Modified MAT54: Composite Material Modeling for Crash Simulation

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The Joint Advanced Materials and Structures Center of Excellence

AMTAS (JAMS) Crashworthiness Research Contributions

Testing

- *Material property testing, quasi-static*
- *Crush testing of 9 element shapes, quasi-static.*
- *Several articles published.*

Analysis

- *LS-DYNA MAT54 CMH-17 RR entry and write-up*
- *LS-DYNA MAT54 single-element characterization*
- *LS-DYNA shapes simulations*
- *MAT54 code/ model modifications & improvement*
- *Complete summary report of RR effort for Crash WG*
- *1 published, 2 in review. 2 FAA Tech Reports delivered*

Educational Module

- *Presentation, lecture notes and video recorded*
- *1 FAA tech report developed*

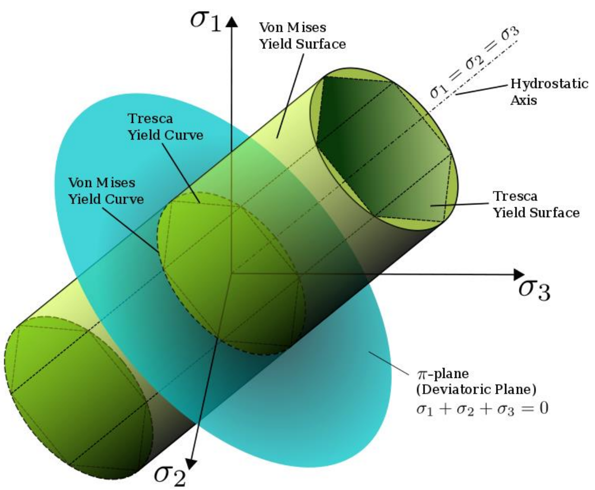
Cert protocol/ guidelines

Challenges in crashworthiness simulation

- *Composites are non homogeneous - damage can initiate and propagate in many ways*
- *Many failure mechanisms can occur (fiber breakage, delamination, cracking, etc.). Damage growth is not self-similar.*
- *Crash events involve exclusively damage initiation and propagation*
- *Importance of failure criterion and degradation scheme is paramount*
- *Time-dependent event requires explicit solvers (non-standard)*
- *Computationally very expensive, requires the use of shell elements (not solids)*
- *Current FEA technology cannot capture details of failure of individual fibers and matrix, but needs to make approximations. The key is to know how to make the right approximations.*
  - *Element failure treated macroscopically: cannot account for differences between failure mechanisms*
  - *Often it cannot account for delamination damage*

Composite modelling strategies with LS-DYNA

- *LS-DYNA considered benchmark for impact and crash analysis*



- *Composites are modeled as orthotropic linear elastic materials within the failure surface*
- *Failure surface is defined by the failure criterion*
- *Beyond the failure surface, elastic properties are degraded according to laws defined by the material model*
  - *Progressive Failure Model (PFM): Specific ply properties go to zero, ply by ply failure until all plies have failed and element is deleted*
  - *Continuum Damage Mechanics (CDM): Uses damage parameters to degrade ply properties in a continuous form*

LS-DYNA MAT54

- *MAT54 is a progressive failure model meant specifically for UD tape*
  - *Four mode-based failure criteria for “fiber” and “matrix” failure in tension and compression*
- *Practical because it primarily requires a set of standardized experimental input parameters based on coupon-level test data*
  - *Tension/ Compression and shear: modulus, strength, strain to failure*
- *Limited number of other factors that cannot be measured by experiment, and need to be calibrated by trial and error*

*MAT_054 (ENHANCED_COMPOSITE_DAMAGE)							
mid	**ro**	**ea**	**eb**	**ec**	**prba**	~~**prca**~~	~~**prcb**~~
1	1.50E-4	1.84E+7	1.22E+6	0.0	0.02049	0.0	0.0
gab	~~**gbc**~~	~~**gca**~~	~~**kf**~~	**aopt**			
6.10E+5	6.10E+5	6.10E+5	0.0	0.0			
xp	**yp**	**zp**	**a1**	**a2**	**a3**	**mangle**	
0.0	0.0	0.0	0.0	0.0	0.0	0.0	
v1	**v2**	**v3**	**d1**	**d2**	**d3**	**dfailm**	**dfails**
0.0	0.0	0.0	0.0	0.0	0.0	0.024	0.03
tfail	**alph**	**soft**	**fbrt**	**ycfac**	**dfailt**	**dfailc**	**efs**
1.1530E-9	0.1	0.0	0.5	1.2	0.0174	-0.0116	0.0
xc	**xt**	**yc**	**yt**	**sc**	**crit**	**beta**	
213000	319000	28800	7090	22400	54	0.5	

1. Constitutive properties: RO, EA, EB, EC, PRBA, PRCA, PRCB, GAB, GBC, GCA, KF

2. Local material axes: AOPT, XP, YP, ZP, A1-A3, MANGLE, V1-V3, D1-D3

3. Shear weighing factors: ALPH, BETA

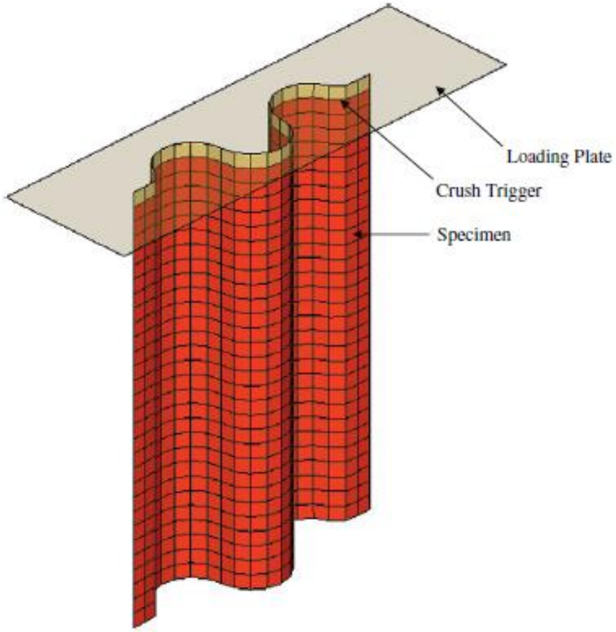
4. Deletion parameters: DFAILM, DFAILS, TFAIL, DFAILT, DFAILC, EFS

