TERM PROJECT

MECH-530

Progress Report 6

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November 17, 2014

Overview: This progress report features the optimization of three design problems using the code that has been developed.

1 Design 1: Design of a Filament Wound Pressure Vessel

Based on the following given parameters, the applied load vectors were obtained. Thus, $N_1 = 0.025$ MN/m and $N_2 = 0.05$ MN/m (tensile loads) while $N_6 = 0$ N/m, and $M_1 = M_2 = M_6 = 0$ N.

- p = 1.25 MPa (pressure inside the cylinder)
- D = 8.0 cm (width/diameter of the cylinder)

$$\begin{aligned} N_1 &= \bar{\sigma_1} \cdot h \\ &= \frac{p \cdot D}{4} \\ &= \frac{1.25 \cdot 10^6 \cdot 0.08}{4} \\ &= 0.025 \cdot 10^6 \text{ N/m} \end{aligned}$$

$$\begin{aligned} N_2 &= \bar{\sigma_2} \cdot h \\ &= \frac{p \cdot D}{2} \\ &= \frac{1.25 \cdot 10^6 \cdot 0.08}{2} \\ &= 0.050 \cdot 10^6 \text{ N/m} \end{aligned}$$

Thus the optimal ply angle for the layup $[\pm\theta]_s$ is for $\theta = 52^o$. This was determined from Figure 1.1 since this value maximizes the Hashin R.

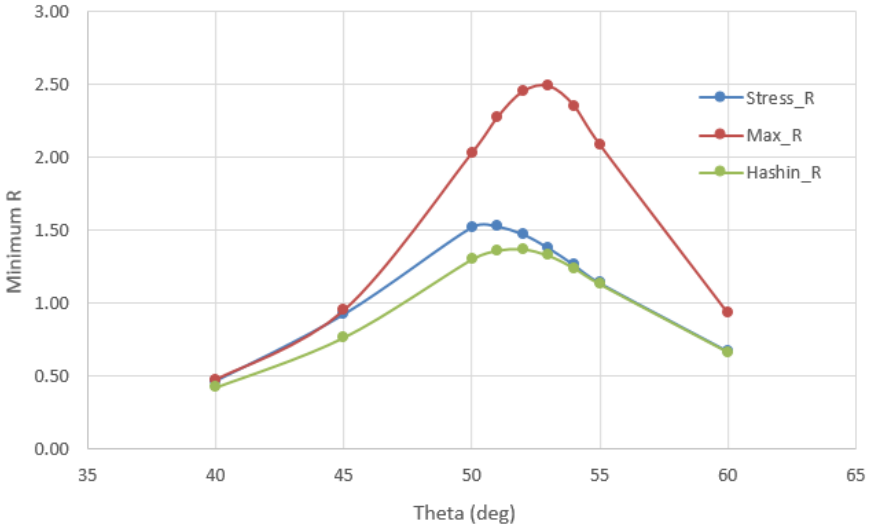

Figure 1.1: Optimization of R Values for Various θ

Refer to Tables A.1 and A.2 in Appendix A for the program output as well as the stresses, strains and safety factor R values per top and bottom of each ply.

2 Design 2: Design of a Laminate

Generally $D_{11} = D_{22}$ for a balanced angle ply with $\theta = 45^o$.

In this case, no load is applied and the layup given in Table 2.1, (also written $[55/\text{-}25/\text{-}55/25]_s$), produces a constant of proportionality $D_{11}/D_{22} = K = 0.9375$ which satisfies the given design requirements. Thus a total of 8 layers are used and the laminate is symmetric. Please refer to the output in Appendix B for further details.

Table 2.1: Layup for Design 2

Ply	Qty	Material	Angle (^{o})	Thickness (mm)
8	1	E-glass/Epoxy	55	0.125
7	1	E-glass/Epoxy	-25	0.125
6	1	E-glass/Epoxy	-55	0.125
4-5	2	E-glass/Epoxy	25	0.250
3	1	E-glass/Epoxy	-55	0.125
2	1	E-glass/Epoxy	-25	0.125
1	1	E-glass/Epoxy	55	0.125

3 Design 3: Design of a Hockey Stick Blade

Table 3.1: Layup for Design 3

Ply	Qty	Material	Angle (^{o})	Thickness (mm)
17	1	T300/N5208	0	0.125
16	1	T300/N5208	10	0.125
15	1	T300/N5208	17	0.125
14	1	T300/N5208	-17	0.125
13	1	T300/N5208	37	0.125
12	1	T300/N5208	-37	0.125
11	1	T300/N5208	35	0.125
10	1	T300/N5208	13	0.125
9	1	CORE	N/A	1.5
8	1	T300/N5208	13	0.125
7	1	T300/N5208	35	0.125
6	1	T300/N5208	-37	0.125
5	1	T300/N5208	37	0.125
4	1	T300/N5208	-17	0.125
3	1	T300/N5208	17	0.125
2	1	T300/N5208	10	0.125
1	1	T300/N5208	0	0.125

The highest compressive loads (both moments and in-plane) are in the 1-axis. To optimize strength, the fiber directions should remain as close to 0^o as possible to combat this; however, there are also loads in the 2 and 3 axes, so a unidirectional laminate is not the solution.

After trial and error, the symmetric layup that meets the requirements is given by Table 3.1, also written $[0/10/\pm17/\pm37/35/13/\mathrm{C}_{1/2}]_s$, where the corresponding minimum safety factors for each of the failure criterion are listed in Table 3.2.

