Material Property Prediction for Ballistic Laminate

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Rev. New. 05.Jan.23

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Problem description

- Typical layered composite – 9 material properties needed for full mathematical description (E_{11}, E_{22}, E_{33}, ν_{12}, ν_{13}, ν_{23}, G_{12}, G_{13}, G_{23})
- Only 3-4 properties are measureable
- Other properties
    - Estimation based on similar material
    - Legacy data (sometimes unknown source)

- What to do in case of a new composite where the material properties are unknown?
    - Scientific article research vs. sensitive material as in case of ballistic protection
    - Supplier of fibers and matrix can be different ->inconsistent input of raw material properties
    - Production process determines the actual result

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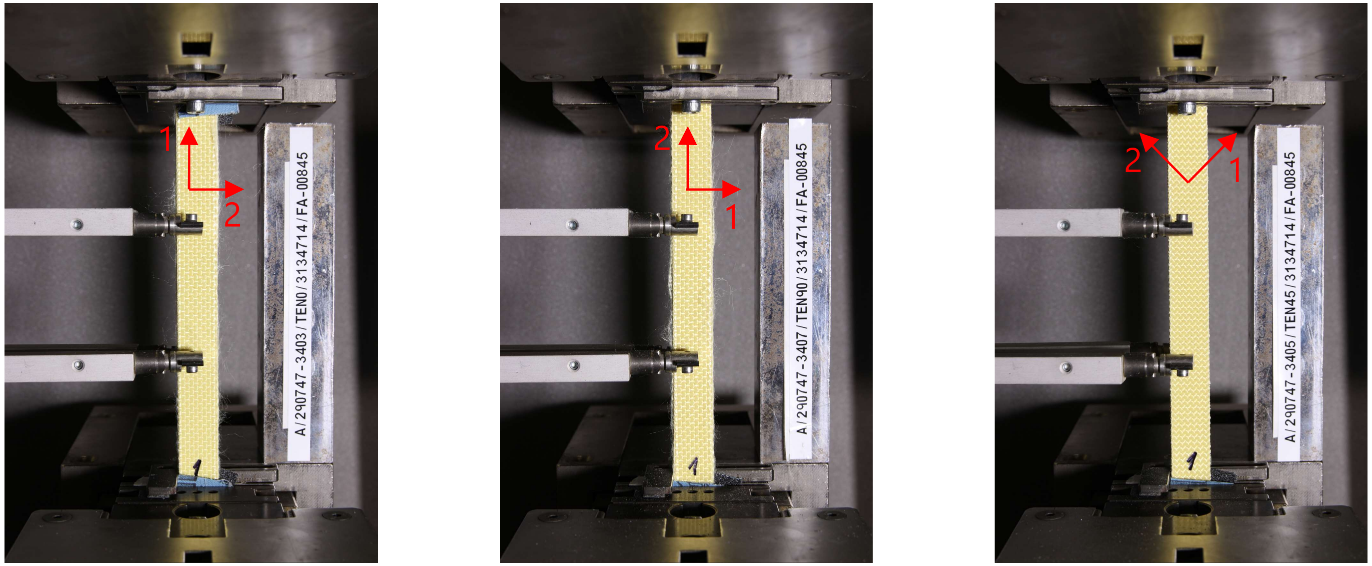
Standard material testing and results

- Standard tensile tests per ASTM D3039 using 0°, 90° and 45° fiber orientation specimens using extensometer
- Results of the test are E_{11}, E_{22}, E_{S45}
- Problem – experiments on weave patern always mix stifness in both directions



direnction 1 = warp direction, direction 2 = weft direction

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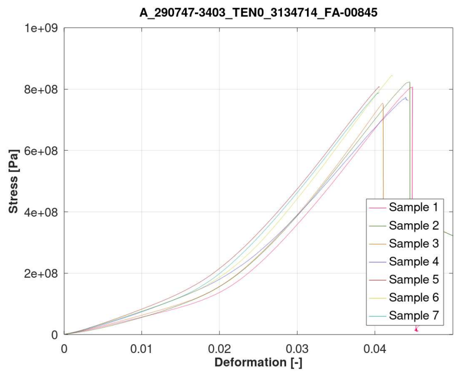

