Modelling Composite Materials: Introduction to ESAComp

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CERN EP-DT-EO

LBNL Composites Workshop

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Main topics of the ESAComp introduction

- Esacomp as a conceptual design tool. From the micro-mechanics to analytical and FEA more powerful tool.

- Some good basic functionalities of the program:
  - A good Data Bank of composite material data to start with
  - Intuitive ply and laminate creation with friendly UI
  - Fundamental laminate design and analysis
  - Some example of plate analysis
  - Integration with other FEA tools (ie Ansys APDL and ACP)

- What is not covered here is micro-mechanics

- More advanced options will not be shown here and we point to the EsaComp website for material download, webinars, ets. A specific presentation by Harri Katajisto is also added to the WS material.

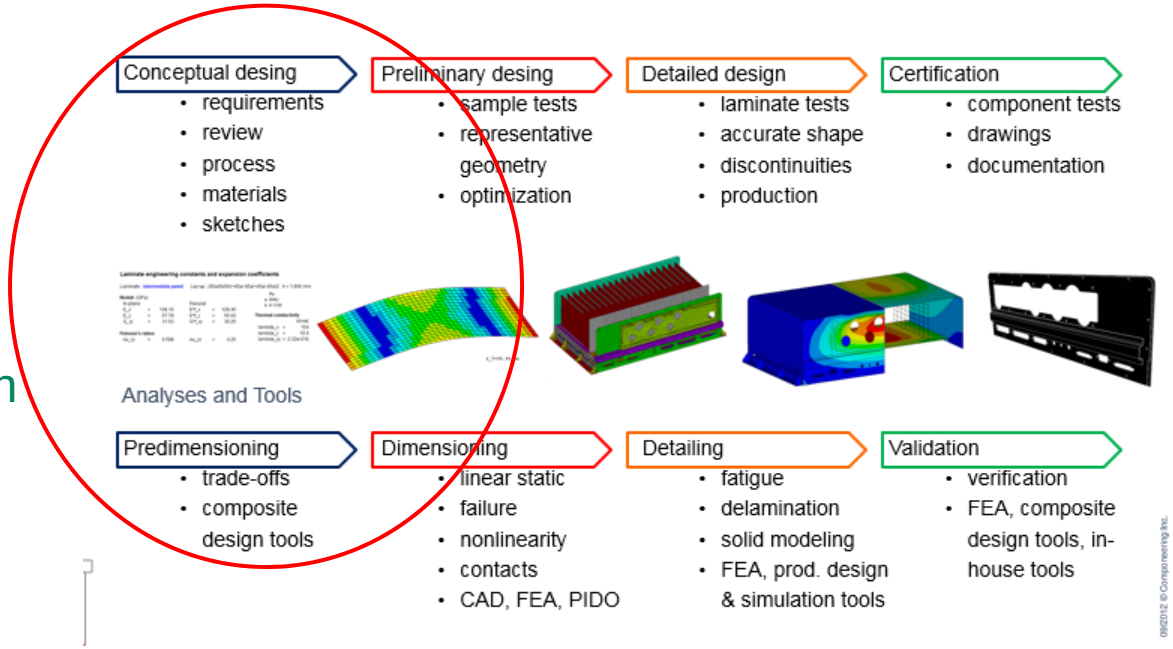
ESAComp and COMPONEERING Inc.

- ESAComp development was initiated by the European Space Agency (ESA)
  - Goal to establish industry standard laminate analysis software to replace in-house tools
  - ESAComp 1.0 was released in 1998
- Developed by Componeering
  - Helsinki, Finland based company

COMPONEERING Inc.

ESAComp Shortly

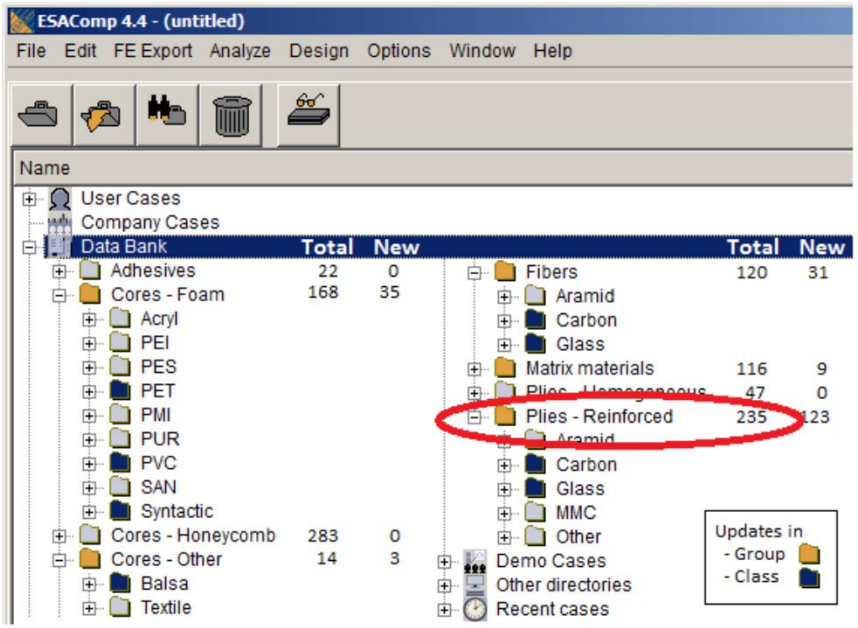
- **A toolbox for composite designers and analysts**
- **Conceptual design**
- Common analyses cover:
  - Laminates analysis
  - Linear static stress/strain prediction,
  - Nonlinearity, buckling
  - Failure of laminates and shell structures

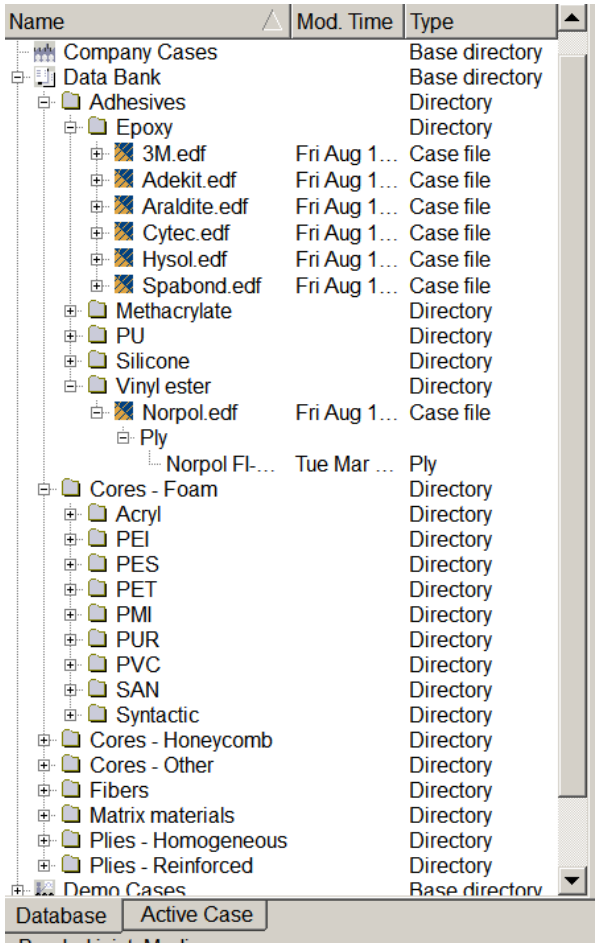


https://indico.desy.de/contributionDisplay.py?sessionId=3&contribId=11&confId=6112

ESAComp Material Data Bank

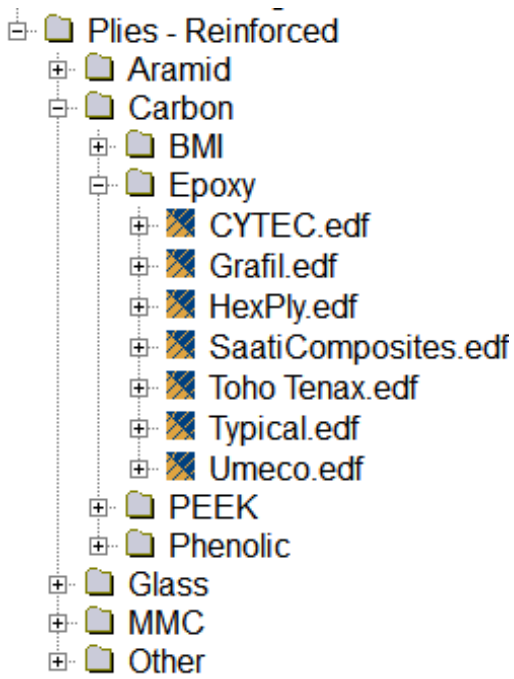
- Updated database of 1000+ material within ESAComp
- Types of materials:
  - Fibers
  - Matrix materials
  - Reinforced plies
  - Core materials
  - Adhesives
  - Homogeneous materials (e.g. metals)