From Engineering Toolbox, the approximate density of Balsa Wood is $\rho = 160\ \mathrm{kg/m^3}$. Thus, the core represents an added weight of 0.72 g to the laminate, as shown below.

$$\begin{aligned} m_{core} &= \rho \cdot W \cdot B \cdot h_o \\ &= 160 \cdot 0.03 \cdot 0.1 \cdot 0.0015 \\ &= 7.2 \cdot 10^{-4}\ \mathrm{kg} \\ &= 0.72\ \mathrm{g} \end{aligned}$$

This layup thus has a total of 17 plies with a mass of 10.32 g, (both of which include the core). The mass without the core is 9.60 g.

Refer to Tables C.1, C.2, C.3 and C.4 in Appendix C for the program output as well as the stresses, strains and safety factor R values per top and bottom of each ply.

Table 3.2: Minimum Safety Factors for Load Cases 1 and 2

	Failure Criterion		
Load Case	Maximum Stress	Quadratic	Hashin
1	2.204	2.162	2.204
2	2.260	2.188	2.260

A Design 1 Output

In [1]:
```
run -i MECH530_main.py
```

```
PLYBOOK (READ FROM EXCEL FILE AND SUMMARIZED HERE)

The laminate is given by the following plybook where the highest ply number '4'
 indicates the top layer, while the first ply number '1' indicates the bottom l
ayer.

Unique Ply #, Fiber/Matrix, Orientation, Thickness
                             (degrees)      (mm)
     4        Kev49/Epoxy        52         0.125
     3        Kev49/Epoxy       -52         0.125
     2        Kev49/Epoxy       -52         0.125
     1        Kev49/Epoxy        52         0.125

PLIES AND THICKNESSES
-Total number of plies in the laminate: 4
-Total thickness of laminate is: 0.500 mm
-There is no core in the laminate (Zc = 0 mm)
-Laminate contains 1 Fiber/Matrix combination. The material properties for this
 combination shall be listed below.

--------------------------------------------------------------------------------
MATERIALS AND MATERIAL PROPERTIES

RESIN/MATRIX 1 of 1: For Kev49/Epoxy, the given material properties are:

-Stiffness and Strength:

Ex =  76.0000 GPa, Ey =   5.5000 GPa, Es =   2.3000 GPa and nu_x =   0.3400

Xt = 1400.0000 MPa, Xc = 235.0000 MPa, Yt =  12.0000f MPa, Yc =  53.0000 MPa an
d Sc =  34.0000 MPa.

-The 'on-axis' matrices are given by the following:
S_on =
[[      0.0   -0.0045       0.0]
 [  -0.0045    0.1818       0.0]
 [      0.0       0.0    0.4348]] [1/GPa]

Q_on =
[[  76.6412    1.8858       0.0]
 [   1.8858    5.5464       0.0]
 [      0.0       0.0    2.3000]] [GPa]

-The linear combinations of the modulus, independent of ply angle are the follo
wing:
Us_1 =    0.1214 [1/GPa]
Us_2 =   -0.0909 [1/GPa]
Us_3 =   -0.0305 [1/GPa]
Us_4 =   -0.0350 [1/GPa]
Us_5 =    0.3128 [1/GPa]

-The linear combinations of the modulus, dependent on ply angle are the followi
```

```
ng:
Uq_1 =   32.4418 GPa
Uq_2 =   35.5474 GPa
Uq_3 =    8.6520 GPa
Uq_4 =   10.5378 GPa
Uq_5 =   10.9520 GPa

-The 'Stiffness' [A] and 'Compliance' [a] matrices are given by the following:
A =
[[   0.0081    0.0091       0.0]
 [   0.0091    0.0167       0.0]
 [      0.0       0.0    0.0093]] [GN/m]

a =
[[ 316.9010 -172.4533      -0.0]
 [-172.4533  153.7231       0.0]
 [      0.0       0.0  107.5774]] [m/GN]

-The 'In-Plane Flexural Modulus' [D] and 'In-Plane Flexural Compliance' [d] mat
rices are given by the following:
D =
[[   0.0002    0.0002    0.0001]
 [   0.0002    0.0003    0.0002]
 [   0.0001    0.0002    0.0002]] [kNm]

d =
[[15530371.6619 -7642652.2161 -1690461.2187]
 [-7642652.2161 8642673.4179 -3364279.7092]
 [-1690461.2187 -3364279.7092 8954671.2946]] [1/MNm]

--------------------------------------------------------------------------------
INPUTS:

Would you like to input a resultant applied stress? ON/OFF/NO
OFF
Enter the applied stress resultant vector [N1, N2, N6] [N/m].
N1 = 25000
N2 = 50000
N6 = 0
Would you like to input a resultant applied moment? ON/OFF/NO
NO

--------------------------------------------------------------------------------
Curvature K =
[[      0.0       0.0       0.0]] [1/m]

OFF-AXIS APPLIED RESULTANTS:

(INPUT) Off-axis Applied stress resultant N =
[[25000.0000 50000.0000       0.0]] [N/m]

(INPUT) Off-axis Applied moment resultant M =
[[      0.0       0.0       0.0]] [N]

--------------------------------------------------------------------------------
FAILURE CRITERION AND ANALYSIS
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```
MAXIMUM STRESS:
-Minimum R = 1.475 and laminate fails in Matrix Tension at TOP of ply 4
-The load vectors which cause the failure are:
R*N =
[[  36.8778   73.7555       0.0]] [kN/m]
R*M =
[[      0.0       0.0       0.0]] [kN]

QUADRATIC POLYNOMIAL:
-Minimum R = 2.455 and laminate fails at TOP of ply 4
-The load vectors which cause the failure are:
R*N =
[[  61.3641  122.7282       0.0]] [kN/m]
R*M =
[[      0.0       0.0       0.0]] [kN]

HASHIN CRITERION:
-Minimum R = 1.372 and laminate fails in Matrix Tension at TOP of ply 4
-The load vectors which cause the failure are:
R*N =
[[  34.3042   68.6085       0.0]] [kN/m]
R*M =
[[      0.0       0.0       0.0]] [kN]
--------------------------------------------------------------------------------
```

