

Input data for a comparison between uni-axial and bi-axial stresses

OB_TG2_R015 rev. 001

Confidential



TG 2

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Change record

| Issue/revision | date | pages | Summary of changes |
|----------------|----------|------------------------|---|
| draft | 16-06-04 | Na | na |
| 1 | 1-7-4 | 11, 13, 14 (Tabels) | Tail and Nose locations were mixed up in the description of the node position |
| | | several | Small editorial changes |
| | | | |
| | | | |



ACKNOWLEDGEMENT

Research funded in part by European Commission in the framework of the specific research and technology development programme Energy, Environment and Sustainable Development.

The Research performed by ECN and WMC is funded in part by Novem, Utrecht. Project number: 2020-01-12-10-002



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1. INTRODUCTION

In order to realistically assess the impact of the type of analysis of the blade, results of a 1-dimensional (beam model) analysis performed with FOCUS is compared with results of a 2-dimensional analysis performed with MSC MARC.

Also included are strain gauge measurements on a blade test of the analysed blade.

1.1. Axis system and load cases

The X-axis is in flap-wise direction, with the positive side towards the compression direction.

The Y-axis is in edge-wise direction, with the positive side towards the tail.

The Z-axis is the radial position, running from 0 (centre of the hub) to 35m (tip).

See also Figure 1.

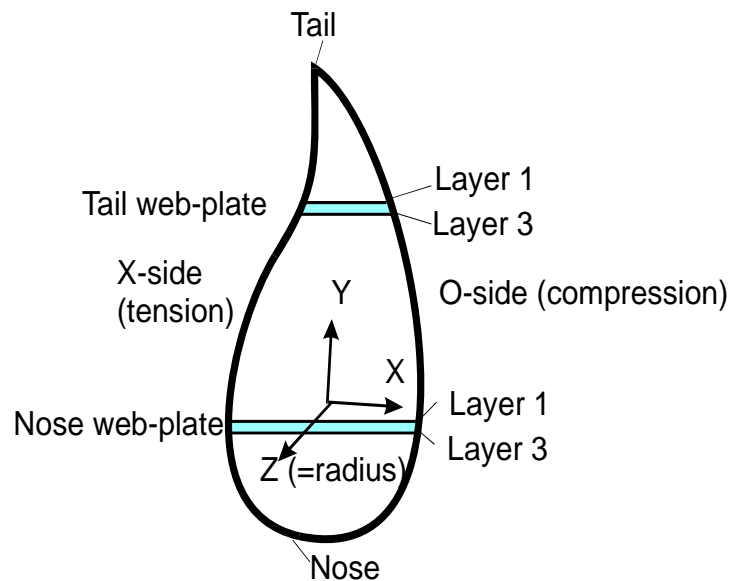


Figure 1 Co-ordinate system used

Two load cases were selected:

- ◆ The first load case consists of a load of 1 kN in positive X-direction
- ◆ The second load case consists of a load of 1 kN in positive Y-direction.

Each load is applied as two forces of 0.5 kN each on the nodes between main (nose) web plate and skin at a radius (Z-coordinate) of 22m.

1.2. Test Set-up

The test set-up is shown in Figure 2. The point R=0 denotes the centre of the hub.

