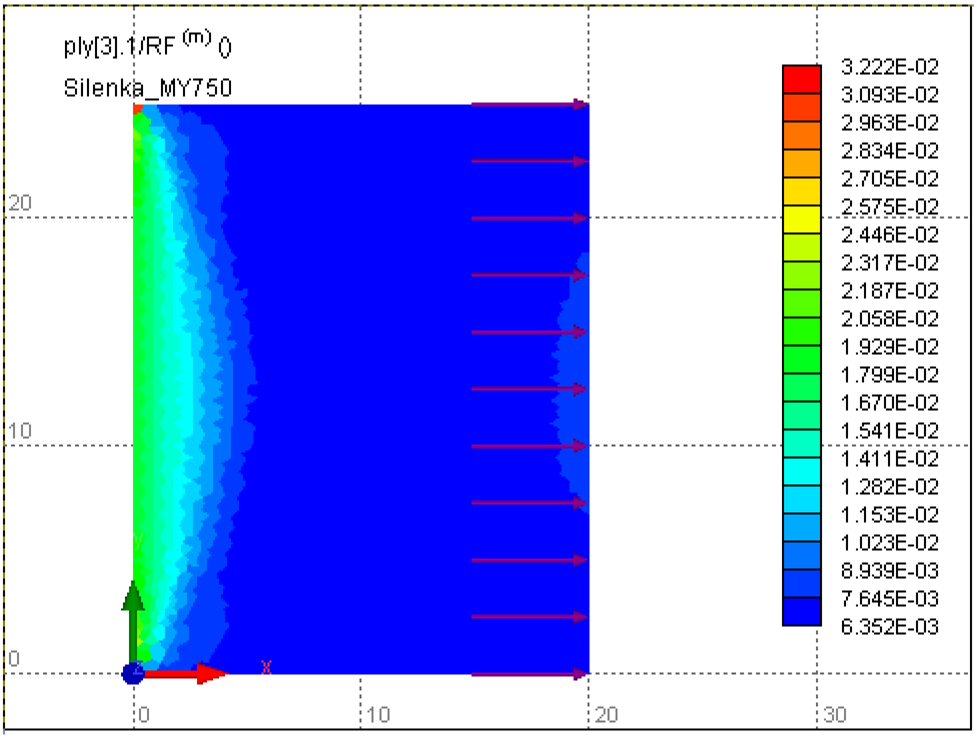
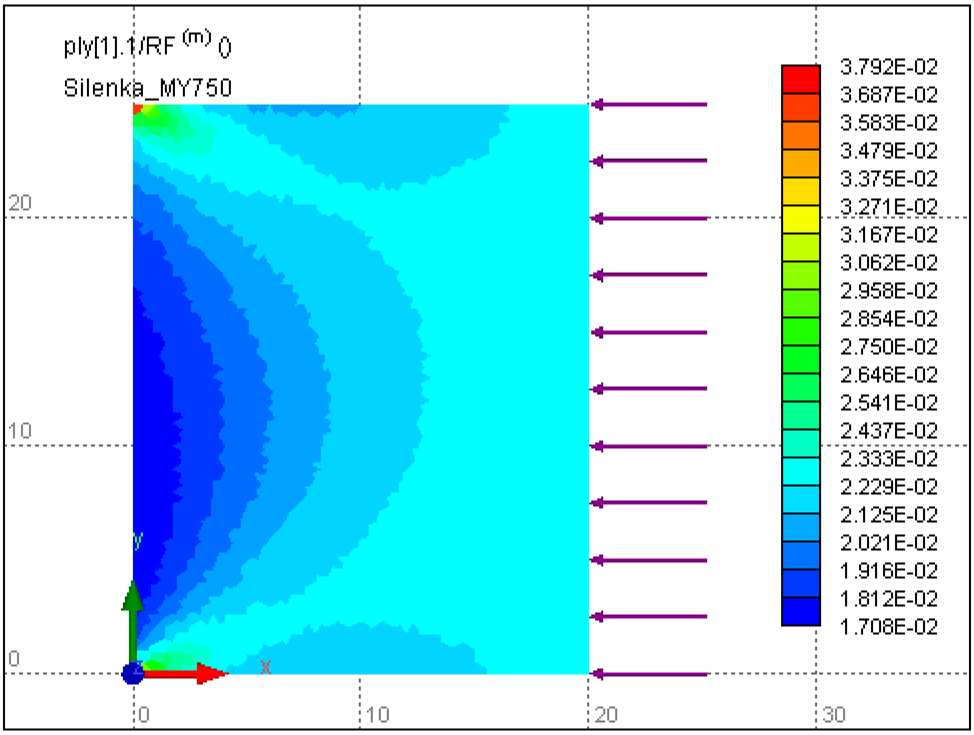