Table A.1: Design 1 Stress and Strain Values

Position	Ply	Angle	ϵ_1	ϵ_2	ϵ_6	ϵ_x	ϵ_y	ϵ_s	σ_x	σ_y	σ_s
		(^{o})							(GPa)	(GPa)	(GPa)
TOP	4	52	-0.0007	0.003375	0	0.00183	0.000844	0.003954	0.141865	0.008135	0.009094
BOT	4	52	-0.0007	0.003375	0	0.00183	0.000844	0.003954	0.141865	0.008135	0.009094
TOP	3	-52	-0.0007	0.003375	0	0.00183	0.000844	-0.003954	0.141865	0.008135	-0.009094
BOT	3	-52	-0.0007	0.003375	0	0.00183	0.000844	-0.003954	0.141865	0.008135	-0.009094
TOP	2	-52	-0.0007	0.003375	0	0.00183	0.000844	-0.003954	0.141865	0.008135	-0.009094
BOT	2	-52	-0.0007	0.003375	0	0.00183	0.000844	-0.003954	0.141865	0.008135	-0.009094
TOP	1	52	-0.0007	0.003375	0	0.00183	0.000844	0.003954	0.141865	0.008135	0.009094
BOT	1	52	-0.0007	0.003375	0	0.00183	0.000844	0.003954	0.141865	0.008135	0.009094

Table A.2: Design 1 Failure Criterion R Values

			Maximum Stress					Quad Poly		Hashin Criterion			
Position	Ply	Angle	FT	FC	MT	MC	S	(+)	(-)	FT	FC	MT	MC
TOP	4	52	9.869	0.000	1.475	0.000	3.739	2.455	-2.595	3.496	0.000	1.372	0.000
BOT	4	52	9.869	0.000	1.475	0.000	3.739	2.455	-2.595	3.496	0.000	1.372	0.000
TOP	3	-52	9.869	0.000	1.475	0.000	3.739	2.455	-2.595	3.496	0.000	1.372	0.000
BOT	3	-52	9.869	0.000	1.475	0.000	3.739	2.455	-2.595	3.496	0.000	1.372	0.000
TOP	2	-52	9.869	0.000	1.475	0.000	3.739	2.455	-2.595	3.496	0.000	1.372	0.000
BOT	2	-52	9.869	0.000	1.475	0.000	3.739	2.455	-2.595	3.496	0.000	1.372	0.000
TOP	1	52	9.869	0.000	1.475	0.000	3.739	2.455	-2.595	3.496	0.000	1.372	0.000
BOT	1	52	9.869	0.000	1.475	0.000	3.739	2.455	-2.595	3.496	0.000	1.372	0.000

B Design 2 Output

In [1]:
```
run -i MECH530_main.py
```

```
PLYBOOK (READ FROM EXCEL FILE AND SUMMARIZED HERE)

The laminate is given by the following plybook where the highest ply number '8'
 indicates the top layer, while the first ply number '1' indicates the bottom l
ayer.

Unique Ply #, Fiber/Matrix, Orientation, Thickness
                             (degrees)      (mm)
     8      E-glass/Epoxy        55         0.125
     7      E-glass/Epoxy       -25         0.125
     6      E-glass/Epoxy       -55         0.125
     5      E-glass/Epoxy        25         0.125
     4      E-glass/Epoxy        25         0.125
     3      E-glass/Epoxy       -55         0.125
     2      E-glass/Epoxy       -25         0.125
     1      E-glass/Epoxy        55         0.125

PLIES AND THICKNESSES
-Total number of plies in the laminate: 8
-Total thickness of laminate is: 1.000 mm
-There is no core in the laminate (Zc = 0 mm)
-Laminate contains 1 Fiber/Matrix combination. The material properties for this
 combination shall be listed below.

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MATERIALS AND MATERIAL PROPERTIES

RESIN/MATRIX 1 of 1: For E-glass/Epoxy, the given material properties are:

-Stiffness and Strength:

Ex =  38.6000 GPa, Ey =   8.2700 GPa, Es =   4.1400 GPa and nu_x =   0.2600

Xt = 1062.0000 MPa, Xc = 610.0000 MPa, Yt =  31.0000f MPa, Yc = 118.0000 MPa an
d Sc =  72.0000 MPa.

-The 'on-axis' matrices are given by the following:
S_on =
[[   0.0259   -0.0067       0.0]
 [  -0.0067    0.1209       0.0]
 [      0.0       0.0    0.2415]] [1/GPa]

Q_on =
[[  39.1673    2.1818       0.0]
 [   2.1818    8.3915       0.0]
 [      0.0       0.0    4.1400]] [GPa]

-The linear combinations of the modulus, independent of ply angle are the follo
wing:
Us_1 =    0.0836 [1/GPa]
Us_2 =   -0.0475 [1/GPa]
Us_3 =   -0.0102 [1/GPa]
```

```
Us_4 =   -0.0169 [1/GPa]
Us_5 =    0.2009 [1/GPa]

-The linear combinations of the modulus, dependent on ply angle are the followi
ng:
Uq_1 =   20.4500 GPa
Uq_2 =   15.3879 GPa
Uq_3 =    3.3294 GPa
Uq_4 =    5.5112 GPa
Uq_5 =    7.4694 GPa

-The 'Stiffness' [A] and 'Compliance' [a] matrices are given by the following:
A =
[[   0.0212    0.0071       0.0]
 [   0.0071    0.0166       0.0]
 [      0.0       0.0    0.0090]] [GN/m]

a =
[[  55.0092  -23.4870      -0.0]
 [ -23.4870   70.3723      -0.0]
 [      0.0       0.0  110.6965]] [m/GN]

-The 'In-Plane Flexural Modulus' [D] and 'In-Plane Flexural Compliance' [d] mat
rices are given by the following:
D =
[[   0.0015    0.0006   -0.0000]
 [   0.0006    0.0016    0.0003]
 [  -0.0000    0.0003    0.0008]] [kNm]

d =
[[812198.1980 -346646.5637 151552.3488]
 [-346646.5637 828946.0612 -329499.4659]
 [151552.3488 -329499.4659 1407375.4402]] [1/MNm]

--------------------------------------------------------------------------------
INPUTS:

Would you like to input a resultant applied stress? ON/OFF/NO
NO
Would you like to input a resultant applied moment? ON/OFF/NO
NO

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--------------------------------------------------------------------------------
```