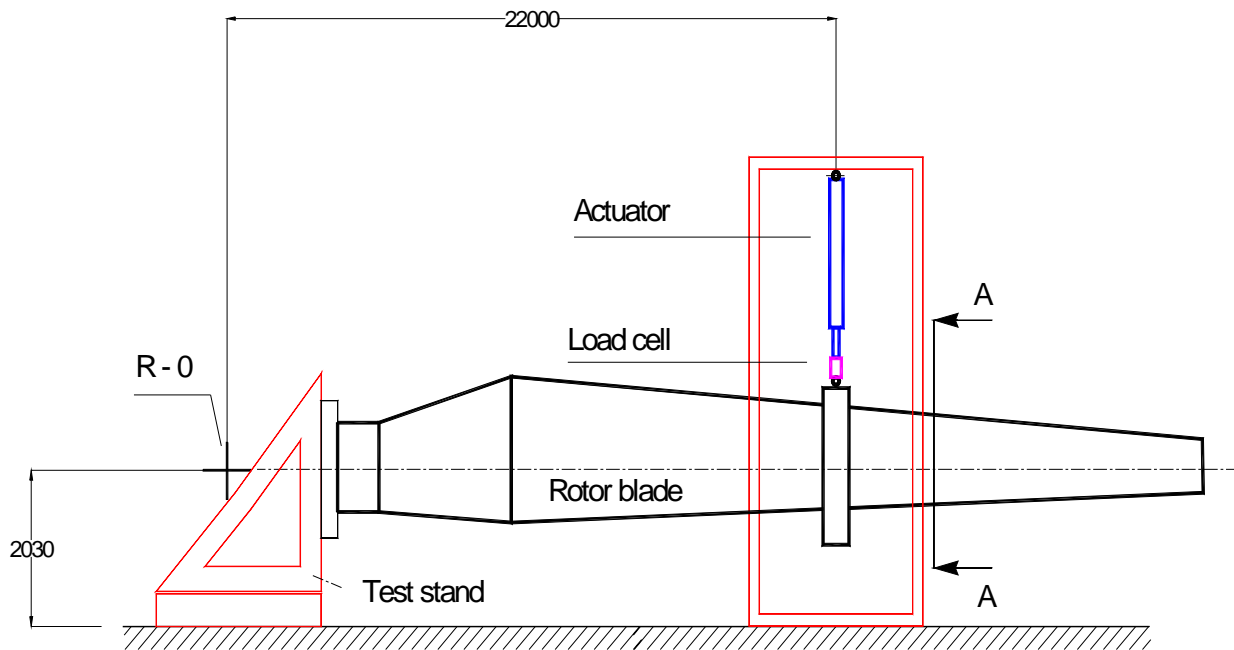


Figure 2 Test set-up

1.3. Cross sections

Three cross sections were selected for the comparison, so as to get an impression of the various stress states which occur on the blade. Care was taken to select cross sections for which measurement data exists as well.

- ◆ The maximum chord has a radial position of $R=7.00$ m, so this section was selected.
- ◆ Further more one section in the transition area was selected at $R=5.00$ m
- ◆ One section after the maximum chord section at $R=10.00$ m.

The numbers and positions of the strain gauges at each cross section are shown, as well as the node numbers of the FE analysis.