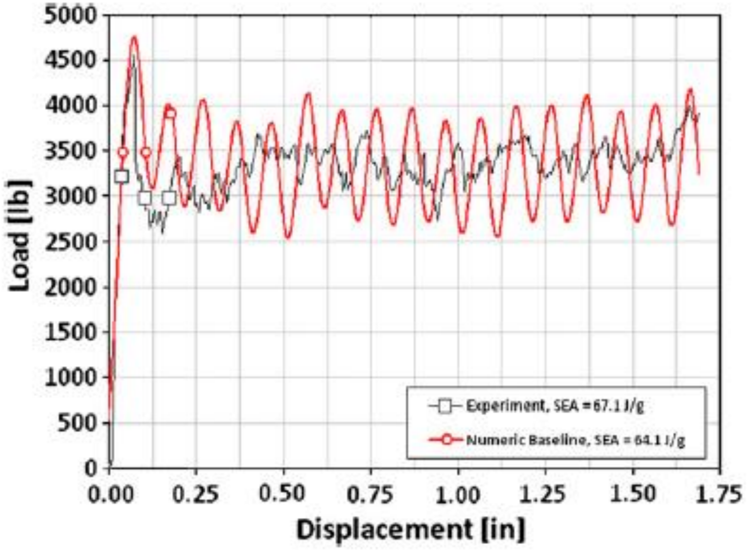
5. Damage factors: SOFT, FBRT, YCFAC

6. Material strengths: XC, XT, YC, YT, SC

7. Failure criterion selection: CRIT

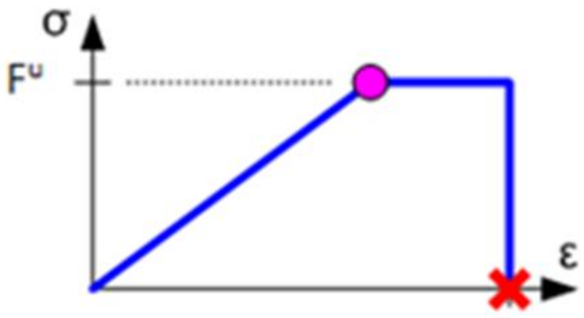
- *After careful calibration of the material card, MAT54 is capable to model composite materials in crash simulations when experimental data is available*
- *However, some shortcomings have been identified which are addressed in the new modified material model*





Areas of improvement identified for MAT54

1. *Elastic response*
   – Improve elastic response by adding two compressive moduli and the compressive transverse strain-to-failure user input parameters
2. *Failure determination*
   – Implement fabric-specific failure criteria
   – Implement an energy based failure criterion
   – Implement a crush stress based failure criterion
3. *Post-failure degradation*
   – Remove plastic behavior and model material following failure as it is physically
   – Implement different degradation schemes following failure, including one to mimic a CDM model



Improved elastic response

- *Add compressive moduli to calculation of compliance matrices before and after failure*

```
eg(i) =em(i)*ef(i)
eh(i) =eg(i)*ed(i)
ex(i) =ymx
ey(i) =ymy
prx(i)=eh(i)*nux
pry(i)=eh(i)*nuy
gxy(i)=1.e-17+sxy
pxy(i)=1.0/(1.-prx(i)*pry(i))
c11(i)=pxy(i)*ex(i)
c12(i)=pxy(i)*prx(i)*ey(i)
c22(i)=pxy(i)*ey(i)
```

Modified Code

```
if (sig1(i).gt.0.) then
   ex(i) =ymx
else
   ex(i)=ymxc
endif
if (sig2(i).gt.0.) then
   ey(i) =ymy
else
   ey(i)=ymyc
endif
```

- Based on the sign of the calculated local stresses **sig1** and **sig2**, either EAC (ymxc) or EA (ymx) is used
- This operation is repeated before and after failure for the two compliance matrices

- *A second strain-to-failure value in the transverse direction called DFAIL2M is introduced*

```
c  matrix tensile rupture
if (dfail1m-strn2(i).lt.0.) then
   efail(i)=0.0
endif

c  matrix compressive rupture
if (strn2(i)+dfail1m.lt.0.) then
   efail(i)=0.0
endif
```

Modified Code

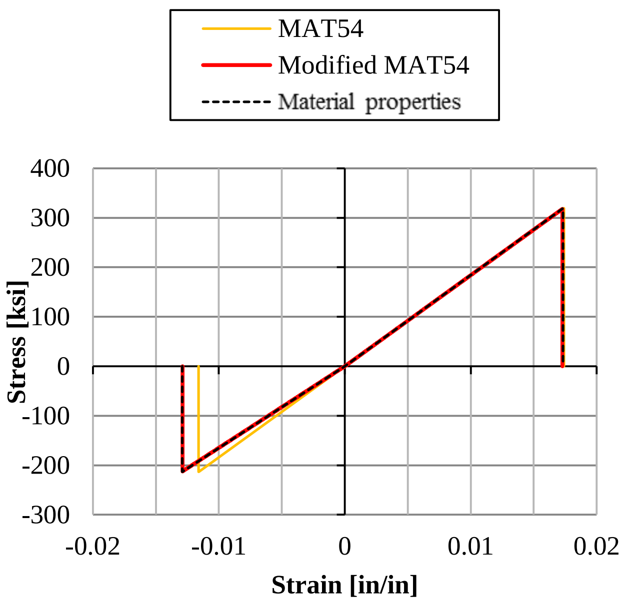
```
c  matrix compressive rupture
if (strn2(i)+dfail2m.lt.0.) then
   efail(i)=0.0
endif
```

- Substituted DFAIL2M for the original DFAILM in the compressive matrix deletion statement

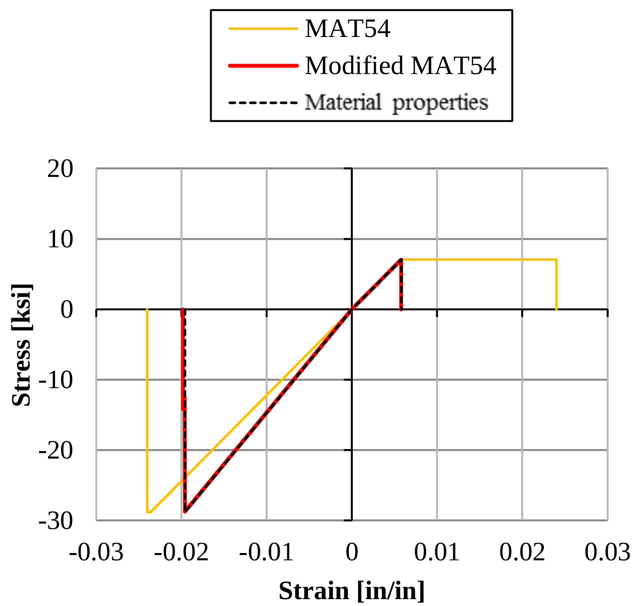
Modified UD single element

- *Single element simulations are repeated with the new material model*
- *Results show that the UD material is better simulated than the original MAT54*
  - Improvement in all stiffnesses
  - Improvement in element deletion