In [2]:
```
0.0015/.0016
```

Out[2]:
```
0.9375
```

C Design 3 Output

In [1]:
```
run -i MECH530_main.py
```

```
PLYBOOK (READ FROM EXCEL FILE AND SUMMARIZED HERE)

The laminate is given by the following plybook where the highest ply number '17
' indicates the top layer, while the first ply number '1' indicates the bottom
layer.

Unique Ply #, Fiber/Matrix, Orientation, Thickness
                             (degrees)      (mm)
    17         T300/N5208         0         0.125
    16         T300/N5208        10         0.125
    15         T300/N5208        17         0.125
    14         T300/N5208       -17         0.125
    13         T300/N5208        37         0.125
    12         T300/N5208       -37         0.125
    11         T300/N5208        35         0.125
    10         T300/N5208        13         0.125
     9               CORE         0         1.500
     8         T300/N5208        13         0.125
     7         T300/N5208        35         0.125
     6         T300/N5208       -37         0.125
     5         T300/N5208        37         0.125
     4         T300/N5208       -17         0.125
     3         T300/N5208        17         0.125
     2         T300/N5208        10         0.125
     1         T300/N5208         0         0.125

PLIES AND THICKNESSES
-Total number of plies in the laminate: 17
-Total thickness of laminate is: 3.500 mm
-The core thickness is 2 Zc = 1.500 mm
-Note that the CORE will be ommitted in the following stress and safety factor
tables
-Laminate contains 1 Fiber/Matrix combination. The material properties for this
 combination shall be listed below.

--------------------------------------------------------------------------------
MATERIALS AND MATERIAL PROPERTIES

RESIN/MATRIX 1 of 1: For T300/N5208, the given material properties are:

-Stiffness and Strength:

Ex = 181.0000 GPa, Ey =  10.3000 GPa, Es =   7.1700 GPa and nu_x =   0.2800

Xt = 1500.0000 MPa, Xc = 1500.0000 MPa, Yt =  40.0000 MPa, Yc = 246.0000 MPa an
d Sc =  68.0000 MPa.

-The 'on-axis' matrices are given by the following:
S_on =
[[      0.0   -0.0015       0.0]
 [  -0.0015    0.0971       0.0]
 [      0.0       0.0    0.1395]] [1/GPa]
```

```
Q_on =
[[ 181.8111    2.8969       0.0]
 [   2.8969   10.3462       0.0]
 [      0.0       0.0    7.1700]] [GPa]

-The linear combinations of the modulus, independent of ply angle are the follo
wing:
Us_1 =    0.0535 [1/GPa]
Us_2 =   -0.0485 [1/GPa]
Us_3 =   -0.0049 [1/GPa]
Us_4 =   -0.0065 [1/GPa]
Us_5 =    0.1198 [1/GPa]

-The linear combinations of the modulus, dependent on ply angle are the followi
ng:
Uq_1 =   76.3682 GPa
Uq_2 =   85.7325 GPa
Uq_3 =   19.7104 GPa
Uq_4 =   22.6074 GPa
Uq_5 =   26.8804 GPa

-The 'Stiffness' [A] and 'Compliance' [a] matrices are given by the following:
A =
[[   0.2716    0.0419    0.0287]
 [   0.0419    0.0405    0.0082]
 [   0.0287    0.0082    0.0505]] [GN/m]

a =
[[   4.5484   -4.3257   -1.8781]
 [  -4.3257   29.6417   -2.3697]
 [  -1.8781   -2.3697   21.2676]] [m/GN]

-The 'In-Plane Flexural Modulus' [D] and 'In-Plane Flexural Compliance' [d] mat
rices are given by the following:
D =
[[   0.4815    0.0561    0.0413]
 [   0.0561    0.0579    0.0105]
 [   0.0413    0.0105    0.0702]] [kNm]

d =
[[2421.4674 -2147.7291 -1103.8042]
 [-2147.7291 19670.0897 -1675.4605]
 [-1103.8042 -1675.4605 15152.8785]] [1/MNm]

--------------------------------------------------------------------------------
OFF-AXIS APPLIED RESULTANTS: CASE 1

Curvature K =
[[  -2.0963    0.3483   -0.2439]] [1/m]

(INPUT) Off-axis Applied stress resultant N =
[[-22400.0000 -3000.0000 -2000.0000]] [N/m]

(INPUT) Off-axis Applied moment resultant M =
[[-1000.0000 -100.0000 -100.0000]] [N]
```