2. STRAIN GAUGE POSITIONS AT SELECTED CROSS SECTIONS

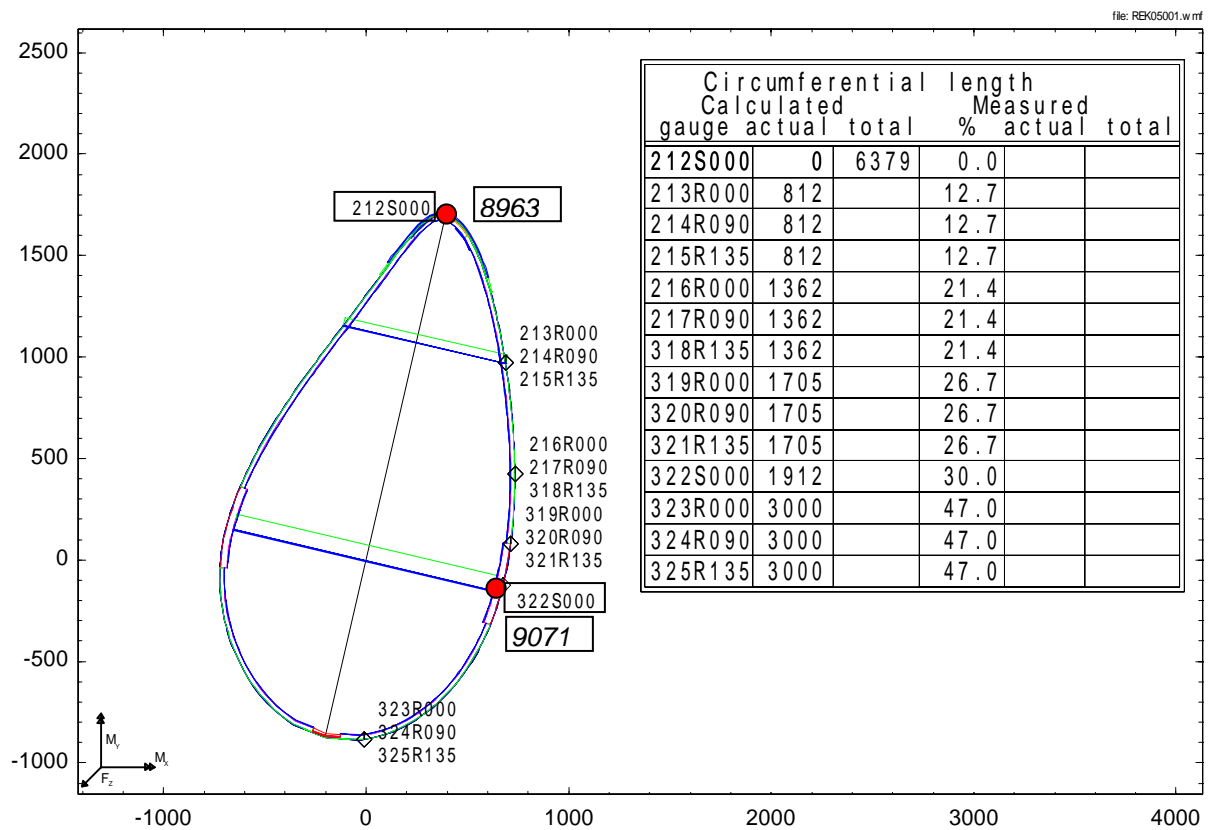