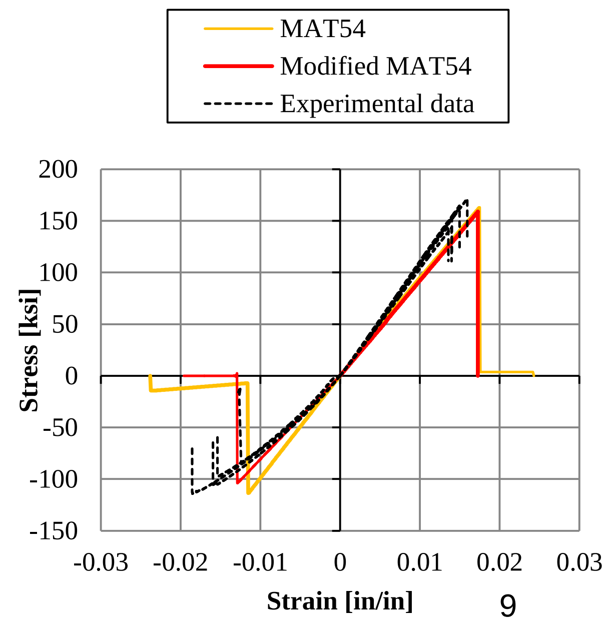
UD axial



UD transverse



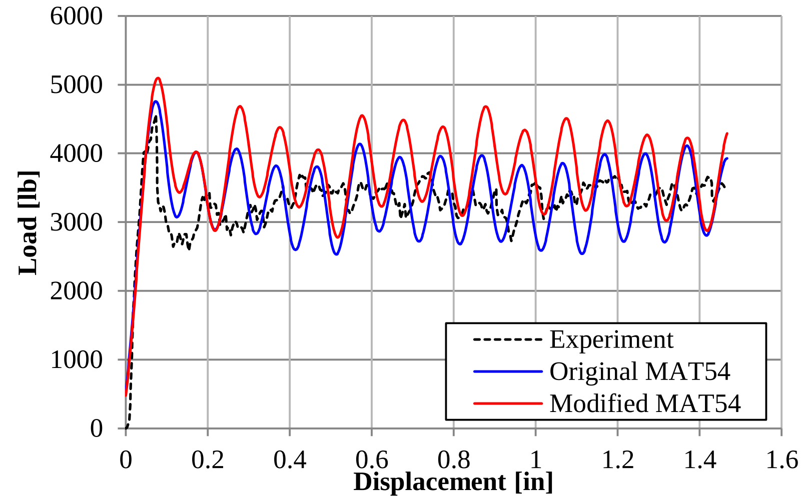
Cross-ply Laminate

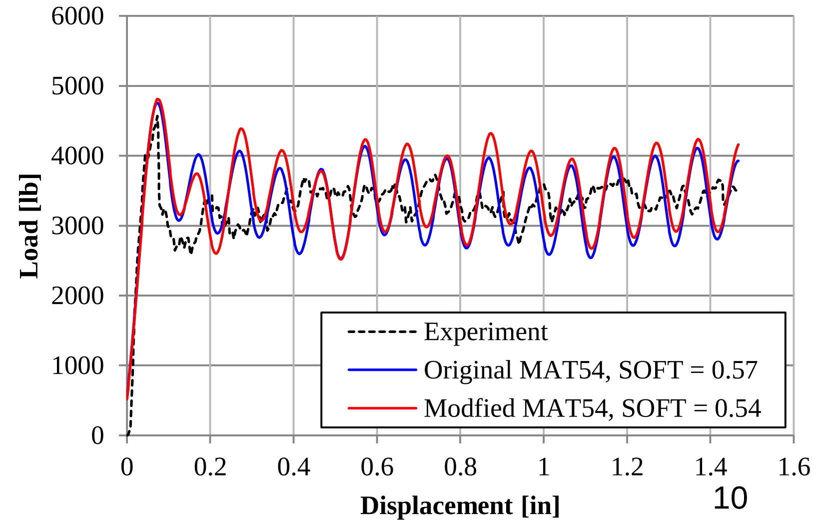


Modified UD sine crush

- *Corrugated crush simulations are repeated with the new material model*
- *For the UD material, the modified material model has minor influence on the simulation*
  - DFAILC is changed such that there is perfect linearity in compression due to the correct usage of EAC

	MAT54	Modified
EAC	18.4 Msi	16.5 Msi
EBC	1.22 Msi	1.47 Msi
DFAILM	0.024	0.0058
DFAIL2M	0.024	0.0196
DFAILC	-0.0116	-0.0129

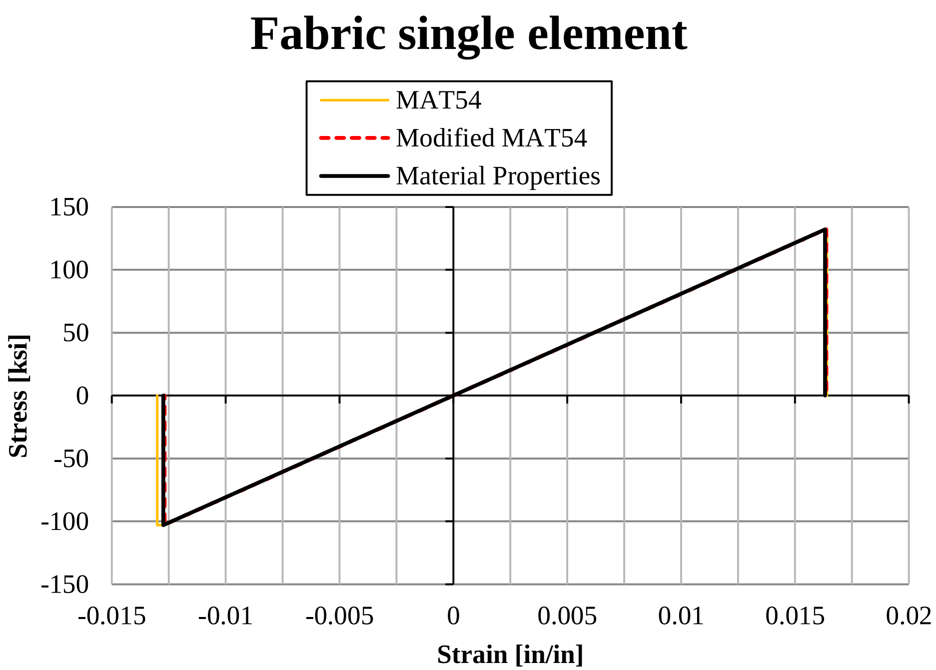




- *As a result of increasing DFAILC, the average crush load of the modified simulation is higher*
- *SOFT is decreased to account for this*

Modified fabric single element

- *Single element simulations of the fabric material using the new material model show no improvement*
- *Original MAT54 model of fabric material already matches experimental properties well, and the modified elastic response model does improve the fabric material simulation*



Modified elastic response

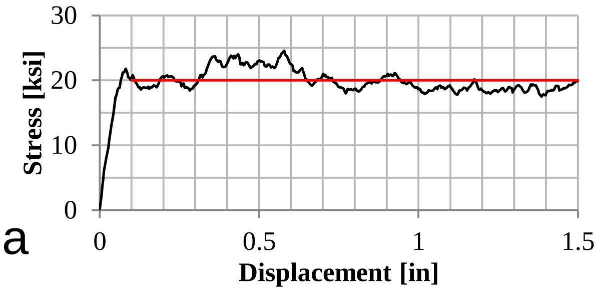
- *The improved material property definition provided a better model of the unidirectional tape material*
  - Single element model
  - Crush model
- *For the fabric material system, implementing additional material parameters did not provide any benefit*
- *In general, the improved material property definition is suitable to better model UD materials, where greater benefit can come from the capability to distinguish between the elastic response in tension and compression*