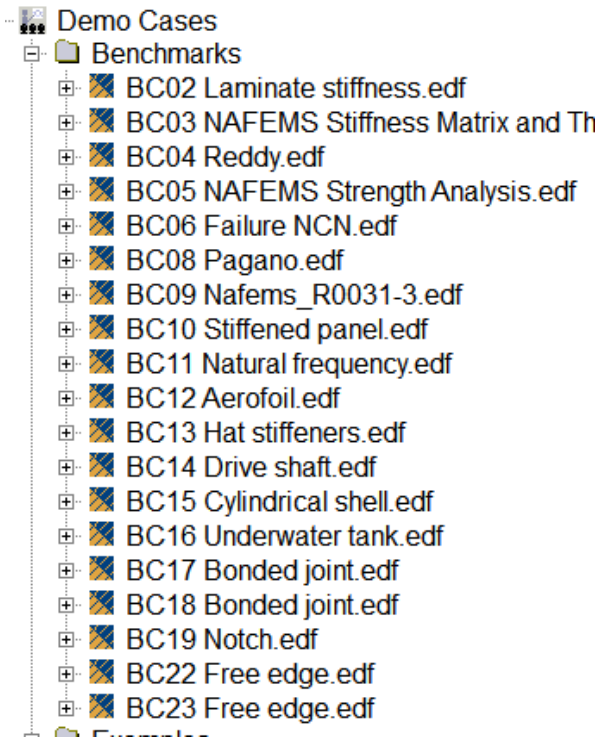


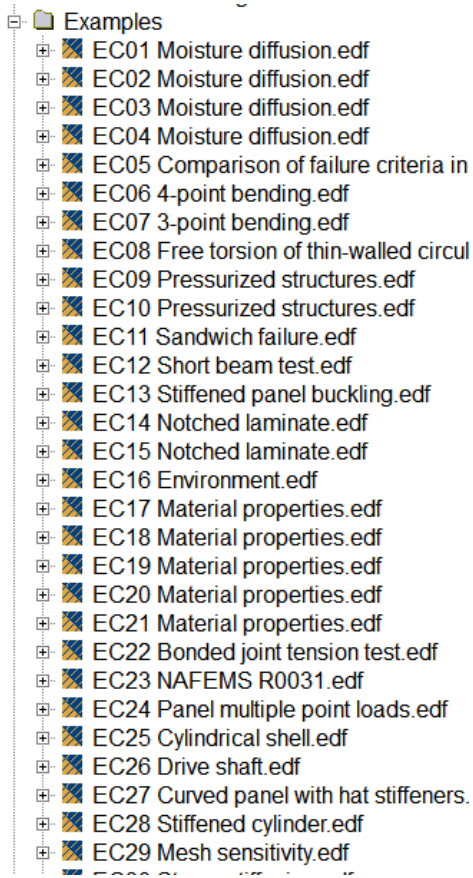


ESAComp Material Data Bank

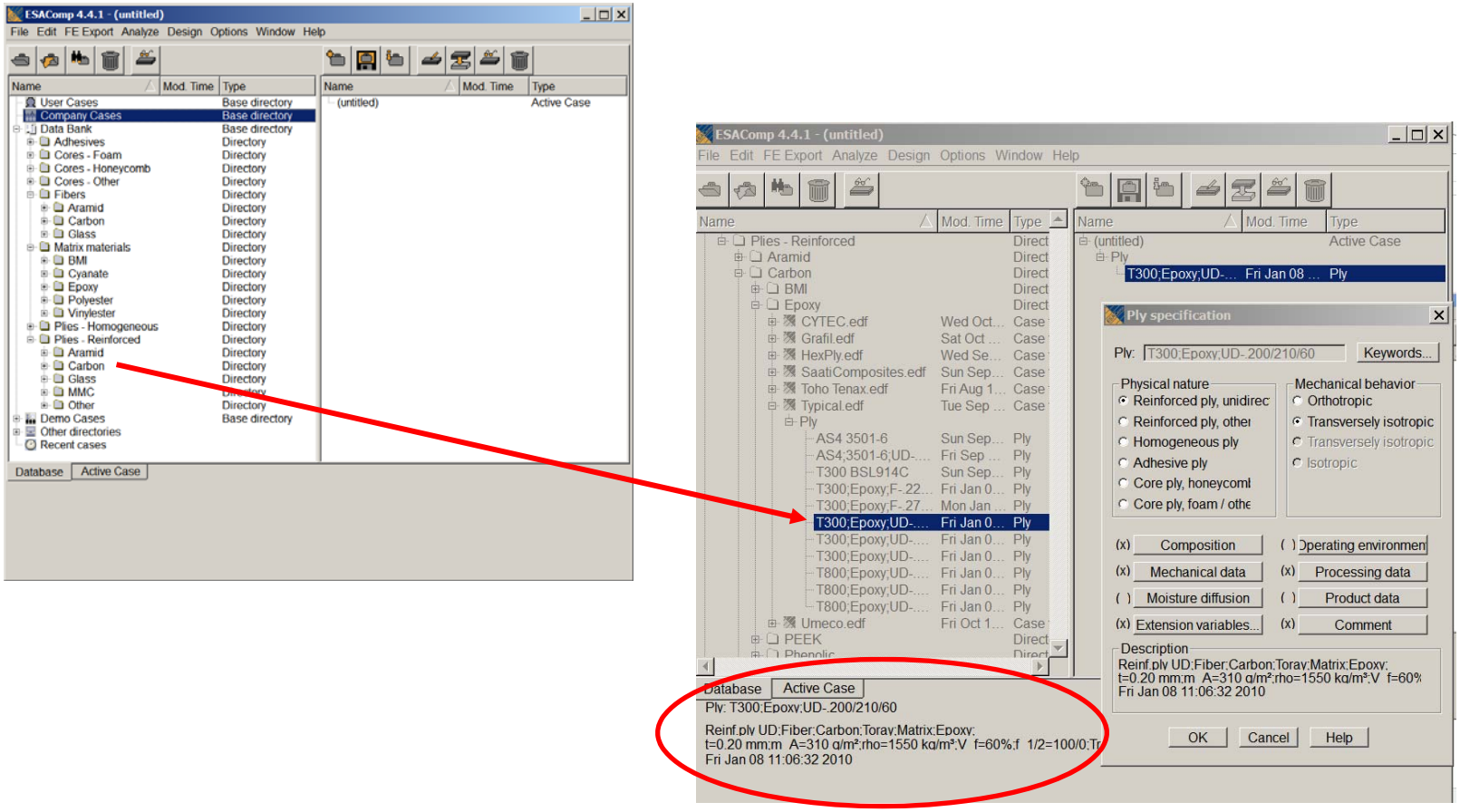
- About **fifty reinforced ply** material systems with statistical test data.
- The information has been extracted from **Advanced General Aviation Transport Experiments (AGATE) and MIL-HDBK-17-2F** material databases.







How to Select (or Create) a Ply



Ply Properties

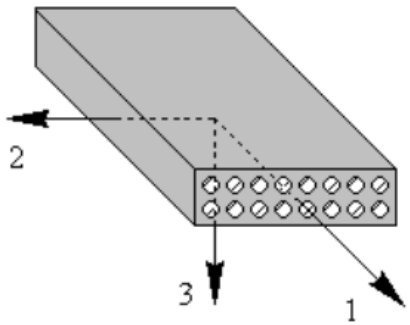
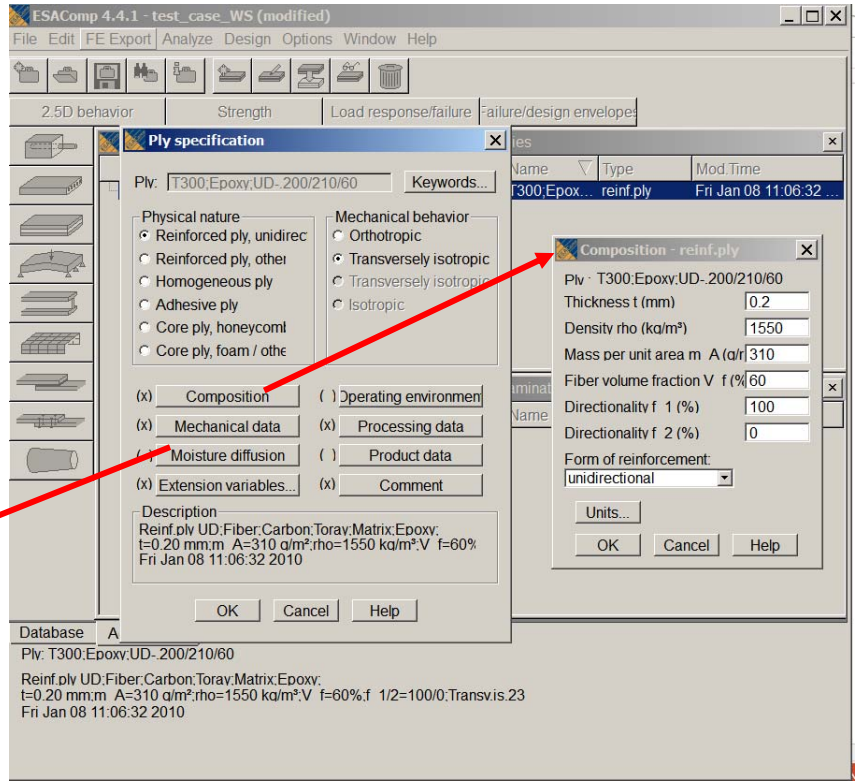
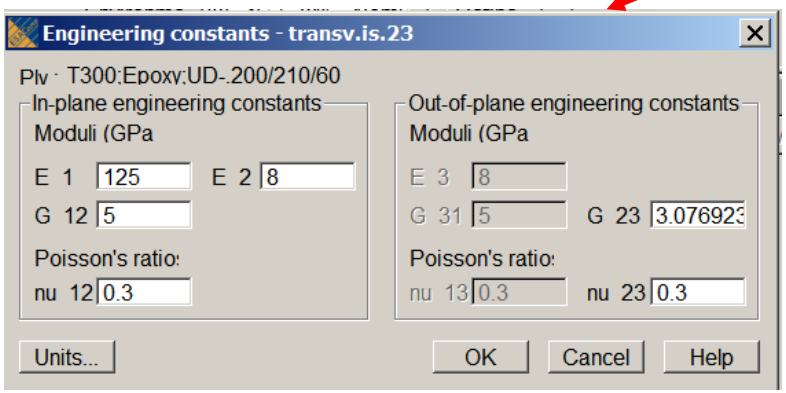


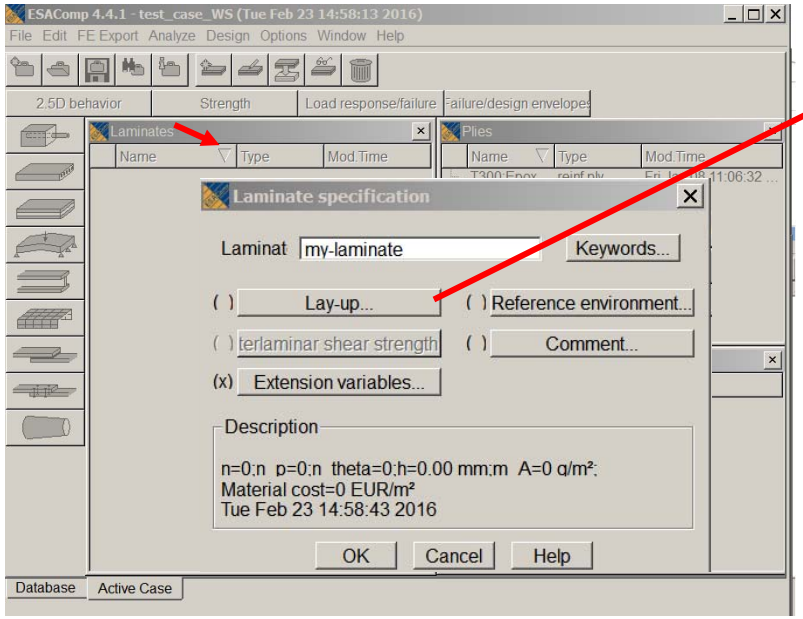
Figure 4.2 Principal coordinate system 123 for plies.