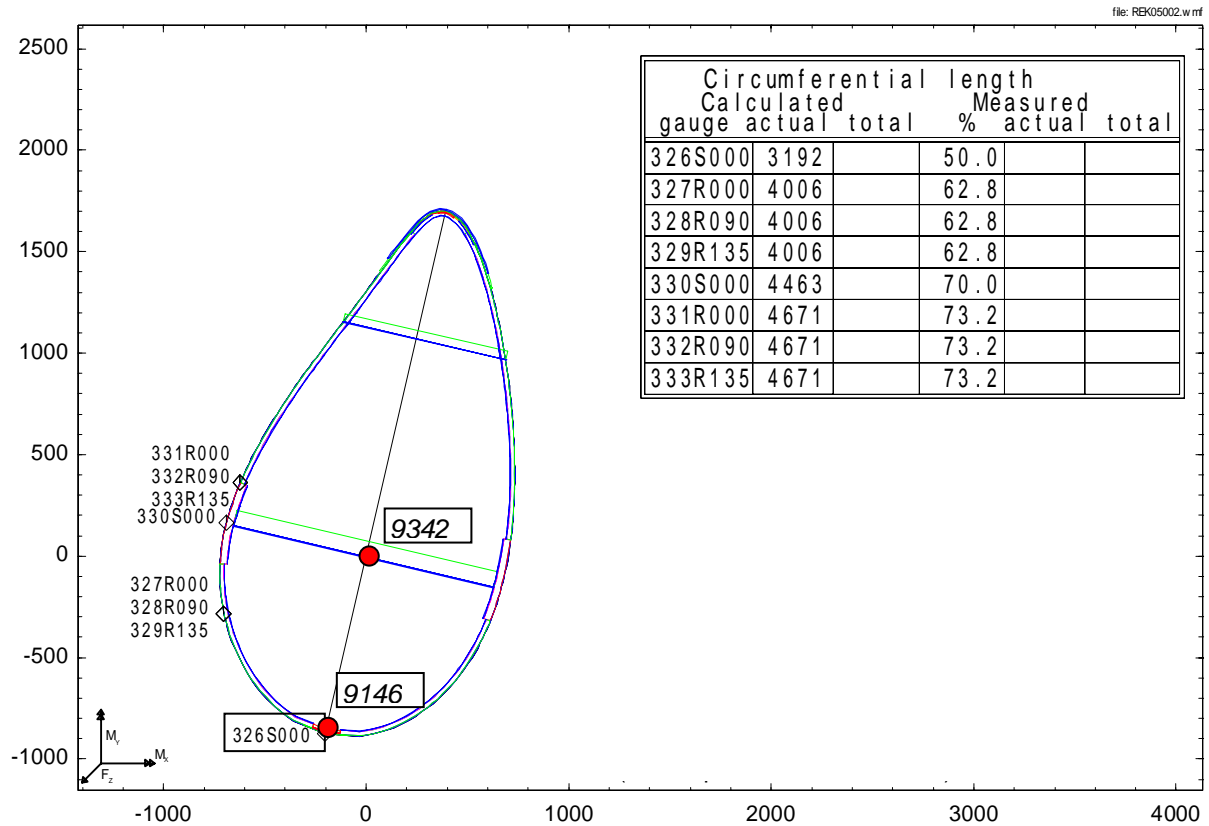
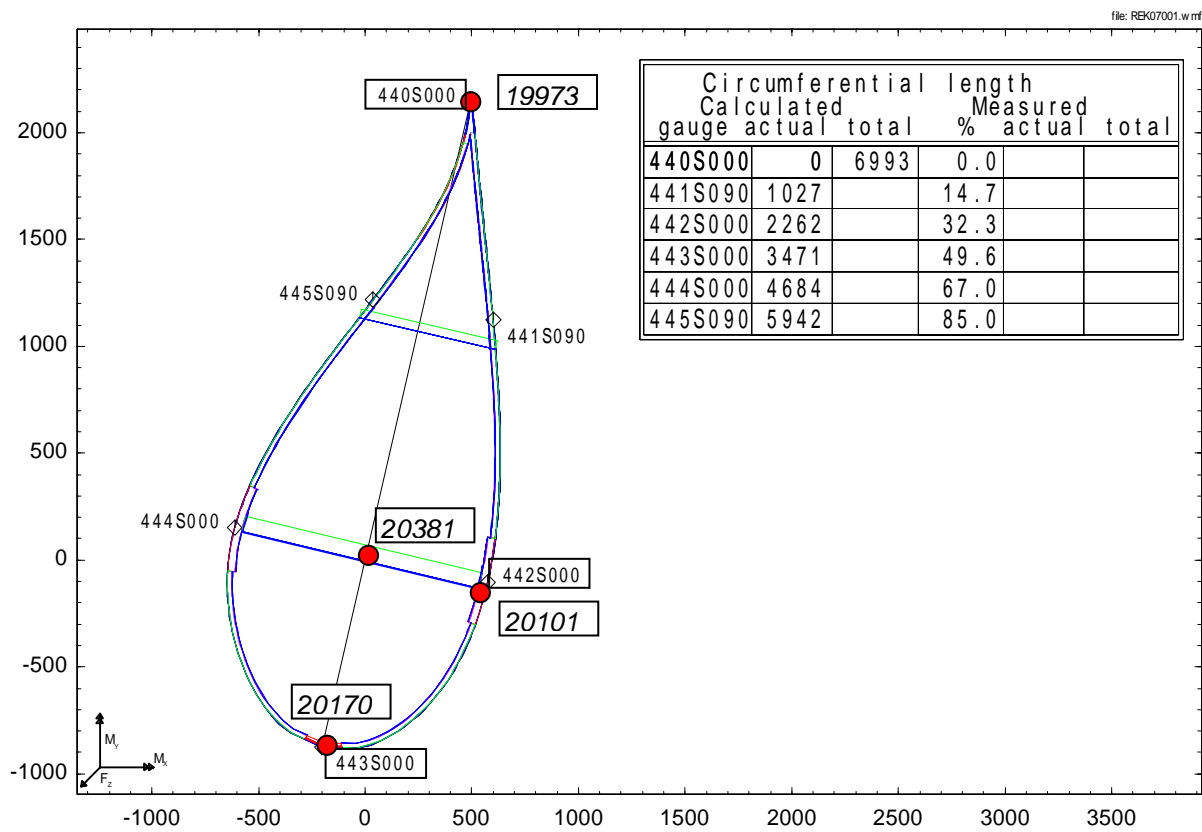