Modified failure criteria

Three new options for failure criteria are explored:

1. *Fabric-specific failure criteria*
   - Assume fiber-dominated failure in both directions
   - Use the Hashin fiber tension and compression criteria in both the axial and transverse directions

2. *Maximum crush stress failure criterion*
   - Measure crush stress from experiment
   - Use this value as a maximum limiting stress experienced by crashfront elements
   - This used in addition to existing Hashin criteria



3. *Strain energy based Wolfe failure criterion*
   - Used in addition to existing Hashin criteria

Fabric failure criteria

- *New code implements the fabric material failure criteria:*
  - Remove damages caused by matrix failure (FBRT, YCFAC) for fabric option
  - Change the matrix failure criteria to those of the fiber

```
      if (stg1(i).gt.0.) then
c        for tensile fiber mode (fabric)
         ef2(i)=qq2(i)*xt2*
     .             max(0.0,stg1(i))**2+beta*sg44(i)-1.0
         ec2(i)=-1.
      else
c        for compressive fiber mode (fabric)
         ef2(i)=-1.
         ec2(i)= qq2(i)*xc2(i)*  min(0.0,stg1(i))**2-1.0
      endif
```

$$e_f^2 = \left(\frac{\sigma_{aa}}{XT}\right)^2 + \beta\left(\frac{\sigma_{ab}}{SC}\right)^2 - 1$$

$$e_c^2 = \left(\frac{\sigma_{aa}}{XC}\right)^2 - 1$$

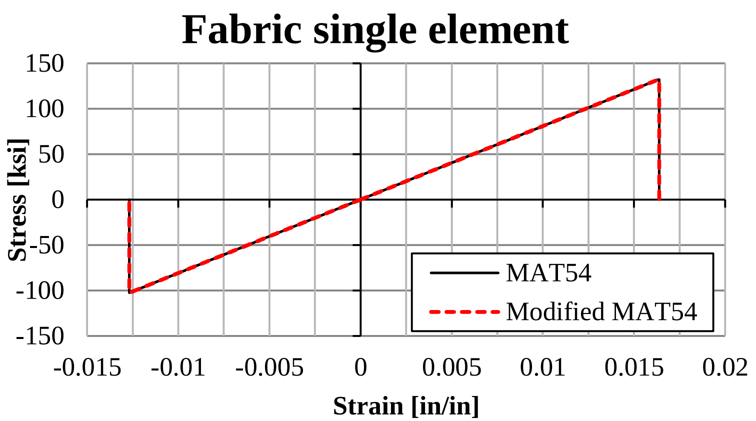
```
      if (stg2(i).gt.0.) then
c        for tensile matrix mode (fabric)
         em2(i)=qq2(i)*yt2*
     .             max(0.0,stg2(i))**2+beta*sg44(i)-1.0
         ed2(i)=-1.
      else
c        for compressive matrix mode (fabric)
         em2(i)=-1.
         ed2(i)=qq2(i)*yc2*  min(0.0,stg2(i))**2-1.0
      endif
```

$$e_m^2 = \left(\frac{\sigma_{bb}}{YT}\right)^2 + \beta\left(\frac{\sigma_{ab}}{SC}\right)^2 - 1$$

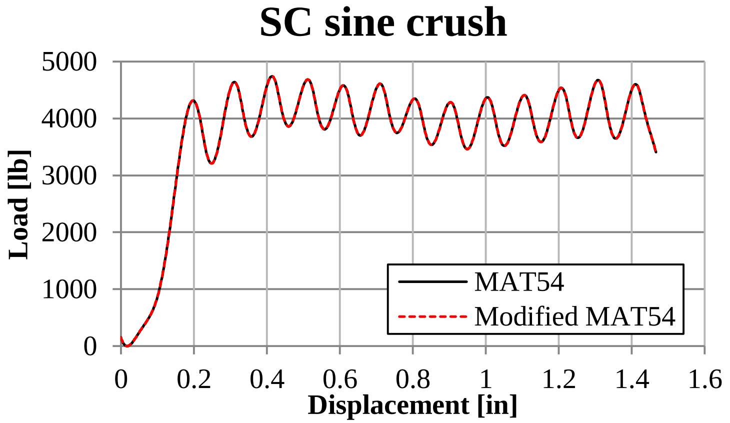
$$e_d^2 = \left(\frac{\sigma_{bb}}{YC}\right)^2 - 1$$

Fabric failure criteria

- *Single element simulation of the fabric material system using fabric-specific failure criteria are identical to original MAT54 Hashin failure criteria*

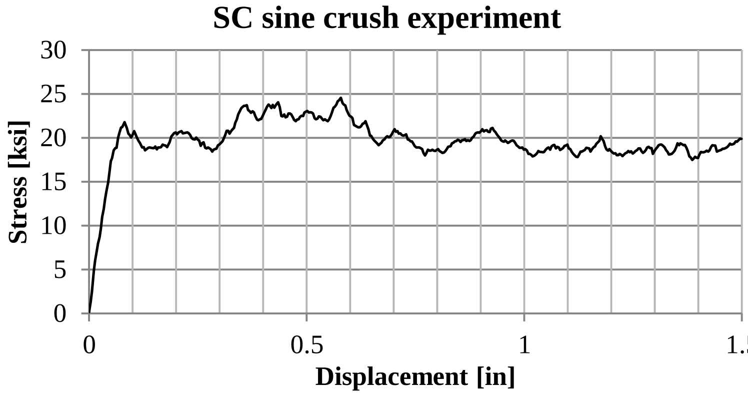


- *The fabric-specific failure criteria did not improve the material model used in crush simulations, and no significant change in results is observed*



Crush stress failure criteria

- *Measured experimental crush stress used as an input parameter*
- *This criterion only applies to crashfront elements*
  - Hashin failure criteria also remain



- *Example of code added for crush stress criterion:*

```
if (qq1(i).ne.1.0) then
     ecr(i)=stg1(i)/sigcr
else
     ecr(i)=0.0
endif

if (ecr(i).eq.1.0) efail=0.0
```