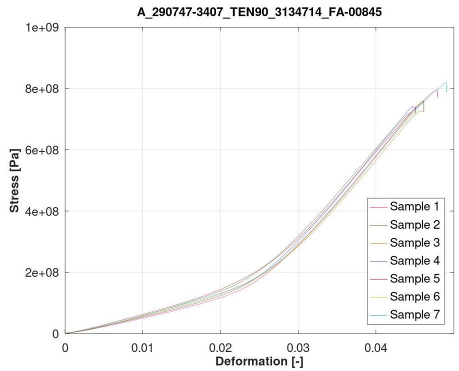

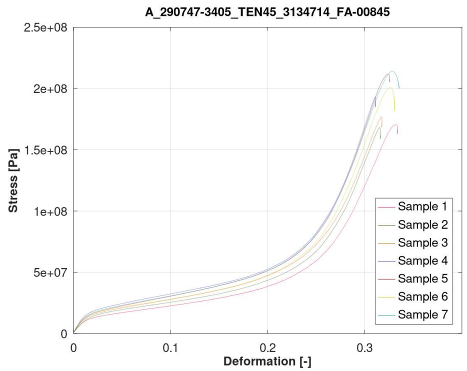

- Strongly nonlinear behavior with material stiffening
- Evaluation for E_{11}, E_{22}, E_{S45} selected at a range of 1000-3000 με

E_{11} [Pa]	E_{22} [Pa]	E_{S45} [Pa]
5.80E+09	4.65E+09	1.09E+09

- Problems
  1. Difference between E_{11} and E_{22} is 20% even though fibers in both directions are identical
  2. Calculation of actual shear modulus G_{12} can be done using formula:

$$\frac{1}{E_{S45}} = \frac{1}{4}\left[\frac{1}{E_{11}} + 2\left(\frac{1}{\nu_{21}E_{11}} + \frac{1}{G_{12}}\right) + \frac{1}{E_{22}}\right]$$

but ν_{21} is not available

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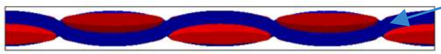
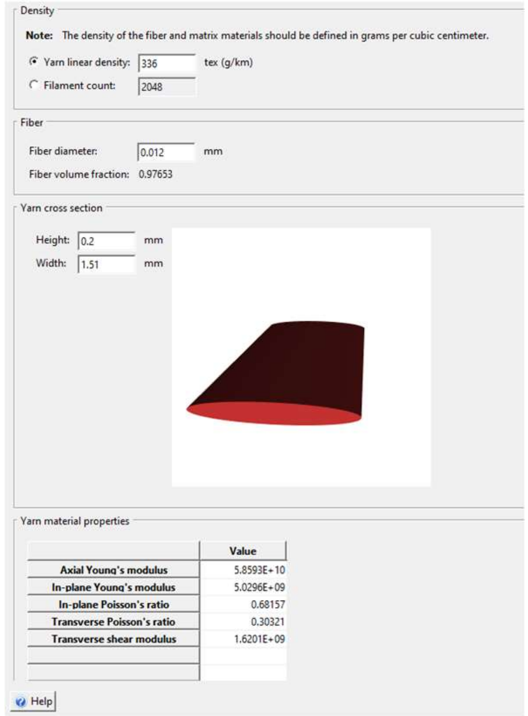
Digimat FE - input parametres

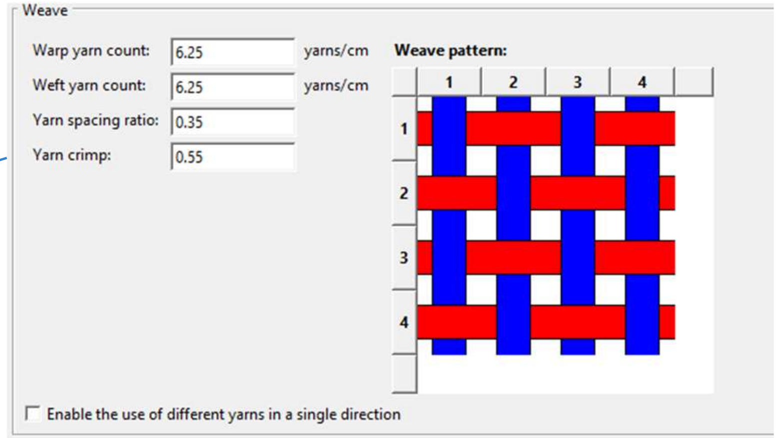
- Above mentioned problems can be solved using the FE homogenization from microstructure simulation
- Material properties of individual constituent must be known

