Model calibration

Composites material model 140 for draping simulation

Problem description

Outline	Calibration of the draping model for dry fabrics including shear and bending stiffness. Validation under various loadings.
Analysis type(s):	Explicit
Element type(s):	Applicable to shell elements (material model 140)
Materials law(s):	PAM-FORM material model 140. Specific deformations calibrated include:

1) Shear (against picture frame test results)
2) Bending (against cantilever test results)

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Model options:	Modelling shear (the picture frame test), bending (cantilever test) and fabric buckling.
Key results:	Calibration strategy and validation against test measurements
Prepared by: Date:	Anthony Pickett, ESI GmbH/Institute for Aircraft Design, Stuttgart September 2012

1 Contents

Part 1: Some test methods for fabric characterisation
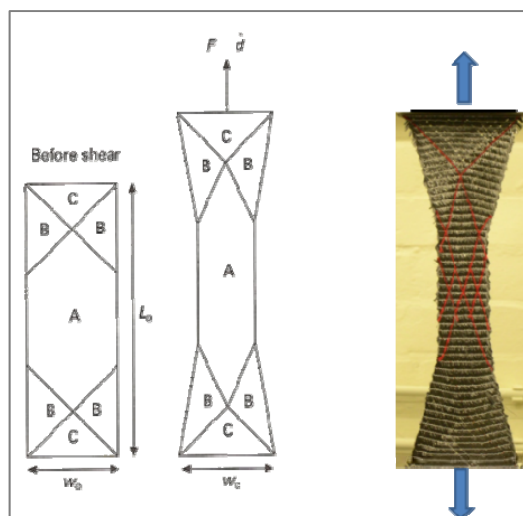
1.1 Shear tests for fabric mechanical properties

Currently there are no standards regarding the shear testing of unidirectional or biaxial engineering fabrics. The two main tests for shear are the picture frame and bias extension tests as shown below.
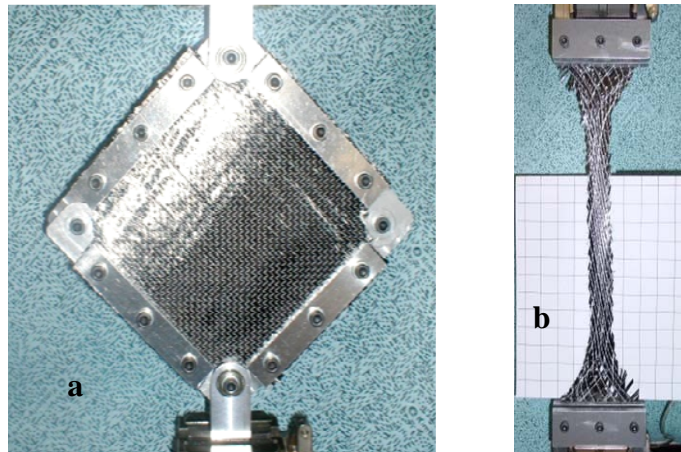
Fabric shear tests; a) Picture frame and b) Bias extension

The picture frame test confines the fabric to pure shear loading and provides both shear force data and the inter-fibre 'locking' angle. This locking is usually defined at the onset of buckling (wrinkling) and fabrics can often reach angles of 40°-60° before this starts to occur.

The bias extension test involves simple extension of a coupon of material with a ±45° fibre angle. Although this test is much easier to perform it is complicated by the inhomogeneous state of shear within the specimen, as shown in the figure below. Further details and methods to extract data from these two tests are given in reference[1].

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[1] Design and manufacture of textile composites, Ed A.C. Long, CRC Press

1.2   Other tests for fabric mechanical properties

With reference to the figure below additional test methods for fabrics could include,

a) Inplane fibre (or transverse) stiffness, particularly if some reinforcement is low stiffness stitching that must be properly modelled. Failure is also possible in PAM-FORM for low strength reinfocements.

b) In-ply test for shear (picture frame or bias extension)

c) Inter-ply friction (and friction at fabric to toll interfaces)

d) Bending stiffness (ASTM D1388-96E1)

Example testing methods for fabric drape properties:
a) In plane tension
b) Shear (Picture frame)
c) Friction (for tool-plies and plies-plies)
d) Bending properties
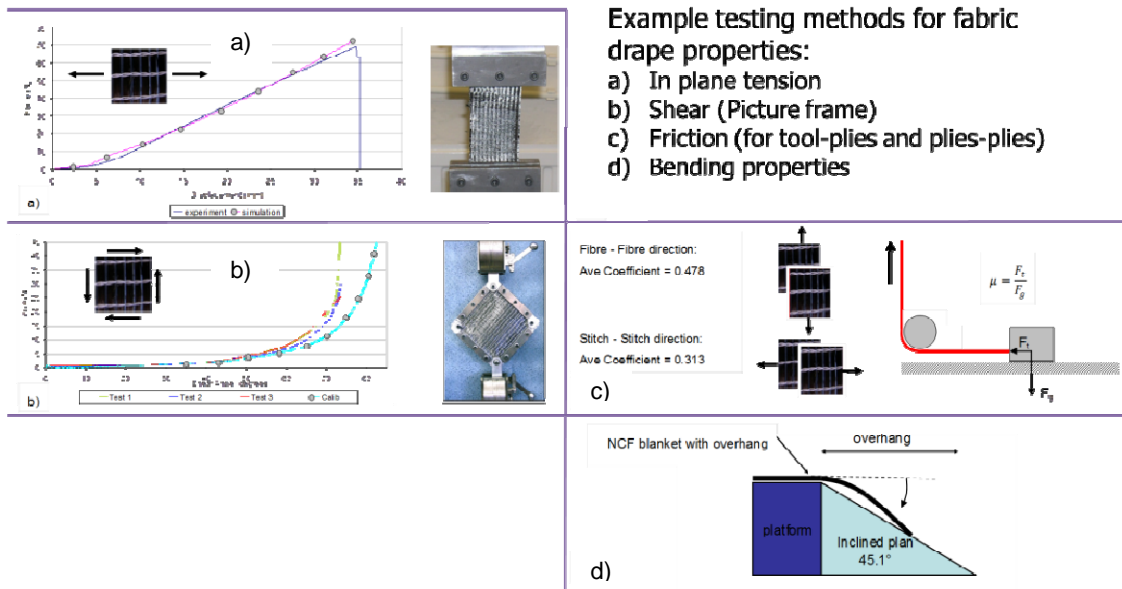
Part 2: The PAM-FORM materials model 140 – Outline and calibration

Material model 140 can be used to represent both dry and viscous fabrics. It is implemented in a shell element and is specifically for draping prediction of composite fabrics. Important features include:

1. The shell element formulation allows fabric buckling to be modeled.

2. Decoupled stiffness laws for the two principle fibre directions and shear behaviour.

3. The fibre reinforcement directions may be orthogonal or non-orthogonal to each other.

4. Each fibre stiffness may be constant, or nonlinear elastic, according to a user defined curve function of stiffness versus strain.