Figure 14: Reserve factor distributions for 45° layer (top) and 0° layer (bottom) at load case M1t



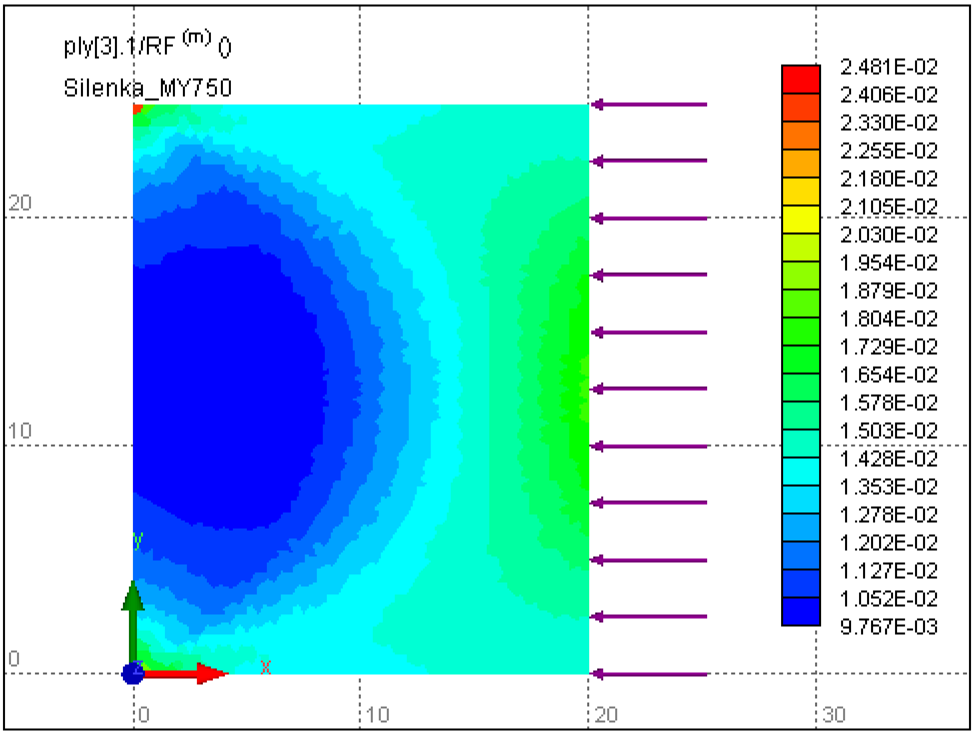


Figure 15: Reserve factor distributions for 45° layer (top) and 0° layer (bottom) at load case M1c (Fx = -40 N/mm)

