Example 7a: Implicitly Integrated Multimechanism GVIPS

This example problem illustrates the use of a new multimechanism GVIPS constitutive model (see Saleeb et al., 2001) that has been implemented within MAC/GMC 4.0. This constitutive model incorporates an arbitrary number of viscoelastic and viscoplastic mechanisms, giving it a wide range of applicability. While this model can be characterized for any material, currently, only material parameters for Ti-21S have been implemented within MAC/GMC 4.0. The multimechanism GVIPS model has an additional distinction from the standard isotropic GVIPS model available within MAC/GMC 4.0 in that it is implicitly integrated on the local level. That is, the model, on the scale of the subcell, returns a new local stress and inelastic strain state rather than the usual local inelastic strain increments. In the standard isotropic GVIPS model available within MAC/GMC 4.0, the local inelastic strain increments returned by the constitutive model are, in contrast, explicitly integrated (to obtain inelastic strains) outside of the model itself. As discussed earlier, global equilibrium iterations are necessary at each increment of the applied simulated loading (as with the incremental plasticity model, see Example 2c).

A major benefit associated with the implicitly integrated multimechanism GVIPS model is that it is unconditionally stable, regardless of the step size employed to apply the simulated loading. Thus, unlike the previous version of GVIPS available within MAC/GMC 4.0, a very large time step size can be employed in cases that utilize this new constitutive model. This example problem illustrates this point by comparing simulations of SiC/Ti-21S composites using both GVIPS constitutive models for the Ti-21S matrix.

☞ Note: In order for non- U.S. government users to access the multimechanism GVIPS capabilities, an additional software license is required.

MAC/GMC Input File: **example_7a.mac**

```
MAC/GMC 4.0 Example 7a - Implicitly Integrated Multimechanism GVIPS
*CONSTITUENTS
  NMATS=2
  M=1 CMOD=6 MATID=E
# -- GVIPS
#  M=2 CMOD=4 MATID=A
# -- Multimechanism GVIPS
  M=2 CMOD=22 MATID=A
*RUC
  MOD=2 ARCHID=6 VF=0.25 R=1. F=1 M=2
*MECH
  LOP=2 REFTIME=57600.
  NPT=3 TI=0.,57600.,57800. MAG=0.,0.,0.02 MODE=2,1
*THERM
  NPT=3 TI=0.,57600.,57800. TEMP=900.,23.,23.
*SOLVER
# -- Multimechanism GVIPS Cases
#  METHOD=1 NPT=3 TI=0.,57600.,57800. STP=5760.,1. ERR=0.001 ITMAX=100
#  METHOD=1 NPT=3 TI=0.,57600.,57800. STP=5760.,2.5. ERR=0.001 ITMAX=100
#  METHOD=1 NPT=3 TI=0.,57600.,57800. STP=5760.,4. ERR=0.001 ITMAX=100
#  METHOD=1 NPT=3 TI=0.,57600.,57800. STP=5760.,8. ERR=0.001 ITMAX=100
  METHOD=1 NPT=3 TI=0.,57600.,57800. STP=5760.,20. ERR=0.001 ITMAX=100
```

```
#  METHOD=1 NPT=3 TI=0.,57600.,57800. STP=5760.,50. ERR=0.001 ITMAX=100
#  METHOD=1 NPT=3 TI=0.,57600.,57800. STP=5760.,100. ERR=0.001 ITMAX=100
# -- GVIPS Cases
#  METHOD=1 NPT=3 TI=0.,57600.,57800. STP=40.,1. ERR=0.001 ITMAX=100
#  METHOD=1 NPT=3 TI=0.,57600.,57800. STP=40.,2.5 ERR=0.001 ITMAX=100
#  METHOD=1 NPT=3 TI=0.,57600.,57800. STP=40.,4. ERR=0.001 ITMAX=100
#  METHOD=1 NPT=3 TI=0.,57600.,57800. STP=40.,5. ERR=0.001 ITMAX=100
#  METHOD=1 NPT=3 TI=0.,57600.,57800. STP=40.,8. ERR=0.001 ITMAX=100
*PRINT
  NPL=6
*XYPLOT
  FREQ=1
  MACRO=2
   NAME=example_7a    X=2 Y=8
   NAME=example_7a_th X=100 Y=1
  MICRO=0
*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)
	Multimechanism GVIPS	(CMOD=22)

☞ Note: To generate all results in this example problem, the appropriate lines in the input file must be commented and uncommented.