FAILURE CRITERION AND ANALYSIS

MAXIMUM STRESS:
-Minimum R = 2.204 and laminate fails in Fiber Compression at TOP of ply 17
-The load vectors which cause the failure are:
R*N =
[[-49.3637   -6.6112   -4.4075]] [kN/m]
R*M =
[[-2.2037   -0.2204   -0.2204]] [kN]

QUADRATIC POLYNOMIAL:
-Minimum R = 2.162 and laminate fails at BOT of ply 1
-The load vectors which cause the failure are:
R*N =
[[-48.4338   -6.4867   -4.3244]] [kN/m]
R*M =
[[-2.1622   -0.2162   -0.2162]] [kN]

HASHIN CRITERION:
-Minimum R = 2.204 and laminate fails in Fiber Compression at TOP of ply 17
-The load vectors which cause the failure are:
R*N =
[[-49.3637   -6.6112   -4.4075]] [kN/m]
R*M =
[[-2.2037   -0.2204   -0.2204]] [kN]

OFF-AXIS APPLIED RESULTANTS: CASE 2

Curvature K =
[[-2.0411   0.3614   -0.4209]] [1/m]

(INPUT) Off-axis Applied stress resultant N =
[[-20800.0000 -280.0000 -2200.0000]] [N/m]

(INPUT) Off-axis Applied moment resultant M =
[[-980.0000 -98.0000 -110.0000]] [N]

FAILURE CRITERION AND ANALYSIS

MAXIMUM STRESS:
-Minimum R = 2.260 and laminate fails in Fiber Compression at TOP of ply 17
-The load vectors which cause the failure are:
R*N =
[[-47.0181   -0.6329   -4.9731]] [kN/m]
R*M =
[[-2.2153   -0.2215   -0.2487]] [kN]

QUADRATIC POLYNOMIAL:
-Minimum R = 2.188 and laminate fails at BOT of ply 1
-The load vectors which cause the failure are:
R*N =
[[-45.5095   -0.6126   -4.8135]] [kN/m]
R*M =
[[-2.1442   -0.2144   -0.2407]] [kN]

```
HASHIN CRITERION:
-Minimum R = 2.260 and laminate fails in Fiber Compression at TOP of ply 17
-The load vectors which cause the failure are:
R*N =
[[ -47.0181   -0.6329   -4.9731]] [kN/m]
R*M =
[[  -2.2153   -0.2215   -0.2487]] [kN]

--------------------------------------------------------------------------------
```