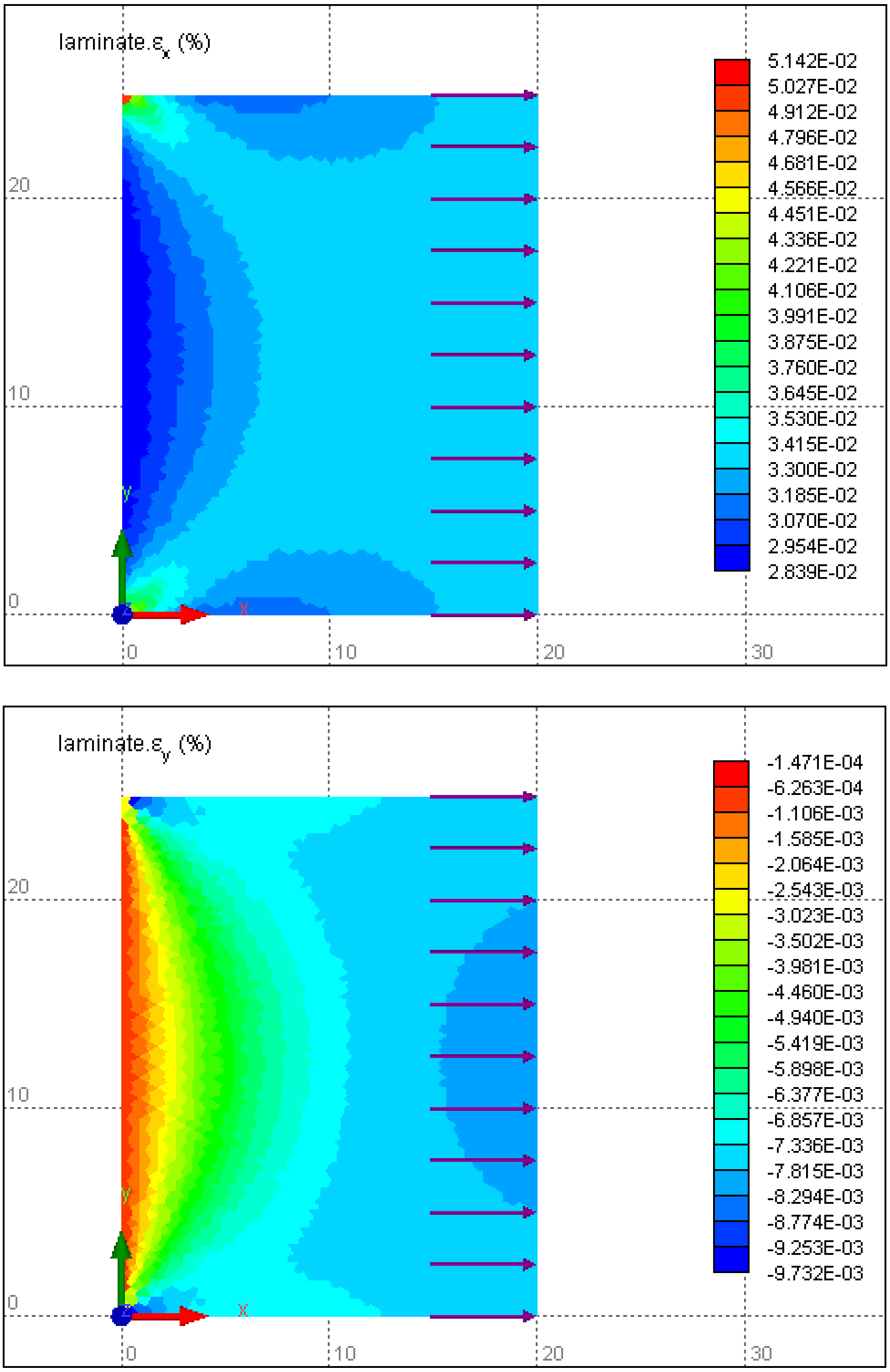
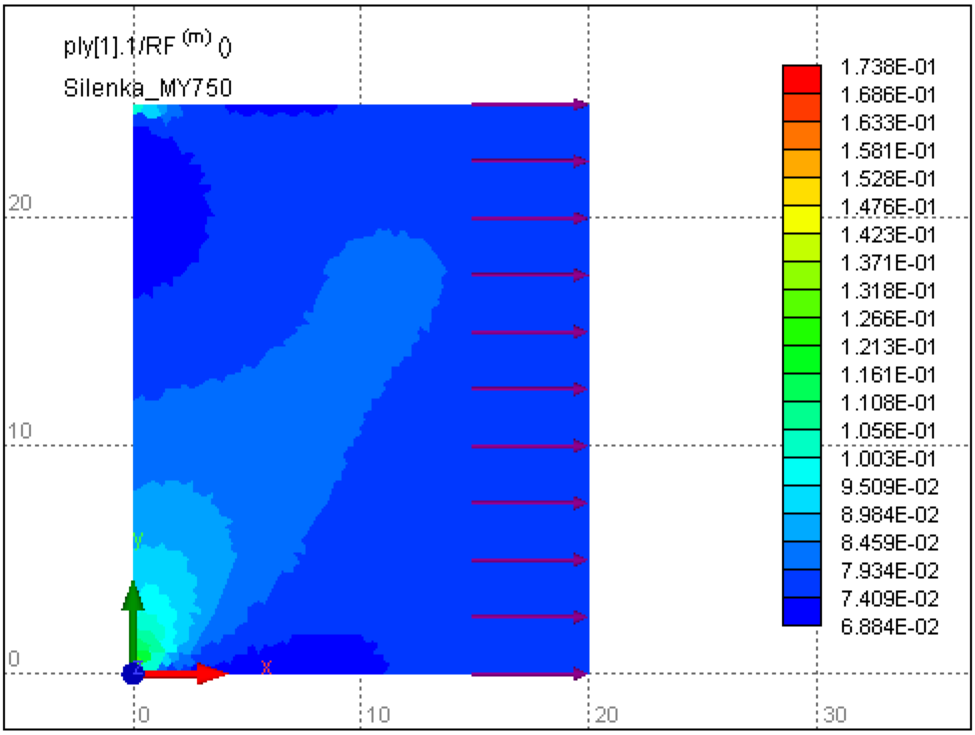