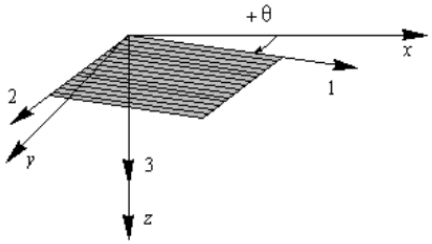


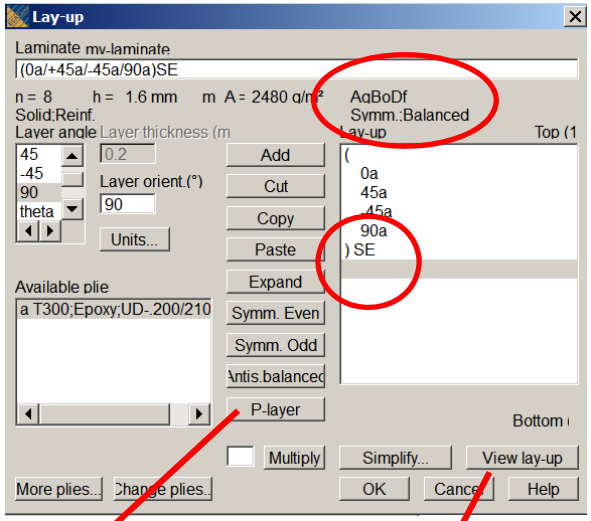
CPT



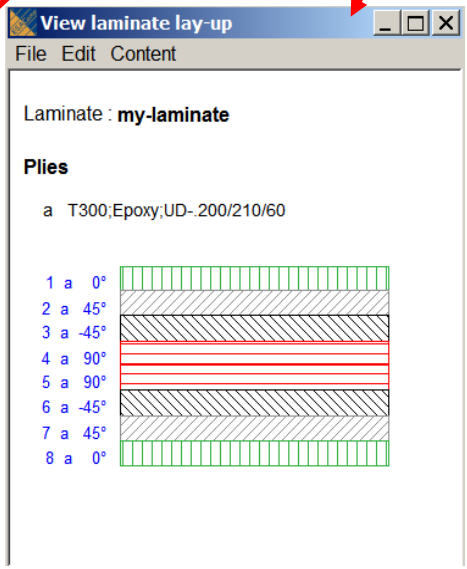
From Ply to Laminate



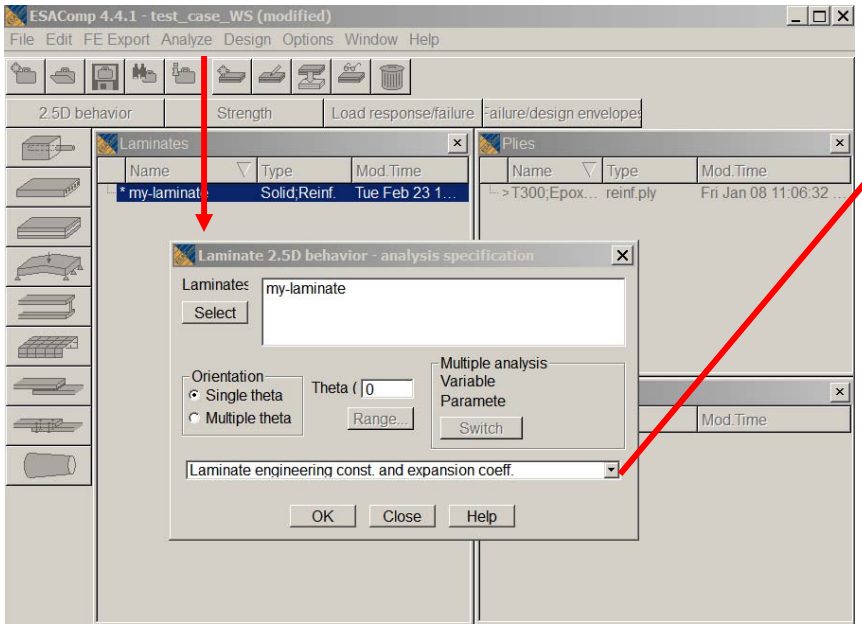


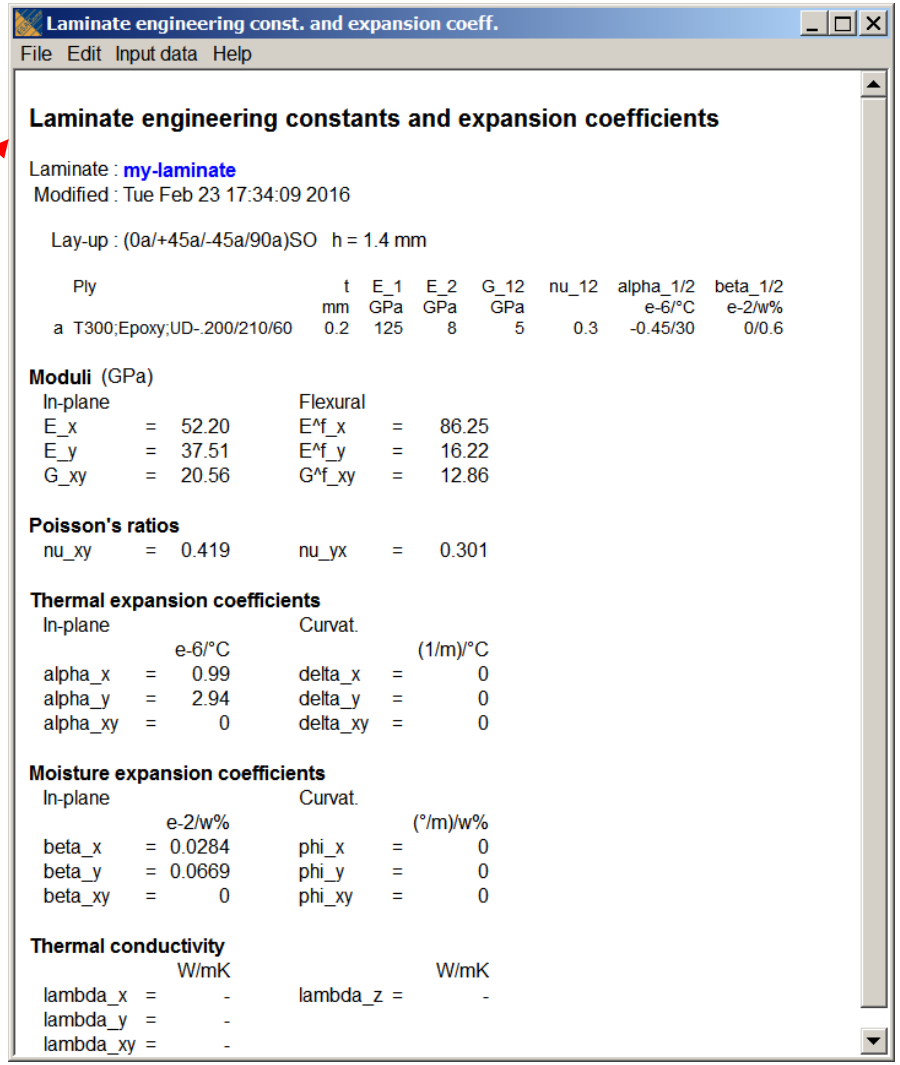


P-layer: a laminate in which the thickness proportion of the selected p-layer(s) is varied in the analyses.



Lay-up Engineering Constants





Laminate engineering const. and expansion coeff.

File Edit Input data Help

Laminate engineering constants and expansion coefficients

Laminate : **my-laminate**
Modified : Tue Feb 23 17:34:09 2016

Lay-up : (0a/+45a/-45a/90a)SO h = 1.4 mm

	Ply	t mm	E_1 GPa	E_2 GPa	G_12 GPa	nu_12	alpha_1/2 e-6/°C	beta_1/2 e-2/w%
a	T300;Epoxy;UD-.200/210/60	0.2	125	8	5	0.3	-0.45/30	0/0.6

Moduli (GPa)

In-plane			Flexural		
E_x	=	52.20	E^f_x	=	86.25
E_y	=	37.51	E^f_y	=	16.22
G_xy	=	20.56	G^f_xy	=	12.86

Poisson's ratios

nu_xy	=	0.419	nu_yx	=	0.301

Thermal expansion coefficients

In-plane		e-6/°C	Curvat.		(1/m)/°C
alpha_x	=	0.99	delta_x	=	0
alpha_y	=	2.94	delta_y	=	0
alpha_xy	=	0	delta_xy	=	0

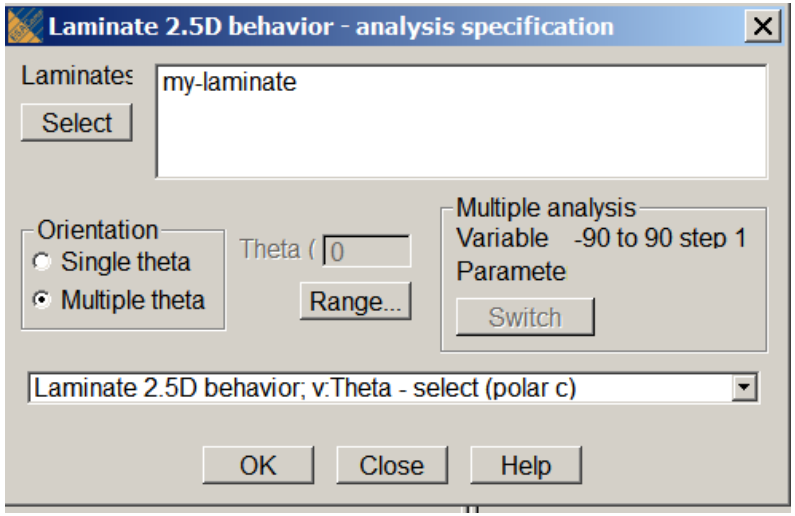
Moisture expansion coefficients

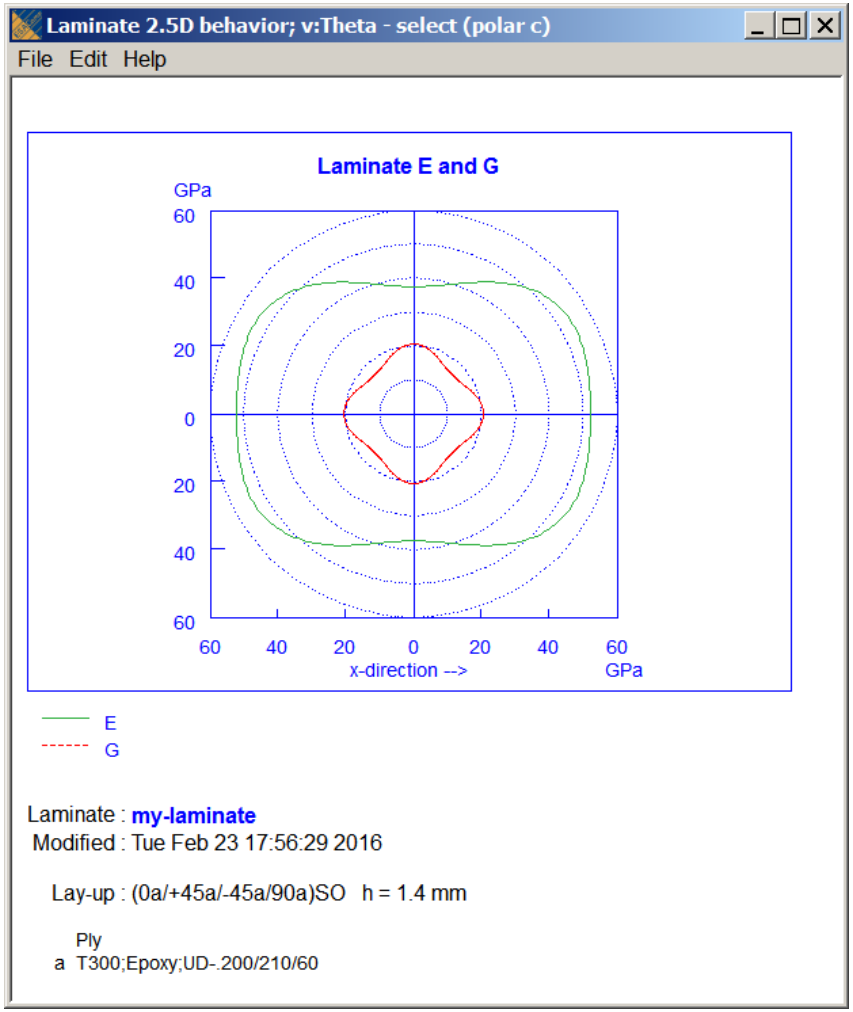
In-plane		e-2/w%	Curvat.		(°/m)/w%
beta_x	=	0.0284	phi_x	=	0
beta_y	=	0.0669	phi_y	=	0
beta_xy	=	0	phi_xy	=	0