5. The shear behaviour is most important to calibrate as fabrics predominantly deform under this mode. The non-linear shear stiffness may be imposed via three parameters for initial stiffness, locking angle and locking stiffness, or via a more accurate user defined curve function.

6. Fabric bending stiffness is decoupled from in plane stiffness and may be properly characterised via different methods.

7. The fabric thickness may be constant or use a constant volume assumption which would be appropriate for impregnated fabrics. Alternatively, a shear versus thickness function curve corresponding to test measurements may be used.

8. A rate dependent viscous response may superimposed to the stiffness response to represent a viscous resin (e.g. for pre-pregs, thermoplastics or a binder).

In the following sections calibration of fabric shear stiffness is first described followed by in plane fibre stiffness and bending. For this description the fabric is assumed to be dry without any viscous binder or resin.

2.1 Main input required for materials model 140

The main input data for material model 140 is shown below. Brief details on this input are described in this document; however, the main issues are characterisation of intra-ply fabric shear, thickness evolution and bending stiffness which will be covered in more detail together with calibration examples.

	IDMAT	MATYP	RHO	ISINT	ISHG	ISTRAT	IFROZ
MATER /	4	140	1E-8	1	0		
BLANK	AUXID1	AUXID2	AUXID3	AUXID4	AUXID5	AUXID6	QVM
	0	0	0	0	0	0	1.
	TITLE						
NAME	Fabric						
BLANK	BLANK	HGM	HGW	HGQ	As		
E1option	E1	BLANK	Fb1	Fs1	ALPHA1	BLANK	
E1	1.		1.	1.	45.		
E2option	E2	BLANK	Fb2	Fs2	RFLAG	Alpha2	BLANK
E2	1.		1.	1.	1	-45.	
G_option	LCS		NUEp	ALPHlock	G_lock	Fbm	Fsm	SRFIL
CURVE	1		0.3	0.	0.		
Eta_optn	Eta	BLANK	T				
Eta	0.						
BLANK	thk_elim	thk_mult	thk_cut				
a0	b0	w0	phi	BLANK	ZHI	f	

- Material model, density and element integration type

- Fibres: Elasticity, transverse shear and bending; direction information

- Fabric in plane shear (Parent sheet)

- Viscous data (thermoplastics and pre-pregs)

- Various additional parameters

3   Shear stiffness

As previously described two test methods are available for fabric (intra-ply) shear data; namely, the picture frame and bias extension tests. Both tests could be used to calibrate the PAM-FORM model, but here experimental data from a picture frame test is used. Section 3.1 gives some basic force and geometric relations for the picture frame test followed by typical test data and the calibration methods.

For calibration two picture frame simulation models are used. First a single element test is modelled which allows quick analysis. This single element model can only deform under pure shear, whereas the second model uses a fine mesh that could also be useful to capture potential fabric buckling which does often occur in testing.

For reference the following is input data required for shear information only in material model 140.

CARD 6 Shear Coupling (parent sheet)

Columns	Item	Format	Name	version/option
1-10	Shear modulus of parent sheet = 0: the parent sheet will not be active	E10.0	G	
or	Five blanks followed by keyword **CURVE**	5X,A5		
11-20	Blank	10X		
or	Function number describing the shear curve	I10	LCS	
21-30	Parent sheet Poisson ratio	E10.0	.	
31-40	Locking angle for in-plane shear	E10.0	$._{lock}$	
41-50	Post-locking shear modulus	E10.0	G_{lock}	
51-60	Bending factor of matrix (default 1) (=0.0 if the stiffness bending entering is not equal to zero in CARD 4 and CARD5)	E10.0	F_{bm}	V2011
61-70	Out-of-plane shear factor of matrix (default 1) (=0.0 if the stiffness bending entering is not equal to zero in CARD 4 and CARD5)	E10.0	F_{sm}	V2011
71-80	Filtering coefficient for viscosity shear rate	E10.0	SRFIL	

3.1 Some basic measurements from a picture frame test

The following figure and formulae give basic details and equations for the relationship between applied frame force, displacements (rotations) and fabric shear stress[2].
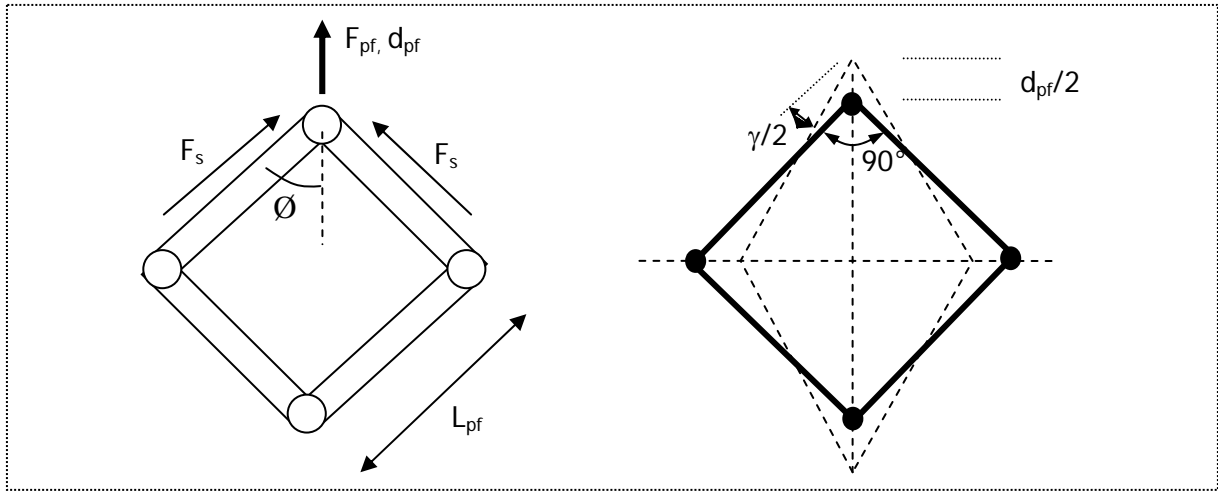
The vertical fabric resistance force F_{PF} measure in the testing machine is balanced by the fabric shear forces F_S,

$$F_S = \frac{F_{PF}}{2\cos\phi}$$

(1)

and fabric shear stress is given by,

$$\tau = \frac{F_S}{L_{PF}c}$$

(2)

where L_{PF} is the length of the picture frame arm and c is the fabric thickness. The fabric shear angle γ is obtained from measure frame angle ϕ using,

$$\gamma = \frac{\pi}{2} - 2\phi$$

(3)