Figure 16: Laminate strain distributions at load case M2t (Fy = 40 N/mm)



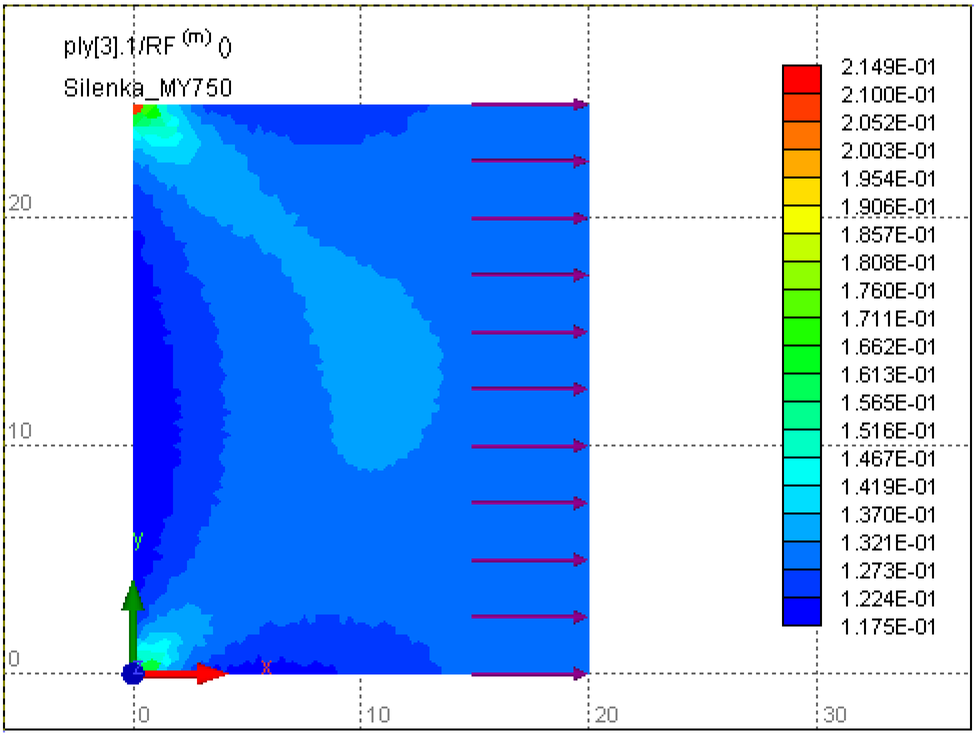


Figure 17: Reserve factor distributions for 45° layer (top) and 0° layer (bottom) at load case M2t

