Example 7c: Electromagnetic Laminate Analysis

This example problem considers an electromagnetic (smart) composite laminate. In particular, a hybrid smart/metal matrix composite laminate is analyzed consisting of a unidirectional B/Al layer sandwiched between two $BaTiO_3/CoFe_2O_4$ layers (see Figure 7.4). By reversing the electromagnetic polarity of the bottom smart composite layer, a completely different laminate response can be obtained. The applied loading involves a through-thickness magnetic field component.

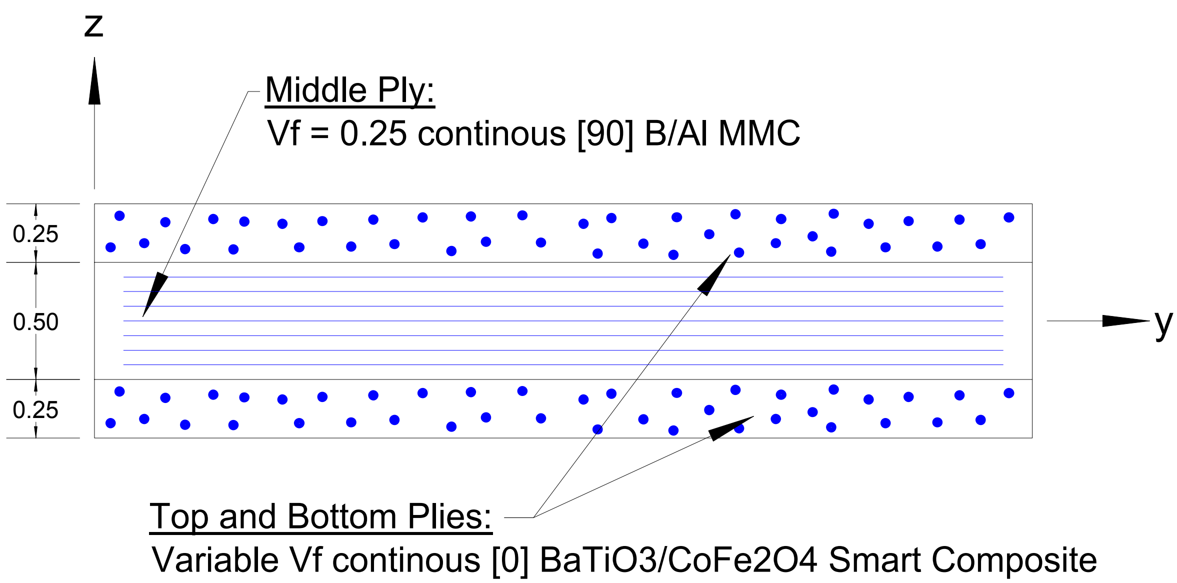

Figure 7.4 Hybrid smart/MMC laminate analyzed in MAC/GMC 4.0 Example Problem 7c.

