TASK GROUP 4: Investigation of Blade Material Behaviour under Complex Stress States

Numerical Prediction of simple specimen mechanical response using CLT and shell FE formulations

version 1

Theodore P. Philippidis, Anastassia Kyrsanidi, Alexandros. E. Antoniou,

CHANGE RECORD

<table>
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<th>date</th>
<th>pages</th>
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<td>03-12-02</td>
<td>all</td>
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<td>31-3-03</td>
<td>29-50</td>
<td>Enhanced colour resolution contour plots</td>
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1 INTRODUCTION

In the frame of WP10, TG4, University of Patras (UP) is participating in the “numerical analysis” exercise aiming at predicting the mechanical response of specimens tested under simple loading conditions, e.g. tension, compression, 3-point bending etc. Numerical analyses at various levels will be performed by different partners; UP is assigned to perform CLT calculations and also moderately thick shell FEM models [1].

As explained in [2], in this first step of the series, 8 cases are treated, referring to tension/compression of OPTIMAT coupon geometries made of UD and MD layup in both in-plane principal material directions. Details on material properties and coupon dimensions are presented in [3].

In the first draft version of the report, results were presented from CLT and shell FE models for the load cases defined in [2] and also treated in [4]. To avoid unnecessary repetitions and overlaps, definition of symbols, loading conditions, geometry etc. follows from previously cited references. The results presented, were derived with ordinary linear analyses up to first ply failure. Non-linear material response, due either to material degradation or non-linear elasticity will be discussed in a future issue.

In the present 1st version of the report, FEM results in the form of colour contour patterns are presented at an enhanced resolution so as to be directly comparable with those presented in [5].
2 CLASSICAL LAMINATION THEORY

Two different computer programs were used, for result consistency; an early version of “Think Composites” software of Stephen Tsai and also an early version of “PC-Laminate” distributed by Technomic Publishing Co. Ltd. They have being both used extensively in the past and their results are reliable. Output presented in the sequel concern the effective engineering elastic constants of the coupon, strain values at the top and bottom faces of each ply, as well as the respective values of Strength Ratio, R (referred also as reserve factor).

2.1 Prediction of UD coupon response

The UD coupon consists of 4 plies, made of the reference material, and tabs as defined in [3]. CLT assumes infinite plate geometry and thus tabs or other boundary conditions are not defined. Loads are given as input in the form of stress, $N_i$ (Nm$^{-1}$) and moment, $M_i$ (N) resultants, $i=x, y, s$.

2.1.1 Tension in the fiber direction (1) of UD material

Engineering elastic constants

\[
E_x = 4.560E+11 \text{ Nm}^{-2} \quad E_y = 1.620E+11 \text{ Nm}^{-2} \quad G_{xy} = 5.830E+10 \text{ Nm}^{-2} \\
\nu_{xy} = 0.2780 \quad \nu_{yx} = 0.9876E-01
\]

Load case

\[
\begin{array}{ccccccc}
N_x & N_y & N_s & M_x & M_y & M_s \\
.4000E+05 & .0000E+00 & .0000E+00 & .0000E+00 & .0000E+00 & .0000E+00
\end{array}
\]

Strain distribution

\[
\begin{array}{cccc}
#Ply & \varepsilon_x & \varepsilon_y & \varepsilon_s (E+06) \\
1 \text{ Bot} & 249.2 & -69.3 & .0 \\
1 \text{ Top} & 249.2 & -69.3 & .0 \\
2 \text{ Bot} & 249.2 & -69.3 & .0 \\
2 \text{ Top} & 249.2 & -69.3 & .0 \\
3 \text{ Bot} & 249.2 & -69.3 & .0 \\
3 \text{ Top} & 249.2 & -69.3 & .0 \\
4 \text{ Bot} & 249.2 & -69.3 & .0 \\
4 \text{ Top} & 249.2 & -69.3 & .0
\end{array}
\]

Strength ratio

\[
\begin{array}{ccc}
#Ply & \text{Angle} & R & 1/R \\
1 & .0 & 113. & .00885 \\
2 & .0 & 113. & .00885 \\
3 & .0 & 113. & .00885 \\
4 & .0 & 113. & .00885
\end{array}
\]
2.1.2 Compression in the fiber direction (1) of UD material