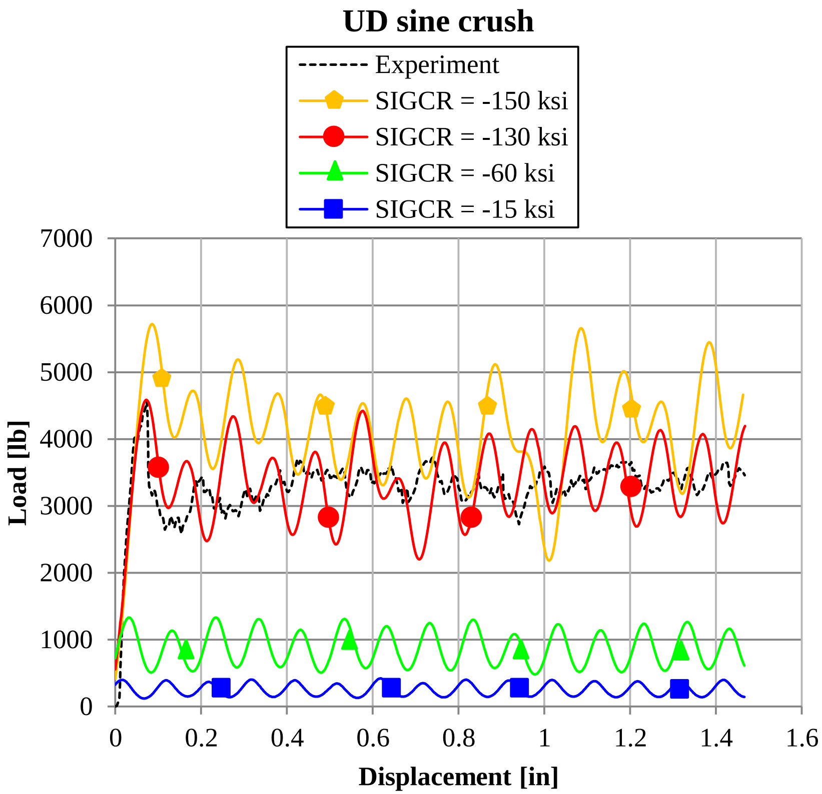
- When qq1 ≠ 1, element is at crashfront, and crush stress criterion is implemented

$$ecr = \frac{\sigma_1}{\sigma_{cr}}$$

- ecr is a failure flag
- When ecr = 1, element is failed

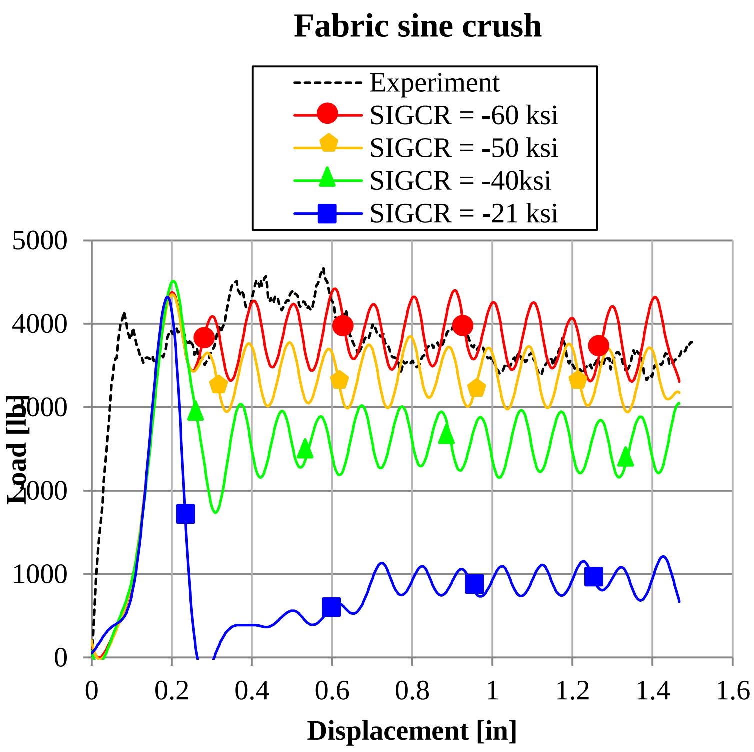
Crush stress failure criteria: UD crush simulation

- *Using the measured experimental value of σ_{cr} = 15 ksi and setting SOFT = 1.0, the simulated crushing of the UD sinusoid is progressive and stable, but the load is too low*
- *The crush stress parameter acts much like SOFT, and controls the average crush load of the simulation*
- *An input value of σ_{cr} = 130 ksi matches the experiment well*



Crush stress failure criteria: fabric crush simulation

- *Using the measured experimental value of σcr = 21 ksi and setting SOFT = 1.0, the simulated crushing of the fabric sinusoid is progressive and stable, but like the UD case, the load is too low*
- *An input value of σcr = 60 ksi matches the experiment well*
- *No observed benefit to using the crush stress versus the SOFT parameter*



Strain energy failure criteria: Wolfe

- *From Wolfe & Butalia [1]:*
  - General form of strain energy based failure criterion for nonlinear orthotropic materials:

$$\left(\frac{\int_{\varepsilon_1}\sigma_1 d\varepsilon_1}{\int_{\varepsilon_1^u}\sigma_1 d\varepsilon_1}\right)^{m_1}+\left(\frac{\int_{\varepsilon_2}\sigma_2 d\varepsilon_2}{\int_{\varepsilon_2^u}\sigma_2 d\varepsilon_2}\right)^{m_2}+\left(\frac{\int_{\varepsilon_6}\sigma_6 d\varepsilon_6}{\int_{\varepsilon_6^u}\sigma_6 d\varepsilon_6}\right)^{m_6}=1$$

Where m_i define the shape of the failure surface in the strain energy space

  - This criterion requires experimental ultimate strain energy values in the axial, transverse, and shear directions, as well as shape function values m_i for each mode (which requires curve fitting of biaxial coupon data)

  - While the strain energy values can be measured from standardized axial coupon tests, the shape function values require curve fitting of biaxial coupon data

[1] Wolfe WE, Butalia TS. A strain-energy based failure criterion for non-linear analysis of composite laminates subjected to biaxial loading. Composites Science and Technology, 58 (1998) 1107-1124.

Wolfe failure criteria

- *User input data added to MAT54:*
  - SEFT : strain energy axial tension
  - SEFC : strain energy axial compression
  - SEMT : strain energy transverse tension
  - SEMC : strain energy transverse compression
  - SES : strain energy shear
  - M1 : shape function factor, axial
  - M2 : shape function factor, transverse
  - M6: shape function factor, shear

- *Failure criterion becomes:*

$$\left(\frac{\int_{\varepsilon_1} \sigma_1 d\varepsilon_1}{SEFT \text{ or } SEFC}\right)^{M1} + \left(\frac{\int_{\varepsilon_2} \sigma_2 d\varepsilon_2}{SEMT \text{ or } SEMC}\right)^{M2} + \left(\frac{\int_{\varepsilon_6} \sigma_6 d\varepsilon_6}{SES}\right)^{M6} = 1$$

where depending on the loading applied, the tensile or compressive value will be used

Wolfe failure criteria

- *Code added to MAT54 for Wolfe criterion:*

```
einc1(i)=(strn1(i)+d1(i))*stg1(i)
einc2(i)=(strn2(i)+d2(i))*stg2(i)
einc4(i)=(strn4(i)+d4(i))*stg4(i)
```

– Strain energy components are calculated

```
if (stg1(i).gt.0.) then
c   for tensile fiber mode
    sef(i)=seft
else
c   for compressive fiber mode
    sef(i)=sefc
endif
...
ew(i)=(einc1(i)/sef(i))+(einc2(i)/sem(i))+
     1         (einc4(i)/ses)**msix

if (ew(i).gt.1.) efail(i)=0.0
```