In [11]:
```
#stress_df1
```

In [12]:
```
#failure_df1
```

In [13]:
```
#stress_df2
```

In [14]:
```
#failure_df2
```

In [15]:
```
#print stress_df1.to_latex()
```

In [16]:
```
#print failure_df1.to_latex(float_format=lambda x:"%.3f" % x)
```

In [17]:
```
#print stress_df2.to_latex()
```

In [18]:
```
#print failure_df2.to_latex(float_format=lambda x:"%.3f" % x)
```

Table C.1: Design 3 Stress and Strain Values: Load Case 1

Position	Ply	Angle	ϵ_1	ϵ_2	ϵ_6	ϵ_x	ϵ_y	ϵ_s	σ_x	σ_y	σ_s
		(^{o})							(GPa)	(GPa)	(GPa)
TOP	17	0	-0.003754	0.000622	-0.000420	-0.003754	0.000622	-0.000420	-0.680662	-0.004437	-0.003013
BOT	17	0	-0.003492	0.000579	-0.000390	-0.003492	0.000579	-0.000390	-0.633147	-0.004128	-0.002795
TOP	16	10	-0.003492	0.000579	-0.000390	-0.003436	0.000523	0.001026	-0.623113	-0.004546	0.007356
BOT	16	10	-0.003230	0.000535	-0.000359	-0.003178	0.000483	0.000950	-0.576313	-0.004208	0.006812
TOP	15	17	-0.003230	0.000535	-0.000359	-0.003008	0.000314	0.001807	-0.546026	-0.005469	0.012959
BOT	15	17	-0.002968	0.000492	-0.000329	-0.002764	0.000288	0.001662	-0.501658	-0.005029	0.011915
TOP	14	-17	-0.002968	0.000492	-0.000329	-0.002580	0.000104	-0.002207	-0.468766	-0.006398	-0.015823
BOT	14	-17	-0.002706	0.000448	-0.000298	-0.002353	0.000095	-0.002011	-0.427449	-0.005832	-0.014417
TOP	13	37	-0.002706	0.000448	-0.000298	-0.001707	-0.000551	0.002949	-0.311899	-0.010643	0.021146
BOT	13	37	-0.002444	0.000405	-0.000268	-0.001541	-0.000498	0.002664	-0.281562	-0.009619	0.019100
TOP	12	-37	-0.002444	0.000405	-0.000268	-0.001283	-0.000756	-0.002811	-0.235508	-0.011536	-0.020158
BOT	12	-37	-0.002181	0.000361	-0.000237	-0.001147	-0.000674	-0.002509	-0.210415	-0.010294	-0.017992
TOP	11	35	-0.002181	0.000361	-0.000237	-0.001457	-0.000364	0.002308	-0.265866	-0.007985	0.016548
BOT	11	35	-0.001919	0.000317	-0.000207	-0.001281	-0.000321	0.002031	-0.233773	-0.007034	0.014564
TOP	10	13	-0.001919	0.000317	-0.000207	-0.001852	0.000250	0.000795	-0.335912	-0.002782	0.005698
BOT	10	13	-0.001657	0.000274	-0.000176	-0.001598	0.000215	0.000688	-0.289967	-0.002408	0.004934
TOP	8	13	0.001487	-0.000248	0.000190	0.001441	-0.000202	-0.000590	0.261371	0.002082	-0.004233
BOT	8	13	0.001749	-0.000292	0.000220	0.001694	-0.000237	-0.000697	0.307315	0.002456	-0.004997
TOP	7	35	0.001749	-0.000292	0.000220	0.001181	0.000276	-0.001843	0.215521	0.006278	-0.013213
BOT	7	35	0.002011	-0.000336	0.000251	0.001357	0.000319	-0.002119	0.247614	0.007229	-0.015197
TOP	6	-37	0.002011	-0.000336	0.000251	0.001041	0.000635	0.002325	0.191066	0.009583	0.016669
BOT	6	-37	0.002273	-0.000379	0.000281	0.001177	0.000717	0.002627	0.216158	0.010825	0.018836
TOP	5	37	0.002273	-0.000379	0.000281	0.001448	0.000446	-0.002472	0.264498	0.008813	-0.017725
BOT	5	37	0.002535	-0.000423	0.000312	0.001614	0.000499	-0.002757	0.294835	0.009837	-0.019771
TOP	4	-17	0.002535	-0.000423	0.000312	0.002195	-0.000083	0.001912	0.398888	0.005504	0.013711
BOT	4	-17	0.002797	-0.000466	0.000342	0.002423	-0.000092	0.002108	0.440205	0.006071	0.015118
TOP	3	17	0.002797	-0.000466	0.000342	0.002614	-0.000283	-0.001541	0.474427	0.004646	-0.011051
BOT	3	17	0.003059	-0.000510	0.000373	0.002858	-0.000309	-0.001687	0.518794	0.005086	-0.012095
TOP	2	10	0.003059	-0.000510	0.000373	0.003015	-0.000466	-0.000871	0.546886	0.003916	-0.006242
BOT	2	10	0.003321	-0.000553	0.000403	0.003273	-0.000505	-0.000946	0.593686	0.004255	-0.006786
TOP	1	0	0.003321	-0.000553	0.000403	0.003321	-0.000553	0.000403	0.602257	0.003898	0.002890
BOT	1	0	0.003583	-0.000597	0.000434	0.003583	-0.000597	0.000434	0.649773	0.004207	0.003108

Table C.2: Design 3 Failure Criterion Safety Factor R Values: Load Case 1

			Maximum Stress					Quad Poly		Hashin Criterion			
Position	Ply	Angle	FT	FC	MT	MC	S	(+)	(-)	FT	FC	MT	MC
TOP	17	0	0.000	2.204	0.000	55.442	22.568	2.555	-2.065	0.000	2.204	0.000	26.158
BOT	17	0	0.000	2.369	0.000	59.588	24.333	2.747	-2.220	0.000	2.369	0.000	28.193
TOP	16	10	0.000	2.407	0.000	54.112	9.245	2.746	-2.177	0.000	2.407	0.000	10.621
BOT	16	10	0.000	2.603	0.000	58.465	9.983	2.969	-2.353	0.000	2.603	0.000	11.468
TOP	15	17	0.000	2.747	0.000	44.984	5.247	2.971	-2.217	0.000	2.747	0.000	5.843
BOT	15	17	0.000	2.990	0.000	48.918	5.707	3.234	-2.413	0.000	2.990	0.000	6.355
TOP	14	-17	0.000	3.200	0.000	38.447	4.297	3.251	-2.265	0.000	3.200	0.000	4.769
BOT	14	-17	0.000	3.509	0.000	42.184	4.717	3.566	-2.485	0.000	3.509	0.000	5.234
TOP	13	37	0.000	4.809	0.000	23.115	3.216	3.776	-2.051	0.000	4.809	0.000	3.633
BOT	13	37	0.000	5.327	0.000	25.575	3.560	4.182	-2.270	0.000	5.327	0.000	4.022
TOP	12	-37	0.000	6.369	0.000	21.324	3.373	4.365	-2.125	0.000	6.369	0.000	3.851
BOT	12	-37	0.000	7.129	0.000	23.898	3.779	4.890	-2.381	0.000	7.129	0.000	4.315
TOP	11	35	0.000	5.642	0.000	30.807	4.109	4.627	-2.609	0.000	5.642	0.000	4.626
BOT	11	35	0.000	6.416	0.000	34.972	4.669	5.260	-2.964	0.000	6.416	0.000	5.257
TOP	10	13	0.000	4.465	0.000	88.437	11.934	4.998	-3.871	0.000	4.465	0.000	13.448
BOT	10	13	0.000	5.173	0.000	102.179	13.782	5.790	-4.482	0.000	5.173	0.000	15.529
TOP	8	13	5.739	0.000	19.215	0.000	16.063	5.019	-6.423	5.404	0.000	12.324	0.000
BOT	8	13	4.881	0.000	16.288	0.000	13.608	4.265	-5.463	4.594	0.000	10.443	0.000
TOP	7	35	6.960	0.000	6.372	0.000	5.147	3.270	-5.736	4.138	0.000	4.004	0.000
BOT	7	35	6.058	0.000	5.534	0.000	4.475	2.843	-4.991	3.599	0.000	3.479	0.000
TOP	6	-37	7.851	0.000	4.174	0.000	4.079	2.570	-5.305	3.620	0.000	2.917	0.000
BOT	6	-37	6.939	0.000	3.695	0.000	3.610	2.274	-4.694	3.203	0.000	2.582	0.000
TOP	5	37	5.671	0.000	4.539	0.000	3.836	2.450	-4.472	3.178	0.000	2.930	0.000
BOT	5	37	5.088	0.000	4.066	0.000	3.439	2.197	-4.011	2.849	0.000	2.626	0.000
TOP	4	-17	3.760	0.000	7.267	0.000	4.959	2.641	-3.797	2.996	0.000	4.096	0.000
BOT	4	-17	3.408	0.000	6.589	0.000	4.498	2.394	-3.442	2.716	0.000	3.715	0.000
TOP	3	17	3.162	0.000	8.609	0.000	6.153	2.567	-3.422	2.812	0.000	5.006	0.000
BOT	3	17	2.891	0.000	7.865	0.000	5.622	2.347	-3.129	2.571	0.000	4.574	0.000
TOP	2	10	2.743	0.000	10.214	0.000	10.894	2.489	-3.127	2.660	0.000	7.451	0.000
BOT	2	10	2.527	0.000	9.401	0.000	10.021	2.292	-2.880	2.450	0.000	6.856	0.000
TOP	1	0	2.491	0.000	10.262	0.000	23.531	2.333	-2.881	2.477	0.000	9.406	0.000
BOT	1	0	2.308	0.000	9.509	0.000	21.876	2.162	-2.671	2.296	0.000	8.720	0.000