Alternatively, from the frame geometry and measured cross head displacement (d_{PF}) the fibre shear angle is given by,

$$\gamma = \frac{\pi}{2} - 2\cos^{-1}\left[\frac{1}{\sqrt{2}} + \frac{d_{PF}}{2L_{PF}}\right]$$

(4)

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[2] Design and manufacture of textile composites, Ed A.C. Long, CRC Press

3.2 Test data for shear

The following figure shows typical experimental results of picture frame resistance force (F_{PF}) versus displacement (d_{PF}) and is the data used in this document.
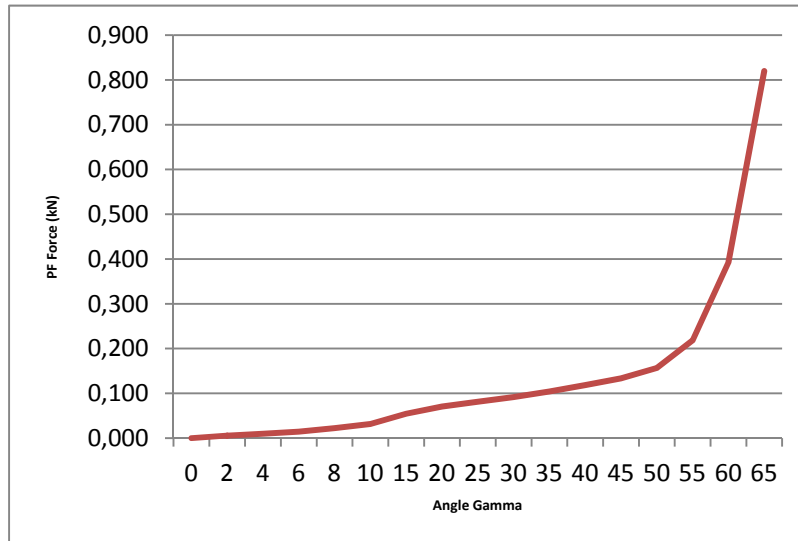
In addition representation of fabric behaviour using material model 140 is best undertaken if the thickness evolution can be reasonably represented. Three possible representations for thickness evolution are possible in PAM-FORM material model 140,

1. Constant thickness.
2. Thickness increase assuming constant volume.
3. Definition of a curve function for thickness versus shear angle.

Generally, impregnated composites have a constant volume behaviour, whereas for dry fabrics under shear the thickness will initially remain constant as inter-tow air voids are filled, followed by thickening once all air is filled. For this calibration a simple (but typical) curve is assumed having constant thickness (=0.5mm) to 30° shear and then a linear increase in thickness to 60° (=1mm thickness). Beyond 60° PAM-FORM will assume linear extrapolation. It is relatively straightforward to measure thickness increase with respect to fabric shear angle and to define a more exact representation.
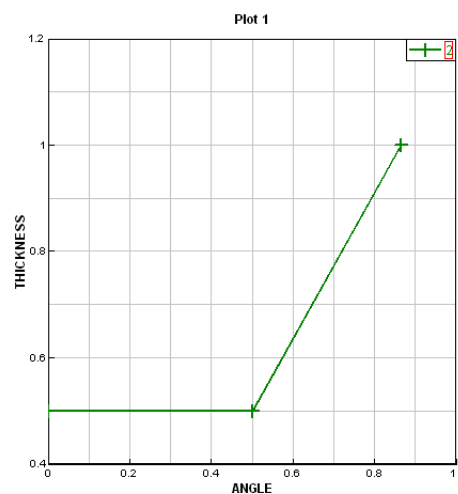
3.3 Calibration of shear for model 140

A simple representation of the picture frame test having a single quadrilateral shell element is first used for calibration against test data. The model is shown inset.

The single quadrilateral shell element (1,2,3,4) has a side element length of 145mm which corresponds to the picture frame test used. Along each side of the shell element one stiff bar element is present. The interconnecting nodes of the bar elements give a hinge.

Velocity loading (or displacement) is applied at node 3 with node 1 being constrained. This arrangement gives the same kinematics as the picture frame apparatus and pure shear is imposed to the shell element.
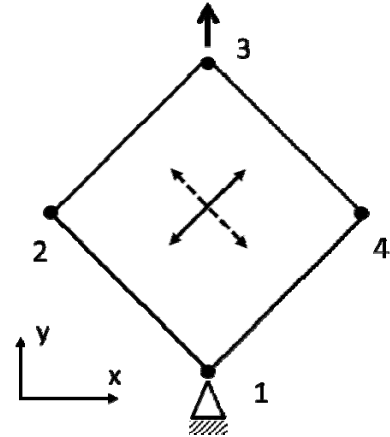
In subsequent sections another shear picture fame model having a fine mesh for the fabric will also be used. This type of model is needed if potential fabric buckling has to be simulated.

The picture frame datasets provided are for a frame having an arm length (L_{PF}) equal to 145mm. It is a simple operation in Visual_Crash PAM to scale these models for different picture frame sizes using the option **Node > Transformation > Scale**.

A simple single element dataset is,

> 145mmFrame_Single_ESI-G3parameters.pc

which can be inspected for loading, boundary conditions and materials definitions using Visual-Crash PAM. In this dataset you will find that the part and fabric material cards define fibre directions to be at ±45° in the x,y plane. Also, fibre axial stiffness is not important under pure shear loading and consequently a low value of 1GPa are assigned (see also the comments in section 4.1). A low density (1e-08 kg/mm^3) is also used to ensure inertia effects do not effect reaction forces. The reaction force to applied loading is recorded as a support section force at the base (node 1).

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3.3.1 The simplified three parameter shear stiffness model

First, a simple three parameter model is available in model 140 to approximate initial low shear stiffness (Ginitial), fibre locking (Gangle) and subsequent higher shear stiffness after locking (Glock). An optimisation tool such as PAM-OPT could be used to adjust the three parameters for a best fit between test and simulation shear behaviour; however, this operation can usually be performed manually by running a picture frame model and adjusting parameters for a good fit.