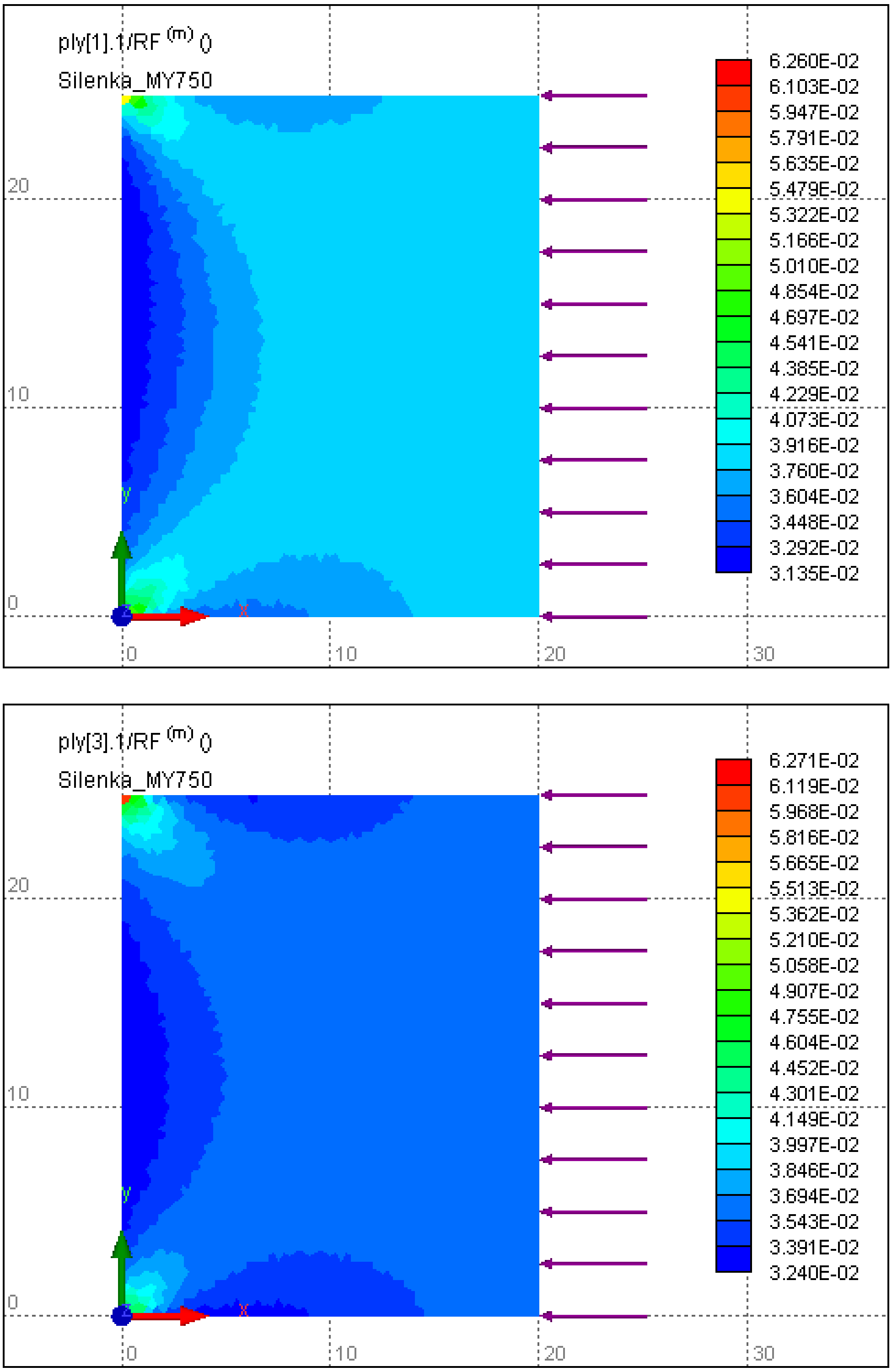


Figure 18: Reserve factor distributions for 45° layer (top) and 0° layer (bottom) at load case M2c (Fy = -40 N/mm)

5 CONCLUSION AND EVALUATION REMARKS

Mechanical properties have been calculated for two standard Optimat Blades test specimens, on basis of assumed material properties.
The stiffness and first-ply-failure strength of an infinite plate has been predicted using the Classical Laminated plate theory for linear stress-strain relationships. For the MD specimen, three failure theories have been applied: maximum stress, Tsai-Hill and Tsai-Wu. For tensile and shear loaded MD plates, the differences between the theories is small. For compression loaded plates, Tsai-Wu predicts higher strengths for the 45° layer and (for Xc) significantly lower strengths for the 0° layer.
The FEM package used is limited in many respects, therefore the results are seen as first order approximations only. Peak stresses (or strains) are in all cases expected at the clamped end of the specimen (at the grip). The specimen length is relatively small, therefore the strains are not expected to be homogeneous in the specimen middle.
Due to the high peak stresses near the grips, the predicted strength of the specimen is much smaller than the values given for the infinite plate, sometimes by a factor of 2-3.

The MD specimen is defined as non-symmetrical. This complicates simple modelling of the specimen. The built-up of the MD specimen has to be checked.

6 LITERATURE

[1] Kolibri package, Kolibri Evaluation Edition, CLC TU Delft-TNO, the Netherlands, see http://www.clc.tno.nl/projects/recent/kolibri.html

[2] 'The Laminator', version 3.1, see www.thelaminator.net

[3] Joosse, P.A.: "Laminae and specimen definitions for FEM analyses TG4"; TU Delft, WMC-Group, doc. OB_TG4_N002 rev2, 10-10-02

[4] Joosse, P.A.: "Proposal for the first analysis step for WP10"; TU Delft, WMC-Group, doc. OB_TG4_N003, 23-10-02