TRANSTRAIN: A PROGRAM TO COMPUTE STRAIN TRANSFORMATIONS IN COMPOSITE MATERIALS

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Science and Engineering Directorate

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**Title and Subtitle**

TRANSTRAIN: A Program to Compute Strain Transformations in Composite Materials

**Author(s)**

Rafiq Ahmed

**Abstract**

This report documents a computer program that generates strain transformations and on-axis stresses in composites given the initial strains and the transformation angles.
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TECHNICAL MEMORANDUM

TRANSTRAIN: A PROGRAM TO COMPUTE STRAIN TRANSFORMATIONS IN COMPOSITE MATERIALS

INTRODUCTION

Over the years, the solid rocket motor community has made increasing use of composite materials for thermal and structural applications. This is particularly true of solid rocket nozzles, which have used carbon phenolic and, increasingly, carbon-carbon materials to provide structural integrity and thermal protection at the high temperatures encountered during motor burn.

To evaluate the degree of structural performance of nozzles and their materials and to verify analysis models, many subscale and full-scale tests are run. These provide engineers with valuable data needed to optimize design and to analyze nozzle hardware. Included among these data are strains, pressures, thrust, temperatures, and displacements. Recent nozzle test hardware has made increasing use of strain gauges embedded in the carbon composite material to measure internal strains. In order to evaluate strength, these data must be transformed into strains along the fiber directions. The fiber-direction stresses can then be calculated. This report concentrates on a computer program written to help engineers correctly manipulate the strain data into a form that can be used to evaluate structural integrity of the nozzle.

OBJECTIVE

The objective of this report is to describe a tool that can be used to transform strains from an arbitrary direction to the on-axis strains along and orthogonal to the fiber directions. The on-axis stresses are subsequently calculated. A computer program was developed to simplify and ease this process.

THEORETICAL BACKGROUND

The program performs the following two steps to find the desired data:

1. Three-axis strain rotation to find the transformed strains

2. On-axis stress computation for an orthotropic material using Gaussian elimination given the compliance matrix.
The program begins with the input data read from the file STR.INP, which contains the three input transformation angles (THETA, GAMMA, and ALPHA), the material properties (Young's moduli, Poisson's ratios, and shear moduli), and the input strains. An orthotropic material is assumed (i.e., no coupling exists between normal and shear stresses).

The three-axis rotation was chosen because it is the most general case and will cover most composite orientations. The initial coordinate system is defined as \( \{x_1, y_1, z_1\} \). The second coordinate system (after the first transformation) is defined as \( \{x_2, y_2, z_2\} \). The third coordinate system is defined as \( \{x_3, y_3, z_3\} \) with the final, transformed coordinate system being defined as \( \{x_4, y_4, z_4\} \). \( \theta \) is the angle of rotation about the \( z_1 \) axis, with \( \gamma \) and \( \alpha \) being the respective rotations about the \( y_2 \) and \( x_3 \) axes. A typical coordinate transformation is shown diagramatically in figure 1. The three coordinate transformations are, respectively:

\[
\begin{align*}
\begin{pmatrix}
  x_2 \\
  y_2 \\
  z_2
\end{pmatrix} &=
\begin{bmatrix}
  \cos \theta & \sin \theta & 0 \\
  -\sin \theta & \cos \theta & 0 \\
  0 & 0 & 1
\end{bmatrix}
\begin{pmatrix}
  x_1 \\
  y_1 \\
  z_1
\end{pmatrix} \\
\begin{pmatrix}
  x_3 \\
  y_3 \\
  z_3
\end{pmatrix} &=
\begin{bmatrix}
  \cos \gamma & 0 & \sin \gamma \\
  0 & 1 & 0 \\
  -\sin \gamma & 0 & \cos \gamma
\end{bmatrix}
\begin{pmatrix}
  x_2 \\
  y_2 \\
  z_2
\end{pmatrix} \\
\begin{pmatrix}
  x_4 \\
  y_4 \\
  z_4
\end{pmatrix} &=
\begin{bmatrix}
  1 & 0 & 0 \\
  0 & \cos \alpha & \sin \alpha \\
  0 & -\sin \alpha & \cos \alpha
\end{bmatrix}
\begin{pmatrix}
  x_3 \\
  y_3 \\
  z_3
\end{pmatrix}
\end{align*}
\]