Thermal conductivity

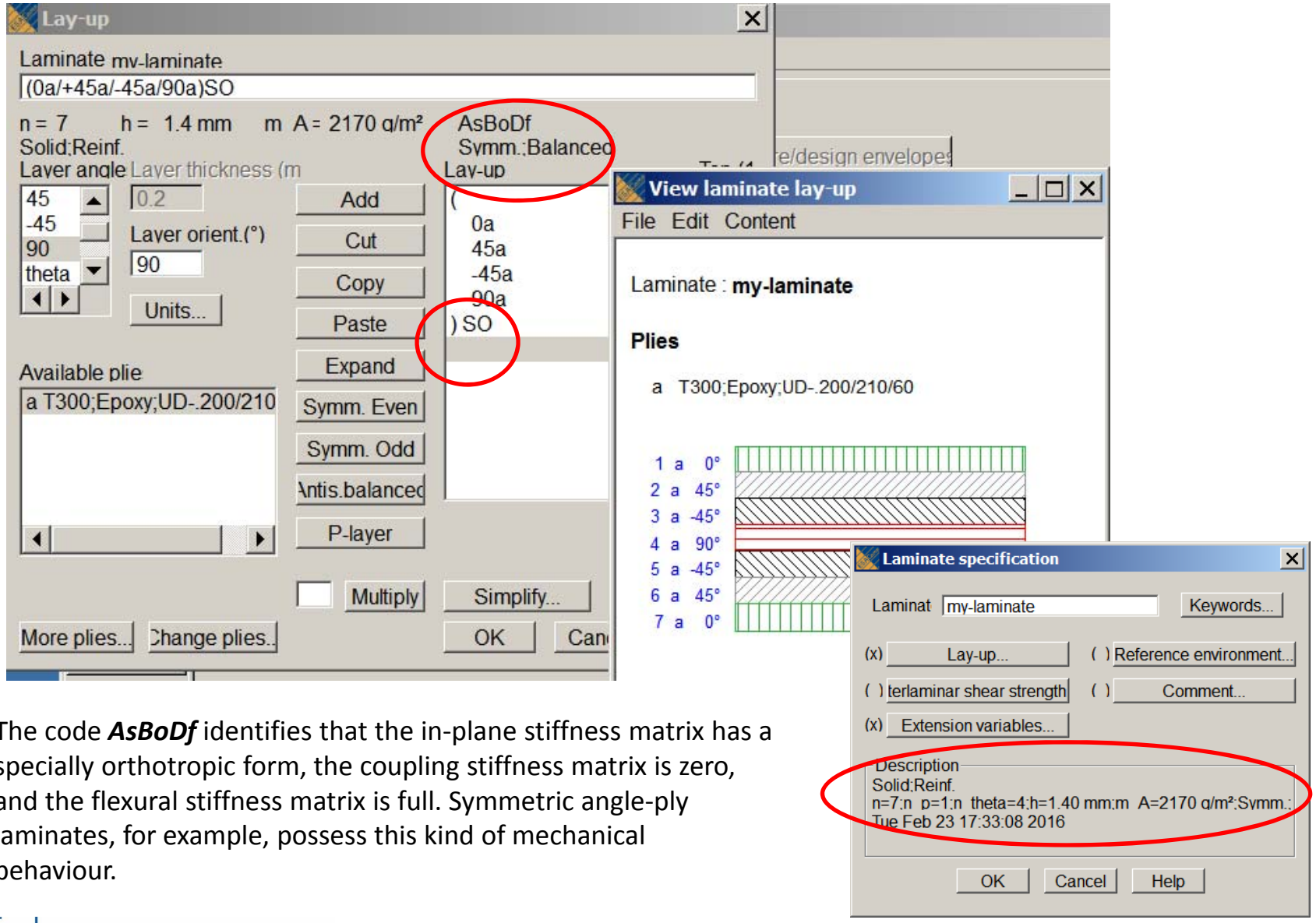
		W/mK			W/mK
lambda_x	=	-	lambda_z	=	-
lambda_y	=	-			
lambda_xy	=	-			

Lay-up Ply Polar Charts





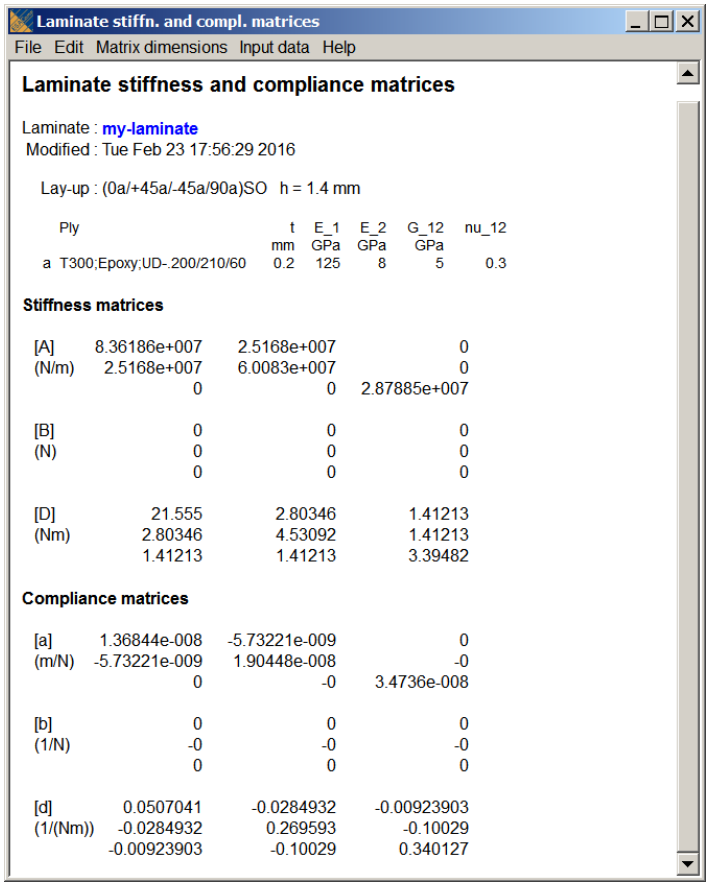
Lay-up Code



The code ***AsBoDf*** identifies that the in-plane stiffness matrix has a specially orthotropic form, the coupling stiffness matrix is zero, and the flexural stiffness matrix is full. Symmetric angle-ply laminates, for example, possess this kind of mechanical behaviour.

Symmetric and Balanced Laminate

- B matrix is zero if you have a **symmetric laminate**.
- A16 and A26 terms (**the in-plane normal shear coupling terms)** are zero then you have a **balanced laminate**.



Laminate stiffn. and compl. matrices

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Laminate stiffness and compliance matrices

Laminate : my-laminate
Modified : Tue Feb 23 17:56:29 2016

Lay-up : (0a/+45a/-45a/90a)SO h = 1.4 mm

Ply	t mm	E_1 GPa	E_2 GPa	G_12 GPa	nu_12
a T300;Epoxy;UD-.200/210/60	0.2	125	8	5	0.3

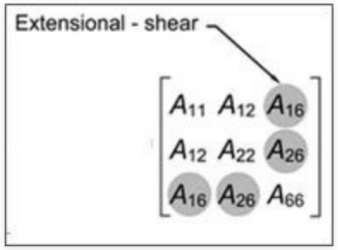
Stiffness matrices

[A]	8.36186e+007	2.5168e+007	0
(N/m)	2.5168e+007	6.0083e+007	0
	0	0	2.87885e+007
[B]	0	0	0
(N)	0	0	0
	0	0	0
[D]	21.555	2.80346	1.41213
(Nm)	2.80346	4.53092	1.41213
	1.41213	1.41213	3.39482

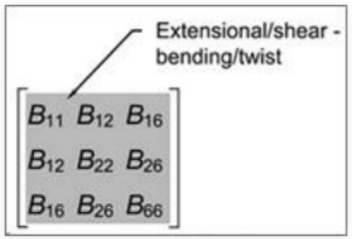
Compliance matrices

[a]	1.36844e-008	-5.73221e-009	0
(m/N)	-5.73221e-009	1.90448e-008	-0
	0	-0	3.4736e-008
[b]	0	0	0
(1/N)	-0	-0	-0
	0	0	0
[d]	0.0507041	-0.0284932	-0.00923903
(1/(Nm))	-0.0284932	0.269593	-0.10029
	-0.00923903	-0.10029	0.340127

A-Terms: characterizes the extension stiffness of a laminate



B-Terms: characterizes the coupling stiffness of a laminate



D-Terms: characterizes the bending stiffness of a laminate

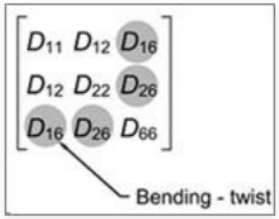


Figure 1: A16 term illustration

Figure 2: B12 term illustration

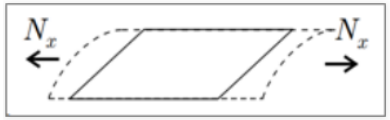


Figure 3: B16 term illustration

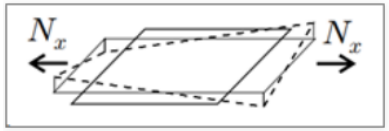


Figure 4: B66 term illustration

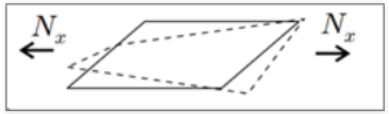
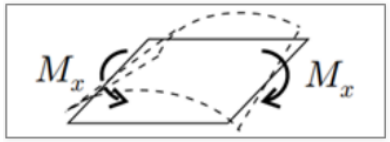
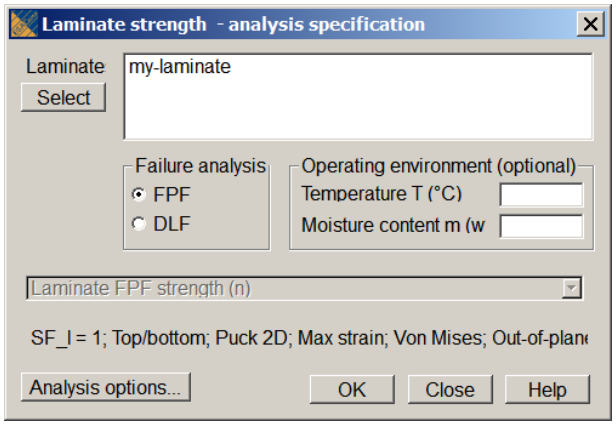
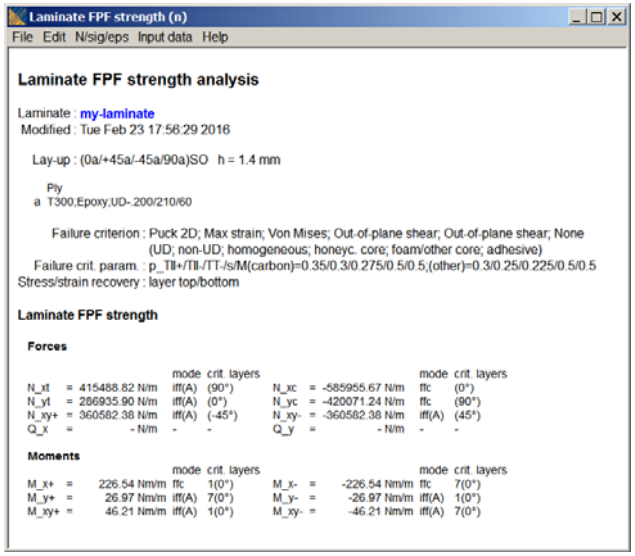