Load case

\[ \begin{matrix}
N_x & N_y & N_s & M_x & M_y & M_s \\
-4.000E+05 & 0.000E+00 & 0.000E+00 & 0.000E+00 & 0.000E+00 & 0.000E+00 \\
\end{matrix} \]

Strain distribution

<table>
<thead>
<tr>
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<th>( \varepsilon_x )</th>
<th>( \varepsilon_y )</th>
<th>( \varepsilon_s ) (E+06)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1 Top</td>
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<tr>
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Strength ratio

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<td>70.4</td>
<td>.0142</td>
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2.1.3 Tension transversely to the fiber direction (2) of UD material

Load case

\[ \begin{matrix}
N_x & N_y & N_s & M_x & M_y & M_s \\
4.000E+05 & 0.000E+00 & 0.000E+00 & 0.000E+00 & 0.000E+00 & 0.000E+00 \\
\end{matrix} \]

Strain distribution

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<tr>
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<th>( \varepsilon_y )</th>
<th>( \varepsilon_s ) (E+06)</th>
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Strength ratio
### 2.1.4 Compression transversely to the fiber direction (2) of UD material

**Load case**

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**Strain distribution**

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<tr>
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**Strength ratio**

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<tr>
<td>4</td>
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<td>.0781</td>
</tr>
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</table>

### 2.2 Prediction of MD coupon response

The MD coupon consists of 14 layers, (±45/0/±45/0/±45/0/±45/0/±45), made of the reference material, and tabs as defined in [3]. 0-deg layers are 0.88 mm thick, while ±45 are 0.61 mm. CLT assumes infinite plate geometry and thus tabs or other boundary conditions are not defined. Loads are given as input in the form of stress, N_i (Nm^{-1}) and moment, M_i (N) resultant, i=x, y, s.

#### 2.2.1 Tension in the fiber direction (1) of the 0-deg layer of the MD laminate

**Engineering elastic constants**

\[ E_x = 0.3291E+11 \text{ Nm}^{-2} \quad E_y = 0.1821E+11 \text{ Nm}^{-2} \quad G_{xy} = 0.9419E+10 \text{ Nm}^{-2} \]
\[ \nu_{xy} = 0.4093 \quad \nu_{yx} = 0.2265 \]

**Load case**

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<th>( N_y )</th>
<th>( N_s )</th>
<th>( M_x )</th>
<th>( M_y )</th>
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**Strain distribution**

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<th>#Ply</th>
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<th>( \varepsilon_y )</th>
<th>( \varepsilon_s ) (E+06)</th>
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<td>1 Top</td>
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**Strength ratio**

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<th>( R_{top} )</th>
<th>( 1/R_b )</th>
<th>( 1/R_t )</th>
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<td>26.7</td>
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2.2.2 Compression in the fiber direction (1) of the 0-deg layer of the MD laminate

Load case

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<th>N_y</th>
<th>N_s</th>
<th>M_x</th>
<th>M_y</th>
<th>M_s</th>
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<td>.0000E+00</td>
<td>.0000E+00</td>
<td>.0000E+00</td>
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Strain distribution

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<th>ε_y</th>
<th>ε_s (E+06)</th>
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<tbody>
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<td>5.2</td>
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### 2.2.3 Tension along direction-2 of the MD laminate

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Strength ratio

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2.2.4 Compression along direction-2 of the MD laminate

Load case

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Strain distribution

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3  FINITE ELEMENT SHELL FORMULATION

For the finite element computations in the frame of this task, the commercial software package ANSYS was used. The 8-node, 3D layered shell element SHELL99, suitable for up to moderately thick composite shell structures was implemented in the FE model. In the mechanics formulation of this element, transverse shear is taken into account in the kinematics analysis.

1425 and 1550 shell elements were used for the UD and MD coupon models respectively, resulting in 20,354 and 22,140 active degrees of freedom. Geometric characteristics of UD and MD coupons are defined in [3]. The difference in their dimensions lies in the unsupported length of each coupon (35 mm for the UD and 40 mm for the MD). Different mesh density was used for the tab and the gauge length area as shown in Fig.1, where the FE model of the MD coupon is displayed. Element size in the gauge length area is 1mm x 1mm.