Figure 3 Cross section at 5 m (left and right hand side)


Figure 4 Cross section at 7 m

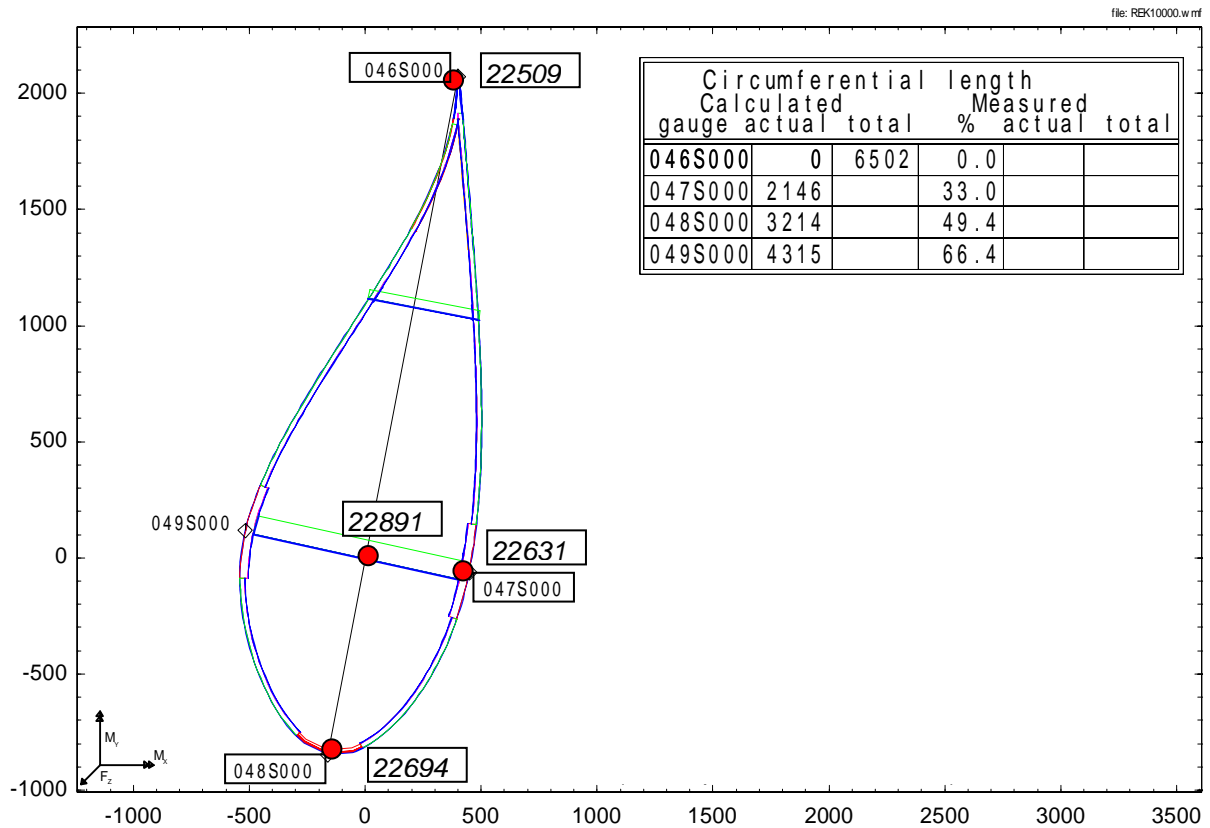


Figure 5 Cross section at 10 m



3. MATERIALS AND ELEMENTS USED

3.1. material overview and corrections

The nodes selected for the comparison are all defined by four surrounding elements. Each of those has its own layer build-up. In general, the variations in element lay-up are small changes in thickness of the layers. However, at nodes 19973 and 20101 one or two layers are finished, changing the number of layers. Since it is unclear how MARC pairs this output, the material lay-up was changed to exclude the thin layers that were ending, by applying one material definition to all four elements, as denoted in the material# column.



| Node | elements | Material# | Layer 1 | Layer 2 | Layer 3 | Layer 4 | Layer 5 | Layer 6 | Layer 7 |
|---|----------|-----------------|---------|---------|---------|---------|---------|---------|---------|
| 8963 <i>R=5</i> <i>Tail</i> | 2940 | 1261 | 5 | 6 | 2 | 11 | 11 | 2 | 5 |
| | 3069 | 1323 | | | | | | | |
| | 3075 | 1329 | | | | | | | |
| | 3200 | 1391 | | | | | | | |
| 9071 <i>R=5</i> <i>Spar</i> | 2976 | 1279 | 2 | 8 | 2 | | | | |
| | 2977 | 1279 | | | | | | | |
| | 3111 | 1347 | | | | | | | |
| | 3112 | 1347 | | | | | | | |
| 9146 <i>R=5</i> <i>Nose</i> | 3001 | 1291 | 5 | 2 | 2 | 5 | 6 | | |
| | 3002 | 1293 | | | | | | | |
| | 3136 | 1359 | | | | | | | |
| | 3137 | 1361 | | | | | | | |
| 9342 <i>R=5</i> <i>Web</i> | 3067 | 1325 | 9 | 10 | 9 | | | | |
| | 3068 | 1325 | | | | | | | |
| | 3203 | 1393 | | | | | | | |
| | 3204 | 1393 | | | | | | | |