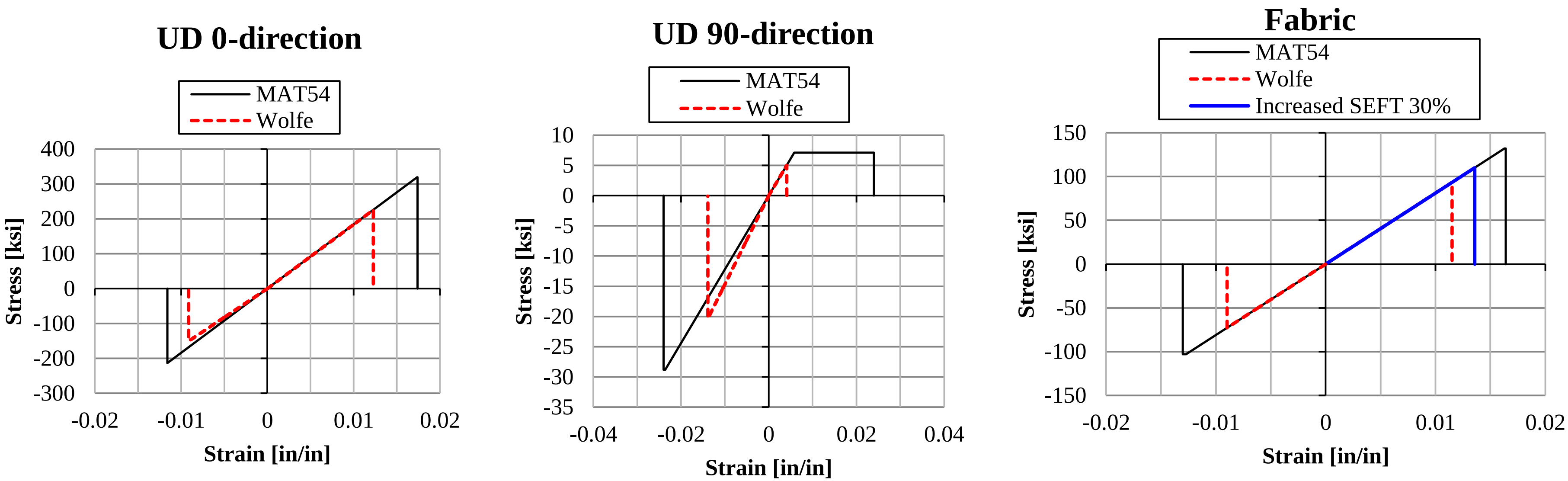
– Depending on the sign of the stress, the tensile or compressive values of maximum axial strain energy (SEF) and transverse strain energy (SEM) are used

– The Wolfe criterion is calculated

– Element failure if Wolfe is violated

Wolfe failure criteria

- *Using measured strain energy component values from material coupon experiments and assumed shape function values from Wolfe, the single element simulations for both the fabric and UD materials do not properly predict failure:*

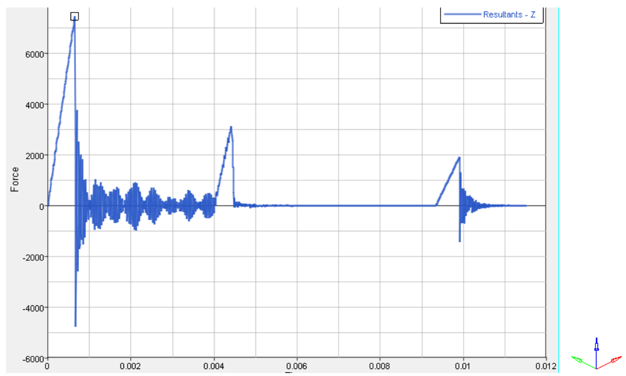


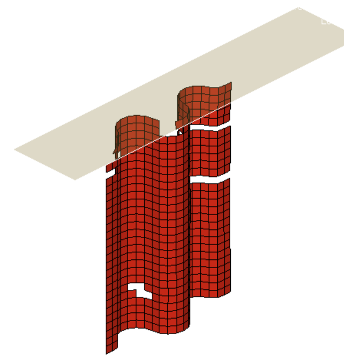
- *Changing the strain energy component input values (i.e. SEFT) does change the simulation as expected*
  - *Increased SEFT allows for an increased stress before failure in Fabric tension single element*

Wolfe failure criteria

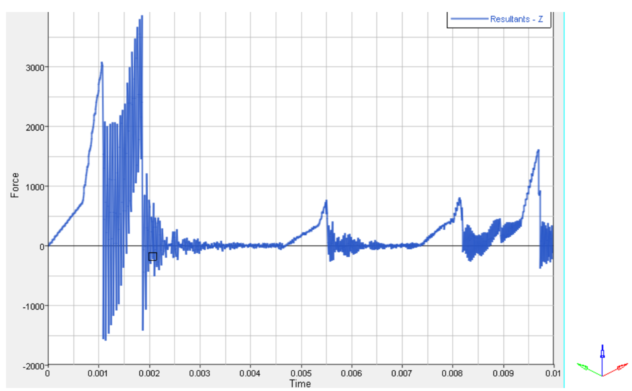
- *Using the Wolfe failure criteria in the crush simulations of the UD and fabric sinusoid element, premature failure is observed away from the crushfront, causing global buckling in both cases:*

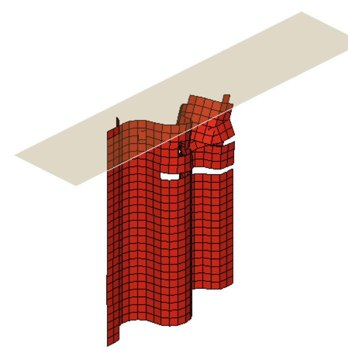
UD sinusoid:





Fabric sinusoid:



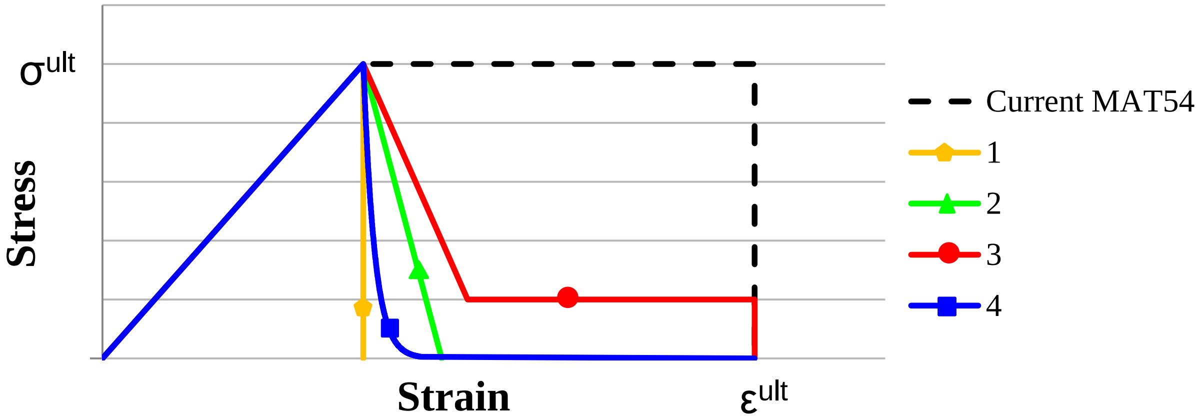


Modified failure criteria

- *Changing the failure criteria to better predict the onset of failure does not improve the capability of the composite material model*
- *Different criteria either perform as good as or worse than the existing MAT54 Hashin failure criteria*
- *In general, the capability of MAT54 to predict the onset of failure using the Hashin failure criteria work well as-is, as evidenced by the single element models*