MAC/GMC Input File: `example_7c.mac`

```
MAC/GMC 4.0 Example 7c - Electromagnetic laminate analysis
*ELECTROMAG
*CONSTITUENTS
  NMATS=5
# -- BaTiO3 (Barium Titanate)
  M=1 CMOD=9 MATID=U MATDB=1 EM=1 &
  EL=111.93E9,116.33E9,0.321,0.307,43.0E9,1.99E-6,8.53E-6 &
  D=1.,0.,0.
  ES=18.6,-4.4,11.6
  QS=0.0,0.0,0.0
  KS=12.6E-9,11.2E-9
  AS=0.0,0.0
  MS=10.0E-6,5.0E-6
  PELS=0.13E5,0.13E5
  PMGS=0.0,0.0
```

```
# -- CoFe2O4 (Cobalt Ferrite) - positive poling direction
  M=2 CMOD=9 MATID=U MATDB=1 EM=1 &
  EL=143.57E9,154.57E9,0.37,0.368,45.3E9,0.00E-6,0.00E-6 &
  D=0.,0.,1.
  ES=0.0,0.0,0.0
  QS=699.7,580.3,550.
  KS=0.93E-10,0.08E-9
  AS=0.0,0.0
  MS=157.E-6,-590.E-6
  PELS=0.0,0.0
  PMGS=0.0,0.0
# -- CoFe2O4 (Cobalt Ferrite) - negative poling direction
  M=3 CMOD=9 MATID=U MATDB=1 EM=1 &
  EL=143.57E9,154.57E9,0.37,0.368,45.3E9,0.00E-6,0.00E-6 &
  D=0.,0.,-1.
  ES=0.0,0.0,0.0
  QS=699.7,580.3,550.
  KS=0.93E-10,0.08E-9
  AS=0.0,0.0
  MS=157.E-6,-590.E-6
  PELS=0.0,0.0
  PMGS=0.0,0.0
# -- Boron
  M=4 CMOD=6 MATID=U MATDB=1 EM=0 &
  EL=400.E9,400.E9,0.20,0.20,166.6667E9,8.3E-6,8.3E-6
# -- Aluminum
  M=5 CMOD=1 MATID=U MATDB=1 EM=0 &
  EL=72.6E9,72.6E9,0.33,0.33,72.283E9,22.5E-6,22.5E-6 &
  VI=1.E4,65.E6,150.E6,50.,10.,1.
*LAMINATE
  NLY=3
  LY=1 THK=0.25 ANG=0. MOD=3 ARCHID=99 EM=1
   NA=1 NB=2 NG=2
   D=1.
   H=0.5,0.5
   L=0.5,0.5
   SM=1,2
   SM=2,2
  LY=2 THK=0.5 ANG=90. MOD=2 ARCHID=1 VF=0.25 F=4 M=5 EM=0
  LY=3 THK=0.25 ANG=0. MOD=3 ARCHID=99 EM=1
   NA=1 NB=2 NG=2
   D=1.
   H=0.5,0.5
   L=0.5,0.5
   SM=1,2
   SM=2,2
#   SM=1,3
#   SM=3,3
*MECH
  LOP=99
  NPT=2 TI=0.,600. MAG=0.,0. MODE=2
  NPT=2 TI=0.,600. MAG=0.,0. MODE=2
  NPT=2 TI=0.,600. MAG=0.,0. MODE=2
  NPT=2 TI=0.,600. MAG=0.,0. MODE=2
  NPT=2 TI=0.,600. MAG=0.,0. MODE=2
  NPT=2 TI=0.,600. MAG=0.,0. MODE=2
  NPT=2 TI=0.,600. MAG=0.,0. MODE=1
```

```
  NPT=2 TI=0.,600. MAG=0.,0. MODE=1
  NPT=2 TI=0.,600. MAG=0.,0. MODE=2
  NPT=2 TI=0.,600. MAG=0.,0. MODE=1
  NPT=2 TI=0.,600. MAG=0.,0. MODE=1
  NPT=2 TI=0.,600. MAG=0.,6.E6 MODE=1
*THERM
  NPT=2 TI=0.,600. TEMP=24.,24.
*SOLVER
  METHOD=1 NPT=2 TI=0.,600. STP=0.25
*PRINT
  NPL=8
*XYPLOT
  FREQ=40
  LAMINATE=5
   NAME=example_7c_ex X=34 Y=1
   NAME=example_7c_ey X=34 Y=2
   NAME=example_7c_ez X=34 Y=3
   NAME=example_7c_kx X=34 Y=7
   NAME=example_7c_ky X=34 Y=8
  MACRO=0
  MICRO=0
*END
```

Annotated Input Data

1) Flags:
   a) Perform electromagnetic analysis (**`*ELECTROMAG`**) [KM_1]:

2) Constituent materials (**`*CONSTITUENTS`**) [KM_2]:

Number of materials:	5	(`NMATS=5`)
Materials:	User-Defined	(`MATID=U`)
Constitutive models:	Arbitrary transversely isotropic	(`CMOD=9`)
	Linearly elastic	(`CMOD=6`)
	Bodner-Partom	(`CMOD=1`)
Material property source:	Read from input file	(`MATDB=1`)
Electromagnetic specifier:	Material is electromagnetic	(`EM=1`)
	Material is not electromagnetic	(`EM=0`)

The boron and aluminum materials are specified with `EM=0` to indicate that they do not have electromagnetic properties associated with them. The cobalt ferrite material properties are specified twice – each time with a different direction vector. Since the direction vector is a material property, the same material with only a change in direction vector constitutes a new material. In the present case, the sign of the direction vector of the cobalt ferrite is reversed. While this has no effect on the mechanical properties, it causes a sign reversal in the material's electromagnetic properties.

