Example 5f: Fiber Breakage

This example problem demonstrates the two methods incorporated within MAC/GMC 4.0 that can be used to model longitudinal fiber breakage in composite materials. The first is the evolving compliant interface (ECI) model, which was applied to transverse fiber-matrix debonding in the previous example problem. Now, instead of applying the ECI model to a fiber-matrix interface, it is applied to an internal fiber interface within a triply periodic RUC. The second model is the Curtin effective fiber breakage model (Curtin, 1991, 1993). This model combines a shear-lag analysis with fiber strength statistics to degrade the stiffness of an effective fiber that represents all fibers within a composite. Both models, as implemented within MAC/GMC 4.0, are capable of predicting the longitudinal strength of continuous fiber composites.

MAC/GMC Input File: **example_5f.mac**

```
MAC/GMC 4.0 Example 5f - Fiber breakage
*CONSTITUENTS
  NMATS=2
  M=1 CMOD=6 MATID=E
  M=2 CMOD=4 MATID=A
*RUC
  MOD=2 ARCHID=1 VF=0.35 F=1 M=2
#  MOD=3 ARCHID=99
#  NA=1 NB=2 NG=2
#  D=1.
#  H=0.5916,0.4084
#  L=0.5916,0.4084
#  SM=1,2
#  SM=2,2
*MECH
  LOP=1 REFTIME=64800.
  NPT=5 TI=0.,24000.,57600.,64800.,64908. MAG=0.,0.,0.,0.,0.018 MODE=2,2,2,1
*THERM
  NPT=5 TI=0.,24000.,57600.,64800.,64908. TEMP=900.,534.583,23.,650.,650.
*SOLVER
  METHOD=1 NPT=5 TI=0.,24000.,57600.,64800.,64908. STP=250.,40.,40.,0.2
#*DEBOND
#  NII=1
#  DBCH=2 NAI=1 NBI=1 NGI=1 FACE=1 BDN=311. LN=0.00000001 BN=3. TOLN=0. &
#  BDS=400 LS=0.1 BS=100 DELAY=64800.
*CURTIN
  NCURT=1
  NBI=1 NGI=1 D=142.E-6 L0=0.0127 SIG0=508. TAU0=2.03 M=17.0 &
  DELAY=64800. ACTION=0
*PRINT
  NPL=6
*XYPLOT
  FREQ=1
  MACRO=1
   NAME=example_5f X=1 Y=7
  MICRO=1
   NAME=example_5f IA=1 IB=1 IG=1 X=1 Y=7
*END
```

Annotated Input Data

1) Flags: None

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

Number of materials:	2	(`NMATS=2`)
Materials:	SiC fiber	(`MATID=E`)
	Ti-21S	(`MATID=A`)
Constitutive models:	SiC fiber: linearly elastic	(`CMOD=6`)
	Ti-21S matrix: Isotropic GVIPS	(`CMOD=4`)

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

Perfect Fiber and Curtin Model Simulations

Analysis model:	Doubly periodic GMC	(`MOD=2`)
RUC architecture:	square fiber, square pack	(`ARCHID=1`)
Fiber volume fraction:	0.35	(`VF=0.35`)
Material assignment:	SiC fiber	(`F=1`)
	Ti-21S matrix	(`M=2`)

ECI Model Simulation

Analysis model:	Triply periodic GMC	(`MOD=3`)
Architecture:	User-defined	(`ARCHID=99`)
No. subcells in x1-dir.:	1	(`NA=1`)
No. subcells in x2-dir.:	2	(`NB=2`)
No. subcells in x3-dir.:	2	(`NG=2`)
Subcell depths:	1.	(`D=1.0`)
Subcell heights:	0.5961,0.4084	(`H=0.5961,0.4084`)
Subcell lengths:	0.5961,0.4084	(`L=0.5961,0.4084`)
Material assignment:	square fiber, square pack	(`SM=1,2 / SM=2,2`)

☞ Note: To generate the results for all three cases presented in the results, the appropriate lines in the input file must be commented and uncommented.

