Example 5b: Subcell Static Failure Analysis

In MAC/GMC 4.0, static failure analysis is completely different from the allowables estimation presented in Example 5a. Since the composite allowables are estimated based on a quick elastic concentration analysis, composite static failure analysis is associated with an entire simulated loading history. During each increment of the applied loading, the specified RUC or subcell failure criteria are checked to determine if failure has occurred. Thus, inelasticity, residual stresses, and even damage can be incorporated within a static failure simulation, giving such a simulation the potential to be considerably more accurate than an allowables estimation. Unlike the estimated allowables, however, a failure stress determined via a MAC/GMC 4.0 simulation is not a property-like quantity for a particular composite. The value can change dramatically based on the loading history applied. Note that the identical graphite/epoxy composite employed in Example 5a is employed in the present example. Now, however, simulated thermal and mechanical loading is applied.

MAC/GMC Input File: example_5b.mac

```
MAC/GMC 4.0 Example 5b - Subcell static failure analysis
*CONSTITUENTS
  NMATS=2
# -- Graphite fiber
  M=1 CMOD=6 MATID=U MATDB=1
  NTP=2
  TEM=23.,150.
  EA=388.2E3,390.E3
  ET=7.6E3,7.6E3
  NUA=0.41,0.41
  NUT=0.45,0.45
  GA=14.9E3,15.1E3
  ALPA=-0.68E-6,-0.45E-6
  ALPT=9.74E-6,10.34E-6
# -- Epoxy matrix
  M=2 CMOD=6 MATID=U MATDB=1
  NTP=2
  TEM=23.,150.
  EA=3.45E3,3.10E3
  ET=3.45E3,3.10E3
  NUA=0.35,0.35
  NUT=0.35,0.35
  GA=1.278E3,1.148E3
  ALPA=45.E-6,55.E-6
  ALPT=45.E-6,55.E-6
*RUC
  MOD=2 ARCHID=13 VF=0.60 R=1. F=1 M=2
*MECH
  LOP=2
  NPT=2 TI=0.,100. MAG=0.,0.02 MODE=1
#  LOP=2 REFTIME=100.
#  NPT=3 TI=0.,100.,200. MAG=0.,0.,0.02 MODE=2,1
*THERM
  NPT=2 TI=0.,100. TEMP=23.,23.
#  NPT=3 TI=0.,100.,200. TEMP=150.,23.,23.
```

```
*SOLVER
  METHOD=1 NPT=2 TI=0.,100. STP=0.1
#  METHOD=1 NPT=3 TI=0.,100.,200. STP=5.,0.1
*ALLOWABLES
  NMAT=2
  MAT=1
   S11=3500. S22=91.2  S33=91.2  S23=31.4  S13=134.  S12=134.  COMPR=SAM
   E11=0.009 E22=0.012 E33=0.012 E23=0.012 E13=0.009 E12=0.009 COMPR=SAM
  MAT=2
   S11=80.   S22=80.   S33=80.   S23=40.   S13=40.   S12=40.   COMPR=SAM
   E11=0.023 E22=0.023 E33=0.023 E23=0.031 E13=0.031 E12=0.031 COMPR=SAM
*FAILURE_SUBCELL
  NMAT=2
  MAT=1 NCRIT=2
   CRIT=1 X11=3500. X22=91.2  X33=91.2  X23=31.4  X13=134.  X12=134.  &
    COMPR=OFF ACTION=1
   CRIT=2 X11=0.009 X22=0.012 X33=0.012 X23=0.012 X13=0.009 X12=0.009 &
    COMPR=OFF ACTION=1
  MAT=2 NCRIT=2
   CRIT=1 X11=80.   X22=80.   X33=80.   X23=40.   X13=40.   X12=40.   &
    COMPR=OFF ACTION=1
   CRIT=2 X11=0.023 X22=0.023 X33=0.023 X23=0.031 X13=0.031 X12=0.031 &
    COMPR=OFF ACTION=1
*PRINT
  NPL=6
*XYPLOT
  FREQ=1
  MACRO=1
   NAME=example_5b X=2 Y=8
  MICRO=0
*END
```

Annotated Input Data

1) Flags: None

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

Number of materials:	2	(NMATS=2)
Constitutive models:	Elastic	(CMOD=6)
Materials:	User-defined (Graphite)	(MATID=U)
	User-defined (Epoxy)	(MATID=U)
Material property source:	Read from input file	(MATDB=1)
Material properties:	See Table 4.1	

3) Analysis type (***RUC**) → Repeating Unit Cell Analysis [KM_3]:

Analysis model:	Doubly periodic GMC	(MOD=2)
RUC architecture:	26×26 circular fiber approx., rect. pack	(ARCHID=13)
Fiber volume fraction:	0.60	(VF=0.60)
Unit cell aspect ratio:	1.0 (square pack)	(R=1.0)
Material assignment:	graphite fiber	(F=1)
	epoxy matrix	(M=2)

4) Loading:

a) Mechanical (***MECH**) [KM_4]:

Loading option:	2	(LOP=2)
Without residual		
Number of points:	2	(NPT=2)
Time points:	0., 100. sec.	(TI=0.,100.)
Load magnitudes:	0., 0.02	(MAG=0.,0.02)
Loading mode:	strain control	(MODE=1)
With residual		
Reference strain time:	100. sec.	(REFTIME=100.)
Number of points:	3	(NPT=3)
Time points:	0., 100., 200. sec.	(TI=0.,100.,200.)
Load magnitudes:	0., 0.02	(MAG=0.,0.,0.02)
Loading mode:	stress control, strain control	(MODE=2,1)

☞ Note: The appropriate lines must be commented and uncommented to execute with and without residual.

b) Thermal (***THERM**) [KM_4]:

Without residual		
Number of points:	2	(NPT=2)
Time points:	0., 100. sec.	(TI=0.,100.)
Temperature points:	23., 23.	(TEMP=23.,23.)
With residual		
Number of points:	3	(NPT=3)
Time points:	0., 100., 200. sec.	(TI=0.,100.,200.)
Temperature points:	150., 23., 23.	(TEMP=150.,23.,23.)

☞ Note: The appropriate lines must be commented and uncommented to execute with and without residual.

c) Time integration (***SOLVER**) [KM_4]:

Time integration method:	Forward Euler	(METHOD=1)
Without residual		
Number of points:	2	(NPT=2)
Time points:	0., 100. sec.	(TI=0.,100.)
Time step size:	0.1 sec.	(STP=0.1)
With residual		
Number of points:	3	(NPT=3)
Time points:	0., 100., 200. sec.	(TI=0.,100.,200.)
Time step sizes:	5., 0.1 sec.	(STP=5.,0.1)

☞ Note: The small step size is employed during the mechanical loading despite the elastic response of the composite is employed in order to detect failure as soon as it occurs. The appropriate lines must be commented and uncommented to execute with and without residual.

5) Damage and Failure:

a) Stress and strain allowables estimation (**`*ALLOWABLES`**) [KM_5]:

Number of materials:	2	(`NMAT=2`)
Fiber stress allowables:	σ_{11} = 3500. MPa	(`S11=3500.`)
(`MAT=1`)	σ_{22} = 91.2 MPa	(`S22=91.2`)
	σ_{33} = 91.2 MPa	(`S33=91.2`)
	σ_{23} = 31.4 MPa	(`S23=31.4`)
	σ_{13} = 134. MPa	(`S13=134.`)
	σ_{12} = 134. MPa	(`S12=134.`)
Fiber strain allowables:	ε_{11} = 0.009	(`E11=0.009`)
	ε_{22} = 0.012	(`E22=0.012`)
	ε_{33} = 0.012	(`E33=0.012`)
	γ_{23} = 0.012	(`E23=0.012`)
	γ_{13} = 0.009	(`E13=0.009`)
	γ_{12} = 0.009	(`E12=0.009`)
Fiber compression flag:	Compression same as tension	(`COMPR=SAM`)
Matrix stress allowables:	σ_{11} = 80. MPa	(`S11=80.`)
(`MAT=2`)	σ_{22} = 80. MPa	(`S22=80.`)
	σ_{33} = 80. MPa	(`S33=80.`)
	σ_{23} = 40. MPa	(`S23=40.`)
	σ_{13} = 40. MPa	(`S13=40.`)
	σ_{12} = 40. MPa	(`S12=40.`)
Matrix strain allowables:	ε_{11} = 0.023	(`E11=0.023`)
	ε_{22} = 0.023	(`E22=0.023`)
	ε_{33} = 0.023	(`E33=0.023`)
	γ_{23} = 0.031	(`E23=0.031`)
	γ_{13} = 0.031	(`E13=0.031`)
	γ_{12} = 0.031	(`E12=0.031`)
Matrix compression flag:	Compression same as tension	(`COMPR=SAM`)

b) Subcell static failure analysis (**`*FAILURE_SUBCELL`**) [KM_5]:

Number of materials:	2	(`NMAT=2`)
Material #1		(`MAT=1`)
Number of criteria:	2	(`NCRIT=2`)
Criterion #1:	Maximum stress criterion	(`CRIT=1`)
Failure stresses:	σ_{11} = 3500. MPa	(`X11=3500.`)
	σ_{22} = 91.2 MPa	(`X22=91.2`)
	σ_{33} = 91.2 MPa	(`X33=91.2`)
	σ_{23} = 31.4 MPa	(`X23=31.4`)

	σ_{13} = 134. MPa	(X13=134.)
	σ_{12} = 134. MPa	(X12=134.)
Criterion #2:	Maximum strain criterion	(CRIT=2)
Failure strains:	ε_{11} = 0.009	(X11=0.009)
	ε_{22} = 0.012	(X22=0.012)
	ε_{33} = 0.012	(X33=0.012)
	γ_{23} = 0.012	(X23=0.012)
	γ_{13} = 0.009	(X13=0.009)
	γ_{12} = 0.009	(X12=0.009)
Compression flag:	Do not check for compressive failure	(COMPR=OFF)
Action to take upon failure:	Zero subcell stiffness and continue	(ACTION=1)

Material #2		(MAT=2)
Number of criteria:	2	(NCRIT=2)
Criterion #1:	Maximum stress criterion	(CRIT=1)
Failure stresses:	σ_{11} = 80. MPa	(X11=80.)
	σ_{22} = 80. MPa	(X22=80.)
	σ_{33} = 80. MPa	(X33=80.)
	σ_{23} = 40. MPa	(X23=40.)
	σ_{13} = 40. MPa	(X13=40.)
	σ_{12} = 40. MPa	(X12=40.)
Criterion #2:	Maximum strain criterion	(CRIT=2)
Failure strains:	ε_{11} = 0.023	(X11=0.023)
	ε_{22} = 0.023	(X22=0.023)
	ε_{33} = 0.023	(X33=0.023)
	γ_{23} = 0.031	(X23=0.031)
	γ_{13} = 0.031	(X13=0.031)
	γ_{12} = 0.031	(X12=0.031)
Compression flag:	Do not check for compressive failure	(COMPR=OFF)
Action to take upon failure:	Zero subcell stiffness and continue	(ACTION=1)

MAC/GMC 4.0 includes three failure criteria: maximum stress (CRIT=1), maximum strain (CRIT=2), and Tsai-Hill (CRIT=3). For all three criteria, the input takes the same form where the critical failure values for each component are specified as Xij=. As in the allowables calculation, the subcell static failure analysis requires a flag to indicate how to handle compression (COMPR=) (this should be omitted in the case of the Tsai-Hill Criterion). In addition, subcell static failure analysis requires specification of the action to take upon detection of a subcell failure (ACTION=). A value of -1 indicates that the code should stop the execution upon 1st failure, a value of 0 indicates that the code should only write notification of the failure to the output file and continue, and a value of 1 indicates that the code should treat the subcell as completely damage (i.e., zero the subcell's stiffness) and continue the execution. For more information on subcell static failure analysis, see the MAC/GMC 4.0 Theory Manual Section 5.2 and the MAC/GMC 4.0 Keywords Manual Section 5.

6) Output:

a) Output file print level (***PRINT**) [KM_6]:

Print level:	6	(NPL=6)

b) x-y plots (**`*XYPLOT`**):

Frequency:	1	(FREQ=1)
Number of macro plots:	1	(MACRO=1)
Macro plot names:	example_5b	(NAME=example_5b)
Macro plot x-y quantities:	ε_{22}, σ_{22}	(X=2 Y=8)
Number of micro plots:	0	(MICRO=0)