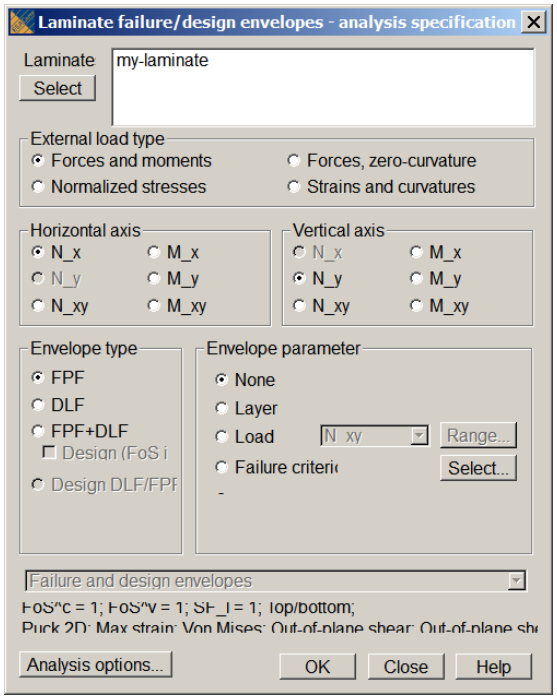
Figure 5: D16 term illustration

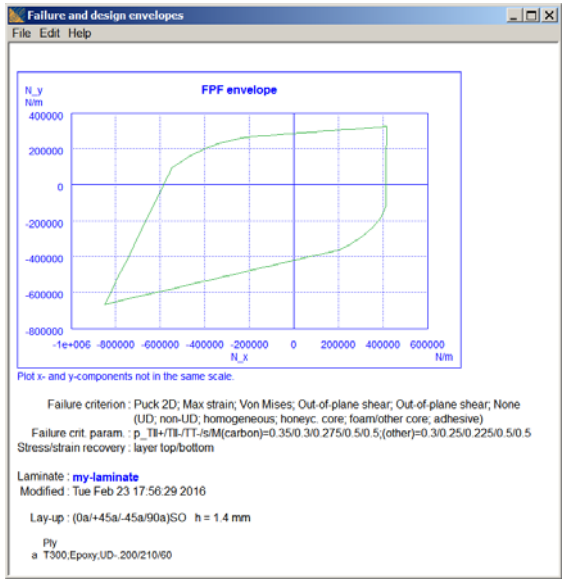


Laminate Strength

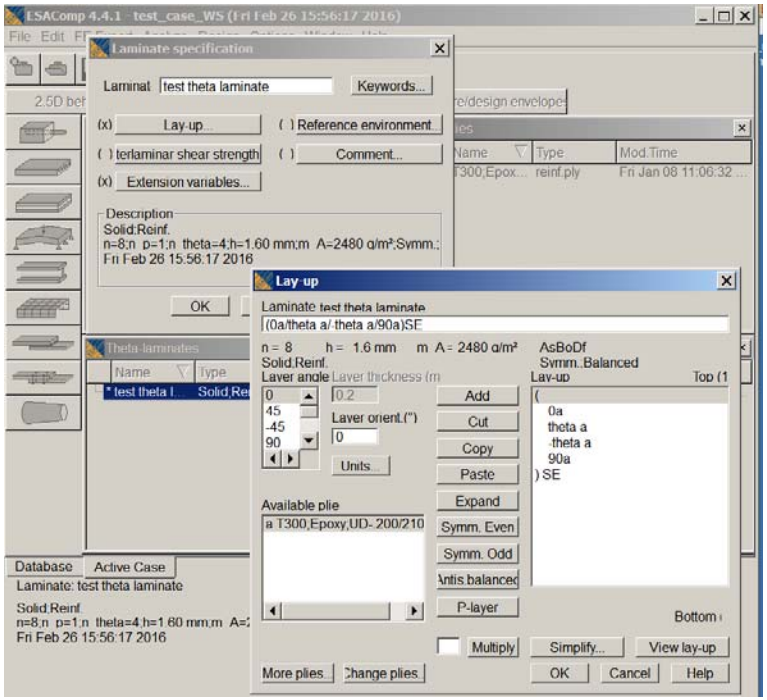


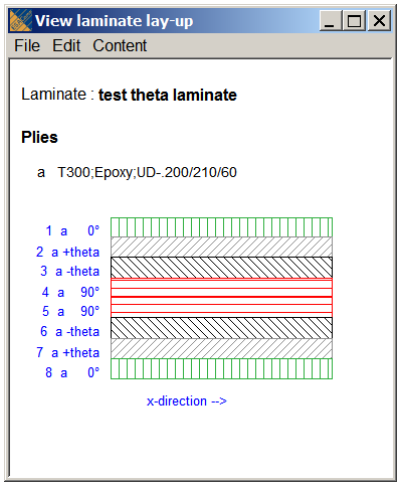


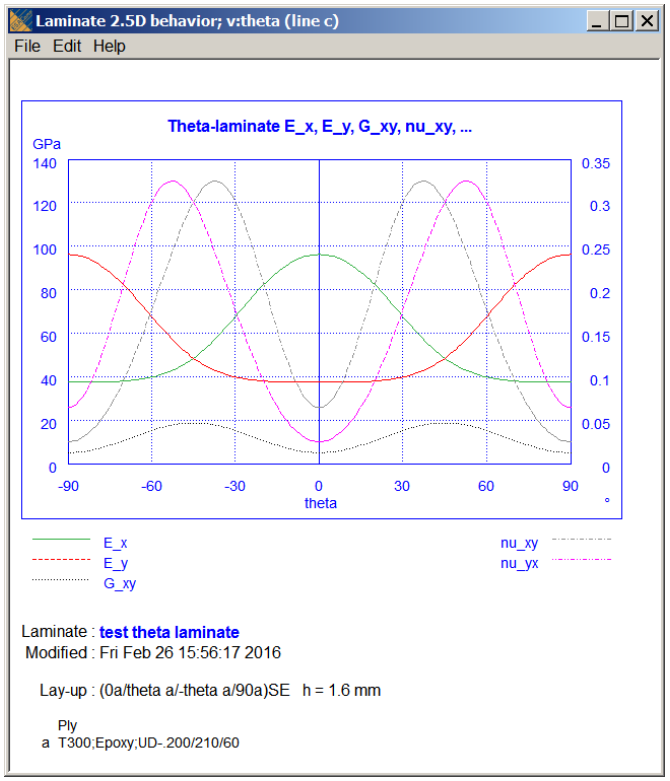




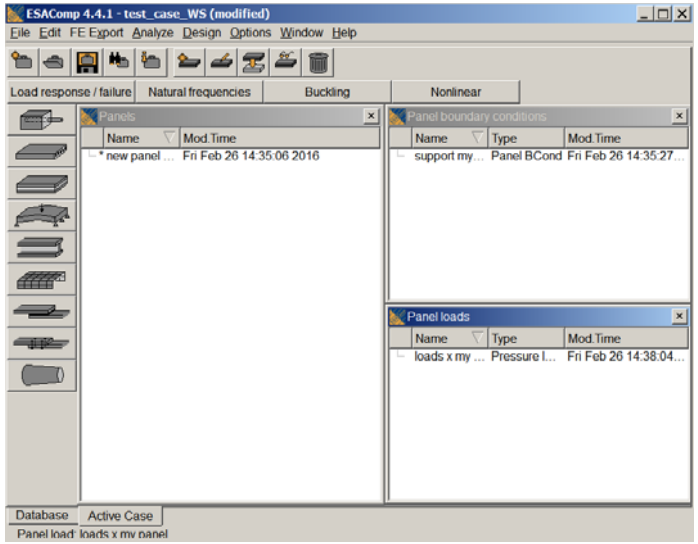
Analysis of Theta Laminates

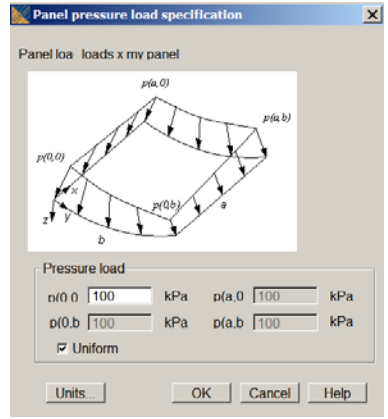


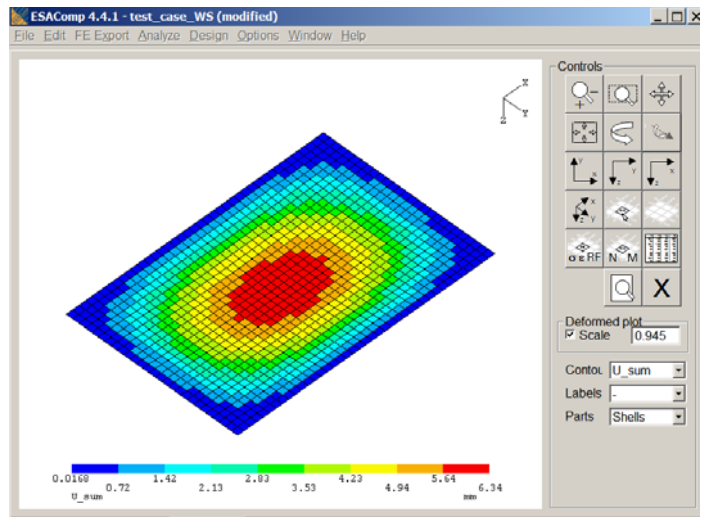


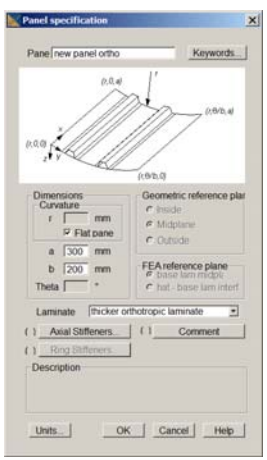


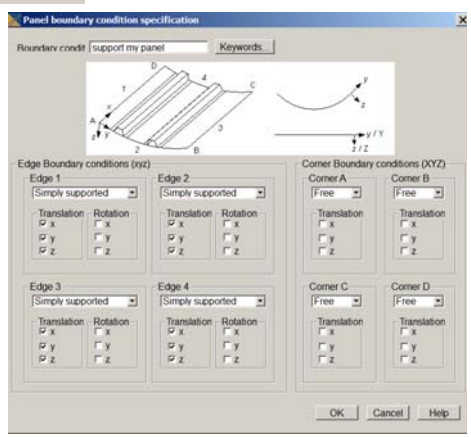
Quasi-Isotropic Laminate Analysis Example