Property	Aramid fibre	Resin
Density [g/cm3]	1.45	1.10
Young's modulus [Pa]	6E+10	7E+07
Poisson ratio [-]	0.30	0.45

Parameters set based on TDS, internet research and correlation to actual test results







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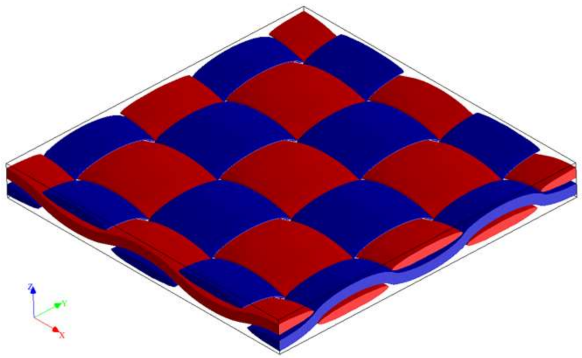
FE model

- Representative cell geometry prepared and meshed
- Each constituent has assigned material properties (warp fibers, weft fibers, matrix)
- Preparation of 6 different analyses and loading the cell in all normal and shear directions



1 000 000 elements

Engineering constants

	Value
E11	6.778E+09
Mismatch on E11	3.40605E-07
E22	5.69133E+09
Mismatch on E22	1.28832E-07
E33	4.71833E+08
Mismatch on E33	2.43964E-08
nu12	0.405233
nu21	0.340233
nu13	0.7328
nu31	0.05101
nu23	0.7556
nu32	0.0626433
G12	6.78467E+08
Mismatch on G12	5.98539E-08
G23	6.203E+07
Mismatch on G23	8.39879E-10
G13	6.04767E+07
Mismatch on G13	7.17177E-09
Global density	1.64028

- Observation: changing of yarn crimp (curvature of weft fibers strongly influences ratio between E_{11}, E_{22} but also all other values -> many iterations performed to get proper ratio
- Furthermore, ν_{21} obtained for recalculation of the E_{S45} to G_{12}

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Correlation of FE model to experiments

Property	Digimat	Experiment	Factor	FEM
E_{11}	6.78E+09	5.80E+09	0.86	5.801E+09
E_{22}	5.69E+09	4.65E+09	0.82	4.646E+09
E_{33}	4.72E+08	-	Average 0.86 and 0.82	3.945E+08
ν_{12}	0.405	-	-	0.405
ν_{21}	0.340	-	-	0.340
ν_{13}	0.733	-	-	0.733
ν_{31}	0.051	-	-	0.051
ν_{23}	0.756	-	-	0.756
ν_{32}	0.063	-	-	0.063
G_{12}	6.78E+08	8.84E+08	1.30	8.84E+08
G_{23}	6.20E+07	-	1.30 as G_{12}	8.08E+07
G_{13}	6.05E+07	-	1.30 as G_{12}	7.88E+07

NOTE: DUE TO THE SAFRAN INTELLECTUAL PROPERTY, PRESENTED DATA ARE NOT ACTUAL MEASURED/CALCULATED VALUES

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Conclusion

- Digimat can be successfully used for material property estimation
- Weave pattern has strong influence on resulting material properties
  - Identical fibers in both directions does not result in identical material properties
  - Force applied during the weft weaving (pulling through the warp fibers and tensioning) can change the stiffness of resulting composite
  - Properties from unidirectional composites can not be compared to woven composites

- Straightening of the fibers within weave during high deformations can be an answer to material stiffening (loading of straight fibers instead of bending the weaves) - extensive non-linear analysis would be required

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