3) Analysis type (**`*LAMINATE`**) → Laminate Analysis [KM_3]:

Number of layers:	3	(`NLY=3`)

Layer	**Analysis Model**	**Thickness**	**Fiber Angle**	**Architecture**	**Volume fraction**	**Fiber material**	**Matrix material**	**E-M Specifier**
(LY=)	(MOD)	(THK)	(ANG)	(ARCHID)	(VF)	(F)	(M)	(EM)
1	GMC-3D	0.25	90°	short fiber square array	0.25	$BaTiO_3$	$CoFe_2O_4$	electro-magnetic
2	GMC-2D	0.50	0°	short fiber square array	0.25	boron	aluminum	not electro-magnetic
3	GMC-3D	0.25	90°	short fiber square array	0.25	$BaTiO_3$	$CoFe_2O_4$	Electro-magnetic

For electromagnetic laminate analysis, there is an additional piece of information required for each layer that specifies whether or not the layer is electromagnetic. `EM=1` indicates that the layer is electromagnetic, while `EM=0` indicates that the layer is not electromagnetic.

☞ Note: To generate the results for the magnetically asymmetric laminate, the appropriate lines in the input file must be commented and uncommented.

4) Loading:
a) Mechanical (**`*MECH`**) [KM_4]:

Loading option: general loading (`LOP=99`)

Component #1 (ε^0_{xx} or N_{xx})
Number of points: 2 (`NPT=2`)

Times (`TI=`) (sec.)	0.	600.
Magnitudes (`MAG=`)	0.	0.
Control (`MODE=`)	force resultant	

Component #2 (ε^0_{yy} or N_{yy})
Number of points: 2 (`NPT=2`)

Times (`TI=`) (sec.)	0.	600.
Magnitudes (`MAG=`)	0.	0.
Control (`MODE=`)	force resultant	

Component #3 (γ^0_{xy} or N_{xy})
Number of points: 2 (`NPT=2`)

Times (`TI=`) (sec.)	0.	600.
Magnitudes (`MAG=`)	0.	0.02
Control (`MODE=`)	force resultant	

Component #4 (κ_{xx} or M_{xx})
Number of points: 2 (`NPT=2`)

Times (TI=) (sec.)	0.	600.
Magnitudes (MAG=)	0.	0.
Control (MODE=)	moment resultant	

Component #5 (κ_{yy} or M_{yy})
Number of points: 2 (NPT=2)

Times (TI=) (sec.)	0.	600.
Magnitudes (MAG=)	0.	0.
Control (MODE=)	moment resultant	

Component #6 (κ_{xy} or M_{xy})
Number of points: 2 (NPT=2)

Times (TI=) (sec.)	0.	600.
Magnitudes (MAG=)	0.	0.
Control (MODE=)	moment resultant	

Component #7 (E_1)
Number of points: 2 (NPT=2)

Times (TI=) (sec.)	0.	600.
Magnitudes (MAG=)	0.	0.
Control (MODE=)	electric field (E_1)	

Component #8 (E_2)
Number of points: 2 (NPT=2)

Times (TI=) (sec.)	0.	600.
Magnitudes (MAG=)	0.	0.
Control (MODE=)	electric field (E_2)	

Component #9 (E_3)
Number of points: 2 (NPT=2)

Times (TI=) (sec.)	0.	600.
Magnitudes (MAG=)	0.	0.
Control (MODE=)	electric field (E_3)	

Component #10 (H_1)
Number of points: 2 (NPT=2)

Times (TI=) (sec.)	0.	600.
Magnitudes (MAG=)	0.	0.
Control (MODE=)	magnetic field (H_1)	

Component #11 (H_2)
Number of points: 2 (NPT=2)

Times (TI=) (sec.)	0.	600.
Magnitudes (MAG=)	0.	0.
Control (MODE=)	magnetic field (H_2)	