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

Analysis model:	Doubly periodic GMC	(MOD=2)
RUC architecture:	7×7 circle approx.	(ARCHID=6)
Fiber volume fraction:	0.25	(VF=0.25)
RUC aspect ratio:	1. (square pack)	(R=1.)
Material assignment:	SiC fiber	(F=1)
	Ti-21S matrix	(M=2)

4) Loading:

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

Loading option:	2	(LOP=2)
Strain reference time:	57600. sec.	(REFTIME=57600.)
Number of points:	3	(NPT=3)
Time points:	0., 57600., 57800. sec.	(TI=0.,57600,57800.)
Load magnitude:	0., 0.02	(MAG=0.,0.02)
Loading mode:	stress/strain control	(MODE=2,1)

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

Number of points:	3	(NPT=3)
Time points:	0., 57600., 57800. sec.	(TI=0.,57600.,57800.)
Temperature points:	900., 23., 23.	(TEMP=900.,23.,23.)

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

Time integration method:	Forward Euler	(METHOD=1)
Number of time points:	3	(NPT=3)
Time points:	0., 57600., 57800. sec.	(TI=0.,57600.,57800.)
Time step sizes:	variable	(STP=*)
Error tolerance for global iteration:	0.001	(ERR=0.001)
Maximum number of iterations:	100	(ITMAX=100)

The error tolerance (ERR) is the maximum allowable fractional difference between a global (cell or laminate level) energy increment value between iterations. Note, to generate all results presented in this example problem, the appropriate lines in the input file must be commented and uncommented. For more information on the implicitly integrated GVIPS constitutive model and its time integration control, see the MAC/GMC 4.0 Keywords Manual Sections 2 and 4 and the MAC/GMC 4.0 Theory Manual Section 4.4.3.

5) Damage and Failure: None

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:	2	(MACRO=2)
Macro plot name:	example_7a	(NAME=example_7a)
	example_4h_th	(NAME=example_7a_th)
Macro plot x-y quantities:	ε_{22}, σ_{22}	(X=2 Y=8)
	temperature, ε_{11}	(X=100 Y=1)
Number of micro plots:	0	(MICRO=0)

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

Results

Figure 7.1 shows the simulated transverse tensile response of the SiC/Ti-21S composite wherein the standard isotropic GVIPS constitutive model (CMOD=4) has been employed to represent the matrix. As this model is explicitly integrated in time, a small time step is required in order to achieve convergence. Figure 7.1 illustrates the effect of using a successively coarser time step to apply the 0.02 global transverse strain over 200 seconds. Convergence is achieved for time step sizes of 1 and 2.5 seconds, but for a time step of 4 seconds, some oscillations are present in the simulated stress-strain curve.

These oscillations become more apparent for a time step of 5 seconds. Finally, for a time step of 8 seconds, the solution diverges (causing the code to fail).

Figure 7.2 shows the same simulations for the SiC/Ti-21S composite, but now the new implicitly integrated multimechanism GVIPS constitutive model (`CMOD=22`) has been employed for the matrix. Employing a time step up to and including 20 seconds allows the simulated stress-strain curve to be well represented without divergence or oscillations. A time step size of 50 seconds still does a reasonable job of reproducing the stress-strain curve predicted using much finer time step sizes. Finally, using a time step size of 100 seconds (which applies the entire simulated load in just 2 steps) the integration still achieves convergence. Note that even though the intermediate point on this simulated stress-strain curve does fall significantly outside the previous predictions, the ending stress (at an applied strain of 0.02) is still within 3.5 % of the previously predicted stress levels. Also, it is important to remember that the global equilibrium iterations required in the case of the multimechanism GVIPS model adds additional overhead to the code's execution. Thus, to preserve the code's efficiency, a relatively large time step should be employed when using the multimechanism GVIPS model.