The following example uses dataset,

145mmFrame_Single_ESI-G3parameters.pc

The result .THP (or .ENF) file is opened with visual and a cross plot of shell element variable fibre angle (Abscissa) is plotted against support section force magnitude (Ordinate).
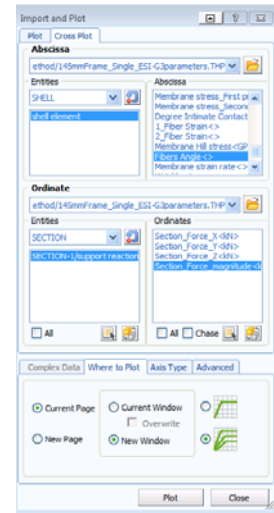
The experimental curve is provided in dataset,

TestCurve_PictureFrame.xyn

This file is opened using File > Open and then plotted using the usual plot curve option. Make sure the tab 'Current Window' is active to overlay the simulation and test plot results.
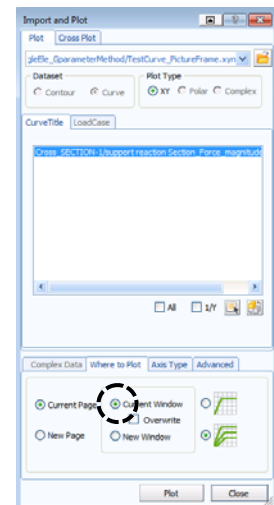
The adjacent plot is obtained for test versus simulation. For this fit the three parameters found are,

Ginitial   = 0.0007 GPa
Gangle   = 40°
G_lock   = 0.0015 GPa
with Poisson's ratio set to 0.3
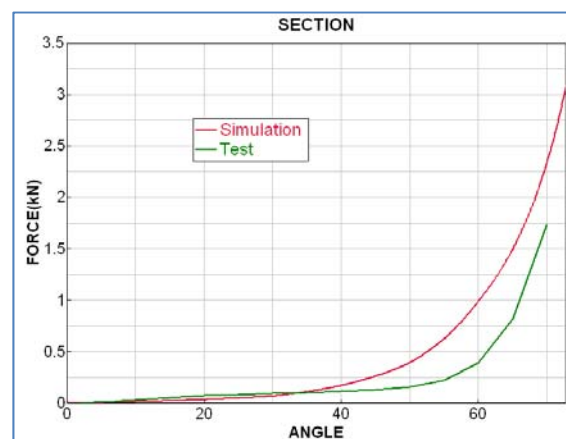
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For many applications this correlation may be acceptable. Further improvements might be possible, but generally it is difficult (or impossible) to get a very accurate fit. For a more accurate fit the following method using a curve function for shear modulus should be used.

3.3.2 The curve function shear stiffness model

It is a non-trivial task to convert picture frame shear force and shear angle data to shear stiffness information for PAM-FORM. Initially fibre angles are orthogonal (90°) to each other and shear stress is given by equation 2. However, as fibres rotate transformations are become necessary to compute fabric stresses from imposed frame loadings. Consequently, ESI have developed an analytical method to estimate fabric shear stiffness as a function of frame displacements (angles).

The analytical solution equates external applied energy to internal fabric energy. Computations are performed in a principle frame to avoid complex transformations. This analytical method is an approximation and cannot properly include important effects of fabric thickness changes with shear; never-the-less it does provide a valuable estimate for shear stiffness versus shear angle that can be further calibrated if necessary. An Excel VBA program of this analytical method is provided in the file,

ShearCalibration_ESIMethod.xlsm

Start the dataset with Excel. If changes are made and the program has to be run then it is first necessary to deactivate the macros as shown below. The required input is force and displacement test data for the picture frame (in orange) and additional information in green for length of the picture frame arms, initial fabric thickness and Poison's ratio (recommended default = 0.3). The parameter 'No Lines' is the last Excel line number of the data points. In this worksheet standard excel operations compute frame angles Gamma from equation 4.
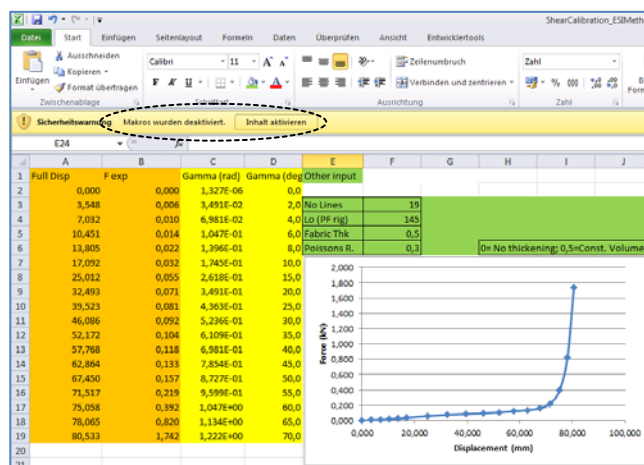

The alt+F11 keys open the VBA code which can be visualised as shown below. Run the program by clicking the green triangle key shown.
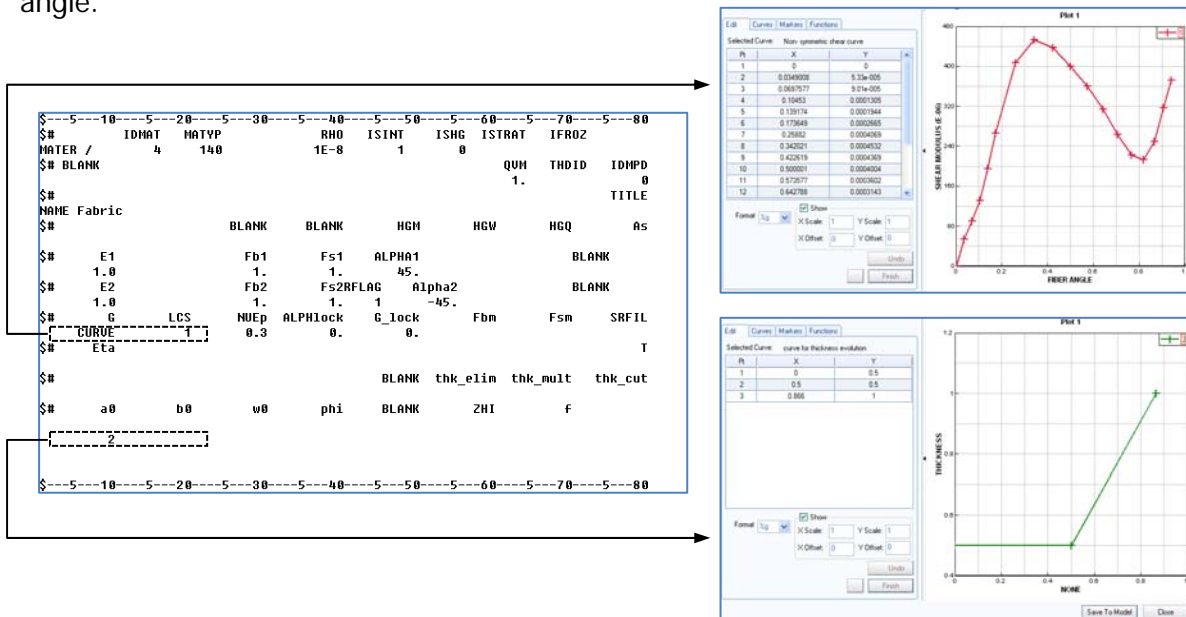
11