| 19973 <i>R=7</i> <i>Tail</i> | 6666 | 2954 | 5 | 2 | 2 | 2 | | | |
| | 6799 | 3009 | | | | | | | |
| | 6812 | 3015 | 2 | 2 | 2 | | | | |
| | 6945 | 3069 | | | | | | | |
| 20101 <i>R=7</i> <i>Spar</i> | 6708 | 2967 | 2 | 12 | 8 | 12 | 2 | | |
| | 6709 | 2969 | 2 | 8 | 2 | | | | |
| | 6854 | 3029 | | | | | | | |
| | 6855 | 3031 | | | | | | | |
| 20170 <i>R=7</i> <i>Nose</i> | 6731 | 2979 | 2 | 2 | 5 | 6 | | | |
| | 6732 | 2981 | | | | | | | |
| | 6877 | 3041 | | | | | | | |
| | 6878 | 3043 | | | | | | | |
| 20381 <i>R=7</i> <i>Web</i> | 6802 | 3011 | 9 | 10 | 9 | | | | |
| | 6803 | 3011 | | | | | | | |
| | 6948 | 3071 | | | | | | | |
| | 6949 | 3071 | | | | | | | |
| 22509 <i>R=10</i> <i>Tail</i> | 7526 | 3291 | 2 | 2 | 2 | | | | |
| | 7651 | 3339 | | | | | | | |
| | 7664 | 3345 | | | | | | | |
| | 7788 | 3393 | | | | | | | |
| 22631 <i>R=10</i> <i>Spar</i> | 7566 | 3303 | 2 | 8 | 2 | | | | |
| | 7567 | 3303 | | | | | | | |
| | 7704 | 3357 | | | | | | | |
| | 7705 | 3357 | | | | | | | |
| 22694 <i>R=10</i> <i>Nose</i> | 7587 | 3313 | 2 | 2 | 5 | 6 | | | |
| | 7588 | 3315 | | | | | | | |
| | 7725 | 3367 | | | | | | | |
| | 7726 | 3369 | | | | | | | |
| 22891 <i>R=10</i> <i>Web</i> | 7654 | 3341 | 9 | 10 | 9 | | | | |
| | 7655 | 3341 | | | | | | | |
| | 7791 | 3395 | | | | | | | |
| | 7792 | 3395 | | | | | | | |

3.2. Material properties

Note that material properties can either be given for FOCUS (beam model, only properties in one direction used and for FE modelling (properties can vary per direction).

Hence E-modulus next to E_11 (radial) and E-22 (circumferential).

Units are N, kg and mm.