Component #12 (H_3)
Number of points: 2 (NPT=2)

Times (TI=) (sec.)	0.	600.
Magnitudes (MAG=)	0.	6,000,000 A/m
Control (MODE=)	magnetic field (H_3)	

☞ Note: Currently, in the case of an electromagnetic laminate, only electromagnetic field components (E_k and H_k) may be applied. The electromagnetic lamination theory does not admit application of laminate level electric displacements (D_k) or magnetic flux density components (B_k), although average laminate electric displacements and magnetic flux densities can arise. For more information on loading specification for electromagnetic analysis, see the MAC/GMC Keywords Manual Section 4.

b) Thermal (***THERM**) [KM_4]:
Number of points: 2 (NPT=2)
Time points: 0., 600. sec. (TI=0.,600.)
Temperature points: 24., 24. (TEMP=24.,24.)

c) Time integration (***SOLVER**) [KM_4]:
Time integration method: Forward Euler (METHOD=1)
Number of points: 2 (NPT=2)
Time points: 0., 600. sec. (TI=0.,600.)
Time step size: 0.25 sec. (STP=0.25)

☞ Note: Unlike Example Problem 7b, this example problem contains an inelastic material (aluminum). Thus, a small time step must be employed to achieve convergence.

5) Damage and Failure: None

6) Output:
a) Output file print level (***PRINT**) [KM_6]:
Print level: 8 (NPL=8)

b) x-y plots (***XYPLOT**) [KM_6]:
Frequency: 40 (FREQ=40)
Number of laminate plots: 5 (LAMINATE=5)
Laminate plot name: example_7c_ex (NAME=example_7c_ex)
example_7c_ey (NAME=example_7c_ey)
example_7c_ez (NAME=example_7c_ez)
example_7c_kx (NAME=example_7c_kx)
example_7c_ky (NAME=example_7c_ky)

Laminate plot x-y quantities:	H_z, ε^0_{xx}	(X=34 Y=1)
	H_z, ε^0_{yy}	(X=34 Y=2)
	H_z, $\bar{\varepsilon}_{zz}$	(X=34 Y=3)
	H_z, κ_{xx}	(X=34 Y=7)
	H_z, κ_{yy}	(X=34 Y=8)
Number of macro plots:	0	(MACRO=0)
Number of micro plots:	0	(MICRO=0)

7) End of file keyword: (***END**)

Results

This example problem highlights the effect of reversing the magnetic polarity of the $CoFe_2O_4$ in one of the $BaTiO_3/CoFe_2O_4$ layers in the hybrid smart/MMC laminate. First, for the case in which the poling direction of both 0° $BaTiO_3/CoFe_2O_4$ layers is the x_3-direction (laminate z-direction), the laminate responds to the applied through-thickness magnetic field with extension (midplane strains), but no curvature. The midplane strain response of the magnetically symmetric laminate is plotted in Figure 7.5. Also plotted is the average through-thickness strain in the laminate. The laminate exhibits more midplane strain in the x-direction than the y-direction because the continuous and stiff boron fibers of the middle 90° layer are oriented in the y-direction. The out-of-plane strain is of the largest magnitude because of the large effect piezomagnetic term q_{33} of the smart plies. It is clear from the knees in the curves plotted in Figure 7.5 the point at which yielding commences in the B/Al ply. The MAC/GMC 4.0 output file confirms that, in addition to non-zero magnetic force resultants, non-zero inelastic force resultants arise in the laminate. It should be noted that, in addition to the strains, the laminate experiences an average electric displacement component, D_x, and an average magnetic flux component B_z.