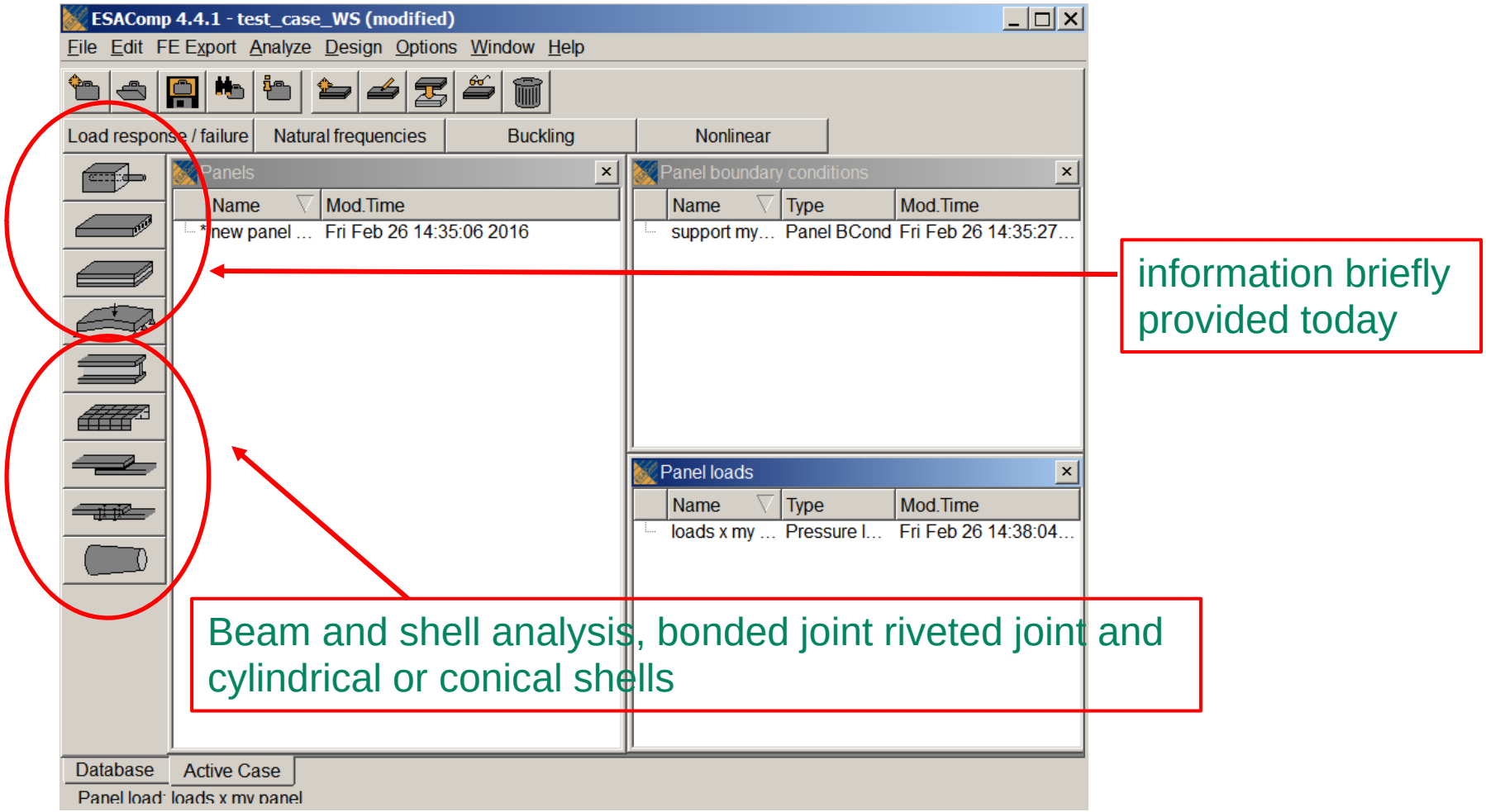
$c_3 := 1.35$ $\quad p := 1 \cdot bar$ $\quad b := 100 \cdot mm$

$E := 48 \cdot GPa$

$h := 3.6 \cdot mm$

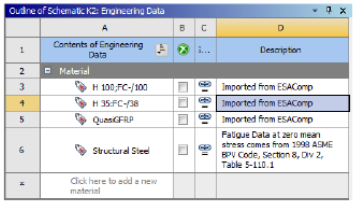
$$f := c_3 \cdot \frac{p \cdot b^4}{E \cdot h^3} = 6.028\,mm$$

Other Analysis Possible



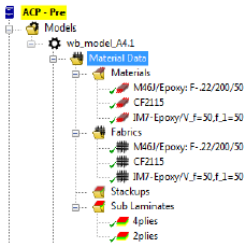
Export Laminate as XML or FEA Input

WB EDM



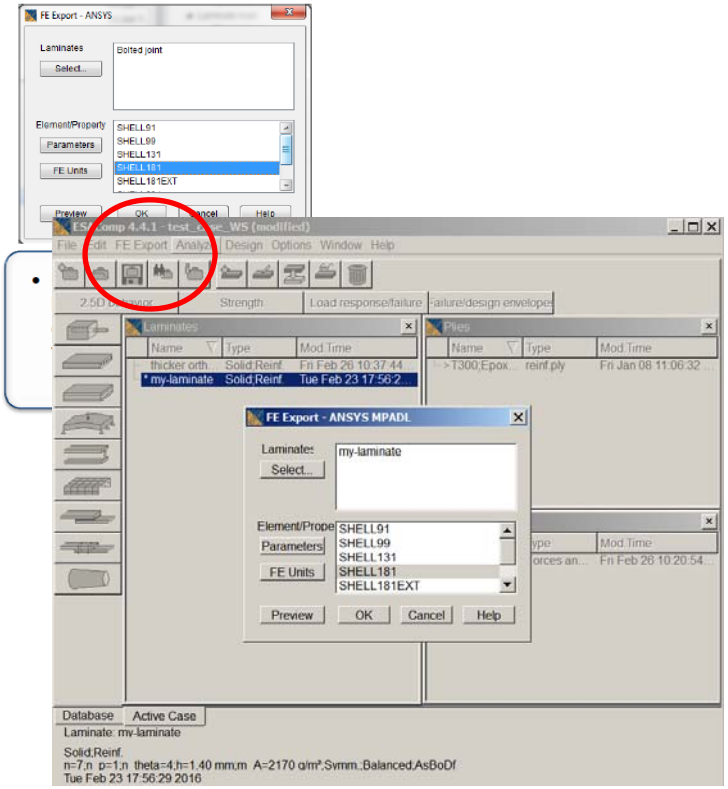
- Export of material engineering constant in WB specific XML-format

ACP



- Export of material and laminate lay-up data in ACP python-format
- Import of material, laminate and load data

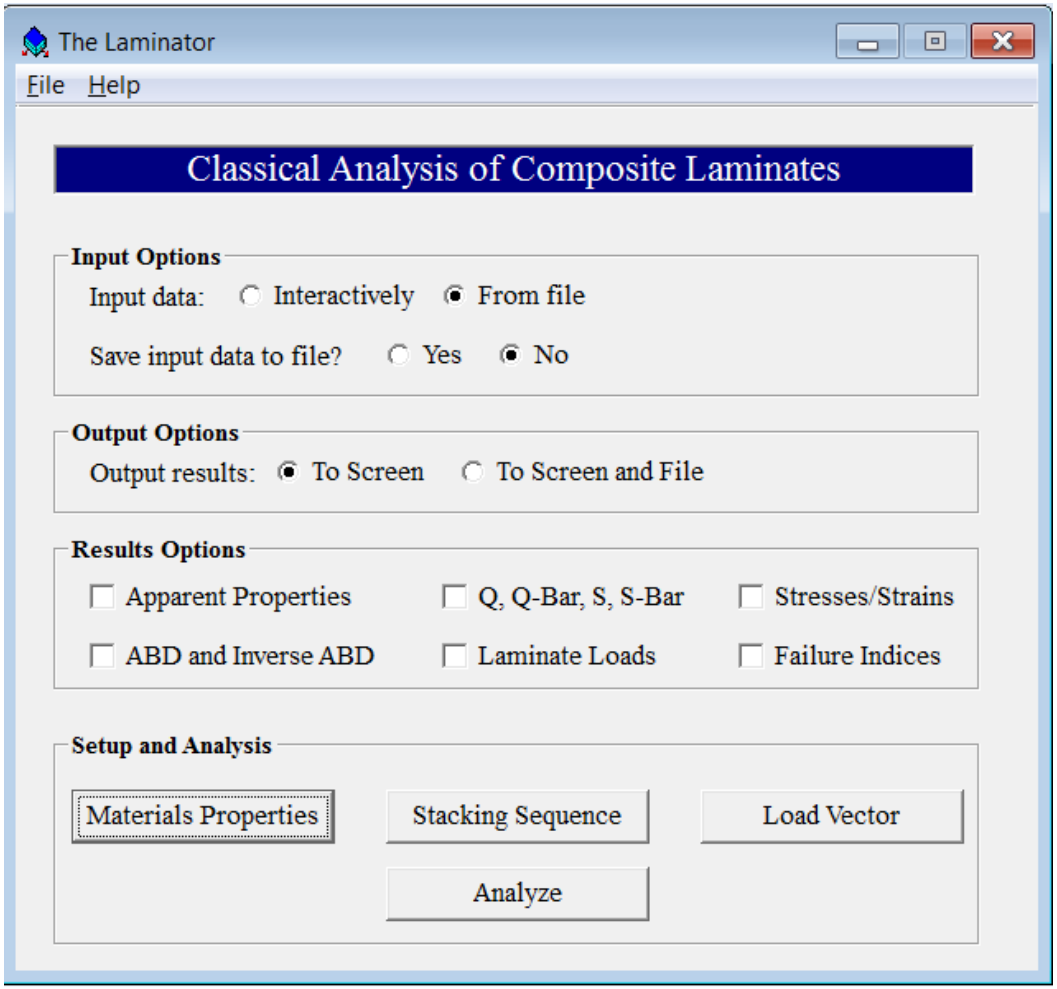
MAPDL




```
! ANSYS export file
....
! Lay-up :       (0a/+45a/-45a/90a)SO
!
! Ply a          T300;Epoxy;UD-.200/210/60
!              Fri Jan 08 11:06:32 2010
!
! ----------
! Laminate : my-laminate
!
et,    1,    181
!
keyopt, 1,    1,    0
...
!
! Ply : T300;Epoxy;UD-.200/210/60
mpdele,all,1
mp,    ex,    1,       1.25e+011
mp,    ey,    1,       8000000000
mp,    ez,    1,       8000000000
mp,    gxy,   1,       5000000000
mp,    gyz,   1,       3076923077
mp,    gxz,   1,       5000000000
mp,    prxy,  1,            0.3
mp,    pryz,  1,            0.3
mp,    prxz,  1,            0.3
mp,    alpx,  1,       -4.5e-007
mp,    alpy,  1,         3e-005
mp,    alpz,  1,         3e-005
mp,    dens,  1,           1550
!
! Failure strains and stresses (first failure)
fcdele,1
fc,    1,    epel,  xten,       0.0128
fc,    1,    epel,  xcmp,       -0.008
fc,    1,    epel,  yten,        0.005
fc,    1,    epel,  ycmp,       -0.0275
fc,    1,    epel,  zten,        0.005
fc,    1,    epel,  zcmp,       -0.0275
fc,    1,    epel,  xy,          0.016
....
!
sdele,1
sectype,        1,      shell,          , my-lamin
!
secdata,     0.0002,        1,        0, 3
secdata,     0.0002,        1,       45, 3
secdata,     0.0002,        1,      -45, 3
secdata,     0.0002,        1,       90, 3
secdata,     0.0002,        1,      -45, 3
secdata,     0.0002,        1,       45, 3
secdata,     0.0002,        1,        0, 3
!
secoffset,  mid
!
```