3.2.1. material 1 (not used, but included as an example)

```
DEF MATERIAL STAAL
E-modulus      210000.
G-modulus      80000.
Density        7800/10^9
Poisson        0.3
```

3.2.2. material 2

```
E-modulus      13100.
G-modulus      10300.
Density        1787/10^9
Poisson        0.483
```

3.2.3. material 5

```
E-modulus      11300.
G-modulus      9300.
Density        1670/10^9
Poisson        0.496
```

3.2.4. material 6

```
Density        1700/10^9
E_11           31000
E_22           9700
G-modulus      4400
Poisson        0.205
```

3.2.5. material 8

```
Density        1860/10^9
E_11           39900
E_22           9850
G-modulus      4500
Poisson        0.26
```

3.2.6. material 9

```
E-modulus      11300.
G-modulus      9300.
Density        1670/10^9
Poisson        0.496
```

3.2.7. material 10

```
E-modulus      35.
G-modulus      22.
Density        55./10^9
Poisson        0.3
```

3.2.8. material 11

```
Density        1837/10^9
E_11           38800
E_22           9500
G-modulus      4830
Poisson        0.260
```

3.3. Element description

The element used for the analysis is MARC element type 72. Since this is a thin shell element, only 3 strain components are produced, namely:

- ◆ ε_{11} (strain in radial direction)
- ◆ ε_{22} (strain in circumferential direction)
- ◆ ε_{12} (in-plane shear).

4. RESULTS OF FE ANALYSIS/FOCUS AND TEST

For the load in Flap-wise direction, no direct test data was available, hence no comparison has been carried out.

Table 1 Comparison of strains for an flap-wise load of 1 kN at R=22m.

| Node | test | FOCUS | FE /test | FOCUS /test | Layer 1 | Layer 2 | Layer 3 | Layer 4 | Layer 5 | Layer 6 | Layer 7 |
|-------|-----------------|-------|----------|-------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 8963 | ϵ_{11} | | | | -2.95E-06 | -3.01E-06 | -3.06E-06 | -3.08E-06 | -3.10E-06 | -3.12E-06 | -3.15E-06 |
| R=5 | ϵ_{12} | | | | -9.50E-07 | -1.83E-06 | -2.53E-06 | -2.77E-06 | -3.01E-06 | -3.26E-06 | -3.70E-06 |
| Tail | ϵ_{22} | | | | 1.01E-06 | 9.90E-07 | 9.73E-07 | 9.67E-07 | 9.62E-07 | 9.56E-07 | 9.45E-07 |
| 9071 | ϵ_{11} | | | | -1.05E-05 | -1.02E-05 | -9.94E-06 | NA | NA | NA | NA |
| R=5 | ϵ_{12} | | | | -3.45E-07 | -2.33E-06 | -4.32E-06 | NA | NA | NA | NA |
| Spar | ϵ_{22} | | | | -4.66E-06 | 2.68E-06 | 1.00E-05 | NA | NA | NA | NA |
| 9146 | ϵ_{11} | | | | 3.03E-06 | 3.03E-06 | 3.04E-06 | 3.04E-06 | 3.06E-06 | NA | NA |
| R=5 | ϵ_{12} | | | | -4.96E-07 | -6.64E-07 | -8.55E-07 | -1.18E-06 | -2.17E-06 | NA | NA |
| Nose | ϵ_{22} | | | | -7.72E-07 | -8.12E-07 | -8.58E-07 | -9.36E-07 | -1.17E-06 | NA | NA |
| 9342 | ϵ_{11} | | | | 2.03E-07 | 1.20E-07 | 3.66E-08 | NA | NA | NA | NA |
| R=5 | ϵ_{12} | | | | -5.08E-06 | -6.26E-06 | -7.43E-06 | NA | NA | NA | NA |
| Web | ϵ_{22} | | | | 1.75E-06 | 5.74E-07 | -5.99E-07 | NA | NA | NA | NA |
| 19973 | ϵ_{11} | | | | -8.08E-06 | -7.99E-06 | -7.81E-06 | NA | NA | NA | NA |
| R=7 | ϵ_{12} | | | | -5.75E-06 | -5.25E-06 | -4.26E-06 | NA | NA | NA | NA |
| Tail | ϵ_{22} | | | | -1.21E-06 | 1.05E-06 | 5.60E-06 | NA | NA | NA | NA |
| 20101 | ϵ_{11} | | | | -1.16E-05 | -1.18E-05 | -1.20E-05 | NA | NA | NA | NA |
| R=7 | ϵ_{12} | | | | -1.73E-07 | -5.60E-07 | -9.46E-07 | NA | NA | NA | NA |
| Spar | ϵ_{22} | | | | -8.03E-07 | 3.79E-06 | 8.39E-06 | NA | NA | NA | NA |
| 20170 | ϵ_{11} | | | | 1.53E-06 | 1.53E-06 | 1.51E-06 | 1.47E-06 | NA | NA | NA |
| R=7 | ϵ_{12} | | | | -1.48E-06 | -1.55E-06 | -1.67E-06 | -2.03E-06 | NA | NA | NA |
| Nose | ϵ_{22} | | | | -2.55E-07 | -3.24E-07 | -4.41E-07 | -7.96E-07 | NA | NA | NA |
| 20381 | ϵ_{11} | | | | 3.44E-07 | 5.51E-07 | 7.59E-07 | NA | NA | NA | NA |
| R=7 | ϵ_{12} | | | | -3.55E-06 | -4.58E-06 | -5.61E-06 | NA | NA | NA | NA |
| Web | ϵ_{22} | | | | -8.39E-07 | -7.88E-07 | -7.36E-07 | NA | NA | NA | NA |
| 22509 | ϵ_{11} | | | | -3.80E-06 | -3.50E-06 | -2.88E-06 | NA | NA | NA | NA |
| R=10 | ϵ_{12} | | | | -3.85E-06 | -4.78E-06 | -6.63E-06 | NA | NA | NA | NA |
| Tail | ϵ_{22} | | | | 3.03E-06 | 2.14E-06 | 3.53E-07 | NA | NA | NA | NA |
| 22631 | ϵ_{11} | | | | -1.50E-05 | -1.47E-05 | -1.43E-05 | NA | NA | NA | NA |
| R=10 | ϵ_{12} | | | | -6.75E-07 | -1.80E-06 | -2.93E-06 | NA | NA | NA | NA |
| Spar | ϵ_{22} | | | | 2.12E-06 | 4.43E-06 | 6.74E-06 | NA | NA | NA | NA |
| 22694 | ϵ_{11} | | | | 7.44E-07 | 7.48E-07 | 7.56E-07 | 7.75E-07 | NA | NA | NA |
| R=10 | ϵ_{12} | | | | -1.90E-06 | -2.02E-06 | -2.22E-06 | -2.74E-06 | NA | NA | NA |
| Nose | ϵ_{22} | | | | -7.10E-07 | -5.99E-07 | -4.10E-07 | 6.46E-08 | NA | NA | NA |
| 22891 | ϵ_{11} | | | | 8.41E-07 | 9.72E-07 | 1.10E-06 | NA | NA | NA | NA |
| R=10 | ϵ_{12} | | | | -6.97E-06 | -8.64E-06 | -1.03E-05 | NA | NA | NA | NA |
| Web | ϵ_{22} | | | | -1.10E-06 | -7.80E-07 | -4.61E-07 | NA | NA | NA | NA |