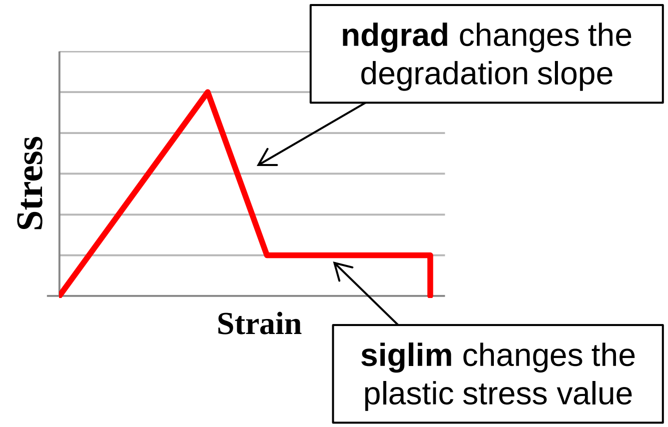
Modified post-failure degradation

- *Want to change the current elastic-perfectly plastic MAT54 stress-strain behavior caused by the post-failure degradation definition*
- *Different approaches are investigated to reduce stress following failure:*
  1. Expected physical behavior: Reduce stress immediately to zero upon failure
  2. Mimic a continuum damage mechanics model: Linearly reduce stress following failure until zero stress
  3. Linearly reduce stress following failure until a low value, and element is deleted by maximum strain parameters
  4. Reduce stress by 1% each time-step until deletion due to maximum strain



New code for stress degradation

- New user input parameters added for post-failure behavior options:
  - **stropt** implements the specified post-failure option:
    0. Regular MAT54 behavior
    1. Zero stress after failure
    2. Linear stress degradation following failure
    3. Linear degradation followed by a constant stress
    4. Logarithmic degradation
  - **ndgrad:** number of degradation iterations following failure (for **stropt** = 2,3)
  - **siglim**: percentage of maximum stress allowed during plastic deformation (for **stropt** = 3)



- The failure stress is recorded in **sigff**, **sigfc**, **sigfm**, and **sigfd**, depending on the failure mode
  - This occurs after the Hashin failure criteria, but just before the iflag failure flags are assigned, so this value can only be saved once

```
if (iflagf.ne.1 .and. ef2(i).gt.0) then
      sigff(i)=stg1(i)
endif
if (iflagm.ne.1 .and. em2(i).gt.0) then
      sigfm(i)=stg2(i)
endif
```

New code for stress degradation

Code added for post-failure behavior options:

- For **stropt** = 1
  - ef, ec, em, and ed are failure flags from the Hashin failure criteria
    - 1: no failure
    - 0: failure
  - efail(i) = 0 causes element deletion

```
if (stropt.eq.1) then
      if (ef(i).lt.1.e-8) efail(i)=0.0
      if (ec(i).lt.1.e-8) efail(i)=0.0
      if (em(i).lt.1.e-8) efail(i)=0.0
      if (ed(i).lt.1.e-8) efail(i)=0.0
endif


...
```

- For **stropt** = 2
  - **dmgkf** and **dmgkm** count iterations following fiber and matrix failure, respectively
  - $\mathbf{dndg} = \frac{1}{\boldsymbol{ndgrad}}$
  - Stress is reduced by **dndg***max stress every iteration for **ndgrad** iterations
  - During the final iteration (**dmgkf** = **dlim**), stresses are set to zero, and the element is deleted

```
if (stropt.eq.2.0) then
  if (ef(i).lt.1.e-8) then
    if (dmgkf(i).lt.dlim) then
      sig1(i)=sig1(i)-(dndg-sigff(i))
      dmgkf(i)=dmgkf(i)+dndg
    else
      sig1(i)=0.0
      sig2(i)=0.0
      sig4(i)=0.0
      efail(i)=0.0
    endif
   else
    dmgkf(i)=0.0
   endif
```

New code for stress degradation

- For **stropt** = 3
  - As long as the counter **dmgkf** is greater than the limit **dlim2**, the stress will degrade according to the number of iterations specified by the user
    - **dlim2** is determined by the user input **siglim**
  - Once the stress reaches the specified plastic limit (**siglim**) it is held constant at this value
  - The element is deleted due to the maximum strain-to-failure limits set elsewhere in the code

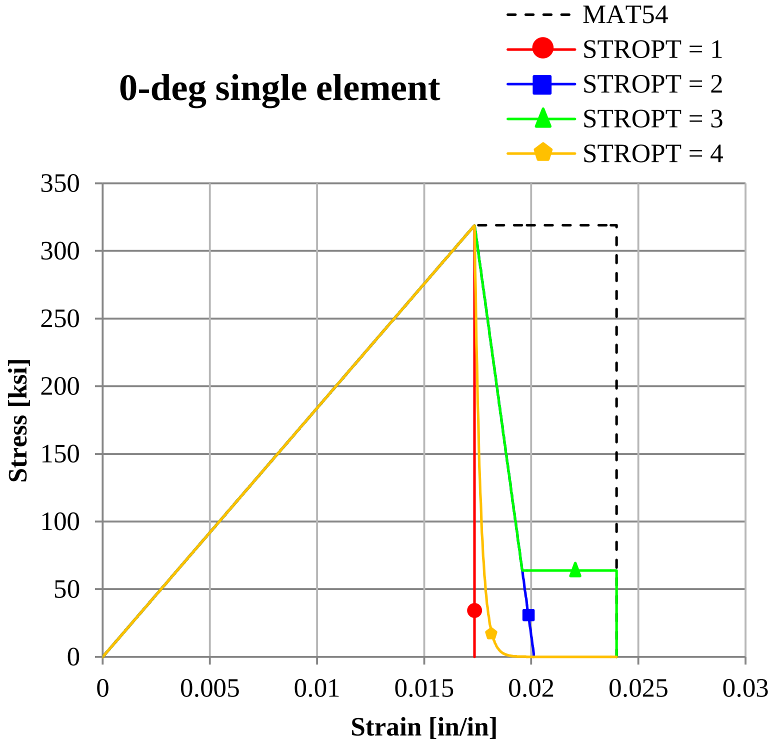
```
if (stropt.eq.3.0) then
  if (ef(i).lt.1.e-8) then
    if (dmgkf(i).lt.dlim2) then
      sig1(i)=sig1(i)-(dndg*-sigff(i))
      dmgkf(i)=dmgkf(i)+dndg
      if (sig1(i).lt.siglim*sigff(i)) then
         sig1(i)=siglim*sigff(i)
         dmgkf(i)=1.0
      endif
    else
      sig1(i)= siglim*sigff(i)
      dmgkf(i)=1.0
    endif
  else
    dmgkf(i)=0.0
  endif

...
```