The combined transformation matrix, \([a]\), is found by matrix multiplication:

\[
\begin{bmatrix}
  \cos \gamma \cos \theta & \cos \gamma \sin \theta & \sin \gamma \\
  -\sin \gamma \cos \theta - \cos \gamma \sin \theta & -\sin \gamma \sin \theta + \cos \gamma \cos \theta & \sin \alpha \cos \gamma \\
  -\cos \gamma \cos \theta + \sin \gamma \sin \theta & -\cos \gamma \sin \theta - \sin \gamma \cos \theta & \cos \alpha \cos \gamma
\end{bmatrix}
\]

After this matrix is calculated, the transformed strains are calculated by using the continuum mechanics relation for strain transformations:

\[
\varepsilon_{ij} = a_{ir} \varepsilon_{rj}
\]
After the transformed strains are calculated, the subroutine TRANS converts them from double index notation to single index notations as follows:

\[
\begin{align*}
\varepsilon_1 &= \varepsilon_{11} \\
\varepsilon_2 &= \varepsilon_{22} \\
\varepsilon_3 &= \varepsilon_{33} \\
\varepsilon_4 &= \varepsilon_{23} \\
\varepsilon_5 &= \varepsilon_{13} \\
\varepsilon_6 &= \varepsilon_{12}
\end{align*}
\]

Finally, the subroutines ORTHOCOMP and ORTHOSTR are called to calculate the on-axis stresses. This is accomplished by solving for the stresses from the strain-stress relationship using Gaussian elimination (performed by GAUSS). The strain-stress relationship (compliance matrix) is derived from the material properties in the subroutine ORTHOCOMP. The strain-stress relationship is shown in the following expression:

\[
\begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\varepsilon_3 \\
\varepsilon_4 \\
\varepsilon_5 \\
\varepsilon_6
\end{bmatrix} =
\begin{bmatrix}
1/E_1 & -v_{12}/E_2 & -v_{13}/E_3 & 0 & 0 & 0 \\
-v_{21}/E_1 & 1/E_2 & -v_{23}/E_3 & 0 & 0 & 0 \\
-v_{31}/E_1 & -v_{32}/E_2 & 1/E_3 & 0 & 0 & 0 \\
0 & 0 & 0 & 1/G_{23} & 0 & 0 \\
0 & 0 & 0 & 0 & 1/G_{13} & 0 \\
0 & 0 & 0 & 0 & 0 & 1/G_{12}
\end{bmatrix}
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
\sigma_4 \\
\sigma_5 \\
\sigma_6
\end{bmatrix}
\]

After all these calculations, the output is written to an output file, "TRSTRAIN.OUT."

**TRANSTRAIN USER’S GUIDE**

The TRANSTRAIN program is currently resident on the Marshall Space Flight Center’s IESL2VAX4 computer under the name "TRANSTRAIN.FOR" and can be copied from the subdirectory ZFA3:[024030.FORTRAN] TRANSTRAIN.FOR. A FORTRAN listing for the program along with sample input and output files are given in the appendix. The input file is written in free format (with commas between each of the entries on a given line) and must be given the name "STR.INP."
The first line should contain the following items in order:

THETA, GAMMA, ALPHA, E1, E2, E3

where THETA is the rotation angle about the $z_1$ axis, GAMMA is the rotation angle about the $y_2$ axis, ALPHA is the rotation angle about the $x_3$ axis, E1 is the warp direction modulus of elasticity, E2 is the fill direction modulus of elasticity, and E3 is the normal direction (at right angles to both the warp and fill directions) modulus of elasticity. The user should keep in mind that THETA, GAMMA, and ALPHA should be chosen in a coordinate system consistent with the initial strain orientations.

The second line of the input file should contain the following items in order:

NU21, NU32, NU31, G12, G23, G13

where NU21 is the longitudinal fill-warp Poisson's ratio, NU32 is the longitudinal normal-fill Poisson's ratio, NU31 is the longitudinal normal-warp Poisson's ratio, G12 is the warp-fill shear modulus, G23 is the fill-normal shear modulus, and G13 is the warp-normal shear modulus.

Each subsequent line should contain one input strain in the following order:

EPS11, EPS12, EPS13, EPS21, EPS22, EPS23, EPS31, EPS32, EPS33

Each of these lines should contain only one strain. The user should note that the following must be true of the input strain matrix: EPS12 = EPS21, EPS13 = EPS31, and EPS23 = EPS32.