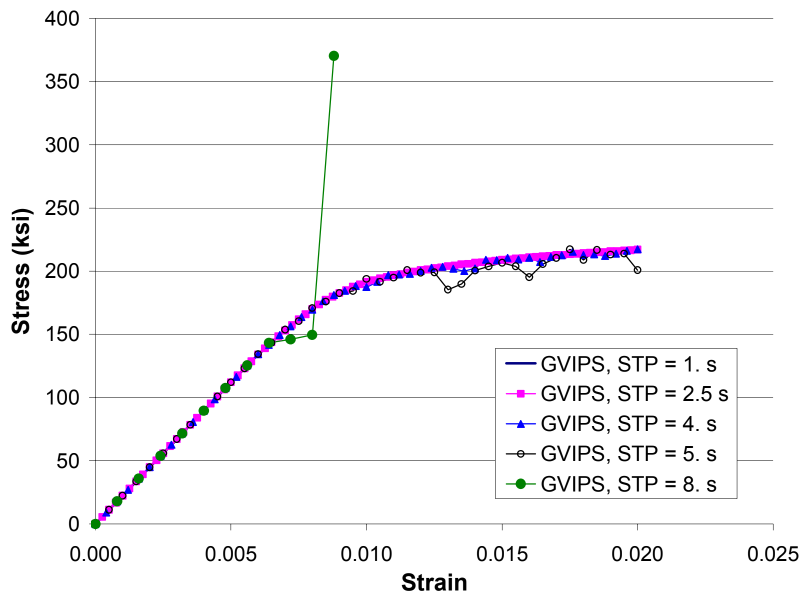

Figure 7.1 Example 7a: Simulated transverse tensile response of 25% SiC/Ti-21S at room temperature wherein the Ti-21S matrix response is simulated using the standard isotropic GVIPS constitutive model. Effect of the loading time step size is highlighted.

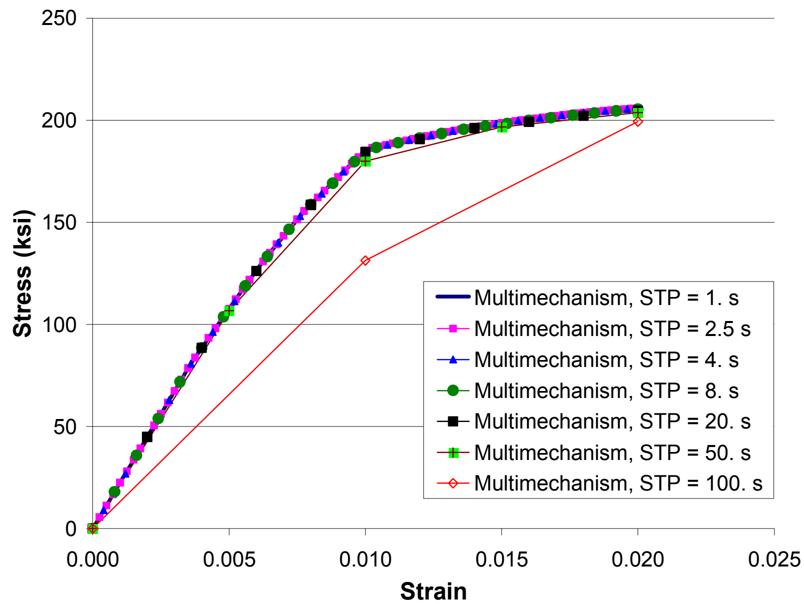

Figure 7.2 Example 7a: Simulated transverse tensile response of 25% SiC/Ti-21S at room temperature wherein the Ti-21S matrix response is simulated using the new implicitly integrated multimechanism GVIPS constitutive model. Effect of the loading time step size is highlighted.