Additional Material

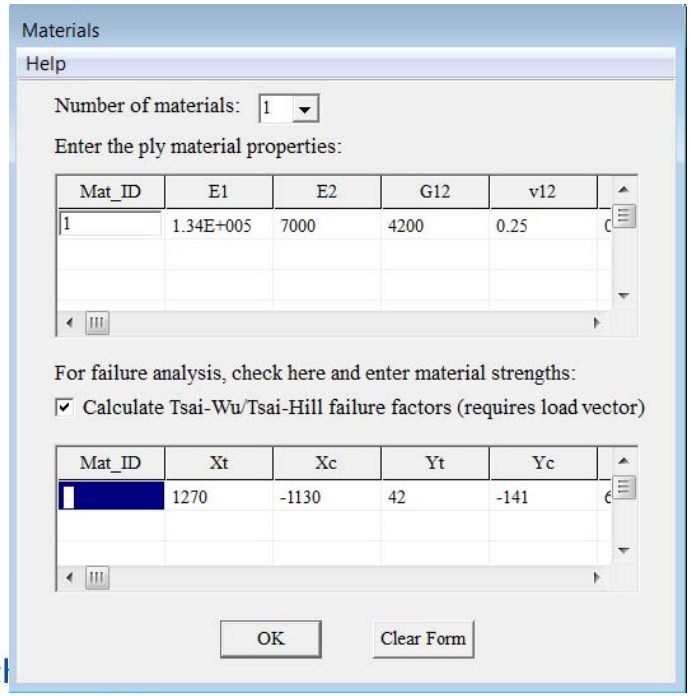
Shareware Laminate Analysis: Laminator

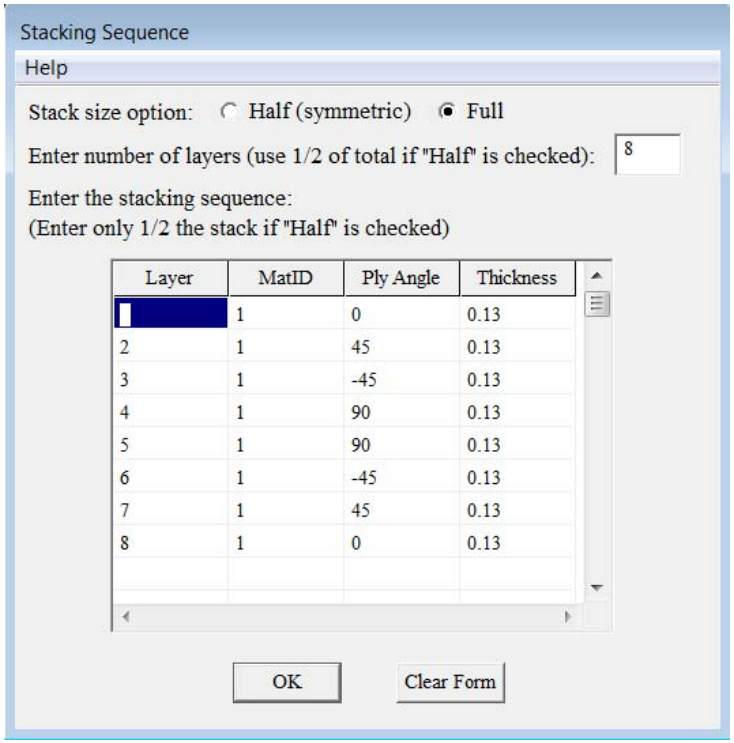


Laminator Input data

- Input data interactive or from text file

```
1
1 1.340e+005 7.000e+003 4.200e+003 0.250  0.000e+000  0.000e+000  0.0000  0.0000
8
 1  1    0.0  1.300e-001
 2  1   45.0  1.300e-001
 3  1  -45.0  1.300e-001
 4  1   90.0  1.300e-001
 5  1   90.0  1.300e-001
 6  1  -45.0  1.300e-001
 7  1   45.0  1.300e-001
 8  1    0.0  1.300e-001
1
 4.4500e+002  0.0000e+000  0.0000e+000  0.0000e+000  0.0000e+000  0.0000e+000
   0.000      0.00
   1270.0   -1130.0      42.0    -141.0      63.0
```

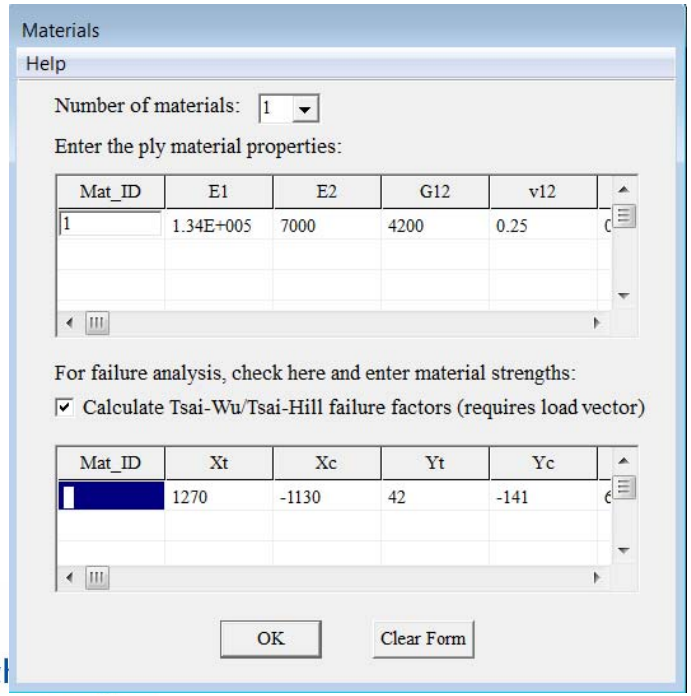


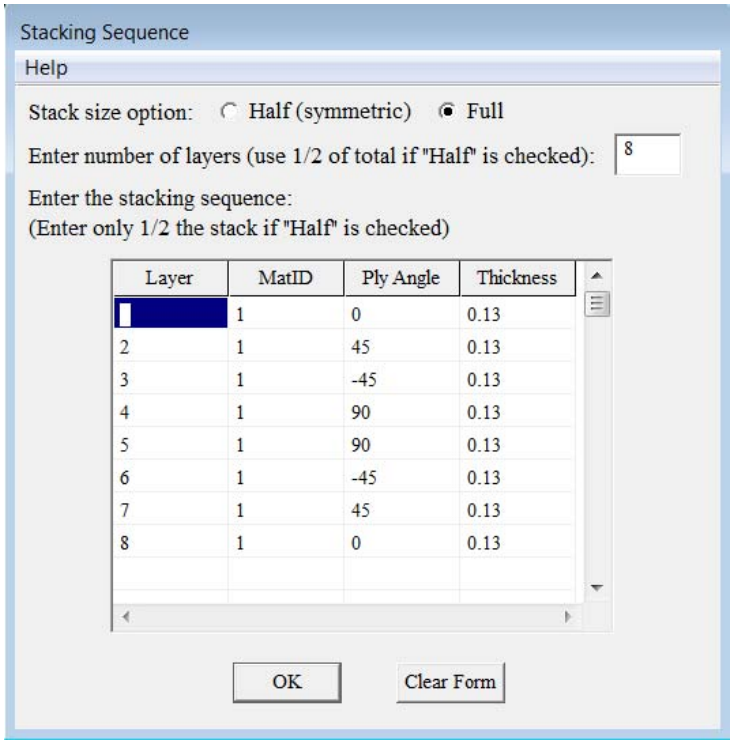


Laminator Input data

- Input data interactive or from text file

```
1
1 1.340e+005 7.000e+003 4.200e+003 0.250  0.000e+000  0.000e+000  0.0000  0.0000
8
 1  1    0.0  1.300e-001
 2  1   45.0  1.300e-001
 3  1  -45.0  1.300e-001
 4  1   90.0  1.300e-001
 5  1   90.0  1.300e-001
 6  1  -45.0  1.300e-001
 7  1   45.0  1.300e-001
 8  1    0.0  1.300e-001
1
 4.4500e+002  0.0000e+000  0.0000e+000  0.0000e+000  0.0000e+000  0.0000e+000
    0.000      0.00
   1270.0   -1130.0      42.0    -141.0      63.0
```





Example of Laminator output

```
Apparent Laminate Engineering Properties
****************************************

     EX          EY          GXY        VXY      nXY,X      nX,XY

 5.045e+004  5.045e+004  1.934e+004  0.304     0.000      0.000
```

```
Stacking Sequence
*****************

 Layer     Matl      Ply Angle      Ply Thickness

   1         1          0.0          1.300e-001
   2         1         45.0          1.300e-001
   3         1        -45.0          1.300e-001
   4         1         90.0          1.300e-001
   5         1         90.0          1.300e-001
   6         1        -45.0          1.300e-001
   7         1         45.0          1.300e-001
   8         1          0.0          1.300e-001
                                     ----------
Total Laminate Thickness :           1.040e+000
```

```
Laminate Matrices
*****************


                                 'ABD' Matrix

  5.781e+004   1.758e+004   9.095e-013   -9.095e-013   1.137e-01
  1.758e+004   5.781e+004   5.184e-011    1.137e-013   0.000e+00
  9.095e-013   5.184e-011   2.012e+004    0.000e+000   0.000e+00

 -9.095e-013   1.137e-013   0.000e+000    8.836e+003   1.318e+00
  1.137e-013   0.000e+000   0.000e+000    1.318e+003   2.118e+00
  0.000e+000   0.000e+000  -2.842e-014    5.599e+002   5.599e+00
```