The input file is now complete. To run the program TRANSTRAIN, the user should follow the FORTRAN run/link procedure prescribed for the computer he is using. The output file is named "TRSTRAIN.OUT" and is created automatically by the program.

**SUMMARY**

This code is a relatively simple, easy to use tool for computing three-axis strain transformations and the resulting stresses for an orthotropic material. Since the code was written by making extensive use of subroutines, it is possible to add additional subroutines to take into account monoclinic materials or other material models where shear coupling occurs. This program can thus prove very useful in both testing and analysis applications.
Figure 1. Typical coordinate transformation.
**PROGRAM TRANSTRAIN**

This program computes the transformed strains from a 3-axis rotation and calculates the compliance matrix. The on-axis stresses are then calculated.

**PROGRAM TRANSTRAIN**

```
DIMENSION EPSP(3,3), EPS(3,3), EP(6), S(6,6), SIGON(6)
REAL THETA, GAMMA, ALPHA, T, E1, E2, E3, NU21, NU32, NU31, G12, G23, G13
INTEGER N
N=6
```

Zero out variables and arrays

```
THETA=0.0
GAMMA=0.0
ALPHA=0.0
DO 2001 I=1,3
  DO 2002 J=1,3
    EPSP(I,J)=0.0
    EPS(I,J)=0.0
  2002 CONTINUE
2001 CONTINUE

DO 3001 I=1,6
  DO 3002 J=1,6
    EP(I)=0.0
    SIGON(I)=0.0
  3002 CONTINUE
3001 CONTINUE

DO 4001 I=1,6
  DO 4002 J=1,6
    S(I,J)=0.0
  4002 CONTINUE
4001 CONTINUE
```

Open input and output files

```
OPEN (UNIT=14,FILE='STR.INP',STATUS='OLD')
OPEN (UNIT=16,FILE='TRSTRAIN.OUT', STATUS='NEW')
DO 1001 L=1,3
  DO 1002 M=1,3
    EPSP(L,M)=0
    EPS(L,M)=0
  1002 CONTINUE
1001 CONTINUE
```

Read and write out input data

```
WRITE(16,101)
101 FORMAT(5X ,'**************************************************')
WRITE(16,102)
102 FORMAT(5X, 'TRANSFORMED STRAIN AND ON-AXIS STRESS OUTPUT')
WRITE(16,103)
103 FORMAT(5X ,'**************************************************')
READ (14, *) THETA, GAMMA, ALPHA, E1, E2, E3
READ (14, *) NU21, NU32, NU31, G12, G23, G13
WRITE(16,120)
120 FORMAT(5X, 'THETA', 5X, 'E1', 9X, 'E2', 9X, 'E3')
WRITE(16,121) THETA, GAMMA, ALPHA
121 FORMAT(6X,F4.1,6X,F4.1,6X,F4.1)
WRITE(16,122)
122 FORMAT('E1', 9X, 'E2', 9X, 'E3')
WRITE(16,123) E1, E2, E3
123 FORMAT(5X,F9.1,2X,F9.1,2X,F9.1)
WRITE(16,124)
```
124 FORMAT(//,5X,'NU21',5X,'NU32',5X,'NU31')
WRITE(16,125) NU21,NU32,NU31
125 FORMAT(5X,F4.3,5X,F4.3,5X,F4.3)
WRITE(16,126)
126 FORMAT(//,5X,'G12',8X,'G23',8X,'G13')
WRITE(16,127) G12,G23,G13
127 FORMAT(5X,F9.1,2X,F9.1,2X,F9.1)
WRITE(16,104)
104 FORMAT(//,5X,'INPUT STRAINS')
DO 98 I=1,3
   DO 99 J=1,3
      READ(14,*) EPSP(I,J)
   99 CONTINUE
98 CONTINUE
DO 80 I=1,3
   DO 81 J=1,3
      WRITE(16,105) I,J,EPSP(I,J)
   81 CONTINUE
80 CONTINUE
105 FORMAT(5X,'EPSP(',II,',',II,') = ',F10.7)

C Call subroutines to calculate transformed strains
C CALL TRSTRAIN(THETA, GAMMA, ALPHA, EPSP, EPS)
CALL TRANS(EPS,EP)