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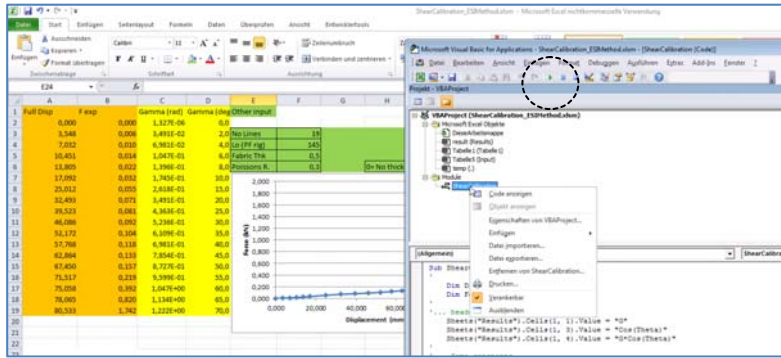
New results are provided in the 'results' worksheet. The required curve function for PAM-FORM material model 140 is the data Cos(Theta) versus G*Cos(Theta) which is in yellow and shown graphically. This data must be 'cut and paste' into the PAM-FORM dataset and formats modified so it can be used as a curve function with material model 140.
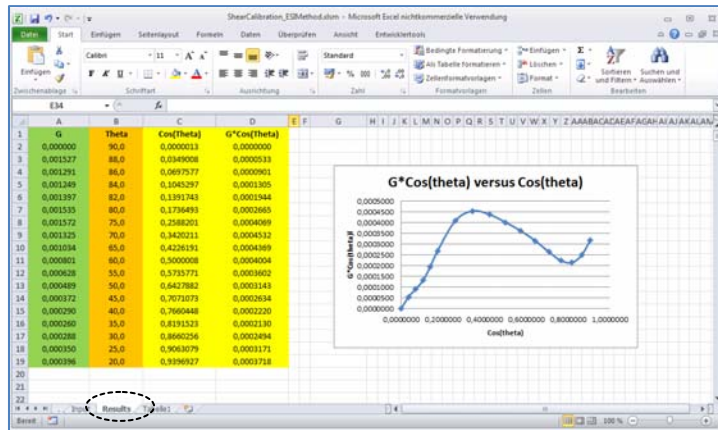

The input material model data is shown below with curve functions defined for shear stiffness (Cos(Theta) versus G*Cos(Theta)) and thickness evolution as a function of shear angle.


```
$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
$#      IDMAT   MATYP           RHO    ISINT   ISHG ISTRAT   IFROZ
MATER /     4     140           1E-8       1       0
$# BLANK                                             QVM    THDID   IDMPD
                                                     1.                  0
$#                                                                    TITLE
NAME Fabric
$#              BLANK    BLANK      HGM      HGW      HGQ      As

$#     E1         Fb1      Fs1   ALPHA1            BLANK
       1.0        1.       1.      45.
$#     E2         Fb2 Fs2RFLAG   Alpha2            BLANK
       1.0        1.       1.      -45.
$#      G    LCS     NUEp ALPHlock   G_lock      Fbm      Fsm    SRFIL
      CURVE    1      0.3      0.       0.
$#    Eta                                                             T

$#                             BLANK thk_elim thk_mult  thk_cut

$#     a0       b0       w0      phi    BLANK      ZHI        f

          2

$---5---10----5---20----5---30----5---40----5---50----5---60----5---70----5---80
```

Composite model 140 for draping simulation

The result .THP (or .ERF) file is opened with Visual-Viewer. A comparison of element fabric shear angle versus support reaction force is obtained and compared with the test curve (TestCurve_PictureFrame.xyn). This shows a good agreement up to about 60°. The latter portion could easily be improved by calibration of input force data in the Excel (.xlms) calibration file to obtain a modified shear stiffness curve.
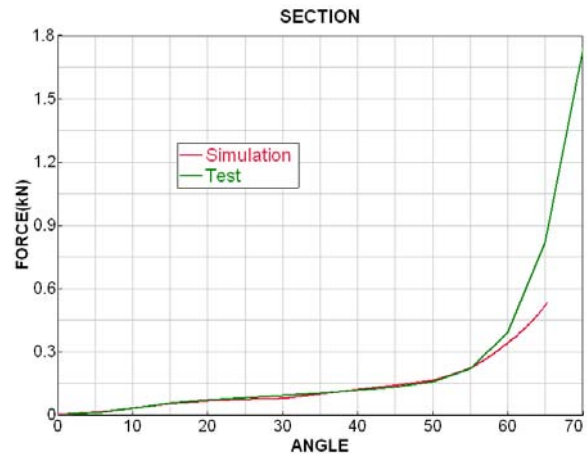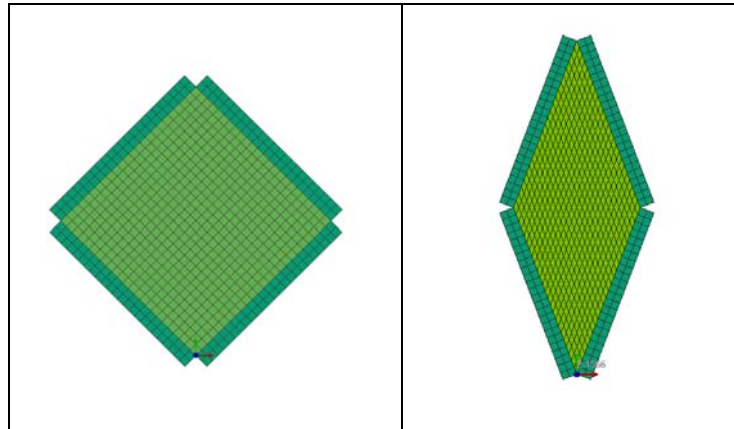

3.4 A fine model of the picture frame shear test

A fine meshed model of the picture frame test is provided in dataset,

145mmFrame_Fine_ESI-Gcurve.pc

This model has the same dimensions as the single element model, but now has a regular fine mesh for the fabric and a stiff frame of elastic shell elements.