![Fig.1 Finite element model of the MD coupon](image_url)

Boundary conditions were applied such as to simulate a “displacement control” type of test. All nodes, therefore, in one of the tab areas were constrained in such a way that all six generalized degrees of freedom were set equal to zero. Nodes contained in the other tab
area were displaced axially by an equal amount, such as, depending on coupon stiffness, an equivalent stress resultant of 40E+03 Nm⁻¹ was developed.

8 different combinations of load and coupon geometry were simulated, as described in [2] and already reported with CLT results.

### 3.1 FE prediction of UD coupon response

Two different models, representative of coupons cut on-axis and transversely to the fiber axis, were implemented, each one of them subjected to tensile and compressive loadings. The lay-up of the elements in the tab area includes both the 4 UD layers and the tab material as it can be seen in Fig.2.

![Fig.2 Stacking sequence of a typical element in the tab area of coupons cut on-axis (UD1) and transversely to the fiber direction, or 90° off-axis (UD2)](image)

It should be noticed that material 2 in the above figure refers to the CSM layer, whereas the reference material layers in the tab laminate are of reduced thickness [3].

#### 3.1.1 Tension in the fiber direction (1) of UD material

Displacement component in nodes of the tab attached to the moving cross-head were set equal to 8.722E-06 m for this case. Results in the form of contour patterns are presented in Figs 3 to 5 for the axial and transverse strain distributions as well as for the inverse value of...
the strength ratio. In this series of results, the entire coupon geometry is shown in the lower part of the figures whereas the gauge length area is magnified in the upper part.

Fig. 3 $\varepsilon_x$ strain distribution for load case U1t ($N_x=40E+03$ Nm$^{-1}$)

Fig. 4 $\varepsilon_y$ strain distribution for load case U1t ($N_y=40E+03$ Nm$^{-1}$)
Fig. 5 Inverse strength ratio distribution for load case U1t \((N_x=40E+03 \text{ Nm}^{-1})\). Failure criterion: Tsai-Hahn \((F_{ij} = \frac{1}{2} \sqrt{F_{ii}F_{jj}})\)

3.1.2 Compression in the fiber direction (1) of UD material

Displacement component in nodes of the tab attached to the moving cross-head were set equal to -8.722E-06 m for this case, apparently. Results are presented in Figs 6 to 8.

Fig. 6 \(\varepsilon_x\) strain distribution for load case U1c \((N_x=-40E+03 \text{ Nm}^{-1})\)
Fig. 7 $\varepsilon_y$ strain distribution for load case U1c ($N_x=40E+03$ Nm$^{-1}$)

Fig. 8 Inverse strength ratio distribution for load case U1c ($N_x=40E+03$ Nm$^{-1}$). Failure criterion: Tsai-Hahn ($F_{ij} = -\frac{1}{2}\sqrt{F_{ii}F_{jj}}$)
3.1.3 Tension transversely to the fiber direction (2) of UD material

Displacement component in nodes of the tab attached to the moving cross-head were set equal to 2.455E-05 m for this case, due to lower coupon stiffness. Results are presented in Figs 9 to 11.

Fig.9 $\varepsilon_x$ strain distribution for load case U2t ($N_x=40E+03$ Nm$^{-1}$)

Fig.10 $\varepsilon_y$ strain distribution for load case U2t ($N_x=40E+03$ Nm$^{-1}$)
3.1.4 Compression transversely to the fiber direction (2) of UD material

Displacement component in nodes of the tab attached to the moving cross-head were set equal to -2.455E-05 m. Results are presented in Figs 12 to 14.