4) Loading:

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

Loading option:	3	(`LOP=3`)
Strain reference time:	57600. sec.	(`REFTIME=57600.`)
Number of points:	5	(`NPT=5`)
Time points:	0., 24000., 57600., 64800., 64908. sec.	(`TI=0.,24000.,`…)
Load magnitude:	0., 0., 0., 0., 0.018	(`MAG=0.,0.,`…`,0.018`)
Loading mode:	stress/strain control	(`MODE=2,2,2,1`)

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

Number of points:	5	(`NPT=5`)
Time points:	0., 24000., 57600., 64800., 64908. sec.	(`TI=0.,24000.,…`)
Temperature points:	900., 534.583, 23., 650., 650. °C	(`TEMP=900.,…,650.`)

☞ Note: The second temperature (534.583 °C) is chosen in order to preserve the rate of change of the temperature.

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

Time integration method:	Forward Euler	(`METHOD=1`)
Number of points:	5	(`NPT=5`)
Time points:	0., 24000., 57600., 64800., 64908. sec.	(`TI=0.,24000.,…`)
Time step sizes:	250., 40., 40., 0.2 sec.	(`STP=250.,40.,40.,0.2`)

5) Damage and Failure:

a) Fiber-matrix debonding (**`*DEBOND`**) [KM_5]:

No. debonding interfaces:	1	(`NII=1`)
Interface subcell indices:	1, 1, 1	(`NAI=1 NBI=1 NGI=1`)
Interface identifier:	x_1-interface	(`FACE=1`)
Normal debond stress:	311. ksi	(`BDN=311.`)
Normal Λ parameter:	0.00000001 /ksi	(`LN=0.00000001`)
Normal B parameter:	3. s	(`BN=3.`)
Load reversal tolerance:	0. ksi	(`TOLN=0.`)
Shear debond stress:	400. ksi	(`BDS=400.`)
Shear Λ parameter:	0.1 /ksi	(`LS=0.1`)
Shear B parameter:	100. s	(`BS=100.`)
Debond time delay	64800. sec.	(`DELAY=64800.`)

b) Curtin effective fiber breakage model (**`*CURTIN`**) [KM_5]:

```
*CURTIN
  NCURT=1
  NBI=1 NGI=1 D=142.E-6 L0=0.0127 SIG0=508. TAU0=2.03 M=17.0 &
  DELAY=64800. ACTION=0
```

No. Curtin model fibers:	1	(`NCURT=1`)
Fiber subcell indices:	1, 1	(`NBI=1 NGI=1`)
Fiber diameter:	142. μm	(`D=142.E-6`)
Fiber gauge length:	12.7 mm	(`L0=0.0127`)
Fiber mean strength:	508. ksi	(`SIG0=508.`)
Fiber-matrix shear friction:	2.03 ksi	(`TAU0=2.03`)
Fiber Weibull modulus:	17.0	(`M=17.0`)
Curtin time delay	64800. sec.	(`DELAY=64800.`)
Action to take upon failure:	Only write notification and continue	(`ACTION=0`)

The format for specifying the Curtin model data is similar to that employed in the debond model data specification. Most of the Curtin model parameters are physical or statistical in nature and relatively easily obtained. The exception is the fiber-matrix frictional sliding shear stress (`TAU0`). Attempts have been made to extract this value from fiber push out or pull out tests on the composite, but this can be problematic since the value will then depend on the residual stress state in the particular composite. Hence, the fiber-matrix frictional sliding shear stress may alternately be thought of as an internal parameter. As in the fiber-matrix debonding data, a time delay must be specified in the Curtin model data. Finally, as in the subcell failure data, an action to take upon Curtin model failure of the fiber must be specified.

☞ Note: In order to execute the three cases presented in the results for this example, the appropriate lines under **`*DEBOND`** must be commented and uncommented.