The nodes at the frame-to-fabric connections have identical coordinates and are joined using nodal constraints (Type 7) giving common translations with free rotations and thus enforcing a hinge condition at the connection points. The uppermost intersection nodes have a velocity load imposed and the lowermost intersection nodes are fully fixed and also defined as a support section output for reaction force information. Finally, the frame is constrained out-of-plane and the fabric is given identical material properties and fibre orientations to the previous single element model.

Three elements in the fabric are specified for time history output. From the results .THP (or .ERF) file in Visual-Viewer the adjacent graph of fibre angle time histories for the three elements is obtained. The three curves show identical results and therefore there is uniform shear distribution within the fabric.

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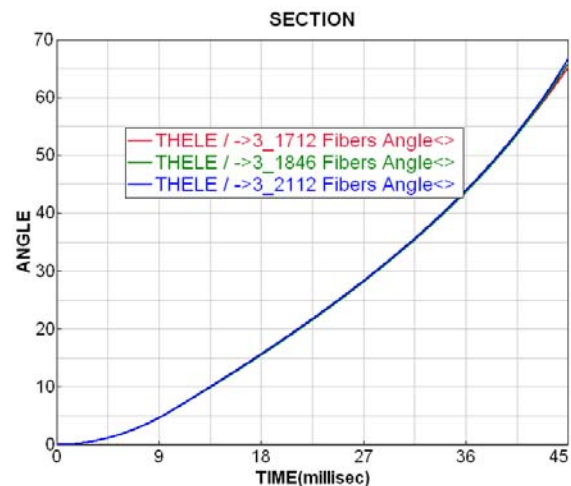
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A comparison of fabric shear angle for one element versus support reaction force and the test curve (TestCurve_PictureFrame.xyn) shows there is a good comparison up to about 60°.

As previously mentioned for the single element case the correlation of test and simulation shear force beyond circa 55° could be improved with some calibration of force data in the .xlms calibration file.
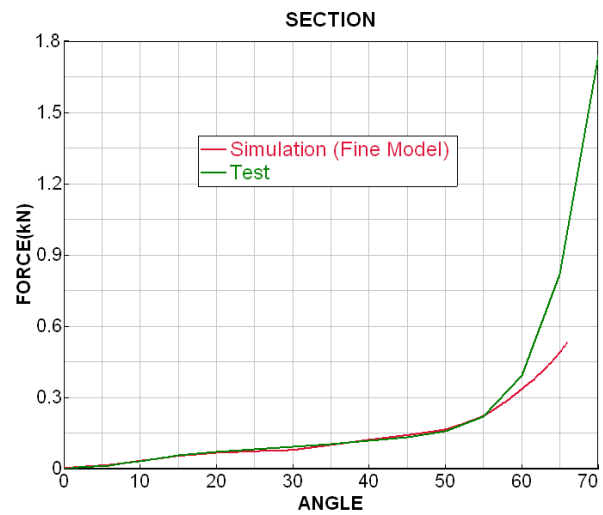
4 In plane fibre reinforcement: Stiffness and bending

The following information is required input data for fibre direction 2. Essentially the same input is required for direction 1. This information mainly concerns axial fibre stiffness, which may be a constant or non-linear curve function and parameters for transverse shear and bending stiffness. Also, information on fibre angles must be specified which are with respect to a reference vector defined on the associated parts cards.

CARD 5 Elastic Properties in Direction 2 (transverse)

| Columns	Item	Format	Name	version/option
1-10	Young's modulus in direction 2	E10.0	E_2	
or	Five blanks followed by keyword **CURVE**	5X,A5		
11-20	Blank	10X		
or	Function number describing the stress/strain curve in direction 2	I10	LC2	
21-30	(1) Bending factor of direction 2 (default 1)	E10.0	F_{b2}	
or or	(2) keyword **STIF_CONST** (3) keyword **STIF_CURVE**	A10		v2011
31-40	Out-of-plane shear factor of direction 2 (default -1)	E10.0	F_{s2}	
41-45	Reinforcement architecture type: = 0: unidirectional reinforcement = 1: two directions reinforcement material	I5	flag	
46-55	Angle to define fiber direction 2 from the reference direction (reference direction is given in PART section)	E10.0	$\cdot_2$	
56-65	Bending Stiffness in direction 2	E10.0	B_2	v2011
or	Function number describing the Moment/curvature curve in direction 2	I10	LCB2	v2011
66-80	Blank	15X		

4.1 Fibre stiffness

Typical stiffness for carbon fibres is 230GPa and Glass 74GPa. However, in practical draping simulation the fabric shear stiffness is several (3-5) orders of magnitude lower and fabric deformations will predominantly occur via shear mechanisms. It is therefore usually realistic to lower the fabric in plane stiff considerably (e.g. 1-10GPa) without affecting results. This has the important benefit that a more economical timestep is possible in the explicit scheme.

Exceptions may be if the low stiffness effects of fibre crimp or low stiffness stitch reinforcements are to be modeled. In these cases a curve function of stiffness versus strain

is possible. Furthermore, if needed the stiffness curve function can have negative modulus to capture the effects of reinforcement failure.