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

Results

The results for Example Problem 5b are shown in Figure 5.3 in the form of the transverse stress-strain response of the composite with and without residual stresses included. Without residual stresses, the failure of the first matrix subcell occurs at 68.1 MPa (due to the maximum stress criterion), which corresponds to the 1st subcell transverse allowable stress estimated for the composite in Example 5a. Because ACTION was set to 1, the subcell(s) that failed at this point have their stiffnesses set to zero, which causes the dramatic drop in the stress-strain response evident in Figure 5.3. Further, the following notification of subcell failure is written to the output file:

```
*******  SUBCELL FAILURE  ******
  SUBCELL #    13    MATERIAL #  2
  FAILED DUE TO THE MAX STRESS CRITERION
  COMPONENT =            2
  STRESS =      80.0299221493631
  ALLOWABLE STRESS =   80.0000000000000
  ACTION = 1 ----> ZERO SUBCELL AND CONTINUE

 *******  SUBCELL FAILURE  ******
  SUBCELL #    14    MATERIAL #  2
  FAILED DUE TO THE MAX STRESS CRITERION
  COMPONENT =            2
  STRESS =      80.0299221493631
  ALLOWABLE STRESS =   80.0000000000000
  ACTION = 1 ----> ZERO SUBCELL AND CONTINUE

 *******  SUBCELL FAILURE  ******
  SUBCELL #   663    MATERIAL #  2
  FAILED DUE TO THE MAX STRESS CRITERION
  COMPONENT =            2
  STRESS =      80.0299221493631
  ALLOWABLE STRESS =   80.0000000000000
  ACTION = 1 ----> ZERO SUBCELL AND CONTINUE

 *******  SUBCELL FAILURE  ******
  SUBCELL #   664    MATERIAL #  2
  FAILED DUE TO THE MAX STRESS CRITERION
  COMPONENT =            2
  STRESS =      80.0299221493631
  ALLOWABLE STRESS =   80.0000000000000
  ACTION = 1 ----> ZERO SUBCELL AND CONTINUE
```

So clearly, four subcells have failed due to the maximum stress criterion. Because the simulated transverse loading is applied under strain control, it can continue despite the drop in the stress-strain response. These drops are due to the instantaneous "zeroing" of the failed subcells stiffness properties. Less dramatic drops would be present were this problem analyzed using HFGMC. As the loading continues in Figure 5.3, additional subcell failures occur, resulting in more drops in the composite transverse response. Clearly, the predicted response without residual stresses reaches its maximum stress just prior to the 1st subcell failure, and as such, this is the predicted composite transverse UTS.

Also plotted in Figure 5.3 is the predicted transverse response of the graphite/epoxy composite in which residual stresses have been included via a simulated cool down from 150 °C. This is intended to simulate the cure temperature of the composite. Now, even though all subcell failure parameters are identical to the case without residual, 1st subcell failure is delayed until the composite reaches a global stress of 77.4 MPa. This is because during the simulated cool down, the matrix is placed in a state of residual transverse compression. Then, upon application of the simulated transverse mechanical loading, this transverse residual compression must first be overcome in addition to loading the matrix subcells to their transverse tensile strength of 80 MPa. Note that, even when residual stresses are included, the estimated allowables for the composite are identical to those presented in Example 5a as the allowables are calculated as a first step in the code's execution and are not linked to the applied loading. In this example, however, it is clear that the MAC/GMC 4.0 subcell static failure analysis is linked to the applied loading. For identical failure parameters, the simulations with and without residual stresses differ by 9.3 MPa (13.7%) in their transverse UTS predictions for the graphite/epoxy composite. It should be noted that, without micromechanics, this effect could not be predicted.

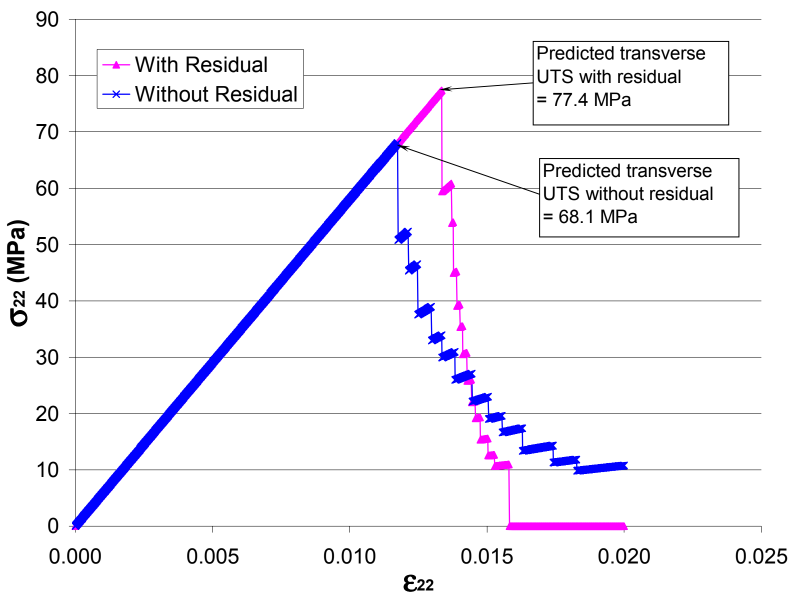

Figure 5.3 Example 5b: Simulated transverse static failure response of unidirection 60% graphite/epoxy at room temperature with and without residual stresses included.