Fig.12 $\varepsilon_x$ strain distribution for load case U2c ($N_x=-40E+03 \text{ Nm}^{-1}$)
Fig. 13 $\varepsilon_y$ strain distribution for load case U2c ($N_x = -40E+03$ Nm$^{-1}$)

Fig. 14 Inverse strength ratio distribution for load case U2c ($N_x = -40E+03$ Nm$^{-1}$). Failure criterion: Tsai-Hahn ($F_{ij} = -\frac{1}{2} \sqrt{F_{ii} F_{jj}}$)
3.2 **FE prediction of MD coupon response**

As for the case of the UD lay-up, two different models, representative of coupons cut on-axis and transversely to the fiber axis of the 0\(^o\)-layer, were implemented as well for the MD coupon, each one of them subjected to tensile and compressive loadings. The lay-up (30 plies in total) of the elements in the tab area includes both the 14 layers of the MD stacking sequence, (±45/0/±45/0/±45/0/±45/0/±45) and the tab material as it can be seen in Fig. 15.

For this specimen, due to the presence of plies of different fiber orientation, FPF predictions according to any failure criterion are not sufficient to describe ultimate coupon failure, i.e. separation in two parts, at least. It is known that the 45\(^o\)-layer will fail first, in the sense of FPF, e.g. fiber splitting, and that ultimate strength is governed by the mechanical response of the fibers in the 0\(^o\) layers. In the first draft issue of this report, only results relevant to the FPF approach are presented. Non-linearity and material degradation modelling will be discussed in a future version.

![Stacking sequence of a typical element in the tab area of coupons cut on-axis (MD1) and transversely to the fiber direction (MD2) of the 0\(^o\)-layer](image)

**Fig. 15** Stacking sequence of a typical element in the tab area of coupons cut on-axis (MD1) and transversely to the fiber direction (MD2) of the 0\(^o\)-layer

### 3.2.1 Tension in the fiber direction (1) of the 0\(^o\)-layer of the MD laminate

Displacement component in nodes of the tab attached to the moving cross-head were set equal to 7.357E-06 m for this case. Results in the form of contour patterns are presented in Figs 16 to 19 for the axial and transverse strain distributions as well as for the inverse values of the strength ratios in the outer 45\(^o\)-layer and the nearest to the surface 0\(^o\) ply. As previously, in this series of results as well, the entire coupon geometry is shown in the lower part of the figures whereas the gauge length area is magnified in the upper part.
Fig. 16 $\varepsilon_x$ strain distribution for load case M1t ($N_x=40E+03$ Nm$^{-1}$)

Fig. 17 $\varepsilon_y$ strain distribution for load case M1t ($N_x=40E+03$ Nm$^{-1}$)
Fig. 18 Top 45°-layer: Inverse strength ratio distribution for load case M1t ($N_x=40E+03$ Nm$^{-1}$). Failure criterion: Tsai-Hahn ($F_{ij} = \frac{1}{2} \sqrt{F_{ii} F_{jj}}$).

Fig. 19 Outermost 0°-layer: Inverse strength ratio distribution for load case M1t ($N_x=40E+03$ Nm$^{-1}$). Failure criterion: Tsai-Hahn ($F_{ij} = \frac{1}{2} \sqrt{F_{ii} F_{jj}}$).
3.2.2 Compression in the fiber direction (1) of the 0°-ply of the MD laminate

Displacement component in nodes of the tab attached to the moving cross-head were set equal to -7.357E-06 m for this case, apparently. Results are presented in Figs 20 to 23.

Fig.20 $\varepsilon_x$ strain distribution for load case M1c ($N_x=-40E+03$ Nm$^{-1}$)

Fig.21 $\varepsilon_y$ strain distribution for load case U1c ($N_y=-40E+03$ Nm$^{-1}$)
Fig. 22 Top 45°-layer: Inverse strength ratio distribution for load case M1c ($N_x = -40E+03$ Nm$^{-1}$). Failure criterion: Tsai-Hahn ($F_{ij} \leq \frac{1}{2} \sqrt{F_{ii} F_{jj}}$).

Fig. 23 Outermost 0°-layer: Inverse strength ratio distribution for load case M1c ($N_x = -40E+03$ Nm$^{-1}$). Failure criterion: Tsai-Hahn ($F_{ij} \leq \frac{1}{2} \sqrt{F_{ii} F_{jj}}$).
3.2.3 Tension along direction-2 of the MD laminate

Axial displacement component in respective nodes were set equal to 1.337E-05 m. Results are presented in Figs 24 to 27.