4.2 Bending stiffness

The following simple calibration and validation example demonstrates calculation of fabric bending stiffness for a fabric. A typical test involves measuring the deflection for various overhang lengths. The applied loading if fabric self weight. From such a test the following example deflection-overhang curve is obtained. In this case the response is initially stiff, followed by a roughly linear behaviour after an overhang length of approximately 80mm.
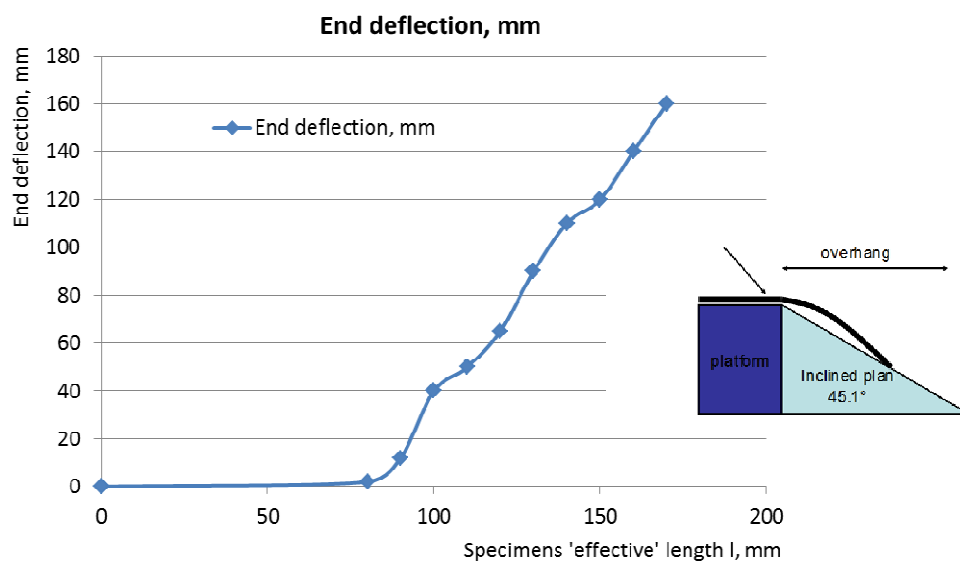
Three methods to define bending stiffness are possible in materials model 140; namely, a calibration factor, a curve function or a constant bending stiffness that is decoupled from in plane stiffness. The following illustrates the later method.

From the experimental curve the required bending stiffness (E) should give, for example, 40mm deflection at 100mm overhang length. The classical analytical formula for load versus deflection for this test setup (= uniformly loaded cantilever beam) is shown below. Note this examples uses a fabric that is slightly different to the previous picture frame fabric.

$q = \dfrac{\text{self weight (= g * mass)}}{L}$

$\delta = qL^4 / (8EI)$
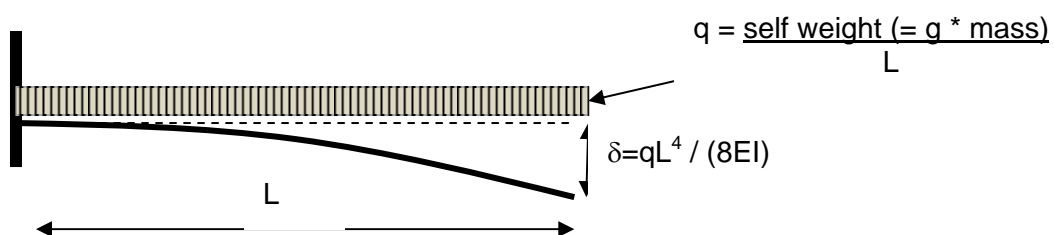
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For 1 ply of the fabric the test dimensions are:

Thickness = 0.25mm,

B = width = 25mm

L = overhang length = 100mm

Density = 1.4E-06 kg/mm^3

The bending inertia is,

$$I = b * d^3 / 12 = 25.0 * 0.25^3 / 12 = 0.0325 \text{ mm}^4$$

The total applied load = Mass * Gravity = 1.4 E-06 *(0.25 * 25.0 * 100) * 0.00981 kN

= 8.58 E-06 kN

q = Total applied load / L = 8.58 E-06 / 100.0 = 8.58 E-08 kN/mm

For the test the measured deflection is 40mm (at 100 mm overhang),

From $\delta = qL^4 / (8EI)$,

gives $E = q L^4 / (8 I \delta)$ = 8.58 E-08 * 100^4 / (8 * 0.0325 *40)

= 0.825 kN/mm^2

The following table gives end deflection for various overhang lengths using the analytical formulae (with the calibrated bending stiffness **E=0.825 kN/mm2**). Also included are test and FE simulation results. The FE datasets are provided which have various overhang lengths and use the estimated bending stiffness:

BendTest_50mmOverhang.pc

BendTest_75mmOverhang.pc

BendTest_100mmOverhang.pc

BendTest_125mmOverhang.pc

BendTest_150mmOverhang.pc

Overhang (mm)	End deflection (mm)		
	Analytical (E = 0.825kN/mm2)	Simulation	Test
50	2.5	2.6	2
75	12.6	13	2
100	40	36	40
125	98	69	70
150	202	109	120