Classic Lamination Theory CLT

- The starting point for the laminate analysis is CLT, Classical Laminate Theory
  - limitations are valid for thin laminates

- ABD-MATRIX: The ABD-matrix characterize the relation between cross-sectional loads - to strains and curvatures of the mid-plane. Solved from ply properties, orientations and stacking sequence
- *Typically compliance matrices [a], [b] and [d] need to be solved since the loads are input and deformations are calculated*

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ \hline M_x \\ M_y \\ M_{xy} \end{bmatrix} = \left[\begin{array}{ccc|ccc} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ \hline B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{array}\right] \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ \hline K_x \\ K_y \\ K_{xy} \end{bmatrix}$$

$$\begin{bmatrix} N \\ \hline M \end{bmatrix} = \left[\begin{array}{c|c} A & B \\ \hline B & D \end{array}\right] \begin{bmatrix} \varepsilon^0 \\ \hline K \end{bmatrix}$$

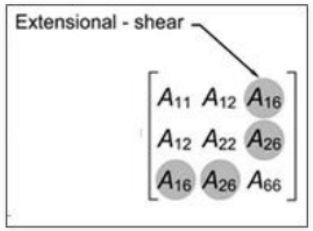
ABD Matrix

Influence of some components of the ABD-matrix:

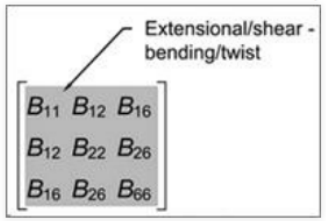
symmetric laminate: your B matrix is zero, no extensional/shear-bending /twisting

balanced laminate. your A16 and A26 terms are zero: no in-plane extensional to shear coupling terms

A-Terms: characterizes the extension stiffness of a laminate



B-Terms: characterizes the coupling stiffness of a laminate



D-Terms: characterizes the bending stiffness of a laminate

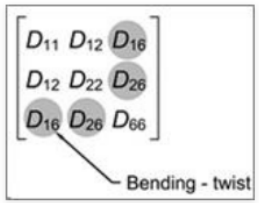


Figure 1: A16 term illustration

Figure 2: B12 term illustration

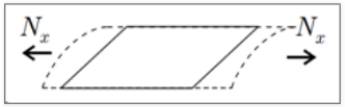


Figure 3: B16 term illustration

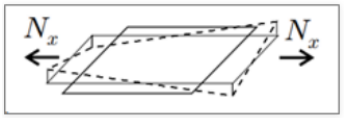


Figure 4: B66 term illustration

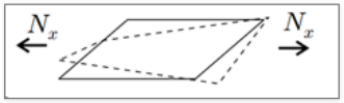
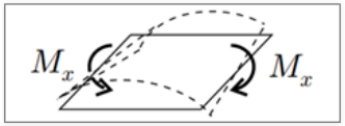


Figure 5: D16 term illustration



Symmetric and Balanced Laminates

- Review the laminate's ABD Matrix stiffness coefficients There **EsaComp provides the ABD elements and a laminate code.**

- **Check if your laminate is symmetric and balanced** (to avoid plate warping). The non-zero locations will show you whether or not you have a symmetric and/or balanced laminate

- **Sym/Bal laminate reduces post cure warpage and in-plane axial/bending and shear/bending coupling**
- The D16 and D26 terms are small compared to the D11 term in the stiffness matrix; if so, you have a flexurally balanced laminate

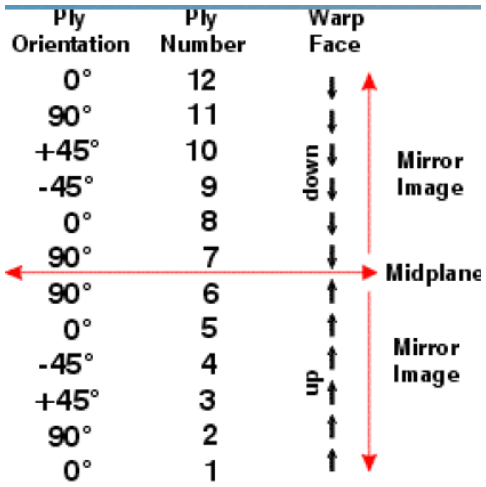
Symmetric and Balanced Laminates

- **Symmetric laminate**
- Symmetry: A laminate is symmetric when the plies above the mid-plane are a mirror image of those below the mid-plane.

- *Symmetrical lay-ups help to avoid thermal twisting of parts as they cool down after curing.*

- **Balanced laminate**
- Balance: A laminate is balanced when it has equal numbers of –and + angled plies.

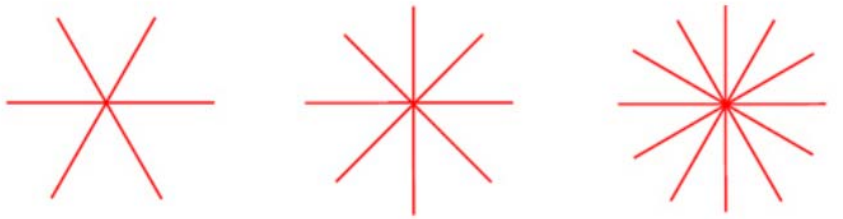
- Note: If the laminate is balanced and symmetric, the entire [B] matrix is zero and the in-plane normal shear coupling terms A_{16} and A_{26} are also zero.



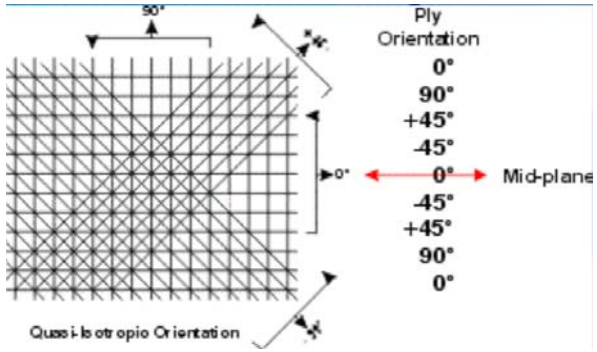
Balanced and Symmetrical Laminate

Quasi-Isotropic Laminate

- Isotropic means having the same properties in all directions.
- Quasi-isotropic means having is ortropic properties in-plane.
- A quasi-isotropic part has either randomly oriented fiber in all directions, or has fibers oriented such that equal strength is developed all around the plane of the part.
- Generally, a quasi-isotropic laminate made from woven fabric has plies oriented at 0º, 90º +45º and –45º, with at least 12.5% of the plies in each of these four directions
- Quasi-isotropic properties can also be achieved with 0º, 60º and 120º oriented unidirectional plies.



$N = 3\ (\Delta\theta = 60°)$ $N = 4\ (\Delta\theta = 45°)$ $N = 6\ (\Delta\theta = 30°)$



EsaComp Lay-up Code

- **Examples of Lay-up code**
- A lay-up code is provided for each intermediate laminate and for the final laminate when the lay-up is being specified. The code identifies layers, layer orientations, and the stacking sequence of layers as follows:
- Layer orientations are given in parentheses from the top surface to the bottom surface. A slash (/) separates the layers. For example, the code (+45/-45/-45/+45) defines a four-layer laminate in which the orientations of the top and bottom layers are +45 degrees and the orientations of the middle layers are -45 degrees.
- A contracted notation may be used in the lay-up code for a symmetric laminate. In this notation layer orientations are given only for the upper half of a laminate. Symmetry is indicated with the letter S after the parentheses. The letter E or O is further used to identify that the laminate has an even or odd number of layers. Thus, the code for the laminate (+45/-45/-45/+45) may be given in the form (+45/-45)SE. Correspondingly, the code (+45/-45)SO refers to the lay-up (+45/-45/+45).
- Codes of antisymmetric balanced laminates may also be contracted to the form that gives layer orientations only the upper half of a laminate. The letters AB after the parentheses specify that the lay-up is antisymmetric balanced. For example, the code (+45/-45)AB defines the lay-up (+45/-45/+45/-45).
- Multipliers after the parentheses may be used to indicate that several layers or layer groups are stacked. For instance, a contracted form for the lay-up (+45/-45/+45/ -45/+45/-45) is (+45/-45)3.
- Several pairs of parentheses may be used in the code. For instance, the code ((+45/-45)2/0)SE is a contracted form for the symmetric lay-up (+45/-45/+45/-45/0/0/-45/+45/-45/+45).
- When a laminate contains different plies, the ply is identified for each layer with a letter that appears after the layer orientation. For instance, the code (+45a/-45b)SE specifies a symmetric four-layer laminate where the ply *a* is used in surface layers and the ply *b* in the middle layers.
- Concerning the specified practice, it should be noted that slightly different forms of the code can be found in the literature. For instance:
- brackets are often used instead of parentheses
- multipliers and letters specifying the symmetry or antisymmetry may be subscripts
- multipliers often appear in front of the parentheses or brackets.

EsaComp Lay-up Code

Classification based on constitutive behavior

Classification based on constitutive behavior is provided for each intermediate laminate and for the final laminate when the lay-up is being specified. Classification is given by identifying the types of the *in-plane stiffness matrix* [*A*], *coupling stiffness matrix* [*B*], and *flexural stiffness matrix* [*D*] that define the following relations:

the in-plane stiffness matrix [*A*] relates the resultant in-plane forces to the midplane strains

the flexural stiffness matrix [*D*] relates the resultant moments to the curvatures

the coupling stiffness matrix [*B*] relates the resultant in-plane forces to the curvatures and the resultant moments to the midplane strains.

The rows and columns of the matrices are referred to with the indexes 1, 2, and 6 which is the normal practice in mechanics of laminates. The code used in the classification is of the form *AfBeDq* where the letters *f*, *e*, and *q* identify the types of the preceding matrices:

f : full matrix

e : elements 11 and 22 of the matrix are equal

q : quasi-isotropic form where the elements 16, 26, 61, and 62 are zero, the elements 11 and 22 are equal, and only two of the elements 11, 12 and 66 are independent

s : specially orthotropic form where the elements 16, 26, 61, and 62 are zero

t : only the elements 16, 26, 61, and 62 exist

l : only the elements 11 and 22 exist

o : all elements are zero.

The following examples illustrate the classification:

The code *AsBoDs* identifies that the in-plane and flexural stiffness matrices have a specially orthotropic form and the coupling stiffness matrix is zero. An example of laminates with such behavior is a symmetric cross-ply laminate.

The code *AsBoDf* identifies that the in-plane stiffness matrix has a specially orthotropic form, the coupling stiffness matrix is zero, and the flexural stiffness matrix is full. Symmetric angle-ply laminates, for example, possess this kind of mechanical behavior.

The code *AfBfDf* identifies that all matrices are full. This is the most general form of mechanical behavior. Due to many types of coupling effects, laminates of this type are not normally used.