Fig. 24 $\varepsilon_x$ strain distribution for load case M2t ($N_x=40E+03$ Nm$^{-1}$)

Fig. 25 $\varepsilon_y$ strain distribution for load case M2t ($N_y=40E+03$ Nm$^{-1}$)
Fig. 26 Top 45°-layer: Inverse strength ratio distribution for load case M2t ($N_x=40E+03$ Nm). Failure criterion: Tsai-Hahn ($F_{ij} = -\frac{1}{2} \sqrt{F_{ii}F_{jj}}$)

Fig. 27 Outermost 0°-layer: Inverse strength ratio distribution for load case M2t ($N_x=40E+03$ Nm). Failure criterion: Tsai-Hahn ($F_{ij} = -\frac{1}{2} \sqrt{F_{ii}F_{jj}}$)
3.2.4 Compression along direction-2 of the MD laminate

Axial displacement component in respective nodes were set equal to -1.337E-05 m. Results are presented in Figs 28 to 31.

Fig.28 $\varepsilon_x$ strain distribution for load case M2c ($N_x=-40E+03$ Nm$^{-1}$)

Fig.29 $\varepsilon_y$ strain distribution for load case M2c ($N_x=-40E+03$ Nm$^{-1}$)
Fig. 30 Top 45°-layer: Inverse strength ratio distribution for load case M2c ($N_x = -40E+03$ Nm$^{-1}$). Failure criterion: Tsai-Hahn ($F_{ij} = -\frac{1}{2} \sqrt{F_a F_{yy}}$)

Fig. 31 Outermost 0°-layer: Inverse strength ratio distribution for load case M2c ($N_x = -40E+03$ Nm$^{-1}$). Failure criterion: Tsai-Hahn ($F_{ij} = -\frac{1}{2} \sqrt{F_a F_{yy}}$)
3.3 Results with Enhanced color resolution, UD coupon

In this paragraph previous results are presented with increased color resolution. Twenty different colors were used. X-axis is always parallel along specimen length and Y-axis is perpendicular. Due to material and load symmetry only one quarter of the specimen free length is presented. In Tsai-Wu failure criterion figures, values of the criterion, below zero couldn’t be displayed due to ANSYS bug.

3.3.1 Tension in the fiber direction (1) of UD material

Fig.32 $\varepsilon_x$ strain distribution for load case U1t ($N_x=40E+03$ Nm$^{-1}$)

Fig.33 $\varepsilon_y$ strain distribution for load case U1t ($N_x=40E+03$ Nm$^{-1}$)
Fig. 34 $\varepsilon_{xy}$ in plane strain distribution for load case U1t ($N_x=40E+03$ Nm$^{-1}$)

Fig. 35 Strength index distribution for load case U1t ($N_x=40E+03$ Nm$^{-1}$).

Failure criterion: Tsai-Hahn ($F_{ij} = \frac{1}{2}\sqrt{F_u F_b}$)
3.3.2 Compression in the fiber direction (1) of UD material

Fig. 36 $\varepsilon_x$ strain distribution for load case U1c ($N_x=-40E+03\ Nm^{-1}$)

Fig. 37 $\varepsilon_y$ strain distribution for load case U1c ($N_y=-40E+03\ Nm^{-1}$)
Fig. 38 $\varepsilon_{xy}$ in plane strain distribution for load case U1c ($N_x=40E+03$ Nm$^{-1}$)

Fig. 39 Strength index distribution for load case U1c ($N_x=40E+03$ Nm$^{-1}$).

Failure criterion: Tsai-Hahn ($F_{ij} = \frac{1}{2} \sqrt{F_{ij} F_{ji}}$)
3.3.3 Tension transversely to the fiber direction (2) of UD material

Fig. 40 $\varepsilon_x$ strain distribution for load case U2t ($N_x=40E+03 \text{ Nm}^{-1}$)

Fig. 41 $\varepsilon_y$ strain distribution for load case U2t ($N_x=40E+03 \text{ Nm}^{-1}$)
Fig. 42 $\varepsilon_{xy}$ in plane strain distribution for load case U2t ($N_x=40E+03\ Nm^{-1}$).