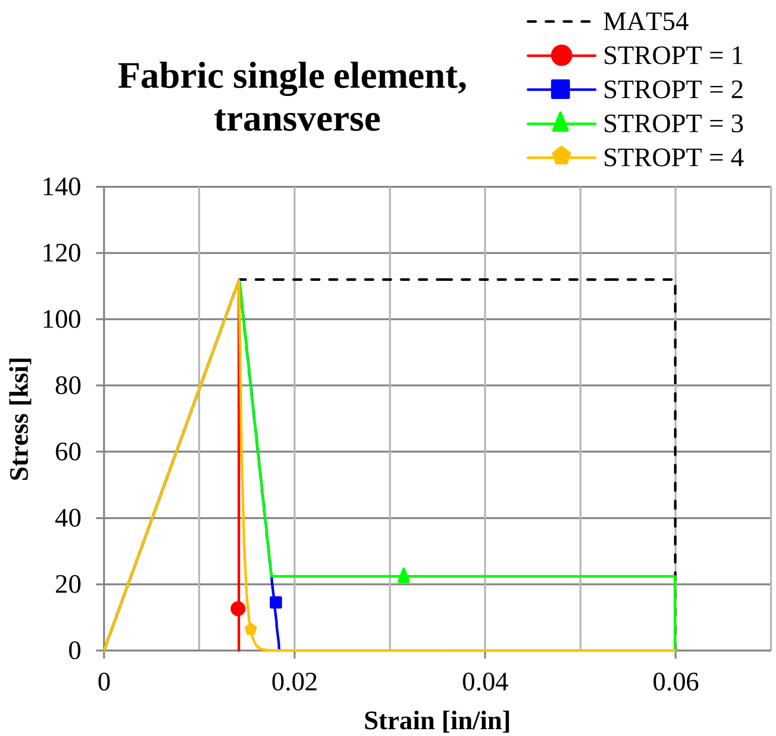
- For **stropt** = 4
  - If fiber failure occurs, the axial stress is reduced by 1% every iteration
  - If matrix failure occurs, the transverse and shear stresses are reduced by 1% every iteration
  - The element is deleted due to maximum strain-to-failure limits set elsewhere in the code

```
if (stropt.eq.4.0) then
if (ef(i).lt.1.e-8 .or. ec(i).lt.1.e-8) then
      sig1(i)=0.99*sig1(i)
endif
if (em(i).lt.1.e-8 .or. ed(i).lt.1.e-8) then
      sig2(i)=0.99*sig2(i)
      sig4(i)=0.99*sig4(i)
endif
```

Single element results

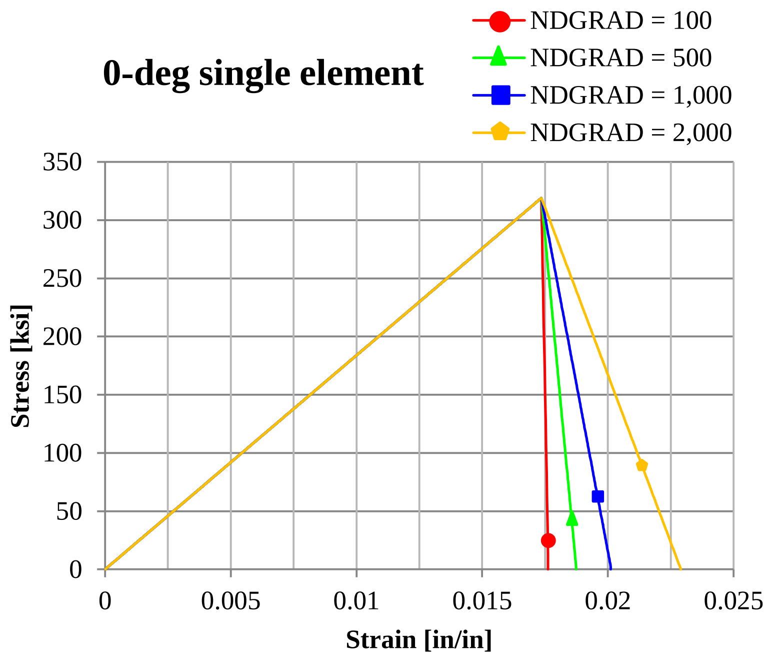
- To investigate the post-failure behavior modifications, the strain-to-failure of the UD single element is extended to 0.024 in/in, while the fabric transverse strain-to-failure value of 0.06 in/in is used, as in the crush simulations
- Baseline values for NDGRAD and SIGLIM are 1,000 and 0.2, respectively
- The new stress degradation schemes work as anticipated

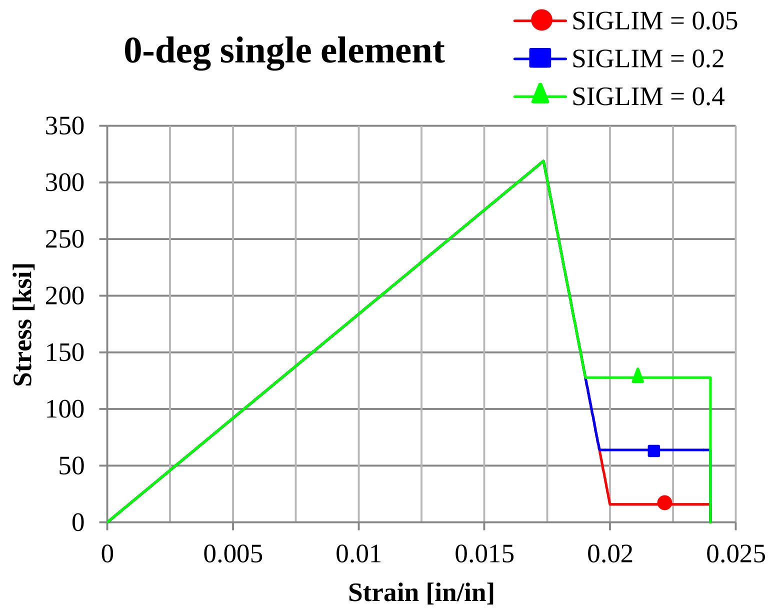




Effect of new user inputs

- *For the STROPT = 2 and 3 degradation options, the new user input parameters **NDGRAD** and **SIGLIM** directly control the slope of the degradation and the plastic stress value, as designed:*





Modified MAT54 results

- *Material model of UD materials improved*
- *New failure criteria do not outperform existing*
  - *SOFT parameter can be replaced by crush stress parameter, however neither are experimentally derived*
- *Post-failure degradation is key for modeling composites in crash*
  - *Some amount of plasticity is necessary after failure to simulate stable crush propagation*
  - *Even in the standard MAT54, the strain to failure is arbitrarily increased above its experimental value*
  - *Modified model gives user opportunity to uniquely define degradation scheme*
- *Crush simulation at the element level still relies on experimental data for matching*