6) Output:

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

Print level:	6	`(NPL=6)`

b) x-y plots (**`*XYPLOT`**) [KM_6]:

Frequency:	1	`(FREQ=1)`
Number of macro plots:	1	`(MACRO=1)`
Macro plot names:	example_5f	`(NAME=example_5f)`
Macro plot x-y quantities:	ε_{11}, σ_{11}	`(X=1 Y=7)`
Number of micro plots:	1	`(MICRO=1)`
Micro plot names:	example_5e	`(NAME=example_5e)`
Micro plot subcell indices:	1, 1	`(IA=1 IB=1 IG=1)`
Micro plot x-y quantities:	ε_{11}, σ_{11}	`(X=1 Y=7)`

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

Results

Figure 5.13 shows the predicted longitudinal tensile response of the composite at 650 °C for the three different cases (perfect fiber, ECI model for the fiber, and Curtin model for the fiber). Both the global (composite) stress vs. strain response and the local fiber stress vs. global strain response are plotted for each case. In the present case, the ECI and Curtin models give similar results both locally and globally. Both models cause the fiber response to diverge from that of the perfect fiber case, reach a maximum, and then decrease. Because the present case involves the longitudinal behavior of the continuous fiber composite, the fiber response has a dominant influence on the global composite response. Both the ECI model and Curtin model composite curves reach a maximum at 173 ksi, which may be considered the predicted UTS of the composite. In fact, the following is written to the output file:

```
CURTIN FAILURE:
   > STRESS =    418.189691475676      X =   0.125681408909315
```

at the time corresponding to the maximum in the Curtin model composite prediction. Were the `ACTION` specifier under **`*CURTIN`** set to -1, execution of the code would have stopped at this point. When employing the ECI model to simulate fiber breakage, it is not possible to stop execution when this maximum in the stress-strain response is reached. After the maximum composite stress is reached, the ECI and Curtin model predictions diverge in what is a non-physical domain of the predictions.

While the ECI and Curtin models give similar results for the present case, the Curtin model is often preferable for modeling the longitudinal fiber breakage behavior of composites. This is because most of the Curtin model parameters have physical interpretation, whereas the ECI model parameters Λ and B are internal variables with no real physical meaning. As shown by Bednarcyk and Arnold (2001), the ECI model debond stress can be assigned based on fiber strength statistics in an RUC containing multiple fibers, but the internal parameters Λ and B still remain to be chosen. The advantage of the ECI model is, that by controlling the parameters for each fiber individual, the model can provide some additional flexibility.

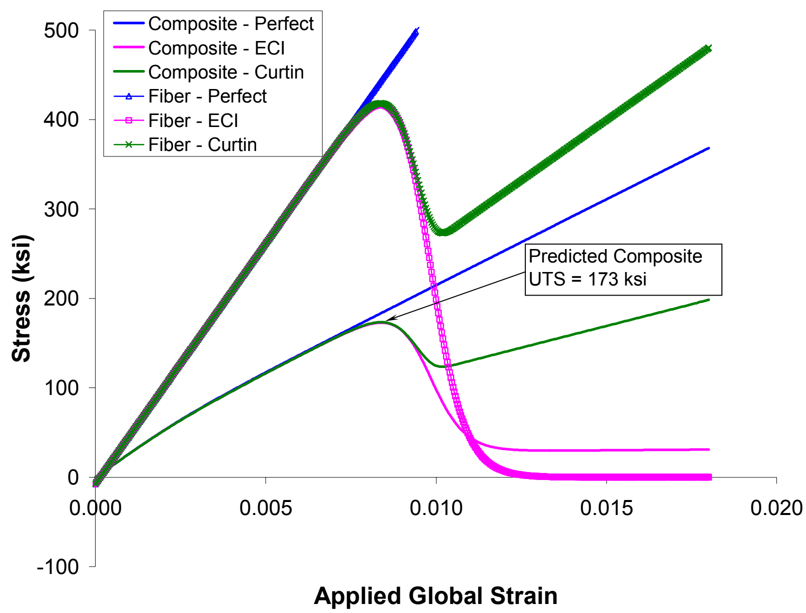

Figure 5.13 Example 5f: Predicted local and global longitudinal stress-strain response of 35% SiC/Ti-21S at 650 °C with fiber breakage.