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Following analysis the .THP (or .ERF) results files are read into Visual-Viewer and the graph below for end tip deflection for the different overhang lengths (50, 75, 100, 125 and 150mm) can be obtained. Note that these datasets use nodal damping to achieve a quasi-static solution.
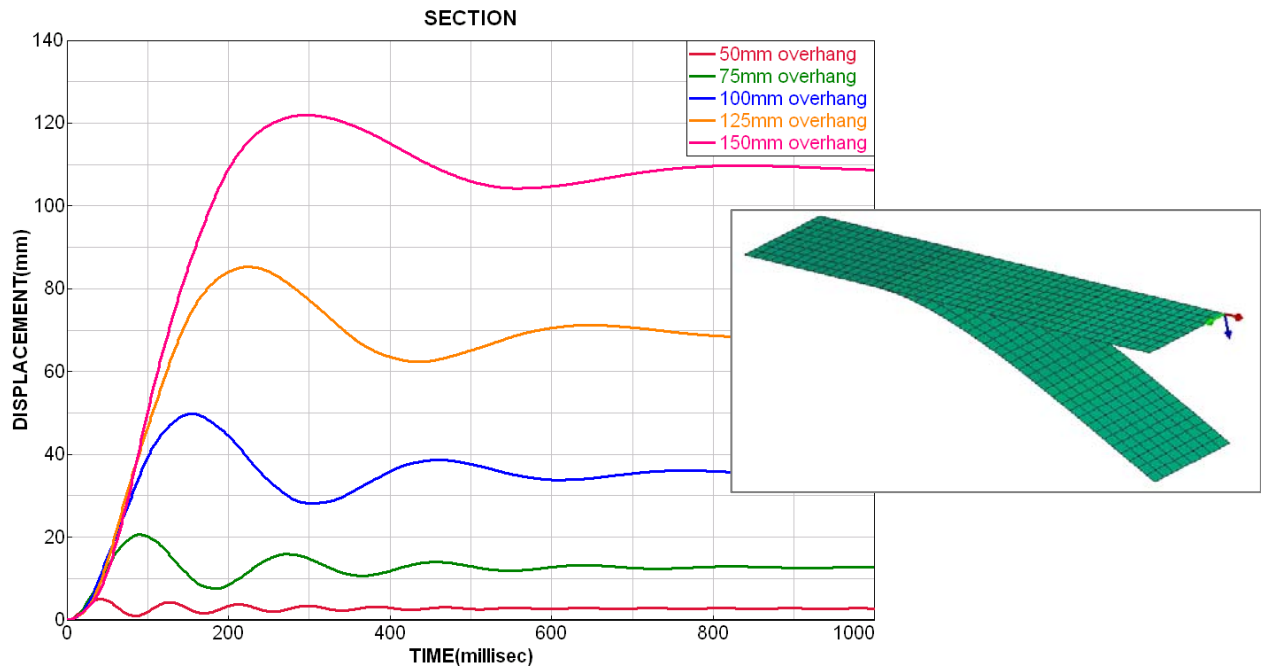
The following graph compares test measurements with analytical and simulation results. The FE results agree well with test, whereas analytical results are poor for large deflections. This is probably due to the method being limited to small displacements.
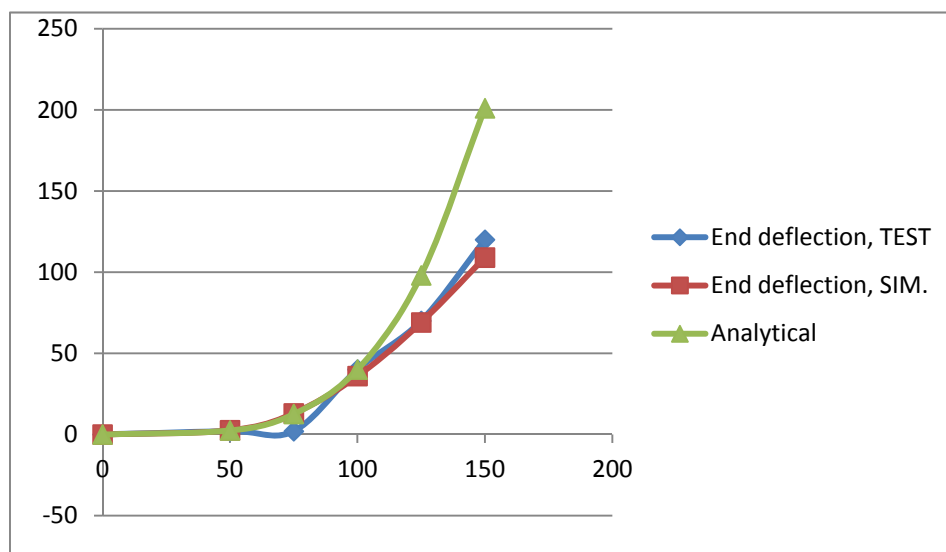
5 Some other parameters

Model 140 does contain some other useful options, for example:

- The fabric thickness can be modified according to different assumptions,

    1. It may be assumed to be constant (= initial value)

    2. It may be updated assuming a constant volume assumption. This is appropriate for rein impregnated composites such as pre-pregs, or thermoplastics.

    3. The thickness may be updated using a curve function of thickness versus shear angle obtained from experiments. This method is used in this document.

- Most fabrics have symmetric shear behavior and the shear stiffness representations shown previously are appropriate. For these fabrics shear resistance is the same for both positive shear strains and negative shear strains.

    However, some fabrics such as Non Crimp Fabrics with Tricot stitching have a non-symmetric shear behavior. This can be represented via a full shear stiffness curve covering both negative and positive shear strains. The fibre orientations must be carefully defined.

- The contribution of viscous effects for impregnated resins can be added.

6 The fine modelled picture frame with bending stiffness and fabric buckling

The shear picture frames so far analysed did not show signs of in plane fabric buckling. For the single element model buckling this is not kinematically possible, but for the fine meshed picture frame this should be possible. The following example combines calibrated shear stiffness data and calibrated bending stiffness data into the fine mesh picture frame model.

This dataset, if created and run, will generally not show fabric buckling although it may occur in practice. This is due to the relatively fast loading of the frame which does not allow buckling to initiate and the perfectly flat fabric finite element geometry. A simple method to help initiate bucking is the provide an initial imperfection. This is done in the following dataset where the fabric central node is displaced 1mm in the z-direction.

145mmFrame_Fine_ESI-GcurveBendingBuckling.pc

Example results for deformations are available from the .DSY (or .ERF) file using Visual-Viewer. The initial imperfection will now initiated fabric buckling. The shape and wavelength of this buckling should reasonably correspond to physical tests.
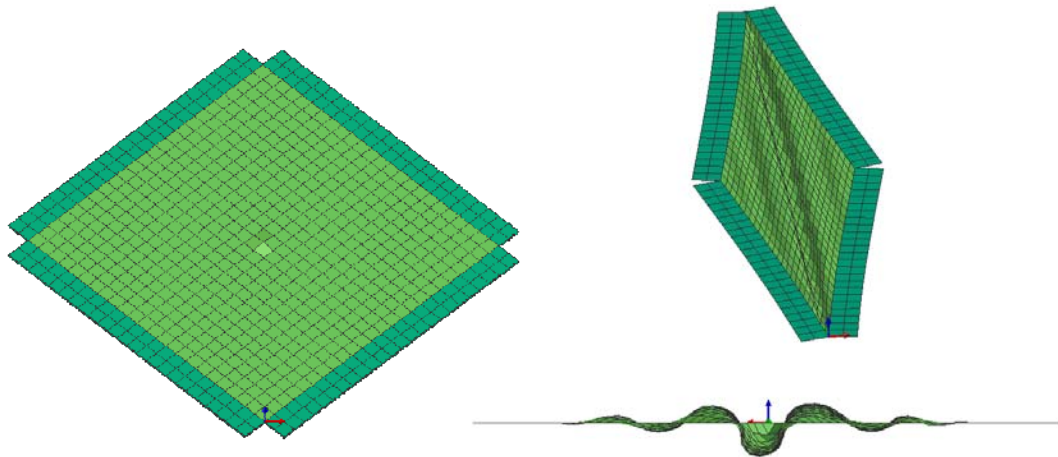
From the .THP (or .ERF) file using Visual-Viewer a plot of fabric shear angle versus resistance force is produced. The inset graph compares these new results with the previous model results where buckling does not occur. The two models show identical results to about 30° then start the differ due to buckling.

It is important to note that the calibration test shear data may be from a test having fabric buckling, in which case it may be necessary to include this effect in the calibration process.

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