When the poling direction of the $CoFe_2O_4$ in the bottom 0° $BaTiO_3/CoFe_2O_4$ layer is reversed, the laminate responds to the applied through-thickness magnetic field in a completely different way. As shown in Figure 7.6, this magnetically asymmetric laminate responds with curvature but no midplane extension. The reversal in poling direction causes a reversal of the sign of the effective q_{ij} and a_{ij} terms for the bottom smart composite layer; the signs are now opposite of those in the top smart composite layer, causing the magnetic asymmetry. As a result, magnetic moment resultants, rather than force resultants, arise in the composite due to the applied magnetic field. An identical average magnetic flux component, B_z arises in the magnetically asymmetric laminate, but the average electric displacement component, D_x, that was present in the magnetically symmetric laminate, is now zero. Note that, mechanically, the two laminates are identical, with identical ABD matrices. A slight knee is present in the curves of Figure 7.6, but the effect of the B/Al ply inelasticity is much smaller than in the magnetically symmetric laminate. The magnitude of the curvature is smaller in the y-direction than the x-direction due to the stiff boron fibers oriented along the y-direction.

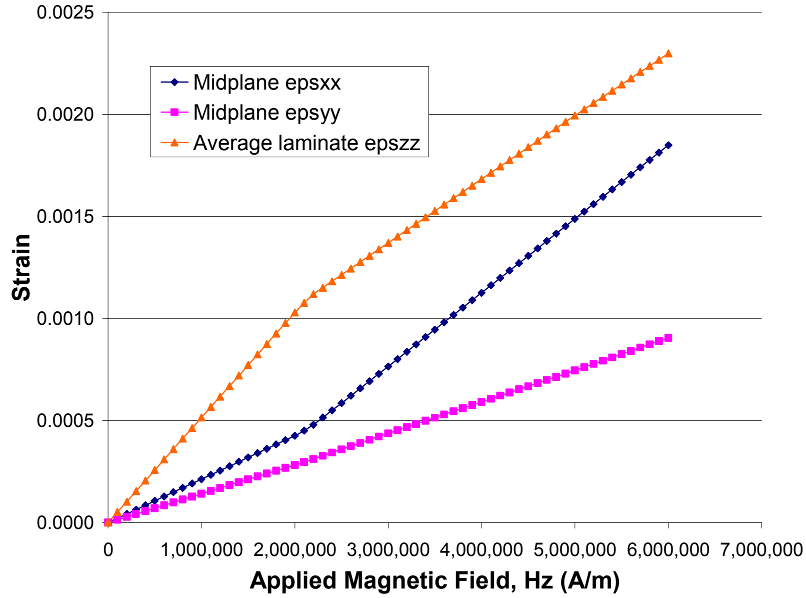

Figure 7.5 Example 7c: Strain response of a symmetric [0°/90°]$_s$ hybrid smart/MMC laminate to an applied through-thickness magnetic field.

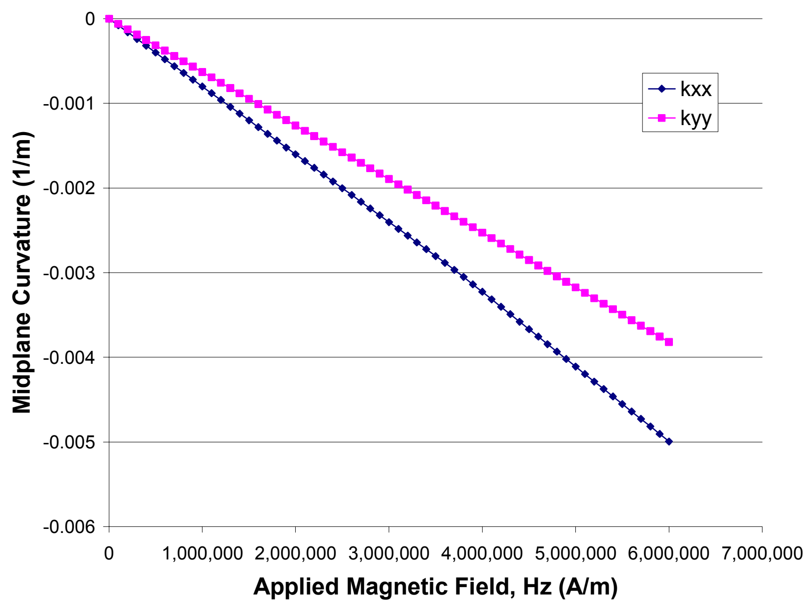

Figure 7.6 Example 7c: Curvature response of a magnetically asymmetric [0°/90°]$_s$ hybrid smart/MMC laminate to an applied through-thickness magnetic field.