Table C.3: Design 3 Stress and Strain Values: Load Case 2

Position	Ply	Angle	ϵ_1	ϵ_2	ϵ_6	ϵ_x	ϵ_y	ϵ_s	σ_x	σ_y	σ_s
		(^{o})							(GPa)	(GPa)	(GPa)
TOP	17	0	-0.003661	0.000719	-0.000744	-0.003661	0.000719	-0.000744	-0.663574	-0.003164	-0.005332
BOT	17	0	-0.003406	0.000674	-0.000691	-0.003406	0.000674	-0.000691	-0.617318	-0.002892	-0.004955
TOP	16	10	-0.003406	0.000674	-0.000691	-0.003401	0.000669	0.000746	-0.616447	-0.002928	0.005350
BOT	16	10	-0.003151	0.000629	-0.000638	-0.003146	0.000624	0.000693	-0.570201	-0.002656	0.004968
TOP	15	17	-0.003151	0.000629	-0.000638	-0.003006	0.000484	0.001584	-0.545186	-0.003698	0.011361
BOT	15	17	-0.002896	0.000584	-0.000586	-0.002762	0.000450	0.001460	-0.500890	-0.003344	0.010469
TOP	14	-17	-0.002896	0.000584	-0.000586	-0.002435	0.000123	-0.002431	-0.442283	-0.005785	-0.017433
BOT	14	-17	-0.002641	0.000539	-0.000533	-0.002220	0.000118	-0.002220	-0.403251	-0.005212	-0.015917
TOP	13	37	-0.002641	0.000539	-0.000533	-0.001745	-0.000357	0.002909	-0.318376	-0.008746	0.020859
BOT	13	37	-0.002386	0.000493	-0.000481	-0.001574	-0.000318	0.002635	-0.287056	-0.007852	0.018893
TOP	12	-37	-0.002386	0.000493	-0.000481	-0.001112	-0.000780	-0.002900	-0.204406	-0.011293	-0.020793
BOT	12	-37	-0.002130	0.000448	-0.000428	-0.000991	-0.000691	-0.002597	-0.182134	-0.010023	-0.018619
TOP	11	35	-0.002130	0.000448	-0.000428	-0.001483	-0.000199	0.002277	-0.270223	-0.006355	0.016325
BOT	11	35	-0.001875	0.000403	-0.000375	-0.001302	-0.000170	0.002013	-0.237220	-0.005532	0.014430
TOP	10	13	-0.001875	0.000403	-0.000375	-0.001842	0.000370	0.000661	-0.333868	-0.001508	0.004742
BOT	10	13	-0.001620	0.000358	-0.000323	-0.001591	0.000329	0.000577	-0.288267	-0.001209	0.004138
TOP	8	13	0.001442	-0.000184	0.000309	0.001427	-0.000170	-0.000435	0.258947	0.002380	-0.003121
BOT	8	13	0.001697	-0.000229	0.000361	0.001678	-0.000211	-0.000520	0.304548	0.002679	-0.003726
TOP	7	35	0.001697	-0.000229	0.000361	0.001233	0.000235	-0.001686	0.224815	0.005999	-0.012091
BOT	7	35	0.001952	-0.000275	0.000414	0.001414	0.000264	-0.001951	0.257818	0.006822	-0.013986
TOP	6	-37	0.001952	-0.000275	0.000414	0.000947	0.000731	0.002254	0.174223	0.010303	0.016163
BOT	6	-37	0.002207	-0.000320	0.000466	0.001068	0.000820	0.002557	0.196495	0.011573	0.018337
TOP	5	37	0.002207	-0.000320	0.000466	0.001516	0.000371	-0.002300	0.276716	0.008233	-0.016493
BOT	5	37	0.002462	-0.000365	0.000519	0.001688	0.000410	-0.002574	0.308036	0.009127	-0.018459
TOP	4	-17	0.002462	-0.000365	0.000519	0.002075	0.000022	0.002011	0.377390	0.006239	0.014420
BOT	4	-17	0.002717	-0.000410	0.000572	0.002290	0.000017	0.002223	0.416423	0.006811	0.015937
TOP	3	17	0.002717	-0.000410	0.000572	0.002610	-0.000303	-0.001275	0.473617	0.004430	-0.009141
BOT	3	17	0.002972	-0.000455	0.000624	0.002854	-0.000337	-0.001399	0.517912	0.004784	-0.010032
TOP	2	10	0.002972	-0.000455	0.000624	0.002976	-0.000459	-0.000586	0.539714	0.003876	-0.004199
BOT	2	10	0.003228	-0.000500	0.000677	0.003231	-0.000504	-0.000639	0.585961	0.004148	-0.004581
TOP	1	0	0.003228	-0.000500	0.000677	0.003228	-0.000500	0.000677	0.585363	0.004173	0.004853
BOT	1	0	0.003483	-0.000546	0.000730	0.003483	-0.000546	0.000730	0.631619	0.004445	0.005231