Fig. 43 Strength index distribution for load case U2t ($N_x=40E+03\ Nm^{-1}$).

Failure criterion: Tsai-Hahn ($F_{ij} = \frac{1}{2} \sqrt{F_{ii} F_{jj}}$)
3.3.4 Compression transversely to the fiber direction (2) of UD material

Fig. 44 $\varepsilon_x$ strain distribution for load case U2c ($N_x=40\times 10^3$ Nm$^{-1}$)

Fig. 45 $\varepsilon_y$ strain distribution for load case U2c ($N_x=40\times 10^3$ Nm$^{-1}$)
Fig. 46 $\varepsilon_{xy}$ in plane strain distribution for load case U2c ($N_x=40E+03\ Nm^{-1}$)

Fig. 47 Strength index distribution for load case U2c ($N_x=40E+03\ Nm^{-1}$).

Failure criterion: Tsai-Hahn ($F_{ij} = -\frac{1}{2} \sqrt{F_a F_b}$)

The specific failure criterion returns negative values in the above presented area. ANSYS could not compute these. The lower obtained value was zero.
3.4 **Results with Enhanced color resolution, MD coupon**

3.4.1 **Tension in the fiber direction (1) of the 0°-ply of the MD laminate**

Fig.48 $\varepsilon_x$ strain distribution for load case M1t ($N_x=40E+03$ Nm$^{-1}$)

Fig.49 $\varepsilon_y$ strain distribution for load case M1t ($N_x=40E+03$ Nm$^{-1}$)
Fig. 50 $\varepsilon_{xy}$ in plane strain distribution for load case M1t ($N_x=40E+03$ Nm$^{-1}$)

Fig. 51 Outermost $0^\circ$-layer: Strength index distribution for load case M1t ($N_x=40E+03$ Nm$^{-1}$). Failure criterion: Tsai-Hahn $F_{ij} = \frac{1}{2} \sqrt{F_{ii}F_{jj}}$
Fig. 52 Top 45°-layer: Strength index distribution for load case M1t ($N_x=40E+03$ Nm$^{-1}$).

Failure criterion: Tsai-Hahn ($F_{ij} = \frac{1}{2} \sqrt{F_{ii}F_{jj}}$)

Fig. 53 Top (-45°)-layer: Strength index distribution for load case M1t ($N_x=40E+03$ Nm$^{-1}$).

Failure criterion: Tsai-Hahn ($F_{ij} = \frac{1}{2} \sqrt{F_{ii}F_{jj}}$)
3.4.2 Compression in the fiber direction (1) of the 0°-ply of the MD laminate

Fig.54 $\varepsilon_x$ strain distribution for load case M1c ($N_x=40E+03$ Nm$^{-1}$)

Fig.55 $\varepsilon_y$ strain distribution for load case M1c ($N_y=40E+03$ Nm$^{-1}$)
Fig. 56 $\varepsilon_{xy}$ in plane strain distribution for load case M1c ($N_x=40E+03$ Nm$^{-1}$)

Fig. 57 Outermost $0^\circ$-layer: Strength index distribution for load case M1c ($N_x=40E+03$ Nm$^{-1}$). Failure criterion: Tsai-Hahn ($F_{ij} = -\frac{1}{2}\sqrt{F_{ii}F_{jj}}$)
Fig. 58 Top 45°-layer: Strength index distribution for load case M1c ($N_x=40E+03$ Nm$^{-1}$).

Failure criterion: Tsai-Hahn ($F_{ij} = -\frac{1}{2} \sqrt{F_{ii}F_{jj}}$). Criterion values less or equal zero

Fig. 59 Top (-45°)-layer: Strength index distribution for load case M1c ($N_x=40E+03$ Nm$^{-1}$).