C Write out transformed strains
C WRITE(16,107)
107 FORMAT(//,5X,'TRANSFORMED STRAINS')
DO 70 I=1,6
   WRITE(16,106) I,EP(I)
70 CONTINUE
106 FORMAT(SX,'EP(',II,') = ',F10.7)

C Call subroutine to calculate compliance matrix
C CALL ORTHOCOMP(EP,S,E1,E2,E3,NU21,NU32,NU31,G12,G23,G13)

C Write out S matrix
C WRITE(16,108)
108 FORMAT(//,5X,'S MATRIX')
DO 50 I=1,6
   WRITE(16,109) S(I,J),J=1,6
50 CONTINUE
109 FORMAT(5X,E10.4,2X,E10.4,2X,E10.4,2X,E10.4,2X,E10.4,2X,E10.4)

C Call subroutine to calculate on-axis stresses
C CALL ORTHOSTR(EF,S,SIGON,N)

C Write out on-axis stresses
C WRITE(16,110)
110 FORMAT(//,5X,'ON-AXIS STRESSES')
DO 40 I=1,6
   WRITE(16,111) I,SIGON(I)
40 CONTINUE
111 FORMAT(5X,'SIG(',II,') = ',F10.5)
STOP
END
This subroutine computes the transformed strains given
input strain values

**SUBROUTINE TRSTRAIN (TH, GAM, ALP, EPSP, EPS)**

**DIMENSION EPSP(3,3), EPS(3,3), A(3,3)**

Calculate strain transformation matrix

\[
\begin{align*}
\text{PI} & = 3.141592638 \\
A(1,1) & = \cos(\text{GAM*PI/180}) \cdot \cos(\text{TH*PI/180}) \\
A(1,2) & = \cos(\text{GAM*PI/180}) \cdot \sin(\text{TH*PI/180}) \\
A(1,3) & = \sin(\text{GAM*PI/180}) \\
A(2,1) & = -\sin(\text{ALP*PI/180}) \cdot \sin(\text{GAM*PI/180}) \cdot \cos(\text{TH*PI/180}) \cdot \cos(\text{TH*PI/180}) \\
& + \cos(\text{ALP*PI/180}) \cdot \sin(\text{TH*PI/180}) \\
A(2,2) & = -\sin(\text{ALP*PI/180}) \cdot \sin(\text{GAM*PI/180}) \cdot \sin(\text{TH*PI/180}) \cdot \cos(\text{TH*PI/180}) \\
& + \cos(\text{ALP*PI/180}) \cdot \cos(\text{TH*PI/180}) \\
A(2,3) & = \sin(\text{ALP*PI/180}) \cdot \cos(\text{GAM*PI/180}) \\
A(3,1) & = -\cos(\text{ALP*PI/180}) \cdot \sin(\text{GAM*PI/180}) \cdot \cos(\text{TH*PI/180}) \cdot \cos(\text{TH*PI/180}) \\
& + \sin(\text{ALP*PI/180}) \cdot \sin(\text{TH*PI/180}) \\
A(3,2) & = -\cos(\text{ALP*PI/180}) \cdot \sin(\text{GAM*PI/180}) \cdot \sin(\text{TH*PI/180}) \cdot \sin(\text{TH*PI/180}) \\
& - \sin(\text{ALP*PI/180}) \cdot \cos(\text{TH*PI/180}) \\
A(3,3) & = \cos(\text{ALP*PI/180}) \cdot \cos(\text{GAM*PI/180})
\end{align*}
\]

Use strain transformation relation to find transformed strains

**DO 1005 I = 1,3
DO 1006 J = 1,3
EPS(I,J) = 0
DO 1007 R = 1,3
DO 1008 S = 1,3
T = A(I,R) \cdot A(J,S) \cdot EPSP(R,S)
EPS(I,J) = EPS(I,J) + T
1008 CONTINUE
1007 CONTINUE
1006 CONTINUE
1005 CONTINUE
RETURN
END