Table C.4: Design 3 Failure Criterion Safety Factor R Values: Load Case 2

			Maximum Stress					Quad Poly		Hashin Criterion			
Position	Ply	Angle	FT	FC	MT	MC	S	(+)	(-)	FT	FC	MT	MC
TOP	17	0	0.000	2.260	0.000	77.752	12.754	2.484	-2.133	0.000	2.260	0.000	14.604
BOT	17	0	0.000	2.430	0.000	85.057	13.725	2.665	-2.295	0.000	2.430	0.000	15.696
TOP	16	10	0.000	2.433	0.000	84.005	12.710	2.665	-2.291	0.000	2.433	0.000	14.458
BOT	16	10	0.000	2.631	0.000	92.612	13.687	2.874	-2.478	0.000	2.631	0.000	15.540
TOP	15	17	0.000	2.751	0.000	66.527	5.986	2.876	-2.352	0.000	2.751	0.000	6.534
BOT	15	17	0.000	2.995	0.000	73.557	6.495	3.121	-2.561	0.000	2.995	0.000	7.081
TOP	14	-17	0.000	3.391	0.000	42.527	3.901	3.155	-2.283	0.000	3.391	0.000	4.264
BOT	14	-17	0.000	3.720	0.000	47.199	4.272	3.449	-2.506	0.000	3.720	0.000	4.666
TOP	13	37	0.000	4.711	0.000	28.128	3.260	3.597	-2.169	0.000	4.711	0.000	3.628
BOT	13	37	0.000	5.225	0.000	31.329	3.599	3.968	-2.402	0.000	5.225	0.000	4.003
TOP	12	-37	0.000	7.338	0.000	21.783	3.270	4.288	-2.129	0.000	7.338	0.000	3.718
BOT	12	-37	0.000	8.236	0.000	24.544	3.652	4.780	-2.387	0.000	8.236	0.000	4.149
TOP	11	35	0.000	5.551	0.000	38.708	4.165	4.375	-2.765	0.000	5.551	0.000	4.609
BOT	11	35	0.000	6.323	0.000	44.471	4.712	4.944	-3.144	0.000	6.323	0.000	5.207
TOP	10	13	0.000	4.493	0.000	163.156	14.339	4.736	-4.120	0.000	4.493	0.000	15.626
BOT	10	13	0.000	5.204	0.000	203.520	16.435	5.440	-4.782	0.000	5.204	0.000	17.805
TOP	8	13	5.793	0.000	16.809	0.000	21.787	5.126	-6.883	5.598	0.000	13.308	0.000
BOT	8	13	4.925	0.000	14.932	0.000	18.250	4.373	-5.794	4.755	0.000	11.557	0.000
TOP	7	35	6.672	0.000	6.668	0.000	5.624	3.423	-6.003	4.300	0.000	4.299	0.000
BOT	7	35	5.818	0.000	5.863	0.000	4.862	2.979	-5.184	3.731	0.000	3.743	0.000
TOP	6	-37	8.610	0.000	3.882	0.000	4.207	2.556	-5.695	3.780	0.000	2.853	0.000
BOT	6	-37	7.634	0.000	3.456	0.000	3.708	2.263	-5.010	3.336	0.000	2.528	0.000
TOP	5	37	5.421	0.000	4.859	0.000	4.123	2.569	-4.610	3.282	0.000	3.144	0.000
BOT	5	37	4.870	0.000	4.383	0.000	3.684	2.304	-4.116	2.938	0.000	2.820	0.000
TOP	4	-17	3.975	0.000	6.411	0.000	4.716	2.614	-3.969	3.039	0.000	3.799	0.000
BOT	4	-17	3.602	0.000	5.872	0.000	4.267	2.372	-3.584	2.752	0.000	3.452	0.000
TOP	3	17	3.167	0.000	9.029	0.000	7.439	2.669	-3.547	2.914	0.000	5.741	0.000
BOT	3	17	2.896	0.000	8.362	0.000	6.778	2.442	-3.233	2.663	0.000	5.266	0.000
TOP	2	10	2.779	0.000	10.320	0.000	16.192	2.561	-3.233	2.739	0.000	8.703	0.000
BOT	2	10	2.560	0.000	9.643	0.000	14.842	2.361	-2.971	2.523	0.000	8.086	0.000
TOP	1	0	2.563	0.000	9.586	0.000	14.011	2.358	-2.971	2.521	0.000	7.911	0.000
BOT	1	0	2.375	0.000	9.000	0.000	13.001	2.188	-2.747	2.336	0.000	7.400	0.000