Failure criterion: Tsai-Hahn ($F_{ij} = -\frac{1}{2} \sqrt{F_{ii}F_{jj}}$). Criterion values less or equal zero
3.4.3 Tension along direction-2 of the MD laminate

Fig. 60 $\varepsilon_x$ strain distribution for load case M2t ($N_x=40E+03$ Nm$^{-1}$)

Fig. 61 $\varepsilon_y$ strain distribution for load case M2t ($N_y=40E+03$ Nm$^{-1}$)
Fig. 62 $\varepsilon_{xy}$ in plane strain distribution for load case M2t ($N_x=40E+03$ Nm$^{-1}$)

Fig. 63 Outermost 0°-layer: Strength index distribution for load case M2t ($N_x=40E+03$ Nm$^{-1}$). Failure criterion: Tsai-Hahn ($F_{ij} = -\frac{1}{2}\sqrt{F_{ii}F_{jj}}$)
Fig. 64 Top 45°-layer: Strength index distribution for load case M2t ($N_x=40E+03$ Nm$^{-1}$).

Failure criterion: Tsai-Hahn ($F_{ij} = -\frac{1}{2} \sqrt{F_{ii}F_{jj}}$).

Fig. 65 Top (-45°)-layer: Strength index distribution for load case M2t ($N_x=40E+03$ Nm$^{-1}$).

Failure criterion: Tsai-Hahn ($F_{ij} = -\frac{1}{2} \sqrt{F_{ii}F_{jj}}$).
3.4.4 Compression along direction-2 of the MD laminate

Fig.66 \( \varepsilon_x \) strain distribution for load case M2c (N_x=40E+03 Nm\(^{-1}\))

Fig.67 \( \varepsilon_y \) strain distribution for load case M2c (N_x=40E+03 Nm\(^{-1}\))
Fig. 68 $\varepsilon_{xy}$ in plane strain distribution for load case M2c ($N_x=40E+03$ Nm$^{-1}$)

Fig. 69 Outermost 0°-layer: Strength index distribution for load case M2c ($N_x=40E+03$ Nm$^{-1}$).

Failure criterion: Tsai-Hahn ($F_{ij} = \frac{1}{2} \sqrt{F_{ii} F_{jj}}$). Criterion values less or equal zero
Fig. 70 Top 45°-layer: Strength index distribution for load case M2c (N_x=40E+03 Nm^{-1}).

Failure criterion: Tsai-Hahn \( F_{ij} = -\frac{1}{2} \sqrt{F_{iijj}} \). Criterion values less or equal zero.

Fig. 71 Top (-45°)-layer: Strength index distribution for load case M2c (N_x=40E+03 Nm^{-1}).

Failure criterion: Tsai-Hahn \( F_{ij} = -\frac{1}{2} \sqrt{F_{iijj}} \). Criterion values less or equal zero.
4 CONCLUSIONS

Theoretical predictions were presented for the mechanical response of OPTIMAT coupons made of UD and MD lay-up. Two types of analysis were performed, namely simple CLT calculations where the plate is assumed infinite and FE-shell computations for the exact coupon geometry. Although the kinematics formulation of the finite shell element used is of the Mindlin type, comparison with the CLT (Love-Kirchhoff theory) results proved that a very good agreement is established, especially in the centre of the coupon. This is valid for both, elastic strains and FPF factors. However, near the free edges of the specimen and the tabs, the stress/strain field is quite different from that predicted by the theory of the infinite plate assumptions. Concerning FPF predictions, actual failure load from the FE analysis is several times smaller than that derived from CLT software. This “reduced strength” factor (ratio of coupon strength as predicted by CLT and FE-shell analysis) was found approximately equal to the values shown in the following table.

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<th>U2t</th>
<th>U2c</th>
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</table>

It should be noticed once again that the above values for the case of the MD plate refer only to a FPF value and that for predicting ultimate failure load of the coupon, more sophisticated analysis, taking into account material property degradation and possibly non-linearity, is required.

FPF predictions either by CLT or FE-shell approaches presented in this report were derived by means of the Tsai-Hahn version of the quadratic failure tensor polynomial. In principle, other failure criteria may yield different results occasionally. This will be investigated partly in TG4, and also in TG2, when comparisons with OPTIMAT experimental data will be possible.
5 REFERENCES

4. Joosse, P.A., “Preliminary prediction of specimen properties. CLT and 1st order FEM analyses”, TU Delft, WMC-Group, OB_TG4_R003(TUD)01.doc, 15-11-02