This subroutine computes the transformed strains in single
index notation

**SUBROUTINE TRANS (EPS,EP)**

**DIMENSION EPS(3,3), EP(6)**

EP(1) = EPS(1,1)
EP(2) = EPS(2,2)
EP(3) = EPS(3,3)
EP(4) = EPS(2,3)
EP(5) = EPS(1,3)
EP(6) = EPS(1,2)
RETURN
END

This subroutine calculates the compliance matrix for an ortho-
tropic material

**SUBROUTINE TRANS (EPS,EP)**

**DIMENSION EPS(3,3), EP(6)**

EP(1) = EPS(1,1)
EP(2) = EPS(2,2)
EP(3) = EPS(3,3)
EP(4) = EPS(2,3)
EP(5) = EPS(1,3)
EP(6) = EPS(1,2)
RETURN
END
SUBROUTINE ORTHOCOMP (EP, S, E1, E2, E3, NU21, NU32, NU31, G12, G23, G13, N, N1)

DIMENSION EP (6), S (6, 6)
REAL E1, E2, E3, NU12, NU21, NU23, NU32, NU31, NU13, NU31, G12, G23, G13, N, N1

NU12 = NU21*E2/E1
NU23 = NU32*E3/E2
NU13 = NU31*E1/E3

DO 1001 I = 1, 6
  DO 1002 J = 1, 6
    S (I, J) = 0
  CONTINUE
CONTINUE

C Compute each term of the S (compliance) matrix for orthotropic material

S (1, 1) = 1/E1
S (1, 2) = -NU12/E2
S (1, 3) = -NU13/E3
S (2, 1) = -NU21/E1
S (2, 2) = 1/E2
S (2, 3) = -NU23/E3
S (3, 1) = -NU31/E1
S (3, 2) = -NU32/E2
S (3, 3) = 1/E3
S (4, 4) = 1/G23
S (5, 5) = 1/G13
S (6, 6) = 1/C12
RETURN
END

****************************************************************
C This subroutine calculates the on-axis stresses from the compliance
C matrix and the transformed strains
****************************************************************

SUBROUTINE ORTHOSTR (EP, S, SIGON, N)

DIMENSION EP (6), S (6, 6), SIGON (6)
INTEGER N

C Call subroutine GAUSS to solve linear equations

CALL GAUSS (EP, N)
DO 500 I = 1, N
  SIGON (I) = EP (I)
500 CONTINUE
RETURN
END

*************************************************************************
C This subroutine solves a system of linear equations via the Gauss-Jordan
C method of elimination
*************************************************************************

SUBROUTINE GAUSS (A, B, N)

DIMENSION A (6, 6), B (6), C (6)
REAL SUM
INTEGER N, N1, K1, K

N1 = N - 1
DO 100 K = 1, N1
  K1 = K + 1
  DO 200 L = K, N
    C (L) = A (K, L)
 200 CONTINUE

AKK = 1/C (K)
BK = B(K)
DO 300 I=K1,N
   AIK = A(I,K)*AKK
   B(I) = B(I) - AIK*BK
DO 400 J=K,N
   A(I,J) = A(I,J) - AIK*C(J)
400 CONTINUE
300 CONTINUE
100 CONTINUE
   K=N
   B(K) = B(K)/A(K,K)
470 K=K-1
   IF (K .LE. 0) THEN
      GOTO 560
   END IF
   K1=K+1
   SUM=0
   DO 700 J=K1,N
      SUM = SUM + A(K,J)*B(J)
700 CONTINUE
   B(K) = (B(K) - SUM)/A(K,K)
   GOTO 470
560 RETURN
END

30.,30.,0.,2600000.,2600000.,2360000.
0.32,0.232,0.232,1000000.,1000000.,1000000.
0.001
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000

This is the STR.INP file
TRANSFORMED STRAIN AND ON-AXIS STRESS OUTPUT

**THETA GAMMA ALPHA**

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<tr>
<td>30.0</td>
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**E1 E2 E3**

<p>| | | |</p>
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**NU21 NU32 NU31**

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<td>0.320</td>
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**G12 G23 G13**

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**INPUT STRAINS**

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**TRANSFORMED STRAINS**

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**S MATRIX**

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**ON-AXIS STRESSES**

| SIG(1) = | 2298.03220 |
| SIG(2) = | 1682.50200 |
| SIG(3) = | 1280.73920 |
| SIG(4) = | 216.50631 |
| SIG(5) = | -324.75952 |
| SIG(6) = | -375.00000 |
BIBLIOGRAPHY


APPROVAL

TRANSTRAIN: A PROGRAM TO COMPUTE STRAIN TRANSFORMATIONS IN COMPOSITE MATERIALS

By Rafiq Ahmed

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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