For the load in edge-direction, FE, FOCUS and measurement data can be directly compared. The results of FOCUS have also been included.

Table 2 Comparison of strains for an edge-wise load of 1 kN at R=22m.

| Node | test | FOCUS | FE /test | FOCUS /test | Layer 1 | Layer 2 | Layer 3 | Layer 4 | Layer 5 | Layer 6 | Layer 7 | |
|-------|----------------------|-----------|-------------|----------------|---------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 8963 | ϵ_{11} | -1.69E-05 | -2.48E-05 | 1.12 | 1.46 | -1.89E-05 | -1.92E-05 | -1.94E-05 | -1.95E-05 | -1.95E-05 | -1.96E-05 | -1.98E-05 |
| | R=5 ϵ_{12} | | | | | -1.56E-06 | -9.02E-07 | -3.88E-07 | -2.03E-07 | -2.89E-08 | 1.56E-07 | 4.89E-07 |
| | Tail ϵ_{22} | | | | | -4.17E-06 | 3.06E-06 | 8.72E-06 | 1.08E-05 | 1.27E-05 | 1.47E-05 | 1.84E-05 |
| 9071 | ϵ_{11} | 7.91E-06 | 9.55E-06 | 0.85 | 1.21 | 6.70E-06 | 6.43E-06 | 6.17E-06 | NA | NA | NA | NA |
| | R=5 ϵ_{12} | | | | | -1.85E-06 | -3.32E-06 | -4.80E-06 | NA | NA | NA | NA |
| | Spar ϵ_{22} | | | | | 2.80E-06 | -9.43E-07 | -4.69E-06 | NA | NA | NA | NA |
| 9146 | ϵ_{11} | 2.70E-05 | 2.09E-05 | 1.12 | 0.77 | 3.02E-05 | 3.03E-05 | 3.04E-05 | 3.06E-05 | 3.11E-05 | NA | NA |
| | R=5 ϵ_{12} | | | | | -8.05E-08 | -6.26E-08 | -4.22E-08 | -7.39E-09 | 9.84E-08 | NA | NA |
| | Nose ϵ_{22} | | | | | -1.18E-05 | -1.16E-05 | -1.12E-05 | -1.07E-05 | -9.07E-06 | NA | NA |
| 9342 | ϵ_{11} | | | | | 1.05E-06 | 2.61E-06 | 4.17E-06 | NA | NA | NA | NA |
| | R=5 ϵ_{12} | | | | | 2.74E-06 | 2.71E-06 | 2.68E-06 | NA | NA | NA | NA |
| | Web ϵ_{22} | | | | | -7.94E-07 | -3.08E-06 | -5.36E-06 | NA | NA | NA | NA |
| 19973 | ϵ_{11} | -4.50E-05 | -3.05E-05 | 1.01 | 0.68 | -4.53E-05 | -4.51E-05 | -4.47E-05 | NA | NA | NA | NA |
| | R=7 ϵ_{12} | | | | | 4.97E-07 | 1.44E-07 | -5.64E-07 | NA | NA | NA | NA |
| | Tail ϵ_{22} | | | | | 1.01E-05 | 1.50E-05 | 2.49E-05 | NA | NA | NA | NA |
| 20101 | ϵ_{11} | 8.28E-06 | 8.89E-06 | 0.89 | 1.07 | 7.41E-06 | 7.69E-06 | 7.98E-06 | NA | NA | NA | NA |
| | R=7 ϵ_{12} | | | | | -2.81E-06 | -2.18E-06 | -1.55E-06 | NA | NA | NA | NA |
| | Spar ϵ_{22} | | | | | 4.18E-06 | -1.75E-06 | -7.68E-06 | NA | NA | NA | NA |
| 20170 | ϵ_{11} | 1.91E-05 | 1.85E-05 | 1.17 | 0.97 | 2.23E-05 | 2.22E-05 | 2.21E-05 | 2.18E-05 | NA | NA | NA |
| | R=7 ϵ_{12} | | | | | -5.77E-07 | -5.55E-07 | -5.18E-07 | -4.04E-07 | NA | NA | NA |
| | Nose ϵ_{22} | | | | | -9.31E-06 | -8.97E-06 | -8.38E-06 | -6.59E-06 | NA | NA | NA |
| 20381 | ϵ_{11} | | | | | 3.81E-06 | 4.79E-06 | 5.76E-06 | NA | NA | NA | NA |
| | R=7 ϵ_{12} | | | | | -2.15E-07 | -7.73E-08 | 6.06E-08 | NA | NA | NA | NA |
| | Web ϵ_{22} | | | | | -5.91E-06 | -4.80E-06 | -3.70E-06 | NA | NA | NA | NA |
| 22509 | ϵ_{11} | -2.91E-05 | -2.87E-05 | 1.05 | 0.99 | -3.07E-05 | -3.06E-05 | -3.04E-05 | NA | NA | NA | NA |
| | R=10 ϵ_{12} | | | | | -2.33E-06 | -1.50E-06 | 1.75E-07 | NA | NA | NA | NA |
| | Tail ϵ_{22} | | | | | 1.32E-05 | 1.39E-05 | 1.55E-05 | NA | NA | NA | NA |
| 22631 | ϵ_{11} | 9.18E-06 | 7.30E-06 | 0.84 | 0.80 | 7.70E-06 | 7.65E-06 | 7.61E-06 | NA | NA | NA | NA |
| | R=10 ϵ_{12} | | | | | -8.08E-07 | -8.11E-07 | -8.14E-07 | NA | NA | NA | NA |
| | Spar ϵ_{22} | | | | | -1.64E-06 | -2.21E-06 | -2.78E-06 | NA | NA | NA | NA |
| 22694 | ϵ_{11} | 1.66E-05 | 1.64E-05 | 1.08 | 0.99 | 1.79E-05 | 1.79E-05 | 1.80E-05 | 1.81E-05 | NA | NA | NA |
| | R=10 ϵ_{12} | | | | | -5.56E-07 | -5.58E-07 | -5.61E-07 | -5.70E-07 | NA | NA | NA |
| | Nose ϵ_{22} | | | | | -8.86E-06 | -8.31E-06 | -7.38E-06 | -4.99E-06 | NA | NA | NA |
| 22891 | ϵ_{11} | | | | | 3.21E-06 | 3.86E-06 | 4.51E-06 | NA | NA | NA | NA |
| | R=10 ϵ_{12} | | | | | -6.76E-07 | -7.19E-07 | -7.61E-07 | NA | NA | NA | NA |
| | Web ϵ_{22} | | | | | -1.70E-06 | -1.75E-06 | -1.81E-06 | NA | NA | NA | NA |



5. SHORT DISCUSSION

The data in this report is just meant as input for comparison between uni- and biaxial stress analysis and as no conclusions will be drawn at this stage.

However, a few observations can be made. From table 2, it can be observed that:

1. The stress component in circumferential direction are often of the same magnitude as those in radial direction. A clear biaxial situation exists in most of the blade.
2. A comparison of results between FE results and measured strains in the test, shows a good agreement, typically within 15% (mostly due to discrepancies between the modelled and the actual blade).
3. A comparison between FOCUS and the measured strains show results to be within 20% in most cases, with a few noticeable exceptions.